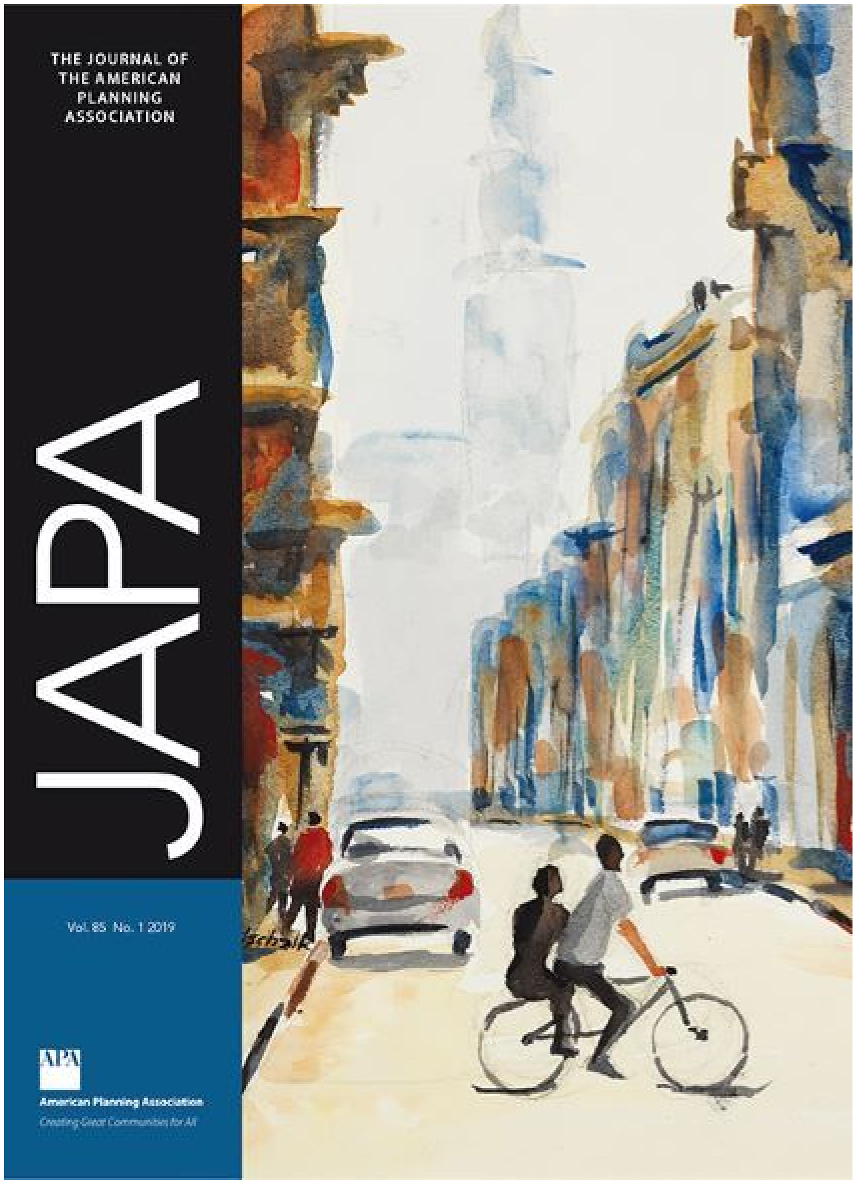

Safe at Home? A Comparison of Factors Influencing Indoor Residential Temperatures during Warm Weather in Three Cities

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Abstract:	Problem: As summer temperatures increase with climate change, indoor residential environments will be an increasing source of dangerous heat exposure. While air conditioning is a recognized preventative measure, many vulnerable residents either lack air conditioning or cannot always afford the electricity. Understanding the relative influence of different building characteristics and percentages of tree canopy coverage on indoor air temperatures during extreme heat events can help urban planners prioritize intervention strategies. Research Strategy: During the warm season, we measured indoor and outdoor temperatures at 140 homes in Detroit, Michigan; Atlanta, Georgia; and Phoenix, Arizona. We surveyed residents to determine whether they had a working central air conditioning system and if they could afford the electricity costs required to maintain comfortable indoor temperatures. For each home, we collected information on year of construction, size, single versus multifamily occupancy, and whether the majority of the façade was masonry and calculated the percentage of tree canopy. Using regression analysis, we were able to compare the relative impact of air conditioning, building characteristics, and tree canopy on indoor air temperature during summertime conditions. Findings: After air conditioning, the relative importance of building characteristics versus tree canopy percentage varied by city. In Detroit, homes with masonry façades exacerbated the influence of outdoor temperatures on indoor temperatures while increased tree canopy coverage moderated the influence outdoor temperatures on indoor temperatures. In Atlanta, building characteristics were not significant but tree canopy moderated indoor temperatures in late afternoon. In Phoenix, tree canopy was not significant while multifamily buildings and larger homes moderated the influence of outdoor temperatures on indoor temperatures in late afternoon. Takeaway for Practice: The influences of tree canopy and building characteristics varied by city depending on its background climate conditions. We conclude with five recommendations for how urban planners can prepare for rising temperatures.

Introduction:

Climate change is increasing the severity, duration, and intensity of extreme heat events as well as increasing average summer temperatures in many parts of the world (Intergovernmental Panel on Climate Change, 2022). Currently, approximately 200 million people live in 350 cities with summer high temperatures that exceed 35° C (95° F). By 2050, 970 cities will have summer high temperatures that exceed 35° C (95° F), many located in Africa, Asia, and North America, (C40, 2018). In the U.S., extreme heat events, also called heat waves, now kill more people on average than any other weather-related causes (Lewis, 2021). Higher summer temperatures will increasingly burden all urban residents but disproportionately harm the most vulnerable residents (Harlan et al., 2006).

While it is important to consider the impacts of increasing outdoor summer temperatures on residents, indoor environments are a common source of heat exposure. In higher income countries, the average person spends 90% of their time indoors (U.S. Environmental Protection Agency, 1989). Indoor environments are a common source of heat exposure and residential environments are of particular concern (Kovats & Hajat, 2008; Quinn, 2017; Wright et al., 2020). A 2013 report by NYC Department of Health and Mental Hygiene determined that in New York City, 80% of individuals diagnosed with life-threatening heatstroke were exposed to extreme heat conditions inside their homes (Wheeler et al., 2013). Lower-income residents, many who are elderly or have significant physical or mental illness, spend a large proportion of their time in the home environment (Mitra et al., 2021). While air conditioning is an effective protective factor against heat illness and death (O'Neill et al., 2005; Sera et al., 2020; Wright et al., 2020) , some homes, particularly in temperate locations, may lack central air conditioning. Additionally, for residents living in a home with a working central air conditioning system, electricity costs may impede their ability to maintain comfortable indoor temperatures (J. Lewis et al., 2020). While a great deal of research has investigated the predictors of urban heat islands, less research has measured summer indoor residential temperatures.

