

**Assessing and Reducing Exposure to Heat Waves in Cuyahoga County, Ohio**

**by**

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## ABSTRACT

In the United States, more people die from heat waves than from any other type of natural disaster. Climate change will increase the frequency and intensity of extreme heat events. Fatalities during hot weather occur primarily in cities, in part due to the urban heat island effect.

This dissertation addresses heat-related exposure in Cuyahoga County, Ohio and is structured around three complementary studies. The first study investigates the urban heat island effect using a mobile measurement platform. Variations in solar radiation and albedo led to greater-than-30°C shifts in the ground surface temperature. Air temperatures recorded downwind from forested areas were 0.25°C cooler than those recorded over impervious, bare soil, or grass land covers. Water provided a cooling effect that was roughly 2.7 times stronger than that of a forest. However, large areas of forest or water were necessary to reduce the local air temperature; 11.8 hectares of water (29.16 acres) resulted in only a 0.67°C reduction in temperature.

A second study addresses exposure in single family detached houses. Five house types were modeled in thermal load software with different configurations of insulation, air infiltration, and windows to evaluate the effect of weatherization on annual energy usage, air-conditioning operation, and indoor temperature. Weatherization lowered the yearly cost to heat and cool a house by \$260 to \$480 USD; it also decreased electricity usage associated with air-conditioning by more than 35%. Weatherization reduced the required size of air-conditioning equipment by 40 to 50% per house. However, if windows remain closed during warm weather, weatherization treatments may increase exposure to temperatures above the ASHRAE thermal comfort zone.

A final study investigates how professionals responsible for reducing exposure to high temperatures define and act to reduce temperature-related morbidity and mortality. Using a system of professions approach, professionals from the health, building science, and urban environment policy sectors were linked to tasks they consider their jurisdiction, such as cooling centers, residential energy efficiency, or developing codes and standards. Results from twenty-eight semi-structured interviews indicate barriers among programs. Collaborative efforts may help to bridge among disciplines and improve strategies to reduce exposure to future heat waves.

## CHAPTER 1

### Introduction and Literature Review

#### 1. Introduction

Each year in the United States, more people die from heat waves than from any other type of natural disaster (CDC 2009). The National Climate Assessment projects an increase in the risk, intensity, and duration of extreme heat events over the next century due to global warming (Melillo et al. 2014). Fatalities associated with increased temperatures occur primarily in cities, in part due to the urban heat island effect (Luber and McGeehin 2008). Heat wave responses fall into two categories: managing health risks and reducing exposure (Huang et al. 2013). While personal health is an important factor in heat-related morbidity and mortality, this dissertation focuses on assessing and reducing exposure to high temperatures in urban environments.

To understand heat-related exposure in cities, this research draws on insights from the environmental health sciences, building science, and urban climate literatures. However, while issues of health, residential energy use, and the urban heat island are interconnected, the responses proposed by policy communities are not well coordinated (Strengers and Maller 2011). This disconnect can lead to an inefficient use of resources and efforts that contradict one another.

For example, a number of authors in the environmental health sciences have advocated for the installation of residential air-conditioning to reduce exposure to high temperatures indoors (Semenza et al. 1996, Keatinge 2003). This is because cities with higher air-conditioning prevalence have lower levels of heat-related mortality (Chestnut et al. 1998, Braga et al. 2002, Anderson and Bell 2009). While these air-conditioning systems reduce interior temperatures, they increase household energy consumption, undoing the work of building scientists whose primary concern is energy efficiency (Guy and Shove 2000). In addition, the cooling system exhausts waste heat from the house to the atmosphere; this strengthens the urban heat island effect (O'Neill et al. 2009).

To address this type of conflict, connections need to be made among the environmental health sciences, building science, and urban climate communities. Focusing on Cuyahoga County, Ohio, this dissertation forges a link among these fields by presenting two complementary studies that quantify exposure at the urban- and residential-level; a third study examines how local professionals define and act to reduce exposure.

Cleveland and its suburbs are the focus of the study because several national-level assessments of heat vulnerability identified the region as being vulnerable to high temperatures due to an older population, poor quality housing stock, a lack of central air-conditioning, and high quantity of impervious surfaces (Reid et al. 2009, Staudt and Inkley 2009, Altman et al. 2012). Although Northeast Ohio is an extreme case, healthy housing and environmental planning programs developed in Greater Cleveland have been used as a template for other cities in the United States (Jacobs et al. 2007, EPA 2012). To this end, the approaches developed in this dissertation can be used in other cities with a similar climate and housing stock; the results are applicable for programs in comparable cities like Detroit, Toledo, and Buffalo.

### *1.1 Structure of the Dissertation*

After this introduction and literature review, Chapter 2 describes a bicycle-based measurement system designed to assess the extent of the urban heat island effect in Cuyahoga County. The study documents the contribution of biophysical factors like albedo and vegetation to local ground surface and air temperatures by adapting a measurement technique from the building science and urban climate communities. The results indicate that a bicycle is a low-cost method of gathering data about microclimates and that the data can be useful for the formation of policy. Recommendations for future versions of the bicycle are also discussed.

Chapter 3 addresses exposure in single family residences, focusing on how the residential energy efficiency strategies termed ‘weatherization’ may temper indoor temperatures while reducing energy demand. This study is a response to a general lack of data quantifying thermal exposure inside low-income single-family detached housing, a gap that exists between the environmental health sciences and building science communities. Results from thermal energy modeling suggest that when combined with natural ventilation, weatherization can reduce exposure to high temperatures during heat waves. In addition, these energy efficiency measures reduce energy use, energy demand, and the required size of air-conditioning equipment.

Chapter 4 investigates how professionals from the environmental health sciences, building science, and urban climate communities address the issue of temperature-related exposure. Using a “system of professions approach” (Abbott 1988), the study links these officials to the set of tasks they consider their jurisdiction, such as the operation of cooling centers, residential energy efficiency, or developing codes and standards. The results indicate gaps among policies at the local, state, and federal levels; I recommend collaborative efforts in the conclusions that may improve adaptation to increased temperatures.

## **2. Literature Review**

Because planning for a warming climate will require city officials to assess exposure related to both the urban heat island and global warming, the first section of this literature review discusses both of these phenomena. Following this overview, the second section discusses differences in vulnerability in cities. The third and final section presents strategies to reduce exposure to temperature.

### *2.1 Urban Heat Islands*

Since the 1830s, studies in Europe, North America, and Asia have investigated the phenomenon called the urban heat island (UHI) (Stewart 2011). UHIs are broadly defined as the temperature difference between urbanized areas and their rural surroundings (Voogt and Oke 2003). UHIs are a byproduct of all human settlements; they are an important topic because they increase temperature exposure during heat waves, increase electrical demand associated with air-conditioning, and increase smog at the ground level (Santamouris 2001).

It is now widely recognized that there are four vertical scales of UHIs: sub-surface, surface, urban canopy layer (UCL), and urban boundary layer (UBL). As their names imply, each is focused on a different cross-section of the city: below grade, at the earth’s surface, from the ground to approximately the average roof height, and above the built environment (Oke 1982, Voogt and Oke 2003, Ferguson and Woodbury 2007). While sub-surface and urban boundary layer urban heat islands are important because they negatively impact groundwater quality and exacerbate air pollution, this dissertation focuses on surface and urban canopy layer urban heat islands because they increase human thermal exposure (EPA 2008).

### *2.1.1 Surface heat islands*

Ground surface heat islands are primarily a daytime phenomenon that form under several conditions: (1) when the albedo of land covers is reduced (e.g., when vegetated area is converted to concrete), (2) when thermal properties of materials increase storage of heat during the daytime, (3) when pollution creates a greenhouse effect that reduces radiative losses, and (4) when urban canyons decrease longwave radiation loss at night (Santamouris 2001). According to Oke (1982), these ground surface heat islands are important to the overall energy balance of the urban climate because they modify air temperatures in the urban canopy layer, exchange energy with the lowest layers of the atmosphere, and directly impact human thermal comfort as a component of radiant temperature.

The average difference in daytime surface temperatures between urban and rural sites is 10 to 15°C; the difference in nighttime surface temperatures is less at 5 to 10°C (Voogt and Oke 2003). The magnitude of ground surface UHIs varies seasonally due to changes in the sun's altitude, weather conditions, and vegetative cover; surface urban heat islands are typically the strongest in summer (Oke 1982). Although the primary impact of surface heat islands is warming of the air, they also increase radiative gain to buildings, increasing air-conditioner usage.

### *2.1.2 Urban canopy layer heat islands*

Whereas ground surface UHIs are stronger during the day, urban canopy layer heat islands tend to be stronger at night. Although they form under similar conditions (Oke 1982), two additional factors cause localized warming of the air: (1) anthropogenic heat is released by the combustion of fuels from mobile and stationary sources, and (2) a reduction of evaporating surfaces puts more energy into sensible rather than latent heat (Santamouris 2001). Canopy layer heat islands are the temperatures directly related to human temperature exposure occurring from roughly one meter above the ground to the average height of the surrounding buildings.

The intensity of canopy layer heat islands depends on the season, prevailing weather conditions, and the properties of urban surfaces. Canopy layer heat islands are less intense than surface heat islands; air temperatures are on average only 1 to 3°C warmer than in rural locations in temperate cities (Oke 1997, Imhoff et al. 2010). However, in a semi-arid climate these differences are exacerbated: Harlan et al. (2006) found a 6°C difference in local temperatures across neighborhoods in the Phoenix metropolitan region. Studies to understand the differences in temperature among neighborhoods is important for tailoring programs to the neighborhoods

with the highest exposure, this work can help find the best locations for cooling centers, energy efficiency programs, or street tree planting.

## 2.2 *Global Climate Change*

Global climate change and the UHI effect interact to increase exposure to temperature, especially during extreme heat events (Stone 2012). Although Lake Erie is a large heat sink that moderates the urban heat island effect in Cleveland and may provide a significant protective effect for the northern portion of Cuyahoga County, recent studies indicate that the frequency of heat waves in the Midwest has increased over the last sixty years (Perera et al. 2012). Compounding the problem, the magnitude of heat stress in the region is projected to grow because of local increases in humidity (Schoof 2013). To understand the significance of these findings, it is helpful to understand how climate change assessments are conducted in the United States.

Climate change assessments are collective, deliberative processes by which scientific experts review, analyze, and synthesize knowledge in response to the information needs of a particular audience (Committee on Analysis of Global Change Assessments 2007). The goal of most assessments is to bring together a multidisciplinary team of physical scientists, social scientists, and political scientists to build consensus around a particular resource management, environmental, or sustainability issue (Michigan Sea Grant and Graham Environmental Sustainability Institute 2009). Assessments generally do not involve additional experimentation such as running a General Circulation Model (GCM) to predict future temperature increases or climate variability. Instead, they rely on research already published in peer-reviewed journals to increase the external validity of the final document. Assessments are frequently divided into a series of sub-reports, often by sectors such as energy, transportation, or human health. One criticism of this format is that it ignores multidisciplinary approaches, or misses opportunities that fall between two or more disciplines, like building science and urban climate.

At the local level, public officials work with mediating organizations such as ICLEI or local universities to further summarize the effects of climate change. These efforts attempt to convey potential impacts in local terms and build community support for action. In contrast to the national assessment, local efforts frequently attempt to address the complex psychological, organizational, and political barriers to climate action, and they frame the debate relative to local needs (Shove 2010). This can promote action to reduce exposure to extreme heat events because insights from multiple fields like the environmental health sciences, building science, and urban

climate are combined to find a custom solution that supports local needs. This collaborative process builds support among community organizations for interventions (Hisschemoller et al. 2001). It may also help to find gaps in national-level climate change policies, informing future assessments.

### **3. Assessing Vulnerability to Elevated Temperatures**

There is no universally accepted definition of elevated temperatures or a heat wave; most approaches incorporate some measure of high temperature as it is experienced over a period of time (Peng et al. 2011). For example, studies that examine the relationship between temperature and mortality often use percentiles of observed temperatures to calculate the increased rate of fatalities, these studies examine the odds of dying after one or more days of extreme temperatures (Anderson and Bell 2009). Within buildings, thermal comfort studies rely on standards like ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy to determine exposure (ASHRAE 2010). At the urban level, studies that investigate the urban heat island effect rely on the physiological equivalent temperature or indices like the National Oceanic and Atmospheric Administration (NOAA) heat index (Oke 2005).

In this risk-hazard approach to vulnerability, negative outcomes are a function of biophysical factors (e.g., changes in temperature) and the potential for loss. In short, exposure to temperature plus sensitivity of a population equals vulnerability (Cutter et al. 2008). When morbidity or mortality actually occur during a heat wave, the relationship between exposure and sensitivity can be determined, and this allows "the ex-post identification of the existence of vulnerability in a system" (Eakin and Luers 2006). While these efforts can help to avoid future fatalities, the results are actually only a rough proxy for vulnerability and may lead to a "conflation of causal processes and conditions with outcomes" (Ibid.). For example, odds ratios of vulnerabilities generated for the 1995 heat wave in Chicago by Semenza et al. (1996) are not applicable in Cleveland, nor are they reliable for future heat wave events in Chicago.

Other approaches, like political economy or political ecology, emphasize the sociopolitical, cultural, and economic factors that explain differential exposure to hazards and different capacities to cope with and adapt to future threats (Eakin and Luers 2006). A good example of an author working in this framework is Klinenberg (1999). Writing about the July 1995 heat wave in Chicago, he argued that the 700 deaths were "a sign and symptom of the new and dangerous forms of marginality and neglect endemic to contemporary American big cities"

(Klinenberg 1999). In the political economy and political ecology literature, vulnerability is not an outcome but rather a state or condition of being, moderated by inequities in access and distribution of resources.

Other approaches are relatively new additions to the discourse on vulnerability. Ecological resilience focuses on the variety of stresses and shocks acting on and within coupled human-environment systems (Eakin and Luers 2006). For example, responding to the discovery that most of the 1995 fatalities in Chicago occurred on the top floors of buildings, Huang (1996) investigated low-cost home retrofits to keep the top floors of buildings cool in Chicago. The study recommended light-colored roofs and insulation in attics to lower indoor temperatures. These recommendations enhance a system's resilience to climate surprises and shocks (Eakin and Luers 2006). In this case, the light colored roofs work at two scales, they both reduce interior temperatures and mitigate the urban heat island effect. This helps the built environment as a whole to remain cool during a heat wave. The Huang (1996) study influenced this dissertation by identifying a promising area of research, the renovation of existing homes, which was not frequently discussed in the literature.

Other hybrid approaches to understanding vulnerability draw on insights from a number of disciplines and all three frameworks. For example, in a study of exposure to heat stress in Phoenix, Arizona, Harlan et al. (2006) investigated the microclimates of urban neighborhoods, population characteristics, thermal environments that regulate microclimates, and the resources individuals possess to cope with high temperatures. Using a spatial, multi-disciplinary approach, they investigated the resources people have to cope with extreme heat (risk/hazard), whether marginalized populations are more likely to live in heat-stressed neighborhoods (political economy/political ecology), how environmental properties are related to spatial inequalities in temperature and exposure (ecological resilience). As Cutter (2003) stated, this new interdisciplinary form of vulnerability science is broader and avoids many of the limitations of any single framework.

In this dissertation, I attempt to use a similar hybrid approach to understand how building and neighborhood-level characteristics may overlap to increase exposure to temperature. I also investigate how different professions define and address the issue of heat-related morbidity and mortality. The hope is that this will uncover new ways to look at the issue of heat-related exposure and address current gaps in the literature.

### *3.1 Building Level*

To assess exposure to temperature, the environmental health sciences use percentiles of observed temperatures; urban climate studies use heat stress metrics such as physiological equivalent temperature or the National Oceanic and Atmospheric Administration (NOAA) heat index. While these metrics calculated from airport weather stations are good proxies for human responses to increased temperatures, the exact exposures experienced inside a building due to outdoor conditions remains relatively unknown.

However, recent field research has been conducted in Detroit, Montreal, and Leipzig to measure exposure indoors and link it to outdoor temperatures. White-Newsome et al. (2012), measured temperature exposure indoors using dataloggers and found that the average home in Detroit experiences varying levels of heat exposure depending on the weather and the physical characteristics of the house. They conclude that people living in single family detached homes built before World War II may be a higher risk for heat exposure during a heat wave; indoor temperatures approached 35°C in these houses during the summer.

In Montreal, Smargiassi et al (2008) measured the interior temperatures in 75 homes in the urban core. They found that dwellings located on the second floor had indoor temperatures that were 1°C higher than those located on the first floor; apartments located on the fourth floor had indoor temperatures 2.5°C higher than those on the ground floor. This shows how temperature exposure can vary vertically; heat rises through a building structure, potentially overheating the top floors of a building.

Finally, in Leipzig, Franck et al (2013), found that there was a tendency for single family and semi-detached homes to have higher temperatures indoors, they also found that temperature varied vertically within a building. While each of these three studies used dataloggers to quantify interior temperatures and relate them to outdoor conditions, there is limited transferability of the results from these three studies to other cities because of variations in the housing and climate.

To overcome these limitations of field research, several recent studies have used building energy models to simulate the multi-variable relationship among housing, outdoor conditions, and the indoor thermal environment (CIBSE 2005, Lee and Steemers 2013). In these studies, the authors investigated how changes to the thermal envelope and building systems might affect interior temperatures under a changing climate. They used future weather year data to investigate overheating for buildings in the United Kingdom, modeling results against a range of future

climate scenarios. They found that buildings with greater thermal mass stay cooler for longer periods of time; adding ventilation with outdoor air kept the interior temperatures near a 28.0°C temperature threshold.

Chapter 3 builds on this work by using similar software to investigate whether energy efficiency strategies might mitigate interior heat exposure and energy use in home types found in Cuyahoga County. However, the analyses used historical weather data and not projected temperatures because future TMY files are not currently available for the majority of the United States (Kalvelage et al. 2014).

### 3.2 *Urban Level*

Quantification of the urban heat island requires measurement of both the ground surface temperature and air temperature under the canopy layer. Ground surface heat islands are typically measured by remote sensing equipment like satellites. For example, Lo and Quattrochi (2003) used the Landsat visible, near infrared, and thermal wavelength data to develop statistical relationships between vegetation and ground surface temperatures in Atlanta. They found that surface temperatures and the normalized differential vegetation index (NDVI) were negatively correlated; this finding suggests that the concrete and asphalt that had replaced forest and cropland increased ground surface temperatures. Using Landsat, IKONOS, and Aqua satellite-based datasets, Imhoff and colleagues (2010) found that impervious surface area explains 70% of the total variation in land surface temperature for thirty-eight of the most populous cities in the United States.

