URBAN THERMAL DIAGNOSTICS AND EXTREME HEAT VULNERABILITY IN UNDERREPRESENTED COMMUNITIES

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URBAN THERMAL DIAGNOSTICS AND EXTREME HEAT VULNERABILITY IN UNDERREPRESENTED COMMUNITIES

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LIST OF ABBREVIATIONS

AAT	Average Air Temperature
ACM	Adaptive Comfort Model
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAPA	Climate Adaptation and Analytics
CDC	Centers for Disease Control and Prevention
EPW	EnergyPlus Weather Format
ER	Emergency Room
GA	Georgia
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel on Climate Change
LED	Light Emitting Diode
LLC	Limited Liability Company
MDH	Minnesota Department of Health
MMWR	Morbidity and Mortality Weekly Report
MRT	Mean Radiant Temperature
NASA	The National Aeronautics and Space Administration
NIHHIS	National Integrated Heat Health Information System
NPU	Neighborhood Planning Unit

NWS	National Weather Service
PMV	Predicted Mean Vote
RGB	Red, Green, Blue
SVI	Social Vulnerability Index
TMY	Typical Meteorological Year
UHI	Urban Heat Island

SUMMARY

According to the MMWR (IPCC), the globally averaged surface temperatures of the Earth have increased by 0.6 ± 0.2°C in the 20th century and models have projected that by 2100 (relative to 1990), the globally averaged surface air temperature to warm 1.4 to 5.8°C (Intergovernmental Panel on Climate Change & Working Group II, 2001).

Urban environments elevate rising temperatures in cities through urban heat island effect. According to Vargo et al., (2013), the rate of warming temperatures in urban environments is "*more than double that of the planet*" (Vargo et al., 2016, p. 367). The rate of global warming in urban environments is further elevated through the urban heat island effect, defined by Dana May as an "*atmospheric phenomenon which manifests as a region of warmer temperatures within and over urban areas compared to the temperature of surrounding rural areas*" (Dana May et al., 2021, p. 5). With global urbanization increasing, this becomes a critical aspect of climate change for research to focus on.

These increasing temperatures mean we are experiencing longer and more intense summers that are leading to extreme heat events called heat waves. Heat waves occur when the temperature increases beyond a certain threshold for a period for a consecutive amount of time, and its dire effects occur exclusively in the summer. These extreme heat events are increasing in frequency, duration, and intensity, and have been correlated with biophysical hazards such as heat stress, air pollution, and associated public health

problems (Zhou & Shepherd, 2010). These hazards, along with heat related mortalities, are expected to increase with rising temperatures significantly. Mortalities, specifically, are expected to increase between 3,500 and 27,000 deaths in the United States alone (Stone et al., 2014).

These impacts are expected to be more intense within vulnerable populations such as the chronically ill, elderly, and young children (Dana May et al., 2021). This makes it crucial to focus urban and building design strategies on the populations most at risk.

Underrepresented communities are vulnerable to the effects of extreme heat due to a combination of several factors, including but not limited to adaptive capacity, exposure, and sensitivity. An underrepresented community is characterized by a multitude of socioeconomic qualities, including race, average income, age, and disabilities. One neighborhood with such qualities is the Grove Park Neighborhood in Atlanta, Georgia.

This thesis identifies vulnerable communities as being more at risk to the effects of extreme heat. The method of investigation is under three main titles. These are, sequentially, data, analytics & evaluation, and strategies. The first section of the thesis is mainly focused on collecting data that will support the definition of heat vulnerability by (Widerynski et al., 2017) as a combination of adaptive capacity, exposure, and sensitivity. The data is organized into three main categories: 1) geographic spatial data and mapping, 2) social demographic data, and 3) building data. The second segment analyzes and evaluates the data which was previously collected. Through modeling software which will simulate the thermal comfort and temperatures during the current climate and future climate, qualitative methods which investigate the demographic and social data collected, and finally interpretation of all the remaining data. All these together can be used to support the claim that this underrepresented community specifically is more susceptible to effects of extreme heat currently and in the long run.

Finally, the research will investigate possible mitigation strategies in both the long term and short term. While the research will be applied to the specific Grove Park neighborhood, this gives us an opportunity to realize how important it is to begin identifying more communities which are at risk and applying similar strategies.

CHAPTER 1. INTRODUCTION

Heat waves are responsible for more deaths annually than all other weather-related hazards combined, and are expected to increase in intensity, duration, and frequency in a warming climate (Mallen et al., 2019). Heatwaves are periods of increased temperatures above the average summer temperature due to global warming which can last for several days and can have biophysical effects on people, leading to heat related mortalities in vulnerable people. According to previous studies, most large US cities are warming double the rate of the planet and this a trend due to the rapid growth in the Urban Heat Island (UHI) (Stone et al., 2013) which is a phenomenon where the impervious materials of urban construction absorb, store, and release heat energy later (Vargo et al., 2016b).

The built environment is the major contributor to UHI (U.S. Environmental Protection Agency, 2008). This is due to an increase in the amount of impermeable surface areas which absorb heat in the summer and a decrease in vegetative space which otherwise aids in evapotranspiration (Belhadj & Kaabi, 2020). Furthermore, waste heat generated by energy usage in buildings contributes to the effect that the built environment possesses on UHI (Y. Li & Zhao, 2012). Currently, population distributions are shifting towards cities, with an expected 70% of the global population living in cities by the year 2050 (Dana May et al., 2021). As cities become more populated, their areas will increase to accommodate larger populations, so it is critical for city governments to mitigate heat through urban and building design strategies.

Heat waves have been correlated with biophysical hazards such as heat stress, air pollution, and associated public health problems (Zhou & Shepherd, 2010). These hazards, along with heat related mortalities, are expected to increase with rising temperatures significantly. Yearly estimates of heat-related deaths in the USA range between 170-690 per year. Mortalities, specifically, are expected to increase between 3,500 and 27,000 deaths in the United States alone. These impacts are expected to be more intense within vulnerable populations such as the chronically ill, elderly, and young children (Dana May et al., 2021). Race and income also determine how vulnerable a community is, contributing to social isolation, poor housing quality, or lack of air conditioning, all increasing the risk of extreme heat exposure. Such communities have lower adaptive capacity and are less resilient in responding to this extreme environmental exposure (Vargo et al., 2016b). This makes it crucial to focus urban and building heat management strategies on the communities at higher risk.

1.1 Research Purpose

1.1.1 Research Goal

This research employs urban thermal diagnostics to identify an underrepresented community as more vulnerable to extreme heat. The Grove Park neighborhood in Atlanta, Georgia is selected as a case study. The terms "underrepresented" and "vulnerable" when referring to the community describe those which are "marginalized and underserved" according to (Fish & Syed, 2020). The terms also refer to communities with poor biophysical, political, social, and economic conditions as well as the lack of ability to respond to extreme environmental conditions.

1.1.2 Research Hypothesis

- A community's heat vulnerability can be identified through a series of characteristics mainly: adaptive capacity, sensitivity, and exposure.
    - Adaptive capacity through thermal imaging and building envelope performance.
    - Sensitivity through modelling thermal comfort during extreme heat.
    - Exposure through collecting information and interpretation of community responses.
- Underrepresented communities are more vulnerable to extreme heat and less equipped to handle the stress, leading to greater risk of biophysical complications related to heat exposure.

1.2 Research Motive & Structure

1.2.1 Research Significance

Through an analysis of one main residents' home, this research shows three main things. First, identifies marginalized and underserved communities are more vulnerable to extreme heat. Second, raises awareness to direct resources and efforts towards these communities. Finally, recognizes strategies, both long term and short term for increasing resiliency in these communities.

1.2.2 Research Questions

- Are underrepresented communities more at risk to extreme heat? And how are their built environments equipped to handle the extreme heat threats?
  - What characteristics in the built environment make a community more vulnerable to extreme heat?
- What are some strategies for mitigating risks associated with extreme heat vulnerability?
- How can data analytics and measurements be used as evaluation metrics to design strategies for mitigating the risks and reducing the climate vulnerability of a community?

1.2.3 Thesis Overview

This thesis is structured as follows. Chapter 1 introduces the thesis and the major goals and objectives. Chapter 2 investigates literature related to extreme heat and urban heat island, heat and humans: adapting, health and comfort, heat vulnerability: adaptive capacity, exposure and sensitivity, and existing mitigation strategies. Chapter 3 discusses the methods for data collection and analysis. Chapter 4 looks at the results of the analysis and determines if the community is considered more vulnerable to extreme heat and possible mitigation strategies. Chapter 5 discusses the limitations of the research and future paths of investigation.

CHAPTER 2. LITERATURE REVIEW

This chapter aims to review literature related to extreme heat, human biophysical hazards when exposed to it, and its effect on vulnerable communities. The literature review also investigates research done regarding extreme heat in Atlanta, and one socioeconomically vulnerable community particularly. Finally, some current responses to heat exposure in urban communities have also been investigated for a better understanding of the relationship between urban design, policy, and building performance.

2.1 Extreme Heat and Urban Heat Island

The Intergovernmental Panel on Climate Change (IPCC) has estimated the global mean temperature to increase 4°C by 2100 (Bayomi et al., 2021) This rise in temperature will be accompanied by implications in the built environment both indoors and outdoors and during the summers will lead to heat waves. Heatwaves are defined as a natural climate event due to global warming that surpasses a maximum temperature for a specific duration of days consecutively that exceeds the average maximum temperature of a location during the summer (Zhou & Shepherd, 2010). Heat waves are expected to increase in intensity, duration, and frequency (Stone et al., 2013) and effects such as heat related stress, mortality and other adverse impacts on the human body will also increase (Dana May et al., 2021).

These heat related implications will be exacerbated in urban regions with higher populations (Collins & Knutti, 2013, as cited by (Habeeb et al., 2015). Urban environments further elevate the rate of warming in cities through the Urban Heat Island effect, an atmospheric phenomenon due to deforestation where the impervious materials of urban construction absorb, store, and release heat energy due to the extensive use of heat-absorbing materials (Dana May et al., 2021; Mallen et al., 2019; Vargo et al., 2016b). Some studies prove that most large cities are warming double the rate of the planet as a whole (Stone et al., 2013). In these urban areas, the urban heat island increases the effects of heat on physical health and heat related mortality and together with the greenhouse effect, the number of extreme heat events occurring in these areas also increases (Lehnert et al., 2020; Stone et al., 2014). Urban warming has been shown in large US cities to be as great, or greater than, the impact of global climate change on local temperature trends (Vargo et al., 2016b).

"*We have two forces—urban heat islands and global warming—that are reinforcing each other and are going to create extremely hot conditions for more than half the world's population*" Gaffin explains (Scott, 2006).

More collaboration between policymakers, researchers and the public can be a first step towards offsetting the risks associated with effects of global warming on urbanized areas (Lanza & Stone, 2016).

2.2 Heat and Humans

In this section, there is a discussion of the literature exploring the effects of extreme heat on the human body.

2.2.1 Adapting

Often, exposure to heat in prolonged periods of times can cause different responses in the human body, and the ability of our body to respond to these differences in temperatures is important and depends on two main factors for regulation: the built environment and the body (Mallen, 2019).

2.2.1.1 Building Physics

The built environment plays a large part in regulating the indoor temperatures in response to outdoor temperatures to keep us safe from extreme heat exposure. Currently, most of the temperature regulation that happens in buildings relies on constant power sources. Active systems, such as air conditioning, are the main method of bringing down the temperature of the indoor environment in hotter climates and the absence of such systems is a major contributor to heat mortality and morbidity (Eisenman et al., 2016). A resilient structure will have the capacity to regulate indoor conditions safely during power outages for limited amounts of time (Holmes et al., 2016) and will have passive habitability as well.