This research is designed to help planners proactively anticipate which residential structures are more likely to have higher indoor temperatures during heat events. The first purpose of this research is to investigate whether different percentages of tree canopy coverage significantly alter indoor temperatures. The second purpose of this research is to identify common building characteristics that contribute to higher indoor temperatures. Building-level information that can be used in combination with census demographics will help planners and public health professionals target their interventions toward the most vulnerable residents. The final purpose of this research is to compare the relative impact of tree canopy, common building characteristics, and air conditioning use on indoor summer temperatures.

We collected information from 140 homes in Detroit, Michigan; Atlanta, Georgia; and Phoenix, Arizona in summer 2016. These homes were selected to represent an array of common building types, such as single family versus multifamily, varied age of construction and size, and masonry versus non-masonry facades. We administered a survey to determine each household's demographic characteristics as well as their cooling strategies. This survey allowed us to determine whether each home had central air conditioning and whether residents were able to use it as needed. We collected air temperature data inside their homes and immediately outside their homes. We hypothesize that air conditioning would have the greatest influence on indoor temperature, followed by building characteristics and then tree canopy. We hypothesized that tree canopy would be more influential in cities with temperate climates, such as Detroit, and that building characteristics would be the more influential in cities with more warmer climates, such as Atlanta and Phoenix.

Literature Review:

This literature review is divided into three sections. In the first section, we identify the importance of pervious surfaces and tree canopy as predictors of elevated outdoor temperatures. We summarize the three mechanisms by which trees affect outdoor temperatures. In the second section, we summarize research to identify four common building characteristics that significantly influence indoor summertime temperatures. In the final section, we note the importance of behavioral adaptations, specifically the use of air conditioning, in reducing indoor air temperatures and highlight recent literature that challenges assumptions that household characteristics, such as income, age, and gender, are necessary predictors of air conditioning use.

Predictors of Elevated Outdoor Temperatures

Outdoor air temperatures vary considerably within urban and suburban areas (Ziter et al., 2019). Urban and suburban areas with elevated temperatures relative to adjacent rural areas are referred to as urban heat islands (UHIs). While UHIs are a distinct phenomenon from climate change, UHIs exacerbate extreme heat events (Larsen, 2015). Stone (2012) organized the causes of UHIs into four categories: 1) loss of vegetation and pervious surfaces; 2) construction and surfacing materials that attract, store, and re-emit heat; 3) clustering of three-dimensional buildings that restrict air flow; and 4) waste heat from vehicles, industrial processes, and mechanical cooling systems (Stone, Jr., 2012). In Chicago neighborhoods, the percentages of impervious surface and tree canopy within the neighborhood block during average heat conditions explained 68% of the outdoor temperature variation and this increased to 91% during extreme heat conditions (Coseo & Larsen, 2014).

However, outdoor temperature only partially explains indoor temperature. In July 2005, Smargiassi et al (2008) measured indoor summer temperatures in 75 apartments (without air conditioning) in Montreal, Quebec. They determined that outdoor temperature explained only 22% of the indoor temperature variance (Smargiassi et al., 2007). Additionally, planners should not assume that indoor temperatures are always cooler than outdoor temperatures. Hawkins-Bell et al. (1994) found that "temperatures indoors [in Philadelphia] can vary significantly relative to temperatures outdoors, being up to 50% higher than those outdoors".

Although both the amounts of impervious surface and tree canopy are strong predictors of elevated urban air temperature, planners generally favor adding trees over removing impervious surfaces. In a recent survey of US planners, urban greening was the most popular planning strategy for addressing rising temperatures (Meerow & Keith, 2021). Trees can often be added in the public right of way and planting and maintaining trees is generally less difficult than making changes to private property (such as removing pavement or buildings). Research has shown that the percentage of tree canopy around the home can significantly affect indoor temperature and reduce cooling loads (Akbari et al., 1997; Shahidan et al., 2012; Taha et al., 1988).

Trees alter microclimates through 1) shading, 2) wind shielding, and 3) evapotranspiration (Huang et al., 1990). The positive impacts of shading on temperature are well documented. In

Sacramento, California, daytime air temperatures under the tree canopy were 1.7° to 3.3° C lower (Taha et al., 1988). In the humid subtropical climate of Austin, Texas, daily maximum air temperatures at a playground shaded by tree canopy were 4.1° C lower, on average, compared to an unshaded playground just 50 meters away (Lanza et al., 2021). Interestingly, wind shielding does not always reduce outdoor temperatures. "At night, trees tend to restrict longwave radiation loss and cooling, as well as restricting ventilation beneath the canopy that can result in slightly higher air temperatures," (Coutts et al., 2016). While "the impact of tree shading in reducing [a building's] summer cooling energy use is many times larger than the negatives effects of reduced windspeed" (Huang et al., 1990), many people do not realize that trees can cause temperature increases. Evapotranspiration (evaporation and transpiration of moisture through the leaves) may have the greatest cooling impact on the local microclimate, but its invisibility disguises its importance. A mature tree can release up to 100 gallons of water a day. Huang et al. (1990) found that evaportranspiration provided substantially more summertime cooling relative to the effects of shading (Huang et al., 1990). To understand whether the impact of tree canopy percentages extended beyond the immediate area of the home to include the broader neighborhood, we measured the percentages of tree canopy directly around the housing unit (within 400 m (¼ of a mile)) as well as in the nearby neighborhood (between 400m to 1600m (¼ and 1 mile)).

Structural Predictors of Indoor Temperature

In addition to outdoor temperature, building characteristics are important predictors of indoor temperature. While a large amount of literature has investigated how a building's design, construction, materials, and orientation affect the efficiency of its thermal envelope to retain heat during winter, fewer studies have investigated the contribution of building characteristics on indoor summer temperatures (Conlon et al., 2011). While our review of the building efficiency and technology literature was not exhaustive, in most studies, building characteristics had a greater impact on the indoor temperature as compared to tree canopy. For example, Oikonomou et al. (2012) modeled the influence of the outdoor temperatures and various building characteristics on summer indoor residential temperatures in London, England, using the EnergyPlus software. The authors determined that changing the structural characteristics produced a 3.3° C difference in the indoor temperature while the outdoor temperature explained only 1° to 1.5° C of difference (Oikonomou et al., 2012).

