Advancing Understanding of Human Health and Societal Vulnerability to Extreme Heat Events in Boston, MA

ADVANCING UNDERSTANDING OF THE HEALTH AND SOCIETAL IMPACTS OF EXTREME HEAT EVENTS IN BOSTON, MA

AUGUSTA A. WILLIAMS

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For Mol, Dad, and Sammy, and all the ones who got me here.

Dissertation Adviser: Dr. John D. Spengler, PhD, MS Augusta A. Williams

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ABSTRACT

Climate change is resulting in heatwaves that are more frequent, severe, and longer lasting, which results in public health threats to both morbidity and mortality. This is especially true in the Northeast United States, where heat-related mortality is projected to potentially triple by the end of the century if adequate climate change mitigation and adaptation strategies are not implemented. The first paper explored how central air conditioning and window air conditioning units were not equally adequate in overcoming high temperature loads indoors, and demonstrated how as thermal decompensation begins, protective behaviors were not widely enacted. The second paper aimed to determine if vital social services are impacted by extreme heat in Boston to help inform future adaptation planning. These results demonstrated that the Boston Police, EMS, and Fire Departments all experience more calls on hot days, with the Fire Department having the greatest relative impact on these days. The third paper used a case-only analysis to compare effect modification by individual, and small-area social and environmental heat-related risk factors on at-home and outside of the home mortality in Boston, MA. Census tracts with a greater proportion of people with limited English proficiency and low-to-no income individuals were more highly represented in those who died during the study period, but area built environment features, like a greater density of street trees and newly renovated buildings were able to reduce the relative odds of death within and outside the home. The fourth research papers aimed to evaluate the spatial distribution of these small-area social and environmental factors that determine heat vulnerability to at-home mortality in Boston, MA. The spatial analysis

of these factors in relationship to at-home mortality rates on hot days found that neighborhoods like Roxbury, East Boston, and Dorchester are socially and environmentally vulnerable to a greater at-home mortality rate on hot days, and should be prioritized in heat adaptation planning.

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AC	Air Conditioning / Air Conditioner
BASE	Building Assessment Survey and Evaluation
BEMS	Boston Emergency Medical Service
BFD	Boston Fire Department
BPD	Boston Police Department
BPM	Beats Per Minute
CO_2	Carbon Dioxide
CT	Census Tract
GSR	Galvanic Skin Response
HI_{MAX}	Maximum Heat Index
HR	Heart Rate
HW	Heat Wave
ICD-10	International Classification of Disease, 10^{th} Revision
IEQ	Indoor Environmental Quality
IRB	Institutional Review Board
KBOS	General Edward Lawrence Logan International Airport, Boston, MA, USA
MA	Massachusetts
NWS	National Weather Service
OR	Odds Ratio
RCP	Representation Concentration Pathway
RR	Relative Risk
T_{MAX}	Maximum Temperature
TS	Time Series
UHI	Urban Heat Island

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BACKGROUND AND INTRODUCTION

Extreme heat is the most health-harmful of all meteorological phenomenon, resulting in significant impacts on cardiovascular [1–3], respiratory[2–5], cerebrovascular[2], behavioral and mental health[6], kidney[5], and diabetes complications[7], reduced sleep duration and quality;[8], impaired cognition and productivity[9–11], poor birth outcomes[12–15], gastrointestinal infections[16], aggressive behavior[17,18], violent crime[19–23], and even mortality in all regions of the world[24–29].

Climate change is increasing the intensity, frequency, and duration of extreme heat events[30–33]. From 1971-2000, Boston, Massachusetts (MA) experienced an average of 11 hot days above 90°F each year. Without aggressive greenhouse gas emissions reductions, it is projected that Boston, MA may have up to 40 hot days above this threshold by 2030, and 90 hot days by 2070. As a result, heat-related deaths in Boston, MA have the potential to triple during this time without adequate adaptation strategies[34].

While extremely valuable information on the health impacts of extreme heat events exists in the aforementioned papers, a few important gaps still exist that have limited the full potential of adaptation strategies that local municipalities can implement. First, the impacts of extreme heat have the potential to wide existing disparities in socioeconomically and health disadvantaged communities across the US, disproportionately impacted populations that are most vulnerable to climate change. Correctly operationalizing heat vulnerability can inform adaptation strategies. To date, much of the existing literature on heat vulnerability has focused on societal risk factors, including but not limited to younger and older individuals, social isolation, limited education and/or income, and higher rate of preexisting diseases, all of which are key to characterizing vulnerability to extreme heat [30,31,35–39]. However, our built and natural environment determine the majority of our exposure to extreme heat, either exacerbating or mitigating temperatures indoors, where we spend up to 90% of our time[40]. The urban heat island also results in urban centers being significantly warmer than surrounding rural and suburban areas due to urban materials and design absorbing higher thermal loads that make it difficult to cool overnight[41]. There is more research needed to understand how both social and environmental factors influence the vulnerability of a neighborhood to the health impacts of extreme heat to best prioritize effective and equitable adaptation strategies.

Second, much of the existing literature on extreme heat impacts on human health have utilized ambient meteorological measurements. This has resulted in temperature exposure misclassification in temperature and public health research in two ways: temperatures vary across the city and buildings modify ambient conditions indoors. Using a single ambient measurement does not adequately characterize the temperatures people are experiencing in reality.

The primary solution we've used to date to cool our indoor environments is air conditioning (AC). Despite AC protecting public health as temperatures rise, it is not a sustainable solution to increasing frequency and severity of extreme heat events. AC is powered by electricity, which produces health-harmful air pollutants, like sulfur dioxide, nitrogen oxides, and particulate matter. Further, the refrigerants found in AC are extremely potent greenhouse gases, furthering the positive feedback to worsening climate change and extreme heat events. In the event power is lost, which may become more possible if our electricity grid is strained on hot days to meet cooling needs, buildings in historically cooler climates will not be passively habitable, and able to stay cool without AC[42]. This puts many people at risk for severe morbidity or even mortality during even normal operating conditions. Lastly, there are disparities in who is able to own and operate AC, with those of lower socioeconomic status being less able to afford AC and older adults having physiologic systems that delay the ability to perceive overheating. Building design and urban planning present important points of intervention for future heat adaptation that can reduce the overall capacity of AC needed to cool our populations, especially in historically cooler climates, like Boston, MA and other parts of New England. It is crucial to know how buildings are modifying temperature exposures so that buildings can be adapted and retrofitted to meet the warmer climates of the future to ensure buildings are resilient to high temperatures, including times when power is lost

Third, given the widespread effect of extreme heat on our health, behavior, and cognitive function, there are sub-clinical outcomes that have the potential to impact individuals that are considered less classically vulnerable. In Cedeno-Laurent et al. (2018) and Park (2016), there were significant reductions in the cognitive function[11] and test scores[10], respectively, in healthy young adults during extreme heat events. Additionally, research on how high temperatures are associated with aggressive and violent behaviors and inhibited risk decision-making further demonstrate how we are all vulnerable to the consequences of extreme heat on our societies, in addition to those that are considered to be more typically vulnerable[17-23]. Yet, more research is needed to understand these patterns at the local level to inform the most effective strategies to combat these societal effects. Characterizing the risks of extreme heat on less outcomes that impact all individuals in a community may increase local action on climate change mitigation and adaptation.

Last, recent research has suggested that the impacts of extreme heat on mortality begin to occur below the current thresholds used by local agencies to issue heat warnings and advisories, as well as enact local adaptation interventions, like the opening of cooling centers or hydration campaigns[43]. In Boston, MA, the most conservative threshold for local responses is when a heatwave is forecasted, where daily temperatures are predicted to be at or above 90°F for at least three consecutive days[44]. Other thresholds and warning products exist, capturing both forecasted temperature and humidity values, but are at thresholds even higher than 90°F (e.g. an Excessive Heat Warning is issued when the heat index is forecasted to be at least 105°F for at least 2 hours[44]). If the risk of mortality on hot days is enhanced on days that are below local extreme heat thresholds, further evidence is needed to assess the temperatures at which the risk of morbidity increases, given the many health outcomes that are impacted by extreme heat.

Dissertation Goals

Heat vulnerability assessments have been found to provide valuable evidence to inform the design, fund, and strategically implement adaptation interventions and solutions to protect vulnerable populations. The goal of this dissertation was to better understand the full extent of extreme heat on public health in the greater Boston, MA area. This involved both furthering the scientific understanding of how buildings and behaviors influence temperature exposures during extreme heat events, as well as broadening the scope of public health outcomes that are impacted by extreme heat. There were four main research questions that are addressed in this dissertation, all of which aid to fill the gaps outlined above.

- How do social and environmental (both natural and built) factors influence heat vulnerability in Boston, MA at the individual and neighborhood level?
- How are buildings vulnerable or resilient to extreme events and what role does that play in public health?
- Are current heat warning thresholds in Boston, MA adequate for capturing public health impacts, and how can we assess this using publicly-available datasets?
- In addition to impacts on morbidity and mortality, are there other societal effects of heat exposure in Boston, MA that impact an entire urban area?

Three studies were completed to this goal to expand the current understanding of both temperature exposures and societal health outcomes during extreme heat events in Boston, MA. In Chapter 1, "Building vulnerability in a changing climate: Indoor temperature exposures and health symptoms in older adults living in public housing during an extreme heat event in Cambridge, MA", examined how indoor heat exposures during an extreme heat event are modified by buildings with and without central air conditioning and the resulting impacts on the health and physiology of seniors living in affordable housing in Cambridge, MA. By characterizing indoor temperatures during extreme heat with varying cooling mechanisms in the field, we are able to reduce exposure misclassification bias, demonstrate how buildings can significantly modify indoor temperatures, and physiologic markers like heart rate can be negatively impacted by heat, even if clinical health symptoms are not yet present.

In Chapter 2, “The influence of heat on emergency services in Boston, MA: relative risk and time-series analyses of police, medical, and fire dispatches”, 2 epidemiologic methods are used to demonstrate how vital social emergency services (police, medical, and fire dispatches) are impacted by extreme heat in Boston, MA. An increased use of emergency services during hot days is imperative for the entire City of Boston, its residents, and its future budgets that must all become more resilient in the face of climate change.

In Chapter 3, “A case-only analysis of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA. ”, I compare the modification of at-home and outside of the home deaths on hot days by social and environmental (both natural and built) factors in Boston, MA with 3 temperature metrics. This research adds valuable information to both this scientific field, as well as to the implementation of local heat adaptation strategies by demonstrating that there are some environmental factors that can exacerbate or mitigate heat vulnerability due to social factors. Further, certain causes of death were more represented in the deaths that were studied, including substance abuse, death from an assault-related altercation, and injuries or accidents, although these are not currently widely represented in heat vulnerability assessments and adaptation planning.

Chapter 4, “Dying at home on hot days: A spatial analysis of at-home mortality in the context of individual and small-area social and environmental vulnerability in Boston, MA”, evaluates the spatial distribution of small-area environmental and social heat vulnerability factors and how they relate to the at-home death rate on hot days. High-resolution temperature data was used to assess differential temperature exposures across Boston with a discussion of how that has the potential to influence heat vulnerability. The neighborhoods of Dorchester, Roxbury, and East Boston were found to be most vulnerable to the impacts of extreme heat on dying at home, driven largely by greater proportion of people of color, those with low-to-no income, and presence of single-family homes. The papers and aims of this dissertation are:

Paper 1	Title	Building vulnerability in a changing climate: Indoor temperature exposures and health symptoms in older adults living in public housing during an extreme heat event in Cambridge, MA
	Aim	To examine how indoor heat exposures during an extreme heat event are modified by building and the resulting impacts on the health and physiology of seniors living in affordable housing in Cambridge, MA.
Paper 2	Title	The influence of heat on emergency services in Boston, MA: relative risk and time-series analyses of police, medical, and fire dispatches
	Aim	To determine if vital social services are impacted by extreme heat in Boston to help inform future adaptation planning.
Paper 3	Title	A case-only analysis of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA.
	Aim	To compare the evaluate effect modification by social and environmental heat-related risk factors on at-home and outside of the home mortality in Boston, MA during extreme heat.
Paper 4	Title	Dying at home on hot days: A spatial analysis of at-home mortality in the context of individual and small-area social and environmental vulnerability in Boston, MA.
	Aim	To compare the spatial distribution of small-area social and environmental factors that determine heat vulnerability to at-home mortality in Boston, MA to identify which neighborhoods may be most vulnerable to extreme heat events.

CHAPTER 1

Building vulnerability in a changing climate: Indoor temperature exposures and health symptoms in older adults living in public housing during an extreme heat event in Cambridge, MA

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Abstract

In the Northeastern U.S., future heatwaves will increase in frequency, duration, and intensity due to climate change. A great deal of the research about the health impacts from extreme heat has used ambient meteorological measurements, which can result in exposure misclassification because buildings alter indoor temperatures and ambient temperatures are not uniform across cities. To characterize indoor temperature exposures during an extreme heat event in buildings with and without central air conditioning (AC), personal monitoring was conducted with 51 (central AC, n = 24; non-central AC, n = 27) low-income senior residents of public housing in Cambridge, Massachusetts in 2015, to comprehensively assess indoor temperatures, sleep, and physiological outcomes of galvanic skin response (GSR) and heart rate (HR), along with daily surveys of adaptive behaviors and health symptoms. As expected, non-central AC units (T_{MEAN} = 25.6 °C) were significantly warmer than those with central AC (T_{MEAN} = 23.2 °C, $p < 0.001$). With higher indoor temperatures, sleep was more disrupted and GSR and HR both increased ($p < 0.001$). However, there were no changes in hydration behaviors between residents of different buildings over time and few moderate/several health symptoms were reported. This suggests both a lack of behavioral adaptation and thermal decompensation beginning, highlighting the need to improve building cooling strategies and heat education to low-income senior residents, especially in historically cooler climates.

1.1 Introduction

Extreme heat events are a significant public health threat that are increasing in frequency, duration, and severity with climate change [1,2]. Globally, people were exposed to an average of 1.4 more heatwave (HW) days in from 2000 to 2017 than from 1986 to 2005, and 18 million more extreme heat exposure events occurred in 2017 than in 2016 [3]. In Boston, Massachusetts (MA), there was an average of 11 days above 90 °F per year from 1971 to 2000, but it is expected to experience up to 40 of these hot days by the year 2030, and up to 90 hot days by 2070, depending on greenhouse gas emission trajectories [4].

As temperatures increase, the human body becomes less effective at thermoregulation, which has direct and indirect health impacts on cardiovascular, respiratory, renal, pancreatic, digestive, cerebrovascular, and cognitive functions that result in significant morbidity and mortality. Extreme heat events, such as the 2003 European HW and the 2015 HW in India, result in extraordinary loss of life [4,5]. However, temperatures that are currently designated as extreme will become more common with climate change, and are expected to result in significantly higher heat-related mortality and morbidity in the U.S. and throughout the world by the end of the century [6,7,8].

The impacts of extreme heat have the potential to widen existing disparities in economically disadvantaged and health-compromised populations in the U.S., as those who are most vulnerable will be most impacted by extreme heat with climate change. Human vulnerability to extreme heat arises from many risk factors, including, but not limited to, infants and the elderly, social isolation, low income, and low education [9]. Semenza et al. found that during the Chicago HW of 1995, there were higher odds of death for those with pre-existing medical conditions [10], and chronic disease has been found to be a risk factor for heat illness across the U.S. [11]. Pre-existing disease can alter sympathetic nervous system response, preventing cardiac responses that allow for thermoregulation adjustments during extreme heat exposure [12].

Older adults are more susceptible to adverse health outcomes during extreme heat events due to high prevalence of pre-existing disease, medications, and autonomic nervous system impairments affecting the thermoregulation and perception of extreme temperature exposure [13]. Skin-related vasoconstriction and vasodilation have both been found to be diminished in older adults, even when considering younger individuals at similar fitness and hydration levels [14]. The number of elderly individuals who are at least 65 years old in the U.S. is expected to more than double by mid-century, and will make up one-quarter of our population by 2060 [15], resulting in a larger group of susceptible individuals that will be vulnerable to the health impacts of HWs.

Air conditioning (AC) has been widely adopted as the main adaptation strategy to mitigate extreme heat exposures indoors and is extremely important in reducing the incidence of poor health outcomes during extreme heat [10,16]. Quinn et al. (2017) found that central AC is more effective as overcoming internal thermal loads during extreme heat and cooling indoor environments compared to portable or window AC units [17]. A 2011 study in New York City has found that, of seniors or adults in poor health, 34% surveyed did not own or use AC during extreme heat events, 30% were unaware of heat warnings, and many did not perceive themselves to be at risk of the extreme temperature exposures [18]. Between a fifth and a third of Massachusetts residents have central AC at home, while 20% of households lack any type of AC [19,20].

Despite the dependence on AC for cooling during extreme heat, one of the many protective factors often studied with regard to heat stress, the role of buildings is less well-understood. Depending on the building architecture, design, orientation, materials, and ventilation, extreme temperatures may be exacerbated indoors, as compared to outdoor temperatures during extreme heat events due to internal heat loads and the building's thermal mass. Individuals who are most vulnerable to the health impacts of extreme heat are less likely to have access to or utilize AC. While upwards of 90% of residents in New York City were found to have some form of AC, roughly only 50% of public housing residents have access to AC [21]. Even in cities with widespread AC use, such as in Maricopa County, Arizona, nearly 40% of heat-related deaths happen indoors due to a variety of factors, including non-functioning ACs, lack of electricity, and disabling ACs to avoid high financial costs [22].

In the United States, adults can spend up to 90% of their time indoors [23]. In buildings without adequate cooling systems, people may be exposed to elevated indoor temperatures, thus increasing the risk of experiencing heat-related health effects. A great deal of the previous research about the health impacts resulting from extreme heat exposure has utilized ambient meteorological measurements to classify heat exposures, which can result in exposure misclassification in two ways: from buildings altering temperatures indoors where people are primarily exposed and from fine spatial differences in ambient temperatures that are not uniform across a city.

There are also a wide range of adaptive behaviors an individual can take that could mitigate or exacerbate heat exposure and poor health outcomes as a result. A past study in Detroit, Michigan found that behaviors like opening windows/doors, using fans or AC, and leaving the house have been used more than behaviors like changing clothes, showering, and going to the basement/porch/yard for urban-dwelling adults [24]. However, these behaviors are most frequently enacted in more moderate temperatures (23.8 °C–26.6 °C), and least used when indoor temperatures exceed 32.2 °C [24]. While there was a large majority (>90%) of older adults surveyed in Australia who reported wearing cooler clothing, closing curtains/shades, and drinking more fluids during hot days, less than 14% reported going to a cooler place [25]. During a 2013 HW in the United Kingdom, the elderly were the least likely to take similar protective measures against the heat, while those with higher income and education reported taking these measures often/always [26]. As is demonstrated here, the use of heat-mitigating adaptive behaviors varies widely.

Several of the risk factors associated to weakened thermoregulation during periods of heat stress are aggravated in older adults: lower capillary blood flow for radiative and convective cooling, lower sensitivity to thermal stimuli and core temperature-activated vasodilation, and maximal skin blood flow; all of these are detrimentally impacted by dehydration [27]. Drinking water during hot periods in urban areas has been found to be associated with a decreased risk of heatstroke [28]. Given the physiologic importance of vasodilation and its dependence on water intake, hydration is a key adaptive behavior that impacts human thermoregulation during periods of extreme heat.

In Cambridge, MA, the location of this study, buildings have been designed based on historical climate (i.e., colder winters and ocean-moderated milder summers). With warming summer temperatures, buildings without adequate cooling systems have the potential to retain heat, even during non-extreme events, in the future. This study characterized the indoor environmental quality (i.e., temperature, relative humidity, carbon dioxide, and noise) in the apartments of older adults residing in public housing in Cambridge, MA during an extreme heat event. In addition, personal physiological parameters were tracked with wearable devices, capturing daily adaptive behaviors, physiological responses to heat, and health symptoms. The use of affordable sensors and personalized monitoring provided a more comprehensive and representative documentation of participants' exposures and experiences over the course of several summer days when an extreme heat event occurred compared to relying on ambient meteorological stations placed throughout a city. Improving the understanding of the exposures experienced by low-income seniors at home during extreme heat events has the potential to inform more equitable adaptation strategies that increase the resilience of this vulnerable population.

1.2 Methods

1.2.1 Study Design and Participants

A cohort of low-income seniors, living in public housing in Cambridge, MA, participated during the summer of 2015. This study took place over three periods: 29 June–3 July, 6 July–14 July, and 28 July–2 August, deploying study instruments when weather was predicted to be especially hot. Participants were recruited from two public housing units in Cambridge, MA. The first residence was a 180-unit multi-story high-rise building with five- and twelve-story sections that was originally built in 1973 and was renovated in 2013, and all residents had central AC ($n = 24$). The second residence was a 180-unit, cast-concrete 19-story high-rise building originally constructed in 1976 (non-central AC, $n = 27$) and had mixed-use AC with residents using either efficiently working window AC units, less efficiently working window AC units, or no window AC unit at all. In both buildings, residents received full energy subsidies to cover energy costs.

Prospective participants received details of the study objectives and protocols at informational meetings held at each of the study sites. Recruitment occurred on a rolling basis until recruitment targets (at least $n = 20$ for each building) were met; the research team only required that groups from both building types were balanced in terms of participant age and sex. Inclusion criteria required that the participant was at least 55 years of age, resided in either of the study buildings, and met a set of predetermined health conditions (not using oral or intravenous antibiotics or chemotherapy, was not using prednisone or nonsteroidal anti-inflammatory drugs, and did not currently have acute infectious disease (cold/flu, gastroenteritis, etc.)). There were no significant differences in the prevalence of pre-existing health conditions between participants living in these two buildings (Table 1). It was found that 92.6% and 79.2% of participants in the non-central AC and central AC groups reported that energy costs did not limit their use of AC ($p = 0.88$, Table 1), which is a common and important reason for not cooling a home environment in other low-income populations. Therefore, we assumed that these populations were comparable and living in either building was independent of the participant's demographics, health status, energy financing restrictions, and potential health outcomes.

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Institutional Review Board (IRB) at the Harvard T.H. Chan School of Public Health (IRB15-1435).

1.2.2 Survey Instruments

Consented participants completed a baseline survey to assess their personal demographics (i.e., age, gender, height, weight, smoking, race, and ethnicity). The baseline survey also included information on sleep habits, as well as perception and satisfaction with existing indoor environmental quality (IEQ, i.e., thermal comfort, indoor air quality, acoustics, and lighting). Two key metrics assessed via the baseline survey were the number of pre-existing conditions each participant had been previously diagnosed with by a healthcare professional, and whether the participant had an appropriate heat action plan, defined by having at least one adaptive measure that they would do during an HW (turn on AC/fan, remove clothing, increase hydration, seek medical attention, etc.). The baseline survey is available in Table 1.S1 (Supplementary Materials).

Participants were instructed to complete a self-administered survey every morning after waking for the duration of the study, which inquired about the previous day's activities, IEQ, sleep quality and duration, and adaptive behaviors (i.e., beverage consumption, physical activity, and window opening/closing). We chose to also specifically assess hydration given its importance in cooling core body temperature via enhanced intracellular fluids to allow for enhanced vasodilation. Additionally, the other adaptive behavior questions (window opening/closing) were not consistently reported by study participants, while hydration (number of glasses of water) was consistent throughout the study period. We used the following symptom groups previously identified by the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) study as the most representative health outcomes associated to IEQ: neurocognitive (dizziness, nausea, headaches, and thirstiness); allergies (skin rash and sneezing); lower respiratory (coughing, breathing problems, and wheezing); irritation (nose bleeds, eye irritation, and sore throat); upper respiratory (ear pain, nasal drip, common cold, and sinusitis), mental health symptoms (tiredness, anxiety, irritation, and depression), and heat stress (nausea, numbness in hands/feet, dry skin, rash, sweating, and clammy skin) [29]. Musculoskeletal symptoms were not included in our survey as they were not a focus of this particular study. Instead, we expanded the number of symptoms associated with mental health disorders. Recognizing that neurocognitive health symptoms may also result from heat stress [30], even in young, healthy adult populations [31], these symptoms were combined with heat stress symptoms to assess symptoms experienced by the study participants. The daily survey is available in Table 1.S2 (Supplementary Materials).

1.2.3 Environmental Measures

IEQ monitors (Netatmo, France) were installed in each participant's bedroom to measure indoor dry-bulb temperature (°C), relative humidity (%), carbon dioxide concentration (CO2, ppm), and noise (dBa). The monitors were installed following a standardized protocol, ensuring they were away from sources of heat (computer screen, direct insolation, etc.) or drafts (e.g., windows and AC vents). Before deployment, CO2 was referenced to outdoor air (~400 ppm) to eliminate a drift error. CO2 drift and gain errors during deployment were estimated by collocating the IEQ monitors next to a recently calibrated instrument (Q-trak 7575, TSI Instruments, Shoreview, MN USA) inside a chamber, following ten stepwise increments from 400 to 3000 ppm. Values from the calibrated instrument were used as a reference to produce monitor-specific adjustment curves to match the experimentally derived values. Hourly outdoor weather variables were obtained from the local airport weather station (Logan International Airport, KBOS), located approximately five miles away from the study site. Indoor temperature exposures were analyzed as continuous measurements (5-min intervals) of daily means respective to each participant's residential unit.

1.2.4 Physiologic Measurements

Participants wore an actigraphy-based sleep tracker (Basis Peak watch, Intel, USA) on their non-dominant wrist and were instructed to wear it at all times, especially during sleep, and except when bathing/swimming. Tosses and turns during sleep were quantified by the tracker. The tracker used photoplethysmography to measure the heart rate (HR) in beats per minute (bpm), and galvanic skin response (GSR) in microsiemens at a 1-min resolution. Hourly HR and GSR means were utilized in statistical analyses.

1.2.5 Statistical Analyses

Building-level characteristics were analyzed with Mann–Whitney–Wilcoxon tests (IEQ variables), Student t-tests (demographic traits), binomial test of proportions (IEQ threshold comparisons), and paired t-tests (hydration). A binary variable having reported at least one moderate or severe heat- or non-heat-related health symptom in a given day was considered as a primary outcome. Generalized additive mixed models were used to evaluate the influence of mean hourly indoor temperatures and physiologic markers. GSR was log-transformed. To investigate the effect of the indoor temperatures on both heat- and non-heat-related self-reported health outcomes, we conducted a mixed-effects logistic regression model with a binomial distribution. Participant, nested within a building, was treated as a random effect in all models to account for repeated measurements within each subject and non-time-varying covariates, such as age, gender, U.S.-born status, and pre-existing health conditions, as well as other unquantifiable differences that may exist between buildings. Exploratory analyses for time spent outdoors and maximum daytime ambient temperature yielded few differences between or within individuals and groups, so these were excluded from the models. The final model evaluated the association of indoor maximum temperature with having at least one self-reported health outcome (binary) while controlling for that having at least two pre-existing conditions (binary) or having an appropriate heat action plan (binary). R (Version 3.5.0, R Core Team, Vienna, Austria) was used for all statistical analysis.