Our ability to adapt to changing temperatures depends partly on our physical environment, which, in most cases is not something that can readily be changed. Aspects such as building orientation, construction materials, window operability, and availability of active mechanical systems which help regulate indoor conditions all have major impacts on the habitability of our environment during extreme heat.

Multifamily buildings in urban areas are particularly vulnerable due to their building age, construction materials, insulation, roof and wall colors, window orientation, apartment configuration, and lack of operable windows (Shorris, 2017). Operable windows can provide fresh air and can reduce energy use, especially during shoulder seasons when temperatures and humidity are lower. Studies show that indoor home temperatures can be 6-7°C higher than outdoor temperatures without air conditioning (Shorris, 2017).

A study assessing the relationship between extreme heat mortality, income, and access to air conditioning in California showed air conditioning and heat related mortality to be inversely proportional to each other (Ostro et al., 2010). Analysis of the 1995 Chicago heatwave proved that access to air conditioning greatly reduced the risk of heat related mortality (An et al., 1996). Another study showed the relationship of access to air conditioning with race, which has found that ownership in white/other households of air conditioning is double that than black households (O'Neill et al., 2005). Furthermore, vulnerability to heat was found to be directly related to housing deterioration and dilapidation in a study done in New York (Klein Rosenthal et al., 2014). Another correlation of heat vulnerability with building insulation was found in a study of a 2003 French heat wave which enforced the idea that lower insulation meant higher temperatures indoors during extreme heat events (Vandentorren et al., 2006).

2.2.1.2 Body Response

Our response to rising temperatures differs from one person to another and is related to several adaptation methods, as well as our surroundings. Some responses can be considered active, behavioral responses, which can include opening windows, removing layers of clothing, turning on the air conditioning or fans, or in some cases can even be heading to the nearest location with active air conditioning such as a cooling center, and others can be considered passive, as our body thermoregulates our temperatures unconsciously in different methods. Research by (Bayomi et al., 2021) mentions the term "Adaptive Capacity" which is a term referring to the ability of humans to respond and mitigate exposure to high temperatures through different actions. Some of these actions are physiological, which our body will control, psychological, which is determined by our perception of the heat and previous experiences and the final is behavioral which is mentioned previously.

Another aspect to observe is the capacity a community must adapt to extreme heat events. This depends on the availability of resources to them (Mallen, 2019). Indicators of a lower socioeconomic status are usually accompanied with vulnerability to rising temperatures and climate change more so than other groups (Mallen, 2019; Mavrogianni et al., 2015; Widerynski et al., 2017). Some of these indicators include income, race, and education levels (Widerynski et al., 2017). In communities with lower socioeconomic statuses, homes are either very old and aren't performing at peak, or people cannot afford to own the homes and instead are living in rented spaces which limits the amount of adaptability they have and forces them to rely on the landlord to implement heat mitigating features. This means that those within these communities, who are the most vulnerable, are also the ones who are exposed most (Mallen, 2019).

2.2.2 Health

Heatwaves form a serious public health threat, especially in vulnerable groups including children, older people, those with chronic health conditions, and poor or underserved communities (Ahima, 2020; Mayrhuber et al., 2018). The impacts of heat waves on human health are widely documented along with the relationship to mortalities. Biophysical hazards such as air pollution, heat stress, and public health problems all occur due to heatwaves.

According to the CDC's Morbidity and Mortality Weekly Report of June 19, 2020, in between the periods of 2004-2018 data collected concluded that annually 702 heat-related deaths occurred in the United States (Vaidyanathan et al., 2020). For the country, annual heat-related deaths may increase by 28,000–34,000 additional deaths by mid-century (Voorhees et al., 2011). One study finds that heat-related mortality could increase by as much as 95% by 2050 in the New York region without proper risk mitigation steps (Knowlton et al., 2007).

Heat exposure can often lead to heat stress, which is defined as a "*physiological state when the human body es exposed to thermal conditions beyond thermal comfort and consequently affects essential body functions*" (Bayomi et al., 2021). The body begins to experience heat stress when it is at risk of overheating which can affect how the body thermoregulates. Thermoregulation is the method by which our body regulates its temperature (Ahima, 2020). Our body's core temperature fluctuates constantly, and the hypothalamus oversees the maintenance of the average core temperature of 37°C, however if the body's temperature exceeds 42°C then it becomes at risk of hyperthermia which can be fatal. In hot environments our body can lose heat through our skin, or through sweating and constant exposure can lead to lower levels of water. This will cause heat cramps and later heat exhaustion. Symptoms can include excessive sweating, headaches, dizziness, irritability, nausea and vomiting, and thirst and finally heat exhaustion can develop into heat stroke which is when the body fails at regulating the temperature and emergency measures need to be taken (Ahima, 2020; Mallen, 2019).

While all populations are at risk from heat-related illness, there is a disproportionate effect on certain populations more than others. This includes those who do not have access to air conditioning, older adults, younger children, people who work outdoors, athletes, socially isolated people, minority groups and people who have existing health conditions (Widerynski et al., 2017). Some components of vulnerability that have been shown to influence heat-related morbidity and mortality and can be useful predictors of heat risk are sensitivity, exposure, and adaptive capacity (Eisenman et al., 2016; Mallen et al., 2019; Widerynski et al., 2017).

2.2.3 Comfort

Thermal comfort is defined as “*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*” - (American Society of Heating, 1992). Some factors affecting thermal comfort which have been mentioned previously include internal and external variables. Internal variables such as our body’s ability to regulate temperatures and external include our environment.

Temperature (˚F)

Relative humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Heat index

Likelihood of heat disorders with prolonged exposure or strenuous activity

Caution | Extreme caution | Danger | Extreme danger

Figure 1 - (National Oceanic and Atmospheric Administration National Weather Service, 2018)**. – [The National Weather Service Heat Index]**

The National Weather Service is a heat index that reports how it “feels”, so when health warnings are issued, they are based on the temperature that it feels instead of the actual measured temperature because of the relationship between humidity and temperature. Warnings for extreme heat are based on 2 consecutive days of the heat index being 105°F-110°F (40° C - 43° C) (Ahima, 2020).

2.3 Heat Vulnerability

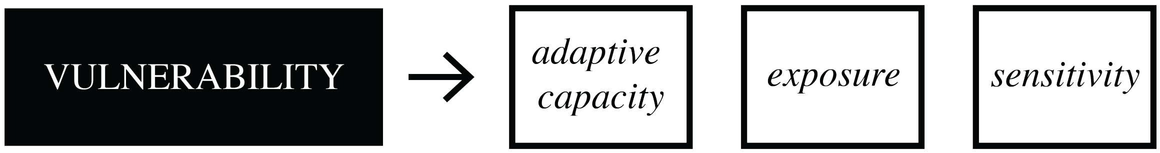

Figure 2 – (Widerynski et al., 2017)**. - [characteristics affecting heat vulnerability]**

According to the Third National Climate Assessment (2014), vulnerability is defined as "*a function of the character, magnitude, and rate of climate variations to which a system is exposed, its sensitivity, and its adaptive capacity*" (Bierbaum et al., 2014). This section will discuss the literature which has explored characteristics affecting heat vulnerability. Those include sensitivity of a population to the different health impacts accompanying heat exposure, exposure to high temperatures, and the capacity of a population to adapt and reduce exposure to high levels of heat which includes its ability to prepare, respond and cope with heat.

2.3.1 Sensitivity

Heat sensitivity is determined partly by biological traits such as health status and age. We can observe in the Morbidity and Mortality Weekly Report of June 19, 2020, that the CDC has collected that heat-related deaths are affected by age (Table 1). We can deduct from Table 1 that the age groups under 1 and those 75 and older are the most vulnerable to heat-related mortalities. Elderly populations are usually at more risk to the effects of extreme heat as well as infants (Mallen, 2019; Vaidyanathan et al., 2020; Vargo et al., 2016b) and this is due to their immature immune systems (Gamble et al., 2016).

Table 1 - Number and rate of heat-related deaths by age group – United States, 2004-2018.

Age Group	All Heat Related Deaths*
<1	247 (0.4)
1-4	428 (0.0)
5-14	73 (0.0)
15-24	328 (0.0)
25-34	660 (0.1)
35-44	1022 (0.2)
45-54	1774 (0.3)
55-64	1919 (0.3)
65-74	1636 (0.4)
75-84	1435 (0.7)
≥85	948 (1.1)

*Crude rate per 100,000 population.

Note. (Adapted from (Vaidyanathan et al., 2020))

Social isolation, race and ethnicity, income, and educational attainment (Widerynski et al., 2017), as well as preexisting health conditions, and physiological ability to adapt to high temperatures are all factors affecting the sensitivity of an individual to heat.

Table 2 - CDC Social Vulnerability Index (SVI) Themes and Variables

SVI Theme	**Variables Included**
Socioeconomic Status	% Below Poverty Level % Unemployed Per Capita Income % Age 25 or Older with No High School Diploma
Household composition and disability	% Age 65 or Older % Age 17 or Younger % Single Parent Household
Minority status and language	% Minority % Age 5 or Older Speak English "Less than Well" _

Table 2 - Continued

Housing and transportation	% Multi-Unit Structures % Mobile Homes % Crowding (More people than rooms) % Households without a Vehicle % In Institutionalized Group Quarters

Note. (Adapted from (Lehnert et al., 2020)

(Lehnert et al., 2020) has shown a relationship between highly vulnerable communities and visits to the Emergency Room (ER) for heat related illnesses based on the CDC's social vulnerability index. The rates of visits to the ER significantly increased by a factor of 1.18 with each 10% increase in the SVI ranking. The Social Vulnerability Index (SVI) is an index by the CDC based on values associated with heat-related visits to the ER and mortality rates in Georgia. The CDC's SVI looks at themes such as socioeconomic status, household composition and disability, minority status and language, and housing and transportation with multiple different variables such as those listed in Table 2. We can see that while there are variables affecting vulnerability that are physical, there are also many more that are social. High social vulnerability is associated with multiple variables such as income, employment, race and ethnicity, housing types, levels of urbanization and population density even. When an individual or community is considered to have a high SVI, this also puts them at risk for heat related illnesses as well, so sensitivity is not only tied to physical health. To conclude, mitigation strategies should consider multiple factors affecting sub-populations in different regions. Where education might make all the difference with one group, policy or financial aid may be necessary with another.

2.3.2 Exposure

Factors that affect exposure include many of the previous variables mentioned which affect the sensitivity but, this section will discuss the climate and external factors such as geographic location, level of urbanization, vegetation, and infrastructure condition.

Figure 2 is a satellite image of urban Atlanta, Georgia, on the left and a thermal image on the right on September 28^{th}, 2000. It shows that the areas which are more heavily urbanized are in red in the thermal image which indicates higher temperatures. The materials in urban infrastructure absorb heat during the day and release it later in the day increasing the temperatures and exposing residents to higher temperatures than those in areas which are vegetated more. This effect is the Urban Heat Island, and the images show that it is worse closer to the urban core, or when the vegetation levels are lower. Tree canopies and green spaces can help facilitate evapotranspiration, which dissipates heat cooling down areas (Widerynski et al., 2017).