Because this research is intended to help planners anticipate which residential structures are more likely to have higher indoor temperatures, we were interested in using common building attributes that could be observed from the street (multi-family versus single-family, masonry façade versus non-masonry, age, and size). While it is more difficult to visually assess age and size from observation, residential buildings within a neighborhood are often similar in size and age and this information is readily available from the local tax assessor's database. We will discuss the importance of air conditioning under behavioral predictors.

Single versus Multi-Family and Age: In Detroit, White-Newsome et al., (2012) collected hourly outdoor and indoor temperature, humidity, and solar radiation measures in 35 housing units during the summer of 2009. While all participants were seniors, they varied in financial stability and well-being. The authors collected information on the housing type (single family or high rise), age of building construction, number of floors, presence of central air-conditioning, and adjacent land use types. The significant housing and neighborhood characteristics explaining higher summer indoor temperatures were 1) single family versus high rise (single family units were warmer due to more exterior surfaces), 2) year of construction (older homes were warmer probably due to a lack of insulation and single pane windows), 3) lack of air conditioning, and 4) exterior wall treatment (vinyl paneling/wood siding was warmer than masonry). The finding that siding is warmer than brick masonry was unexpected and the authors note that only 2 of 35 homes in their sample had vinyl paneling/wood siding. Based on White-Newsome et al. (2012), we hypothesize that single family units will have higher indoor temperatures relative to multi-family units.

Masonry/Non-Masonry Exterior: Wright et al.'s (2005) research paid special attention to the impact of masonry versus non-masonry walls on indoor temperature. Their findings contradicted those of White-Newsome et al., (2012). The authors concluded that while brick walls were slower to warm up, initially keeping the indoor temperatures cooler, brick walls retained heat over longer periods and were slower to release heat when nighttime cooling began. Therefore, during an extreme heat event, we expect that the protective effect of masonry quickly ends and masonry exteriors increase indoor summer temperatures(Wright, A J, Young, A N and Natarajan, 2005). We hypothesize that residential buildings with masonry walls will have higher indoor temperatures.

Age of Construction: Nahlik et al., (2017) used a computer model to investigate the contribution of a building's thermal envelope to indoor heat vulnerability in structures without air conditioning in Los Angeles, CA, and Phoenix, AZ (Nahlik et al., 2017). When the researchers analyzed the building characteristics, 70% of the indoor temperature variation in Los Angeles was due to the age of construction, with older buildings heating up faster. In Phoenix where the buildings are generally newer, the age of building construction only explained 30% of the variation. Building age was also a significant determinant of interior temperature in London, England (Mavrogianni et al., 2012). Based on these studies, and supported by White-Newsome et al. (2012), we hypothesize that older buildings will have higher indoor temperatures.

Size of Home: Tamerius et al., (2013) measured summer and winter indoor temperatures in 327 New York City homes. In summer, the second most important explanatory variables was the number of rooms (more rooms were cooler) (Tamerius et al., 2013). We hypothesize that smaller homes will have higher indoor temperatures compared to larger homes.

Behavioral Predictors of Indoor Temperature

From May to October 2017, Tsoulou et al. (2020) measured indoor and outdoor temperature in 24 units located in three senior apartment buildings in New Jersey. In addition to information on the buiding characteristics, researchers collected information on residents' adaptive behaviors (A/C, window opening, fan use, clothing adjustment) and demographic characteristics. With regression analysis, the researchers determined that 1) outside temperature, 2) living in the oldest/poorest quality of the buildings, 3) living on an upper floor, and 4) being active in the community explained .08 of the variance in indoor temperature. However, when they added variables representing the presence of A/C and window opening, that increased the R^2 to .71. During a heat wave, the same variables generated a R^2 value of .46. The researchers concluded that adaptive behaviors were more important than demographic characteristics in predicting interior temperatures (Tsoulou et al., 2020).

Using a subset of data from this study, Wright et al. (2020) monitored indoor temperatures in 46 Phoenix homes at 5-minute intervals over several summer months to understand air conditioning behaviors and compare household levels behaviors with demographic survey data. The authors found that indoor temperature profiles varied widely by household and the authors did not observe strong relationships between air conditioning behaviors and commonly cited risk factors such as household income, age, and gender. Wright et al. (2020) concluded that, “resource-constrained households may be prioritizing AC over other necessities because Phoenix is dangerously hot for most of the summer.” Their findings, consistent with Tsoulou et al. (2020), challenge the notion that demographic characteristics are sensitive proxies for predicting air conditioning use. We highlight this new research in part because we believe it is largely unrealistic to believe planners can conduct detailed household surveys in all neighborhoods of concern.

The final purpose of this research is to compare the relative impact of tree canopy, common building characteristics, and air conditioning use on indoor summer temperatures. To date, few studies have collected indoor temperature data from within residential environments during the warm season and no studies, that we are aware of, have conducted this type of research in ‘real homes’ in cities located in three climatic regions of the U.S.

Methods:

This research was conducted in Detroit, Michigan; Atlanta, Georgia; and Phoenix, Arizona as part of an interdisciplinary collaboration between researchers at the University of Michigan, Georgia Institute of Technology, and Arizona State University. Each city is in a different climate zone. Detroit has a hot-summer humid continental climate and currently receives 787 mm (31 inches) of precipitation annually. Atlanta has long, hot, humid summers (humid subtropical) and currently receives 1270 mm (50 inches) of precipitation annually. Finally, Phoenix has the hottest climate of any major U.S. city. The climate of Phoenix is categorized as tropical and subtropical desert and this city currently receives 203 mm (8 inches) of precipitation annually (*World Climate*, n.d.).

In spring of 2016, following IRB approval, we recruited 50 participants in each of our three cities (Detroit, Michigan; Atlanta, Georgia; and Phoenix, Arizona). Each city's sample was not a random sample. We purposefully sought participants who lived in housing units that were a mixture of 1) single- and multi-family units, 2) masonry and non-masonry, and 3) located in low- and middle-income neighborhoods with racial diversity. A detailed explanation of the sampling process is contained in Appendix A. Photographs of housing units from each city's sample are included in Appendix E, F, & G. At each home, we conducted a household survey, positioned the indoor and outdoor sensors, periodically collected air temperature measures throughout the summer and early fall, and then removed the sensors in fall. Problems with temperature sensors or participants opting out of the study resulted in a total of 140 data sets across the three cities.