Measurement of air temperature in an urban environment is difficult because most developed areas do not allow researchers to follow standard guidelines for site selection and instrument exposure (Oke 2006). Of particular concern is interference from local waste heat sources like building air-conditioning equipment, industrial sites, or vehicle exhaust if the goal is a representative measurement for a large area. Recent efforts by Stewart (2011) have encouraged authors to report critical information about equipment type, calibration, and screen height to facilitate cross-comparison of studies; newly developed land cover classifications will also help to accurately define the source area of sensors (Stewart and Oke 2012). For stationary measurements of the canopy layer, most studies either use a weather station or microdataloggers to make observations of the local air temperature. Limitations in the ground surface and air temperature measurement methods informed Chapter 4 of this dissertation.

## **4. Mitigating Exposure to Temperature**

This section of the literature review describes how exposure to temperature is mitigated by the health, building science, and urban climate communities.

### *4.1 Health*

In the 1950s, U.S. Navy physicians conducted a series of case control studies to determine a statistical relationship among air temperature, humidity, wind speed, solar radiation and heat-related illness (Minard 1957). This analysis became the basis for the wet-bulb globe temperature (WBGT) heat warning system still in use today (Budd 2008). Many U.S. cities use similar forecasting systems, though most are based on either synoptic climatology or the NOAA heat index. These systems help public health officials decide when to increase heat wave messaging, open cooling centers, or provide air-conditioning systems to vulnerable populations (O'Neill et al. 2009, White-Newsome et al. 2014).

Cooling centers and central air-conditioning provide a protective effect by lowering air temperature and humidity; they dramatically reduced the odds of dying during the 1995 heat wave in Chicago (Semenza et al. 1996). However, not all residents have access to a cool location during a heat wave because of limited mobility or a lack of transportation (Sampson et al. 2013). For this reason, residential air-conditioning systems are frequently discussed in the heat health literature as an additional protective strategy (Chestnut et al. 1998, Braga et al. 2002, Anderson and Bell 2009). In Cuyahoga County, municipalities operate cooling centers during heat waves, and local non-profits distribute free air-conditioning systems to qualifying households (CEOGC 2011).

While distributing free air-conditioners eliminates first cost as a barrier, operating costs may present a longer-term issue (Sheridan 2007, Sampson et al. 2013). Compounding the problem, new electric demand charges threaten to increase the cost of electricity during high use periods (Alexander 2010). Although the Low Income Home Energy Assistance Program (LIHEAP) provides funding to low-income households to pay utility bills, this assistance does not address a broader issue: air-conditioning systems have strained electrical distribution systems in the United States (Eggers and Thackeray 2007). Therefore, alternatives to residential air-conditioning are important because these passive systems do not require electricity to provide a protective effect (Dahl 2013).

## 4.2 *Buildings*

Before the advent of air-conditioning, passive systems were the norm in building design; window shading, light-colored materials and coatings, insulation, and radiant barriers are all building-level systems that reduce indoor exposure to temperature. Passive systems use no purchased energy to operate, play multiple roles in a building design, and are tightly integrated with the building structure (Grondzik et al. 2010). While passive systems can moderate interior temperatures, they cannot eliminate heat-related morbidity and mortality during heat extremes; these systems provide conditions within a few degrees Celsius of the outdoor air temperature (Givoni 2011).

However, there is a renewed interest in passive systems because they do not require electricity and because they continue to provide some protective effects during a brownout or blackout; this effect is called ‘passive survivability’ (Wilson 2005, Institute of Medicine 2011). In addition, they do not exhaust waste heat that increases the urban heat island effect. While passive systems are easily incorporated by architects into the design of a new building, in existing residences these systems are frequently installed as part of a weatherization retrofit.

### 4.2.1 *Weatherization Assistance Program*

*Weatherization* is broadly defined as the steps taken to increase energy efficiency by limiting unintended air and heat exchange between the indoor and outdoor environments. The primary goal of weatherization programs in the United States is to reduce conductive losses and infiltration of air (Institute of Medicine 2011). Weatherization may represent an ideal way to identify households at risk for exposure to extreme temperatures. Because people apply to these federally subsidized programs, they presumably have experienced uncomfortable conditions within their home or are struggling to make their utility payments (Khawaja et al. 2006).

Congress first authorized the Weatherization Assistance Program (WAP) in 1976. The scope of the program has remained relatively unchanged over its 37-year history (Kaiser and Pulsipher 2004). The current scope and purpose of the WAP is to:

Increase the energy efficiency of dwellings owned or occupied by low-income persons or to provide such persons renewable energy systems or technologies, reduce their total residential expenditures, and improve their health and safety, especially low-income persons who are particularly vulnerable such as the elderly, persons with disabilities, families with children, high residential energy

users, and households with high energy burden (Code of Federal Regulations 2009).

WAP is administered by all 50 states, the District of Columbia, U.S. territories, and tribal nations through community action agencies and state energy offices. WAP is the largest energy conservation program for low-income households in the country; more than \$10 billion has been spent on the program, though the American Recovery and Reinvestment Act (ARRA or stimulus) of 2009 authorized roughly \$5 billion of that amount in the period beginning in 2009 and ending in mid-2012.

The DOE provides weatherization assistance grants to states and other authorized applicants to plan and implement the weatherization program. States contract with sub-grantees, such as community development corporations, for program delivery. The WAP has evolved from a relatively simple program that used unskilled labor to install low-cost retrofits in low-income homes into a program that conducts advanced home energy audits, installing a broad range of energy conservation materials (Kaiser and Pulsipher 2004).

States identify a home's need for weatherization assistance when the client's application is processed. The characteristics of the household, including income, energy consumption, energy burden, and number of elderly, disabled, and children in the household, are processed to determine if the applicant is eligible for service. If the applicant is eligible, the dwelling unit is audited. If the dwelling unit can be weatherized in a cost-effective manner, then the client becomes a candidate for assistance.

A priority list is normally established and the client enters a service queue. If structural problems such as a leaking roof prevent the installation of measures such as insulation, the project is referred to other agencies or funding sources such as Habitat for Humanity for repair prior to the weatherization work. In general, DOE funding may not be used for non-energy-related repair work, though small repairs are permissible.

Community agencies determine need based on contact with the resident. Direct contact allows agencies to assess the relative needs of two households. For example, if two applicants are identical in all respects except that one household has an elderly person, preference will be given to the applicant with the elderly resident. Similarly, if two households are identical in all respects except that one household has a higher energy burden or a small child, priority will be given to the more vulnerable household.

In national assessments, the WAP is recognized as a cost-effective program, with a typical benefit-cost ratio exceeding 1.3 (Schweitzer 2005). The benefit-cost test used by DOE examines the energy savings over the life of each treatment. The DOE requires that the total cost of weatherization and program administration is less than the expected energy savings benefit. Although evaluations of the WAP have quantified some of the non-energy benefits of weatherization (Schweitzer and Tonn 2002), and these theoretically should count toward the efficacy of these programs, they currently are not factored into program management decisions.

In Ohio, the program is monitored annually for cost-effectiveness and accountability by the Ohio Development Services Agency and the DOE. Periodically, the State contracts with a third party for a statewide program evaluation. The 2006 evaluation found that the program was cost-effective and that it had helped low-income households to save more than 20% on their annual energy costs (Karg et al. 2006, Khawaja et al. 2006). In addition, disconnections of utility service for non-payment decreased by 50% in weatherized homes (Khawaja et al. 2006). For low-income households, these are significant improvements in financial stability and the quality of life.

#### *4.3 Urban Environment*

The U.S. Environmental Protection Agency (2008) recommends four strategies to prevent or lessen UHIs: (1) altering urban geometry, (2) increasing vegetation in urban areas, (2) modifying the properties of urban materials, and (4) reducing waste heat emissions. Altering the geometry of the built environment is less applicable to this dissertation since Cuyahoga County is fully built out, however the other three strategies can help to lessen the UHI effect in the region.

To increase vegetation in urban areas, cities frequently encourage the planting of street trees or the installation of green roofs. Vegetation provides shading to pavement and buildings and increases evaporation of water, lowering local ground surface and air temperatures. Using simulations, Rosenzweig et al. (2006) estimated the amount of space available for tree planting and green roofs in New York City. They found that installing green infrastructure for roughly 10% of the land cover would have a significant city-wide temperature impact, ranging from  $<0.1^{\circ}\text{C}$  averaged over all days to  $0.7^{\circ}\text{C}$  during heat waves. Because of the energy savings associated with planting trees and increasing the insulating value of roofs, they believe that the benefits would far outweigh the costs of such an initiative.

The second strategy, modifying the properties of building materials, is also common; cities frequently encourage the installation of cool roofing materials or pervious paving. To evaluate the impact of paving on local air temperatures, Coseo (2013) installed dataloggers in eight Chicago neighborhoods. His analysis showed that cool pavement strategies used by the City of Chicago reduced local air temperatures by more than 0.61°C. However, this relationship varied with wind speed because local heat sources and heat sinks influenced the measurements.

In another study of the Chicago UHI, Coseo and Larsen (2014) examined the importance of waste heat emissions on daytime temperatures. They argued that most urban climate studies have focused on changes in vegetation and albedo and ignored the influence of industrial processes, vehicular traffic, and air-conditioning. They found that a neighborhood's air temperature was 0.45°C warmer every kilometer it was closer to an industrial site. This finding is significant for a place like Greater Cleveland which has a number of operational steel mills in the Cuyahoga River Valley. In addition, many of the neighborhoods with older, lower quality housing stock are immediately adjacent to these industrial areas; residents may be exposed to higher temperatures both because of the configuration of their home and the heat emitted by process equipment.

## **5. Gaps in the Literature**

When Dagenhart and Sawicki (1992) inventoried the disciplines of architecture and urban planning, they hoped to discover why two professions that are historically related have diverged and no longer share a common discourse. Using a similar approach, Corburn (2009) retraced the roots of city planning and public health to document how disconnects between the two fields emerged. In their conclusions, these authors all argue that rather than attempting to regain the historical link between the professions, it is important to outline and then challenge the conventions of each field to strengthen responses to pressing environmental issues.

This dissertation takes a step in that direction by drawing on the environmental health sciences, building science, and urban climate literatures to strengthen the response to extreme heat events. While programs dedicated to heat health, residential energy use, and the urban heat island are interconnected, the policy responses are not well coordinated, and may either contradict one another or lead to an inefficient use of resources (Strengers and Maller 2011).

To this end, Chapter 2 begins by examining exposure at the urban scale, asking *"What are the physical characteristics of neighborhoods that explain the distribution of the urban heat*

*island?"* Although using carts to study indoor thermal comfort and using automobile transects to analyze the urban canopy layer are both well-established approaches within the building science and urban climate literatures, until recently few efforts bridged the gap between these micro- and mesoscale methods. Collecting these microclimatic data is necessary to establish how physical characteristics (e.g., solar radiation, albedo, sky view factor, vegetation) contribute to local variations in temperature exposure. Collecting these data also suggest how urban design strategies (e.g., shading, light colored pavements, zoning codes, street tree planting) can reduce exposure during heat waves.

Chapter 3 addresses a gap between the environmental health sciences and building science literatures. The primary research question is *"Do weatherization measures improve indoor comfort and energy use during a heat wave?"* To answer this question, I used house configuration data from weatherization program assessments to create a set of average homes representative of Cuyahoga County. These average home typologies were then modeled in the BEopt/EnergyPlus simulation engine to determine if weatherization treatments reduced exposure to high temperatures indoors. The modeling suggests that some of the strategies typically selected for weatherization can increase interior temperatures during extreme heat events if natural ventilation is not addressed, exposing a potential conflict between heat health and energy efficiency efforts.

Finally, to promote collaboration among all three disciplines, Chapter 4 describes the professions involved in reducing exposure to heat stress in Cuyahoga County. A system of professions approach links professionals (e.g., weatherization installers, environmental planners, public health officials) to the set of tasks they consider their jurisdiction, such as weatherizing homes, developing codes and standards, or providing social services to reduce exposure.

The primary questions of this chapter are as follows: *"How do professionals define and act on issues related to temperature in the built environment, and what are the barriers to collaboration among these professionals?"* The results from semi-structured interviews with thirty-two officials indicates that each profession has different diagnoses, methods of inference, and treatments it recommends to alleviate thermal stress; this creates barriers that can inhibit interdisciplinary collaboration.

Finally, Chapter 5 summarizes and discusses the results from each of the three chapters. The dissertation concludes with suggestions for future research that will build upon the results of this dissertation and fill additional gaps that were uncovered during the study.

## **6. Statement of Impact**

In addition to contributing to the literature on climate change impacts, energy efficiency, and vulnerability, a goal of my dissertation has been to assist public health officials, energy efficiency program managers, and urban planners in their efforts to reduce exposure to extreme temperatures. To that end, I have worked with officials from the City of Cleveland and Cuyahoga County to integrate my findings into their climate adaptation planning efforts. Chapters 2 through 4 will help these officials quantify exposure, test adaptation strategies at the urban and residential scale, and reduce the greenhouse gas footprint of Greater Cleveland.

Understanding the structure of the UHI, modeling exposure indoors, and finding common ground among professionals is timely and relevant because a number of organizations are currently working to reduce the threat of extreme heat. These efforts include messaging, cooling centers, utility bill pay programs, weatherization, healthy homes programs, and air pollution/urban heat island programs. This dissertation can help to overcome conflicts among disciplinary approaches and promote an efficient use of funding.

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## CHAPTER 2

### Assessing Microclimate Variation Using Fine-Scale Mobile Measurements

#### 1. Introduction

Over the last century, the average air temperature in the United States has increased by 0.7°C to 1.1°C (Melillo et al. 2014). While this increase should be of concern, and spur national action to reduce greenhouse gas emissions, air temperatures in a city are frequently 1.0 to 3.0°C warmer than rural locations (Oke 1997, Imhoff et al. 2010). In addition, temperatures can vary by several degrees Celsius among the neighborhoods of a city because of variations in impervious surfaces, vegetation, and waste heat from vehicles and buildings (Harlan et al. 2006, Coseo and Larsen 2014). While data taken by airport weather stations are reliable indicators of regional weather patterns, and are often used as the basis for heat warning systems (Sheridan 2002), these data are not necessarily representative of microclimatic conditions (Oke 2006).

While techniques like remote sensing can provide block-level estimates of land surface temperature, this information is less useful for estimating exposure to air temperature, a critical variable for planning responses to heat wave events (White-Newsome et al. 2013). Therefore, collecting a fine scale of microclimatic data is necessary to establish how physical characteristics (e.g., solar radiation, albedo, sky view factor, vegetation) contribute to local variations in exposure. Collecting these data suggest how urban design strategies (e.g., shading, light colored pavements, zoning codes, street tree planting) can reduce exposure to temperature (Coseo 2013).

However, urban microclimate measurement poses substantial challenges. Fixed weather stations cannot be deployed in advance of a heat wave, are difficult to site, and are subject to damage or vandalism (Oke 2006). In an effort to overcome these issues, I have designed, constructed, and validated a mobile measurement bicycle. This relatively low-cost system permits movement from space to space within a city to assess the physical and thermal properties of neighborhood-level microclimates.

The following chapter describes the design and construction of the bicycle system, explains the testing and validation procedures, and presents results from Cuyahoga County,

Ohio. Northeastern Ohio is the focus of this research because several national-level assessments of heat vulnerability identified the region as being extremely susceptible to high temperatures due to significant quantities of impervious surfaces and a high rate of poverty (Reid et al. 2009, Staudt and Inkley 2009, Altman et al. 2012). While Cleveland and its suburbs represents a single case, the results from this research are applicable in similar climates, and the methods are appropriate for use in other Great Lakes cities like Detroit, Toledo, and Buffalo.

## **2. Literature Review**

The following literature review is organized into three sections. The first part discusses the link between the physical characteristics of the built environment and increased ground surface and air temperatures. The second portion describes the use of mobile measurement systems to analyze thermal comfort and the urban canopy layer. The third and final section introduces the research questions that guided the research.

### *2.1 Urban Heat Islands*

Since the 1830s, studies in Europe, North America, and Asia have investigated the urban heat island (UHI) effect (Stewart 2011), though the first article to use the term “heat island” was not published until 1958 (Manley 1958, Imhoff et al. 2010). UHIs are broadly defined as the temperature difference between urbanized areas and their rural surroundings (Voogt and Oke 2003). UHIs are a byproduct of all human settlements regardless of their size; they are an important topic for research because they increase temperature exposure during heat waves, increase electrical demand associated with air-conditioning, and increase the formation of ground-level smog (Santamouris 2001).

Although nearly two hundred years of study have been devoted to the UHI effect, there are no standardized ways to precisely define UHI types (e.g., sub-surface, surface, near-surface air in the urban canopy layer, above roof-level in the urban boundary layer), nor is there agreement on the limitations of different measurement systems (e.g., remote sensing, weather stations, mobile measurements) (Oke 2006). This limits the generalizability of studies and the transferability of results, and it creates unnecessary divisions among the disciplines that make up the urban climate community.

However, there is a renewed interest in overcoming these barriers because the UHI effect amplifies the negative impacts of global climate change, especially heat waves (Stone 2012).

Recently, there have been efforts to develop a classification system to uniformly define urban and rural sites (Stewart and Oke 2012), and systematic reviews of the literature have helped to improve studies of the urban climate (Stewart 2011). It is now widely recognized that there are four vertical scales of UHIs: sub-surface, surface, urban canopy layer (UCL), and urban boundary layer (UBL). As their names imply, each is focused on a different cross-section of the city: below grade, at the earth's surface, from the ground to approximately the average roof height, and above the built environment (Oke 1982, Voogt and Oke 2003, Ferguson and Woodbury 2007).

While sub-surface and urban boundary layer UHIs are important because they negatively impact groundwater quality and exacerbate air pollution, this chapter focuses on surface and urban canopy layer UHIs because they increase thermal exposure for people outdoors and within buildings during extreme heat events. The following subsections outline how these UHIs form, measurement techniques, and their impacts on the urban climate (EPA 2008).

### *2.1.1 Surface Heat Islands*

Ground surface heat islands are primarily a daytime phenomenon that form under several conditions: (1) when the albedo of land covers is reduced (e.g., when vegetated area is converted to concrete); (2) when thermal properties of materials increase storage of heat during the daytime; (3) when pollution creates a greenhouse effect that reduces radiative losses; and (4) when urban canyons decrease longwave radiation loss at night (Santamouris 2001). According to Oke (1982), these ground surface heat islands are important to the overall energy balance of the urban climate because they modify air temperatures in the urban canopy layer, exchange energy with the lowest layers of the atmosphere, and directly impact human thermal comfort as a component of mean radiant temperature.