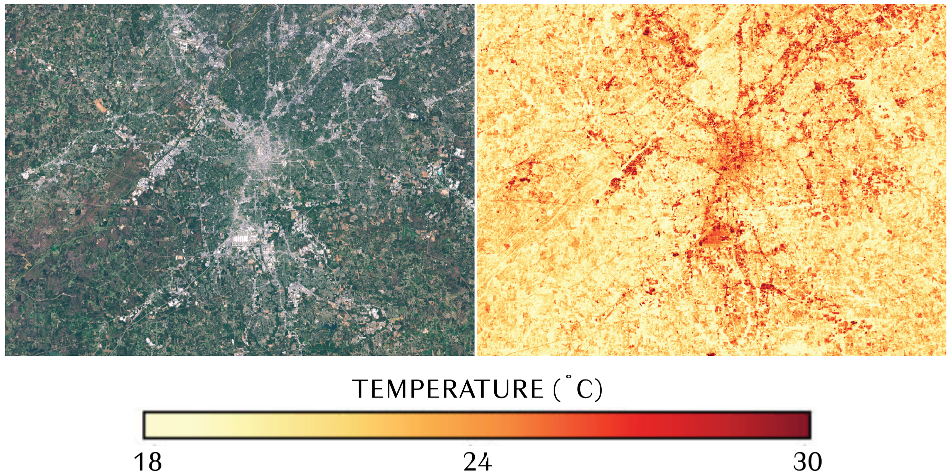

Figure 3 – (Jentoft-Nilsen, 2006)**. - [The images illustrate satellite images of Atlanta on September 28, 2000. Surface temperature (right) shows the urban heat island, with the red representing hotter areas. NASA images by Marit Jentoft-Nilsen, based on Landsat-7 data]**

Table 3 shows that race, and levels of urbanization are correlated to the number or heat-related deaths based on the Morbidity and Mortality Weekly Report (MMWR) by the Center for Disease Control and Prevention (CDC) for June 19, 2020, (Vaidyanathan et al., 2020).

Table 3 - Number and rate of heat-related deaths.

Characteristic	No. of deaths(rate)*
Race/ethnicity	
Hispanic	1349 (0.2)
Black, non-Hispanic	1965 (0.3)
White, non-Hispanic	6602 (0.2)
Other	611
Level of Urbanization	
Large central metro	4402 (0.3)
Large fringe metro	1607 (0.1)
Medium metro	1764 (0.2)
Small metro	990 (0.2)
Other	1764

*Crude rate per 100,000 population.

Note. (Adapted from (Vaidyanathan et al., 2020)

2.3.3 Adaptive Capacity

The definition of adaptive capacity according to the International Panel on Climate Change (IPCC) "*is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*" (Intergovernmental Panel on Climate Change & Working Group II, 2001). The system mentioned in the definition can refer to government infrastructures, civil society, institutions, or social capital in community networks (Widerynski et al., 2017).

The ability of a community to respond to climate change can depend on social, political, and economic factors. These factors affect the resources being invested in communities to equip them for quicker and effective responses to climate change such as extreme heat. The main method for reducing vulnerability of a community to climate change would be through investments in adaptive infrastructure, which is expensive. This leaves out rural or poorer and minority communities to remain more susceptible to the impacts of heat exposure (Intergovernmental Panel on Climate Change & Working Group II, 2001). An example would be of a community living in deteriorating infrastructures due to limited economic sources.

Furthermore, race and income are contributors to social isolation, poor housing quality and lack of air conditioning which all increase the risk associated with extreme heat and decrease the capacity of such communities to adapt increasing their vulnerability. Some more factors affecting adaptive capacity include "*socioeconomic status, the condition and accessibility of infrastructure, the accessibility of health care, certain demographic characteristics, human and social capital (the skills, knowledge, experience, and social cohesion of a community), and other institutional resources*" (Bierbaum et al., 2014).

Heat stress is experienced by many people in their buildings due to the lack of cooling methods available to them. In vulnerable communities this can look like a lack of access to functioning air conditioning, or not having the means to pay the bills for running the air conditioning during periods of excessive heat exposure

2.4 Atlanta and Vulnerability

The average temperatures in the Southeastern United States have been increasing since the 1970s, including Georgia. This increases the chance of more intense heatwaves occurring in the future (KC et al., 2015). Atlanta, specifically, has developed an increased urban heat island over the past few decades due to growth and urbanization (Vargo et al., 2016b). A study by National Geographic predicts that by 2050 Atlanta will have a total of 104 dangerous days per year (Stephen Leahy, 2019). The term dangerous here refers to the National Weather Service (NWS) heat index above 90°F (National Oceanic and Atmospheric Administration National Weather Service, 2018). According to Zhou & Shepherd (2010), Atlanta's heat waves can last 14.18 days, with a mean maximum temperature of 35.86°C (96.55°F, based on criteria collected from 1984-2007) with the mean number of heat waves occurring in the summer being 1.83 (Zhou & Shepherd, 2010). Fulton County alone could experience an average of 54 days per year with a heat index above 105°F which is considered dangerous per the NWS heat index (Figure 4).

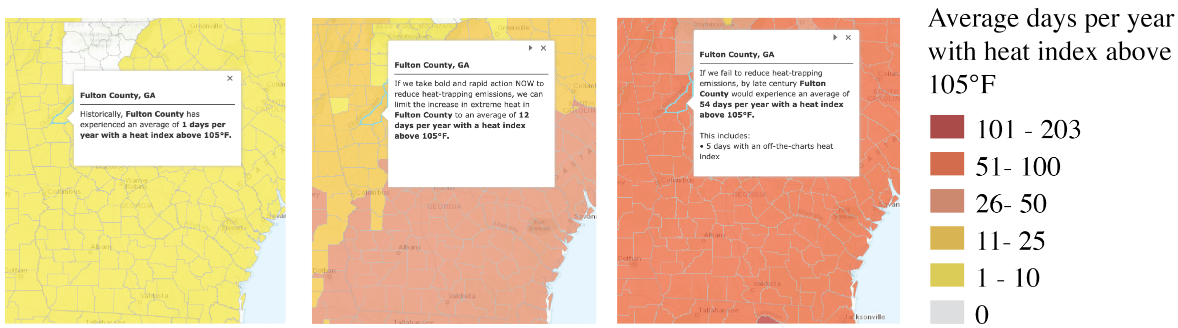

Figure 4 – [Number of Days with a heat index above 105F - Historic Model (left), with no action to reduce emissions (center), and with rapid action(right)] Source: (Dahl et al., 2019)

A study by Vargo et. al. (2016b) has identified that some urban heat management strategies have a larger effect on mortality rates in low incomes groups in Atlanta. This is because lower income populations are more concentrated within the high-density areas in Atlanta (Vargo et al., 2016b). One neighborhood with such qualities is the Grove Park Neighborhood in Atlanta, Georgia. With a population of black individuals three times higher than Atlanta (96%), most residents between the ages of 15-24 or 65+, more than half the residents having incomes less than $25,000 (Lombard et al., 2018).

Figure 5 overlays the outline of the grove park neighborhood onto a map of the spatial distribution of the composite vulnerability index score in metro Atlanta. Grove Park neighborhood is in the 75th percentile or greater of the index, indicating how vulnerable it is considered relatively. The composite heat vulnerability index score is an index used by Manangan et al., (2014a) to determine how vulnerable a location is to heat based on a combination of sensitivity factors, historic heat exposure, and hospital insufficiency.

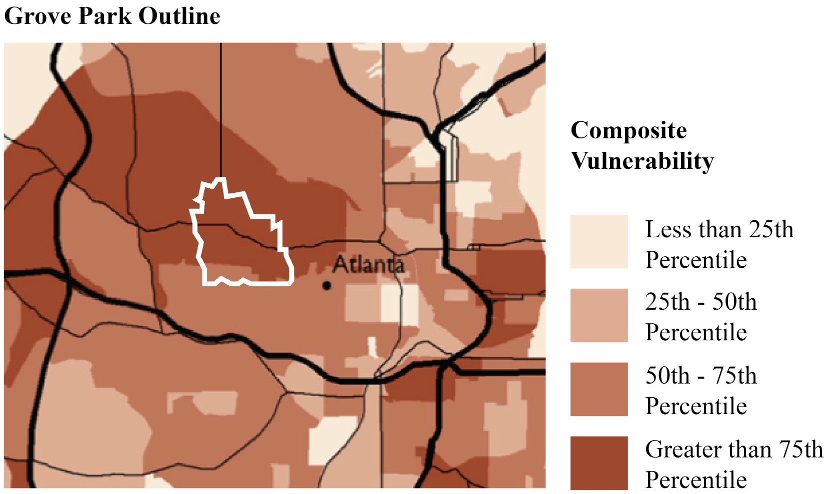

Figure 5 – (Ponce Manangan et al., 2014a)**. [Spatial distribution of composite vulnerability index score in metro Atlanta (left) and grove park neighborhood location, right].**

2.5 Existing Mitigation Strategies

It should be noted that various community-based adaptation measures for heat-health already exist or are being developed in many areas such as: neighborhood cooling centers or outdoor water-mist stations, vulnerable population relocation plans, heat-health alert services (Farnham, Emura, & Mizuno, 2015; Mavrogianni, Taylor, Davies, Thoua, & Kolm- Murray, 2015; PHE, 2014; PlaNYC, 2013).

Some programs which focus on community responses to extreme heat include New York's "Be-A-Buddy Program" (Bock et al., 2021), Chicago's Climate Action Plan (City of Chicago, 2008), Wisconsin's extreme heat toolkit and climate 101 training

(Department of Health, 2019), and finally Atlanta's local climate action and resiliency plans with the NIHHIS (National Integrated Heat Health Information System) and CAPA Strategies Organization. These are all examples of community-based programs that help the population better recover from extreme heat events.

In New York resiliency is promoted through outreach efforts to vulnerable populations. An example is the "be-a-buddy" program which shares information with vulnerable residents. This program is developed to help keep residents safe during extreme heat events. The program developed and tested strategies for protecting at risk New Yorkers from the health impacts of extreme heat in heat-vulnerable areas. The program was successfully piloted by The POINT CDC, a community organization in the Bronx during a heat wave event in summer 2019 and was able to reach 500 people. The goal was to spread the program through other vulnerable communities but currently there is no funding (Bock et al., 2021).

Chicago has identified urban heat island hotspots to target reduction strategies such as green infrastructure, reflective roofing, and rooftop gardens. A task force was created to identify 2 actions for mitigating greenhouse gas emissions and nine actions to prepare for climate change (City of Chicago, 2008).

The Minnesota Department of Health (MDH) established a team to conduct a vulnerability assessment for the state of Minnesota in 2014. The team mapped how vulnerable the population was to climate change for each county. In 2019, the MDH later published an “extreme heat tip sheet” which serves as a guide to educate about extreme heat exposure and strategies to avoid it or identify it (Department of Health, 2014).

In Atlanta, The Spelman College Environmental and Health Sciences Program is also working alongside Georgia Tech and many others including Emory University, West Watershed Alliance, National Weather Service, The City of Atlanta, Atlanta-Fulton County Emergency Management Agency, and the DeKalb County Emergency Management Agency on an Atlanta Heat Watch Campaign. The Urban Climate lab at Georgia Tech focuses on collecting thermal data in urban areas in the urban core. These groups are all working together with the CAPA Strategies organization and the NIHHIS to produce information that can support Landsat imaging of the city that indicates record levels of urban heat island and increased temperatures throughout the city. They have measured and mapped the spatial pattern of heat risk with more precision than prior work in Atlanta. They also aim to document how heat risk and aspects of population vulnerability align with vulnerability to climate change. Their overall goal is to develop local climate action and resiliency plans in the long term (Spelman College, 2021).

CHAPTER 3. METHODOLOGY

An objective of this study was to investigate the increased vulnerability of an underrepresented community to extreme heat. The case of the Grove Park neighborhood in Atlanta demonstrates this investigation. While a variety of definitions of heat vulnerability have been suggested, this paper will refer to it as a combination of adaptive capacity, sensitivity, and exposure (Widerynski et al., 2017).

3.1 Experiment Goals & Objectives

This study uses a case study approach to investigate five main objectives. These objectives include:

1) Identification of a vulnerable community for the case study investigation.
2) Collection of demographic data and geographic data from existing databases.
3) Analysis of the data through modeling and simulation software and interpretive techniques.
4) Identification and description of heat vulnerabilities in the community using deductive reasoning.
5) Responses to community vulnerabilities with actionable strategies.