Building characteristics:

For each housing unit, we linked the unit's address to the parcel number and census tract. Then, we accessed the appropriate record from the county tax assessor-collector's office. The County

Tax Assessor databases provided us with information on the year of construction, interior area, and whether the home was in a single family or multi-family building. We determined whether the unit had a majority of masonry versus non-masonry on exterior walls through visual inspection of each home's exterior in Google Street View and site visits. We should note that a limitation of our study was that we didn't determine the type of wall construction/materials under the masonry façade.

To ensure consistency of information on tree canopy cover across the three cities, we used the 2016 National Land Cover Database (NLCD) (https://www.mrlc.gov/national-land-cover-database-nlcd-2016). Within a geographic information system (GIS), we calculated the percentages of tree canopy cover within a 400 meter Euclidean buffer around the housing unit. Then, we calculated the percentage of tree canopy in the surrounding concentric ring between 400 and 1600 meters from the home. Using NLCD data to measure percentage of tree canopy was a limitation of this study due to its coarse resolution (Nowak & Greenfield, 2010). We prioritized consistency over higher resolution images that varied by year and season for each city. This limitation reduces the likelihood that we accurately captured the shading potential of trees but should capture the important influence of evapotranspiration.

Air temperature measurements:

We used calibrated Onset Corporation HOBO Temperature/Relative Humidity 2.5% Data Loggers (UX100-011) and (U23-002) to monitor the residential air temperatures indoor and outdoor of 140 homes in Detroit, Michigan; Atlanta, Georgia; and Phoenix, Arizona, respectively. Each sensor collected air temperature and relative humidity data every 5 minutes.

We placed the indoor sensor in the room in which residents said they spent the majority of their waking hours. For most participants this was their living/great room. These sensors were located approximately 1.5 m above the floor and were not located near air conditioning vents, waste heat sources, or direct sunlight. Outdoors, we attached the sensor to a 2-meter wooden stake that could be pushed into the ground in the yard (or a shared green space if the home was in a multi-family structure). Although we followed protocols for the placement of indoor and outdoor sensors (Oke, 2007), some variability did occur, particularly in the outdoor spaces where we had to avoid areas of impervious surface as well as respect the resident's preferences.

Results:

Demographic Characteristics Compared to City-wide Census Characteristics:

Table 1 compares the demographic characteristics of each city's sample to the population statistics from the US Census (2014-2018). While we do not claim that our small samples were representative of each city's population, we compared each sample's descriptive statistics to the city's population statistics in Appendix B. We purposefully sampled to include people of color consistent with the city's statistics and a significant number of lower income households.

Sample Building Characteristics:

Table 2 summarizes the housing characteristics from our sample. We purposely sampled to include single versus multi-family housing (1/3 of homes in each city were multi-family) and masonry versus non-masonry homes. The average year of construction reflects each city's historical development. In Detroit, 75% of the sampled homes were built before 1939 and only 19% were built after 1951. In Atlanta, 50% of sampled homes were built after 1951 while in Phoenix, 78% of sampled homes were built after 1951.

Sample Air Conditioning Presence and Use:

The most striking difference among the homes in the three different cities is the difference in the use of air conditioning. In our survey, we asked participants if they had a working central air-conditioning system and if their use of air conditioning was constrained by utility costs using a scale of 1(highly constrained) to 4 (not constrained). If participants rated their use as 3 or higher, we coded them as using air conditioning as needed. In Detroit, only 35% of respondents had and used their central air-conditioning as needed as compared with 57% in Atlanta and 95% in Phoenix.

Indoor, Outdoor, and Airport Temperatures:

Although we collected both temperature and heat index readings, temperature was highly correlated with heat index (Detroit's correlation = 0.99; Atlanta's correlation = 0.97; and Phoenix's correlation = 0.91) and for clarity, we chose to report temperature. We summarized the indoor and outdoor temperatures in the three cities (Appendix C). We focused on the temperatures at 5 am (generally when the urban heat island is least) and 5 pm (generally when the urban heat island is most pronounced) to illustrate the extremes. For each city, we calculated the mean indoor and outdoor temperatures at 5 am and 5 pm and categorized extreme heat conditions at temperatures that equaled or exceeded the 95th percentile. In the early mornings in Detroit and Atlanta, indoor temperatures were always higher than outdoor temperatures. However, in late afternoon in Detroit and Phoenix, indoor temperatures were always lower than outdoor temperatures. In Phoenix, indoor temperatures never exceeded outdoor temperatures regardless of time of day or average versus extreme heat conditions.

We applied a multivariable repeated measures fixed effects linear regression, with an indicator variable for each home. The dependent variable was indoor air temperature at either 5 am or 5 pm. The inclusion of an indicator variable (a fixed effect) for each home eliminates all confounding by non-time-varying characteristics, e.g., siding, air conditioning, neighborhood, etc. We make no attempt with this type of model to estimate, in general, how much hotter homes are if they have masonry or lack AC, for example. Instead, we give every household unit in our sample its own baseline temperature (i.e., intercept). Then, we can examine how building characteristics and percentage tree canopy *moderate the effect of* outdoor temperature on indoor temperature by including interactions of non-time-varying characteristics with temperature. In other words, we can examine how the *rate of change of* indoor temperature with increasing outdoor temperature varies by each characteristic. The independent variable, outdoor temperature at either 5 am or 5 pm, was additionally interacted with each of the tree canopy and building characteristics simultaneously in a single model, to account for confounding among these variables. Importantly, we have not analyzed how building and tree canopy characteristics influence indoor temperatures on average. This latter analysis would be susceptible to the actual temperatures experienced during the measurement period. For example, a mild summer could reasonably show no difference between homes with and without air conditioning. (See Appendix D for more details on the regression analysis).

For each city, we created two regression models for 5 am and 5 pm, with interaction terms between outdoor temperature and each building and tree canopy characteristic so that we could isolate the impact of the independent variables on how responsive indoor temperatures were to increases in outdoor temperatures. In each analysis, outdoor temperatures and indoor temperatures were highly correlated, as expected, and outdoor temperature explained by far the most variance in indoor temperatures (Appendix D). In interpreting the findings, it is important to note that the influences of the percentage of tree canopy within 400 m and between 400 and 1,600 m were not linear. To better represent the non-linear relationships, we divided each variable to measure the impact of a change in the percentage of tree canopy from low to medium (5th percentile-50th percentile) and from medium to high (50th percentile -95th percentile).

Regression Findings:

Trees Canopy:

In Detroit in the early morning, tree canopy about the home significantly modereated indoor temperatures. At 5am, increasing the percentage of tree canopy around the home (within 400 m) from 9.6% (5^{th} percentile) to 15.8% (50^{th} percentile) lessened the impact of a 10° C increase in outdoor temperature by 1 C on the indoor temperature.