1.3 Results

1.3.1 Descriptive Results

There were no significant differences in demographic characteristics (age, gender, ethnicity, etc.) or in the prevalence of pre-existing health conditions between participants living in these two buildings (Table 1.1). The number of participants with a heat action plan was marginally different (p = 0.08) with more participants without central AC reporting protective measures. The average daily survey completion rates for the study were 79.0% for the central AC building and 77.5% for the non-central AC building throughout the study period. Therefore, we assumed that these populations were comparable and living in either building was independent of the participant's demographics, health status, or potential health outcomes.

Table 1.1 Descriptive statistics for demographics, pre-existing medical diagnoses, and indoor environmental quality of study participants living in public housing with and without central air conditioning (AC) in Cambridge, MA.

Descriptive Statistics	Non-Central AC (n = 27)	Central AC (n = 24)	p-Value
Demographic information			
Age, mean (SD) years	65.3 (7.9)	65.5 (7.5)	0.90
Sex, n (%) male	11 (45.8)	11 (40.7)	0.71
Race, n (%) non-white	7 (29.2)	10 (37.0)	0.83
Born in the United States, n (%)	16 (66.7)	21 (77.8)	0.37
Good + self-assessment of health, n (%)	19 (70.4)	13 (54.1)	0.23
Ever smoker, n (%)	15 (62.5)	21 (77.8)	0.23
Energy costs (do not limit AC use), n (%)	25 (92.6)	19 (79.2)	0.88
Have a heat action plan, n (%)	20 (74.1)	13 (54.2)	0.08
Indoor environmental quality			
Temperature, mean (SD) (°C)	25.6 (2.28)	23.2 (1.8)	<0.001
Relative humidity, mean (SD) (%)	57.9 (7.3)	67.0 (6.7)	<0.001
Absolute humidity, mean (SD) (g/m3)	0.0140 (0.002)	0.0141 (0.001)	0.5356
Vapor pressure, mean (SD) (hPa)	1939.7 (343.9)	1935.9 (209.0)	<0.001
Noise, mean (SD) (dB)	54.3 (8.1)	48.0 (8.1)	<0.001
Carbon dioxide, mean (SD) (ppm)	559 (176.9)	546 (161.2)	<0.001
Pre-existing medical diagnosis, n (%)			
Chronic migraines	7 (25.9)	7 (29.2)	0.80

Table 1.1 (Continued)

Severe headaches	5 (19.2)	7 (29.2)	0.41
Asthma	8 (30.8)	3 (12.5)	0.12
Chronic bronchitis	6 (23.1)	5 (20.8)	0.85
Allergies	12 (44.4)	12 (50.0)	0.69
Eczema	3 (11.1)	3 (12.5)	0.88
Hives	2 (7.7)	3 (12.5)	0.57
Sleep apnea	9 (34.6)	8 (33.3)	0.92
ADD/ADHD	3 (11.1)	5 (20.8)	0.34
Hearing loss	5 (18.5)	4 (16.7)	0.86
Thyroid	5 (18.5)	4 (16.7)	0.86
Diabetes	9 (33.3)	7 (29.2)	0.75
Heart disease	5 (16.7)	4 (16.7)	0.81
Chronic fatigue/Fibromyalgia	2 (7.4)	4 (16.7)	0.31
Depression	7 (25.9)	10 (41.7)	0.23
Anxiety	8 (29.6)	12 (50.0)	0.14
COPD	4 (14.8)	2 (8.3)	0.74

As expected, mean indoor values of temperature, vapor pressure, noise, and CO_2 were significantly higher in the non-central AC residences than in the central AC residences ($p <$ 0.001). The mean indoor relative humidity was significantly higher in the central AC group than in the non-central AC building ($p < 0.001$), but absolute humidity was similar between building groups ($p = 0.5356$) (Table 1.1). Indoor temperatures of the non-central AC residences closely followed the ambient temperatures, but as outdoor temperatures rose, the indoor temperatures of the central AC residences dissociated from this correlation with ambient temperatures (Figure 1). In both the central AC and non-central AC buildings, the daytime differences between indoor and outdoor temperatures (AC: −3.7 °C, non-central AC: −1.1 °C) were significantly different than the night-time differences between indoor and outdoor temperature (AC: −3.7 °C, non-central AC: −1.5 °C) ($p = 0.029$ and $p = 0.024$ for daytime and night-time situations, respectively) (Figure 1.2). The difference in nighttime indoor-outdoor temperature difference between buildings was also statistically significant ($p < 0.001$). Even though mean indoor temperatures were cooler than ambient temperatures for both buildings, 45.7% (central AC) and 63.3% (non-central AC) of daytime hours and 64.5% (central AC) and 82.8% (non-central AC) of overnight hours had mean indoor temperatures that exceeded ambient temperatures, which were significantly different between buildings ($p < 0.001$).

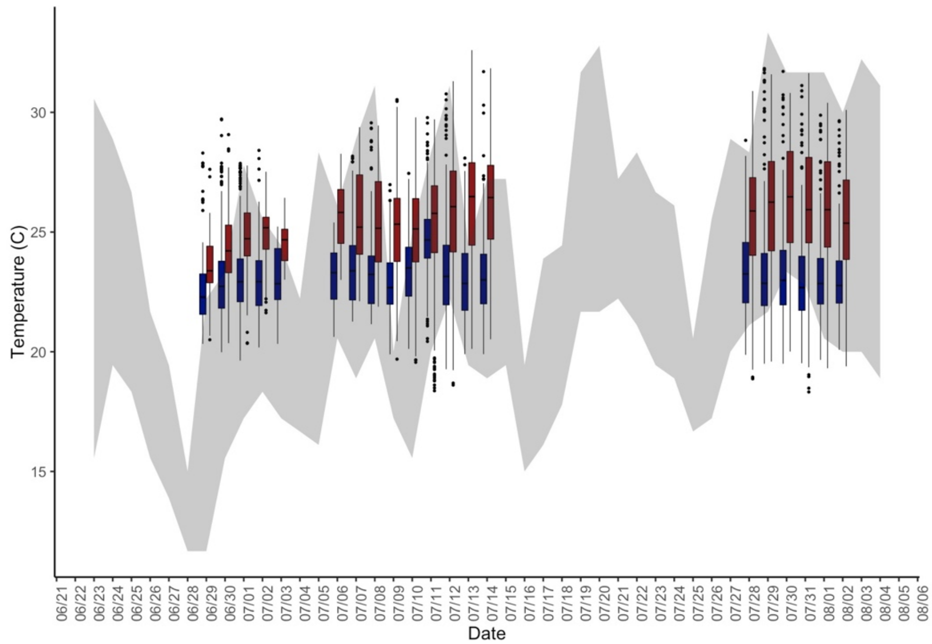


Figure 1.1. Indoor temperature distribution (boxplots) of non-central AC (red) and central AC (blue) groups; daily range of ambient temperature (grey shading).

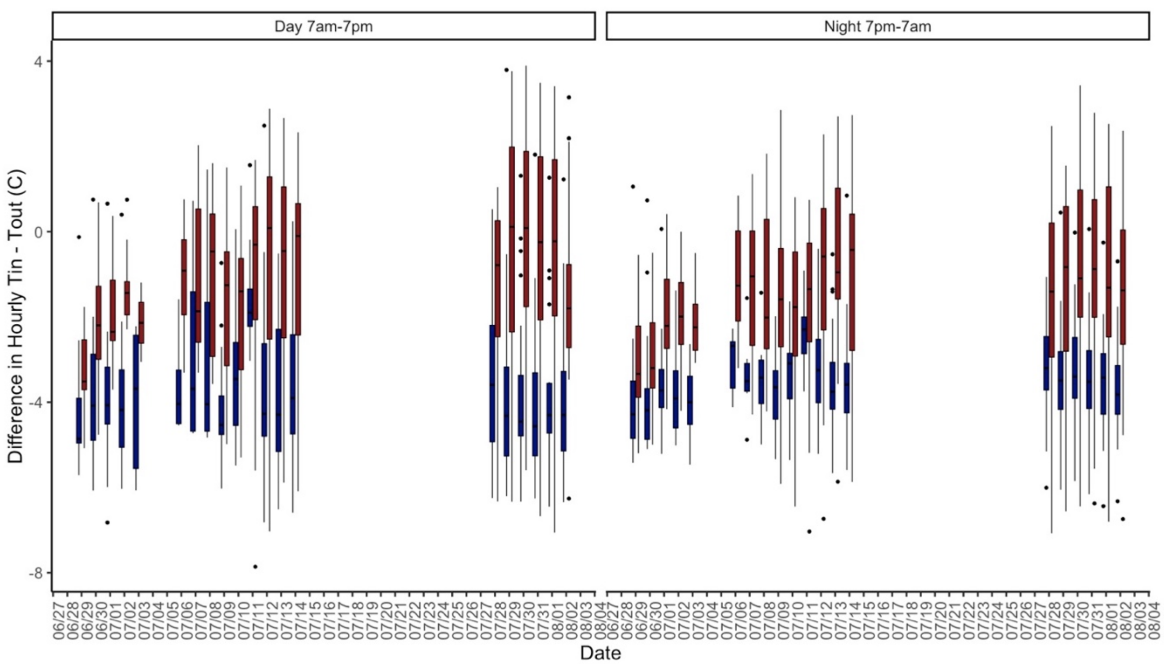


Figure 1.2. Difference between hourly indoor and outdoor temperatures (boxplots) of non-central AC (red) and central AC (blue) groups during both day (7 am–7 pm) and night (7 pm–7 am) periods.

1.3.2 Physiology and Sleep

The relationship between tosses and turns and indoor temperature was modeled as a Poisson model of the toss and turn counts per night and viewed as a dependent variable, and mean temperature overnight and building were regarded as independent variables. When analyzing the reported duration of sleep from the daily surveys or the watches, there was no significant association with indoor temperature or building. However, the number of tosses and turns recorded by the watches during sleep, as quantified by the personal sensors, increased with indoor mean temperatures (Figure 1.3). No significant effect of building was observed (p = 0.496).

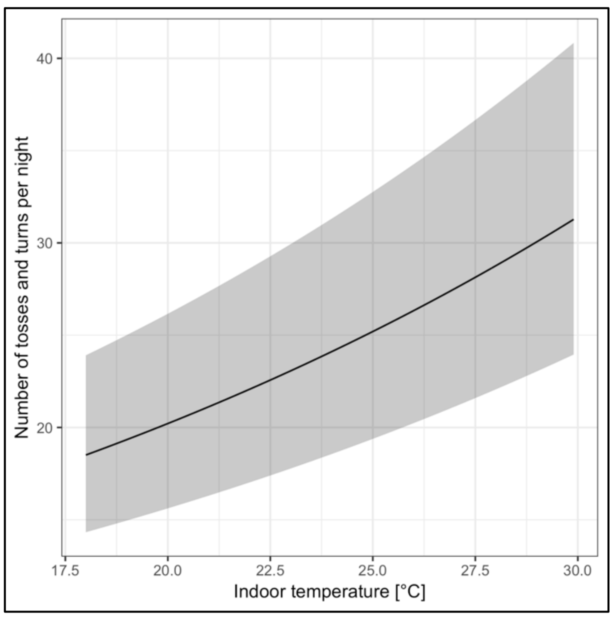
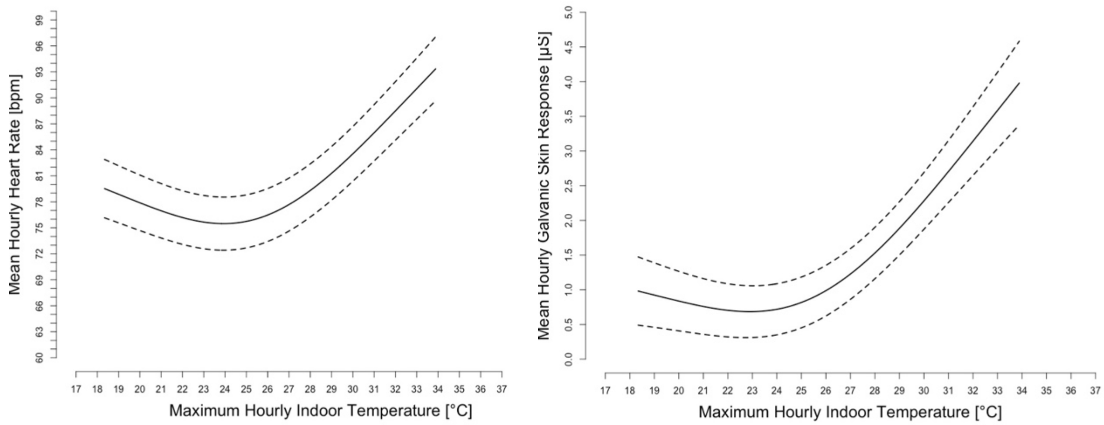


Figure 1.3. Relationship between indoor temperatures and number of tosses and turns during sleep periods. The gray shading represents the 95% confidence interval.

The objective physiologic parameters, as measured by the watches, showed that the maximum hourly indoor temperature was a significant predictor ($p < 0.001$) of mean hourly HR after adjusting for building and had a non-linear relationship. An optimum of HR and GSR was found at around 24 °C (~75.2 °F). Both GSR and HR were found to increase once temperatures exceeded approximately this optimum threshold of 24 °C. (Figure 1.4). Both of these objective parameters demonstrated that as indoor temperatures were above or below this threshold, there were significant decrements in these physiologic markers. This threshold is higher than the threshold documented in a study using similar methodology for assessing the impact of heat on students' cognitive functioning (~22 °C) [31].

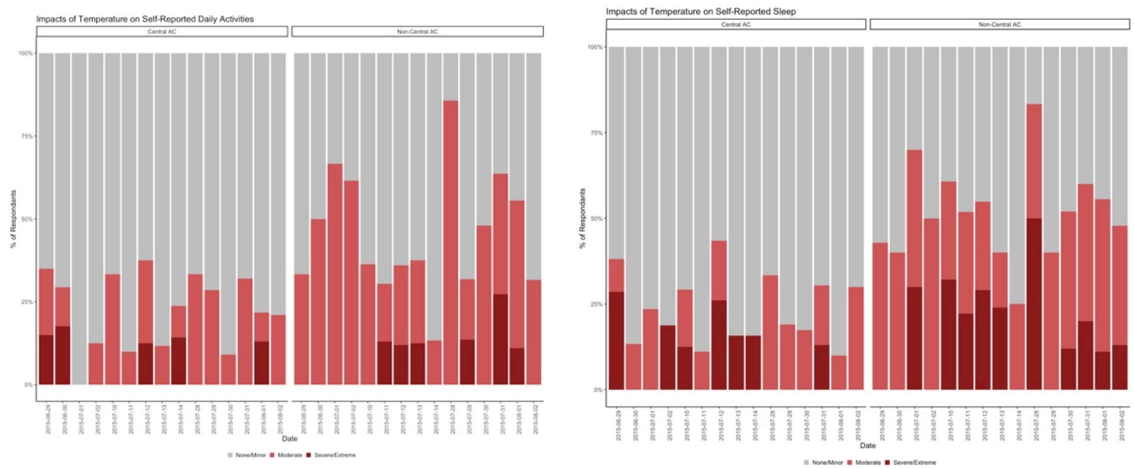


(a) (b)

Figure 1.4. Non-linear association between hourly indoor temperatures and mean hourly heart rate (HR), after adjusting for building (a). Non-linear association between hourly indoor temperatures and mean hourly log-transformed galvanic skin response (GSR), after adjusting for building, and HR (b). The dotted lines represent the 95% confidence intervals.

1.3.3 Perception and Self-Report Health Symptoms

As expected, the number of participants who reported their unit was too hot increased as the study period went on, which follows increases in temperature (Figure 1.S1, Supplementary Materials). The impact of thermal conditions at home on daily activities (Figure 1.5a) and on sleep (Figure 1.5b), as assessed through the daily survey, worsened throughout the study period. Approximately equal proportions of residents were satisfied, dissatisfied, or neither satisfied or dissatisfied between the non-central and central AC buildings at baseline (Figure 1.S2, Supplementary Materials). However, almost 75% of participants in the non-central AC building indicated that their apartment's temperature was too hot, while less than 25% of central AC building occupants felt too hot at baseline (Figure 1.S2, Supplementary Materials).



(**a**) (**b**)

Figure 1.5. (a) Percent of respondents indicating the impact the thermal conditions of their apartment have on their self-reported daily activities**. (b)** Percent of respondents indicating the impact the thermal conditions of their apartment have on their self-reported sleep.

Comparing hydration throughout the study period, the number of glasses of water consumed on hot days during the study (T_{MAX} > 32.2 °C (90 °F)) was not significantly different than on days below this threshold for either building (central AC: p = 0.48; non-central AC: p = 0.64). Hydration was also not significantly different on days that were warm but did not meet extreme heat thresholds (>29.4 °C (85 °F)) (central AC: p = 0.89; non-central AC: p = 0.21). Thus, despite an enhanced perception of hotter indoor living conditions and reporting greater impact of these thermal conditions on routine living functions, the study participants did not drink more water, which many highlighted as a key action to take to protect themselves from heat stress.

During the study period, 9 participants reported 177 moderate and severe health symptoms, with 44 of those symptoms being heat-related. The number of daily self-reported health symptoms in any category, as well as those related to heat, was highest in the units at the highest indoor temperature quartiles for those with and without pre-existing conditions. The final models for experiencing at least one self-reported health outcome, which follows on previously methodology in Quinn and Shaman [32], controlled for mean daily indoor temperature and having either pre-existing conditions or a personal heat action plan. Given the relative rarity of these outcomes being reported in the study period, models examining the interaction between these covariates or with additional covariates were not assessed because of lack of statistical power (Table S3 and Table S4, Supplementary Materials; Equations (1) and (2)).

1.4 Discussion

Many studies have shown the association between heat exposure and health outcomes through the use of laboratory-controlled settings and/or through ambient exposure metrics. This study comprehensively characterized individual temperature exposures at home and IEQ using personal sensors and wearable devices. Simultaneously, it also incorporated environmental and behavioral factors that influence resilience and adaptive capacity during extreme heat events, which influence an individual's susceptibility to poor health outcomes during an extreme heat event. The results showed that indoor temperatures alter physiology, increasing both GSR and HR, with an optimum range for these physiologic markers centered at around 24 °C. Simultaneously, participants' perception of indoor temperatures and the impact of these exposures on their activities and sleep worsened. However, these changes did not result in a significant change in hydration, signaling a lack of enacting an important adaptive behavior and thermal decompensation beginning as the body is unable to thermoregulate.

While outdoor temperatures are associated with public health outcomes, these analyses underscore the importance of characterizing exposures to temperatures indoors and accounting for building conditions for understanding health risks during and after extreme heat events. All of these residents, given their close proximity, were exposed to the same ambient conditions, but their residential building played a role in either exacerbating or mitigating heat exposures. It also demonstrated the complex nature of heat vulnerability, pre-existing conditions, adaptive behaviors, and access to and use of AC (either well-functioning window units or less efficient window units for those in the non-central AC building). The success of using wearable sensors devices to monitor indoor and personal exposures demonstrated the feasibility of resolving a previous research limitation [27,28]. As sensor technology develops further and becomes more widespread, it may be possible to intervene before someone experiences life-threatening heat stress.

About 37% of all public housing residents in the U.S. are seniors over age 62, while 48% of public housing residents in Massachusetts are seniors [32]. By 2030, it is projected that 20% of the U.S. population will be seniors [15] and almost 90% of seniors have reported that they want to stay in their homes, living independently, as long as possible [33]. Living environments that are adequately cooled to meet the needs of older adults and effective personal heat mitigation strategies will be crucial to protect the health of seniors in the future in a warmer climate. Harnessing available technologies to track the IEQ of living environments, as well as the health conditions, of this population in real time, has the potential for greater independence while aging in place.

The suite of measurements utilized in this study revealed several interesting features of the indoor environments of public housing senior residents. Even though the majority of those without central AC did have access to window AC units, at a variety of efficiency and frequency of use preferences, these residences were continually warmer than those with central AC. This follows on findings from Quinn et al. (2017) that apartments cooled by window and portable AC are warmer than those with central AC and retain the heat for upwards of 1 day after ambient heat subsides [17]. In this study, window AC units were of a variety of ages and conditions, or were not used regularly or soon enough by the participants, yielding increasingly hotter temperatures indoors that persist as outdoor temperatures rise and then subside.

During the overnight hours, the differences between the indoor and outdoor temperatures were most pronounced across all units, and the building without central AC was significantly warmer than the building with central AC. Researchers have recently preferred a shift from the thermal comfort model where the percentage of satisfied occupants is based on climate chamber experiments to a thermal health model that involves not only environmental parameters but also individual physiological and psychological factors that are specific to vulnerable populations, like low-income seniors, to best protect public health [34, 35, 36].

Not being able to identify adaptive behaviors that would be protective during extreme heat events has been found to be a marker of increased susceptibility to heat exposure. Analyses suggested that having a heat action plan did increase the odds of reporting any or heat-related health symptoms, although not significantly. When assessing these results in the context of hydration, or the lack thereof, the result suggested that although residents were aware of protective actions during heat, they did not implement them in effective ways. This highlights an important area for intervention.

Takahashi et al. (2015) demonstrated that adaptive cooling behaviors were improved in elderly residents in Japan that received heat wave warnings in tandem with water distribution [37]. Although a great deal of the existing literature on the effectiveness of hydration during thermal stress has been done in the field of sports medicine and/or with adults under physical exertion and the study population here is largely sedentary, water levels within the bodies of older adults and thirst responses decrease with age [27], so thermoregulatory responses are weakened in these individuals. Marked changes in GSR as temperatures increased demonstrated that the study participants were losing water at a greater rate as it got hotter indoors, without increasing hydration to replenish body fluids. Future studies should examine hydration, in quantity and quality, in coordination with other adaptive behaviors for the most comprehensive description of adaptive responses.

These results provide evidence that not all vulnerability metrics, e.g., not having central AC, older age, low income, and pre-existing conditions, are equally determinant of poor health during extreme heat exposures. Åström et al. (2011) have noted the importance of studying non-fatal events and how housing modifies these outcomes in the elderly [38]. While the association between indoor temperatures, pre-existing conditions, and all health outcomes was not significant when modeled, the results of this study suggested areas of further investigation with a higher sample size, extended assessment periods, and more robust measurements of these outcomes.

While increasing utilization of AC is an obvious response to increasing heat, it will increase energy demand and shed more heat to ambient environments. AC should not be the only adaptation considered, in part because of the inherent economic disparities about who can afford to purchase AC and pay for the energy. Despite AC units becoming more efficient over time [39], utilizing AC with our present energy infrastructure contributes to positive feedback cycles that further propagate climate change and ambient air pollution emissions on hot days when electricity is generated by fossil fuels [40,41]. The exhaust heat from current air-cooling systems has also been found to exacerbate the problem of urban heat island effect [42]. Further, the refrigerants used in ACs, hydrofluorocarbons, are potent greenhouse gases that contribute to climate change. Thus, even though AC is effective in mitigating heat exposures indoors and protecting public health, additional adaptation strategies, such as adopting alternative refrigerants as proposed in the Kigali Amendment [43], designing our buildings and cities to be less thermally absorptive, and rapidly expanding renewable energy uptake, must be incorporated into our long-term solutions to reduce health-damaging air pollutants and greenhouse gas emissions that contribute to climate change, and to make climate adaptation more economically attainable for all sectors of the population, especially those who are most vulnerable.

Modeling studies have found that in the UK, external shutters, especially when combined with energy efficient upgrades to buildings, reduced heat-related mortality from 30% to 52% [44], while less heat-absorbent materials incorporated into buildings can significantly reduce indoor heat stress risk [45]. Energy-intensive AC will become more prevalent in homes across the world in coming decades and will be a crucial strategy in protecting populations from heat exposures. However, as discussed by Kwok and Rajkovich (2010), thermal comfort standards should be re-evaluated to better balance the mitigation of greenhouse gas emissions and provide healthful indoor environments for vulnerable populations to best equip our built environment for climate change [46]. Their point is underscored by the fact that current thermal comfort standards are not based on elderly populations with more underlying health risks.

Alternative adaptive/coping strategies need to be available for a growing number of vulnerable people in case cooling is not always available, like for example, during a power outage. Designing for the passive habitability of buildings, which would allow “habitable indoor conditions without power for limited amounts of time” [47,48] creates greater resilience among our building stock and better protects the individuals inside.

While the findings of this research present valuable information for public health practitioners and building managers, there were several limitations that are important to recognize. There were short gaps in the study period due to weather forecasts predicting only 1–2 days of extreme heat in mid-July when our objective was to characterize a longer period of extreme heat and its impact on indoor environments, and therefore the instruments were only deployed when weather was predicted to be especially hot. It would have been preferable to have a clearer HW signal to create more delineated ambient exposure periods with lower temperatures during the other study days, but unfortunately this was not possible with this type of study outside of a laboratory setting. However, the magnitude of these results may increase given even more extreme ambient temperature conditions.

The small sample size (n = 51) and rarity of the reporting of moderate/severe health symptoms (only 9 participants) may present limitations and limit our analysis of the impact of indoor heat on health symptoms in this study. Additionally, the daily surveys were self-administered at home, which is less controlled than if they were recorded by the study team. Even though we lacked information on the functionality and efficiency of the window AC units that were present, personal questions about thermal conditions of the apartments and participant activities were corroborated with environmental and personal monitors that recorded indoor temperatures, which reinforce the reliability of these measurements. Participants used time-activity logs but their data on hourly location was not very complete across the study period. Given the associations found between indoor temperature exposure and sleep and physiology, as well as with poor health symptoms, it is plausible to assess whether or not sleep is a mediating factor between indoor temperatures and poor health symptoms. We were unable to assess this here, due to the rarity of health symptoms reported, but are eager to explore in future studies.

The amount of time indoor and outdoor was consistent (about 2–3 hours/day outdoors) between all participants, regardless of building, as well as over time, so indoor temperatures were used as the exposure of interest since people were spending the majority of their time indoors and at home. Even though outdoor temperature exposures are not characterized at the individual level, the vast amount of indoor temperature exposure data utilized decreases the amount of exposure misclassification that may exist in other studies. However, some exposure misclassification may still exist if participants were outside or not at home for the entirety of the day

The limited, older age range of the participants may mean that the results are not generalizable to younger, healthier populations who may be less susceptible to extreme heat exposures. However, given the severity of climate change and future extreme heat scenarios, compounded by an aging population in the United States, there are likely still important lessons to be learned from this analysis for an increasing proportion of our population. Further research should examine the influence of the building in modifying health outcome and physiologic measures in other demographic populations of interest, as well as to other geographic locations, potentially over a longer period of times to account for multiple and recurring extreme heat events.