Both qualitative and quantitative data collection methods were employed in this investigation. Some important categories considered in data collection include:

- Geographic area of interest.

- Features and characteristics in the built environment which improve or reduce community resiliency to extreme heat.
- Members of the community, and their experiential data, availability of resources.
- Possible sources of data.
- Analysis methods to investigate heat vulnerability in communities.
- Metrics needed to determine heat vulnerability.

The following part of this chapter moves on to describe in greater detail the methods used to collect the data, analyze, and evaluate the data, and respond to the results.

3.2 Experiment Design

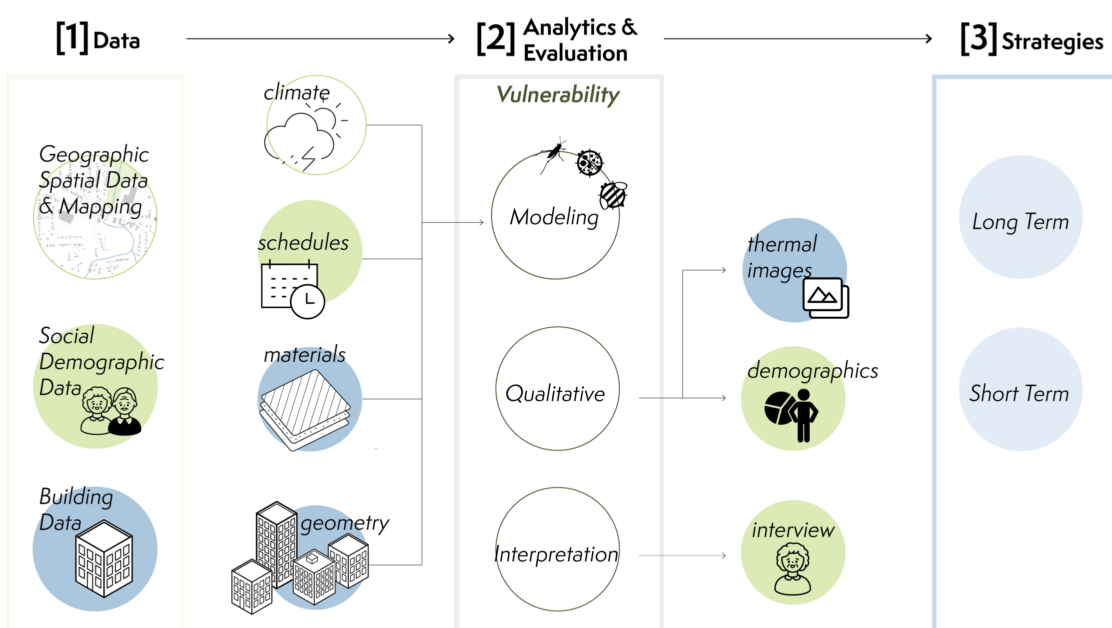

Figure 6 - Research workflow

Figure 6 presents an overview of the research workflow as follows:

The first step in this workflow is the data collection and categorization. Three main categories classify this data:

1) Geographic spatial data and mapping. The data are collected from existing databases such as 'Google Maps', 'CADMAPPER'. This also includes climate specific data collected from online resource 'Climate.OneBuilding'.
2) Social demographic and experiential data. The demographic data are collected via existing online sources and the experiential data via a semi-structured resident interview. This included resident behavioral details which informed occupancy times, lighting and equipment information used later in the analysis phase.
3) Building geometry data. This is data relating to physical characteristics of the building assessed. Including material information, measurements of the interior and the exterior, and building age and deterioration through thermal imaging. The data are collected through interrogative, observational, and qualitative techniques.

This phase includes site selection and identification of a candidate for interviewing. The address of the resident will remain private, but a specific location is selected for the following phase.

Following the data collection step, the analysis and evaluation were then performed. The first step of this phase included using 3D modeling software 'Rhinoceros' to represent the geometry of the home selected previously. Next, employing the geographic spatial and the building geometry data, a simulation is run to represent thermal data at a specific time of the year using the 'Ladybug' and 'Honeybee' plugins for the parametric modelling tool in 'Rhino' called 'Grasshopper'. The information from the thermal simulation is then applied to generate and visualize thermal maps that are interpreted to inform human comfort metrics.

Using deductive reasoning, the previous metrics, together with the data collected regarding demographics is then used to evaluate heat vulnerability. This is a process which will infer based on the previous literature studied, the data collected, and the observed results of the simulation.

Finally, the research concludes with strategies responding to the results of the previous phase. This is approached through two main parts:

1) Long-term strategies.
2) short-term strategies.

3.3 These will be discussed further in Chapter 4: 4.2 Response Strategies

.

It is important to note at this point that this workflow is based on the adoption of Widerynski et al.'s definition of heat vulnerability to include adaptive capacity, sensitivity, and exposure (Widerynski et al., 2017). Within the workflow, there is a secondary structure that focuses on defining heat vulnerability based on this definition. The research will support each of the three characteristics mentioned above and is discussed in detail in Chapter 4: Results.

3.3.1 Data Collection

To identify the correct sources for the data, an area of interest has been determined for the case study. Grove Park was selected for the study and is considered vulnerable due to the following observations. The first is based on a study by (Ponce Manangan et al., 2014b) which establishes a composite vulnerability score for the city of Atlanta. In Figure 7, the first image from the left displays an outline of the area considered to be within the 75th percentile of vulnerability. The second displays an outline of the Neighborhood Planning Unit J (NPU-J) which is in the closest proximity to the previous outlined area. The third is an image of the historically redlined and yellow lined areas in Atlanta within the vicinity of the previous images. Lastly, the Grove Park Neighborhood is outlined because it is the largest neighborhood falling under all the previous categories and serves as an example of one community which is, at first glance, is considered vulnerable. With the area of interest determined, geographic spatial data is collected, and the site of interest is mapped.

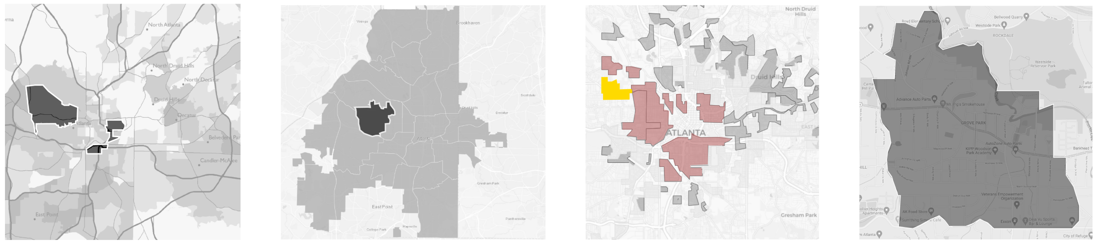

Figure 7 – Maps displaying the criteria used to select grove park neighborhood as a case study. (From left to right) An outline of the area near Atlanta with a composite vulnerability index above the 75th percentile (Ponce Hannagan et al., 2014b)**, an outline of the Neighborhood Planning Unit (NPU) J, outlines displaying historically red and yellow-lined areas around Atlanta, the outline of Grove Park Neighborhood.**

Figure 8 – The area of interest based on Figure 7: Grove Park Neighborhood.

The final section of data collection included the building geometry. Building physical characteristics, material information, measurements of the interior and the exterior, and building age and deterioration through thermal imaging were collected and used to build a 3D model discussed further in this chapter. The model was calibrated based on investigative, observational, and qualitative techniques. This included a physical investigation of the interior and exterior of the building which encompassed thermal imaging, photographic RGB imaging, and taking measurements.

3.4 Analysis & Evaluation

To first analyze then evaluate the data collected from the previous section, three main approaches were developed. The following section will discuss these approaches in detail.

3.4.1 Modelling

Modelling is the initial approach for the analysis portion. The first step in this process was to construct a model using 3D modelling software 'Rhinoceros' based on the previous data collected. This includes dimensions of the exterior and the interior of the building, information regarding the materials, and occupancy information.

On the north side of the house, moving from the west to east is the kitchen, dining room, and living room. Similarly, on the southern side of the house is the guest bedroom, corridor and bathroom, the bedroom, and the study area. There are closed doors between the guest bedroom and the corridor, and between the study area and living room only. The rest of the house has either open doors or no doors. You can see this modelled in Figure 9.

The next step is to assign the thermal zones. Thermal zones are air volumes at a "*uniform temperature plus heat transfer and storage all bounded inside of that volume*" (Solar Cormorant, 2018). The interior spaces have been modelled based on images taken inside the home previously. Figure 9 shows the plan of the home, with each thermal zone labeled in a number and color assigned based on the program. (1. Kitchen 2. Living room 3. Guest room 4. Services 5. Bedroom 6. Study). The geometry has been validated based on the home before the simulation runs. The next step of the process included material assignment to each surface in the model.

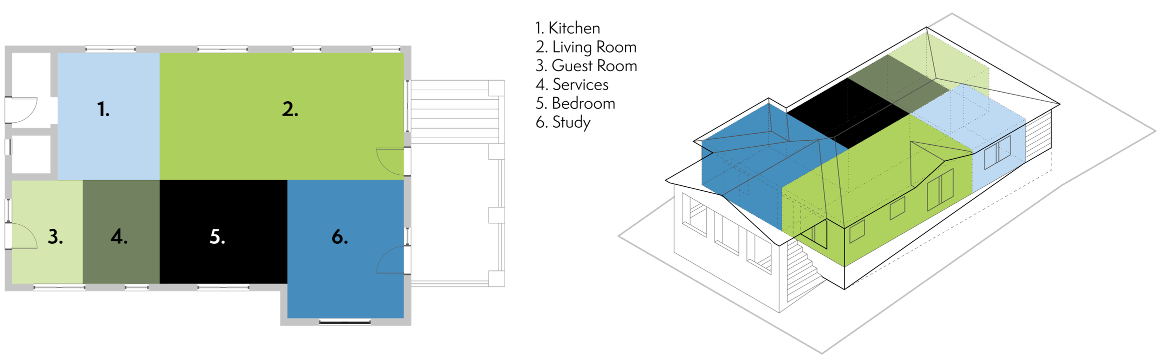

Figure 9 - Plan of the home used to run comfort analysis displaying thermal zones and their programs (top) and orthographic 3D view of the modelled home.

Once the physical model is complete, the materials are assigned. This is done through the environmental analysis plug-ins for 'Grasshopper' called 'Ladybug' and 'Honeybee'. Ladybug connects the geometries in 'Rhinoceros' and 'Grasshopper' with open-source weather data from ‘EnergyPlus’ files (referenced file: https://climate.onebuilding.org/WMO_Region_4_North_and_Central_America/USA_United_States_of_America/GA_Georgia/USA_GA_Atlanta-Fulton.County.AP-Brown.Field.722195_TMYx.2004-2018.zip) and creates climate analysis graphics. ‘Honeybee’ connects ‘Rhinoceros’ geometry and ‘Grasshopper’ functionality to energy modeling and simulation programs such as EnergyPlus (Baker Lighting Lab, 2021; Ladybug Tools LLC, 2018). Honeybee contains a library with materials based on existing standards, construction periods, and location. Generic materials are assigned to the model however, some of the materials in the existing ‘Ladybug’ database need to be modified to make custom materials to resemble the case study as accurately as possible. Table 4 displays the custom materials with their corresponding R-values.

Table 4 – Materials and their R-values used to run Honeybee simulation for comfort analysis.