In Atlanta in the late afternoon, tree canopy around the home (within 400 m) and in the nearby area (400m – 1,600 m) significantly impacted indoor temperatures but in opposite directions. At 5 pm, increasing the percentage of tree canopy around the home from 49% (50^{th} percentile) to 61.3% (95^{th} percentile) lessened the impact of a 10° C increase in outdoor temperature by .4 C on the indoor temperature. However, at 5 pm, increasing the percentage of tree canopy in the nearby area from 19.1% (5^{th} percentile) to 48% (50^{th} percentile) increased the impact of a 10° C rise in outdoor temperature by 1° C. We speculate that having a moderate amount of tree canopy in the nearby area decreased the impact of cooling winds as compared with a lower amount of tree canopy.

In Phoenix at 5 am and 5 pm, neither the percentage of tree canopy immediately around the home nor in the neighborhood significantly moderated the effect of a 10° C increase in outdoor temperatures on indoor temperatures.

Building Characteristics:

In Detroit, masonry was the only significant building characteristic. When the home's façade was more than 50% masonry it exacerbated increases in outdoor temperature at both 5 am and 5 pm. For every 10° C increase in outdoor temperatures, masonry façades exacerbated indoor temperatures by .9° C higher at 5 am and 1.1° C at 5 pm.

In Atlanta, none of the four building characteristics influenced indoor temperatures when outdoor temperatures increased by 10° C.

In Phoenix, two building characteristics, multifamily versus single family and size, had significant moderating impacts at 5 pm. Multifamily family homes lessened a 10° C increase in temperature by -0.6° C as compared to single family homes. At 5 pm, larger homes in Phoenix were cooler than smaller homes. Specially, the indoor temperature of homes that measured 188 m^2 (2024 ft^2) homes was moderated by 0.7° C for every 10° C increase in outdoor temperature as compared with 97.6 m^2 (1050 ft^2) homes.

Air Conditioning:

In Detroit, when residents reported both having and using their central air conditioning as needed, it moderated a 10° C increase in outdoor temperatures by 1.2° C on indoor temperatures at 5am and 1.0° C at 5 pm. In Atlanta, when residents reported both having and using their central air conditioning as needed, it moderated an increase in outdoor temperatures of 10° C by 3.7° C at 5 am and 1.0° C at 5 pm. Because only 2 of the Phoenix homes lacked central air conditioning, our sample size was insufficient to support conclusions about its moderating effect.

Conclusions and Recommendations:

We hypothesized that tree canopy would be more influential in cities with temperate climates, such as Detroit. In Detroit, in addition to air conditioning, both tree canopy and masonry were roughly equivalent in their impact, but opposite in direction. Masonry facades exacerbated the effect of increasing outside temperatures in both morning and evening. This finding is consistent with Wright et al.'s findings (2005). Going forward, planners in Detroit may consider using masonry facades and lower percentages of tree canopy as possible indicators of higher indoor temperatures.

We hypothesized that building characteristics would be more influential than tree canopy in cities with more warmer climates, such as Atlanta and Phoenix. In the late afternoon in Atlanta, tree canopy, and not building characteristics, had a greater impact on indoor temperatures. By 5 pm in Atlanta, in addition to air conditioning, changes in the tree canopy significantly affected indoor temperature. Increasing tree canopy from medium to high directly around the home mediated indoor temperatures by .4° C while increasing tree canopy from low to medium in the neighborhood area (between 400 and 1,600 m) increased indoor temperature by 1° C (perhaps due to less air circulation). While these tree canopy findings are contradictory, planners need to prioritize increasing tree canopy immediately around homes for the net benefit of all residents. In Phoenix at 5 pm, building characteristics were more influential compared to tree canopy coverage. In Phoenix, we believe that the severity of the climate reduced the impact of tree canopy on the indoor temperature. The questionable contribution of the vegetation in Phoenix is consistent with other research (but we are aware that our use of lower resolution of NCLD tree canopy data may have been a factor). In a comparison of white versus green roofs in several US cities using climate modeling, Georgescu et al., 2014 determined that white roofs were more effective than green roofs in lowering urban temperatures in Phoenix, Arizona, while in cities in Florida, green roofs were more effective than white roofs. The differences in impacts of tree canopy and building characteristics between Atlanta and Phoenix may be due to the background climate. Phoenix's desert climate may be the reason that the building characteristics are more important relative to tree canopy. Atlanta's humid subtropical climate with abundant rainfall may favor changes in tree canopy over building characteristics. As we noted earlier, there has been little research focused directly on measuring indoor temperatures and this research suggests further study could yield important findings.

Our findings underscore the importance of the most effective preventative factor, air conditioning. Emergency managers, public health professionals, social service providers, and urban planners need to advance equitable approaches to provide air conditioning. In retrospective studies of heat mortality, less expensive mechanical options, such as room air conditioners, had little effect on heat-related mortality compared with central air conditioning (O'Neill et al., 2005). Central air conditioning will become increasingly important as the number, intensity, and duration of extreme heat events increases. In our sample of lower- and middle-income households in Detroit, only 35% of homes had central air conditioning and were able to use it regularly to manage comfortable indoor temperatures. This increased to 57% in Atlanta and to 95% in Phoenix.

We conclude with five recommendations. First, as extreme heat events increase and average summer temperature increase with climate change, we need more spatially explicit information at the census tract level to identify areas where many households lack a working central air conditioning system or where poverty limits residents' use of air conditioning. The specificity of this information, perhaps added to the US census, would help prioritize both short-term extreme heat responses as well as long-term neighborhood-level interventions such as targeted outreach for housing renovation grants and loan programs for vulnerable individuals and cooling assistance programs.

Second, to promote access to air conditioning in rental properties, municipalities should establish and enforce maximum indoor temperature thresholds. In climates with cold winters, some cities' building regulations set minimum temperature thresholds for rental housing. Similar to discussions underway in Toronto, Ontario (Medical Officer of Health, 2015), we recommend that cities establish enforceable maximum indoor temperature thresholds for rental housing.