1.5 Conclusion

In this study, sensors were used to quantify indoor temperatures during an extreme heat event, reducing temperature exposure misclassification, and associated increases in HR and GSR of 51 older adults living in public housing. Assessment of adaptive behaviors demonstrated that hydration did not increase and the reporting of subclinical health symptoms was rare during the same time period. This signals that despite thermal decomposition occurring, even during a heat event that was not severe, older adults are not effectively implementing adaptive behaviors, like drinking more fluids.

With warming summer temperatures, buildings without adequate cooling systems have the potential to retain heat, even during non-extreme events, and individuals who are most vulnerable to the health impacts of extreme heat are less likely to have access to or utilize AC. Understanding how building elements modify indoor temperatures and monitoring indoor temperature conditions in real time is essential knowledge for identifying vulnerable indoor environments and informing adaptation and mitigation strategies to reduce the impact of excessive heat. Strategies that do not solely depend on AC, like enhanced shading/shutters and less heat-absorbed materials, will be vital adaptation solutions to buildings that maintain elevated indoor temperatures during extreme heat. Further, local heat action plans and HW programing by public health practitioners should account for the indoor temperature exposures that may be exacerbated by the built environment to improve messaging, public health campaigns, and distribution of cooling resources (hydration, transportation to cooling shelters, energy subsidies for AC, etc.).

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1.7 Supplemental Information

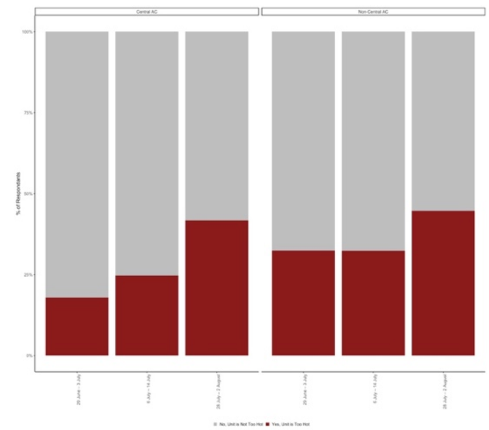
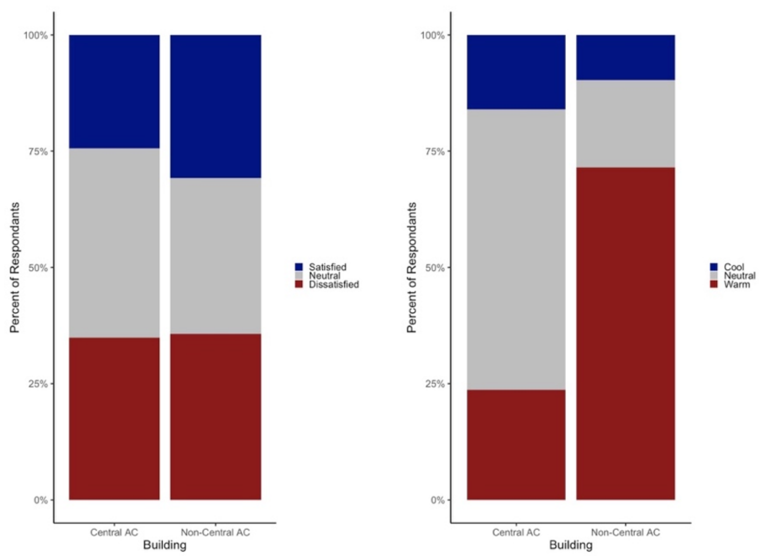


Figure 1.S1. Percent of respondents indicating the thermal perception of their apartment during the 3 periods of the study.



(**a**) (**b**)

Figure 1.S2. Percent of respondents indicating the satisfaction with (a) and perception of **(b)** the thermal conditions of their apartment at the baseline of the study period.

Table 1.S1. Baseline survey used to assess personal demographics, sleeping habits, perception/satisfaction with IEQ, and pre-existing demographics.

1. PID: Participant ID Number	
2. Building: Housing Development	

Table 1.S1 (Continued)

	1-Central AC
	2-NonCentral AC / Window AC
3. Date	
4. How many years have you lived here?	
5. How many people, beside you, are currently living in your apartment?	
6. How many people (total) are currently living in your apartment?	
7. Thinking about the last week, how would you describe the temperature in your bedroom?	
	1-Too cold
	2-Cold
	3-Slightly cold
	4-Neutral
	5-Slightly warm
	6-Hot
	7-Too warm
8. Thinking about the last week, please indicate the impact of temperature in your apartment on your activities:	
a. Daily Activities (e.g. writing, reading, chores, etc.)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
b. Relaxing (e.g. watching tv)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
c. Sleeping	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
9. Thinking about the last week, how many days did you take the following actions to modify the temperature in your apartment? Open/close the windows	
	1-Never
	2-1-2 days

Table 1.S1 (Continued)

	3-3-4 days
	4-5-6 days
	5-everyday
10. Thinking about the last week, how many days did you take the following actions to modify the temperature in your apartment? Open/close doors	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
11. Thinking about the last week, how many days did you take the following actions to modify the temperature in your apartment? Adjust temperature controls using a fan	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
12. Thinking about the last week, how many days did you take the following actions to modify the temperature in your apartment? Adjust temperature controls using the air conditioner	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
13. Thinking about the last week, how many days did you take the following actions to modify the temperature in your apartment? Other	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
14. Are the temperature controls in your apartment easy to access?	
	1-Yes
	2-No
	3-NA
15. Overall, how satisfied have you been with the temperature in your apartment during the last week?	
	1-very satisfied
	2-satisfied
	4-neutral

Table 1.S1 (Continued)

	6-dissatisfied
	7-very dissatisfied
16. Overall, how satisfied were you with the temperature in your apartment during this past winter?	
	1-very satisfied
	2-satisfied
	4-neutral
	6-dissatisfied
	7-very dissatisfied
17. What do you do when your apartment gets too hot in the summer? (check all that apply)	
	a. Shed clothes
	b. Adjust shades
	c. Adjust windows
	d. Use AC
	e. Use a fan
	f. Use a ceiling fan
	g. Adjust the thermostat
	h. Other____________
18. What do you do when your apartment gets too hot in the winter? (check all that apply)	
	a. Shed clothes
	b. Adjust shades
	c. Adjust windows
	d. Use AC
	e. Use a fan
	f. Use a ceiling fan
	g. Adjust the thermostat
	h. Other____________
19. What do you do when your apartment gets too cold in the summer? (check all that apply)	
	a. Shed clothes
	b. Adjust shades
	c. Adjust windows
	d. Use AC
	e. Use a fan
	f. Use a ceiling fan
	g. Adjust the thermostat
	h. Other____________
20. What do you do when your apartment gets too cold in the winter? (check all that apply)	
	a. Shed clothes

Table 1.S1 (Continued)

	b. Adjust shades
	c. Adjust windows
	d. Use AC
	e. Use a fan
	f. Use a ceiling fan
	g. Adjust the thermostat
	h. Other____________
21. What is the normal thermostat temperature in your apartment in the summer?	
22. What is the normal thermostat temperature in your apartment in the winter?	
23. Does the temperature of your apartment generally stay constant throughout the day and night?	
	1-yes
	2-no
a. If you answered No to the previous question, what do you think are the reasons for the temperature change throughout the day and night?	
	a. Thermostat doesn't work properly
	b. Temperature outside is too hot or cold
	c. The sun heats up the apartment interior
	d. Other _________________
24. Overall, how satisfied are you with the temperature in your apartment currently?	
	1-very satisfied
	2-satisfied
	4-neutral
	6-dissatisfied
	7-very dissatisfied
25. What would you guess is the temperature of this room right now?	
26. Thinking about the past week, express your satisfaction with the following indoor air quality parameters in your apartment:	
a. Air drafts	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
b. Air freshness	
	1-very dissatisfied
	2-dissatisfied
	4-neutral

Table 1.S1 (Continued)

	6-satisfied
	7-very satisfied
c. Odor intensity	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
27. Thinking about the last week, please indicate the impact of indoor air quality in your apartment on your activities:	
a. Daily Activities (e.g. writing, reading, chores, etc.)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
b. Relaxing (e.g. watching tv)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
c. Sleeping	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
28. Thinking about the last week, how many days did you take the following actions to modify the indoor air quality in your bedroom?	
a. Open/close windows	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
b. Open/close doors	
	1-Never

Table 1.S1 (Continued)

	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
c. Use air freshener	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
d. Use incense	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
e. Other ________________________	
	1-Never
	2-1-2 days
	3-3-4 days
	4-5-6 days
	5-everyday
29. Overall, how satisfied have you been with the indoor quality inside your apartment during the last week?	
	1-very dissatisfied
	2-dissatisfied
	3-neutral
	4-satisfied
	5-very satisfied
30. Thinking about the last week, express your satisfaction with the following acoustic conditions in your apartment.	
a. Noise from the outside	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
b. Noise from other rooms within the building	
	1-very dissatisfied

Table 1.S1 (Continued)

	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
c. Noise from the lights/heat/plumbing/ventilation system	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
31. Thinking about the last week, please indicate the impact of acoustic conditions in your apartment on your activities.	
a. Daily Activities (e.g. writing, reading, chores, etc.)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
b. Relaxing (e.g. watching tv)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
c. Sleeping	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
32. Overall, how satisfied have you been with the amount of noise inside your apartment during the last week?	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
33. Thinking about the last week, express your satisfaction with the following lighting conditions in your apartment.	

Table 1.S1 (Continued)

a. Amount of daylight	
	14-very dissatisfied
	15-dissatisfied
	17-neutral
	19-satisfied
	20-very satisfied
b. Amount of electric lighting	
	14-very dissatisfied
	15-dissatisfied
	17-neutral
	19-satisfied
	20-very satisfied
34. Thinking about the last week, have you experienced any of the following lighting conditions in your bedroom?	
a. Frequent flickering lighting	
	1-yes
	2-no
b. Electric lighting with an undesirable color	
	1-yes
	2-no
c. Insufficient desk lighting	
	1-yes
	2-no
d. Glare on the television	
	1-yes
	2-no
e. Excess light coming from outdoors while trying to sleep	
	1-yes
	2-no
f. Too bright	
	1-yes
	2-no
g. Too dark	
	1-yes
	2-no
35. Thinking about the last week, please indicate the impact of lighting conditions in your apartment on your activities.	
a. Daily Activities (e.g. writing, reading, chores, etc.)	

Table 1.S1 (Continued)

	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
b. Relaxing (e.g. watching tv)	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
c. Sleeping	
	1-No impact
	2-Minor impact
	3-Moderate impact
	4-Severe impact
	5-Extreme impact
36. Overall, how satisfied have you been with the lighting conditions in your apartment during the last week?	
	1-very dissatisfied
	2-dissatisfied
	4-neutral
	6-satisfied
	7-very satisfied
37. Thinking about the last week, how would you describe your sleep? (Choose all that apply)	
a. I have difficulties getting to sleep	
	1-always
	2-sometimes
	3-never
b. I wake up in the middle of the night	
	1-always
	2-sometimes
	3-never
c. I have difficulties waking up	
	1-always
	2-sometimes
	3-never
d. I can barely stay awake	

Table 1.S1 (Continued)

	1-always
	2-sometimes
	3-never
e. feel refreshed when I wake up	
	1-always
	2-sometimes
	3-never
f. I take medications to help me sleep	
	1-always
	2-sometimes
	3-never
g. I wear an eyemask to sleep	
	1-always
	2-sometimes
	3-never
h. I wear earplugs to sleep	
	1-always
	2-sometimes
	3-never
i. I use a sound machine.	
	1-always
	2-sometimes
	3-never
j. Other____________	
	1-always
	2-sometimes
	3-never
38. On average, how many hours (a day) have you slept during the last week?	
	1-4 hours or less
	2-5 hours
	3-6 hours
	4-7 hours
	5-8 hours
	6-9 hours or more
39. Has a health professional ever told you that you had any of the following conditions?	
1-yes	
2-no	
	Migraines

Table 1.S1 (Continued)

	Severe Headaches
	Asthma
	Chronic Bronchitis/Post Nasal Drip
	Chronic Runny Nose
	Chronic Sinus Infection
	Other Lung Conditions___
	Allergies
	Psoriasis
	Eczema
	Hives
	Sleep Apnea/Sleep Disorder
	Immune Disorder
	ADD/ADHD
	Hearing Condition
	Raynaud's Syndrome Or Problems With Circulation In Your Extremities
	Thyroid Condition
	Diabetes
	Heart Disease
	Chronic Fatigue/Fibromyalgia
	Depression
	Anxiety
	Other Major Chronic Disease_______________________
40. Thinking about the past week, how many days have you experiences the following symptoms? (Check all that apply)	
1-never	
2-1-2 days	
3-3-4 days	
4-5-6 days	
5-everyday	
	Difficulty Remembering Things Or Concentrating
	Unusual Tiredness, Fatigue, Or Drowsiness
	Tension, Irritability, Or Nervousness
	Feeling Depressed
	Dizziness Or Lightheadedness
	Headache
	Tired Or Strained Eyes
	Dry, Itching, Or Irritated Eyes

Table 1.S1 (Continued)

	Wheezing
	Sore Or Dry Throat
	Chest Tightness
	Stuffy Or Runny Nose, Or Sinus Congestion
	Pain Or Arthritis In Back, Shoulder, Or Neck
	Cough
	Sneezing
	Shortness Of Breath
	Nausea Or Upset Stomach
	Dry Or Itchy Skin
	Numbness In Hands Or Wrists
	Abnormal Rash
	Profuse Sweating
	Clammy Skin Or Chills
	Hallucinations
41. In the past 30 days, of those symptoms you have experienced from the previous page, indicate the correct treatment and impact of each below.	
a. Have you sought treatment? Are you currently being treated?	
	1-Have previously sought treatment
	2-Currently being treated
	3-Have previously sought treatment and currently being treated
b. Indicate the correct impact of the symptom below.	
	1-no impact
	2-mild impact
	3-severe impact
42. In general, would you say your health is…	
	1-excellent
	2-very good
	3-good
	4-fair
	5-poor
43. Have you smoked at least 100 cigarettes in your entire life?	
	1-yes
	2-no
44. Do you now smoke cigarettes every day, some days, or not at all?	

Table 1.S1 (Continued)

	1-everyday
	2-some days
	3-not at all
45. How often in the last 12 months have you seen signs of pests in your apartment? (This includes actually seeing pests and indications of pests such as feces and droppings, chewed packages, etc.)	
a. Roaches	
	1-never
	2-few times a year
	3-few times a month
	4-few times a week
	5-everyday
b. Mice	
	1-never
	2-few times a year
	3-few times a month
	4-few times a week
	5-everyday
c. Other___________	
	1-never
	2-few times a year
	3-few times a month
	4-few times a week
	5-everyday
46. Have you seen any mold on any surfaces (ie. walls, ceilings, floors in your apartment in the past year (12 months)? (Mold is a growth of fungi on a surface. In an apartment, it usually appears as a dark patch of 'fuzzy' growth on a wall, ceiling or other surface that has been wet for a period of time.) **very small mold patches in or around bathroom tiles should not be included.	
	4-yes
	5-no
	6-don't know
47. Do you currently have mold in your apartment?	
	1-yes
	2-no
	3-don't know
48. When the temperatures are really hot, what are some ways that you receive help?	
49. How often do you attend social events in the community?	
	1-never

Table 1.S1 (Continued)

	2-few times per year
	3-few times per month
	4-few times a week
	5-everyday
50. Do energy costs limit your use of an air conditioner?	
	1-yes
	2-no
	3-don't know
51. Do you have an air conditioner?	
	1-yes
	2-no
52. Overall, how satisfied have you been living in the apartment you currently live in?	
	1-very dissatisfied
	2-dissatsified
	4-neutral
	6-satisfied
	7-very satisfied
53. Age: how old are you, in years?	
54. Sex: What is your sex?	
	1 - female
	2-male
55. What is your height?	
56. What is your weight?	
57. Do you use hearing aids?	
	1-yes
	2-no
58. Do you use contact lenses?	
	1-yes
	2-no
59. Do you have continence issues or take any medications (like diuretics) that would influence water loss?	
	1-yes
	2-no
60. do you have pets?	
	1-yes
	2-no
a. yes, does that pet sleep in the same bed as you?	
	1-yes

Table 1.S1 (Continued)

	2-no
61. Please specifiy your ethnicity	
	1-White/Caucasian
	2-Black or African American
	3-Asian
	4-Native Hawaiian and other Pacific Islander
	5-American Indian or Alaska Native
	6-Latino
	7-Multiracial
	8-no response
	9-other_______________
62. Were you born in the United States?	
	1-yes
	2-no
63. Please share with us any other comments about your residential space that you think need improvement	

Table 1.S2. Daily survey used to assess the previous day's activities, IEQ, sleep quality, adaptive behaviors, health symptoms.

1. Date	
2. Participant Identification Number	
3. Time survey was completed by the participant	
4. Please indicate how many hours you spent in your living room yesterday.	
5. Time Activity Log: Please check off which location you were in during each time period	

	6am-9am	9am-12pm	12pm-2pm	2pm-4pm	4pm-6pm	6pm-8pm	8pm-10pm	10pm-12am	12am-6am
Living Room									
Bedroom									
Common Area									
Outside									
Other									

6. Did you experience any of the following environmental conditions while in your apartment yesterday? Please mark the box indicating your response.	
a. Temperature too hot	
b. Temperature too cold	
c. Too loud	
d. Too quiet	
e. Too much air movement	
f. Too little air movement	
g. Air too humid	
h. Air too dry	
i. Unpleasant chemical odors	
j. Other unpleasant odors (e.g. body odor, food odor, perfume)	
7. Please indicate any negative impacts of temperature in your apartment on your activities yesterday. Please mark the box indicating your response.	
a. Daily Activities (e.g. writing, reading, chores)	
1-No Impact	
2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
b. Relaxing (e.g. watching tv)	
1-No Impact	
2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
c. Sleeping	
1-No Impact	

Table 1.S2 (Continued)

2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
8. Please indicate any negative impacts of noise in your apartment on your activities yesterday. Please mark the box indicating your response.	
a. Daily Activities (e.g. writing, reading, chores)	
1-No Impact	
2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
b. Relaxing (e.g. watching tv)	
1-No Impact	
2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
c. Sleeping	
1-No Impact	
2-Minor Impact	
3-Moderate Impact	
4-Severe Impact	
5-Extreme Impact	
9. What would you guess is the temperature in your apartment right now?	
10. How thirsty did you feel yesterday, on average?	
1-not at all thirsty	
2-a little thirsty	
3-moderately thirsty	
4-quite thirsty	
5-extremely thirsty	
11. How many full glasses of water (~8oz) did you have yesterday?	
12. What time was your last drink of water yesterday?	
1-6am-12pm	
2-12pm-6pm	
3-6pm-9pm	
4-9pm-12am	
5-12am-6am	

Table 1.S2 (Continued)

13. How many drinks containing alcohol did you have yesterday?		
14. What time was your last alcoholic drink yesterday?		
1-6am-12pm		
2-12pm-6pm		
3-6pm-9pm		
4-9pm-12am		
5-12am-6am		
15. How many caffeinated drinks did you have yesterday?		
16. What times was your last caffeinated drink yesterday?		
1-6am-12pm		
2-12pm-6pm		
3-6pm-9pm		
4-9pm-12am		
5-12am-6am		
17. How much time did you spend watching TV or using a computer after 5pm yesterday before going to sleep?		
18. How much time did you spend exercising yesterday?		
19. How many times did you open or close your windows to modify the temperature in your bedroom?		
1-0times		
2-1 time		
3-2+ times		
20. How many times did you adjust the temperature controls to modify the temperature in your bedroom?		
1-0times		
2-1 time		
3-2+ times		
21. Did you take OTC or prescription medications to help you sleep yesterday before going to sleep:		
1-Yes		
2-No		
22. What time was sleep medication 1 taken?		
1-6am-12pm		
2-12pm-6pm		
3-6pm-9pm		
4-9pm-12am		
5-12am-6am		
23. What time was sleep medication 2 taken?		
1-6am-12pm		

Table 1.S2 (Continued)

2-12pm-6pm	
3-6pm-9pm	
4-9pm-12am	
5-12am-6am	
24. What time was sleep medication 3 taken?	
1-6am-12pm	
2-12pm-6pm	
3-6pm-9pm	
4-9pm-12am	
5-12am-6am	
25. How many hours of sleep did you get last night?	
26. What time did you go to sleep last night?	
27. What time did you wake up this morning?	
28. How long did it take you to fall asleep last night?	
1-0-10 minutes	
2-10-30 minutes	
3-30-60 minutes	
4- 60+ minutes	
29. Was your sleep interrupted last night, and if so, how many times?	
1-0 interruptions	
2-1 interruption	
3-2 interruption	
4-more than 2 interruptions	
30. How would you rate the quality of your sleep?	
1-Very poor	
2-Poor	
3-Fair	
4-Good	
5-Very good	
31. How rested or refreshed did you feel after you woke up?	
1-Not at all rested	
2-Slightly rested	
3-Somewhat rested	
4-Well-rested	
5-Very well-rested	
32. How happy did you feel over the course of the day yesterday?	
14-Very unhappy	
15-Unhappy	

Table 1.S2 (Continued)

16-Neither happy nor unhappy		
17-Happy		
18-Very happy		
33. How stressed did you feel over the course of the day yesterday?		
4-Very Stressed		
9-Stressed		
5-Neither stressed nor relaxed		
6-Relaxed		
7-Very relaxed		
34. Did anything unusual happen yesterday that you think affected your sleep last night?		
35. Did you experience each of the following symptoms yesterday? If you answer yes, please indicate the severity of that symptom.		
1-Mild Severity		
2-Moderate Severity		
3-Severe Severity		
Difficulty remembering things or concentrating		
Unusual tiredness, fatigue, or drowsiness		
Tension, irritability, or nervousness		
Feeling depressed		
Dizziness or lightheadedness		
Headache		
Tired or strained eyes		
Dry, itching, or irritated eyes		
Wheezing		
Sore or dry throat		
Chest tightness		
Stuffy or runny nose, or sinus congestion		
Pain or arthritis in back, shoulder, or neck		
Cough		
Sneezing		
Shortness of breath		
Nausea or upset stomach		
Dry or itchy skin		
Numbness in hands or wrists		
Abnormal rash		
Profuse sweating		

Table 1.S2 (Continued)

Clammy skin or chills	
Hallucinations	

Table S3. Generalized logistic mixed effect regression output Odds Ratios (OR) for any health symptom or heat-related health symptoms adjusting for daily mean indoor temperature and having at least 2 preexisting conditions (model 1) or and having a personal heat action plan (model 2), with participant as a random effect*.

	Model 1		Model 2	
Any Health Symptom	OR	95% CI	OR	95% CI
Daily Mean Indoor Temperature (°C)	1.077	(0.944, 1.23)	1.009	(0.788, 1.29)
Preexisting Conditions	0.638	(0.255, 1.59)		
Heat Action Plan			1.556	(0.541, 4.47)
Heat-Related Health Symptoms	OR	95% CI	OR	95% CI
Daily Mean Indoor Temperature (°C)	1.032	(0.883, 1.205)	1.004	(0.812, 1.24)
Preexisting Conditions	0.273	(0.087, 0.854)		
Heat Action Plan			1.614	(0.601, 4.34)

*Model 1 demonstrates a generalized logistic mixed effect regression for any health symptom or heat-related health symptoms adjusting for daily mean indoor temperature and having at least 2 preexisting conditions, with participant as a random effect (Equation (1)). Model 2 was a generalized logistic mixed effect regression for any health symptom or heat-related health symptoms adjusting for daily mean indoor temperature and having a personal heat action plan, with participant as a random effect (Equation (2)). The model results in Table 2 demonstrate that the odds of reporting any health symptom or a heat-related health symptom increased 7% and 3% times for each degree °C increase of daily mean indoor temperature on average, respectively. However, the 95% confidence intervals of these estimates contain the null (OR = 1). The odds of reporting a heat-related health symptom decreased by 72% times when having at least two preexisting conditions (95% CI = (0.09, 0.87). Given the acute nature of the symptoms assessed in this study, models using the same-day daily mean indoor temperature were utilized and shown here.

Table S4. Generalized logistic mixed effect regression models.

$$Logit\left(Health\ Symptoms_{ij} \middle| b_{1i}\right) = \beta_1 + \beta_2 * Daily\ Mean\ Indoor\ Temperature_{ij} + \beta_2 * At\ Least\ 2\ Preexisting\ Conditions + b1\left(Building(participant)\right) + \varepsilon_{ij}$$	(1)
$$Logit\left(Health\ Symptoms_{ij} \middle| b_{1i}\right) = \beta_1 + \beta_2 * Daily\ Mean\ Indoor\ Temperature_{ij} + \beta_2 * Heat\ Action\ Plan + b1\left(Building(participant)\right) + \varepsilon_{ij}$$	(2)

CHAPTER 2

The influence of heat on emergency services in Boston, MA: relative risk and time-series analyses of police, medical, and fire dispatches

American Journal of Public Health. Under Review.

Abstract

Objective: This study aims to examine the relationship between extreme heat and all emergency services in Boston, MA.

Methods: Relative risk and time-series analyses were used on 911 dispatches by City of Boston public safety agencies, which included the Police Department, Fire Department, and Emergency Medical Services, from Nov 2010-Apr 2014 to assess the impact of extreme heat on emergency services.

Results: There were 11% more police, 16% more EMS, and 18% more fire dispatches on days where maximum temperature ≥ 90°F). Time-series analyses showed a 10-degree change in daily maximum temperature from 80ºF to 90ºF resulted in 1.046, 1.023, and 1.027 times the expected number of daily police, EMS, and fire dispatch calls, on average after adjusting for other predictors.

Conclusions: While heat stress-related ambulance and crime-related police reports have been well documented, this study demonstrates that the burden on local services may be larger in Boston, MA than previously known.

Policy Implications: It is important to account for the greater societal burden of extreme heat impacts to most effectively, sustainability, and equitably inform climate change adaptation strategies.

2.1 Introduction

Extreme heat is a significant public health threat that is increasing in frequency, duration, and severity with climate change[1]. Compared to 1971-2000, where Boston, MA experienced an average of 11 hot days above 90ºF per year, Boston could experience up to 40 hot days by 2030, and 90 hot days by 2070, depending on greenhouse gas emission trajectory[2]. Although the definition of heatwaves and extreme heat events varies by location and agency, heat has been the leading cause of death of all meteorological phenomena in recent decades in the United States (US)[3].