Construction Material	R-values (H*ft2*F/btu)
Single Pane Window (clear 3mm)	0.018928
12” Brick Wall	1.994648
Attic Roof	0.337336
Interior Floor (insulation R2.37 + ½" gypsum)	3.918184
Exterior Wood Siding (wood siding + Insulation R0.73)	2.866111
Interior Ceiling (insulation R2.37+ ½” gypsum)	12.088468
Plywood	0.277362

Once the model has been built and the materials assigned, the next step includes details regarding the weather file selected. This is an EnergyPlus Weather Format (.epw) file which the grasshopper script references when running the simulation and ensures that the results obtained when running the simulation are location specific. The airport collecting and reporting the information that makes up the EPW file is the Fulton County airport, located just outside the Atlanta city limits. The weather file is critical for the simulation. There are two main weather files that are used in the simulation. The first is the TMYx 2004-2018 file which is a file containing typical meteorological data derived from hourly weather data through 2018. The second file is a morphed file predicting climate data for the year 2080 which has been generated using the 'Climate Change World Weather File Generator' (CCWorldWeatherGen) which is 'Microsoft Excel' based and transforms weather files into future weather files to use in building performance simulations (Jentsch et al., 2013). This allows for the understanding of the implications of climate change on the current built environment.

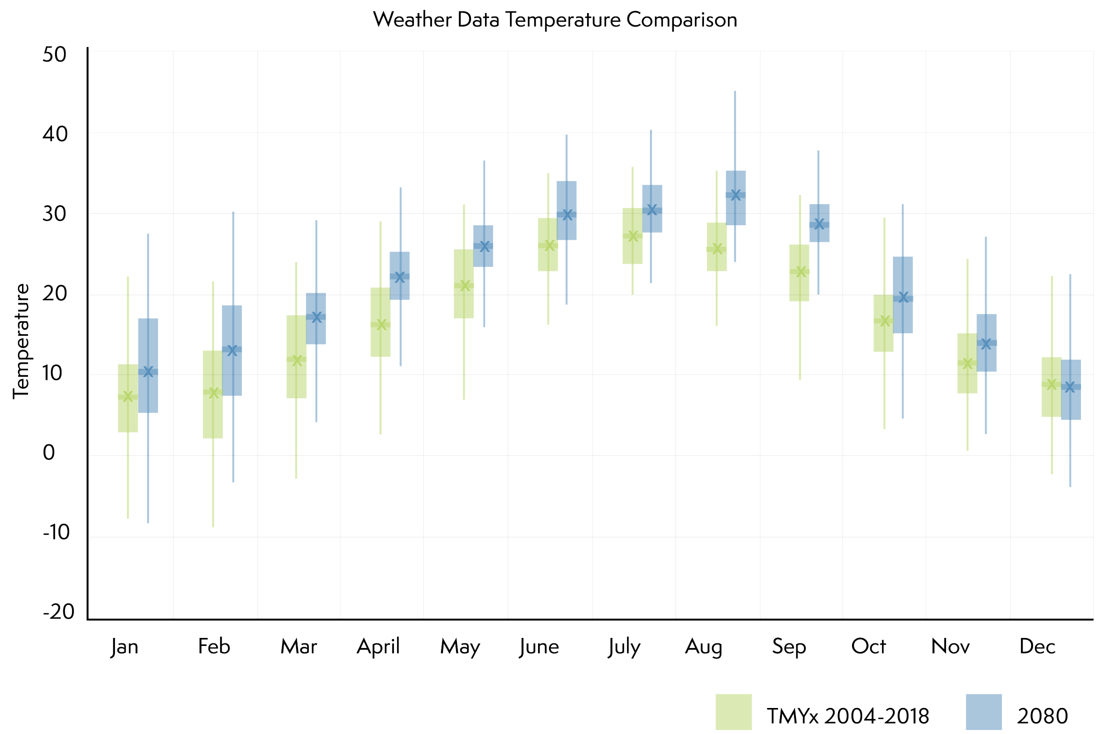

Figure 10 – Box and Whisker chart displaying the difference in temperatures between the current TMYx 2004-2018 EPW file (green) and the 2080 EPW file (blue) (Fulton County Airport – Brown Field (FTY), Atlanta, GA).

Using 'CCWorldWeatherGen' the weather file is morphed into a future (2080) predicted EPW and the file is plugged into the 'Grasshopper' script to run.

The next portion of this chapter discusses the evaluation aspect in the workflow. The model constructed contains building geometry, thermal zones, materials, and climate information. However, to construct an accurate model representing the building that is being studied, there is one more piece of information that will further increase the accuracy of the results. This information includes behavioral data that has been collected prior to constructing the model in the software throughout the data collection phase. This data has been collected through an interview with the resident involving details of their activity throughout the different spaces in the home. This informed occupancy times, lighting, and equipment information has been input into the grasshopper script through a scheduling component which allows customization for different parts of the day, different days of the weak and, for each season of the year. This part of the modelling process allows supports accurate results.

Furthermore, since heat waves only occur during the hot summer season, an analysis period is added as a parameter for the model. Based on the study by Zhou & Shepherd, historically (1991-2007), Atlanta heat waves have occurred throughout the months of June, July, and August (Zhou & Shepherd, 2010). The period selected for the simulation was between August 1^{st} at 1:00 until August 31^{st} at 24:00.

Finally, the simulation is run, and thermal data is available for the case study. The final step is to visualize the results as thermal heat maps. Four main thermal maps are visualized to better understand thermal comfort. These are:

1) Mean Radiant Temperature (MRT). The MRT is defined as "*the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual nonuniform enclosure*" (Thorsson et al., 2007). Comfort is affected by gaining heat from a warm surface or losing heat to a cold surface. This depends on the strength of heat or cold from surfaces and this will affect our comfort because we experience a net heat gain or loss. For example, we can experience cold standing next to an open fridge on a hot day. This difference in the heat energy is the MRT (H. Li, 2016).

2) Average Air Temperature (AAT). This is the temperature indicated by a thermometer. The ambient air temperature is the same as the current air temperature in any one location.
3) Adaptive Comfort Model (ACM) (Brager & de Dear, 2001) The adaptive comfort model is based on a survey conducted in the oil field about thermal comfort and reveals that the thermal comfort temperature is a function relating to the outdoor air temperature (Yao et al., 2009). This model applies to naturally ventilated environments and considers outdoor temperatures and corresponds them to indoor comfort (Brager & de Dear, 2001).
4) Predicted Mean Vote (PMV) The PMV model is calculated with MRT and air temperature, along with the metabolic rate, clothing insulation, air speed, and humidity (Fanger, 1986). This method considers the combined effect of these factors on thermal comfort and seeks to capture people's responses to the thermal environment in terms of the physics and physiology of heat transfer (Yao et al., 2009).

3.4.2 Interpretative Methods

The second portion of analysis is an interpretation of two methods of data collection. The first is of the interview conducted with the resident of the building studied. A series of open-ended questions were asked to collect behavioral information regarding the occupancy of the resident. Based on these results, schedules were made to represent times of occupancy, lighting use, and equipment use. These schedules were later input into the 'Grasshopper' script to perform a thermal simulation on the home with accuracy. This schedule is a list of the fractional numbers representing values per square meter. Based on occupant habits throughout the week, schedules have been constructed for the bedroom, living room and kitchen.

When interviewing the resident, information was collected about the current state of the residence. This included any negative experiences the resident had while occupying the space during warmer parts of the year. A particularly important piece of information was regarding the amount of daylight entering the spaces. Due to residents' personal preferences the blinds are never open. In fact, many of the blinds are pinned to each other to reduce the amount of light entering the space. Upon further questioning, it was noted that the resident was uncomfortable opening them due to privacy. This was an indication that there is a decrease in the amount of sunlight entering the space, increasing the need for the lights to constantly be switched on. However, during the hotter summer months, heat was still entering the space and being trapped, causing even higher indoor temperatures.

Based on information interpreted from the resident, the building is unoccupied between the times of 8am and 4pm every day. Most of their time during the day is spent at the study and bedroom (Figure 9). All the light bulbs were recently changed by Georgia Power to LED lights, decreasing the lighting power density of the home. Regarding the equipment power density, during the summer electric fans are used, and during the winter electric heaters are used in both the study and living room areas. This increased the amount of energy used, increasing the cost of the monthly electricity bill considerably compared to common single family residential homes. This is a monthly cost which could be put towards use for air conditioning and heat which are more efficient and safer. There is a standalone air conditioning unit that does not work between the bedroom and the guest bedroom which raises the concern for temperature regulation throughout the hotter months. There are also three AC single units installed in the windows that either aren't used or don't work.

The only occupant of the home is the single resident, with no other occupancy to consider. However, it was mentioned that the programs most occupied throughout the home were the bedroom, the living room, and the kitchen. Based on this information, the 'Grasshopper' script was constructed around the data collected for these occupied programs specifically.

Based on the previous information, Figure 11 shows the schedules used in the 'Grasshopper' script. The y axis displays the load and is in watts per square meter, this is a fractional number representing the amount of light, equipment load, or occupants per square meter of the space. The x axis represents the time of day and runs from 1 to 24 hours in a day. These are the annual schedules for the bedroom, kitchen, and living rooms (reference Figure 9).

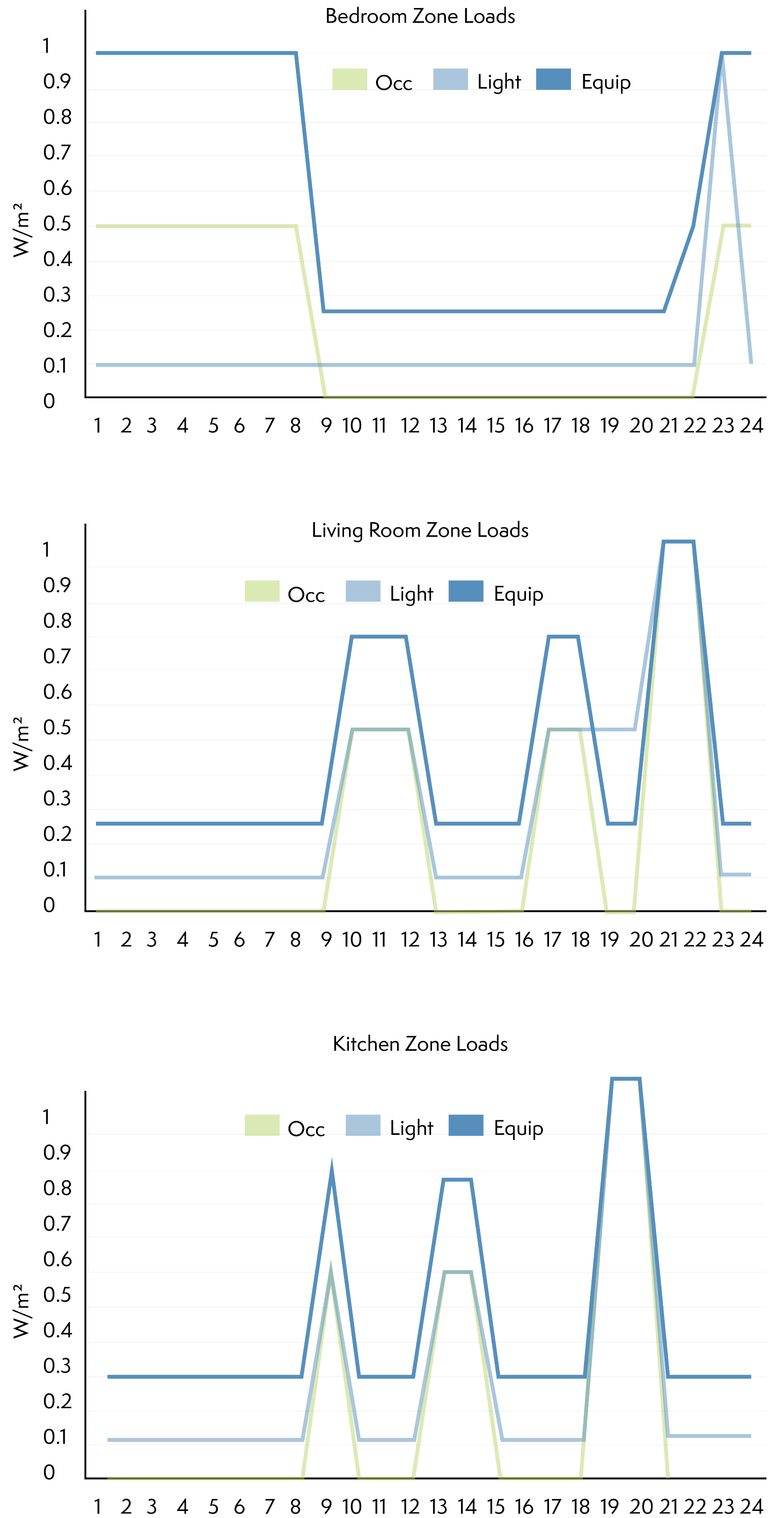

Figure 11 – Bedroom occupancy schedule, lighting, and equipment loads (top), living room occupancy schedule, lighting, and equipment loads (center), and kitchen occupancy schedule, lighting, and equipment loads (bottom).