Ground surface heat islands are typically measured by remote sensing equipment like satellites. For example, Lo and Quattrochi (2003) used the Landsat visible, near infrared, and thermal wavelength data to develop statistical relationships between vegetation and ground surface temperatures in Atlanta. They found that surface temperatures and the normalized differential vegetation index (NDVI) were negatively correlated, which suggests that the concrete and asphalt that replaced forest and cropland had increased ground surface temperatures. Using Landsat, IKONOS, and Aqua satellite-based datasets, Imhoff and colleagues

(2010) found that impervious surface area explains 70% of the total variation in land surface temperature for thirty-eight of the most populous cities in the United States.

Under calm, cloudless conditions, the average difference in daytime surface temperatures between urban and rural sites is 10 to 15°C; the difference in nighttime surface temperatures is less at 5 to 10°C (Voogt and Oke 2003). The magnitude of ground surface UHIs varies seasonally due to changes in the sun's altitude, weather conditions, and vegetative cover. Surface UHIs are typically the greatest in the summer (Oke 1982). Although the primary impact of ground surface heat islands is a warming of the air, they also negatively affect stormwater temperatures and increase radiative gain to buildings, thereby increasing air-conditioner usage.

### *2.1.2 Urban Canopy Layer Heat Islands*

Urban canopy layer heat islands form under similar conditions to ground surface UHIs (Oke 1982). However, two additional factors cause localized warming of the air: (1) anthropogenic heat is released by the combustion of fuels from mobile and stationary sources; (2) a reduction of evaporating surfaces puts more energy into sensible rather than latent heat (Santamouris 2001). Canopy layer heat islands are the temperatures directly related to human temperature exposure occurring from roughly one meter above the ground to the average height of the surrounding buildings.

Measurement of air temperature in the urban canopy layer is difficult because most developed areas do not conform to standard guidelines for site selection and instrument exposure (Oke 2006). Of particular concern is the impact of local waste heat sources like building air-conditioning equipment, industrial sites, or vehicle exhaust if the goal is a representative measurement for a large area (Coseo and Larsen 2014). Recent efforts by Stewart (2011) have encouraged authors to report critical information about equipment type, calibration, and screen height to facilitate cross-comparison of studies; newly developed land cover classifications will also help to accurately define the source area of sensors (Stewart and Oke 2012). For stationary measurements of the canopy layer, most studies use either a weather station or microdataloggers to make observations of the local air temperature. The next section considers mobile measurement methods in detail.

Canopy layer UHIs are weak during the day but become stronger after sunset due to the release of stored heat from the built environment. The timing and intensity depends on the season, prevailing weather conditions, and the properties of urban surfaces. Canopy layer heat

islands are less intense than surface heat islands; air temperatures are on average only 1 to 3°C warmer than in rural locations in temperate cities (Oke 1997, Imhoff et al. 2010). However, these differences are exacerbated in a semi-arid desert climate: after controlling for open space and vegetated cover, Harlan et al. (2006) found that minority and low-income neighborhoods in Phoenix were 6°C warmer than in the surrounding rural areas.

## *2.2 Mobile Measurement of the Thermal Environment*

Data from airport weather stations do not have the resolution necessary to support microclimate studies at the district or neighborhood scale. While remote sensing can provide data on ground surface temperatures, vegetation levels, and albedo, limitations of aerial imagery include timing, cost, and spatial resolution. Additional fixed weather stations are expensive, are difficult to site, require permission for installation, are subject to vandalism and theft, and cannot be deployed quickly to capture data from a heat wave (Oke 2006). Due in part to these limitations, researchers have developed mobile measurement systems to analyze human thermal comfort and the urban canopy layer.

### *2.2.1 Human Thermal Comfort*

Thermal comfort carts are a simple way to gather data from inside buildings to assess human thermal comfort. At one end of the cost spectrum, Kwok (1998) describes the use of a simple push cart to transport handheld tools to evaluate thermal comfort in tropical classrooms. At the other end, Benton and colleagues (1990) describe a portable thermal comfort field measurement system that gathered inputs from more than ten thermal environmental sensors and stored the results to a laptop. This second system had a budget of approximately \$25,000 and was used to support a large multi-building study.

While the complexity of the systems varies, the results from field studies of thermal comfort are comparable to one another because they typically reference ASHRAE Standard 55 to determine transducer height, accuracy, and response time (ASHRAE 2010). However, a review of building thermal comfort research has revealed a lack of information on human response to conditions in semi-conditioned transitional spaces like passageways, courtyards, atria, and arcades. To address this gap, Potvin (1997) investigated urban arcades using a backpack-based system, comparing thermal environmental conditions to established thermal comfort models. Building on this research, Chun and Tamura (2005) used a cart to ferry equipment through a

shopping mall, department store, and train station in Japan while surveying subjects. Their research showed that mobile methods could be extended to cover larger distances (~1 kilometer) and semi-conditioned spaces, helping to bridge a gap in research between the indoor and outdoor thermal environments.

### *2.2.2 Urban Canopy Layer*

Mobile measurement of the urban canopy layer provides a simple way to gather data along a transect that spans urban and rural land uses. Mobile surveys are commonly used in urban climate studies to assess air temperature within canopy layer UHIs (Oke 1973, Unger et al. 2001); they can also be used as part of a larger observation network (Hedquist and Brazel 2006). Automobiles, vans, or light trucks are the most common platform for these studies; temperature sensors are typically attached in front of the engine or to the roof or to avoid thermal contamination (Conrads and Van Der Hage 1971, Straka et al. 1996). Advantages of mobile surveys include high temporal resolution of data, low cost compared to the expense of installing multiple stationary weather stations, and no need to cross-calibrate sensors and data from multiple sites (Stewart 2011).

Although using carts to study indoor thermal comfort and using automobile transects to analyze the urban canopy layer are both well-established approaches within their respective literatures, until recently few efforts bridged the gap between these micro- and mesoscale methods. Melhuish and Pedder (1998) were the first to demonstrate that UHIs could be measured at very little cost by using handheld equipment transported by bicycle. Heusinkveld et al. (2010) constructed a high-end mobile platform on a Dutch cargo tricycle to measure mean radiant and air temperatures in Rotterdam; their data were used to validate a thermal comfort model (Dai et al. 2012).

Brandsma and Wolters (2012) split the difference between these two approaches by collecting air temperature data using a micrologger attached to the front of a bicycle. Over a three-year period, they collected data along a 14-kilometer-long transect in Utrecht to describe the magnitude of the local UHI. They then used a regression model to predict the mean and maximum UHI intensity using local land covers as independent variables. This study had the greatest influence on this research; it showed how a bicycle could be used to obtain high-resolution observations of the UHI along a transect.

Finally, Coseo (2013) used an industrial tricycle to transport a full weather station with a telescoping 3-meter measurement mast to measure the microclimates of eight neighborhoods in Chicago, Illinois. While all of these studies demonstrate the utility of using cycles to take measurements, the methodology is still evolving. This chapter presents the use of a bicycle to gather ground and air temperature data along an urban-to-rural transect in Northeastern Ohio.

### *2.3 Research Questions*

This chapter examines how physical characteristics contribute to elevated ground and air temperatures. It is structured around two research questions. First, which physical characteristics explain ground and air temperature differences along an urban-to-rural transect in Cuyahoga County, Ohio? Drawing on a review of the literature, I hypothesize that incoming solar radiation, albedo, and sky view factor (SVF) explain the variation in ground surface temperatures along each transect; a reference air temperature, ground surface temperature, and land cover types explain the variation in air temperatures.

A second research question is whether a bicycle is a practical method to measure the physical characteristics of microclimates. Drawing on recently completed studies by others (Heusinkveld et al. 2010, Brandsma and Wolters 2012, Coseo 2013) and my own experience in Greater Cleveland in the summer of 2012, I hypothesize that bicycles are a viable alternative to stationary weather stations, microdataloggers, and automobile-based measurements of microclimates. I also posit that data gathered by a bicycle-based system can inform urban design, natural resource management, and public policy.

## **3. Methodology**

Cuyahoga County is located in the humid, mid-latitude zone of the United States at approximately 41.5°N and 81.7°W. The climate of the region is characterized by two distinct seasons: a warm-humid summer and a cold-dry winter. The average temperature in July is 23.1°C with a high of 28.1°C; the average temperature in January is -2.2°C with a low of -5.7°C (National Oceanic and Atmospheric Administration 2014).

The northern border of Cuyahoga County is Lake Erie; this large body of freshwater moderates temperatures in the height of summer. Although this heat sink provides a protective effect for Greater Cleveland, the frequency of heat waves in the Midwest has increased over the last sixty years (Perera et al. 2012). In addition, the magnitude of heat stress in the region is

projected to grow because of local increases in humidity (Schoof 2013). Therefore, understanding how factors like land cover moderate local temperatures is an important first step in reducing heat-related morbidity and mortality.

### *3.1 Mobile Measurement System Design*

For my research, the primary goal for the vehicle design was to take mobile measurements similar to those of automobile-based studies of the rural to urban temperature gradient, but to use a bicycle to avoid the contamination from vehicle engine exhaust and the necessity of traveling on a road. Although other studies have used bicycles as a platform to analyze the urban canopy layer, these studies gathered air temperature and relative humidity with either handheld equipment or microdataloggers attached to the bicycle. This is the first time a research-grade weather station has been installed on a bicycle to gather multiple types of data (e.g., ground surface temperature, solar radiation, sky view factor) for analysis. I also wanted to determine the amount of equipment that could be carried, whether a bicycle was a suitable platform for this type of analysis, and what limitations non-motorized transportation imposed on the investigation of rural-to-urban transects.

Because I needed to place meteorological equipment at least 1.25-meters above grade to avoid interference from the ground and to move up to 50 kilometers per transect (Oke 2006), I chose a cargo bicycle as a base for the equipment. Cargo (or trekking) bicycles are commonly used for bicycle touring with large amounts of camping equipment. They differ from standard bicycles in that they have a heavier-duty frames, spokes, and brakes, as well as longer wheelbases to improve stability under load.

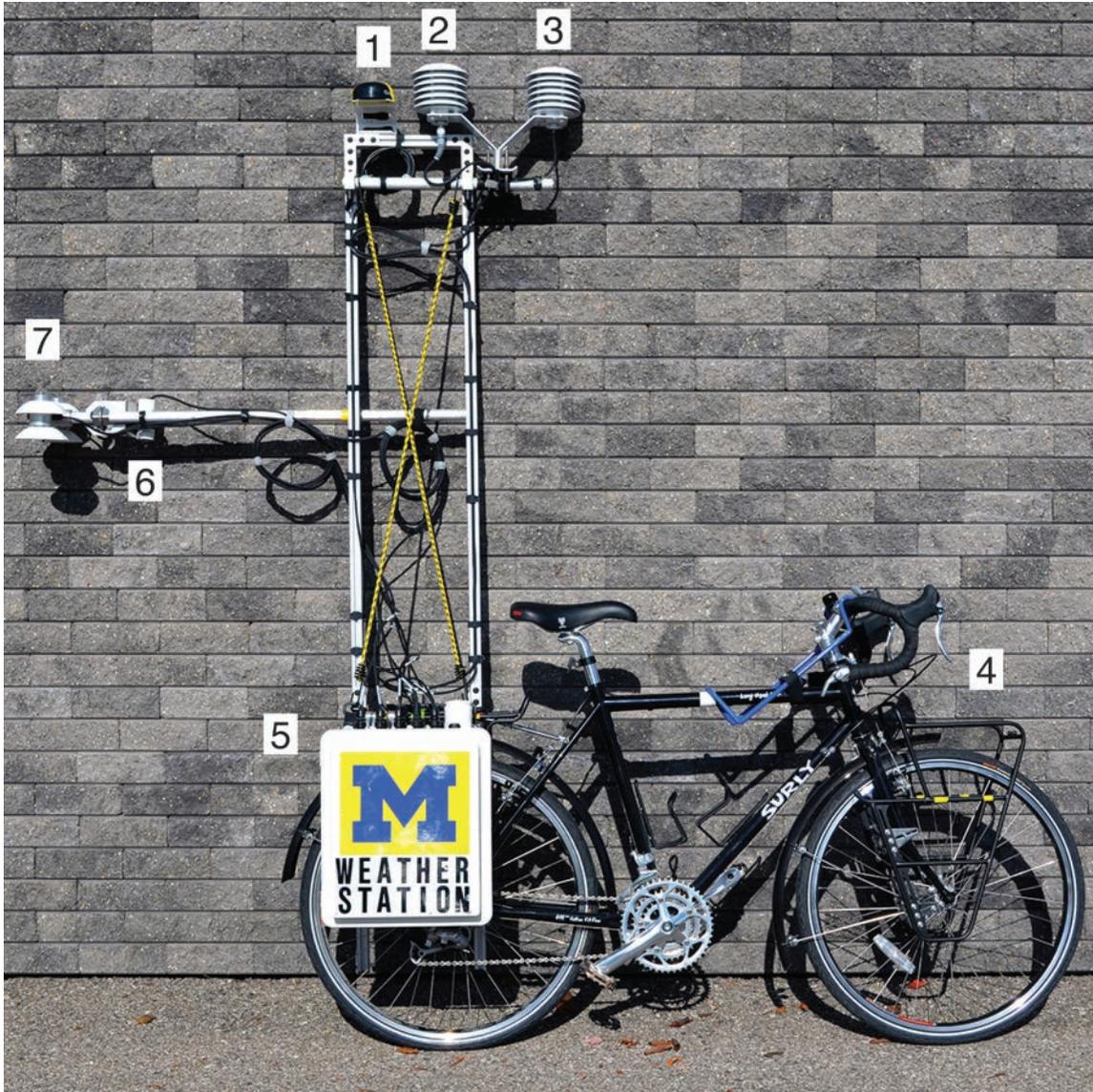


Figure 2.1: Image of the bicycle-based mobile measurement system: (1) GPS, (2) relative humidity and air temperature, (3) air temperature, (4) sky view factor camera (not shown, see Figure 2.2 for detail), (5) datalogger and barometric pressure, (6) ground surface temperature, (7) four component net radiometer

I was especially interested in bicycles with high weight capacities (>100kg) to hold the equipment on front- and rear-mounted racks, multiple gears to assist pedaling from site to site, and a size small enough that I could store the bicycle on a standard automobile bicycle rack. I worked with a local expert on cargo bicycles and a bicycle distributor in Ann Arbor, Michigan to select the base for the vehicle.

Table 2.1: Equipment Installed on Mobile Measurement System

	Description	Location	Accuracy
Air Temperature	BetaTherm 100K6A11A Thermistor in 6-Plate Radiation Shield	Top of mast, 2m	±0.2°C
Relative Humidity	Campbell CS215	Top of mast, 2m	±0.2°C, ±4% RH
Incoming/Outgoing Solar Radiation	Hukseflux NR01 Net Radiometer	Off back of mast, 1.25m	±2.5%, ISO Second Class
Incoming/Outgoing Longwave Radiation			
Ground Surface Temperature	Apogee SI-111 Infrared Radiometer	Off back of mast, 1.25m	±0.2°C
Latitude/Longitude	Garmin GPS16X-HVS	Top of mast, 2m	<3m with DGPS correction
Time			1 μs
Wind Speed	N/A		
Barometric Pressure	Vaisala PTB110	In datalogger enclosure	±0.3 hPa at +20°C
Sky View Factor	Nikon D5100 w/ Sunex 5.6mm Fisheye Lens	Front Bicycle Rack	Not Specified
	Nikon GP-1		
Datalogger	Campbell CR3000	Rear Bicycle Rack	Varies by Input Type
Datalogger Enclosure	Campbell PWENC 12/14		N/A
Total Weight	Bicycle: ~15 kg, Equipment: ~30 kg		
Cost	~\$16,000 USD		

Note: Table format adapted from Benton et al., (1990). Data provided by Campbell Scientific, Inc. and individual sensor manufacturers.

Figure 2.1 illustrates the final configuration of the equipment on the cargo bicycle; Table 2.1 presents the specifications for each piece of equipment. A thermocouple unit, hygrometer unit, and GPS unit were installed at the top of a 2.0-meter-tall aluminum tower constructed of extruded aluminum sections. The GPS unit collected latitude, longitude, and speed, and provided a time stamp to synchronize fisheye images taken by a camera to determine sky view factor. A four component net radiometer and infrared radiometer were installed off the back of the bicycle 1.25 meters above the ground to gather information about incoming and outgoing short- and longwave radiation and ground surface temperature. All of the equipment took a reading once every second; the datalogger averaged the measurements for each minute and stored it to an onboard solid state hard drive.

The aluminum bar installed horizontally off of the back of the bicycle was an attempt to move the net radiometer and infrared radiometer as far away as possible from the bicycle to reduce interference; through trial and error attempts, I determined that the 1.0-meter distance balanced the overall bicycle weight from front to back. I decided against using a bicycle trailer for this purpose because the equipment might be damaged if I rode over an obstruction or rough pavement (the net radiometer contained a platinum fine wire thermistor that could easily be

damaged). A watertight box contained the datalogger and a barometer to measure atmospheric pressure. Both the tower and datalogger box were connected to a bicycle rack using standard bicycle pannier hardware that facilitated quick assembly on site.