Utility poverty is a real concern. In the United States, households that spend more than 6% of their gross household income are defined as having an energy burden. Using this definition, 25%

of American households bear an energy burden (J. Lewis et al., 2020). Since 1981, the Low Income Home Energy Assistance (LIHEAP), a federal program through the Department of Health and Human Services (DHSS), has helped lower-income and vulnerable residents with their utility costs (US Department of Health and Human Services, n.d.). While LIHEAP was started to address the energy burden of heating costs, states have considerable latitude in how they allocate their funds. In June 2021, every state received a letter from DHSS encouraging them to include cooling assistance in their upcoming allocation plans (Howard & Christopher, 2021) . However, by reviewing each state's publicly available LIHEAP distribution plans (submitted several months after this letter), we found only 36 of 49 states currently include cooling assistance (South Dakota's plan was not accessible). States such as Georgia, Michigan, Illinois, Indiana, Missouri, and Nevada currently do not offer cooling assistance. Additionally, lower income housing energy retrofit programs that currently add insulation and replace inefficient windows could be expanded to include the addition or servicing of central air conditioning systems. Our third recommendation for planners is to advocate for cooling assistance in their state's LIHEAP distribution plan, if it is omitted, and investigate if adding or maintaining central air conditioning systems is included in the state's weatherization and crisis response funding.

Extreme heat events can coincide with sporadic disruptions of the electrical grid due to increased demand. The combination of a heat wave and power outage resulted in the death of 739 people in Chicago in July 1995 (Klinenberg, 2015). With increasing heat extremes, future heat waves and concurrent black outs could have devastating impacts. Our fourth recommendation is that planners recast cooling centers as resilient neighborhood centers. In Ann Arbor, Michigan, community centers that serve as cooling centers are being equipped with solar photovoltaic generation and energy storage systems to avoid power outages. One clear conclusion from this study is that neither building characteristics nor tree canopy approach the importance of access to central air conditioning in extreme heat conditions.

While increasing access to air conditioning is a pressing need, we need to ensure that the electricity used to power these systems is derived from renewable sources. Renewable energy systems provide greater reliability than diesel generators without emitting harmful greenhouse gases. If we (society) use energy derived from fossil fuel sources to address the problem of extreme heat, we will exacerbate the climate change problem. Our fifth recommendation is that urban planners ensure that efforts to aid vulnerable residents are accompanied by efforts to shift energy sources toward renewables.

Proactively addressing extreme heat events and rising summer temperatures highlight many interconnected issues of environmental and social justice, air conditioning access and utility poverty, and housing quality and safety. Urban planners need to recognize that existing residential indoor environments are often the source of dangerous heat exposure and climate adaptation planning for increasing temperatures will require more than urban greening efforts.

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Table 1. Descriptive Statistics of Sample Compared with City's Demographics (US Census 2014-2018)

	Detroit Sample	US Census Detroit	Atlanta Sample	US Census Atlanta	Phoenix Sample	US Census Phoenix
# Households	48		46		46	
% Respondent - Female	87.5%	52.7%	54.3%	51.3%	58.7%	50.20%
Race/Ethnicity						
% Black or African-American	60.4%	78.6%	39.1%	51.8%	6.5%	6.90%
% Hispanic, Latino, Mexican, Mexican-American, or Spanish	25.0%	7.6%**	8.7%	4.3%**	26.1%	42.6**
% White	10.4%	14.6%	41.3%	40.3%	65.2%	72.3
% Other*	4.2%		10.9%		2.2%	
Household Size	3.7	2.6	2.6	2.2	2.5	2.87
Years in Current Home	11.6		13.1		11.8	
Respondent Owns Home	50.0%	47.4%	60.9%	43.5%	78.3%	53.8%
Single Family Home	60.4%		68.8%		69.6%	
% Uses Air Conditioning	37.5%		56.6%		95.7%	
Income						
% Less than $20,000	41.7%		23.9%		8.7%	
% $20,001-$40,000	29.2%		17.4%		17.4%	
% $40,001-$60,000	8.3%		4.3%		15.2%	
% $60,001 and Above	20.8%		54.4%		58.7%	
Median Household Income (US Census)		$29,481		$55,279		$54,765

*Other represents Native American, Asian or Asian American, Middle Eastern, Native Hawaiian or Other Pacific Islander, Other, or Prefer Not to Answer
**In the US Census, Hispanic and Latino categorization is separate from race

Table 2. Building and Tree Canopy Characteristics by City.

	Detroit	Atlanta	Phoenix
Sample Size	48	46	46
% Built 1900-1939	36 (75%)	18 (39%)	6 (13%)
% Built 1940-1950	3 (6%)	5 (11%)	4 (9%)
% Built 1951 - onward	9 (19%)	23 (50%)	36 (78%)
% Multi-Family	17 (35%)	16 (35%)	15 (32%)
% Masonry	19 (39%)	30 (64%)	23 (49%)
% Uses Air Conditioning	17 (35%)	26 (57%)	44 (95%)
Area of the Home m^2	141 m^2	146 m^2	140 m^2
	(1520 sq ft)	(1567 sq ft)	(1503 sq ft)
Average % Tree Canopy Cover within 400 m	17.10%	46.30%	9.50%
Average % Tree Canopy Cover between 400 m (.25 miles) and 1600 m (1 mile)	15.50%	42.40%	9.00%

Table 3: For Detroit, the added increase in indoor temperature (C) for each outdoor temperature increase of 10 C.[1]

Independent Variable	Indoor Temperature Change at 5:00 am (95% Confidence Interval)	Indoor Temperature Change at 5:00 pm (95% Confidence Interval)
1) **Uses central air conditioning**	**-1.2****	**-1.0 ***
	(-1.7, -0.6)	(-1.8, -0.2)
2) Building characteristics		
Year of Construction	-0.2	0.3
Built in 1900-1939 compared to 1951 or later	(-1.3, 0.9)	(-1.3, 1.8)
Built in 1940-1950 compared to 1951 or later	-0.3	-0.1
	(-1.8, 1.1)	(-2.3, 2.1)
Multifamily Structure compared to Single Family	-0.7	-0.1
	(-1.5, 0.2)	(-1.1, 0.9)
Masonry Exterior compared to Non-Masonry	**0.9***	**1.1 ****
	(0.2, 1.7)	(0.3, 1.9)
Building area (m^2)	0.6	-0.1
Increase from smaller area to larger area[1]	(-0.0, 1.3)	(-0.8, 0.5)
3) Tree canopy characteristics		
Tree Canopy within 400 m	-0.1	-0.4
Increase from 5th percentile to median	(-0.7, 0.6)	(-1.1, 0.3)
Tree Canopy within 400m	-0.2	0.1
Increase from median to 95th percentile	(-1.2, 0.8)	(-1.2, 1.4)
Tree Canopy 400m to 1,600 m Increase from 5th percentile to median	**-1.0 ****	-0.2
Tree Canopy 400m to 1,600 m Increase from median to 95th percentile	-0.1	-0.2
R^2 of the model	**0.75**	**0.68**

[1] Independent variables highlighted in bold significantly altered the rate at which indoor temperature increased with increasing outdoor temperatures. Negative coefficients indicate that the factor slowed the increase in indoor temperatures. Positive coefficients indicate that the factor accelerated the increase indoor temperatures.