Figure 12 – Images of the exterior conditions of the home

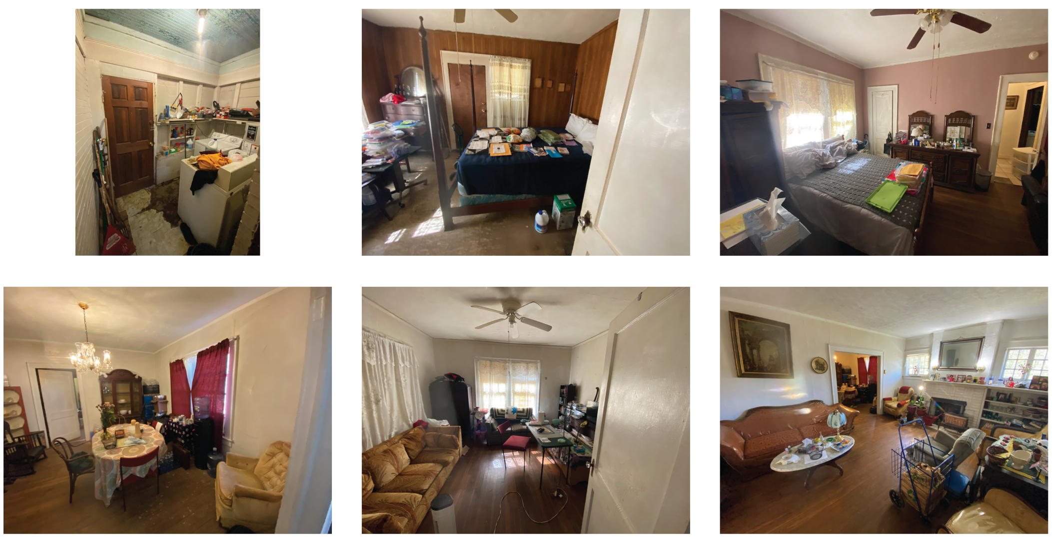

Figure 13 – Images of the interior conditions of the home

The second method of data collection is through RGB photography. The images are collected using a phone camera. The photographs of the house reveal several conditions:

- The brick façade was previously painted white, but this has peeled off in different areas.
- The roof is free from any defects and appears recently renovated (a fact that was confirmed when speaking with the resident).
- There is a boarded-up window on the west elevation that needs to be addressed.
- The interior view of the kitchen reveals poor natural lighting in the space.

3.5 Constraints & Limitations

In this investigation there are several sources for error. In particular, the main constraint for this research is the availability of the data. The research focuses on underrepresented communities, which mean the data needed to determine heat vulnerability is not always readily available or easy to locate. There must be an increase in data collection efforts to focus on more marginalized and underrepresented communities. This will make vulnerability assessments easier, and more reliable. It will also increase research efforts that focus on such communities that may be overlooked simply due to the lack of existing data.

Another major source of uncertainty is in the method used to collect the information from the resident. Conducting interviews with older residents means that emailing or sending text messages is not a reliable method. At the time this thesis was written, the COVID pandemic had impacted the ability to have in person interviews and other residents could not participate. Therefore, the most reliable alternative method to collecting this data becomes through phone calls, which means more outreach to community leaders to help find willing participants is needed. This process can become lengthy and can increase the timeline of the research, however the benefit to this process is that better and stronger relationships are formed with community members. These relationships can evolve into partnerships in the future and become essential to help the community long term.

Furthermore, an important aspect to consider is the accuracy of the morphed weather file (epw) being used. The file employed in the research has not considered any climate change efforts. Taking measures to reduce the urban heat island effect such as adding vegetation and decreasing heat absorbing materials used in the urban environment can make significant impacts on the overall microclimate of such areas, reducing accuracy of such a study. Moreover, changes in the built environment are inevitable. The study takes a glance into the year 2080 without considering any changes on the building envelope at all. Further research can include implementing design interventions or changes to the home to produce more realistic predictions.

This study considers different categories of data (i.e., demographics, building geometries, climate information, behavioral data, and building performance metric) to determine whether a community is more vulnerable to extreme heat, however, there is much more information which can, and must be included in this kind of research. It is important that the definition of heat vulnerability is not oversimplified, excluding crucial information. While it is difficult to ensure that this research has encompassed all possible interrogation methods, a large effort is made to focus on the residents' experience and the built environmental performance. Moreover, more studies like this one should be done and more comprehensive results can help target more vulnerable communities at larger scales.

In a study such as this one, where the demographic data collected is based on a census tract, it is significant to note that this information may not directly represent the Grove Park community with accuracy. To obtain higher resolution data regarding underserved communities, more work collecting data is required. Obtaining results for one home within a larger community is only the first step to understanding vulnerability regarding extreme heat. To produce more comprehensive results more fieldwork must be completed throughout the neighborhood.

CHAPTER 4. RESULTS

This chapter presents the results to support the hypothesis that the Grove Park neighborhood is more vulnerable to extreme heat due to socioeconomic and building physics characteristics.

4.1 Heat Vulnerability

4.1.1 Adaptive Capacity

In the context of this study, adaptive capacity refers to the ability of a system to cope or adjust to hazardous exposures due to climate change (Ponce Manangan et al., 2014b). In order to measure this, data is used regarding access to health infrastructure (i.e., number of emergency rooms withing 15-mile radius), general demographics (i.e., the percentage of the population above 65, living alone and the percentage of the population below 18 years in the Neighborhood Planning Unit (NPU) J), social demographics (i.e., percentage of civilian non-institutionalized population ages 5 and over with a disability, and percentage of civilian non-institutionalized population ages 65 and over with a disability), economic demographics (i.e., percentage of population below poverty, percentage of population under 18 years below poverty, and percentage of population 65 years and over below poverty), housing demographics (i.e., number of total housing units, number of occupied housing units, number of units built between 1980-1999, and number of units built in 1979 or earlier), number of extreme heat events (defined as the number of events of two consecutive days or more exposed to 90°F temperature or more), policies, and responsive systems in the built environment. This was compiled using data from the National Environmental Public Health Tracking Network for the Fulton County census tract 13121008500 (tract ID 85).

Table 5 shows data specific to census tract ID 85 which encompasses the study area of Grove Park. While the disabilities of the population are not categorized into types, it is assumed that those with any kind of disability are more susceptible to the physical risks associated with heat exposure. All disabilities are considered “riskier” meaning that above 65% of the population is at risk. As previously mentioned in the literature, the ability of then body to thermoregulate is diminished with age. With exposure to heat, the body is put under heat stress and even at younger ages, ability to adapt decreases exposing the body to increased biophysical risks. Since 40% of the population is 65 years or older and 18 years or younger, this decreases the capacity of the community to adapt to extreme heat. According to Georgia Power, on average a family pays $190 a month during the hot seasons for air conditioning. Moreover, since almost 30% of the population is below the poverty line, this clearly limits how much access to air conditioning a low-income household has, if it has any. Out of 6166 total housing units, a large 87.7% or 5404 house were built in 1979 or earlier. People living in older, or less insulated homes are at risk to temperatures increasing beyond outdoor temperatures and this, paired with the inability to use air conditioning (or lack of it), sets up dangerous indoor conditions.

An expansive healthcare infrastructure was also considered to indicate a higher adaptive capacity to cope with the health impacts during extreme heat. However, based on the collected data there are only 5 emergency rooms located within a 15-mile radius of the resident's home.

Table 5 – Census data collected from ID tract 85 related to demographics

Demographics	
Population % >65, living alone	28.3
Population% <18	14.2
Economics	
% Population below poverty	26.7
% Population under 18 years below poverty	48.3
% Population 65 years and over below poverty	11.3
Social	
% Civilian non-institutionalized population ages 5 and over with a disability	23.1
% Civilian non-institutionalized population ages 65 and over with a disability	43.1
Housing	
# Total housing units	6166
# Occupied housing units	3736 (60.6%)
# Units built 1980 to 1999	378 (6.1%)
# Units 1979 or earlier	5404 (87.7%)
Resources	
# Of emergency rooms withing 15-mile radius	5
Exposure	
# Of extreme heat events [1]	40-61

[1] Heat event defined as period of 2 days or more at 90°F or above

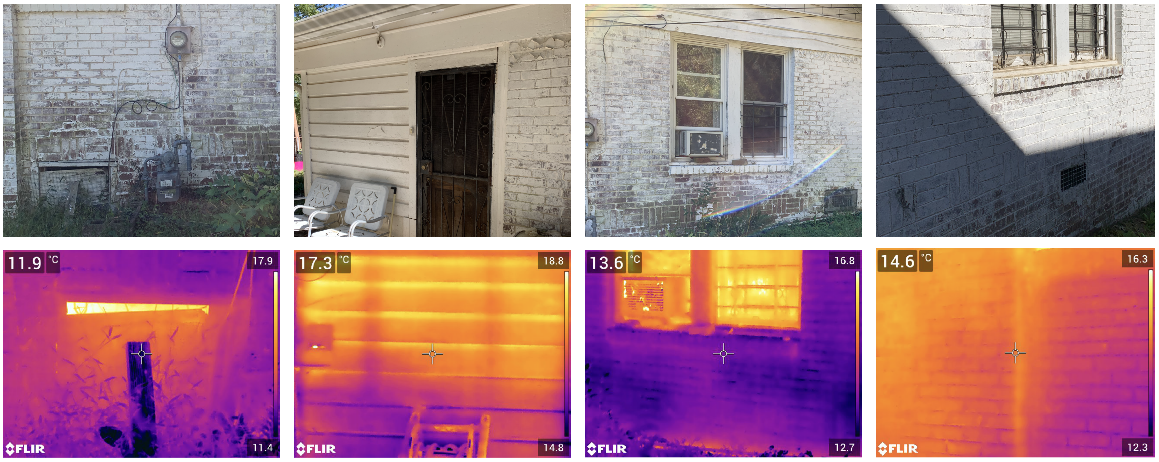

Figure 14 – thermal images of the building envelope

Adaptive capacity encompasses the building physical qualities as well as the communities' resources. The case study was assessed using a 'FLIR' thermal imaging camera and images were collected informing the analysis of the thermal performance of the building envelope.