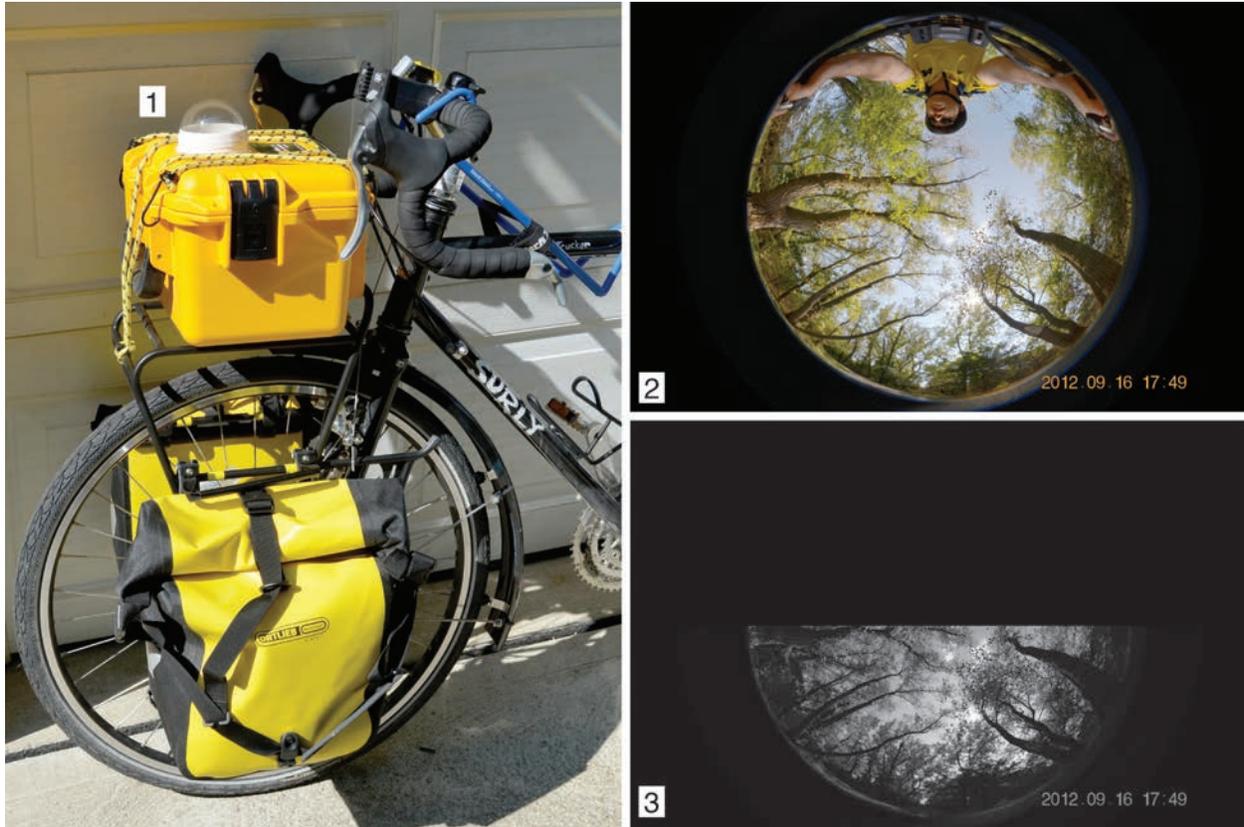


Figure 2.2: Image of the front of the bicycle-based mobile measurement system: (1) Sky view factor camera housing mounted on the front of the bicycle, (2) fisheye image collected by the camera, (3) image after mask applied and ready for analysis

### 3.1.1 Sky View Factor Measurement

Several authors have described the use of fisheye lenses for measurement of SVF (Herbert 1987, Clark and Follin 1988), and Frazer et al. (2001) described the advantages of digital- over film-based systems. However, the design of my SVF measurement system was most influenced by Grimmond et al. (2001), who used a digital camera with a fisheye lens to gather SVF data in Bloomington, Indiana.

I used a newer version of the same Nikon camera, the D5100, which had an on-board intervalometer to take an image every minute. In addition, I used an accessory GPS unit to synchronize the photography with the datalogger data collection cycle and to geocode each

image. I chose a fixed f/5.6 Sunex 5.6mm fisheye lens because it had a 185° field of view and no moving parts that might be damaged by vibration.

The photographic equipment was placed in an air- and watertight plastic box with a clear acrylic dome on the top (Figure 2.3). The plastic case contained protective foam in case the apparatus fell off the bike. In the box on the front of the bike, the camera lens was 0.75 meters above the ground. Through trial and error, I determined that the best shutter speed was 1/1000 sec under overcast and clear sky conditions. As the lens had a high fixed f-stop, every image was in focus and had a good depth of field.

Because the camera was facing upward, solar radiation tended to overheat the interior of the box and the camera. A reusable icepack was chilled in a refrigerator to ~4°C and placed in the box prior to each transect to keep the camera cool. In addition, white electrical tape was placed around the base of the clear plastic dome to reflect as much solar radiation as possible without obstructing the image.

The camera collected a hemispherical image every minute of the transect. After each ride, it was necessary to crop out the half of the image that was obscured by the rider and equipment. I developed a computer script to automate the cropping, reduce the file size, and convert the image to black and white for analysis. After all of the images were processed, I then input them into the SkyViewFactor Calculator software, version 1.1 (University of Gothenburg Department of Earth Sciences 2011). Using the time and geocode on each image, I could match the SVF data with the other meteorological data gathered by the bicycle.

### 3.2 *Route Selection*

To test the limitations of the bicycle, I selected a number of bicycle paths in Cuyahoga County that had a variety of land covers, topographies, distances from Lake Erie, and paving types. The Cleveland Metroparks and the Cuyahoga Valley National Park maintained the bicycle paths I chose; both organizations required research permits and liability insurance prior to the first ride.

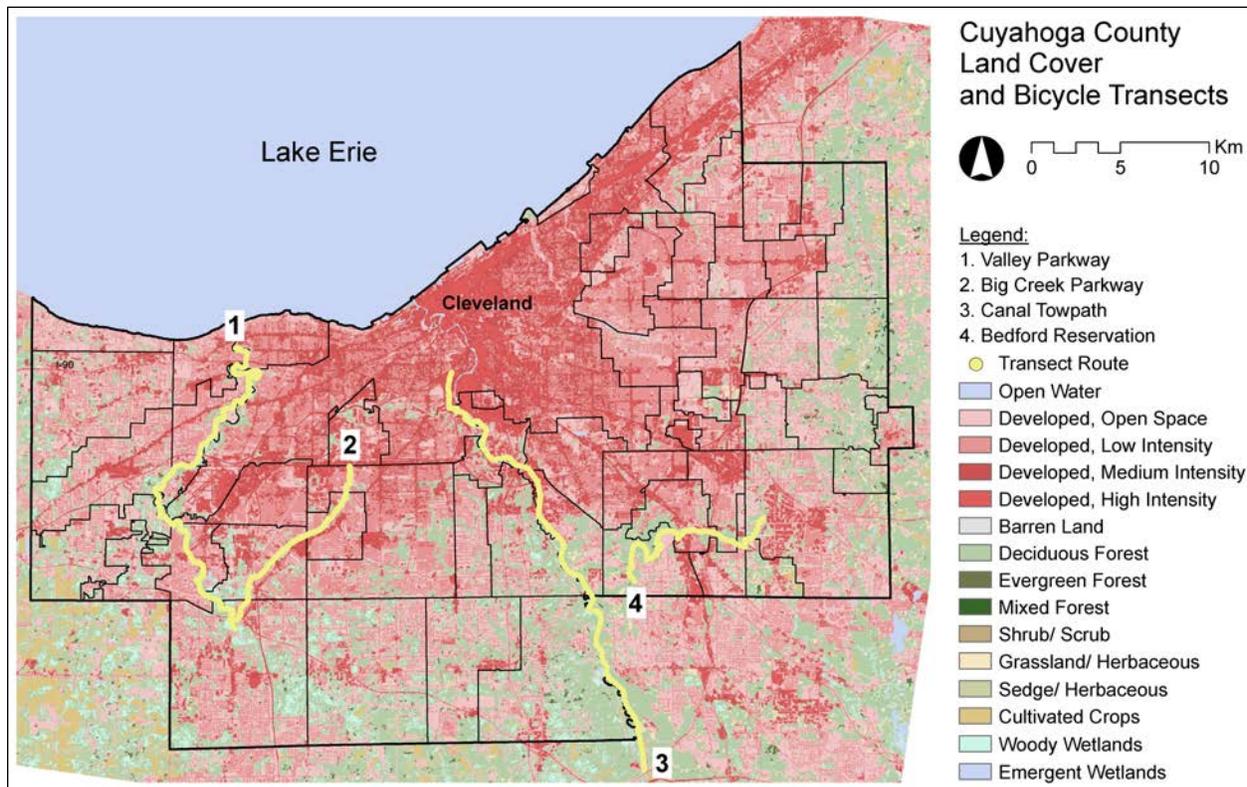


Figure 2.3: Map of transect routes. Data sources: Cuyahoga County Geographical Information Systems Department (2012), U.S. Census Bureau (2010), National Land Cover Database (2006).

I first walked each of the paths to identify low clearances that could damage the equipment. Basing my decisions on the on-site evaluation, I further limited my rides to the four paths presented in Figure 2.3.

Because one goal of the research was to correlate air temperature with land cover, I rode the bicycle on days immediately before or after a Landsat 7 acquisition date (Appendix A). Landsat 7 was on a 16-day acquisition cycle; this allowed me to prepare for rides several weeks in advance and to perform ongoing checks of equipment calibration between rides. However, when I post-processed the data I found that I was unable to use the Landsat data because of cloud cover and gaps in the data. I opted instead to use a 10-meter resolution land cover analysis recently completed by the Cuyahoga County Geographical Information Systems (GIS) Department (Cuyahoga County GIS Department 2014).

I numbered each section of the bicycle paths and used a random number table to select the path and direction I rode each day. I attempted to ride the paths during the hottest part of the day, typically in the late afternoon. Due to safety concerns, I did not ride the bicycle at night. In total I completed twelve rides on the bicycle paths where the data was deemed usable.

### 3.3 *Data Quality Control and Reference Air Temperatures*

For my air temperature analysis, I found it necessary to have an air temperature from a local station to control for daily weather conditions. I reviewed data from KCLE, Burke Lakefront Airport (KBKL), Akron-Canton Regional Airport (KCAK), and the National Oceanic and Atmospheric Administration (NOAA) site CND01. KCAK was located more than 40 kilometers from the sites, so I decided that it would not be representative of the conditions in Cuyahoga County. While the other two airports (KCLE and KBKL) were viable options, I chose to use data from site CND01 because it recorded measurements every 6 minutes, limiting the need for interpolation between data points.

According to the NOAA National Data Buoy Center website, the CND01 weather station is located at 41.542°N and 81.637°W. Air temperature on site is measured at 3.9m above the ground; wind speed is gathered at 7.77m above the ground (NOAA 2014). Before using data from this weather station, I visited the site and concluded that the equipment would not be subject to contamination from local heat sources like automobile exhaust or air-conditioning equipment. It also appeared that the equipment was regularly maintained by NOAA.

### 3.4 *Data Processing*

Using spreadsheet software, I was able to link the data from the bicycle with the reference air temperature data from station CND01 using the timestamps. I then input this spreadsheet into GIS software to begin examining spatial relationships among the data. Using the latitude and longitude data associated with each measurement point, I geolocated the data points on the Canal Towpath and then overlaid them onto the 10-meter resolution land cover from the Cuyahoga County GIS Department.

Local ground and air temperatures under the canopy layer are affected by land covers; this is frequently called the “source area” or “footprint” of the measurement (Oke 2006). Source areas are often assumed to have a circular or elliptical shape (Brandsma and Wolters 2012, Coseo and Larsen 2014). To facilitate comparison of my results with those of Brandsma and Wolters (2012) and Coseo and Larsen (2014), I selected circles with radii varying from 25 to 600m. I also selected an ellipse that was 500m long and 300m wide, with the long axis of the ellipse facing upwind at each point. Once I had determined the size of the circles and ellipses for testing, I then used the GIS software to extract the fraction of each of the five land covers around each measurement point.

## 4. Results

The results section of this chapter follows the order of the two research questions presented at the end of the literature review. Several hypotheses were developed to test each of the questions; each of these hypotheses is presented along with the results from my analysis in the following section. The conclusions section of this chapter elaborates on the results and describes the implications for policy, program design, and program management.

Table 2.2: Bivariate Correlations among Physical Characteristics and Ground Surface Temperature

	Ground Surface Temp.	Reference Air Temp.	Solar Rad.	Albedo	SVF	Bicycle Speed	Ride 2 Dummy	Ride 3 Dummy	Ride 4 Dummy	Lat.	Long.	Lat. <sup>2</sup>	Long. <sup>2</sup>
Reference Air Temp.	0.130***												
Solar Rad.	0.696***	-0.164***											
Albedo	-0.308***	0.529***	-0.123***										
SVF	0.297***	-0.309***	0.417***	-0.292***									
Bicycle Speed	-0.005	-0.201***	0.045	-0.229***	0.161***								
Ride 2 Dummy	0.253***	0.416***	0.318***	0.437***	-0.208***	-0.252***							
Ride 3 Dummy	-0.297***	0.108**	-0.095**	-0.024	-0.012	0.102**	-0.400***						
Ride 4 Dummy	-0.060	-0.857***	0.135***	-0.541***	0.341***	0.199***	-0.340***	-0.309***					
Lat.	0.260***	-0.619***	0.209***	-0.614***	0.491***	0.225***	-0.375***	-0.237***	0.687***				
Long.	-0.234***	0.655***	-0.186***	0.625***	-0.444***	-0.196***	0.380***	0.263***	-0.733***	-0.977***			
Lat. <sup>2</sup>	0.260***	-0.619***	0.209***	-0.614***	0.491***	0.224***	-0.375***	-0.237***	0.687***	1.000***	-0.977***		
Long. <sup>2</sup>	0.234***	-0.655***	0.186***	-0.625***	0.444***	0.196***	-0.380***	-0.263***	0.733***	0.977***	-1.000***	0.977***	
Lat. x Long.	-0.255***	0.632***	-0.204***	0.619***	-0.481***	-0.218***	0.378***	0.245***	-0.703***	-0.998***	0.987***	-0.998***	-0.987***

\* $p < 0.025$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

### 4.1 Ground Surface Temperature Bivariate Correlations

2012 was the warmest year on record in Cuyahoga County; twelve days had record high temperatures. Because of the day-to-day variability of weather, it was necessary to control for local conditions and unobserved phenomena during each ride. To this end, I included several control variables in my analysis. These variables included the reference air temperature from station CND01, the speed of the bicycle, dummy variables for each of the four rides, and five latitude and longitude variables to account for spatial autocorrelation.

Before performing a statistical analysis, I first conducted a bivariate analysis to understand the relationship among the independent variables and the ground surface temperature on the four rides on the towpath. Table 2.2 presents the correlation among these variables. The 11 significant bivariate correlations ( $p < 0.001$ ) were (1) reference air temperature (0.130), (2)

incoming solar radiation (0.696), (3) albedo (-0.308), (4) sky view factor (0.297), (5) dummy variable for the second ride on July 25, 2012 (0.253), (6) dummy variable for the third ride on July 25, 2012 (-0.297), (7) latitude (0.260), (8) longitude (-0.234), (9) latitude to the second power (0.260), (10) longitude to the second power (0.234), and (11) latitude multiplied by longitude (-0.255). Neither the dummy variable for the fourth ride nor the speed of the bicycle were statistically significant. The bivariate correlations help to clarify the relationship among variables before I proceeded to a regression model.

Although there was high correlation among all five of the latitude and longitude variables, they are only used as a control for spatial autocorrelation and are not statistically significant in the final regression model. Any inflation in the variance and standard error would be limited to these spatial variables. While I could have omitted several of these variables to reduce multicollinearity among the spatial variables—for example, by using only latitude and longitude as a control—it was important to include latitude and longitude to the second power because the variation in observations might not vary linearly. I also included latitude multiplied by longitude to account for any interactive effect between latitude and longitude, since the towpath route is oriented NNW to SSE. This approach is consistent with those of other studies that include spatial variables in regression models, for example Immergluck and Smith (2006) and Galster et al. (2004).

#### *4.2 Ground Surface Temperature Regression Analysis*

Drawing on the results of the bivariate correlation and a review of the literature, I hypothesized that incoming solar radiation, albedo, and sky view factor would explain the variation in ground surface temperatures along each transect. To test this hypothesis, I performed an ordinary least squares (OLS) regression to determine the explanatory power of the independent variables on ground surface temperature.

I tested my hypothesis with three models. Model 1 included only the independent variables and a control for bicycle speed. Model 2 utilized all of the variables from the first model and added three dummy variables to control for unobserved phenomena on each ride. Model 3 included five spatial variables based on the latitude and longitude of each observation to control for spatial autocorrelation. Results from the regression analysis appear in Table 2.3.

Model 1, which includes reference air temperature, incoming solar radiation, albedo, sky view factor, and the bicycle speed, explains 71.8% of the variation in ground surface

temperature. The model is statistically significant, with an F-Value of 382.64. With the exception of sky view factor, all of the independent variables are statistically significant ( $p < 0.01$ ).

Including the dummy variables for each of the four rides gives Model 2 an adjusted  $R^2$  of 0.845, an improvement of 0.127 over Model 1. This model is also statistically significant, with an F-Value of 511.90. In the second model, all of the variables are significant except sky view factor and the control variable for bicycle speed ( $p < 0.001$ ).

Table 2.3: OLS Regression Analysis for Ground Surface Temperatures on the Canal Towpath

	Model 1			Model 2			Model 3		
	$\beta$	SE	t-Statistic	$\beta$	SE	t-Statistic	$\beta$	SE	t-Statistic
Reference Air Temperature	1.300***	0.060	21.52	1.007***	0.078	12.91	1.023***	0.076	13.50
Incoming Solar Radiation	0.014***	0.000	33.32	.016***	0.000	40.31	.015***	0.000	40.57
Albedo	-36.350***	1.723	-21.09	-37.589***	1.367	-27.50	-34.011***	1.441	-23.61
Sky View Factor	0.367	0.415	0.89	.180	0.326	0.55	-.277	0.336	-0.83
Bicycle Speed	-0.168**	0.065	-2.59	-.082	0.049	-1.67	-.068	0.049	-1.41
Ride 2 Dummy				-2.475***	0.239	-10.35	-2.011***	0.241	-8.34
Ride 3 Dummy				-5.162***	0.208	-24.73	-4.632***	0.217	-21.31
Ride 4 Dummy				-3.927***	0.389	-10.09	-4.839***	0.411	-11.78
Latitude							-2780.866	28945.53	-0.10
Longitude							3650.522	41717.6	0.09
Latitude <sup>2</sup>							143.972	247.177	0.58
Longitude <sup>2</sup>							50.716	380.544	0.13
Latitude x Longitude							111.713	581.365	0.19
Constant	7.363***	1.467	5.02	15.643***	1.861	8.41	205958.3	1222943	0.17

$n$	759	759	759
F	382.64	511.90	340.32
Adjusted $R^2$	0.718	0.845	0.856
Change in $R^2$		0.127	0.011

\* $p < 0.025$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

Adding the five latitude/longitude variables to control for spatial autocorrelation in Model 3 improves the adjusted  $R^2$  to 0.856, an improvement of 0.011 over Model 2. However, the F-Value of the model drops to 340.32, likely because five additional variables that are not statistically significant were added to the model. In this third model, only the reference air temperature, solar radiation and albedo are statistically significant ( $p < 0.001$ ), and they have similar coefficient values to Model 2. This may mean that spatial variables could be omitted

from a ground temperature model; however, further analysis of additional rides would be necessary to test this claim.

#### 4.3 Air Temperature Bivariate Correlations

Before performing a statistical analysis, I first conducted a bivariate analysis to understand the relationship among the independent variables and the air temperatures on three rides on the towpath. I omitted the fourth ride on September 16, 2012 because the air temperatures were low, and I was primarily interested in the relationship among physical characteristics and air temperatures on hot days (>27°C). Table 2.4 presents the correlations among these variables.