Notes: The estimates for the three variables building area (sqm), % tree canopy within 400m and % tree canopy between 400 and 1,600 m were obtained as a combination of a linear and a quadratic term of model fit.

The 25th, median, and 75th percentiles of building area were 93.6 m^2, 119.7 m^2, and 167.2 m^2, respectively.

The 5th, median, and 95th percentiles of tree canopy within 400 m were 9.6%, 15.8%, and 25.4% respectively.

5th, median, and 95th percentiles of tree canopy 400 m to 1,600 m were 9.0%, 15.8%, and 22.5% respectively.

Significance level codes:

* indicates significance with 95% confidence

** indicates significance with 99% confidence

Table 4: For Atlanta, the added increase in indoor temperature (C) for each outdoor temperature increase of 10 C.[1]

Independent Variable	**Indoor Temperature Change** at 5:00 am (95% Confidence Interval)	**Indoor Temperature Change** at 5:00 pm (95% Confidence Interval)
1) Uses central air conditioning	**-3.7**** (-5.0, -2.4)	**-1.0 **** (-1.6, -0.4)
2) Building characteristics		
Year of Construction Built in 1900-1939 compared to 1951 or later	-0.1 (-1.3, 1.1)	-0.2 (-0.7, 0.2)
Built in 1940-1950 compared to 1951 or later	1.8 (-0.3, 3.9)	0.7 (-0.2, 1.7)
Multifamily Structure compared to Single Family	0 (-1.8, 1.8)	-0.1 (-1.0, 0.8)
Masonry Exterior compared to Non-Masonry	0.3 (-1.0, 1.7)	0 (-0.5, 0.5)
Building area (m^2) Increase from smaller area to larger area	0.5 (-0.5, 1.5)	0.1 (-0.4, 0.7)
3) Tree canopy characteristics		
Tree Canopy within 400 m Increase from 5th percentile to median	0.9 (-0.9, 2.8)	0.3 (-0.2, 0.9)
Tree Canopy within 400m Increase from median to 95th percentile	-0.3 (-1.0, 0.5)	**-0.4*** (-0.8, -0.1)
Tree Canopy 400m to 1,600 m Increase from 5th percentile to median	1.5 (-0.7, 3.7)	**1.0*** (0.2, 1.8)
Tree Canopy 400m to 1,600 m Increase from median to high (95th percentile)	-0.1 (-0.6, 0.4)	-0.1 (-0.3, 0.1)
R^2 of the model	**0.92**	**0.93**

[1]Independent variables highlighted in bold significantly altered the rate at which indoor temperature increased with increasing outdoor temperatures. Negative coefficients indicate that the factor slowed the increase in indoor temperatures. Positive coefficients indicate that the factor accelerated the increase indoor temperatures.

Notes: The estimates for the three variables building area (sqm), % tree canopy within 400m and % tree canopy between 400 and 1,600 m were obtained as a combination of a linear and a quadratic term of model fit.

The 25th, median, and 75th percentiles of building area were 83.5 m^2, 120.8 m^2, and 166.1 m^2, respectively.

The 5th, median, and 95th percentiles of tree canopy within 400 m were 22.3%, 49.0%, and 61.3% respectively.

The 5th, median, and 95th percentiles of tree canopy 400 m to 1,600 m were 19.1%, 48.0%, and 53.7% respectively.

Significance level codes:

* indicates significance with 95% confidence

** indicates significance with 99% confidence

Table 5: For Phoenix, the added increase in indoor temperature (C) for each outdoor temperature increase of 10 C.[1]

Independent Variable	**Indoor Temperature Change** at 5:00 am (95% Confidence Interval)	**Indoor Temperature Change** at 5:00 pm (95% Confidence Interval)
*1) **Uses central air conditioning***	***1.3**** *(0.4, 2.2)*	*-0.2* *(-1.0, 0.6))*
2) Building characteristics		
Year of Construction Built in 1900-1939 compared to 1951 or later	-0.5 (-1.3, 0.3)	-1.0 (-0.9, 0.7)
Built in 1940-1950 compared to 1951 or later	0.3 (-0.8, 1.5)	0.7 (-0.4, 1.9)
Multifamily Structure compared to Single Family	0.0 (-0.6, 0.7)	**-0.6*** (-1.3, 0.0)
Masonry Exterior compared to Non-Masonry	0.1 (-0.4, 0.6)	-0.0 (-0.5, 0.5)
Building area (m^2) Increase from smaller to larger area	-0.2 (-0.7, 0.4)	**-0.7*** (-1.3, -0.2)
3) Tree canopy characteristics		
Tree Canopy within 400 m Increase from 5th percentile to median	-0.1 (-0.6, 0.4)	0.4 (-0.0, 0.8)
Tree Canopy within 400m Increase from median to 95^{th} percentile	0.4 (-0.8, 1.5)	0.3 (-1.0, 1.5)
Tree Canopy 400m to 1,600 m Increase from 5th percentile to median	0.4 (-0.5, 1.3)	0.2 (-0.5, 1.0)

Tree Canopy 400m to 1,600 m Increase from median to high (95th percentile)	-0.1 (-0.9, 0.8)	-0.2 (-1.0, 0.7)
R^2 of the model	**0.85**	**0.80**

[1] Independent variables highlighted in bold significantly altered the rate at which indoor temperature increased with increasing outdoor temperatures. Negative coefficients indicate that the factor slowed the increase in indoor temperatures. Positive coefficients indicate that the factor accelerated the increase indoor temperatures.

Notes: The estimates for the three variables building area (sqm), % tree canopy within 400m and % tree canopy between 400 and 1,600 m were obtained as a combination of a linear and a quadratic term of model fit.
The 25th, median, and 75th percentiles of building area were 97.6 m^2, 115.6 m^2, and 183.1 m^2, respectively.
The 5th, median, and 95th percentiles of tree canopy within 400 m were 4.0%, 7.7%, and 18.6% respectively.
5th, median, and 95th percentiles of tree canopy 400 m to 1,600 m were 4.8%, 7.8%, and 18.8% respectively.
Significance level codes:
* indicates significance with 95% confidence
** indicates significance with 99% confidence

Appendix A: Sampling Process

Establishing building criteria – In planning our sampling strategy, we reviewed the literature to identify structural characteristics that influence indoor temperature relative to outdoor temperature. Then, for each city, we identified common housing typologies based on a review of housing census data and street-level photographs for lower and moderate-income neighborhoods. We compared the typologies and selected three characteristics of thermal efficiency common to all cities and easily observable (single/multi-family, masonry/non masonry, size). While we hypothesized that age would be a significant predictor, we did not purposefully sample for building ages (too difficult in Detroit). In each city, 1/3 of our sample households lived in multi-family structures. For multi-family structures, we limited our selections to townhomes or apartment buildings with 4 or fewer floors.