In Figure 14 several thermal anomalies are observed which indicate bad insulation, gaps where air can escape the home, and thermal bridges. The first image (from left) displays a window into the basement which has been boarded up with wooden materials. In the thermal image beneath it, the bright orange indicates an increased temperature where the part of the window underneath is exposed. This indicates a loss of heat from the basement which is an undesired quality in the façade. During the hot temperatures, this will almost act as an open window, increasing indoor temperatures. The second image shows an enclosed space to the East of the kitchen (refer to Figure 9). The thermal image underneath shows two stud-appearing long vertical pieces holding up the panel from the inside and has no insulation otherwise. This area has not been included in the interior zoning of the model and is an outdoor space adjacent to the kitchen. Since the material surrounding the space is bright orange, it is a conductor of heat and can lead to warmer temperatures in the kitchen during the summer. In the third image, the thermal image of the façade shows dark patches under the window revealing potential inconsistencies in the wall's insulation. This is an opportunity for conduction to occur and increase temperatures in the bedroom. The final image shows a vertical thermal bridge in the northern wall and like previous anomalies, this decreases the performance of the thermal envelop. These characteristics together with the previous data and lack of air conditioning construct a dangerous environment during the hot summer months in Atlanta.

Based on the evaluation of the thermal envelope of this home and the information regarding community resources and demographics above, the capacity to adapt to extreme heat events and increased temperatures is low. In the next section, thermal comfort inside the home is investigated based on predicted mean vote, adaptive comfort, average air temperature, and mean radiant temperature.

4.1.2 Exposure

In this portion of the study, the amount of heat the occupant is exposed to is explored. In this case study, the model constructed in the previous portions of the research is used to run a thermal simulation of the interior, which informs the comfort model. The environment has been simulated to resemble the exact characteristics of this home closely. Materials have been represented as accurate as possible, the spaces and thermal zones are based on measurements and personal on-site investigations, and the occupancy habits are all established from interviewing the current resident.

The results have been simulated for the month of August as mentioned previously to characterize one of the hottest months in the Atlanta summer. Figure 15 shows the thermal and comfort maps resulting from the simulation. From top to bottom, is the ACM, the PMV, the AAT, and the MRT. From left to right is the TMYx 2004-2018 weather file and the 2080 file. The results have been simulated without air conditioning and assumed to have no natural ventilation or open windows and each thermal zone is an enclosed volume.

The Adaptive Comfort maps indicate that while currently, the rooms are bearable during the summer, the future increase in temperatures will not relieve the heat, in fact it will increase considerably and make the interior dangerous to the resident without any air conditioning which is currently the case.

The Predicted Mean Vote maps visualize how uncomfortable the interior is during the month of August, rising above any comfort range throughout all the volumes. The values -3 to 0, the color blue, correspond to a cool climate and the values from 0 to 3, the color red, correspond to a warmer climate with 3 and -3 being the most uncomfortable. In the results for the current climate, the eastern spaces within the home are the most comfortable even though they are almost red. However, in the future morphed climate file, every space inside the home is at a number 3 corresponding to uncomfortably warm.

Both the adaptive comfort model and the predicted mean vote have indicated that the interior of the home is uncomfortable, which is an indicator that the occupant will be exposed to an environment that is considered unsafe.

The bottom two rows display the Average Air Temperature and Mean Radiant Temperature. There is a notable difference between current weather and future climate regarding AAT. The average air temperature during August 2080 lies between 30°C and 34°C (86°F - 93°F). According to the NWS heat index, 86°F at 40% humidity indicates caution. The MRT is higher than the AAT rising to temperatures of 36°C (96.8°F) and higher.

The results support the claim that this home is exposed to increased temperatures indoors due to a lack of air conditioning.

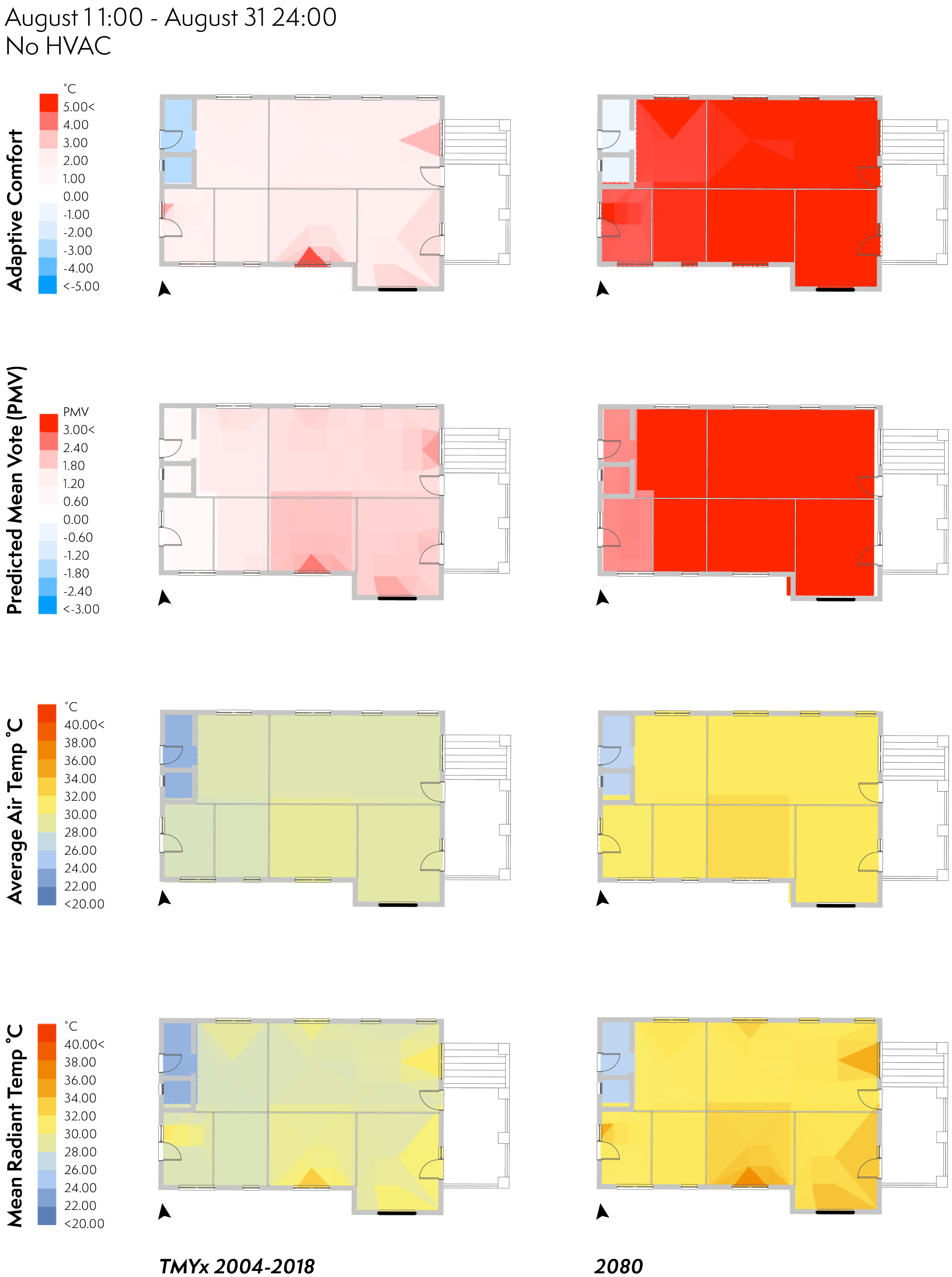

Figure 15 – Results of thermal simulation. For current weather and predicted weather in 2080 (left to right): Adaptive comfort, Predicted Mean Vote, Average Temperature, Mean Radiant Temperature (top to bottom).

4.1.3 Sensitivity

Sensitivity, in this context refers to the capability of both the built environment and human body to withstand and adapt to heat. Social isolation, race and ethnicity, income, and educational attainment (Widerynski et al., 2017), as well as preexisting health conditions, and physiological ability to adapt to high temperatures are all factors affecting the increased sensitivity of an individual to heat.

The questions asked during an interview with the occupant of the home are listed in Table 6. The answers listed and the demographics collected previously all lead to an interpretation that this home and resident are extremely sensitive to heat exposure, and both are vulnerable to heat. Some questions which can be added to future interviews include occupant experiences during the summers. One question that can be asked is "When does it start to feel uncomfortable inside your home during high temperatures?".

The combination of the previous factors: thermal studies, physiological capabilities, resource availability, and age and health indicate that this occupant is part of an underrepresented community that is exposed to extreme heat during the summer months and is especially prone to biophysical hazards associated with heat and even death. The following section discusses possible strategies that can be taken to help reduce this stress.

Table 6 – Questions asked interviewing the resident

Questions	Answers
Do you have air conditioning?	No
Do you use air conditioning?	No, electric fans are used.
Does the air conditioning work?	No, even though a unit was installed it has never functioned.
How do you keep cool in the summer?	Electric fans
Do you open windows throughout the day?	No
You have air conditioning units installed in the windows; do you use them?	No
How long have you lived in this house?	It belonged to the occupants' mother in 1930s
Do you have any blinds/curtains and if so, how often do you open or close them?	Blinds cover almost all the windows and are always pinned close due to privacy concerns.

4.2 Response Strategies

This section discusses strategies that can be applied to respond to the hazards associated with extreme heat exposure in underrepresented communities such as Grove Park. Currently, there are no active strategies that protect the community from this environmental hazard, however the Urban Climate Lab at the Georgia Institute of Technology is doing relevant research in the areas of Atlanta close to the campus and this can serve as a starting point for future partnerships or collaborations. The approach to help Grove Park will be twofold, first will be short-term strategies that can help the community become more resilient, and the second is longer term solutions that require some more data collection and observation efforts.

4.2.1 Short-term

A first step to take for a short-term solution is to address the foremost problem. Currently, a high priority needs to consider getting residents to safer locations during extreme heat events in the summer to prevent any heat stress or mortalities. Since the nearest emergency room is not within walking distance, it becomes important to prevent such trips. The first strategy is to identify possible cooling centers for residents to take shelter in during increased temperatures (Widerynski et al., 2017).