The fractions of forest and water were calculated from the Cuyahoga land cover database as the percentage of each land cover in an ellipse that was 500m long and 300m wide with the long axis oriented upwind from the observation (Oke 2006, Coseo and Larsen 2014). While the Cuyahoga County land cover database characterized land covers for five types (impervious, barren, grass, forest, and water), I found that impervious and grass land covers had a similar coefficient that increased air temperature. Very few of the observations (<5%) had bare soil in the upwind ellipse. Therefore, I folded these three land covers (impervious, barren, grass) into one classification called “impervious” for my analysis.

Table 2.4: Bivariate Correlations among Physical Characteristics and Measured Air Temperature

	Measured Air Temp.	Reference Air Temp.	Ground Surface Temp.	Fraction Forest	Fraction Water	Bicycle Speed	Ride 1 Dummy	Ride 2 Dummy	Lat.	Long.	Lat. <sup>2</sup>	Long. <sup>2</sup>	Lat. x Long.
Measured Air Temp.	1												
Reference Air Temp.	0.734***	1											
Ground Surface Temp.	0.232***	0.050	1										
Fraction Forest	-0.090	0.111*	-0.209***	1									
Fraction Water	-0.142**	-0.026	-0.140**	-0.119*	1								
Bicycle Speed	-0.114*	-0.117*	-0.017	-0.181***	-0.005	1							
Ride 1 Dummy	0.199***	0.013	0.028	-0.189***	-0.058	0.010	1						
Ride 2 Dummy	0.235***	0.360***	0.316***	0.207***	-0.124**	-0.220***	-0.507***	1					
Latitude	-0.003	-0.169***	0.470***	-0.402***	-0.305***	0.170***	0.160***	-0.041	1				
Longitude	0.011	0.157***	-0.487***	0.397***	0.268***	-0.160***	-0.209***	0.082	-0.976***	1			
Latitude <sup>2</sup>	-0.003	-0.169***	0.470***	-0.402***	-0.305***	0.169***	0.161***	-0.041	1.000***	-0.976***	1		
Longitude <sup>2</sup>	-0.011	-0.157***	0.487***	-0.397***	-0.268***	0.160***	0.209***	-0.082	0.976***	-1.000***	0.976***	1	
Latitude x Longitude	0.005	0.166***	-0.476***	0.402***	0.298***	-0.168***	-0.173***	0.051	-0.999***	0.986***	-0.999***	-0.986***	1

\* $p < 0.025$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

The 11 significant bivariate correlations ( $p < 0.025$ ) were (1) the reference air temperature at station CND01 (0.734), (2) ground surface temperature (0.232), (3) fraction water (-0.142), (4) bicycle speed (-0.114), (5) dummy variable for the first ride on June 27, 2012 (0.199), (6) dummy variable for the second ride on July 25, 2012 (0.235), (7) latitude (-0.003), (8) longitude (-0.011), (9) latitude to the second power (-0.003), (10) longitude to the second power (-0.011), and (11) latitude multiplied by longitude (0.005). The fraction of forest in the upwind ellipse was not statistically significant. The bivariate correlations helped to clarify the relationship among variables before I proceeded to a regression model.

#### 4.4 *Air Temperature Regression Analysis*

Drawing on the results of the bivariate correlation and a review of the literature, I hypothesized that reference air temperature, ground surface temperature, and land cover types would explain the variation in air temperatures along each transect. To test this hypothesis, I performed an ordinary least squares (OLS) regression to determine the explanatory power of the independent variables on air temperature. Because of the day-to-day variability of weather, it was necessary to control for local conditions and unobserved phenomena during each ride. To this end, I included several control variables in my analysis. These variables included reference air temperature from station CND01, the speed of the bicycle, dummy variables for each of the four rides, and five latitude and longitude variables to account for spatial autocorrelation.

I tested my hypothesis with three models. Model 1 included only the independent variables and a control for bicycle speed. Model 2 used all of the variables from the first model and added two dummy variables to control for unobserved phenomena on each ride. Model 3 included five spatial variables based on the latitude and longitude of each observation to control for spatial autocorrelation. I limited my analysis to temperatures over 27°C because I am primarily interested in the relationship among the independent variables and air temperature on the hottest days to help quantify exposure during heat waves. Results from the regression analysis appear in Table 2.5.

Model 1, which includes reference air temperature, ground surface temperature, fraction forest, and fraction water, explains 60.8% of the variation in air temperature. Note that sky view factor was omitted from the model, as preliminary modeling showed that it was not correlated with air temperature, nor was it statistically significant in the ground temperature study. With the exception of bicycle speed, all of the independent variables are statistically significant ( $p < 0.001$ ).

Including the dummy variables for each of the four rides improves the adjusted  $R^2$  of Model 2 to 0.630, an improvement of 0.022 over Model 1. However, the F-Value declines from 139.73 to 109.51. In the second model, all of the independent variables are statistically significant; the control variable for bicycle speed and the dummy variable for the second ride are the only factors that do not achieve statistical significance at the 0.001 level.

Table 2.5: OLS Regression Analysis for Measured Air Temperature on the Canal Towpath

	Model 1			Model 2			Model 3		
	$\beta$	SE	t-Statistic	$\beta$	SE	t-Statistic	$\beta$	SE	t-Statistic
Reference Air Temperature	0.490***	0.020	24.520	0.483***	0.021	22.590	0.479***	0.020	23.520
Ground Surface Temp.	0.014***	0.003	4.620	0.014***	0.003	4.330	0.020***	0.003	5.940
Fraction Forest	-0.476***	0.090	-5.320	-0.387***	0.090	-4.310	-0.249*	0.104	-2.410
Fraction Water	-0.875***	0.215	-4.060	-0.771***	0.212	-3.640	-0.677**	0.215	-3.150
Bicycle Speed	-0.022	0.012	-1.860	-0.019	0.012	-1.670	-0.013	0.011	-1.150
Ride 1 Dummy				0.171***	0.039	4.440	0.226***	0.037	6.070
Ride 2 Dummy				0.016	0.047	0.330	-0.009	0.045	-0.210
Latitude							11795.720	6127.608	1.930
Longitude							-25575.51**	9797.343	-2.610
Latitude <sup>2</sup>							277.327***	57.064	4.860
Longitude <sup>2</sup>							-48.836	83.202	-0.590
Latitude x Longitude							425.646***	124.343	3.420
Constant	16.930***	0.483	35.050	16.931***	0.512	33.070	-1287504***	309841.4	-4.160

<i>n</i>	448	448	448
F	139.73	109.51	80.31
Adjusted $R^2$	0.608	0.630	0.680
Change in $R^2$		0.022	0.05

\* $p < 0.025$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

Adding the five spatial variables to control for autocorrelation in Model 3 improves the adjusted  $R^2$  to 0.680, an improvement of 0.05 over Model 2. However, the F-Value of the model drops further to 80.31, likely because five variables with limited statistical significance were added to the model. However, it was important to control for spatial autocorrelation because observations near one another could skew the direction of the coefficients and their value. In this third model, all of the independent variables are statistically significant at the 0.025 level.

#### 4.4.1 Testing Diameters of Source Areas

Although the model presented in the last section used an upwind 500m-by-300m ellipse to quantify land cover, I also tested several radii of circles around each observation point to determine their contribution to air temperature. I conducted this analysis so that I could compare my results with the findings of Brandsma and Wolters (2012), the only other study that used a bicycle to gather air temperature data to quantify a canopy layer UHI. I also tested a series of “nested” models where a smaller-diameter circle was inside a larger-diameter circle (e.g., a 50m circle inside 500m circle); however, none of these tests proved to be statistically significant.

Table 2.6: Comparison of Radii Used for Air Temperature OLS Regression Analysis

	500m Radius	400m Radius	300m Radius	200m Radius	100m Radius	50m Radius	25m Radius	500m x 300m Ellipse
n	263	273	286	435	494	499	503	448
F	52.29	53.43	55.20	75.87	86.85	88.08	88.58	80.31
Adjusted R <sup>2</sup>	0.701	0.698	0.695	0.674	0.676	0.677	0.677	0.680

	β	β	β	β	β	β	β	β
Reference Air Temperature	0.454***	0.460***	0.468***	0.476***	0.474***	0.474***	0.473***	0.479***
Ground Surface Temperature	0.019***	0.019***	0.020***	0.020***	0.020***	0.020***	0.021***	0.020***
Fraction Forest	-0.512	-0.447	-0.311	-0.367**	-0.218	-0.166**	-0.079***	-0.249*
Fraction Water	0.180	-0.521	-0.479**	-0.264	-0.429	-0.221	-0.032	-0.677**

\* $p < 0.025$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

Table 2.6 presents the results of this analysis; note that the control variables including bicycle speed and latitude/longitude have been omitted from the table for clarity. Overall, the models explained between 67.4 and 70.1 percent of the variation in air temperature. While the model with a 500m radius of land cover had the highest R<sup>2</sup> at 0.701, there was only one model in which all of the dependent variables were statistically significant and the coefficient was in the expected direction: the model that used the upwind ellipse in the calculation. This model explained 68.0% of the variation in air temperature. In addition, the F-Value was higher for the ellipse model than the 500m radius model.

These findings confirm that the ellipse shape was the best fit for my OLS regression model, for three reasons. First, while land covers are somewhat homogenous around each observation point, they are not necessarily symmetrical upwind and downwind of each observation. For example, the Cuyahoga River and Ohio and Erie Canal are adjacent to the path along parts of the route; if one used a large radius circle (~500m), they would be included in

almost every observation, which would reduce the statistical power of this independent variable. Second, while a circle takes into account the surrounding source areas of land covers, it would ignore waste heat that might be carried by the wind to an observation point. Because the ellipse varies with wind direction, the regression model “assigns” this warming to a land cover type. Finally, the towpath runs along the southeast edge of the county. Several of the observations fell outside the land cover database provided by the county; this is why the number of observations in Table 2.6 varies. If the number of all of the land cover observations were consistent, these results might be different; for example, there might be greater variation in  $R^2$  and F-Value among the models.

#### 4.5 *Visualizing Transect Data*

Drawing on the work of others (Heusinkveld et al. 2010, Brandsma and Wolters 2012, Coseo and Larsen 2014), I hypothesized that bicycles are a viable alternative to stationary weather stations, microdataloggers, and automobile-based measurements of microclimates. While the regression analysis determined the utility of the bicycle to estimate the contribution of biophysical variables to ground and air surface temperatures, graphing and mapping the results of the June 27, 2012 transect shows the increased temporal and spatial resolution of bicycle-based measurements.

Figure 2.4 compares the temporal resolution of the bicycle with four fixed weather stations in Cuyahoga County. During the two-hour transect on June 27, 2012, three fixed airport weather stations (KCGF, KBKL, and KCLE) each took two air temperature measurements at a rate of once per hour. Station CND01 took an air temperature measurement once every six minutes for a total of twenty-one measurements. While three of the four weather stations indicate a warming of the air temperature over the two-hour period, the data from station CND01 shows that this change is not perfectly linear.

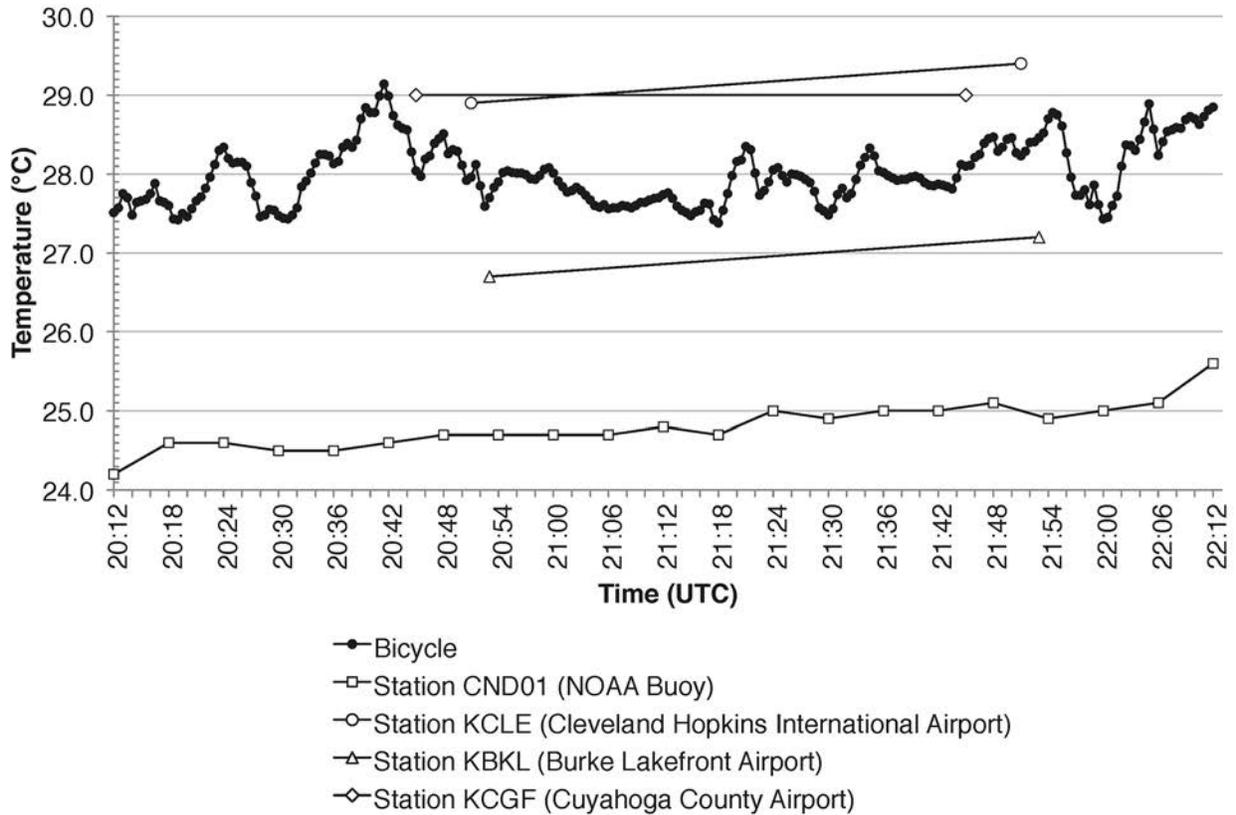


Figure 2.4: Graph showing frequency of air temperature data measurement by four fixed stations in Cuyahoga County (KCGF, CND01, KBKL, KCLE) and the bicycle transect on June 27, 2012.

In addition, there was significant variation in measured temperatures among three of the fixed weather stations. Stations KCLE and KCGF recorded similar temperatures over the two-hour period, averaging approximately 29°C, while temperatures at KBKL and CND01 were 2 and 4°C lower, respectively. This is likely because KCLE and KCGF are located inland, and are subject to warming from surrounding impervious surfaces and waste heat. Stations KBKL and CND01 are both on the shore of Lake Erie, and are therefore influenced more by water temperature.

Comparing the temperature difference between KCLE and KBKL shows how much temperature can vary in a short distance. As mentioned in the methods section, CND01 is located adjacent to a nature preserve, and is approximately 4 kilometers from downtown Cleveland. KBKL is located immediately adjacent to the commercial district in Cleveland, at the airport. During the June 27 transect, the fixed weather stations recorded a 2°C difference between CND01 and KBKL, likely because of waste heat emissions from the airport and its location next to downtown Cleveland.

In contrast, the bicycle recorded 178 data points during the same period, and because the results were geocoded, they could be compared against land covers from a 27-kilometer-long transect of the Cuyahoga Valley. This procedure eventually can be used to create maps of how temperature varies in neighborhoods by overlaying land covers onto each neighborhood's boundary and assigning the expected increase or decrease in temperature. This type of mapping exercise would be helpful for planning of heat wave responses because the graph in Figure 2.5 shows how air temperature varied in very short distances (<2 kilometers) during the June 27<sup>th</sup> transect. Although there was only a range of only 1.5°C recorded, there was still more variation than found at the other four fixed stations during the same time period. In addition, a 1.5°C temperature difference can have significant impact on personal exposure to temperature or air-conditioning operation in a building.

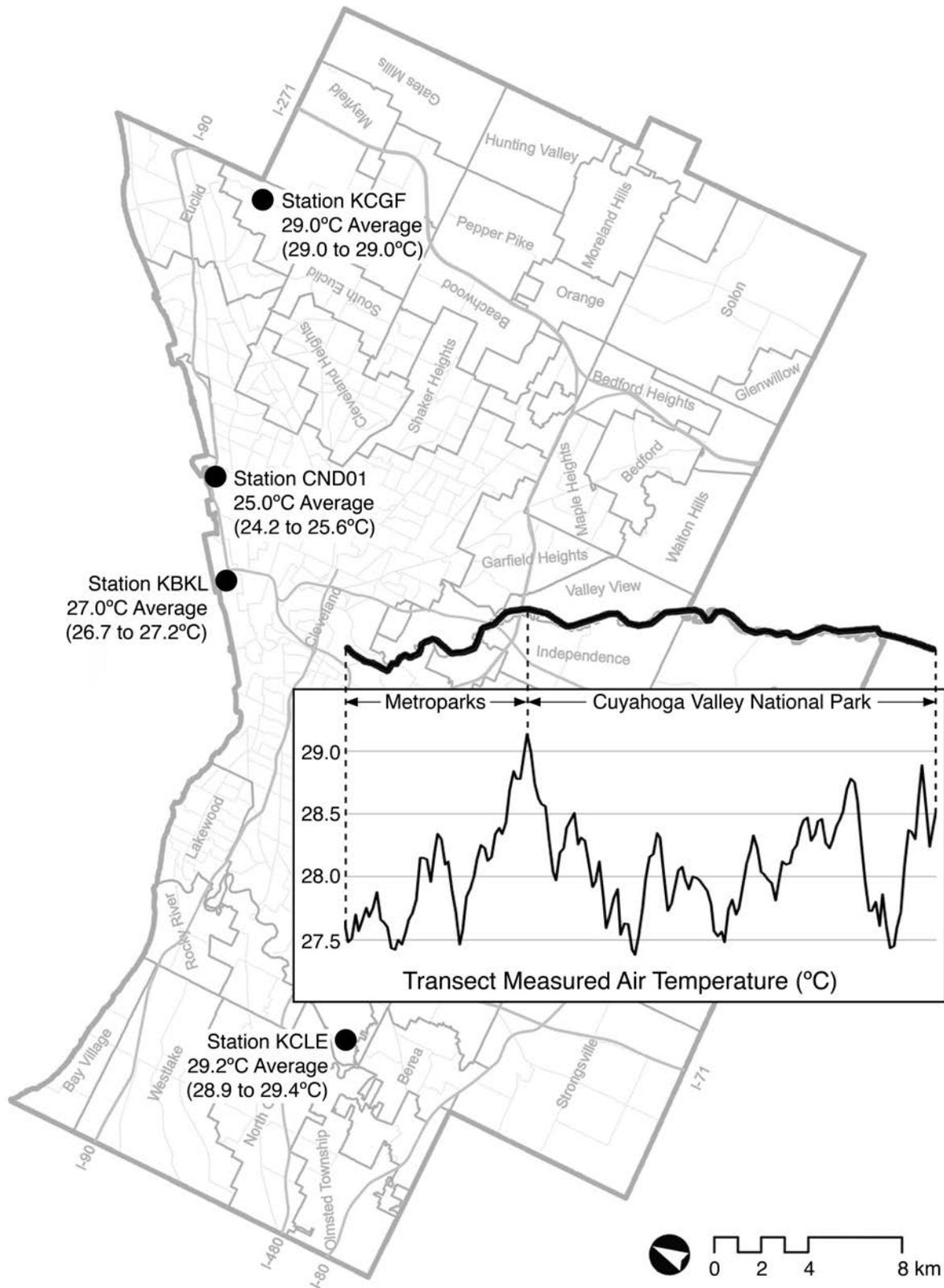


Figure 2.5: Map and graph showing air temperature data from four fixed stations in Cuyahoga County (KCGF, CND01, KBKL, KCLE) and the bicycle transect on June 27, 2012.