In Detroit, we worked with three community-based organizations that had existing relationships with residents. These organizations identified potential residents in three neighborhoods on the Southwest, East Jefferson, and Parkside neighborhoods. Each Detroit organization provided researchers with a list of an addresses that satisfied one or more of the four housing criteria (single/multi-family, masonry/non masonry, size, age). From this list, we then contacted residents purposefully to capture the different criteria. In Atlanta, researchers used a snowball sampling approach through personal contacts in addition to seeking participants with help from EPA Region 4's Office of Environmental Justice and Sustainability to identify study participants predominantly from the English Avenue and Vine City neighborhoods. The participants in Atlanta were from the Midtown, Vine City, English Avenue, and Buckhead neighborhoods, with a few exceptions. In Phoenix, we conducted a screening survey in four different study sites in the city. We overlaid maps of income and demographic data along with maps of highlighting building characteristics. The participants in Phoenix were from Downtown Phoenix, Camelback/Arcadia, South Mountain, and Cave Creek. The housing units in our sample were within the municipal boundary of each city.

Appendix B: Comparison of each city's sample to the population

In Detroit, similar to Census findings, approximately one half of our sample rented their home and had a household income beneath the median. There were four differences in our Detroit sample: our sample had a high percentage of women respondents (88%), a lower percentage of African-American or Black residents (60% compared to 78%), a higher percentage of Hispanic residents (25% compared with 8%), and a larger average family size of 3.7 (compared with 2.5 in the Detroit population). In our Atlanta sample, 61% of our respondents owned their home as compared with 44% according to the Census; approximately 45% of our Atlanta respondents had a household income at or below the median. There were three differences in our sample of Atlanta residents: these included a lower percentage of African-American or Black residents (39% compared with 51% in the population), a higher percentage of Hispanic residents (8.7% compared with 4.3% in the Atlanta population), and wealthier participants compared to the average. In Phoenix, there were three differences between our sample relative to the population. Our sample had lower percentages of Hispanic (26.1% compared with 42.6%) and higher percentages of Non-Hispanic White residents (65.2% compared with 42.5%), and also a higher percentage of homeowners (78.3% compared with 54.4%). In all three cities, our respondents had lived in their current home for an average of over 10 years (11.6 years in Detroit, 13.1 years in Atlanta, and 11.8 years in Phoenix).

Appendix C: Indoor and Outdoor Temperatures

	Detroit		Atlanta		Phoenix	
5:00 AM	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Mean Temperature °C	25.6	19.7	25.8	23.5	25.8	25.8
95th Percentile Temperature °C	29.1	25.4	30	25.7	28.8	31.1
	Detroit		Atlanta		Phoenix	
5:00 PM	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Mean Temperature °C	26.7	27.2	26.8	31.3	27.2	37.2
95th Percentile Temperature °C	30.2	33.1	32.2	35.7	30.2	43

Appendix D: Interaction Terms and Sensitivity Analysis

The categorical interaction terms used for each city were: 1) year built (1900-1939 and 1940-1950 with 1951 to present serving as the reference, 2) multi versus single family, 3) majority masonry exterior walls versus other materials such as aluminum or wood siding, and 4) whether the resident both had and used central air conditioning. The continuous predictor variables used for each model were: 1) size of the housing unit, 2) percentage of tree canopy nearby, and 3) the percentage of tree canopy in the neighborhood. Squared terms for the continuous predictors were also interacted with temperature to account for non-linearity. There was minimal change in the R^2 from the full to the reduced models for all cities and all models. For each city for each model (outdoor 5 am, outdoor 5 pm), the R^2 of the full model (main outdoor temperature effect and interaction terms) versus the reduced model (no interaction terms) were as follows:
Detroit at 5 am (0.746 vs. 0.711) and Detroit at 5 pm (0.656 vs. 0.626)
Atlanta at 5 am (0.917 vs. 0.910) and Atlanta at 5 pm (0.932 vs. 0.924)
Phoenix at 5 am (0.851 vs. 0.844) and Phoenix at 5 pm (0.802 vs. 0.795)

In examination of the partial autocorrelation function of residuals from a multiple linear regression model without random effects, moderate temporal lag 1 autocorrelation was evident. This finding violated the assumption of independence in regression analysis. This was expected given the strong temporal correlation in temperature time series, i.e., the strong influence of the previous day's temperature on the current day's temperature. Therefore, we chose an autoregressive-1 correlation structure. To account for this correlation structure, we performed analyses in a generalized estimating equations (GEE) framework with an autoregressive-1 correlation structure using the geepack package in R 3.5. (Halekoh et al., 2006; Yan, 2006; Yan & Fine, 2004).

Halekoh, U., S, H., & Yan J. (2006). The R Package geepack for Generalized Estimating Equations. *Journal of Statistical Software*, *15*(2), 1–11.
Yan, J. (2006). geepack: Yet Another Package for Generalized Estimating Equations. *R-News*, *3*, 12–14.
Yan, J., & Fine, J. (2004). Estimating Equations for Association Structures. *Statistics in Medicine*, *23*, 859–880.

Sensitivity Analysis
As a sensitivity analysis, we repeated the above analyses in a mixed effects framework using the nime package in R 3.5.0 with the main effects of the neighborhood and housing characteristics, in addition to the interactions and random (rather than fixed) effects for housing units(Pinheiro J, Bates D, DebRoy S, Sarkar D, 2020). To account for the previously identified correlation structure, we specified an autoregressive-1 correlation structure. Random effects model results were qualitatively similar to those from the fixed effects models.

Pinheiro, J., Bates, D., DebRoy, S., & sarkar, D. (2020). *nlme: Linear and Nonlinear Mixed Effects Models R package version 3.1-151*. 2020. https://cran.r-project.org/package=nlme

Appendix E: Examples of Single and Multi-Family Housing Units from Detroit, Michigan

Appendix F: Examples of Single and Multi-Family Housing Units from Atlanta, Georgia






Appendix G: Examples of Single and Multi-Family Housing Units from Phoenix, Arizona