There is a vast body of literature that has shown that exposure to extreme heat is harmful to health. Across a variety of exposure metrics and geographic locations, scientific research has demonstrated that extreme heat is associated with a myriad of poor health outcomes[4,5]. Recent research has shown that even at lower thresholds than previously thought, heat has the ability to impact public health and societal services [6]. It has been well documented that heat-stress related ambulance calls [7–10], and violent crime[11–17] also increase on hot days. However, given what is known about the impacts of heat on public health, there are several other pathways through which extreme heat influences the provision of emergency services in urban areas. The premise of this study was that heat-related impairments of cognitive function and sleep, increased violence and aggression, and inhibited risk-taking and decision making [18] could result in increased needs for all sectors of emergency services – police, medical, and fire – during extreme heat.

These broader societal impacts on emergency services have not yet been included in local adaptation planning or budgeting. Improving the understanding of the broad impacts of extreme heat on society informs resiliency and adaption solutions of that population. The objective of this study was to determine if emergency services in Boston, MA, experienced greater need during extreme heat, through analysis of police, ambulance, and fire dispatches, and utilized both relative risk and time series analyses to evaluate these relationships.

2.2 Methods

2.2.1 Emergency Dispatch Data and Outcome Assessment

Daily counts of emergency dispatch calls for were publicly available from the City of Boston for November 1, 2010 to April 21, 2014 from the Boston Department of Innovation and Technology[19]. These calls represented three agencies – Boston Police Department (BPD), Boston Emergency Medical Services (BEMS), and Boston Fire Department (BFD). Major holidays including Christmas Eve/Day, New Year's Eve/Day, the Boston Marathon and Independence Day, as well as several Nor'easters, Hurricane Irene, and Superstorm Sandy were considered as "special events". Descriptive statistics on dispatch distributions within agencies across the full year and warm season were computed using a Student's t-test.

2.2.2. Meteorological Data and Exposure Assessment

Daily temperatures for this time period were obtained from Boston Logan International Airport. Daily maximum temperature (T_{MAX}) was used as a continuous value to assess temperature exposure each day. A common measure of extreme temperature exposure in Boston is when daily $T_{MAX} \geq 90°F$, defined by the local National Weather Service (NWS)[20]. City agencies utilize this definition to enact local warnings and responses (e.g. opening of cooling centers).

Days where $T_{MAX} \geq 90°F$ were defined as hot days, with all other days being non-hot days. Although the presence of heatwaves (HWs), where $T_{MAX} \geq 90°F$ for at least 3 consecutive days, is also an important indicator of heat, there were only 14 HW events during this study period, and therefore, hot days were used instead of HW days. The magnitude, direction, and significance of model parameters were not significantly changed when using hot days or HW days, so hot days were kept to maintain a greater amount of statistical power. Descriptive statistics on temperature distribution during both the full year and warm season were computed using a Student's t-test.

2.2.3. *Relative Risk Analysis*

The relative risk (RR) of an agency's dispatch call on a heat day compared with non-heat days was analyzed using a Poisson regression. While seasonally the population shifts due to a large student population in the spring and fall, it is assumed that year-over-year the overall population of Boston remains similar during this three-and-a-half year period. The relative-risk analyses were done on the full year, as well as also restricted to the warm season. The RR model equation (Eq. 1) is as follows:

$$\log(\mu_j) = \beta_0 + \beta_1 I_j[HeatDay] \quad (1)$$

where μ_j is the expected count of dispatch calls for an agency on day j, and $I_j[HeatDay]$ is the indicated of hot days. The same model was utilized on a dataset restricted to the warm season.

2.2.4. Time Series Analysis

Time-series (TS) analyses were used assess the relationship between T_{MAX} and dispatch call counts for each agency, using a quasi-Poisson regression. The TS models used non-parametric splines to account for the non-linear effects of both heat and other predictors on dispatch call counts. Day of the week was controlled for with indicator variables for each day, with reference to Friday. Long-term trends were adjusted using natural splines to account for changes in emergency services and temperature over time and throughout the year, seasonally. Results are reported as percent increase in number of dispatch calls for each agency for an increase from 80°F to at least 90°F, as well as from moderate temperatures of 50-80°F to at least 90°F. The inflection points of the non-linear temperature exposure were calculated for each agency.

Previous work done by Reid et al. has shown that ambient ozone, a health-harmful air pollutant, should be considered as a causal mediator rather than a confounder[21]. For this research question, we were interested in the total effects of temperature, including those both mediated and not mediated through ambient ozone, and therefore did not consider this air pollutant as a confounder.

2.2.5. Human Subjects Research

No personal data was used in this study, so IRB approval was not required.

2.3 Results

2.3.1. Descriptive Statistics

All special events were kept in the primary analyses, for a total of 1,268 days analyzed. The secondary analysis using restrained to just the warm season, a total of 459 days, excludes all special events other than Independence Day. The mean temperature of Boston, MA during the full year is 53.2°F (Table 2.1), while the warm season mean temperature is 68.9°F. Of the 1,268 days studied, 43 days exceeded 90°F and were classified as hot days.

Table 2.1. Descriptive statistics for meteorological conditions, 2010-2014, as measured at Boston Logan International Airport (KBOS).

	Full Year (°F (°C))	Warm Season (°F (°C))
Minimum Temperature	45.6 (7.6)	61.1 (16.2)
Mean Temperature	53.2 (11.8)	68.9 (20.5)
Maximum Temperature	60.4 (15.8)	76.2 (24.5)
p-value	<0.001	

There were a total of 3,474,332 emergency dispatch calls during the study period: 77.5% of the total number of dispatch calls were for BPD, 14.2% for BEMS, and 8.3% for BFD (Table 2). Across all agencies, the mean number of dispatches per day was significantly greater during the warm season than during the full year (all $p<0.001$) (Table 2.2).

Table 2.2. Descriptive data for Boston agency-specific dispatch calls, 2010-2014.

Total Dispatches	Full Year Analyses	Warm-Season Restricted Analyses	
BPD	2,691,191	1,037,897	
BEMS	494,615	187,284	
BFD	288,526	109,804	
Average Dispatches Per Day	**Full Year Analyses**	**Warm-Season Restricted Analyses**	**p-value**
BPD	2122.4	2261.2	<0.001
BEMS	390.1	408.0	<0.001
BFD	227.5	239.2	<0.001

2.3.2. Relative Risk Analysis

The RR analysis of dispatch data, representing all calls from each emergency service agency on hot days, was computed for both the full year and in an analysis restricted to the warm season. The risk of a dispatch call on a hot day, where $T_{MAX} \geq 90°F$, compared with a non-hot day increased for all agencies, in both the full year and warm season analyses (Table 2.3). The magnitude of this increase was greater for BEMS and BFD dispatch calls (16% and 18%, respectively) than BPD dispatch calls (11%) during the full year. During the warm season, the RR of dispatch calls for any agency on hot as compared to non-hot days were slightly attenuated than during the full year analysis – BPD (4%), BEMS (11%), and BFD (12%). For both analyses, the 95% confidence intervals excluded the null (RR=1.0).

Table 2.3. The relative risk of dispatch calls for each agency on hot-days compared to non-hot-days, calculated for both throughout the full year and during only the warm season.

Full Year Analyses	Relative Risk	95% CI
BPD	1.11	(1.098, 1.122)
BEMS	1.16	(1.133, 1.191)

Table 2.3 (Continued)

	Relative Risk	95% CI
BFD	1.18	(1.138, 1.214)
Warm-Season Restricted Analyses	**Relative Risk**	**95% CI**
BPD	1.04	(1.031, 1.054)
BEMS	1.11	(1.085, 1.141)
BFD	1.12	(1.084, 1.157)

2.3.3. Time Series Analysis

The estimated effects of T_{MAX} were non-linear for dispatches from all agencies, with higher RR at hot temperatures for BPD and BEMS and higher risks at hot and cold temperatures for BFD (Figure 2.1). Hot days were not a significant predictor for any agency's dispatch calls. All days of week were significant predictors for BPD and BEMS, but only weekend days were for BFD.

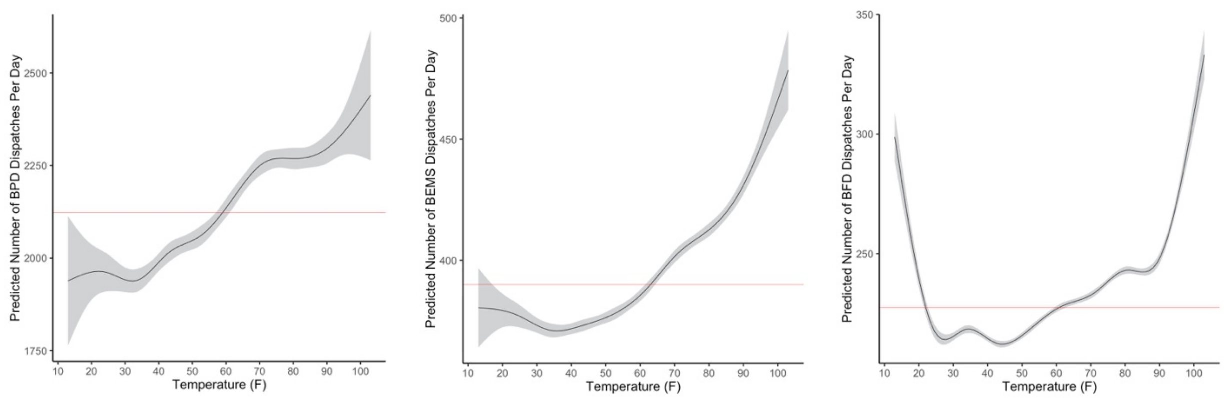


Figure 2.1. Predicted number of dispatch calls per unit temperature (°F) for each agency, after adjusting for heatwave event, long-term trend, and day of week, as well as seasonal trend throughout the full dataset. 95% CIs are shaded in grey, while the mean number of dispatch calls for each agency per day is shown in red.

When utilizing the TS analysis results for temperature-specific predictions, increased risk was seen for all dispatch call frequency as temperatures increased from warm to hot. During the full year, a 90°F day was found to have 1.046, 1.023, and 1.027 times the expected number of BPD, BEMS, and BFD dispatches per day, compared to an 80°F day, respectively. When comparing all days where 53°F (mean temperature of Boston, MA) ≤ T_{MAX} <90°F to those where T_{MAX} ≥90°F, there were 1.036, 1.024, and 1.028 times the expected number of BPD, BEMS, and BFD dispatches per day.

The non-linear effect of temperature on BPD had inflection points at 83°F, 89°F, and 97°F. For BEMS, these inflection points were 74°F and 85°F, while for BFD they were 82°F and 88°F. These inflection points were used at threshold values for a secondary RR (Table 2.S1).

2.4 Discussion

This study offers a comprehensive analysis of the impacts of heat on emergency services in Boston, MA. It assess the impacts of extreme heat and high temperatures on the frequency of emergency dispatch calls across Boston, during the full year and within the warm season. Moreover, the increased demand for police, medical, and fire services reported herein captures an additional public health burden from extreme heat that has not yet been fully captured in research examining the impacts of climate change on public health and societal services. These findings can inform climate change adaptation strategies, for both budgets and institutional preparedness, to ensure the resilience of emergency services as HWs increase in frequency, severity, and duration in Boston.

The RR of dispatch calls for BPD (11%), BEMS (16%), and BFD (18%) increased on hot days compared to non-hot days during the full year. These results were slightly attenuated when analyses were constricted to the warm season, but significant increases were still observed for BPD (4%), BEMS (11%), and BFD (12%). When warming from a 80°F to days at or above 90°F, there was 1.046, 1.023, and 1.027 times the RR of BPD, BEMS, and BFD dispatch calls, respectively.

Assessing the RR of increased BPD, BEMS, and BFD dispatch calls with increasing temperature based on the inflection points in the TS analyses, we found evidence for lowering local temperature thresholds for extreme heat to below 90°F There was a significant increase in the RR for BPD at 83°F (RR=1.083; 95% CI: 1.080, 1.087), 89°F (RR=1.095; 95% CI: 1.088, 1.101), and 97°F (RR=1.137; 95% CI: 1.118, 1.155), for BEMS at 74°F (RR=1.095; 95% CI: 1.088, 1.102) and 85°F (RR=1.109; 95% CI: 1.098, 1.120), and for BFD at 82°F (RR=1.104; 95% CI: 1.093, 1.116) and at 88°F (RR=1.149; 95% CI: 1.131, 1.167) in the full year analysis. The effects were still significant when analyses were restricted to just the warm season (Table 2.S1). This demonstrates that a significant risk of increased need for emergency services is present well below the current heatwave criteria of 90°F, supporting previous work that saw increased rates of morbidity and mortality in New England below current heat advisory criteria set by the NWS[22].

As mentioned earlier, ambulance calls [7–10,23], and violent crime[11–17] have been found to increase on hot days, hospitalizations related to heat stress and other heat-related health outcomes increase during higher ambient temperatures[24–26]. All of these relationships provide potential mechanisms for heat to result in increased need of BPD and BEMS services, as there could be increases in crime, traffic accidents, or other emergency situations that require police or emergency medical technicians that are broader than just violent crime or heat stress related health outcome alone. Our findings, increases in BPD and BEMS dispatches as temperatures increase, support the existing body of literature, while also establishing evidence that HWs and high ambient temperatures have an agency-wide impact on emergency services for these two agencies. Future analyses on the nature of each dispatch call would be necessary to fully understand this.

Most previous research on the influence of weather on fire department services shows strong links between climate change and wildfires[1] as well as cold temperatures and residential fires[27], which is not the focus of this study, neither of which are what is taking place here. However, this is one of the first studies to provide evidence that BFD services are impacted by extreme heat. There is limited scientific literature to discuss this relationship. Firefighters, including those in Boston, respond to many emergency scenarios across a variety of needs, including medical emergencies. Thus, we hypothesize that the increase in BFD dispatch calls during days with high temperatures follows similar pathways as BPD and BEMS dispatches increase, but has been underrepresented in the body of scientific evidence highlighting the impact of heat on emergency services and attendant climate adaptation planning. This association warrants more analysis to best understand the drivers of increased BFD dispatches during hot days.

This study has several limitations. The duration of extreme heat, including how many consecutively hot days have existed, may be an important relationship to understand in association with emergency services, but was not included in this study given the relative few number of HW events during this study period. As HWs increase in the future, or in hotter climates in the U.S., the risk modification of the duration of extreme heat would be important to assess. The use of ambient temperature measurements likely introduces a non-differential exposure misclassification into the analysis, as the temperatures throughout Boston were different than at the airport and varied throughout the city. Further, our assessment of extreme heat did not include humidity, and only focused on high temperatures. RR analyses using daily heat index ≥ 95°F yielded results that were not largely different than using temperature, so were not incorporated into time-series analyses (Table 2.S2).

We also did not have information on those utilizing these emergency services, so we could not do any further analyses on age, sex, other modifiable factors, or the geographic distribution of these services. Additionally, the co-provision of services from multiple emergency agencies at one time (i.e. we do not know for any given call if both BPD and BEMS were dispatched). However, if a call warranted multiple agencies to arrive, there is still a personnel and a financial cost to those services, and those must be included to best understand the full impact on these services during HWs in order to most appropriate plan for the future. Future studies will include additional information on high-resolution temperature exposures, sociodemographic, and built environment parameters to comprehensively assess vulnerability to these increases in emergency services spatiotemporally, with records on the details of each dispatch call.

Despite these limitations, to our knowledge this was the first study to document the impact of heat on BFD dispatches, as well as one of the first to examine the impacts of heat on agency-wide BPD and BEMS dispatches in Boston, expanding the scientific understanding beyond violent crime and heat-stress related ambulance calls. A strong effect was seen across all agencies in both a RR and a TS analysis, during both the full year and analyses restricted to the warm season. While summers in Boston are getting hotter, Boston's climate is more moderate than many other urban centers in the U.S. given its proximity to the ocean and sea breezes influenced by the concavity of its coast and topography allowing summer temperatures to remain cooler than they otherwise might[29]. Additionally, Boston rate of some emergency situations, like violent crime, may differ than other cities across the U.S. The analysis framework used in this study would allow the methods to be generalized to other cities to evaluate local effects and inform local adaptation strategies. Effects may be even stronger in other cities where either heat exposure or emergency scenarios that are more extreme than in Boston.

Historically, Boston, MA experiences an average of 11 hot days each year[2]. During this 1,268 day study period, there were 43 hot days. BFD and BPD are both within the Office of Public Safety, while BEMS falls within the Public Health Commission. Fire suppression services and BFD alarm dispatch services were budged $232,440,200 during 2018, making up 80.8% of the BFD annual budget. The delivery of police services by BPD were budget for $220,148,500, which is 57.1% of the BPD annual budget. In 2018, BEMS consisted of 85.1% of the Public Health Commission's annual budget, securing $54,380,100. Assuming the mean cost per dispatch is equal among all dispatch call types and remains constant over time, we estimate that dispatch calls per hot day have the potential to cost an additional $44,000 for BPD, $16,000 for BEMS, and $75,000 for BFD in 2018 dollars. Over the 43 hot days during this study period, a rough estimation yields an additional $1.9 million for BPD, $0.7 million for BEMS, and $3.3 million for BFD, equivalent to over $5.8 million dollars, compared to costs during the warm season on average.

With low and moderate greenhouse gas emissions mitigation strategies enacted, it is projected that Boston will see an average of 20.2 (Representative Concentration Pathway 4.5, where greenhouse gas emissions peak in 2040, or RCP 4.5) or 22.2 (Representative Concentration Pathway 8.5, where greenhouse gas emissions continue to rise through the 21st Century, or RCP 8.5) hot days by 2030 and 25.7 (RCP 4.5) or 35.3 (RCP 8.5) by 2050, with even greater frequency in the second half of the 21st Century[30]. Using the same estimates and assumptions, increased frequency of hot days could cost these Boston public services an additional $2.7 - $4.8 million dollars annually in 2050, dependent upon future greenhouse gas emissions trajectories and adaptation strategies enacted in the near future. While these financial estimates are a rough first approximation, these budgetary concerns will need to be accounted for in the near future, and will be especially important in rural and suburban communities that rely on volunteer medical technicians and firefighters, where financial and personnel resources are limited but extreme heat will still be present.

The impacts of hot days on increased emergency dispatch calls is not only financial. An additional area of consideration that must be accounted for is the occupational heat stress that is experienced by these first responders on hot days [31], which would likely increase in the future as heat becomes more pervasive,

Despite research demonstrating the impact of extreme temperatures on health and societal services, climate adaptation plans more often account for mitigating health impacts of extreme heat than for increased need of a broad number of societal services. In Boston, the impacts of storm-related flooding and sea level rise on emergency services are well documented: increased stormwater flooding at fire and police stations will impede access and response, high tide flooding events will expose $1.3 billion in property value in essential facilities, including fire, EMS, and police infrastructure, and low probability flood events have the potential to inundate approximately 25% of police stations, which has led to Boston prioritizing flood-related adaptation for emergency service facilities[2]. When it comes to extreme heat, despite the vast range of demonstrated societal impacts (i.e. negative health impacts, increased stress on electricity grid for air conditioning, expansion of roads and rails, poorer air quality, etc.), municipal services are only suggested to install backup power generation systems to adapt to extreme heat in the future [2]. It is vital to also include the greater societal burdens during periods of extreme heat, including those on vital emergency services. Adaptation strategies like cool roofs, increased tree canopy, more efficient cooling systems, and targeted planning approaches that account for climate change-induced increases in extreme heat events will be essential in mitigating future heat exposure.

2.5 Public Health Implications

This paper expands scientific understanding of the many ways extreme heat influences public health and society, demonstrating that heat impacts the agency-wide dispatch services of the BPD, BEMS, and BFD. Although all of these services increase as temperatures warm, RR analyses showed that the RR of dispatch significantly increased on hot days (T_{MAX} ≥90°F) by 4% (BPD), 11% (BEMS) and 12% (BFD) compared to other days in the warm season, but with significant increases in dispatches well below 90°F. A local reexamination of heat criteria and the associated social services that are provided once these thresholds are met (i.e. opening of cooling centers, transportation to cooling centers) may better protect the population and reduce negative societal consequences of extreme heat.

Climate change risk assessments and adaptation plans often account for the significant mortality and morbidity health impacts attributed to extreme heat. However, it is important to account for the greater societal burden of extreme heat impacts, including those on vital emergency services. While this will be beneficial to ensuring the provision of services, the increase in first responders and budgets needed to meet a higher demand for services at higher temperatures should also be considered to allow Boston to most effectively, sustainability, and equitably implement climate change adaptation strategies.

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2.7 Supplemental Information

Table 2.S1. The relative risk of dispatch calls for each agency with maximum daily temperature thresholds at the main inflection points.

RELATIVE RISK					
BPD		**T_{MAX}≥90°F**	**IP 1: T_{MAX}≥ 83°F**	**IP 2: T_{MAX}≥ 89°F**	**IP 3: T_{MAX}≥ 97°F**
Full	PE	1.110139	1.083951	1.094692	1.13656
	HIGH	1.122266	1.087916	1.101097	1.155285
	LOW	1.098142	1.08	1.088324	1.118138
Warm	PE	1.042053	1.013814	1.026614	1.067028
	HIGH	1.053551	1.018057	1.032854	1.084685
	LOW	1.03068	1.009588	1.020411	1.049659
BEMS		**T_{MAX}≥90°F**	**IP 1: T_{MAX}≥ 74°F**	**IP 2: T_{MAX}≥ 85°F**	
Full	PE	1.161738	1.094521	1.108695	
	HIGH	1.190895	1.101535	1.119634	
	LOW	1.133295	1.087552	1.097864	
Warm	PE	1.11245	1.060044	1.06009	
	HIGH	1.140677	1.069967	1.071637	
	LOW	1.084922	1.050212	1.048668	
BFD		**T_{MAX}≥90°F**	**IP 1: T_{MAX}≥ 82°F**	**IP 2: T_{MAX}≥ 88°F**	
Full	PE	1.175674	1.104451	1.148807	
	HIGH	1.214229	1.115979	1.167221	
	LOW	1.138344	1.093041	1.130684	
Warm	PE	1.120199	1.05436	1.099386	
	HIGH	1.15734	1.06741	1.11793	
	LOW	1.084249	1.04147	1.08115	

Table 2.S2. The relative risk of dispatch calls for each agency days with maximum heat index ≥ 95°F compared to those with maximum heat index <95°F, calculated for only the warm season.

Boston Agency	**Warm Season Restricted Analysis**	
	Relative Risk	*95% CI*
Police	1.09	(1.085, 1.094)
EMS	1.11	(1.102, 1.122)
Fire	1.11	(1.101, 1.127)

CHAPTER 3

A case-only analysis of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA.

Abstract

Climate change is resulting in heatwaves that are more frequent, severe, and longer lasting, which results in public health threats to both morbidity and mortality. This is especially true in the Northeast United States, where heat-related mortality is projected to potentially triple if adequate climate change mitigation and adaptation strategies are implemented. A case only analysis was used to examine subject and small-area neighborhood characteristics that modified the association between hot days and mortality, and geographic weighted regression analyses were used to examine these relationships spatially. All deaths of Boston, Massachusetts residents that occurred at home from 2000-2015 were included in this analysis. Meteorological data were obtained from the National Centers for Environmental Information, while modifying characteristics were obtained from both the mortality records and geographic data sets. Census tracts with a greater proportion of low-to-no income individuals or those with limited English proficiency were more highly represented in those who died during the study period, but area built environment features, like albedo and enhanced energy efficiency, were able to reduce the relative odds of death within and outside the home. On days where the heat index ≥86°F, individuals living in CTs with newer or more recently renovated residential buildings or a greater density of street trees had a lower relative risk of dying at home. Further, even at temperatures below current local thresholds used for warnings, advisories, and local interventions, there were significantly higher relative odds of death from unknown causes, substance abuse, injury/accidents, and assault, most of which are not currently being incorporated into heat vulnerability assessments and adaptation planning.

3.1 Introduction

Global climate change is increasing the frequency, duration, and severity of extreme heat events around the world [1,2]. Extreme heat is one of the most severe public health impacts of climate change, resulting in increased mortality throughout the world [3–6]. In Boston, MA, the focus of this study, there is expected to be an increase of hot days above 90ºF from 11 (1971-2000) to 40 by 2030, and potentially 90 days by 2070 [7]. Projections have shown that that heat-related mortality has the potential to triple in the Northeast United States [8] without adequate climate change mitigation and adaptation strategies implemented, with the effects being disproportionally experienced by the most vulnerable individuals.

There has been significant research done to further the concept of heat vulnerability, to determine and understand which individuals and communities are most vulnerable to the impacts of extreme heat. Much of this literature has focused on social factors, like income, race, sex, education, and age, to determine vulnerability. For example, reviews of heat and mortality epidemiologic studies have found that non-Hispanic black individuals, women, those of a lower socioeconomic status, those with preexisting medical conditions (e.g. diabetes), elderly individuals over 65 and infants and children under 5 have been found to be most vulnerable to poor health outcomes, including death, during extreme heat events [4–6,9–11].

Buildings are modifiers on the effect of climate change on human health outcomes [12], as they have the ability to alter the heat capacity of indoor spaces, either exacerbating or mitigating indoor heat exposures given the same ambient conditions. The urban heat island (UHI) effect occurs when land surface temperatures in an urban area are higher than surrounding rural or suburban areas, and urban design with enhanced urban canyons, greater use of materials of high thermal absorption (e.g. asphalt, brick), and densely built areas can create temperatures much higher than surrounding areas and prevent urban areas from cooling at night. Despite spending up to 90% of time within buildings and built environments that determine our exposure to ambient conditions, few heat vulnerability and adaptation assessments include widespread information on buildings and the built environment.

As this body of work has progressed, some attention has been paid to other factors in the surrounding urban environment that may exacerbate or mitigate underlying social vulnerability to extreme heat. Some of the risk factors associated with building and urban design have been incorporated into previous heat vulnerability research. Living in a multi-family apartment building has been found to increase the incidence of poor health outcomes during extreme heat events [13,14]. Building materials with a high thermal mass prevent a building from passively cooling during the overnight hours, increasing the need for cooling in subsequent days [15,16]. Having urban tree canopies can keep surrounding buildings cool, reducing electricity consumption from cooling demands use while also keeping communities cooler and mitigating heat stress-related health conditions [17], and surrounding greenspace can reduce vulnerability to heat morbidity and mortality [11].As buildings have become more energy efficient, higher thermal insulation and greater airtightness have increased the risk of potential overheating [12], especially in times of power loss when mechanical cooling may not be available.