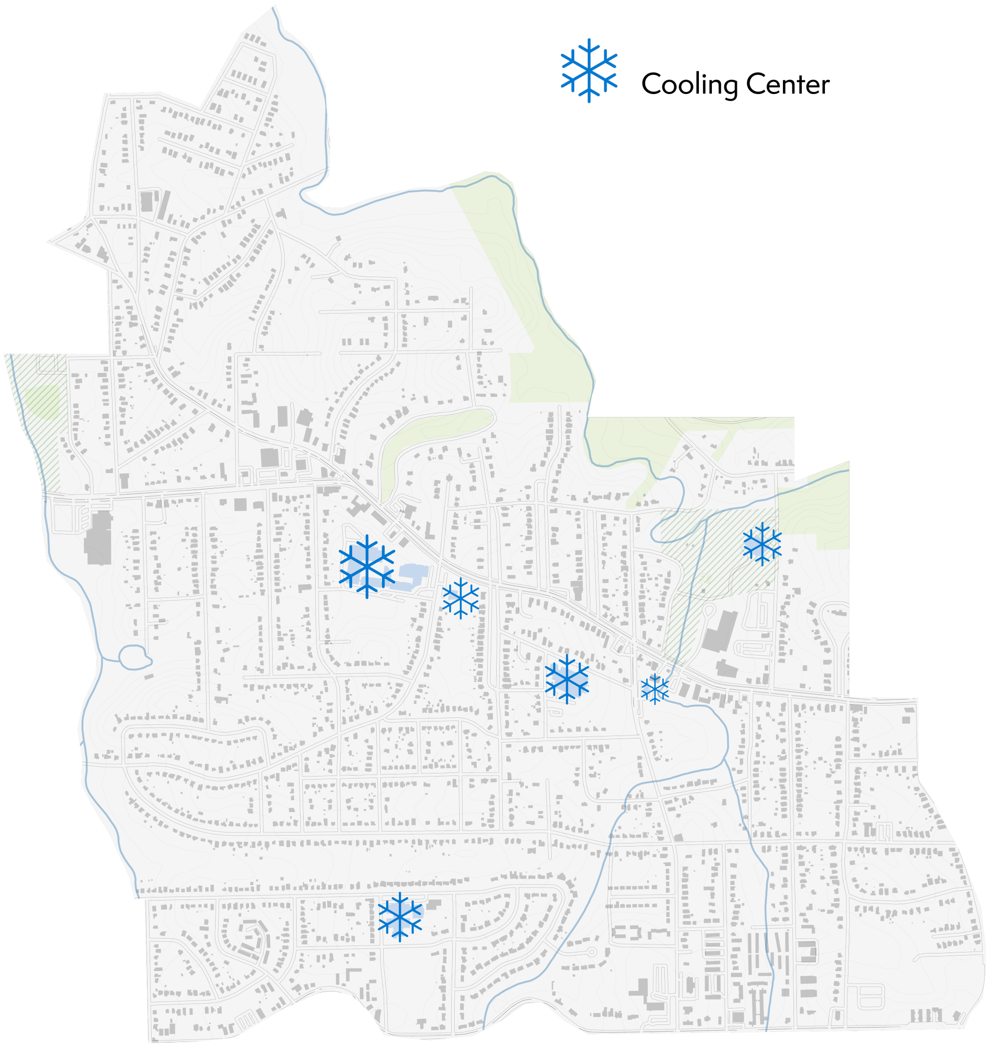

Figure 16 – Possible Cooling Centers in Grove Park Neighborhood

One significant characteristic to consider is the proximity of the cooling centers to the community. At least one center must be identified within walking distance to the community. The center can be any large building which has reliable air conditioning and can always provide access to community members. Examples include schools, churches, community or senior centers, and libraries. These centers can be identified on a map and the data can be used in a Geographic Information System (GIS) database. Regarding the Grove Park Neighborhood, multiple locations have been identified as possible cooling centers (for example: John Lewis Invictus Academy, Harper-Archer Middle School, KIPP Woodson Park Academy, White Elementary School, Dogwood Library, New Bethel Baptist Church, and the Grove Park Recreation Center) and they are mapped in Figure 16. Maps and visuals such as this one can be posted in the neighborhood for clear identification. Large signs and posters can be made publicly visible, and communications can be made spreading information about the locations to the community members.

Another strategy which can be implemented is a heat alert program, which would include messaging and communication about extreme heat events or even natural disasters at a larger scale (Weinberger et al., 2018). This would include outreach to a neighborhood association or group that would act as a liaison for the residents. Phone numbers and emails can be collected regarding neighborhood occupants and information about the program can then be shared. Residents would be given an option to opt into emails, texts, or phone calls communicating extreme heat risk. Through continued observations of the weather forecasts or temperatures throughout the hotter season, communication with residents would be fulfilled to ensure alerts have been received.

Using broadcasting mobile applications to send out mass emails or text messages to residents in the community can be one method, however portions of the community may not have access to these methods proposed, so it would be more reliable to call or knock-on doors to ensure resident safety. Implementing this direct and intricate method of communication would be based on some form of a volunteering program. The following section discusses long term proposals which includes strategies for implementation.

4.2.2 Long-term

While the shorter-term strategies can save residents from being exposed to the hazards associated with exposure to heat, there are longer term goals that can be achieved which increase community resiliency to climate change in the future.

Initially, more research is recommended to identify policies already in place supporting the community response to extreme heat. In the case that there are some established.

Second, outreach to community-based programs which are already focusing on extreme heat in urban environments. A group such as the Urban Climate Lab at the Georgia Institute of Technology (Stone et al., 2019) can be involved in efforts such as heat surveillance using sensors. This can also serve as a source for thermal data related to extreme heat in Grove Park. Moreover, this data can support research regarding vulnerable communities such as Grove Park.

Third, the constant development of tools and guides to educate about extreme heat and rising temperatures due to climate change is important. These can be implemented through education programs in younger populations such as middle and high schools in different areas to raise awareness (Department of Health, 2014).

Finally, redesigning the community to become energy resilient. This can be done through incorporating a renewable energy smart grid. For example, renewable energy storage can be done in the community through installing photovoltaics on rooftops. Requests for funding can be made in order to implement such methods. In the long run, this would allow some homes to support other homes during power outages or extreme heat events. If one resident could not afford to keep their air conditioning unit functioning during a heat wave, then energy can be harvested from solar panels or other rooftops (Charani Shandiz et al., 2020).

CHAPTER 5. DISCUSSION, FUTURE RESEARCH, AND CONCLUSIONS

This section discusses the results of this research, and some of the limitations faced. Future research and trajectories are also identified, and conclusions are made about the work.

5.1 Discussion

As mentioned in the literature review, Widerynsky et al., (2017) introduces the factors affecting heat vulnerability as adaptive capacity, exposure, and sensitivity. According to the referenced work, a combination of these factors is a reliable way to assess vulnerability in communities. Throughout the research data has been collected under the general guidance of these characteristics, the results have been discussed, and response strategies have been identified regarding the underrepresented community of Grove Park.

Adaptive capacity was identified as the capability of a system to respond and adapt to the effects of heat and the hazardous effects associated with it. A combination of demographic data related to census tracts and thermal images were collected that have aided in determining building performance. Based on the results of this part of the assessment identification of specific faults in the building envelope of a home in Grove Park were made. This directly affect the capacity of the current environment to protect the resident. This, along with data available from existing databases has informed some important strategies to be implemented to support communities such as Grove Park in their response to climate change.

Exposure is directly related to the amount of heat the occupant was exposed to inside the space. This is based on a combination of several factors including the building materials, building age, and the occupants behavior. Exposure is closely tied to sensitivity and both categories support each other regarding the data. Sensitivity focused on the physiological traits of the occupant. The study concludes that the building and community is considered vulnerable to heat and measures must be taken to mitigate the effects of extreme heat on the Grove Park community.

Some current strategies include more research, identification of cooling centers, implementing a heat alert program, policy change, community-based programs, and education. These can aid Grove Park in becoming more resilient to climate change in the future.

5.2 Future Research

These results of this study can be used to develop targeted interventions aimed at mitigating the effects of extreme heat in vulnerable populations in the future. Such interventions would be included the development of a community-based program in areas such as that of the grove park neighborhood in Atlanta, Georgia.

Future work includes development of a program that will connect the community with researchers and students. The first step is to establish a framework for heat mitigation in vulnerable communities.

Second is to establish a community-based program that intends on using research to support a heat response plan for the Grove Park neighborhood which mitigates the effects of extreme heat on the residents. The research will look at short- and long-term interventions regarding the built environment both at the building scale and urban scale. Some of the responses that will be included in the program include:

- Identifying possible cooling centers which act as shelters during heatwaves.
- Identifying hotspots and cool spots based on outdoor thermal analysis.
- Current and future surveillance of temperatures informing a heat alert program.
- Increasing the education of the community and surrounding communities regarding climate change vulnerability.

Some steps that will be taken to implement a community-based program in Grove Park neighborhood will first include communication with some stakeholders (such as the community members and researching institutions) to gauge interest in participation. The Urban Climate Lab at Georgia Tech and the Environmental and Health Sciences Program at Spelman College are both candidates for a program in Atlanta. The data being produced by these institutions can help build a database regarding urban heat island in the Grove Park area. Students in the Urban Design program at Georgia Tech can map hot and cool spots in the urban environment based on the previous information. Members of the

High Performance Building Lab at Georgia Tech can collect thermal images and conduct building audits for different residents of the community. Other students and researchers can be recruited for developing an interface for mapping the data collected. This can be done through a stand-alone mobile application or through a plugin for an existing application such as 'Google Maps' for example. Volunteers will be recruited and assigned to different community members. The volunteers will either educate community members on the use of this application or monitor the app themselves to alert those without access to the internet or a reliable smart phone. Other positions within the program can include educating local high- and middle-schools about climate change resiliency. The High Performance Building Lab has a relationship with the John Lewis Invictus Academy in Grove Park and can begin giving educational lectures and courses for those students interested. In the future, these students can become volunteers and help such a program grow in scale.

5.3 Conclusions

The purpose of the current study was to determine increased heat vulnerability in underrepresented communities through a case study of Grove Park in Atlanta, Georgia. This has been done through data collection, analysis, and evaluation, and finally response strategies have been advised. Guided by a definition of heat vulnerability in previous literature by (Widerynski et al., 2017), three main categories are addressed: adaptive capacity, sensitivity, and exposure. Geographic and spatial data was collected, and the area of interest was mapped. Behavioral data was also collected through an interview process and the model was calibrated based on this information. Finally, thermal images and RGB images were taken, and demographics were obtained from online sources. The data was used to construct a 3D model which provided thermal mappings of the interior spaces. The thermal maps were then used to provide information regarding exposure to extreme heat, concluding that the home was at risk due to exposure to high indoor temperatures. The thermal images and demographic data confirmed that Grove Park and specifically the case being studied had little capacity to adapt to extreme heat. Regarding sensitivity, the interview supported the claim that the occupant is more sensitive to heat events.

The results of this investigation show that the home in Grove Park and the occupant are at a great risk to extreme heat. Overall, this study strengthens the notion that marginalized and underrepresented groups and communities are at high risk to the effects of extreme heat events due to climate change.

Since the study was limited to one home in Grove Park, it was not possible to definitively identify Grove Park as a vulnerable community. Instead, the claims are generally made regarding the data that has been included.

Despite its limitations, the study certainly adds to our understanding of the methods to assess heat vulnerability in underrepresented communities. Moreover, this study has created a framework for assessing other homes in the Grove Park community and future work includes an increase in scale regarding data collected, homes assessed, and climate change hazards taken into consideration.

The findings provide the following insights based on the research questions for future research:

- Are underrepresented communities more at risk to extreme heat? Underrepresented communities are generally considered to be at an increased risk to extreme heat.
- How are their built environments equipped to handle the extreme heat threats? Communities are at most risk to extreme heat when there are less resources available to them. Resources include financial support, better performing building envelopes, increased access to cooling centers, education on the importance of climate resiliency, and an overall increased effort from the government to create resiliency. All these characteristics equip a community to better respond to extreme heat.
- Data which can help support this claim include: building envelope performance, access to health infrastructure (i.e., number of emergency rooms withing 15-mile radius), general demographics (i.e., the percentage of the population above 65, living alone and the percentage of the population below 18 years in the neighborhood) social demographics (i.e., percentage of civilian non-institutionalized population ages 5 and over with a disability, and percentage of civilian non-institutionalized population ages 65 and over with a disability), economic demographics (i.e., percentage of population below poverty, percentage of population under 18 years below poverty, and percentage of population 65 years and over below poverty), housing demographics (i.e., number of total

housing units, number of occupied housing units, number of units built between 1980-1999, and number of units built in 1979 or earlier), number of extreme heat events (defined as the number of events of two consecutive days or more exposed to 90°F temperature or more), policies, and responsive systems in the built environment.

- What are some strategies for mitigating risks associated with extreme heat vulnerability? Through short and long-term solutions, some strategies can be implemented to better prepare vulnerable communities for heat exposure. These include heat alert programs, identifying cooling center locations, policy changes, climate surveillance, education strategies, and design interventions. Regarding Grove Park, identification of cooling centers, establishing a heat alert system, and starting a community-based program are some strategies specifically.
- How can data analytics and measurements be used as evaluation metrics to design strategies for mitigating the risks and reducing the climate vulnerability of a community? Data analytics such as thermal simulations can be used to identify the risk associated with extreme inside buildings during specific periods of time. Thermal imaging in this study specifically provides an example for a measurement which can identify a defective building envelope. This provides a guide for design strategies in the future.

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