## 5. Discussion

The research was structured around two questions and their associated hypotheses. In the following paragraphs, I discuss the relevance of the results and their implications for urban design, natural resource management, and public policy.

First, I hypothesized that incoming solar radiation, albedo, and sky view factor would explain the variation in ground surface temperatures along each transect. An OLS regression model that incorporated spatial effects to control for autocorrelation was found to be statistically significant. The results indicate that for a  $600 \text{ W/m}^2$  reduction in incoming solar radiation, roughly equivalent to being in the shade instead of the full sun, there would be an  $8.4^\circ\text{C}$  drop in the ground surface temperature. Solar radiation ranged from approximately 100 to  $900 \text{ W/m}^2$  on the towpath transects. For every 10% increase in albedo, roughly the difference between asphalt paving and concrete, there was a corresponding  $3.4^\circ\text{C}$  drop in the ground surface temperature. On the towpath rides, variations in solar radiation and albedo led to greater-than- $30^\circ\text{C}$  shifts in the ground surface temperature.

Although sky view factor is frequently mentioned in studies of the UHI effect, it was not found to be statistically related to ground surface temperature in my model. This may be because solar radiation and sky view factor were positively correlated, and therefore one of the two variables had to drop from the model. It may also be due to the unique nature of the towpath route, which passed through low-rise commercial/industrial spaces and natural areas as opposed to a typical downtown.

Second, I hypothesized that a reference air temperature, ground surface temperature, and land cover types would explain the variation in air temperatures along each transect. An OLS regression model that incorporated spatial effects to control for autocorrelation was found to be statistically significant. The results indicate that for a  $10^\circ\text{C}$  increase in the ground surface temperature, there is a  $0.2^\circ\text{C}$  increase in the local air temperature. This demonstrates a link between local ground surface temperatures and air temperature; the selection of paving materials has a significant effect on both surface and atmospheric UHIs. However, one might expect this relationship to be stronger; I believe that the ratio relating air and ground surface temperature would change if data was taken on days with a higher air temperature ( $>29^\circ\text{C}$ ). These results may also indicate that waste heat from industrial facilities or highways may play a larger role than expected in determining local air temperatures, consistent with Coseo and Larsen (2014).

Temperatures recorded downwind from a forest were 0.25°C cooler than those recorded over impervious, bare soil, or grass land covers. Water also provided a cooling effect that was roughly 2.7 times stronger than that of a forest. However, very large areas of forest or water were necessary to achieve a drop in the local air temperature; roughly 11.8 hectares of water (29.16 acres) produced only a 0.67°C drop in the local air temperature.

Third, I hypothesized that bicycles are a viable alternative to stationary weather stations, microdataloggers, and automobile-based measurements of microclimates. The bicycle performed well as a platform to gather data to analyze ground and surface temperatures. It allowed me to reach locations that would be inaccessible by automobile and was less expensive than setting up multiple research-grade weather stations. In addition, riding a bicycle helped in the validation of land cover data, something that would be difficult to accomplish from the confines of an automobile. Although I am unaware of any studies that compare bicycle- and automobile-based measurements, I believe that using a bicycle may improve the validity of results because the data are not subject to contamination from vehicle exhaust.

However, bicycles do have significant limitations, such as safety concerns, heat stress, rider fatigue, and difficulty scaling steep terrain. Interpretation of weather data from mobile measurement systems is also more difficult than interpreting results from static weather stations, though collecting data with one set of sensors avoids the need to cross calibrate equipment. Although the cost of building the bicycle is lower than purchasing multiple research grade weather stations, or getting custom remote sensing data from satellites or airplanes, the cost is still significant. Future work could other setups to gather mobile data, like Brandsma and Wolters (2012) who simply attached a datalogger to a bicycle, or using other low-cost datalogging systems to produce a similar analysis.

My fourth and final hypothesis was that data gathered by a bicycle-based system can inform urban design, natural resource management, and public policy. Throughout this study, I have worked with officials from Cuyahoga County and the City of Cleveland to integrate findings into their climate adaptation planning efforts. In the near future, I hope to utilize the results from this study to create fine scale maps of the UHI effect across the county.

However, while the data from the bicycle is helpful for understanding the physical characteristics of microclimates and the extent of the UHI effect, more research is needed before the results can broadly inform policy and practice. For example, rides along the Canal Towpath

may not be representative of the microclimatic conditions in every neighborhood of the county. Since the measurements were taken in the summer, they may also not capture differences in neighborhood temperatures caused by variations in Lake Erie temperatures in the spring or fall.

In addition, there is no document for mobile measurements like the Oke (2006) guidelines for obtaining representative meteorological observations from urban sites. From the limited number of bicycle-based studies completed to date (Melhuish and Pedder 1998, Heusinkveld et al. 2010, Brandsma and Wolters 2012, Coseo and Larsen 2014), it is clear that there is no standardization among equipment, measurement heights, or protocols for data collection and analysis. This limits comparison of results and the ability to interpolate results from city to city. It would be beneficial for the urban climate community to develop uniform standards for collecting data by vehicle, similar to the efforts to standardize indoor thermal environmental research completed by de Dear, Brager, and Cooper (1998). Their groundbreaking work led to an international database of measurements of the thermal environment in buildings; this work eventually informed new thermal comfort standards like ASHRAE 55 (2010). A similar database would promote comparison of results among climate zones, and potentially reduce the number of custom studies conducted around the world.

### *5.1 Limitations of the Study*

Like any study, this research has a number of limitations. First, due to a Scan Line Corrector failure on the Landsat 7 satellite, the imagery I originally intended to use for land cover analysis contained significant gaps. An estimated 22 percent of each scene was lost; the data gaps occur along the edge of each image acquired by the satellite (U.S. Department of the Interior and U.S. Geological Survey 2013). While it is possible to patch together one or more images to create complete scenes, most of the Landsat 7 images taken during the summer of 2012 also had cloud cover that obscured the land cover below, making the patching process unreliable. For these two reasons, I decided to utilize Cuyahoga County's 2011 land cover classification. While the classification was consistent with current aerial photographs and my experience riding along the canal, in future investigations of microclimates I intend to use Landsat 8 data that correspond to the same dates as a transect.

Second, it would be helpful to ride the bicycle more times and with a higher temporal resolution to establish strong statistical relationships among all of the data. As a comparison, Brandsma and Wolters (2012) completed 183 transects along a 14-km route in Utrecht over the

course of three years, taking air temperature and relative humidity measurements every second. For future studies, I plan to consolidate my rides on one path with the widest range of land covers, such as the Canal Towpath. I also plan to increase the temporal resolution of the data to once per second and to ride the bicycle at night to determine the maximum heat island effect. I am also investigating more sensitive air temperature equipment that might pick up on very small (0.01°C) changes in the local air temperature.

## **6. Conclusions**

Assessing exposure to high temperature will require understanding both how average temperatures are expected to shift with global warming and how local temperatures are modified by the urban heat island effect. Although airport weather stations and remote sensing all help to estimate ground surface and air temperatures in a city, finer scale data is needed to support preventative programs at the neighborhood-level like cooling centers or the planting of street trees to reduce temperatures.

Using a bicycle, I collected a fine scale of microclimate data to determine how physical characteristics (e.g., solar radiation, albedo, sky view factor, vegetation) contributed to local variations in ground and air temperatures. This bicycle expanded on a methodology used by the building science and urban climate communities. I found that solar radiation and albedo explain the variation in ground surface temperatures along a transect in Cuyahoga County, Ohio. In turn, the ground surface temperature and land cover types explained the variation in air temperatures.

This study shows that bicycles are a viable and low-cost alternative to stationary weather stations, microdataloggers, and automobile-based measurements of microclimates. Because of its relatively low cost, city planners may want to develop similar systems to estimate exposure in their own cities. However, additional work is needed to standardize measurement protocols to allow for comparative studies among cities and climates.

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## CHAPTER 3

### **Modeling the Effect of Wintertime Weatherization Treatments on Heat-Related Exposure and Energy Use**

#### **1. Introduction**

From 1979 to 2003, more people in the United States died from heat waves than from hurricanes, lightning, tornadoes, floods, and earthquakes combined (CDC 2009). Assessments of climate change project an increase in the intensity, frequency, and duration of extreme heat events (Karl et al. 2009). Research in the environmental health sciences has shown that increasing access to air conditioning is a strong protective measure for reducing heat-related mortality (Semenza et al. 1996). However, improving the efficacy of a building's thermal envelope to reduce heat gain may be preferable because it has the potential to improve indoor thermal environmental conditions while reducing the demand for electricity (CIBSE 2005).

To create a link between the fields of heat health and building science research, this chapter investigates how exposure to high temperatures might be reduced by residential weatherization. *Weatherization* is broadly defined as the steps taken to increase energy efficiency by limiting unintended air and heat exchange between the indoor and outdoor environments; the primary goal of weatherization programs in the United States is to reduce conductive losses and infiltration of air (Institute of Medicine 2011). Since buildings consumed 38.9% of the total primary energy used in the United States in 2006 (Energy Information Administration 2006), and 34.8% of that energy was used for space conditioning and ventilation, research linking indoor temperature exposure and space conditioning can both reduce heat-related illness and energy use.

Vulnerable populations frequently live in older housing stock that may have lower levels of insulation, high rates of infiltration, and no air-conditioning. These residents may be exposed to a wider range of temperatures and pay a greater percentage of their income to condition their home. For this reason, Northeastern Ohio is the focus of the study because several national-level assessments have identified the region as being extremely susceptible to high temperatures due to high poverty rates, an older population, poor-quality housing stock, and a lack of central air-

conditioning (Reid et al. 2009, Staudt and Inkley 2009, Altman et al. 2012).

Ohio was also selected because it is a recognized leader in providing energy efficiency and healthy housing services to low-income residents; programs developed in Northeastern Ohio have been used as a template for other cities in the United States (Jacobs et al. 2007). The results from this research are applicable across Ohio and much of the Midwest; the methods are appropriate for use in other cities with similar housing stock like Detroit, Toledo, and Buffalo.

## **2. Literature Review**

The following literature review is organized into four sections. The first section discusses the link between the form of the built environment and heat-related morbidity and mortality. The second section describes how housing modifies outdoor air temperatures and can either temper or amplify local conditions. The third section outlines the U.S. Department of Energy Weatherization Assistance Program, a federal initiative to improve thermal comfort and energy performance in low-income homes. The fourth and final section introduces the research questions that guided the study.

### *2.1 The built environment and exposure to temperature*

Urban climate is the study of meteorological processes, atmospheric phenomena, and the climate of the built environment (Oke 2005). Urban planners, architects, public health officials, and city administrators are increasingly interested in the climate of cities because recent research has shown that they are warming more quickly than rural areas, amplifying many of the negative effects of climate change (Stone 2012). Urban climatologists come to the field from a variety of backgrounds including meteorology, climatology, civil engineering, and planning.

Urban climate uses heat stress metrics such as physiological equivalent temperature and the National Oceanic and Atmospheric Administration (NOAA) heat index to assess exposure to temperature in cities. While these metrics calculated from airport weather stations are good proxies for human responses to increased temperatures, the exact exposures experienced inside a building due to outdoor conditions remain a relative unknown. As discussed in Chapter 2, field research has recently been conducted in Detroit (White-Newsome et al. 2012), Montreal (Smargiassi et al. 2008), and Leipzig (Franck et al. 2013), but the results have limited generalizability among cities due to variations in the climates and housing stock. To measure exposure indoors and link it to outdoor air temperature and land cover, additional research is

necessary. Many of the recent studies have used building energy models to simulate the relationship between the configuration of housing, outdoor conditions and the indoor thermal environment; these studies are discussed in the methods section of this chapter.

Investigating this relationship is important because a lack of vegetation, impervious surfaces, and waste heat emissions all contribute to urban warming. Conditions vary significantly within a city. In a 2006 study of Phoenix neighborhoods, the percentage of hours that exceeded a severe/dangerous heat threshold was inversely related to the average income of the residents. These results indicated an inequity in temperature among neighborhoods; in less affluent Phoenix neighborhoods, it was hotter and stayed hotter for longer periods of time (Harlan et al. 2006).

At the building level, there are two competing philosophies of human thermal comfort. These “static” and “adaptive” models have contrasting assumptions about the way people respond to the indoor environment. The static model uses data from climate chamber studies to support its theory, best characterized by the work of Fanger (1972), and relies on mechanical systems to achieve interior comfort. The adaptive model uses data from field studies of occupants in buildings (Nicol and Humphreys 1973) and acknowledges a variety of techniques such as high thermal mass and operable windows to provide conditioning (Nicol and Roaf 2007).

Occupants tolerate a wider range of indoor thermal environmental conditions than the static model suggests. While this observation is helpful in creating policies to condition the indoor environment, such as ASHRAE Standard 55-2010, little of this research connects to urban microclimates or health outcomes. Addressing this link is important because assessments of climate change project an increase in the intensity, frequency, and duration of extreme heat events in North America (Karl et al. 2009). Planning for a warmer future will require public officials to determine the vulnerability of residents to higher temperatures (O'Neill et al. 2009); vulnerability is defined as the function of sensitivity and exposure (Cutter et al. 2008). Factors such as education, race, age, income, security, social capital, and personal health overlap to produce varying levels of sensitivity to temperature within a city (Klinenberg 2002, Duneier 2006, Reid et al. 2012).

The term *exposure* is used by many different disciplines, but the definition is not always consistent (U.S. Environmental Protection Agency 1992). For this chapter, exposure is defined as being exposed to an indoor environment that exceeds the acceptable thermal environmental

limits outlined by the adaptive model of ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy (ASHRAE 2010). Exposure duration is the amount of time the thermal environment exceeds the ASHRAE Standard 55 thresholds, calculated as both total hours and cumulative hours of exposure (Lee and Steemers 2013). Planned adaptations to mitigate the effects of heat waves generally fall into two categories: managing health risks and reducing exposure (Huang et al. 2013). This chapter focuses on reducing exposure to temperature in single-family detached housing.

## *2.2 Housing as a modifier of outdoor temperatures*

Ex-post studies of extreme heat events like the 1995 heat wave in Chicago have shown that air-conditioning is an important strategy in reducing exposure to high temperatures, morbidity, and mortality (Semenza et al. 1996). The heat health literature frequently encourages the installation of air-conditioning, and some municipalities provide free air-conditioning systems to homeowners (CEOGC 2011). While these programs eliminate first cost as a barrier, the operating costs may present a significant problem for low- or fixed-income residents (Sheridan 2007, Sampson et al. 2013). Compounding the problem, new electric utility time-of-use rates will increase the cost of electricity during periods of high demand (Alexander 2010).

The Low Income Home Energy Assistance Program (LIHEAP) is frequently discussed as a way to provide funding to low-income households to help pay their utility bills. However, this assistance does not address a broader issue: air-conditioning systems have strained electrical distribution systems in the United States. By 2005, 87.4% of households in the United States reported that they had some form of air-conditioning (Eggers and Thackeray 2007). Data from the North American Electric Reliability Corporation (NERC) shows that the frequency of power outages in the United States has increased during the same period (Stone 2012). Alternatives to compressor-based cooling are therefore preferable because these passive systems have the potential to reduce strain on electrical systems while reducing exposure (Dahl 2013).

Passive systems use no purchased energy to operate, play multiple roles in a building design, and are tightly integrated with the building structure (Grondzik et al. 2010). These thermal environmental systems were the norm in building design before the advent of air-conditioning; window shading, light-colored materials and coatings, insulation, and radiant barriers are all examples of building-level passive systems that reduce indoor air temperatures. While passive systems can moderate interior temperatures, they cannot eliminate heat-related

morbidity and mortality during heat extremes; these systems provide conditions within roughly 2°C of the outdoor air temperature (Givoni 2011). Therefore, they may not provide a total protective effect during a heat wave.

However, there is a renewed interest in passive systems because they do not require electricity, do not contribute to greenhouse gas emissions, and continue to provide some protective effects during a brownout or blackout; this last effect is called ‘passive survivability’ (Wilson 2005, Institute of Medicine 2011). While passive systems are easily incorporated into the design of new buildings, in existing residences these systems are frequently installed as part of a weatherization retrofit.

Research indicates that passive systems can reduce interior temperatures in summer, and weatherization can improve wintertime indoor thermal comfort, reduce heating bills, and reduce health risks associated with exposure to low temperatures (Howden-Chapman et al. 2005, Chapman et al. 2009). What remains relatively unknown is how to link these cold- and warm-climate treatments to combat heat-related morbidity and mortality. Since the U.S. Department of Energy (DOE) has spent more than \$10 billion to upgrade houses since 1976, making connections between cold weather and warm weather strategies is an important step in combating all temperature-related morbidity and mortality.

### *2.3 DOE Weatherization Assistance Program*

In the United States, the DOE Weatherization Assistance Program (WAP) is a block grant program that provides no-cost retrofit services to low-income households. There are a number of ways that the federal government defines low-income for the purposes of this program. The Department of Health and Human Services (HHS) LIHEAP has historically defined eligibility as household income at or below 150 percent of the Federal Poverty Income Guidelines or 60 percent of state median income, whichever is higher. Alternatively, the DOE WAP defines eligibility as household income at or below 200 percent of the Poverty Income Guidelines or a home that is HHS LIHEAP eligible (Eisenberg 2010).