Using air conditioning (AC) has been the primary defense to extreme heat exposure. However, AC is not currently an equitable or sustainable adaptation strategy. A recent study in New York City (NYC) found that the odds of not having AC were found to be greatest for non-Hispanic black people and those with low-to-no income [18], and only 50% of NYC public housing residents have access to AC [19]. Approximately two-thirds of Massachusetts residents lack central AC at home, while 20% of households lack any type of AC [20]. Further, the electricity used to power AC produces health-harmful pollutants, which are increased on hot days from enhanced power production [21]. Lastly, the refrigerants found within AC systems contain hydrofluorocarbons, a greenhouse gas that is exponentially more harmful to our climate than carbon dioxide.

The study here aims to explore which individual and neighborhood characteristics within one metropolitan area are most vulnerable to mortality on hot days. This case-only analysis examines whether at-home mortality on hot days in Boston, MA varied based on individual and small-area environmental and social characteristics at a variety of temperature exposure definitions.

3.2 Methods

3.2.1 Exposure Data

Hourly meteorological data was accessed for Boston Logan International Airport via the National Centers for Environmental Information. Daily maximum ambient temperatures (T_{MAX}) ≥90°F was used as a binary measure of it being a “hot day”, a common temperature threshold used to enact local cooling strategies in Boston. Recent evidence in Boston, MA has found that societal governance, through an assessment of emergency services, increases around 85°F, so T_{MAX} ≥85°F was used to define “warm days”. To account for humidity in addition to temperature, the heat index (HI) was also considered by using days where HI_{MAX} ≥86°F, which was the 95th percentile of the HI during the warm season in Boston.

These assessments use single day exposures, and are consistent with findings that mortality risk or effect modification of heat-mortality relationships increase on individual days of extreme heat [5,22–24]. These temperature metrics are also at values that are below current heat advisory criteria, but recent evidence has shown that there are significant increases in mortality at temperatures from 75-85°F in New England [25]. All analyses were conducted using only the warm season data, May-September, to remove any seasonal confounding that exists between temperature and mortality.

3.2.2. Social Parameters

Small-area neighborhood data was assigned at the census tract (CT) level for each at-home mortality record, corresponding to the 2010 Census. CTs are small, relatively permanent subdivisions, usually have around 4,000 people within, and are designed to be “homogeneous with respect to population characteristics, economic status, and living conditions” [26]. CT-based assessments of socioeconomic status (SES) have been found to be adequate measurements for individual estimates in MA [27]. There are 178 CTs in the City of Boston, but 14 of these CTs have little or no population, leaving 164 CTs for analysis. We obtained data on CT social characteristics including population density, inclusion of utilities in rent, inequality via the (GINI), and unemployment from the 2010 Census [28]. The proportion of those in each CT with a disability older adults ≥65 years, children ≤5 years, people of color, low income, limited English proficiency and with medical illnesses was accessed from the 2016 City of Boston’s Climate Ready Boston Social Vulnerability Data [29].

3.2.3. Environmental Parameters

We obtained data on CT environmental characteristics including availability of street trees in 2011 from Boston Open Data [30], the 2005 impervious surface fraction and mean albedo from MassGIS and as summarized by the Boston Area Research Initiative (BARI) [31]. 2017 building assessments from the City of Boston Assessing Department and as summarized by BARI provided CT-level summaries of residential buildings, including decade/year built or last renovated. BARI also provides a mean residential energy efficiency score, which is an aggregated variable based on age of building, heating system, and cooling type, with higher values indicating a more energy efficient residence. We also used the mean value of residential building/land and per area [32]. When evaluating local real estate prices in Boston, triple decker homes and luxury apartment buildings have the highest value per area, so this indicator is used a proxy for these types of residences.

3.2.4 Outcome Data

Data on all deaths occurring in Massachusetts for the period January 2000 – December 2015 were obtained from The Commonwealth of Massachusetts Executive Office of Health and Human Services Department of Public Health. Data included the primary (and in some cases, secondary) causes of death classified using the International Classification of Disease, 10th Revision (ICD-10) codes, age, sex, race, place of death, education, occupation, and industry of work. All deaths, regardless of the primary causes, were included in this analysis given the wide range of health outcomes that can be negatively impacted or exacerbated by extreme heat [23,33–40].

All deaths of Boston residents from 2000-2015 that occurred at home or outside of the home (excluding an inpatient or nursing facility) were included in this analysis. Deaths that occurred at home were used as we were interested in assessing at-home heat vulnerability based the surrounding neighborhood social and environmental characteristics. The use of this mortality data was approved by both the Harvard TH Chan School of Public Health and The Commonwealth of Massachusetts Institutional Review Boards.

3.2.5 Statistical Analyses

The case-only design, which was originally proposed to examine gene-environment interactions [41], can also be used to study how slow-varying characteristics modify the effects of a time-varying environmental exposure on a specified outcome [42]. The case-only methodology is applied here to analyze whether mortality on hot days is modified by individual and small-area (CT) social and environmental characteristics. Three levels of modifiers were assessed here, including personal factors, primary cause of death, and area-level characteristics, similar to Zanobetti et al. (2013) [43].

To conduct the case-only analyses, logistic regression was used to examine whether modifiers of interest were associated with an increased relative odds of death on days where

T_{MAX}≥90°F, T_{MAX}≥85°F, or HI_{MAX}≥86°F during the warm season. Individuals were considered to either have a personal modifier or not, or were dichotomized based on being either below the 25th percentile or above the 75th percentile of the values for neighborhood modifiers across Boston, following previous studies using the same methodology [43]. Effect estimates and 95% confidence intervals are reported.

3.3 Results

During this 15-year study period, there was a total of 14,200 deaths in Boston that occurred at home. Death records missing a correct death date were excluded and only records that occurred during the warm season (May – September) were utilized, leaving 6,102 deaths that occurred at home. 34,404 deaths occurred outside of the home, but not within an inpatient or nursing facility, that had complete information during this time period (Table 1). Of the deaths that happened at home, 197 (8.5%) occurred on days with T_{MAX} ≥90°F, 186 (8.0%) on days with HI_{MAX} ≥86°F, and 475 (20.4%) on days with T_{MAX} ≥85°F. For deaths that happened not at home, 201 happened on days with T_{MAX} ≥90°F, 287 on days with HI_{MAX} ≥86°F, and 540 on days with T_{MAX} ≥85°F. Descriptive statistics of the CTs in Boston are provided in Table 1. Maps of the distribution of each small-area social and environmental factor are provided in Figure 3.S1.

Table 3.1. Descriptive statistics for the Boston, MA warm season climate, analyzed deaths from all causes from 2000-2015, and small-area social and environmental parameters at the census tract (CT) level.

Characteristic	
Warm Season Temperature [°F]	
Maximum (mean (SD))	75.7 (10.2)
Mean (mean (SD))	67.3 (8.9)
Minimum (mean (SD))	60.1 (7.8)
Frequency of T_{MAX} ≥90°F (% of all warm season days)	201
Frequency of HI_{MAX} ≥86°F (% of all warm season days)	287
Frequency of T_{MAX} ≥85°F (% of all warm season days)	540
At-Home Deaths (*n*)	6,102
Male (*n* (%))	3,197 (52.4)
Race, Non-Caucasian (*n* (%))	2,276 (37.3)
≥65 years old (*n* (%))	3,865 (63.3)
Outside of the Home Deaths (*n*)	34,404

Table 3.1 (Continued)

Male (*n* (%))	20,744 (60.3)
Race, Non- Caucasian (*n* (%))	4,322 (12.6)
≥65 years old (*n* (%))	19,732 (57.4)
Assessed value of residential building/area ($)(mean (SD))	5,910 (28,000)
Assessed value of residential land/area ($)(mean (SD))	408 (463)
Energy efficiency score of residential buildings (mean (SD))	6.25 (0.352)
Year residential buildings were built/renovated (mean (SD))	1970 (15.9)
Decade residential buildings were built/renovated (mean (SD))	1980 (33.9)
Albedo (mean (SD))	0.124 (0.0114)
Impervious Surface Fraction (mean (SD)) [%]	0.787 (0.141)
Number of street trees/area (mean (SD))	0.00017 (0.00008)
Proportion of population with at least one disability (mean (SD)) [%]	11.4 (7.4)
Proportion of population that is ≤5 years old (mean (SD)) [%]	16.6 (10.4)
Proportion of population with at least 1 medical illness (mean (SD)) [%]	38.6 (3.19)
Proportion of population that is ≥65 years old (mean (SD)) [%]	10.5 (6.79)
Proportion of population that receives low-to-no income (mean (SD)) [%]	28.0 (17.1)
Proportion of population with limited English proficiency (mean (SD)) [%]	38.5 (17.8)
Proportion of population that is not Caucasian (mean (SD)) [%]	51.6 (30.3)
Proportion of population with utilities excluded from rent (mean (SD)) [%]	82.2 (17.6)
Proportion of population that is unemployed	0.0905 (0.0662)
Gross Rent	1,180 (471)
Ratio of Females-to-Males	1.06 (0.324)
GINI Index	0.416 (0.0829)
Population Density (mean (SD))	23,800 (18,300)

3.3.1 Deaths At-Home

There was not a significantly higher relative odds of dying at home than outside of the home for all temperature exposure definitions: T_{MAX} ≥90°F odds ratio (OR)=1.1.01 (95% confidence interval [CI]: 0.91, 1.11), HI_{MAX} ≥86°F OR=1.06 (95% CI: 0.95, 1.17), and T_{MAX} ≥85°F OR=1.07 (95% CI: 1.00, 1.14). Compared with at-home deaths occurring on other warm season days, individuals living in CTs with a higher proportion of low-to-no income people (OR=1.30, 95% CI: 1.06, 1.59) or with limited English proficiency (OR=1.29, 95% CI: 1.05, 1.57) had a higher relative odds of dying at home on days with T_{MAX} ≥90°F than those in communities without these traits. Individuals who died at home living in CTs with a higher assessed building value per area were more highly represented among all at-home deaths than on days with T_{MAX} ≥90°F with an OR=1.26 (95% CI: 1.04, 1.53) (Fig. 3.1a). Those who died at home of a circulatory or heart-related complication had a higher relative risk of dying on hot days than those who died of other causes of death, OR=1.21 (95% CI: 1.01, 1.46) (Fig. 3.2a). No other causes of death were significantly more or less represented among those who died at home on these days.

When considering humidity in relation to temperature, none of the personal or neighborhood social factors were significant modifiers between hot and humid days, where HI_{MAX} ≥86°F, and at-home mortality. However, individuals living in CTs with newer or more recently renovated residential buildings or a greater density of street trees had a lower relative risk of dying at home with OR=0.77 (95% CI: 0.62, 0.95) and OR=0.76 (95% CI: 0.60, 0.97), respectively (Fig. 3.1b). There were no primary causes of death that were significant modifiers of this association on hot and humid days (Fig. 3.1c). There were also no significant individual, community social, or community environmental modifiers on days where T_{MAX} ≥85°F for at-home deaths. All attendant ORs and 95% CIs for each modifier of interest for the case-only at-home analyses can be found in Table 3.S1.

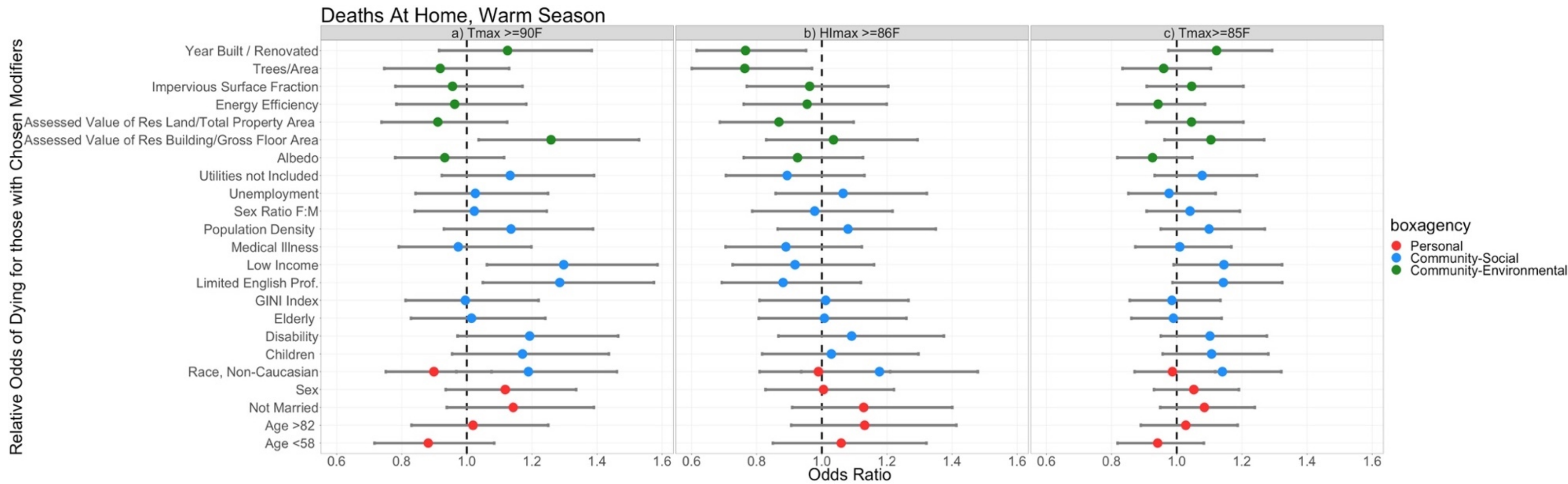

Figure 3.1. Relative odds of dying at home on days where a) $T_{MAX} \geq 90^{\circ}$ F, b) $HI_{MAX} \geq 86^{\circ}$ F, and c) $T_{MAX} \geq 85^{\circ}$ F during the warm season for those who had the following characteristic (Personal) or lived in a census tract with the characteristic (Social, Environmental), compared with those who did not, Boston, 2000-2015. Corresponding OR estimates and 95% confidence interval values can be found in Table 3.S1.

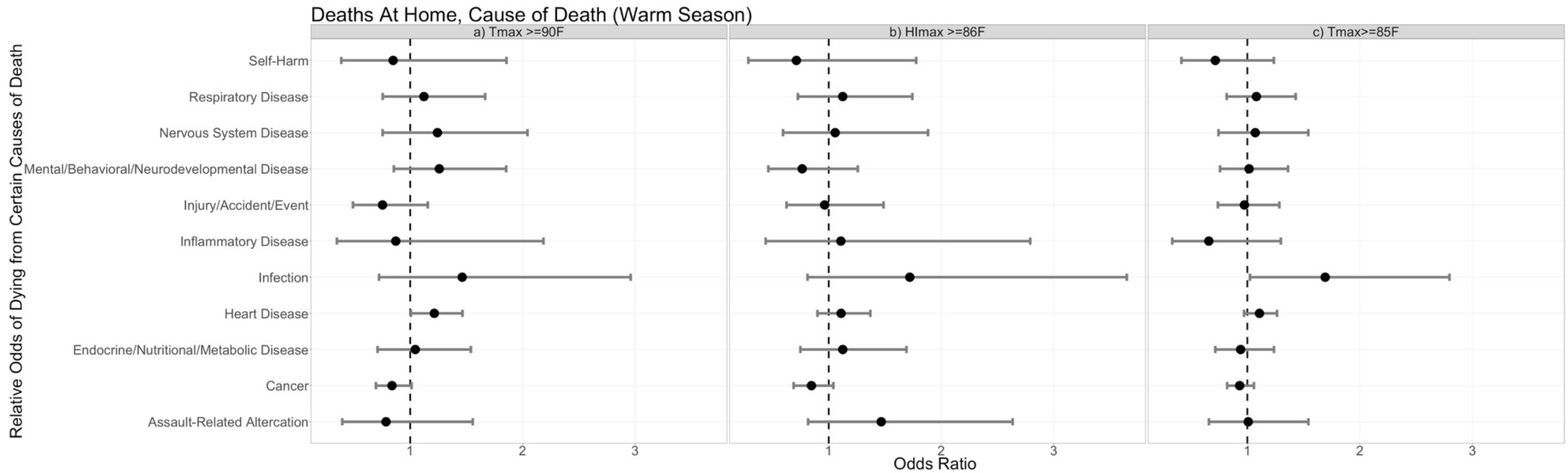

Figure 3.2. Relative odds of dying at home on days where a) $T_{MAX} \geq 90^{\circ}$ F, b) $HI_{MAX} \geq 86^{\circ}$ F, and c) $T_{MAX} \geq 85^{\circ}$ F during the warm season for those who died from these specified primary causes of death, compared to those who did not have that primary cause of death Boston, 2000-2015. Corresponding OR estimates and 95% confidence interval values can be found in Table 3.S1.

3.3.2 Deaths Outside of the Home

When considering deaths that occurred outside of the home, we first examined all deaths that occurred in the City of Boston that did not occur at home, or in a nursing or inpatient facility. This resulted in 34,402 deaths to consider, and we only considered how the relative odds of death on days meeting certain heat criteria were modified by either personal characteristics or primary causes of death, as we did not have corresponding social and environmental characteristics of their home neighborhoods. On hot days, deaths from injuries, accidents, or other events were slightly more represented among deaths outside of the home, OR=1.12 (95% CI: 0.96, 1.31), but not significantly so. Similar to on hot days, no personal characteristics were significant modifiers on hot and humid days where HI_{MAX} ≥86°F. Deaths from assaulted-related altercations had a relative OR=1.23 (95% CI: 0.98, 1.53) that was marginally higher on hot and humid days.

On warm days, where T_{MAX} ≥85°F, we saw that deaths from circulatory/heart-related disease were less represented in deaths outside of the home, with OR=0.94 (95% CI: 0.89, 0.99). On these warm days, individual characteristics significantly modified the association between heat and deaths such that non-Caucasian individuals (OR=0.92; 95% CI: 0.85, 1.00) and individuals over age 82 (OR=0.93; 95% CI: 0.87, 0.98) had lower relative odds of death, but individuals over age 52 had a higher relative odds of death (OR=1.09; 95% CI: 1.02, 1.16). All corresponding ORs and 95% CI's for deaths that occurred outside the home are available in Table S2.

We also considered deaths of Boston residents that happened outside of the home, but not within a nursing or inpatient facility. We assessed effect modification by individual, home area social and environmental, and causes of death. On hot days, where T_{MAX} ≥90°F, deaths from substance abuse (OR=2.88; 95% CI: 1.42, 5.86) and unknown causes (OR=2.38; 95% CI: 1.13, 5.02) were more highly represented. On days were HI_{MAX} ≥86°F, individuals in the youngest quartile of mortality records, below age 58, had a greater relative odds of death, with OR=1.53 (95% CI: 1.07, 2.18), as were deaths from injuries, accidents, and other events (OR=1.70, 95% CI: 1.00, 2.90). On warm days where T_{MAX} ≥85°F, there were several personal traits and causes of death that were significant modifiers of outside of the home mortality: females (OR=0.77; 95% CI: 0.59, 1.00) and individuals under age 58 (OR=1.31; 95% CI: 1.05, 1.62). Deaths from assault-related altercations had 1.79 times the relative odds of occurring on warm days (95% CI: 1.24, 2.58). All corresponding ORs and 95% CI's for deaths that occurred outside the home are available in Table S2.

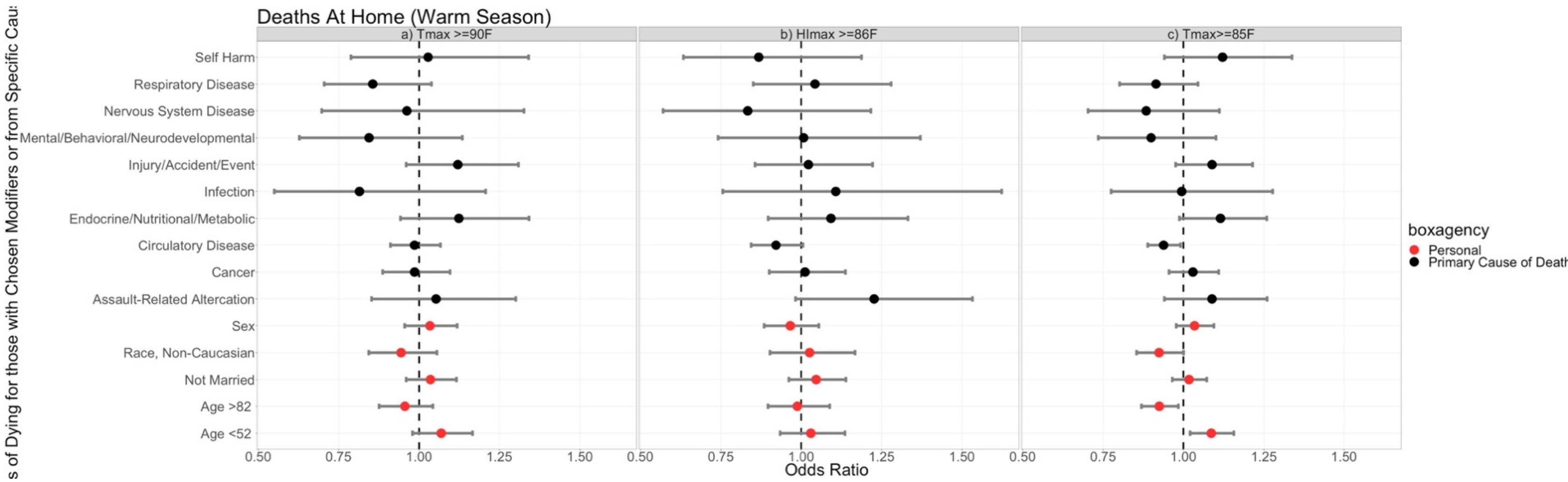

Figure 3.3. Relative odds of dying outside of the home, but not within a nursing or inpatient facility, on days where a) T_{MAX} ≥90° F, b) HI_{MAX} ≥86° F, and c) T_{MAX} ≥85° F during the warm season for those who had the following characteristic (Personal) or who died of the specified primary cause of death, compared to those who did not, Boston, 2000-2015. Corresponding OR estimates and 95% confidence interval values can be found in Table 3.S2.

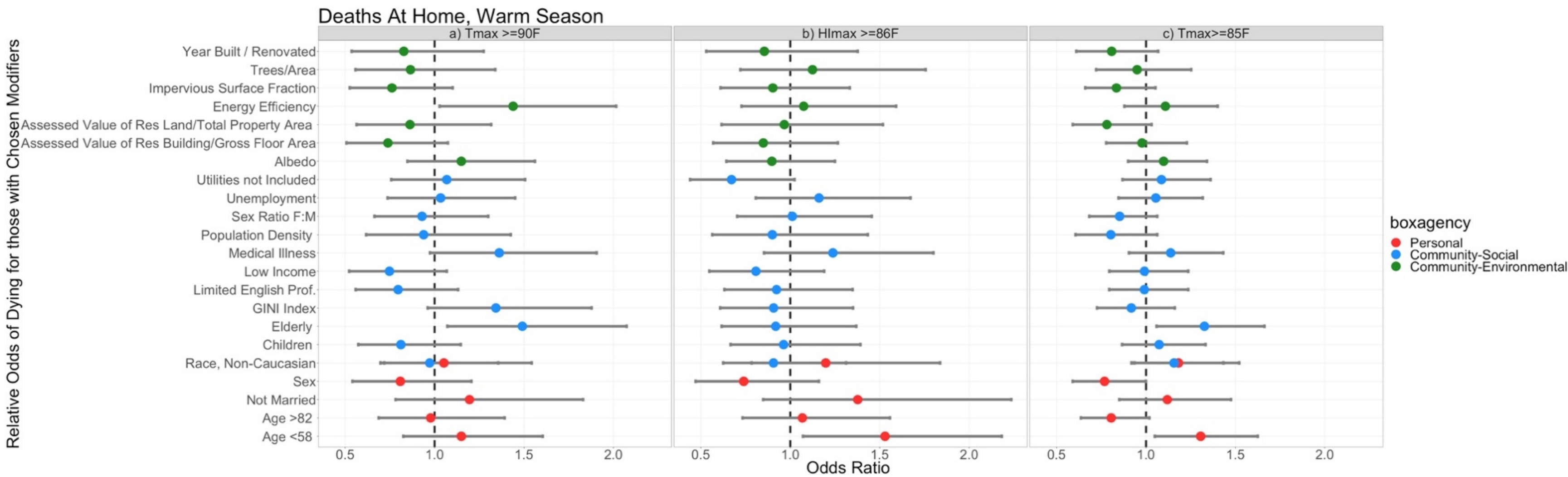

Figure 3.4. Relative odds of dying outside of the home, but not within a nursing or inpatient facility for Boston residents on days where a) $T_{MAX} \geq 90^{\circ}$ F, b) $HI_{MAX} \geq 86^{\circ}$ F, and c) $T_{MAX} \geq 85^{\circ}$ F during the warm season for those who had the following characteristic (Personal) or who died of the specified primary cause of death, compared to those who did not, Boston, 2000-2015. Corresponding OR estimates and 95% confidence interval values can be found in Table 3.S3.

3.4 Discussion

Heat vulnerability assessments have been found to provide valuable evidence for the design and strategic implementation of adaptation interventions and solutions that most effectively protect vulnerable populations. The results from this study provide invaluable local heat vulnerability knowledge to Boston, MA, while also furthering the evidence of heat-mortality relationships in the Northeast US. This study examined several small area-level and individual social and environmental factors that are associated with an increased likelihood of dying at home during extreme heat events. In the case only analyses, those living in CTs with a greater prevalence of well-known social vulnerability factors, like people of color and limited English proficiency had an increased relative odds of dying at home on a hot day during the warm season in Boston, MA. However, some environmental parameters, like surface albedo and energy efficiency were able to reduce the relative odds of death for those dying at home on hot days. Even at lower temperature thresholds, there were personal, social, and environmental factors that modified the relationships between temperature exposure and dying both at and outside of the home, providing evidence that current local thresholds may not be capturing all public health risks during extreme heat exposure.

Past research has found that deaths on hot days are more likely to occur outside of hospitals [5,44] and more likely to occur at home than in hospitals or other institutions [18], which was similar to the findings in this study when defining heat exposure as days with HI_{MAX} ≥86°F. We found that persons living in CTs with a higher proportion of low-to-no income individuals had a greater relative odds of dying at home on days where T_{MAX} ≥90°F and where T_{MAX} ≥85°F (when the proportion of those with a disability and with limited English proficiency were also significant modifiers). This follows on findings from previous heat vulnerability literature, including similar studies in NYC where there was a higher odds of death on hot days among black individuals [18]. CTs with a higher surface reflectance had a lower relative odds of dying at home, at both temperature thresholds, but not when considering humidity in combination with temperature. There was not a significantly higher relative risk for elderly individuals or CTs with a greater proportion of elderly individuals, dying at home at any temperature definition, which is also similar to in NYC [18], despite older adults enhanced susceptibility to extreme heat and previous findings documenting increased vulnerability [4,5].