The Office of Weatherization and Intergovernmental Programs (OWIP) at DOE oversees the WAP program at the federal level. The DOE allocates funding appropriated by Congress to states, tribal governments, and territories to plan and implement the weatherization program. States in turn contract with sub-grantees such as cities, counties, community action agencies, or community development corporations for program delivery (Kaiser and Pulsipher 2004). In the

State of Ohio, the Ohio Development Services Agency (ODOD) oversees the management of the statewide WAP; funds are distributed by the state to Cuyahoga County or delegates like the Cleveland Housing Network.

While the WAP initially emphasized temporary measures such as caulk and plastic sheeting over windows, the current program focuses on long-term improvements such as wall insulation, attic insulation, air sealing, and furnace replacement/repair. Energy efficiency treatments must pass a cost-benefit test as determined by a software tool called the Weatherization Assistant.

Since 1994, replacement air-conditioners, ventilation equipment, and window shading are provided in warm climate states where these treatments pass a cost-benefit test, though states typically use a 2000 cooling degree day (base 10°C) threshold to determine whether or not to include cooling measures in their program. Because most of Ohio has fewer than 2000 cooling degree days, the ODOD does not include cooling measures in its weatherization program. Recently, the DOE has included measures such as the replacement of appliances and improvements to electric lighting.

Although most of the funding in the United States goes to cold climate states to reduce exposure to low wintertime temperatures (Kaiser 2004), precedent from warm climate states such as Arizona and Florida indicates that measures to improve summertime comfort could be added. A limiting factor is that these treatments may not pass a Weatherization Assistant cost-benefit test, or, in the case of window shading, may also increase wintertime energy usage because the treatment reduces solar gain. Including measures that reduce exposure to both low and high temperatures is an important next step for weatherization programs to consider. While issues of energy security, climate change, and heat-related mortality are interconnected, policies of energy efficiency, greenhouse gas emissions reductions, and access to air-conditioning are not well coordinated and sometimes even contradict each other (Strengers and Maller 2011).

An assumption of this chapter is that the WAP is an ideal way to reduce vulnerability to extreme temperatures. Because occupants have to apply to participate in these programs, they have presumably experienced uncomfortable conditions within their home or are struggling to make utility payments to keep their house conditioned. This assumption helped to structure the research questions, the modeling methodology, and the policy recommendations presented in subsequent sections.

## 2.4 *Research questions and hypotheses*

This study fills knowledge gaps regarding the role that housing may play in personal temperature exposure, which is important for improving heat epidemiology and guiding prevention programs (White-Newsome et al. 2011). In addition to contributing to the heat-related morbidity and mortality literature, a goal of this research is to assist weatherization program administrators in their efforts to improve comfort while increasing energy efficiency.

I structured this chapter around three research questions. My first question is “What is the effect of wintertime weatherization measures on thermal comfort and energy usage during a heat wave?” I generated three hypotheses to address this question. First, in houses with closed windows, wintertime weatherization will reduce maximum temperatures, but it will increase minimum temperatures and the total number of hours an occupant is overheated. Second, operable windows will help a house’s interior to remain within the acceptable temperature ranges of ASHRAE Standard 55-2010 during a heat wave. Third, wintertime weatherization will reduce the required cooling capacity of an air-conditioning system; a smaller capacity air-conditioning system has lower electrical demand and uses less energy during the cooling season.

My second research question is “What additional weatherization measures would improve thermal comfort and decrease electrical demand during a heat wave?” I created two hypotheses to address this question. First, in houses with closed windows, warm climate weatherization reduces maximum temperatures and the total number of hours an occupant is overheated. Second, warm climate weatherization increases energy usage during the heating season.

My third and final research question for this chapter is “What is the effect of housing characteristics on thermal comfort and energy usage during a heat wave?” I produced a single hypothesis to address the effect of housing characteristics on comfort and energy usage: foundation contact with the ground tempers interior temperatures and decreases maximum temperatures during a heat wave.

## **3. Methodology**

Cuyahoga County is located in the humid, mid-latitude zone of the United States at approximately 41.5°N and 81.7°W. The climate of the region is characterized by two distinct seasons: a warm-humid summer with an average July high temperature of 28.1°C, and a cold-dry winter with an average January low temperature of -5.7°C. The city averages 5,762 heating

degree days in winter and 817 cooling degree days in summer, both base 18.3°C (Grondzik et al. 2010, National Oceanic and Atmospheric Administration 2014).

The northern border of Cuyahoga County is Lake Erie; this large body of freshwater moderates temperatures in the height of summer. Although this heat sink provides a protective effect for Greater Cleveland, the frequency of heat waves in the Midwest has increased over the last sixty years (Perera et al. 2012). In addition, the magnitude of heat stress in the region is projected to grow because of local increases in humidity (Schoof 2013).

The methodology used for this modeling study is based on the Chartered Institution of Building Services Engineers (CIBSE) document “Climate change and the indoor environment: impacts and adaptation” (CIBSE 2005). While the CIBSE study used future weather year data to investigate overheating for buildings in the United Kingdom, this study did not project results into the future because similar files are not readily available for the United States (Kalvelage et al. 2014). However, the metrics utilized are consistent with those of other studies of adaptation in buildings (Porritt et al. 2012, Lee and Steemers 2013). As climate projections are developed, the results can be updated.

### *3.1 House configuration*

I used house configuration data from the Cuyahoga County Auditor to identify a set of average houses that would represent the majority of the housing stock in the county (Table 3.1). I used a number of variables including wall construction, foundation type, and siding type to identify the most common characteristics to include in the modeling. For example, wood frame homes with a full basement with metal, vinyl, or wood siding make up more than two-thirds of the houses in Cuyahoga County (66.83%).

In addition to wood frame homes with a full basement, I selected four other house styles for analysis: (1) wood frame with a crawlspace, (2) wood frame with a slab foundation, (3) solid wall with a full basement, and (4) manufactured/mobile home. Together, these five house types are representative of 97.32% of all single-family detached houses in Cuyahoga County. I then matched these housing types with a classification system used by the ODOD to identify weatherization treatments.

Table 3.1: Distribution of Foundation Types, Wall Types, and Siding Types<sup>1</sup>

		Wood Frame Construction				Row Totals
		Metal, Vinyl, or Wood	Asbestos	Stucco	Composition	
Foundation	Post	<i>5.59%</i> <sup>2</sup>	0%	0%	0%	5.59%
	Slab	<i>7.96%</i> <sup>2</sup>	0.06%	0.02%	0.02%	8.06%
	Crawlspace	<i>1.44%</i> <sup>2</sup>	0.04%	0%	0.01%	1.49%
	Full	<i>66.83%</i> <sup>2</sup>	0.72%	0.30%	0.21%	68.06%
Total		81.82%	0.82%	0.32%	0.24%	83.20% <sup>3</sup>

		Solid Wall Construction					Row Totals
		Brick	Stucco	Stone	Concrete Block	Other	
Foundation	Post	0%	0%	0%	0%	0%	0.00%
	Slab	0.72%	0.01%	0.01%	0.02%	0.01%	0.77%
	Crawlspace	0.10%	0%	0%	0.01%	0.02%	0.13%
	Full	<i>15.50%</i> <sup>2</sup>	0.18%	0.11%	0.05%	0.06%	15.90%
Total		16.32%	0.19%	0.12%	0.08%	0.09%	16.80% <sup>3</sup>

1. Data provided by the Cuyahoga County Information Services Center for 2011.
2. Percentages in italics represent the five housing typologies modeled in BEopt/EnergyPlus.
3. The five housing typologies are representative of 97.32% of all single-family detached houses in Cuyahoga County. There are 417,891 units of single-family houses in the county.

I then established levels of insulation, U-Factor, and infiltration levels that I would test in the energy model. I set the baseline as an uninsulated home (R=0) with single pane windows (U=0.84, SHGC=0.63) with a high rate of infiltration (20 at ACH50). I based this prescriptive approach toward energy code compliance on the Ohio Home Weatherization Assistance Program Formula State Plan; Table 3.2 presents a comparison of program requirements versus new construction energy code requirements. The goal was to identify how combinations of wall insulation, attic insulation, window upgrades, and reductions in infiltration affected energy use and temperature indoors. Examples of the tables prepared from the energy modeling data appear in Appendix A.

Table 3.2: Building Thermal Envelope Requirements for Single-Family Houses

	New Construction Requirements <sup>1</sup>	ODOD Weatherization Program Requirements <sup>2</sup>
Ceilings	R-38.	Uninsulated ceilings with less than R-19 of insulation are insulated to R-38.
Wood Framed Walls	R-13 of insulation between studs with R-5 of continuous insulated sheathing.	Uninsulated walls are insulated to R-15.
Brick/Concrete Walls	R-13 of insulation between studs or R-17 of continuous insulated sheathing.	N/A. Installing insulating sheathing over wall is cost prohibitive.
Floors	R-30 over unconditioned space or insulation sufficient to fill the framing cavity, R-19 minimum.	Uninsulated floors over unconditioned space are insulated to R-19 or perimeter insulation is provided to achieve R-11 in crawl spaces or basements where insulation will remain undisturbed.
Windows	Maximum U-Factor of 0.35.	Incidental energy-related repairs may not exceed \$600, including labor and materials.
Doors	Maximum U-Factor of 0.5.	
Infiltration	Tested air leakage is less than 6 ACH when tested with a blower door at a pressure of 50 pascals.	Reduce air leakage based on a blower door test by sealing holes and cracks in the thermal envelope.
Slab	R-10 of perimeter insulation at least 2'-0" in from the edge of the slab.	N/A. Installing insulation under floor slab is cost prohibitive.

1. Data from the Residential Code of Ohio for One-, Two-, and Three-Family Dwellings.
2. Data from the Home Weatherization Assistance Program 2012 Formula State Plan prepared by the Ohio Department of Development.

### 3.2 *Building orientation, floor areas, and neighbors*

Using data from the Cuyahoga County Auditor, I established representative floor areas, number of floors, orientation of the homes, and other basic information to use in the models. I referenced modeling protocols created by the National Renewable Energy Laboratory (NREL) for each of these factors (Hendron and Engebrecht 2010). Table 3.3 presents my assumptions for the pre-weatherized homes; note that manufactured homes deviate from the other homes in the table because they are smaller and raised above the ground on a post foundation.

Table 3.3: Assumptions for Pre-Weatherized Houses Used in Energy Modeling

	Wood Frame, Basement	Wood Frame, Crawlspace	Wood Frame, Slab	Solid Wall, Basement	Manufactured/ Mobile Home
Floor Area <sup>1</sup>	134m <sup>2</sup>				88m <sup>2</sup>
Number of Floors <sup>2</sup>	2 stories above grade.				1 story above grade.
Orientation <sup>3</sup>	Long axis of the house East to West.				Long axis of the house Northeast to Southwest.
Distance to Neighbors <sup>4</sup>	No neighbors.				3m
Operation <sup>5</sup> :	Heating thermostat set point of 21.1°C, no air-conditioning system.				
Walls <sup>6</sup>	Uninsulated wood stud walls, gypsum board on the interior, gray vinyl siding on the exterior.			Uninsulated 15cm thick brick walls.	Uninsulated wood stud walls, gypsum board on the interior, gray vinyl siding on the exterior.
Ceilings/Roofs <sup>6</sup>	Uninsulated ceilings with wood rafters, gypsum board on the interior. Asphalt shingles, medium color.				
Foundation/ Floors <sup>6</sup>	Uninsulated foundation and floors with wood joists over unconditioned space.				Uninsulated floor over open air.
Windows and Shading <sup>7</sup>	Windows equal 15% of the floor area, distributed equally across all facades.				
Airflow <sup>7</sup>	Tested air leakage is 20 ACH when tested with a blower door at a pressure of 50 pascals.				
Major Appliances <sup>7</sup>	Standard efficiency refrigerator, cooking range, dishwasher, clothes washer, and clothes dryer.				
Lighting <sup>7</sup>	20% of lighting is compact fluorescent; 80% is standard incandescent.				
Space Conditioning <sup>7</sup>	78% AFUE gas furnace, no air-conditioning.				
Water Heating <sup>7</sup>	Standard gas water heater, 0.59 EF.				

1. Floor areas derived from Ohio Department of Development data on weatherized homes.
2. Number of floors based on data from Cuyahoga County Information Services Center for 2011.
3. A preliminary analysis identified these two building orientations as the worst-case scenario for overheating.
4. A preliminary analysis identified this distance to neighbors as the worst-case scenario for overheating.
5. Thermostat set point based on preliminary results from the National Retrospective Evaluation of the Weatherization Assistance Program.
6. Wall construction derived from Ohio Department of Development data on weatherized homes.
7. House configuration adapted from the 2010 Building America House Simulation Protocols produced by the National Renewable Energy Laboratory.

### 3.3 *Energy modeling*

I then input these representative homes into the DOE EnergyPlus 7.0 thermal load simulation engine; the analysis was controlled using graphical user interface BEopt 1.3 developed by NREL (Horowitz et al. 2008). For each of the five housing types, I developed hourly profiles of interior air, mean radiant, and operative temperatures to estimate exposure. In total, I created and analyzed more than 1,600 models for this study. For consistency, all of the analyses utilized the same Typical Meteorological Year (TMY) weather data for Cleveland Hopkins International Airport (KCLE) for the period 1991 through 2005 (Wilcox and Marion 2008).

Using the TMY3 data for Cleveland Hopkins International Airport, I calculated the upper boundary of thermal comfort to be an operative temperature of 28.9°C. This threshold is slightly higher than the 28°C overheating threshold recommended by CIBSE (2005); however, because it is based on the adaptive model of thermal comfort, it takes into account some acclimatization to temperature.

## 4. **Results**

This section follows the order of the three research questions presented at the end of the literature review. Immediately following the presentation of these data, the conclusions section describes the implications for policy, program design, and program management.

### 4.1 *Wintertime weatherization measures, thermal comfort, and energy usage*

In the initial stages of the energy modeling, I assumed that the houses did not have air-conditioning and the windows remained closed during periods of hot weather. This is a worst case scenario for overheating associated with heat-related mortalities; decedents are frequently found in overheated homes with all windows and doors closed. My subsequent analyses investigated the effect of operable windows on warm weather exposure after weatherization. Table 3.4 presents the impacts of wintertime weatherization on comfort for all five housing types.

In winter months, the model indicates that in houses before weatherization, occupants are exposed to low air temperatures even if they have an operational furnace with a thermostat set to 21.1°C. Total hours of exposure to this low air temperature range from 8 to 59 hours per year, depending on wall and foundation type. This is because during the coldest part of the winter, typically the end of January and early February in Northeast Ohio, there is significant conductive and radiative heat loss from the interior to the exterior walls in homes without insulation.

Insulating and air sealing a house reduces the rate of heat loss, and a furnace is then able to maintain a 21.1°C set point.

Table 3.4: Comfort Impacts of Wintertime Weatherization Measures

Wall Type, Foundation Type	Pre- or Post-Weatherization Window Type	Annual Operative Temperature Impacts					
		Total Hours $T_a$ below 21.1°C (hours) <sup>1</sup>	Total Hours $T_{op}$ above 28.9°C (hours) <sup>2</sup>	CHE, $T_{op}$ above 28.9°C (hours) <sup>3</sup>	Total Hours $T_{op}$ above 37°C (hours) <sup>4</sup>	CHE, $T_{op}$ above 37°C (hours)	Max $T_{op}$ (°C)
Wood Frame, Basement	Pre-Weatherization, Sealed	59	1,266	45	92	8	41.3
	Post-Weatherization, Sealed	0	1,681 (+32.8%)	209 (+464.4%)	46 (-50%)	9 (+12.5%)	39.3 (-2)
	Post-Weatherization, Operable	0	35 (-97.2%)	8 (-82.2%)	0	0	32.3 (-9)
Wood Frame, Crawlspace	Pre-Weatherization, Sealed	26	1,620	138	197	11	43.1
	Post-Weatherization, Sealed	0	1,912 (+18.0%)	258 (+87.0%)	78 (-60.4%)	11 (0%)	39.9 (-3.2)
	Post-Weatherization, Operable	0	45 (-97.2%)	8 (-94.2%)	0	0	32.7 (-10.4)
Wood Frame, Slab	Pre-Weatherization, Sealed	30	1,386	70	103	9	41.5
	Post-Weatherization, Sealed	0	1,290 (-6.9%)	164 (+234.3%)	0	0	36.9 (-4.6)
	Post-Weatherization, Operable	0	51 (-96.3%)	7 (-90.0%)	0	0	31.8 (-9.7)
Solid Wall, Basement	Pre-Weatherization, Sealed	8	1,582	140	157	11	42.3
	Post-Weatherization, Sealed	0	2,212 (+39.8%)	425 (+303.6%)	120 (-23.6%)	15 (36.4%)	40.2 (-2.1)
	Post-Weatherization, Operable	0	1 (-99.9%)	1 (-99.3%)	0	0	28.2 (-14.1)
Manufactured/ Mobile Home, Post	Pre-Weatherization, Sealed	33	1,576	46	320	11	44.9
	Post-Weatherization, Sealed	0	2,347 (+48.9%)	425 (+923.9%)	242 (-24.4%)	15 (36.4%)	42 (-2.9)
	Post-Weatherization, Operable	0	51 (-96.8%)	7 (-84.8%)	0	0	35.2 (-9.7)

1. 21.1°C is the thermostat set point temperature. Hours below this threshold represent an inability of the furnace to maintain a comfortable temperature indoors due to excessive heat loss.
2. An operative temperature ( $T_{op}$ ) of 28.9°C corresponds to the upper boundary of the adaptive model of ASHRAE Standard 55.
3. CHE is the consecutive hours of exceedance (Lee and Steemers, 2013).
4. A  $T_{op}$  of 37°C corresponds to normal body temperature; above this threshold the body may experience dangerous overheating.

During warm weather, however, the results are mixed. Wintertime weatherization measures appear to make a house warmer throughout the year, which might be expected because insulation and air sealing are intended to reduce heat loss. For four of the five housing types, weatherization increases the total number of hours the interior is above the upper comfort boundary (28.9°C) between 18.0 and 48.9%. However, houses with a slab foundation see a reduction (-6.9%) in the total number of hours the interior exceeds 28.9°C. The number of consecutive hours the temperature exceeds 28.9°C increases significantly for all five housing types; for manufactured/mobile homes it is more than a nine fold increase (923.9%).