On days where HI_{MAX} ≥86°F, individuals living in CTs with newer or more recently renovated residential buildings or a greater density of street trees had a lower relative risk of dying at home. There was not a significantly higher relative risk for elderly individuals or CTs with a greater proportion of elderly individuals, dying at home at any temperature definition, which is also similar to in NYC [18], despite older adults enhanced susceptibility to extreme heat and previous findings documenting increased vulnerability [4,5].

The small-area neighborhood social and environmental factors surrounding the homes of those who died were not as important for deaths that occurred outside of the home as compared to those that happened at home. This makes sense, as the home neighborhood characteristics will likely not play as much of a role for deaths that occur elsewhere as they would for deaths that occur at home. However, individuals who were in the youngest quartile of deaths outside of the home were more highly represented in those that died on warm, as well as hot and humid days. The oldest individuals who died in this study were not more highly represented among those who died within or outside of the home at any temperature definition examined. We hypothesize that these individuals, who are extremely vulnerable to heat-related mortality, may be more frequently dying within inpatient or nursing facilities, so were not captured in this analysis. Further, those who are oldest may be themselves aware of their enhanced susceptibility to heat-related medical complications, so may take precautions on these days (or have a support system that aides them in doing so).

Interestingly, the temperature thresholds used did yield modification by different primary causes of death. Deaths at home were more highly represented by those who died of heart disease, which is similar to previous findings [4]. However, Boston residents who died outside of the home during this time period had 2.88 and 2.38 times the relative odds of dying from substance abuse or unknown causes when T_{MAX} ≥90°F days and 1.79 times the relative odds of dying from an assault-related altercation on days when HI_{MAX} ≥86°F. Given that past research has shown that heat-related mortality is frequently misclassified, and that sometimes a proper causes if not listed at all, we believe that the high relative odds of dying from unknown causes presents a clear signal of heat-related mortality effects. Further, Research has demonstrated that aggressive and violent behaviors increase on hot days [46–49]. In Boston, there are significant increases in police, fire, and medical services across the city at temperature around 83-85°F, which provides evidence that societal governance is impact by heat at these lower temperatures [50]. Our findings of increased relative odds of dying from substance abuse follows patterns seen in past studies in other geographic locations [51,52]. To our knowledge, these causes of deaths are not captured in local assessments of the public health impacts of extreme heat and mortality risk factors, despite some anecdotal information provided to us at the start of this study (personal communications with the City of Boston Public Health Commission).

The results of this study highlight the differential individual, social, environmental drivers of heat vulnerability in Boston, MA, and some of the resulting consequences those have for the causes of death on hot days. Most of the current efforts to mitigate poor health outcomes during extreme heat events for those that have been found to be socially vulnerable, rely on behavioral change. Required behavioral change may be limited by the lack of cognizant realization on hot days that these behaviors are needed, which has been seen most commonly in seniors and other vulnerable populations as they exhibit optimism bias on hot days [53,54], or by socioeconomic status since some of these behaviors, like running fans/AC or travelling to a cooler location often require time and financial resources.

Many strategies have been evaluated in populations that have a high social heat vulnerability, although the uptake and effective use of these strategies has been variable. In vulnerable populations, like older adults, strategies have included increased suggestions of using fans, operating AC, going to a cool location, changing clothes, drinking more water, taking a cold shower, etc. are widely communicated during hot days. However, these behaviors have been found to be more frequently enacted at more moderate temperatures, but not when it's extremely hot [55]. Further, even though older adults living in public housing reported knowing which strategies to use when it was hot outside, like drinking more water, individuals did not actually follow through on the behavior [56]. Similar things were found in the United Kingdom, with older adults being least likely but those of high income and education being most likely to protect themselves during heat [57]. The City of Boston has also launched hydration campaigns and water distribution on hot days, with initiatives to raise awareness about vulnerability and protective strategies in communities with vulnerable individuals (personal communications with the Boston Mayor's Office of New Mechanics).

The goal of this study was to demonstrate how our surrounding built and natural environment exists concurrently with our social environment and can provide an important point of intervention that relies less on behaviors changing that can be used in tandem with existing communication of heat-harm-reduction strategies. As was seen at several temperature exposure definitions here, some area environmental factors can provide protection from heat-related mortality on hot days. Those who lived in CTs that had newer, or newly renovated, residential buildings and CTs with a greater density of street trees had lower relative odds of dying at home on hot days. Boston has one of the oldest residential building stocks in the United States, with a median age of 54 years [58] and 62% of homes in Massachusetts were constructed before 1970 [59]. Older buildings, which tend to use more traditional materials, have been found to have higher thermal masses [60], making them prone to overheating. Low-income individuals and people of color are more likely to live in homes that are overcrowded and/or are of poor environmental and physical quality [61]. While these relationships between housing and public health are not new, demonstrating the quantitative effect these built environment factors have on a climate change relevant public health outcome provides local actionable evidence.

As stated in the methods section of this paper, an original goal of this study was to tie building-level features with the obtained death records to assess well known vulnerability and resilient factors, like presence of central/window AC, immediate access to street trees and building materials, height, and age, but too few matching cases existed. Future studies on the specific local building archetypes and how these modify indoor temperature exposures will fill a gap that remains from this study and provide the most actionable evidence when constructing or retrofitting buildings to be more heat resilient. As Boston is currently exploring altering building codes to enhance resilience for flooding and sea level rise, it will be critical to evaluate these policy measures for extreme heat as well.

Adaptation strategies like improved and reflective urban materials, cool, green, or evaporative roofs, enhanced residential building shading, and increased density of street trees have the potential to reduce the range of summertime temperatures in the Northeast US and reduce the impact of the increased number of hot days that we are expected to experience by the end of the century [50]. While these strategies do occur on different temporal scales, and may not be feasible for all buildings in the immediate future, nearly three-quarters of the global infrastructure needed by 2050 has not yet been built [62]. Further, buildings here have been historically designed for harnessing heat during the cold, winter months, and may not be resilient to our hotter future. With warming climates, this means that our built infrastructure has an enhanced probability of overheating during non-extreme events and routine operations [16]. Planning for the health impacts of extreme heat in the design and retrofit of buildings is vital for protecting public health in a changing climate. This will be important in urban areas, but also suburban areas and satellite cities around major urban areas that have been found to show a rapidly increasing vulnerability to extreme heat [63].

It is important to consider the limitations of these analyses. Even though 3 temperature exposure definitions were used in this study (T_{MAX} ≥90°F, HI_{MAX} ≥86°F, and T_{MAX} ≥85°F) exposure misclassification likely still exists using this single ambient temperature measurement from Logan International Airport. This presents misclassification bias in 2 ways: first, temperatures vary across the city, and the temperature at the airport is likely not representative of temperatures in other neighborhoods of Boston, with hotter temperatures located inland from the coast. Second, our goal was to address how buildings influence heat exposure and resulting health effects but using these small-area level building summaries still does not get at building specifics and the true exposure the individuals represented in this study were experiencing.

A case-only analysis is limited in that it only assesses the relative risk of mortality with individual and neighborhood characteristics, and not the greatest absolute risk. Although we have removed the effect of season, residual confounding may still be present if there is an interaction between season and any of the effect modifiers being examined. This study relies heavily on CT-level boundaries and information. There were likely changes in the social/environmental parameters over this study period, but only cross-sectional estimates that were available at different points in this study period were utilized to assign these parameters across an entire 15-year time period. Finally, one well known heat-mitigating environmental factor – proximity to greenspace – was not included in this study, as Boston is only one of 2 cities in the US where 100% of its population is within 10 minutes from a park [64].

Despite these limitations, which also exist in much of the preexisting heat vulnerability research, there are many strengths to the analyses within this paper. A case-only analysis that assesses the change in heat-related mortality risk by individual and neighborhood characteristics can be used to create composite heat-related vulnerability indices to prioritize the most vulnerable neighborhoods based on social and environmental factors. This information can be used to compare how non-time varying characteristics – or characteristics that change very slowly over time – modify the effect of a time-varying environmental exposure like extreme heat on excess mortality. A case-only analysis that is focused in the warm season only also removes the effect of season, which reduces potential seasonal confounding, reduces potential confounding by variables typically associated with mortality (e.g. smoking), simplifies modeling, and reduces the model's sensitivity to misspecification bias. By including some health-promotive covariates, like street trees and albedo we can assess protective neighborhood features, instead of just harmful features. The inclusion of both positive and adverse covariates allows us to both focus on strategies that create more health-protective environments and reduce harmful environments, respectively, for all.

Further, from the many ways to measure temperature and assess extreme heat, three temperature exposure definitions were used: T_{MAX} ≥90°F, HI_{MAX} ≥86°F, and T_{MAX} ≥85°F. Even though local National Weather Service branches use higher thresholds for issuing heat warnings and advisories, recent research has suggested that there are increased rates of morbidity and mortality in New England on days where temperatures are below current National Weather Service criteria [23], and that heat alerts issued in 20 US cities only had a significant reduction in mortality in Philadelphia [65]. The temperature threshold chosen for this study was supported by previous research, including findings by Guo et al. (2017) that daily maximum temperatures for defining a heat wave are better at predicting mortality than minimum temperature [66] and by Kingsley et al. (2016) that there are significant increases in mortality at temperatures from 75-85°F in Rhode Island [25]. This threshold was also used because of local heat interventions that are enacted in Boston when temperatures reach 90°F, including opening of cooling centers, transportation for vulnerable persons, and is therefore important to local heat responses.

Future studies will utilize high resolution temperature models to better assign ambient temperature values throughout the study area, instead of relying on temperature from the airport that may not be representative of temperatures throughout the rest of the city. We will also examine the role of building-specific parameters, like materials, number of floors, orientation, etc. in the relationships between extreme heat and mortality, to better identify common local building archetypes that are most vulnerable to extreme heat. Forthcoming building-level adaptation strategies will be the most effective at reducing poor health outcomes at home during extreme heat events. Future research would also be beneficial to elucidate the environmental factors that exacerbate or mitigate mortality outside of the home on hot days, to better address heat exposures in places outside of the home and inform adaptation strategies throughout a city and enhance the resilience of vital public spaces.

3.5 Conclusion

Future climate change adaptation will be implemented at the local level, so decision makers need data and evidence at that scale to best inform policy and infrastructure decisions. This study examined mortality at home and outside of the home on hot days in Boston, MA. We evaluated how individual and small-area social, built environment, and natural environment characteristics modify the association between heat and mortality at three temperature thresholds. While some neighborhoods had greater social vulnerability, some of the environmental factors examined were able to reduce the relative odds of death within and outside the home. Further, even at temperatures below current local thresholds used for warnings, advisories, and local interventions, there were significantly higher relative odds of death from unknown causes, substance abuse, injury/accidents, and assault, most of which are not currently being incorporated into heat vulnerability assessments and adaptation planning.

3.6 References

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3.7 Supplemental Information

Table 3.S1. Relative odds of dying at home during extreme heat, during the warm season for those who had the following characteristic (Personal, Primary Cause of Death) or lived in a census tract with the characteristic (Social, Environmental), compared with those who did not, Boston, 2000-2015. Bold indicates the OR is significant at an *p*<0.05.

	T_{MAX} ≥90°F		HI_{MAX} ≥86°F		T_{MAX} ≥85°F	
Personal	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Sex	1.12	(0.94, 1.34)	1.01	(0.83, 1.22)	1.05	(0.93, 1.19)
Not Married	1.14	(0.94, 1.39)	1.13	(0.91, 1.4)	1.08	(0.95, 1.24)
Race, Non-Caucasian	0.90	(0.75, 1.08)	0.99	(0.81, 1.21)	0.99	(0.87, 1.12)
Age <57	1.02	(0.83, 1.25)	1.13	(0.91, 1.41)	1.03	(0.89, 1.19)
Age >81	0.88	(0.72, 1.08)	1.06	(0.85, 1.32)	0.94	(0.82, 1.08)
Social						
Low Income	**1.30**	**(1.06, 1.59)**	0.92	(0.73, 1.16)	1.14	(0.99, 1.32)
Unemployment	1.03	(0.84, 1.25)	1.07	(0.86, 1.32)	0.98	(0.85, 1.12)
GINI Index	1.00	(0.81, 1.22)	1.01	(0.81, 1.27)	0.98	(0.86, 1.13)
Population Density	1.14	(0.93, 1.39)	1.08	(0.86, 1.35)	1.10	(0.95, 1.27)
Sex Ratio F:M	1.02	(0.84, 1.25)	0.98	(0.79, 1.22)	1.04	(0.91, 1.19)
Utilities not Included	1.13	(0.92, 1.39)	0.89	(0.71, 1.13)	1.08	(0.93, 1.25)
Disability	1.19	(0.97, 1.46)	1.09	(0.87, 1.37)	1.10	(0.95, 1.28)
Children	1.17	(0.95, 1.44)	1.03	(0.82, 1.3)	1.11	(0.96, 1.28)
Elderly	1.01	(0.83, 1.24)	1.01	(0.81, 1.26)	0.99	(0.86, 1.14)
Limited English Prof.	**1.29**	**(1.05, 1.57)**	0.88	(0.69, 1.12)	1.14	(0.99, 1.32)
Race, Non-Caucasian	1.19	(0.97, 1.46)	1.18	(0.94, 1.48)	1.14	(0.98, 1.32)
Medical Illness	0.97	(0.79, 1.2)	0.89	(0.7, 1.12)	1.01	(0.87, 1.17)
Environmental						
Energy Efficiency	0.96	(0.78, 1.18)	0.95	(0.76, 1.2)	0.94	(0.82, 1.09)
Assessed Value of Res Land/Total Property Area	0.91	(0.74, 1.12)	0.87	(0.69, 1.1)	1.05	(0.91, 1.2)
Assessed Value of Res Building/Gross Floor Area	**1.26**	**(1.04, 1.53)**	1.04	(0.83, 1.29)	1.10	(0.96, 1.27)
Year Built / Renovated	1.13	(0.91, 1.38)	**0.77**	**(0.62, 0.95)**	1.12	(0.97, 1.29)
Trees/Area	0.92	(0.75, 1.13)	**0.76**	**(0.6, 0.97)**	0.96	(0.83, 1.1)
Albedo	0.93	(0.78, 1.11)	0.93	(0.76, 1.13)	0.93	(0.82, 1.05)
Impervious Surface Fraction	0.96	(0.78, 1.17)	0.96	(0.77, 1.2)	1.05	(0.91, 1.2)
Primary Cause of Death						
Infection	1.46	(0.72, 2.96)	1.72	(0.81, 3.65)	**1.69**	**(1.02, 2.8)**
Cancer	0.84	(0.69, 1.01)	0.85	(0.69, 1.04)	0.93	(0.82, 1.06)

Table 3.S1 (Continued)

Inflammatory Disease	0.87	(0.35, 2.18)	1.11	(0.44, 2.79)	0.66	(0.33, 1.3)
Endocrine/Nutritional/Metabolic Disease	1.05	(0.71, 1.54)	1.12	(0.75, 1.69)	0.94	(0.72, 1.24)
Mental/Behavioral/Neurodevelopmental Disease	1.26	(0.86, 1.85)	0.76	(0.46, 1.26)	1.02	(0.76, 1.36)
Nervous System Disease	1.24	(0.76, 2.04)	1.06	(0.59, 1.88)	1.07	(0.74, 1.54)
Heart Disease	**1.21**	**(1.01, 1.46)**	1.11	(0.9, 1.37)	1.11	(0.97, 1.26)
Respiratory Disease	1.12	(0.76, 1.67)	1.12	(0.73, 1.74)	1.08	(0.82, 1.43)
Injury/Accident/Event	0.75	(0.49, 1.16)	0.96	(0.62, 1.49)	0.97	(0.74, 1.29)
Self-Harm	0.85	(0.39, 1.86)	0.71	(0.29, 1.78)	0.72	(0.41, 1.24)
Assault-Related Altercation	0.79	(0.4, 1.56)	1.47	(0.82, 2.63)	1.01	(0.66, 1.54)

Table 3.S2. Relative odds of dying outside of the home during extreme heat, during the warm season for those who had the following characteristic (Personal, Primary Cause of Death) or lived in a census tract with the characteristic (Social, Environmental), compared with those who did not, Boston, 2000-2015. Bold indicates the OR is significant at an *p*<0.05.

	T_{MAX} ≥90°F		HI_{MAX} ≥86°F		T_{MAX} ≥85°F	
Personal	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Sex	1.03	(0.95,1.12)	0.97	(0.88,1.05)	1.03	(0.98,1.09)
Not Married	1.04	(0.96,1.12)	1.05	(0.96,1.14)	1.02	(0.97,1.07)
Race, Non-Caucasian	0.94	(0.84,1.06)	1.03	(0.9,1.17)	0.92	(0.85,1)
Age >82	0.96	(0.88,1.04)	0.99	(0.9,1.09)	**0.93**	**(0.87,0.98)**
Age <52	1.07	(0.98,1.17)	1.03	(0.93,1.14)	**1.09**	**(1.02,1.16)**
Primary Cause of Death						
Infection	0.81	(0.55,1.21)	1.11	(0.76,1.62)	0.99	(0.77,1.28)
Cancer	0.99	(0.89,1.1)	1.01	(0.9,1.14)	1.03	(0.96,1.11)
Blood/Immune	1.06	(0.62,1.81)	0.95	(0.51,1.75)	0.87	(0.59,1.29)
Endocrine/Nutritional/Metabolic	1.12	(0.94,1.34)	1.09	(0.9,1.33)	1.12	(0.99,1.26)
Mental/Behavioral/Neurodevelopmental	0.84	(0.63,1.14)	1.01	(0.74,1.37)	0.9	(0.73,1.1)
Nervous System Disease	0.96	(0.7,1.33)	0.83	(0.57,1.22)	0.88	(0.7,1.11)
Circulatory Disease	0.99	(0.91,1.07)	0.92	(0.84,1.01)	**0.94**	**(0.89,0.99)**
Respiratory Disease	0.86	(0.71,1.04)	1.04	(0.85,1.28)	0.92	(0.8,1.05)
Congenital Disease	1.54	(0.7,3.41)	0.24	(0.03,1.74)	1.4	(0.77,2.53)
Injury/Accident/Event	1.12	(0.96,1.31)	1.02	(0.86,1.22)	1.09	(0.98,1.22)
Self-Harm	1.03	(0.79,1.34)	0.87	(0.63,1.19)	1.12	(0.94,1.34)
Assault-Related Altercation	1.05	(0.85,1.3)	1.23	(0.98,1.53)	1.09	(0.94,1.26)

Table 3.S3. Relative odds of Boston residents dying outside of the home during extreme heat, during the warm season for those who had the following characteristic (Personal, Primary Cause of Death) or lived in a census tract with the characteristic (Social, Environmental), compared with those who did not, Boston, 2000-2015. Bold indicates the OR is significant at an *p*<0.05.

	T_{MAX} ≥90°F		HI_{MAX} ≥86°F		T_{MAX} ≥85°F	
Personal	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Sex	0.81	(0.54, 1.21)	0.74	(0.47, 1.16)	0.77	(0.59, 1)
Not Married	1.20	(0.78, 1.83)	1.38	(0.85, 2.24)	1.12	(0.85, 1.47)
Race, Non-Caucasian	1.05	(0.72, 1.54)	1.2	(0.78, 1.84)	1.18	(0.92, 1.52)
Age >82	0.98	(0.69, 1.39)	1.07	(0.73, 1.56)	0.81	(0.64, 1.02)
Age <58	1.15	(0.82, 1.6)	**1.53**	**(1.07, 2.18)**	1.31	(1.05, 1.62)
Social						
Low Income	0.75	(0.52, 1.07)	0.81	(0.55, 1.19)	0.99	(0.79, 1.24)
Unemployment	1.03	(0.74, 1.45)	1.16	(0.81, 1.67)	1.06	(0.85, 1.32)
GINI Index	1.34	(0.96, 1.88)	0.91	(0.61, 1.35)	0.92	(0.73, 1.16)
Population Density	0.94	(0.62, 1.43)	0.9	(0.56, 1.43)	0.8	(0.61, 1.06)
Sex Ratio F:M	0.93	(0.66, 1.3)	1.01	(0.7, 1.46)	0.85	(0.68, 1.06)
Utilities not Included	1.07	(0.76, 1.51)	0.67	(0.44, 1.02)	1.09	(0.87, 1.36)
Children	0.81	(0.57, 1.15)	0.96	(0.67, 1.39)	1.07	(0.87, 1.33)
Elderly	**1.49**	**(1.07, 2.07)**	0.92	(0.62, 1.37)	1.33	(1.06, 1.66)
Limited English Prof.	0.8	(0.56, 1.13)	0.92	(0.63, 1.35)	0.99	(0.79, 1.24)
Race, Non-Caucasian	0.97	(0.7, 1.36)	0.91	(0.62, 1.31)	1.16	(0.94, 1.43)
Medical Illness	1.36	(0.97, 1.91)	1.24	(0.85, 1.8)	1.14	(0.91, 1.43)
Environmental						
Energy Efficiency	**1.44**	**(1.03, 2.02)**	1.08	(0.73, 1.59)	1.11	(0.88, 1.4)
Assessed Value of Res Land/Total Property Area	0.86	(0.56, 1.32)	0.97	(0.62, 1.52)	0.78	(0.59, 1.03)
Assessed Value of Res Building/Gross Floor Area	0.74	(0.51, 1.07)	0.85	(0.57, 1.27)	0.98	(0.78, 1.23)
Year Built / Renovated	0.83	(0.54, 1.28)	0.85	(0.53, 1.38)	0.81	(0.61, 1.07)
Trees/Area	0.86	(0.56, 1.34)	1.12	(0.72, 1.76)	0.95	(0.72, 1.25)
Albedo	1.15	(0.85, 1.56)	0.90	(0.64, 1.25)	1.1	(0.9, 1.34)
Impervious Surface Fraction	0.76	(0.53, 1.10)	0.90	(0.61, 1.33)	0.83	(0.66, 1.05)
Primary Cause of Death						

Table 3.S3 (Continued)

Infection	0.54	(0.07, 4.02)	1.4	(0.6, 1.14)	**0.77**	**(0.62, 0.96)**
Liver Disease	0.46	(0.06, 3.45)	3.58	(0.59, 2.39)	1.14	(0.7, 1.86)
Cancer	0.88	(0.59, 1.31)	0.85	(0.77, 1.48)	0.96	(0.77, 1.21)
Diabetes	1.16	(0.55, 2.44)	1.67	(0.3, 1.93)	1.26	(0.75, 2.1)
Heart Disease	0.9	(0.64, 1.24)	0.65	(0.12, 2.1)	1.26	(0.68, 2.35)
Nervous System Disease	1.11	(0.49, 2.5)	0.78	(0.46, 3.91)	0.8	(0.33, 1.93)
Substance Abuse	**2.88**	**(1.42, 5.86)**	1.16	(0.6, 3.98)	1.75	(0.9, 3.39)
Inflammatory Disease	0.88	(0.21, 3.77)	1.07	(0.69, 8.62)	1.6	(0.56, 4.58)
Cerebrovascular Disease	0.27	(0.04, 1.95)	0.33	(0.06, 3.48)	1.14	(0.42, 3.08)
Digestive System Related Disease	0.66	(0.09, 4.97)	**1.74**	**(1.17, 6.73)**	1.75	(0.89, 3.47)
Unknown Causes	**2.38**	**(1.13, 5.02)**	1.98	(0.82, 4.76)	1.66	(0.92, 2,99)
Assault-Related Altercation	1.49	(0.87, 2.54)	0.92	(0.39, 38.48)	**1.79**	**(1.24, 2.58)**
Injury/Accident/Event	0.8	(0.42, 1.49)	1.42	(0.75, 2.68)	1.11	(0.77, 1.6)
Self-Harm	1.00	(0.36, 2.80)	0.92	(0.28, 2.98)	0.99	(0.50, 1.94)

Figure 3.S1. Distribution of the all small-area social and environmental vulnerability factors, Boston, 2000-2015.

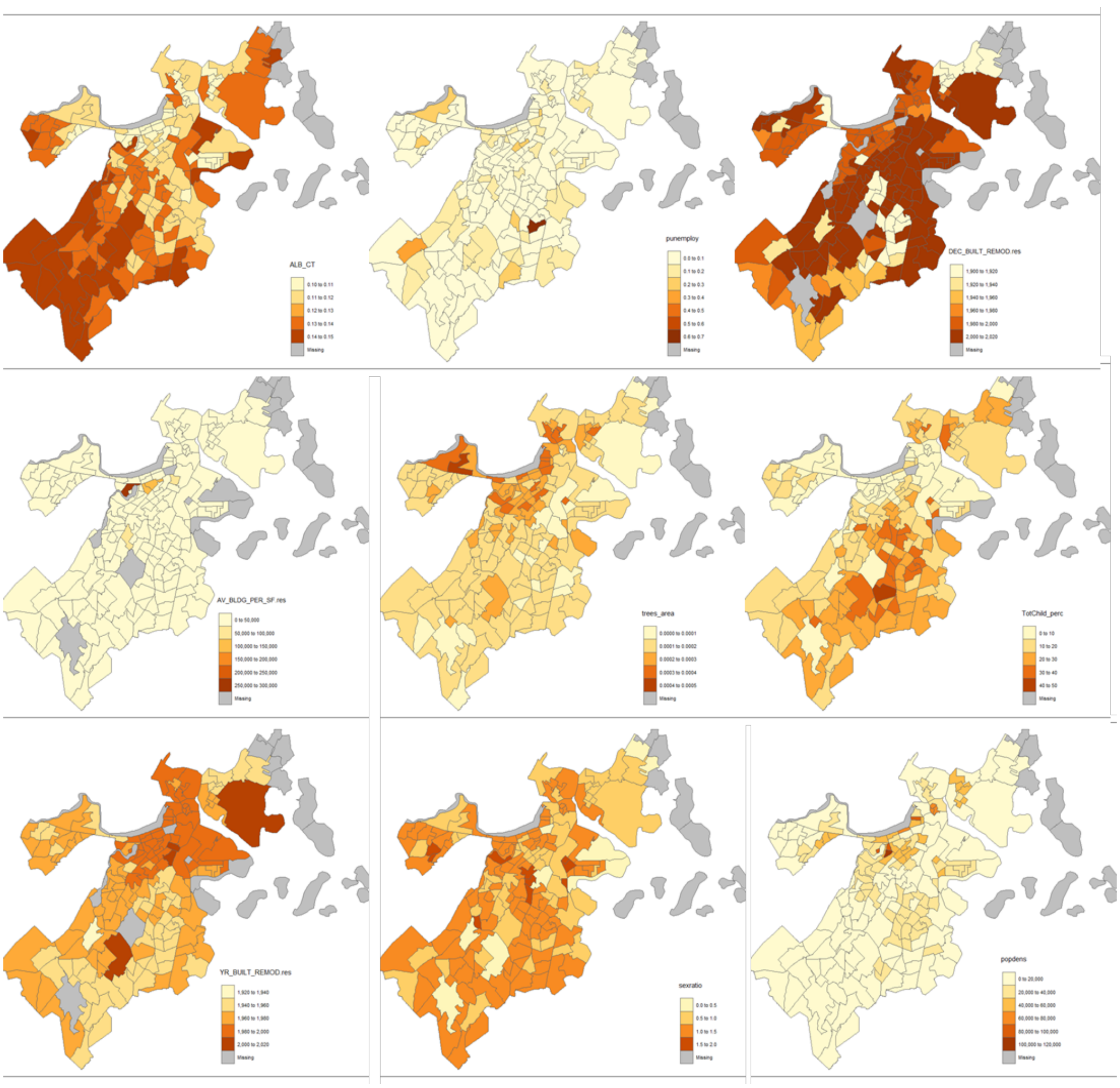
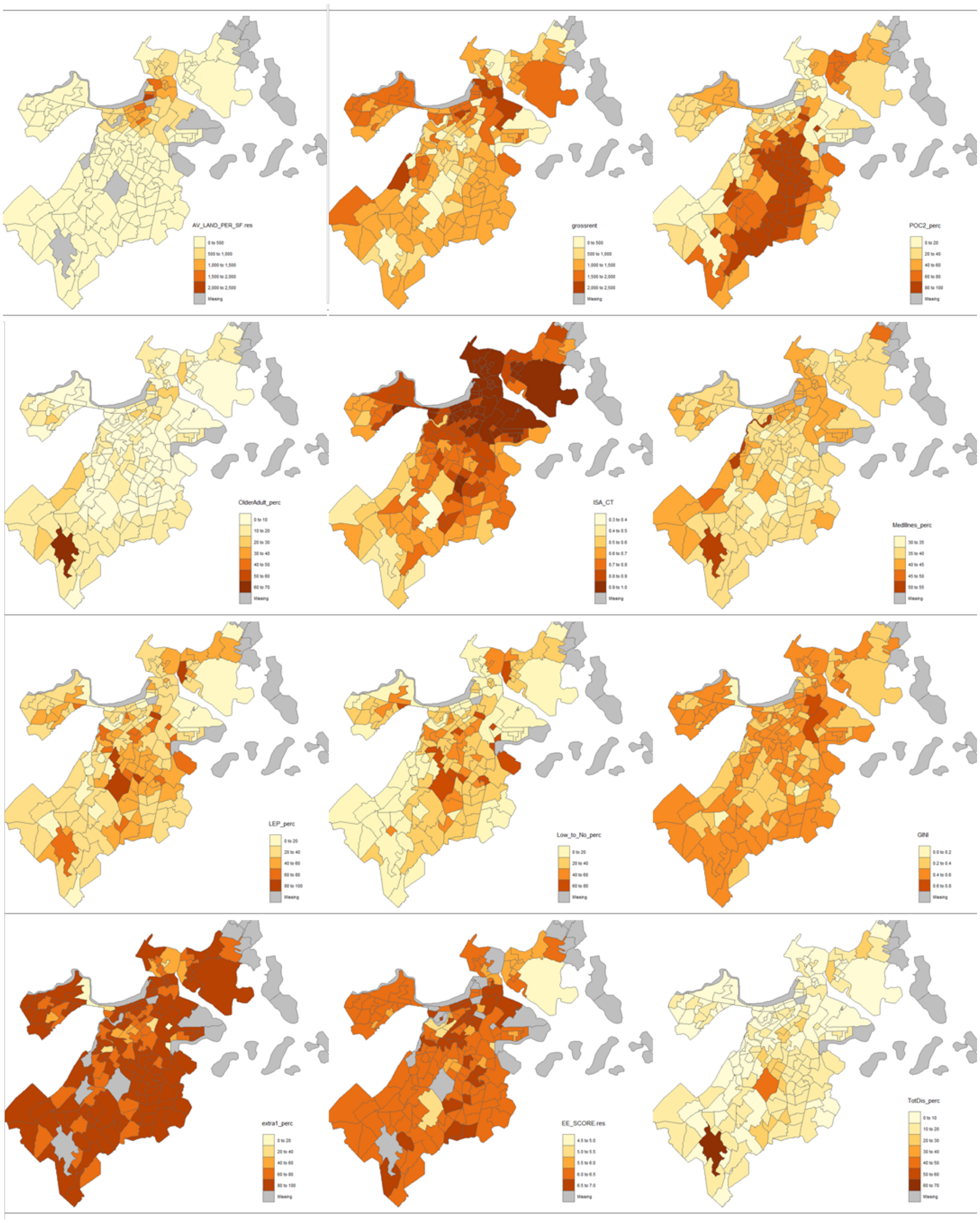


Figure 3.S1. (Continued)



CHAPTER 4

Dying at home on hot days: A spatial analysis of at-home mortality in the context of individual and small-area social and environmental vulnerability in Boston, MA.

Abstract

Although heatwaves are currently the most deadly of all meteorological phenomena, climate change is continuing to increase their frequency, duration, and severity, which studies have shown may double-to-triple heat-related mortally in Boston, MA. We spend upwards of 90% of our time indoors, and 70% of our time indoors is spent in our homes, on average. Past analyses of significant heat wave events in the United States have found that dying at home is more likely than dying outside of the home during these extreme heat events, yet current local heat vulnerability assessments do not adequately capture the impacts of the built environment in combination with the many social factors that have been found to contribute to heat vulnerability. All deaths of Boston, Massachusetts residents that occurred at home from 2000-2015 were analyzed in coordination with small-area (census tract) social, natural environment, and built environment factors that contribute to heat vulnerability or resilience, to determine the spatial distribution of at-home deaths on hot days. A high-resolution gridded climate dataset was used to assign temperatures at the location of each at-home death. At-home mortality on hot days was driven by both social and environmental factors, differentially across the City of Boston. The neighborhoods of Dorchester, Roxbury, and East Boston were found to be most vulnerable to the impacts of extreme heat on dying at home, driven largely by greater proportion of people of color, those with low-to-no income, and presence of single-family homes.

4.1 Introduction

Extreme heat is the most deadly of all meteorological phenomena [1], and these events are increasing in frequency, duration, and severity with climate change [2,3]. Heat-related mortality is projected to double-to-triple in the Northeast United States [4] without adequate climate change mitigation and adaptation strategies, with the effects being disproportionally experienced by the most vulnerable individuals. There has been extensive research on heat vulnerability, much of which has focused on social parameters, like income, race, education, and age. [5–10].

One group of factors that determines much of our exposure to extreme heat are the natural and built environment. Buildings modify our exposure to ambient temperature conditions, either exacerbating or mitigating indoor heat exposures given the same ambient conditions [11]. As buildings have become more energy efficient, higher thermal insulation and greater airtightness have increased the risk of potential overheating [11], These increases in energy efficiency in heat-dominated climates, like that of Boston, MA, may potentially be adversely impacting the resiliency of buildings to extreme heat [12]. Overheating is a great risk in times of power loss when mechanical cooling may not be available. The risk of major and widespread power outages that affect a large number of customers that would result in “heat disasters” appears to be growing [13]. Research has shown that summertime overheating of residential buildings may increase by upwards of 25% by the middle of the 21st Century [14].

Some of the risk factors associated with building and urban design have been incorporated into previous heat vulnerability research, or have been evaluated after sever heatwaves have occurred. During the France 2003 heatwave, well-insulated homes were found to be protective factor against mortality [15], and neighborhoods of Barcelona with older buildings have had higher heat-related mortality rates in the past [15]. In the UK, 21% of heat-related mortality has been attributed to the urban heat island [16]. Urban tree canopies can keep surrounding buildings cooler than without shading, reducing the amount of cooling that might be needed and protecting the residents within [17], and surrounding greenspace can reduce vulnerability to heat morbidity and mortality [10]. Despite spending up to 90% of time within buildings and built environments that determine our exposure to ambient conditions, few local heat vulnerability and adaptation assessments include widespread information on buildings or the built and natural environments.

There have only been a few local assessments of heat vulnerability in Boston, MA. Although a framework for assessing heat vulnerability has been created [9], past application of this at the local level in Phoenix, AZ found that only about half of all census tracts were correctly characterized as vulnerable. This demonstrates the need for tailoring and implementation of heat vulnerability assessments at the local level.

In 2000 , Boston's daily heat-related mortality rate was 2.9 deaths per 100,000 people [4]. This is projected to increase to 5.9-6.5 deaths in 2020 and 8.8-11.7 deaths in 2050 per 100,000 people, depending on near-term greenhouse gas emissions trajectories [4]. In 2015, a Boston-based heat vulnerability and urban heat island assessment was conducted by students at Tufts University and prepared for by the Trust for Public Land [18]. This plan outlined several solution that would reduce Boston's heat vulnerability, mainly through community engagement and adaptations to the built environment, and was largely based on helpful and informative case studies of strategies implemented here and elsewhere in the US. While this assessment included some built environment factors like land use and central AC penetration, addition local research is needed on the role of buildings and the built environment in driving heat vulnerability in Boston to most effectively enact these interventions.

In this study, we aim to further local heat vulnerability research by incorporating building and environmental characteristics in combination with social factors that are well-known heat vulnerability risk factors. We also tie the vulnerability factors to a critical public health outcome – deaths that happen at home. People without a regular care provider and African American individuals are at risk for poor health outcomes during extreme heat events, and research has shown that these individuals are less likely to seek emergency medical care when needed compared to other groups [19]. Examining at-home deaths demonstrates one of the most severe heat-related outcomes that disproportionately impact vulnerable populations. This comprehensive assessment of the underlying vulnerabilities and their social and environmental drivers will be vital implementing heat action planning in the future. With the inclusion of local context, as well as a more comprehensive set of social, natural environment, and built environment parameters, this study evaluates the spatial distribution of at-home deaths on hot days.

4.2 Methods

4.2.1 Exposure Data

Hourly meteorological data from 2000-2015 was accessed for Boston Logan International Airport via the National Centers for Environmental Information. Daily maximum ambient temperatures (T_{MAX}) ≥90°F was used as a binary measure, as it is a common temperature threshold used to enact local cooling strategies in Boston. To account for humidity in addition to temperature, the heat index (HI) was also considered by using days where HI_{MAX} ≥86°F, which was the 95th percentile of the HI during the warm season in Boston. All temperature thresholds were assessed using single day exposures, as heat-mortality relationships have been found to increase on individual days of exposure [6,20–22]. All analyses were conducted using only the warm season data, May-September, to remove any seasonal confounding that exists between temperature and mortality.

One area of exposure misclassification that exists in much of the heat-mortality research is that a single weather station is used to provide a temperature value for an entire geographic location, even though temperature may vary spatially over this. To address this, we used the Parameter–Elevation Regressions on Independent Slopes Model (PRISM) was used to provide high-resolution modeled temperature values as derived from weather station data, elevation models, and other spatial datasets to generate gridded estimates of climatic parameters [23]. Daily maximum temperature and vapor pressure, at a 800 meter^2 resolution was used to assign the maximum daily temperature for hot days where T_{MAX} ≥90°F and HI_{MAX} ≥86°F at Logan International Airport to reduce exposure misclassification and assign a more representative temperature on the study days of interest. This data was available from 2003-2015.

4.2.2. Social Parameters

Small-area neighborhood data was assigned at the census tract (CT) level for each at-home mortality record, available from the 2010 Census. CTs are small, relatively permanent subdivisions, usually have around 4,000 people within, and are designed to be "homogeneous with respect to population characteristics, economic status, and living conditions" [23]. CT-based assessments of socioeconomic status (SES) have been found to be adequate measurements for individual estimates in MA [24]. There were 164 CTs analyzed.

We obtained data on CT social characteristics including population density, inclusion of utilities in rent, inequality via the GINI, and unemployment from the 2010 Census [25]. The proportion of those in each CT with a disability older adults ≥65 years, children ≤5 years, people of color, low income, limited English proficiency and with medical illnesses was accessed from the 2016 City of Boston's Climate Ready Boston Social Vulnerability Assessment, which utilized the 2008-2012 American Community Survey estimates of these variables [26].

4.2.3. Environmental Parameters

We obtained data on CT environmental characteristics including availability of street trees in 2011 from Boston Open Data [27], the 2005 impervious surface fraction and mean albedo from MassGIS and as summarized by the Boston Area Research Initiative (BARI) [28]. 2017 building assessments from the City of Boston Assessing Department and as summarized by BARI provided CT-level summaries of residential buildings, including year built or last renovated [29]. BARI also provides a mean residential energy efficiency score, which is an aggregated variable based on age of building, heating system, and cooling type, with higher values indicating a more energy efficient residence. We also used the mean value of residential building/land and per area. In Boston, examination of real estate data suggests that residential buildings of the highest value per area are luxury apartment buildings or triple decker homes (Figure 1.S1), which are common a common residential archetype in Boston, and purchases of these types of homes increased the most in these neighborhoods during the 1990s [43]. Historically, these homes were built to house immigrant workers, and when their popularity surged in the late 1980s, it was common for them to be bought be absentee landlords and not well maintained [44].

4.2.4 Outcome Data

Data on all deaths occurring in Massachusetts for the period January 2000 – December 2015 were obtained from The Commonwealth of Massachusetts Executive Office of Health and Human Services Department of Public Health. All deaths of Boston residents from 2000-2015 that occurred at home were included in this analysis, regardless of the primary causes, were included in this analysis given the wide range of health outcomes that can be negatively impacted or exacerbated by extreme heat [21,30–37]. Deaths that occurred at home were of interest for two reasons. First, past research has found that deaths on hot days are more likely to occur outside of hospitals [6,38] and more likely to occur at home than in hospitals or other institutions [39]. Second, we were interested in assessing at-home heat vulnerability based the surrounding neighborhood social and environmental characteristics. The use of this mortality data was approved by both the Harvard TH Chan School of Public Health and The Commonwealth of Massachusetts Institutional Review Boards.

4.2.5 Statistical Analyses

The objective of this study was to determine which neighborhoods in Boston have greater social and environmental vulnerability to heat-related at-home mortality. At-home deaths were spatially analyzed at the residential address using geocoded latitude and longitude and summarized as the outcome in the model as the daily tract-specific death rate per 100,000 people. The original objective of this research question was to pair building specific details with the death records, but too few death records with complete building information existed to do so, so area-level summaries are used for the building characteristics, as well as the social and environmental parameters.

The first method used to assess this was with a geographic weighted regression model. First, a generalized linear model (GLM) with a Poisson distribution was used to fit the model to assess the impact of temperature, neighborhood social and environmental parameters on the tract- and day-specific mean at-home death rate on hot days. The linear model was fit using backwards stepwise fitting, first considering all covariates of interest in the model eliminating those with $p<0.20$. An ANOVA goodness of fit test determined that the nested model was an adequate fit compared to the full model. This same model was then used in the generalized geographically weighted regression (GWR) with a Poisson distribution with an appropriate covariance structure.

The second method used to assess this was with a Poisson mixed effects model, adjusted for CT to capture non-time varying covariates of the population that are associated with heat-related mortality risk, which will allow us to spatially and quantitatively assess which neighborhoods are most susceptible to at-home deaths during extreme heat. A first order autoregressive covariance structure that assumes the correlation between days decreases with time was used [32]. CT and presence of a hot day ($T_{MAX} \geq 90°F$) was treated as a random effect to account for time non-varying covariates. To avoid overfitting, those covariates in the final GLM that had a correlation ≥0.5 were not included in the mixed effects model. A sin and cosine term for year were included to control for any long-term trends in at-home deaths or hot days. All statistical analyses were conducted using R Version 1.1.423.

4.3 Results

During this 15-year study period, there was a total of 14,200 deaths in Boston that occurred at home. Death records missing a correct death date were excluded and only records that occurred during the warm season (May – September) were utilized, leaving 6,102 deaths that occurred at home that contained data for all covariates and a correct latitude and longitude (Table 1). Of the deaths that happened at home, 549 (9.0%) occurred on days with T_{MAX} ≥90°F and 445 (7.3%) on days with HI_{MAX} ≥86°F. Descriptive statistics of the CTs in Boston are provided in Table 1. Maps of the distribution of each small-area social and environmental factor are provided in Figure S1.

Table 4.1. Descriptive statistics for the Boston, MA warm season climate, analyzed deaths from all causes from 2000-2015, and small-area social and environmental parameters at the census tract (CT) level.

Characteristic	
Warm Season Temperature [°F]	
Maximum (mean (SD))	75.7 (10.2)
Mean (mean (SD))	67.3 (8.9)
Minimum (mean (SD))	60.1 (7.8)
Frequency of T_{MAX} ≥90°F (% of all warm season days)	201
Frequency of HI_{MAX} ≥86°F (% of all warm season days)	287
At-Home Deaths (*n*)	6,102
Male (*n* (%))	3,197 (52.4)
Race, Non-Caucasian (*n* (%))	2,276 (37.3)
≥65 years old (*n* (%))	3,865 (63.3)
Assessed value of residential building/area ($)(mean (SD))	5,910 (28,000)
Assessed value of residential land/area ($)(mean (SD))	408 (463)
Energy efficiency score of residential buildings (mean (SD))	6.25 (0.352)
Year residential buildings were built/renovated (mean (SD))	1970 (15.9)
Decade residential buildings were built/renovated (mean (SD))	1980 (33.9)
Albedo (mean (SD))	0.124 (0.0114)
Impervious Surface Fraction (mean (SD)) [%]	0.787 (0.141)
Number of street trees/area (mean (SD))	0.00017 (0.00008)
Proportion of population with at least one disability (mean (SD)) [%]	11.4 (7.4)
Proportion of population that is ≤5 years old (mean (SD)) [%]	16.6 (10.4)
Proportion of population with at least 1 medical illness (mean (SD)) [%]	38.6 (3.19)
Proportion of population that is ≥65 years old (mean (SD)) [%]	10.5 (6.79)

Table 4.1 (Continued)

Proportion of population that receives low-to-no income (mean (SD)) [%]	28.0 (17.1)
Proportion of population with limited English proficiency (mean (SD)) [%]	38.5 (17.8)
Proportion of population that is not Caucasian (mean (SD)) [%]	51.6 (30.3)
Proportion of population with utilities excluded from rent (mean (SD)) [%]	82.2 (17.6)
Proportion of population that is unemployed	0.0905 (0.0662)
Gross Rent	1,180 (471)
Ratio of Females-to-Males	1.06 (0.324)
GINI Index	0.416 (0.0829)
Population Density (mean (SD))	23,800 (18,300)

PRISM data was available for 12 of the 15 study years, from 2003-2015. On average, there was a 2.97°F temperature difference (ΔT_{MAX}) throughout the City of Boston on the when airport temperature data indicated that daily T_{MAX} ≥90°F. On these days, the lowest T_{MAX} value in the City of Boston, on average, was 86.0°F, while the highest T_{MAX} value on these days was 88.95°F, on average. The daily modeled vapor pressure and T_{MAX} were used to calculate the daily heat index on days when HI_{MAX} ≥86°F at Logan International Airport. On average, the ΔHI_{MAX} was 8.1°F across Boston, with the lowest HI_{MAX} and highest HI_{MAX} across Boston being 83.6°F and 91.8°F, respectively.

4.3.1 Geographic Weighted Regression Analyses

Geographic weighted regression analyses were conducted, where only those at-home deaths that happened on hot days were utilized (n=389). The nested GLM that was found to be an appropriate fit compared to the full model using an ANOVA goodness of fit test and is found in Formula (1).

$$Total\ Daily\ Death\ Rate \sim \beta_0 + \beta_1(Albedo) + \beta_2(Street\ Trees/CT Area) + \beta_3\left(\frac{Value}{Area}\right) + \beta_4(Impervious\ Surfaces) + \beta_5(Population\ Density) + \beta_6(Prop.Disability) + \beta_7(Prop.Older) + \beta_8(Prop.Low\ Income) + \beta_8(T_{MAX-LOCAL}) \tag{1}$$

The covariates from the GLM showed that the density of street trees in a CT and the proportion of those in the CT who were older adults were significant predictors of the daily at-home death rate (Table 4.2).

Table 4.2. Summary of results from GLM analyses limited to only hot days. Bold p-values are significant at an α=0.05 level. All covariates were analyzed using a standardized z-score to center and scale each them respectively.

	Estimate	Standard Error	t value	p-value
Intercept	3.34	0.19	17.28	**<0.001**
T_{MAX}	0.00	0.01	-0.10	0.92
Mean CT Albedo	-0.05	0.04	-1.09	0.28
Trees/CT Area	0.05	0.02	2.09	**0.04**
Mean Value of Building/Area	0.00	0.02	-0.04	0.97
Impervious Surface Fraction	0.07	0.04	1.71	0.09
Population Density	-0.03	0.03	-0.89	0.37
Proportion of those in CT with a Disability	-0.03	0.03	-0.82	0.41
Proportion of those in CT Age≥65	0.08	0.03	3.08	**<0.001**
Proportion of those in CT with Low-to-No Income	-0.04	0.03	-1.17	0.24

Applying the same GLM model to the GWR, the GWR model (Formula 2) was found to have a pseudo R^2=0.89.

$$(2)$$

$$Total\ Daily\ Death\ Rate \sim \beta_0 + \beta_1(Albedo) + \beta_2(Street\ Trees/CT Area) + \beta_3\left(\frac{Value}{Area}\right) + \beta_4(Impervious\ Surfaces) + \beta_5(Population\ Density) + \beta_6(Prop.Disability) + \beta_7(Prop.Older) + \beta_8(Prop.Low\ Income) + \beta_8(T_{MAX-LOCAL}) + offset(\log(Population))$$

The mean CT albedo, population density, proportion of those with a disability, the proportion of those with low-to-no income or who are people of color had local regression coefficients that were negative, indicating negative relationships between the daily mean death rate and these 4 CT characteristics (Table 4.3). The median values of local coefficients for the daily T_{MAX}, trees/CT area, impervious surface fraction, and the proportion of those who are older adults of age 65 or older were positive, indicating positive relationships between the daily mean death rate and these CT parameters.

Table 4.3. Summary of results from semiparametric GWR model analyses, restricted to those at-home deaths that occurred on hot days, using the same model that was found to be the best fit from the GLM, but allowing the covariates to vary spatially. All covariates were analyzed using a standardized z-score to center and scale each them respectively.

	Minimum	**1st Qu.**	**Median**	**3rd Qu.**	**Maximum**	**Global**
Intercept	-12.88	8.90	20.33	37.44	114.00	15.53
T_{MAX}	-2.68	-0.25	0.01	0.41	1.24	0.13
Mean CT Albedo	-25.64	-8.48	-1.34	6.46	31.79	-0.94
Trees/CT Area	-14.13	-2.27	3.44	6.35	23.58	1.39
Mean Value of Building/Area	-73.78	0.20	2.08	13.28	158.29	-0.31
Impervious Surface Fraction	-20.68	-3.82	1.50	5.99	23.28	2.41
Population Density	-22.83	-4.18	-0.08	9.08	41.24	-0.80
Proportion of those in CT with a Disability	-14.58	-5.37	-3.08	3.19	20.81	-1.31

Table 4.3 (Continued)

Proportion of those in CT Age≥65	-14.61	-0.87	2.19	4.28	19.33	2.65
Proportion of those in CT with Low-to-No Income	-46.33	-11.87	-1.27	7.40	15.14	-1.02

Figure 4.1 provides a map of the local coefficients for each of the covariates included in the GWR model that was restricted to just the deaths occurring at home on hot days. The strongest positive local coefficients (yielding an increase in at-home mortality) were seen with increases in the proportion of people of color in East Boston, Roxbury, and Dorchester, increased population density in parts of Mission Hill and into Jamaica Plain, the proportion of trees per the CT area in Dorchester, the value of building per area in East Boston, and increased surface albedo from Roslindale through Hyde Park The strongest negative local coefficients (yielding a decrease in at-home mortality) were seen with a higher proportion of those with low-to-no income from Mission Hill south through Roslindale and Hyde Park, increased surface albedo from Charlestown through Downtown to Dorchester.

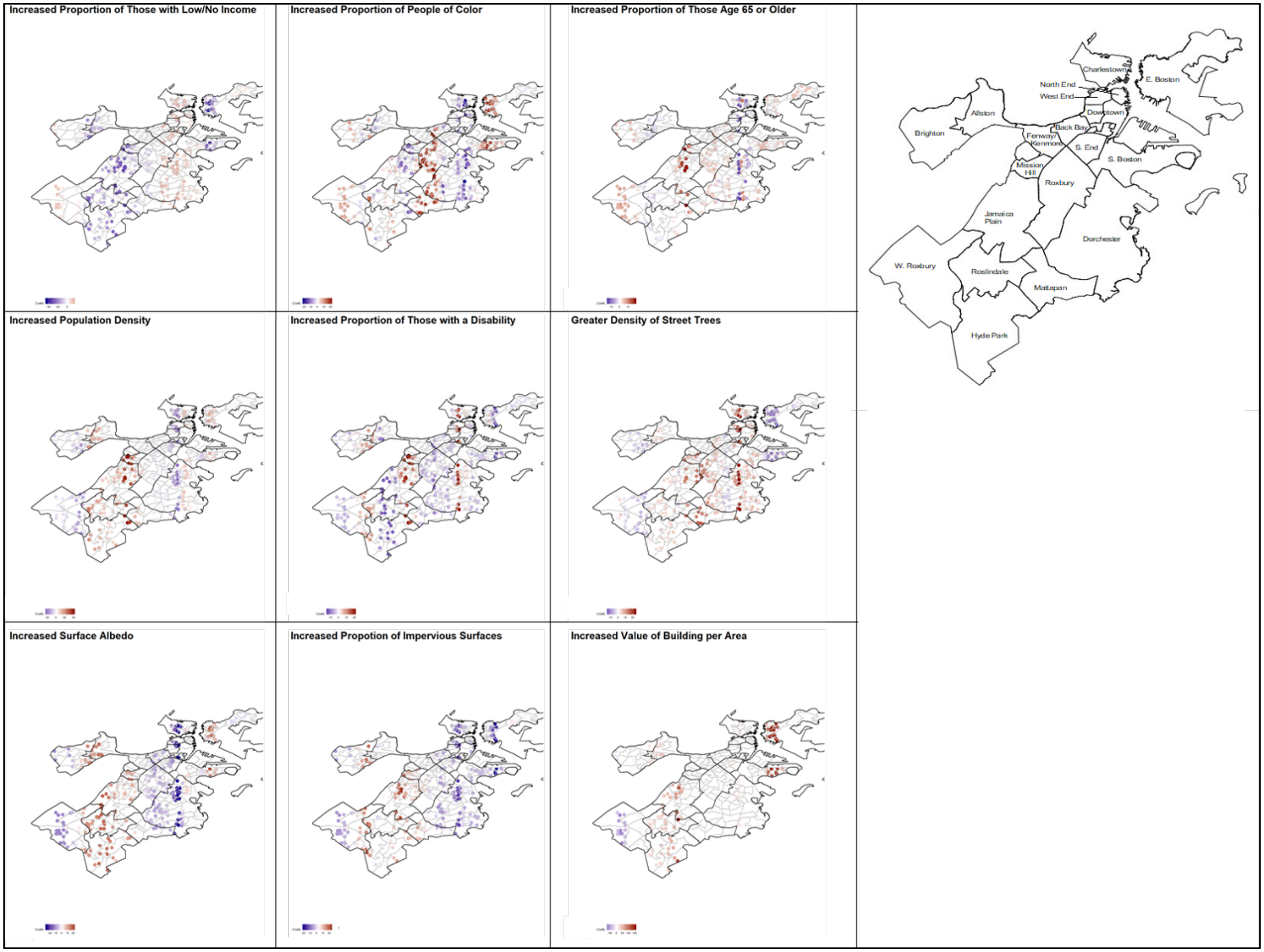


Figure 4.1. Local GWR coefficients, with blue colors representing negative coefficients and red colors representing positive coefficients, in relation to daily at-home death rate on hot days.

4.3.2 Mixed Effects Model Analyses

A mixed-effects model was fit, and those covariates in the final GLM that had a correlation ≥0.5 were not included to avoid overfitting (Formula 3). The model converged in 10 iterations and a random effect was used for CT and a random slope for whether or not it was a hot day.

$$Total\ Daily\ Death\ Rate \sim \beta_0 + \beta_1(Street\ Trees/CTArea) + \beta_2\left(\frac{Value}{Area}\right) + \beta_3(Population\ Density) + \beta_4(Prop.Older) + \beta_5(Prop.People\ of\ Color) + \beta_8(Hot\ Day) + sinYear + cosYear + (\sim 1 + HotDay|CT) \tag{3}$$

When completing the mixed effects analyses, the fixed effects of it being a hot day and the density of street trees in the CT were both significant (Table 4.4). The fixed effect for it being a hot day was -0.58. The coefficient for hot day for each census tract are mapped in Figure 4.2. There were a few census tracts that demonstrated a slightly negative local effect of hot day (shaded in Fig. 4.2 as lightest yellow shades). There were a few CTs that were in the strongest quintile of hot-day effects, but there was not a demonstrable visual neighborhood pattern.

Table 4.4. Fixed effects from the linear mixed effects model for the mean daily death rate for each CT on hot days. Bold p-values are significant at an α=0.05 level. All covariates were analyzed using a standardized z-score to center and scale each them respectively.

Covariate	Coef.	Std. Error	t-value	p-value
Intercept	31.92	1.05	30.51	**<0.001**
Hot	-0.58	0.18	-3.21	**<0.001**
Trees/Area	-2.02	0.57	-3.54	**<0.001**
Mean Value of Building/Area	0.12	1.05	0.11	0.91
Population Density	1.27	0.77	1.65	0.10
Proportion of those ≥65 years	0.28	0.79	0.35	0.73
Proportion of People of Color	-1.85	1.04	-1.78	0.07

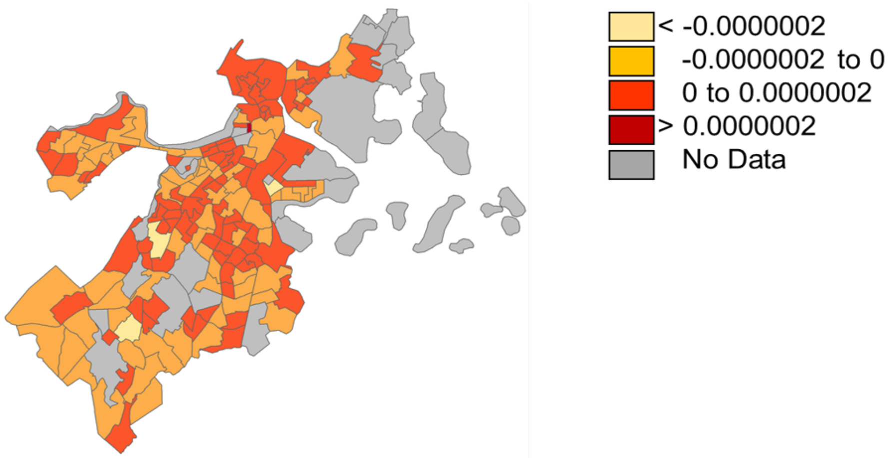


Figure 4.2. Map of Boston and the CT-specific coefficient for hot day (T_{MAX} ≥90°F) from the mixed effects model with a random effect for CT and random slope for it being a hot day.

4.4 Discussion

This study examined several small area-level and individual social and environmental factors that are associated with an increased likelihood of dying at home during extreme heat events. In the GWR analyses, Dorchester, Roxbury, and East Boston were found to be most vulnerable to the impacts of extreme heat on dying at home, driven largely by greater proportion of people of color and presence of triple-decker homes. Even as the density of street trees in Roxbury and Dorchester increased, there was a positive (increasing) relationship with at-home mortality on hot days.

These neighborhoods – Dorchester, Roxbury, and East Boston – face chronic social and environmental stresses that have resulted from a long history of inequity. Dorchester, which is more than 70% people of color, faced widespread disinvestment from the 1950s to the 1980s [40] that has had lasting effects on housing and environmental quality. East Boston has faced rapid transition in recent years, and 50% of its population is Latino and 44% of the population lacks English proficiency [40], which can make it difficult to access information on avoiding heat exposure on hot days if materials are not provided in the native language. There was a large influx of immigrants into Roxbury in the 1940s-1950s, and today more than 80% of its population is people of color and lacks access to quality infrastructure and built environment. This context is important when discussing the joint role social and environmental factors play on heat-related outcomes.

When comparing this information to previous heat vulnerability assessments in Boston, MA, a few interesting trends emerge. A 2015 assessment of a heat vulnerability index found that 11 CTs in Boston had the greatest heat vulnerability despite access to cooling resources (e.g. cool centers, spray pads, etc.), including in East Boston, Chinatown, Fenway, the South End, Mattapan, Roslindale, and 5 CTs in Roxbury, all primarily driven by social and environmental vulnerability [18]. The area of East Boston that was found to be highly vulnerable also corresponded to areas of East Boston that were found to have increased social and environmental vulnerability to extreme heat. These analyses did not find that Chinatown, Fenway, or the South End was particularly vulnerable to dying at home on hot day. However, mortality is the most extreme outcome that is possible with extreme heat exposure, with deaths at home comprising a small fraction of all deaths, so these other neighborhoods may still be vulnerable to other negative health outcomes, if not to at-home mortality. Alternatively, with Boston's recent adaptation of heat mitigation strategies, it would be worth investigating if any social or environmental interventions had taken place during this study period that could attenuate the at-home death rate on hot days in certain neighborhoods.

The 2016 Climate Ready Boston report highlights the CTs where the greater proportion of socially vulnerable individuals live in the city, including those who are persons of color, of older age, younger age, with a disability or a medical illness, with limited English proficiency, or of low-to-no income. The neighborhoods of Dorchester, Roxbury, East Boston, Brighton, Downtown, South End, and Mission Hill appear to be the most vulnerable from these factors. While these neighborhoods have some overlap with the findings of this study – especially in Dorchester, Roxbury, and East Boston, the others do not have as much overlap. Again, the results of this study are not saying that residents of these other neighborhoods are not vulnerable, but instead that they are not as socially or environmentally vulnerable as Dorchester, Roxbury, and East Boston to dying at home on hot days.

The results of this analysis highlight interesting trends in some of the environmental vulnerability factors we analyzed, where in some areas features considered beneficial, like street trees, demonstrate a negative relationship on at-home mortality. We hypothesize that this may be related to the differential quality of environmental features that are present. One example of this is present with a discussion of quality over quantity of street trees. In many neighborhoods, the GWR analyses suggests a positive relationships between the density of street trees and at-home mortality on hot days, such that as the density of street trees increases, so does at-home mortality, which is counterintuitive to what one may expect. The quality of these trees is important in determining how much shading effect may be available, but we don't have quantitative information on the quality of the trees in each neighborhood. Figure 4.S2 demonstrates some of the features of trees that may be influencing their role in shading residential buildings, including if they are in an ill-state of health, are young trees, or are not equally distributed within neighborhoods (i.e. only located on one side of a street). We are eager to explore the role of this building archetype and design and street tree quality on indoor temperature exposures in future studies.

One of the most unique aspects of this research is the application of a gridded climate dataset to refine temperature exposure throughout Boston. Many of the strongest coefficients, in either direction, align with I-93 in the eastern most part of Boston. This boundary may also be indicative of the extent of the sea breeze on hot days. On these hot days, the mean wind direction at Logan International Airport during the day was 89.5°, indicating easterly winds off of the Atlantic Ocean. Past analyses of Boston's sea breeze have found that it is one of the most developed in mid-latitudes with peaks in July and August. Within the City of Boston, there is both a smaller bay breeze effect, as well as a larger sea breeze effect, which often doesn't penetrate much further inland than the coastline due to abrupt topographic shifts in western Boston [41]. We hypothesize that this boundary, seen stretching north-to-south from Downtown to Dorchester, may be due to proximity to major roadway, which has documented negative health effects on surrounding residents [42], or from stark changes in temperature due to a microclimatic effect, like a bay breeze or the marine layer, or perhaps a combination of these elements and requires further research. By using a refined exposure assessment and capturing temperature variations across the city, we are able to distinguish this local climate effect, which influences heat exposure, and thus heat vulnerability.

The results of this study highlight the differential social and environmental drivers of heat vulnerability in Boston, MA. Locally, there have been active efforts to mitigate poor health outcomes during extreme heat events for those that have been found to be socially vulnerable. However, it is important to remember that the natural and built environment play a large role in determining an individual's exposure to extreme heat, and interact with the social factors to create unique vulnerabilities for each neighborhood. As was seen in East Boston, as the proportion of street trees/CT area increased, there was a decrease in the at-home mortality rate. Lessons learned from the deployment of street trees in this neighborhood may inform future adaptation strategies that increase the urban tree canopy most effectively. A recent study found that nearly 80% of those living in almost 100 different US cities were in neighborhoods with less than 20% tree cover [17]. Most CTs in Boston are also below this threshold [18]. Researchers then simulated in these cities an improved urban tree canopy and found that 245-346 deaths per year could be avoided as well as reducing building-related heat stress so that cooling demand and attendant electricity consumption could decrease [17].

Adaptation strategies like improved urban materials, cool roofs, evaporative roofs, and increased density of street trees have the potential to reduce the range of summertime temperatures in the Northeast US and reduce the impact of the increased number of hot days that we are expected to experience by the end of the century [50]. The median age of residential buildings in Boston, MA is 54 years, and one of the most common residential building archetypes in Boston were predominantly built in the late 19th and early 20th centuries. Currently, Boston has primarily relied on mechanical cooling to mitigate hot indoor temperatures, but without that cooling, many of our residential buildings are not passively habitable, and cannot provide safe and survivable indoor conditions without mechanical cooling in times of extreme heat [43]. In order to be most resilient to future extreme heat events of the next century, our residential buildings and surrounding built environments need to consider climate adaptive architecture and design that reduces the thermal loads of our urban areas. Planning for the health impacts of extreme heat in the design and retrofit of buildings is vital for protecting public health in a changing climate. This will be important in urban areas, but also suburban areas and satellite cities around major urban areas that have been found to show a rapidly increasing vulnerability to extreme heat [44].

It is important to consider the limitations of these analyses. Although we have removed the effect of season, residual confounding may still be present if there is an interaction between season and any of the effect modifiers being examined. There were likely changes in the social/environmental parameters over this study period, but only cross-sectional estimates that were available at different points in this study period were utilized to assign these parameters across an entire 15-year time period.

There are many ways to measure temperature and assess extreme heat. The temperature thresholds used within this study are supported by recent research, including findings by Guo et al. (2017) that daily maximum temperatures for defining a heat wave are better at predicting mortality than minimum temperature [45] and by Kingsley et al. (2016) that there are significant increases in mortality at temperatures from 75-85°F in Rhode Island [46]. We also were able to use modeled daily temperatures at the location of each of the residences examined in this study, which reduces temperature misclassification that is commonly present in heat-health research. However, we also acknowledge that metrics like the duration of extreme heat and whether or not an extreme heat event is the first of a season or not are important [20], and that buildings influence heat exposure, so further work is needed to fully remove any bias from temperature exposure misclassification.

Despite these limitations, which also exist in much of the preexisting heat vulnerability research, there are many strengths to the analyses within this paper. Focus on resilience-promoting covariates, like albedo and street trees, we can assess the success of protective neighborhood features, instead of just harmful features. This study also takes a vast body of heat vulnerability research and metrics that have been demonstrated to be important for heat-mortality relationships, and assessed them at a local level, where context and scale are considered are tailored to Boston, MA.

Future studies will examine Boston-specific building archetypes to model the range of indoor temperature exposure that are possible in current and future climates. Integrating this work with simulated adaptation strategy implement can elucidate which building-focused adaptation strategies will be the most effective at reducing poor health outcomes at home during extreme heat events.

4.5 Conclusion

This study examined mortality at home on hot days in Boston, MA and how the relationship between individual and small-area characteristics and their association between heat and mortality, spatially vary across the city. While many neighborhoods have been found to be socially vulnerable in past studies, there are some neighborhoods – like Roxbury, Dorchester, and East Boston – where both social and environmental vulnerability exists, highlighting priority locations for the implementation of a wide range of adaptation solutions. We also found that local climate effects, like a sea breeze, influence temperatures across the city, influencing temperature exposure and resulting vulnerability. Heat vulnerability assessments provide critical local information at a helpful scale that can be integrated into the design and implementation of adaptation planning, climate policy and infrastructure decisions.

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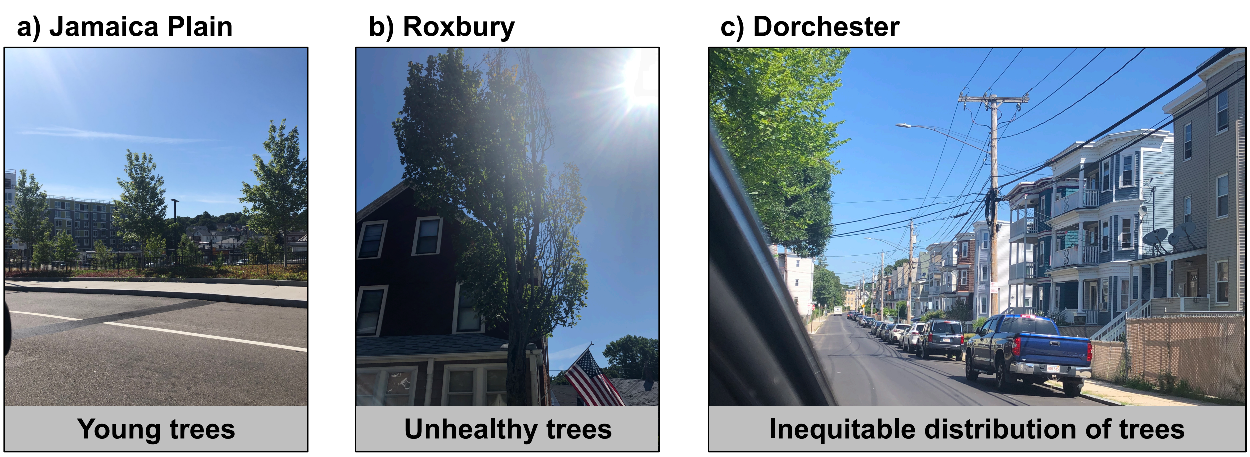
4.7 Supplemental Information

Figures 4.S1. Image of triple-decker homes that are common in Boston, MA.



Figures 4.S2. Images of street trees found in (a) Jamaica Plain, (b) Roxbury, and (c) Dorchester demonstrating the variety in design and quality of street trees.

SUMMARY AND IMPLICATIONS

This study was motivated by the significant social, economic, and health impacts that are likely to occur in Boston, MA without adequate and timely greenhouse gas emissions mitigation and climate adaptation. Motivation was also drawn from an attempt to further the understanding of both heat exposure and relevant societal outcomes to better inform adaptive solutions. As extreme heat events increase in frequency, duration, and severity with climate change[1–3], the potential exists for heat-related mortality in Boston to triple by the middle of the 21st Century[4]. To further the understanding of the health and societal impacts of extreme heat in Boston, MA this dissertation sought to further elucidate the answers to a 4 research questions:

- How do social and environmental (both natural and built) factors influence heat vulnerability in Boston, MA at the individual and neighborhood level?
- How are buildings vulnerable or resilient to extreme events and what role does that play in public health?
- Are current heat warning thresholds in Boston, MA adequate for capturing public health impacts, and how can we assess this using publicly-available datasets?
- In addition to impacts on morbidity and mortality, are there other societal effects of heat exposure in Boston, MA that impact an entire urban area?

The first study, found in Chapter 1: “Building vulnerability in a changing climate: Indoor temperature exposures and health symptoms in older adults living in public housing during an extreme heat event in Cambridge, MA”, found that indoor temperatures were significantly higher during an extreme heat event for those without central AC. This resulted in increased heart rates and galvanic skin response, but without the activation of adaptive responses, like drinking more water. This demonstrates that central AC and window AC units were not equally adequate in overcoming high temperature loads indoors, and that even though poor health symptoms were not widely reported, thermal decompensation was beginning to occur, even though an official ‘heatwave’ was not declared.

The second study, Chapter 2: “The influence of heat on emergency services in Boston, MA: relative risk and time-series analyses of police, medical, and fire dispatches”, assessed the impact of high temperatures on the use of emergency services, and found that there was a significant increase in the need for police, medical, and fire services on hot days during the warm season. This established local evidence on the impact of extreme heat on the entire Boston community, which may be important for increasing the acceptance and urgency of climate adaptation action.

Chapter 3, “A case-only analysis of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA.”, demonstrated that social and environmental factors modify the association between at-home mortality on hot days. Census tracts with a greater proportion of people of color, limited English proficiency, and low-to-no income individuals were more highly represented in those who died during the study period, but area built environment features, like albedo and enhanced energy efficiency able to reduce the relative odds of death within and outside the home.

Chapter 4, “Dying at home on hot days: A spatial analysis of at-home mortality in the context of individual and small-area social and environmental vulnerability in Boston, MA.”, we found that while at-home mortality on hot days was driven by both social and environmental factors, these relationships varied spatially across the City of Boston. The neighborhoods of Dorchester, Roxbury, and East Boston were found to be most vulnerable to the impacts of extreme heat on dying at home, driven largely by greater proportion of people of color, those with low-to-no income, and presence of single-family homes

While each of these papers separately has their own interesting findings and implications, together they contribute valuable information to both expanding this area of scientific research at the intersection of environmental public health, the built environment, and climate change, as well as to the implementation and informing of local heat adaptation strategies.

Furthering the Science and Informing Adaptation Strategies

Vulnerability is Complex: Social and Environmental Drivers of Heat Vulnerability

The results described in this dissertation provide important contributions to the field of environmental health, specifically for those working on the public health impacts of climate change, as well as the field of urban design and building management, in the context of heat vulnerability. There is a vast amount of research containing helpful heat vulnerability assessments [5–13], and while AC penetration and access to greenspace have been incorporated in a variety of local heat vulnerability assessments, other environmental and building parameters (e.g. street trees, building materials, building energy efficiency, etc.) have not, despite their role in exacerbating or mitigating our exposure to extreme temperatures.

The results from Chapters 1 and 4 contribute important knowledge on how social and building-related environmental factors jointly influence heat vulnerability. In Chapter 1, a highly vulnerable population – low income seniors – were followed in their natural environments, to find that despite living near each other, those with central AC had much healthier indoor temperatures and fewer public health impacts compared to those using window AC units. There were different indoor exposures and resulting health outcomes in those considered to be similarly socially vulnerable to heat. In Chapter 4, we see that some neighborhoods of Boston are socially vulnerable to an increased at-home death rate on hot days, while others are environmentally vulnerable to this outcome. However, three neighborhoods – Dorchester, Roxbury, and East Boston – were found to have both high social and environmental vulnerability, highlighting the need to prioritize multi-faceted adaptation strategies in these neighborhoods to effectively reduce health burdens on hot days.

Indoor Temperatures during Extreme Events: Overcoming Exposure Misclassification

To date, air conditioning (AC) has been widely accepted as the main adaptation strategy to mitigate extreme heat exposures, as has been found to reduce the incidence of poor health during extreme heat events[14,15]. Quinn et al.(2017) found that central AC was most effective at cooling down indoor environments during extreme heat events, and window AC units were not cooler compared to having no AC at all[16]. This was further supported in the findings from Chapter 2. Most of the participants in our study that lacked central AC did still have window AC units, but as ambient temperatures rose, these window units were unable to mitigate hot temperatures indoors. This was due to a wide variety of factors that, as in not wanting to use AC until after it was already too hot or that the window unit lacked cooling efficiency. These findings support Quinn et al.'s (2017) findings that central AC should be considered a more protective heat adaptation strategy than other forms of AC.

Despite AC protecting public health as temperatures rise, it is not currently a sustainable solution in combating the increasing frequency and severity of extreme heat events for four reasons: (1) AC is powered by electricity, which produces health-harmful air pollutants, (2) the refrigerants currently used in AC are extremely potent greenhouse gases, (3) in the event power is lost, most buildings are unable to maintain passive habitability without mechanical cooling, and (4) those who are most vulnerable to extreme heat are those that are less likely to own and effectively use AC. In the Northeast US, only about 50% of people have access to central AC at home[17], and less than 30% of MA residents have residential central AC[18]. Further, 62% of homes in Massachusetts were constructed before 1970[18] and the median age of residential buildings in Boston, MA is 54 years[19], and buildings here have been historically designed for harnessing heat during the cold, winter months, and may not be resilient to our hotter future. With warming climates, this means that our built infrastructure has an enhanced probability of overheating during non-extreme events and routine operations[20].

The results from Chapter 3 demonstrate how neighborhood-level environmental parameters can reduce the rate of at-home deaths on hot days. For example, as the density of street trees increased some neighborhoods, there was a decrease in the at-home death rate. While social and environmental vulnerability is complex and dynamic relationship, understanding how building design, including things like materials used, roof design or orientation, and urban design, including things like street trees, impervious surfaces, or reflective materials can aid in reducing thermal stress in an area, which can reduce the need for AC, enhancing the passive habitability of buildings.

When Extreme is not Extreme: Evidence for Lower Heat Warning Thresholds

The definition of extreme heat is very dependent on the geographic location, local adaptation strategies, and the underlying risk of the population. In the Northeast US, a heat advisory is issued when the heat index is at least 105°F for at least 2 hours[21]. A heatwave, or when the daily maximum temperature is forecasted to be at least 90°F for 3 consecutive days, is a common threshold used by local agencies in Massachusetts to enact local interventions, like the opening of cooling centers. However, recent research has found that the impacts of extreme heat on mortality in this region begin to occur below these current thresholds.

The results from Chapter 1 demonstrate dangerously hot indoor environments for some participants, and increased sleep disruptions, HRs, and GSRs as indoor temperatures increased. This study occurred during days when the City of Boston didn't actually reach full "heatwave" status, and only had 1 day where the maximum temperature was above 90°F. In Chapter 2, it was demonstrated that the threshold for increased emergency services on hot days was 82–84°F, depending on the agency. At these lower temperatures, there are fewer, if any, local interventions available, even though we see health and societal impacts beginning to occur. Incorporating health- and societal-relevant outcomes into heat advisory definitions into heat-health warning systems have been found to have benefits that far exceed the costs, by several orders of magnitude[22].

In Chapter 3, we saw significant increased relative odds of dying from substance abuse or assault-related altercations at temperature thresholds far below current thresholds used by local agencies to enact heat advisories or warnings. This provides corroborating evidence for Chapter 2 demonstrating how emergency services are impacted by extreme heat, since incidents related to substance abuse and assaults require emergency service agencies.

Broadening the Scope of the Problem: Societal Impacts of Extreme Heat

Extreme heat has negative impacts on a wide variety of health outcomes, ranging from death to the exacerbation of cardiovascular, respiratory, and cerebrovascular disease, to decreased cognitive function, disrupted sleep, and increased frequency of violent and aggressive behaviors[1,3,23,24]. Despite all of these relevant outcomes, heat is often seen as a silent threat, with few people perceiving its dangers. In a recent national survey, the mean heat perception score of the US was 40 out 100, where 100 indicated highest perception of the risk of extreme heat, the same score Suffolk County received (which consists of Boston, MA)[25]. A survey across four US cities found that even though people knew there was an extreme heat event, most people didn't know what to do, and less than half of people altered their behavior[26]. This is all occurring as climate change becomes increasingly politicized and federal action to mitigate greenhouse gas emissions has nearly stopped.

The results of this dissertation contribute valuable findings about the broader impacts of extreme heat that have the potential to impact all of us. Most specifically, in Chapter 2, there is a significant increase in police, medical, and fire department dispatches. Previous research had highlighted that heat-stress related ambulance calls and violent crime increase, but these broader increases in all types of emergency calls highlight a city-wide risk to all Boston residents. Increased traffic accidents, occupational heat stress, and interpersonal altercations are all hypothesized to also increase on hot days, which could equally affect any individual, not just those considered to be more classically vulnerable. They also put first responders at greater risk due to field injury or occupational heat stress. These factors are currently not well accounted for in planning or future budgeting. Characterizing those outcomes that impact all individuals in a community, may increase local action on climate change mitigation and adaptation.

Conclusion

Extreme heat is the most health-harmful of all meteorological phenomenon, and heat-related deaths in Boston, MA have the potential to triple by the end of the century without adequate adaptation strategies. To date, much of the existing literature on heat vulnerability has focused on societal risk factors, but our built and natural environment determine the majority of our exposure to extreme heat, either exacerbating or mitigating temperatures indoors. Further, the main heat adaptation solution that we've relied upon is AC, which is limited in its sustainability and equity. The results contained within this dissertation demonstrate how buildings can significantly modify indoor temperatures, how physiologic markers like heart rate can be negatively impacted by heat, even if clinical health symptoms are not yet present, that vital social emergency services (police, medical, and fire dispatches) are shown to be impacted by extreme heat in Boston, MA, but are not adequately incorporated in future climate adaptation plans, and that some of the neighborhoods of Boston are differentially vulnerable to an increased rate of at-home mortality on hot days due to social or environmental factors.

In conclusion, this dissertation helps to illustrate the complexities of social and environmental vulnerability to health and societal impacts during extreme heat. It demonstrates that adaptation solutions that strategically prioritize the most vulnerable people and buildings can have a positive impact on public health. Climate change is the biggest public health threat of the 21st Century, so most importantly, aggressive greenhouse gas emissions reductions are necessary to reduce the extent of climate change and the resulting public health impacts.

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