However, it is important to note that the results do not indicate that wintertime weatherization measures create dangerously hot conditions indoors, defined for this chapter as exceeding an operative temperature of 37°C. In fact, weatherization reduced the total hours the operative temperature indoors exceeded 37°C by anywhere from 23.6% to 100%. While these measures did slightly increase the cumulative hours of exceedance (CHE) for three of the housing types, wintertime weatherization measures decreased the maximum operative temperature by at least 2°C in all cases.

For all five housing types, ensuring that the windows were operable for natural ventilation reduced the number of hours a home exceeded 28.9°C to a range of 1 to 51 hours. This corresponds to a 96.3% to 99.9% reduction from the baseline pre-weatherized homes with sealed windows. In addition, none of the homes had operative temperatures above 37°C, and there was an average 10.6°C reduction in the maximum operative temperature.

Figure 3.1 illustrates these results for a wood framed home with a full basement. The period illustrated is two weeks in mid- to late July where the air temperatures are typically the highest of the summer. The dotted line indicates the outdoor air temperature during this timeframe. In the figure, uninsulated houses have a significant mean daily range of operative temperatures, with high temperatures regularly over 37°C. Weatherized (Wx) homes have a smaller mean daily range and lower maximum temperatures; however, nighttime temperatures are warmer because the heat that accumulates over the course of the day is trapped indoors.

As described above, homes with operable windows stay near or within the comfort zone throughout the two-week period of hot weather, a stark contrast to the home with sealed windows. During the hottest three days of a typical summer, the maximum interior operative temperature for a home with operable windows is approximately 10°C cooler than it is for a

house with sealed windows. This means that operative temperatures exceed the ASHRAE 55 comfort zone on only two of those three days.

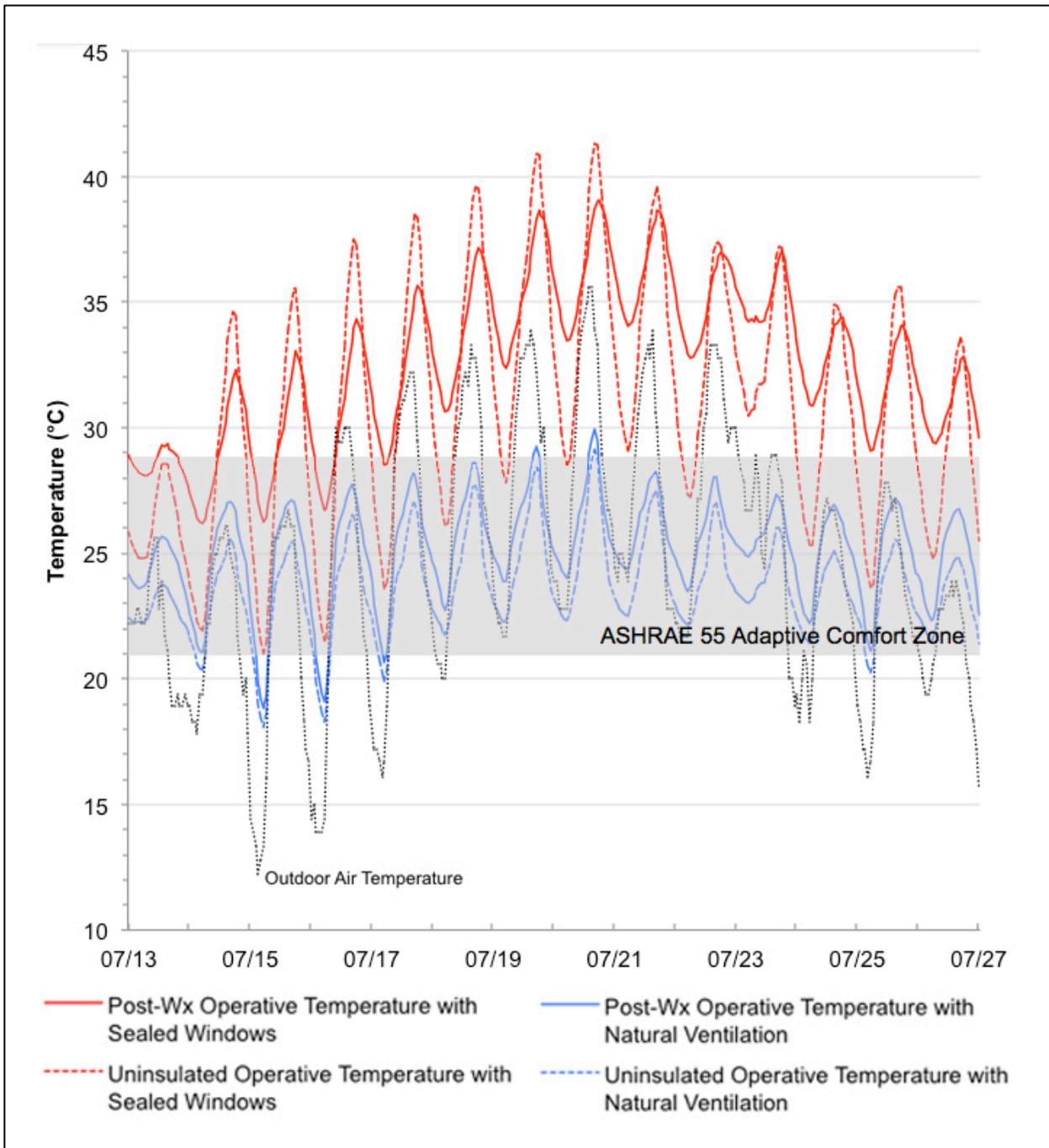


Figure 3.1: Comparison of summer indoor operative temperatures for a wood framed home with a full basement pre- and post-weatherization (Wx) with windows open or sealed

The weatherization strategies used by the State of Ohio improve interior thermal environmental conditions in homes in the summer and winter. If windows and doors remain sealed, however, it may stay uncomfortably warm at night during a heat wave because the added insulation and air sealing prevent the dissipation of heat. Ensuring that windows are operable and residents know how to naturally ventilate their home during periods of hot weather would be an important addition to the Ohio Home Weatherization Assistance Program.

#### 4.1.2 Energy usage

As expected, wintertime weatherization reduced natural gas usage for heating, electricity usage associated with furnace motor operation, and the annual cost to heat a home. Table 3.5 presents the results of the energy modeling. The energy savings ranged from 20.5% to 28.9%, varying by wall and foundation type. This equaled \$260 to \$480 in savings per year per home. These results are consistent with a 2006 evaluation of the Ohio weatherization program, which found that the average natural gas savings after weatherization was 29% (Khawaja et al. 2006).

Table 3.5: Annual Energy Impacts of Wintertime Weatherization Measures

Wall Type, Foundation Type	Pre- or Post-Weatherization	Natural Gas Usage (therms) <sup>1</sup>	Elec. Usage (kWh)	Annual Cost (\$) <sup>2</sup>	Annual Savings (\$)	Savings (%)
Wood Frame, Basement	Pre-Weatherization	1,794	7,339	1,672	\$469	28.1%
	Post-Weatherization	905	6,625	1,203		
Wood Frame, Crawlspace	Pre-Weatherization	1,776	7,332	1,663	\$480	28.9%
	Post-Weatherization	865	6,605	1,183		
Wood Frame, Slab	Pre-Weatherization	1,810	7,359	1,681	\$452	26.9%
	Post-Weatherization	952	6,673	1,229		
Solid Wall, Basement	Pre-Weatherization	1,162	6,250	1,267	\$260	20.5%
	Post-Weatherization	670	5,858	1,007		
Manufactured/ Mobile Home, Post	Pre-Weatherization	1,351	6,401	1,366	\$395	28.9%
	Post-Weatherization	601	5,803	971		

1. A therm is a unit of natural gas billing used in the United States. It is equivalent to 100,000 Btu or 29.3 kWh.
2. Average natural gas cost of \$0.4291 per therm, average electricity cost of \$0.1229 per kWh.

Because the heat health literature frequently mentions air-conditioning as a treatment to reduce heat-related morbidity and mortality, and public health programs often advocate for the installation of compressor-based cooling, additional modeling investigated the impact of weatherization on summertime energy usage, energy costs, and air-conditioning system size. Results for all five of the house types modeled in BEopt appear in Table 3.6.

In all cases, air sealing, wall insulation, and attic insulation reduced the total amount of electricity used by an air-conditioning system. Energy savings ranged from 35.7% to more than 45% of operating costs. However, the most significant result was related to the air-conditioning system size required to maintain comfortable conditions within the home. For all home types, the required size dropped by at least 40%, representing a significant reduction in electrical demand (kW) associated with running a compressor.

Table 3.6: Wintertime Weatherization Measures' Impacts on Air-Conditioning

Wall Type, Foundation Type	Pre- or Post-Wx	System Size (tons) <sup>2</sup>	Electrical Demand (kW) <sup>3</sup>	Electrical Usage (kWh)	Annual Electrical Savings (%)	Energy Cost <sup>1</sup> (\$)	Annual Energy Cost Savings (\$)
Wood Frame, Basement	Pre-Wx	6	5.5	4,070	45.2%	500	\$226
	Post-Wx	3	2.8	2,232		274	
Wood Frame, Crawlspace	Pre-Wx	6	5.5	4,213	43.2%	518	\$224
	Post-Wx	3	2.8	2,392		294	
Wood Frame, Slab	Pre-Wx	8	7.4	4,348	42.1%	534	\$225
	Post-Wx	4	3.7	2,516		309	
Solid Wall, Basement	Pre-Wx	5	4.6	3,739	35.7%	460	\$165
	Post-Wx	3	2.8	2,402		295	
Manufactured/Mobile Home, Post	Pre-Wx	5	4.6	3,732	44.8%	459	\$206
	Post-Wx	3	2.8	2,060		253	

1. Average electricity cost of \$0.1229 per kWh. Fuel prices from Public Utilities Commission of Ohio (PUCO) survey, 2012 (<http://www.puco.ohio.gov/puco/index.cfm/apples-to-apples/>).
2. A refrigeration ton is equivalent to 12,000 Btu/h or 3,517 W.
3. Electricity demand is calculated based on an EER 13 air-conditioner.

In areas of Greater Cleveland where electrical distribution systems are strained by summertime peak loads, reducing the overall energy demand of buildings during a heat wave is critical to preventing brownouts and blackouts. Reducing the size of air-conditioning equipment helps toward this goal.

According to the ODOD, in 2012, 2,932 homes were weatherized in Cuyahoga County. If two-thirds of these homes were wood frame houses (1960 homes) with a full basement, and only half of these homes had air-conditioning, weatherization may have reduced total electrical demand associated with air-conditioning by more than 2,600 kW (2.6MW). This is roughly the equivalent of taking the demand associated with 260 to 463 single-family homes off the electrical distribution system.

In addition, the weatherization work would have reduced electrical bills for low-income customers by more than \$220,000 each year. If these customers were enrolled in a bill pay

program like LIHEAP, this could have resulted in significant savings to the program, or allowed the program to extend benefits to a wider pool of applicants. This rough calculation does not take into account electricity time-of-use rates that would increase the cost of electricity during periods of high demand even further, but it does illustrate the potential for weatherization to have an impact on the local grid.

#### *4.2 Warm climate weatherization measures*

In addition to the wintertime weatherization strategies described above, I modeled additional summertime weatherization strategies typically employed in warm climate states like Arizona or Florida. These strategies included radiant barriers in the attic, white roof coatings, converting all of the electric lighting in the house from incandescent to fluorescent lighting, and solar window films; one model included all four of the strategies. Table 3.7 presents the results for all five housing types. To maintain consistency with the other models, I assumed that windows remained closed in the house at all times and there was no air-conditioning system.

Each of the four strategies reduces the number of hours the operative temperature is above the upper comfort boundary (28.9°C). However, they have little impact on the number of hours above 37°C; they reduce exposure to dangerously high temperatures only if all four cooling measures are employed at the same time. For example, radiant barriers and white roofs have a negligible impact on comfort and energy savings. They fail to reduce interior operative temperatures and save at most an additional \$7 per year in energy. These results suggest that installing these two measures is unlikely to be cost effective for a weatherization program in a temperate climate like Cleveland.

Converting all incandescent lighting in the home to fluorescent lighting was the only measure that improved annual savings beyond what the winter weatherization measures provided; however, lighting had a minimal impact on total exposure to temperature. Installing solar window film increased energy usage, likely because these films reduce solar gain in both the summer and winter, increasing natural gas usage for heating.

Combining all four of the warm climate weatherization measures had a negative impact on natural gas usage in Cleveland's temperate climate; however, these losses were offset by electrical savings from the lighting upgrade. The combined configuration reduced total hours exposed to higher temperatures and decreased the maximum interior temperature between 1.4 and 2.2°C.

Table 3.7: Impacts of Warm Climate Weatherization Measures

Wall Type, Foundation Type	Cooling Season Energy Efficiency Measures	Annual Temperature Impacts						Energy Impacts			Annual Savings in Addition to Winter Wx Measures (\$)
		Total Hours $T_a$ below 21.1°C (hours) <sup>1</sup>	Total Hours $T_{op}$ above 28.9°C (hours) <sup>2</sup>	CHE, $T_{op}$ above 28.9°C (hours) <sup>3</sup>	Total Hours $T_{op}$ above 37°C (hours) <sup>4</sup>	CHE, $T_{op}$ above 37°C (hours)	Max $T_{op}$ (°C)	Natural Gas Usage (therms) <sup>5</sup>	Elec. Usage (kWh)	Annual Cost (\$) <sup>6</sup>	
Wood Frame, Basement	Post-Wx, Sealed	0	1,681	209	46	9	39.3	905	6,625	1,203	N/A
	Radiant Barrier	0	1,646	209	33	9	39.0	903	6,623	1,201	2
	White Roof	0	1,666	209	43	9	39.2	907	6,627	1,204	-1
	Lighting Upgrade	0	1,623	208	37	9	39.1	921	6,011	1,135	68
	Window Film	8	1,319	185	19	6	38.1	1,017	6,715	1,262	-26
	All Measures	12	1,186	164	10	4	37.6	1,032	6,100	1,193	10
Wood Frame, Crawlspace	Post-Wx, Sealed	0	1,912	258	78	11	39.9	865	6,605	1,183	N/A
	Radiant Barrier	0	1,874	236	64	11	39.6	862	6,603	1,181	2
	White Roof	0	1,895	236	72	11	39.8	866	6,606	1,183	0
	Lighting Upgrade	0	1,840	235	64	11	39.7	881	5,992	1,114	69
	Window Film	0	1,516	206	25	8	38.6	979	6,696	1,243	-60
	All Measures	0	1,412	186	21	6	38.2	992	6,079	1,173	10
Wood Frame, Slab	Post-Wx, Sealed	0	1,290	164	0	0	36.9	952	6,673	1,229	N/A
	Radiant Barrier	0	1,230	164	0	0	36.6	969	6,687	1,238	-9
	White Roof	0	1,265	164	0	0	36.8	980	6,696	1,243	-14
	Lighting Upgrade	0	1,203	164	0	0	36.6	996	6,082	1,175	54
	Window Film	0	933	138	0	0	35.9	1,097	6,789	1,305	-76
	All Measures	1	843	138	0	0	35.5	1,104	6,168	1,232	-3
Solid Wall, Basement	Post-Wx, Sealed	0	2,212	425	120	15	40.2	670	5,858	1,007	N/A
	Radiant Barrier	0	2,165	425	91	14	39.7	663	5,852	1,004	3
	White Roof	0	2,178	425	111	14	40.0	672	5,860	1,009	-2
	Lighting Upgrade	0	2,157	425	110	14	40.1	682	5,402	957	50
	Window Film	0	1,865	259	50	11	39.2	746	5,918	1,047	-40
	All Measures	0	1,744	258	28	9	38.4	753	5,458	994	13
Manufactured/ Mobile Home	Post-Wx, Sealed	0	2,347	425	242	15	42.0	601	5,803	971	N/A
	Radiant Barrier	0	2,306	425	189	15	41.4	588	5,793	964	7
	White Roof	0	2,311	424	217	15	41.8	598	5,801	970	1
	Lighting Upgrade	0	2,296	424	215	15	41.8	607	5,343	917	54
	Window Film	0	1,967	211	121	13	40.8	672	5,859	1,008	-37
	All Measures	0	1,822	210	66	11	39.8	679	5,399	955	16

- 21.1°C is the thermostat set point temperature. Hours below this threshold represent an inability of the furnace to maintain a comfortable temperature indoors due to excessive heat loss.
- An operative temperature ( $T_{op}$ ) of 28.9°C corresponds to the upper boundary of the adaptive model of ASHRAE Standard 55.
- CHE is the consecutive hours of exceedance (Lee and Steemers, 2013).
- A  $T_{op}$  of 37°C corresponds to normal body temperature; above this threshold the body may experience dangerous overheating.
- A therm is a unit of natural gas billing used in the United States. It is equivalent to 100,000 Btu or 29.3 kWh. The table is ordered by annual natural gas usage.
- Average natural gas cost of \$0.4291 per therm, average electricity cost of \$0.1229 per kWh.

### 4.3 Foundation type and heat gain

Houses with less ground contact, like manufactured/mobile homes on post foundations, are subject to higher operative temperatures during a heat wave. This is because houses with limited ground contact are decoupled from the cooling effect of the ground; the thermal mass of the earth tempers interior conditions. Table 3.8 summarizes the number of hours a house has an operative temperature above 37°C before weatherization.

Table 3.8: Impacts of Wall and Foundation Type on Maximum Temperatures

Wall Type, Foundation Type	Total Hours $T_{op}$ above 37°C (hours) <sup>1</sup>	CHE, $T_{op}$ above 37°C (hours)	Max $T_{op}$ (°C)
Manufactured/Mobile Home, Post	320	11	44.9
Wood Frame, Crawlspace	197	11	43.1
Solid Wall, Basement	157	11	42.3
Wood Frame, Slab	103	9	41.5
Wood Frame, Basement	92	8	41.3

1. A  $T_{op}$  of 37°C corresponds to normal body temperature; above this threshold the body may experience dangerous overheating.

I found similar results if insulation is installed in the ceiling of a basement, thermally separating the cellar from the upper floors of the house (Figure 3.2). In this illustration, I configured the energy model to show two configurations of a wood framed house with a full basement: a code-compliant home and a post-weatherization home. Both fully insulated houses have a lower mean daily range than an uninsulated home, but they also have higher minimum temperatures at night. A house without insulation between the basement and the first floor has lower maximum temperatures and lower minimum temperatures, which may be useful as a protective measure if a house does not have air-conditioning.

From these results, I note that manufactured/mobile homes may have a greater tendency to overheat. In addition, it may be advisable to insulate the rim joists of the foundation rather than the floor between the basement and the first floor, as this avoids decoupling the house from the cooling effect of the ground.

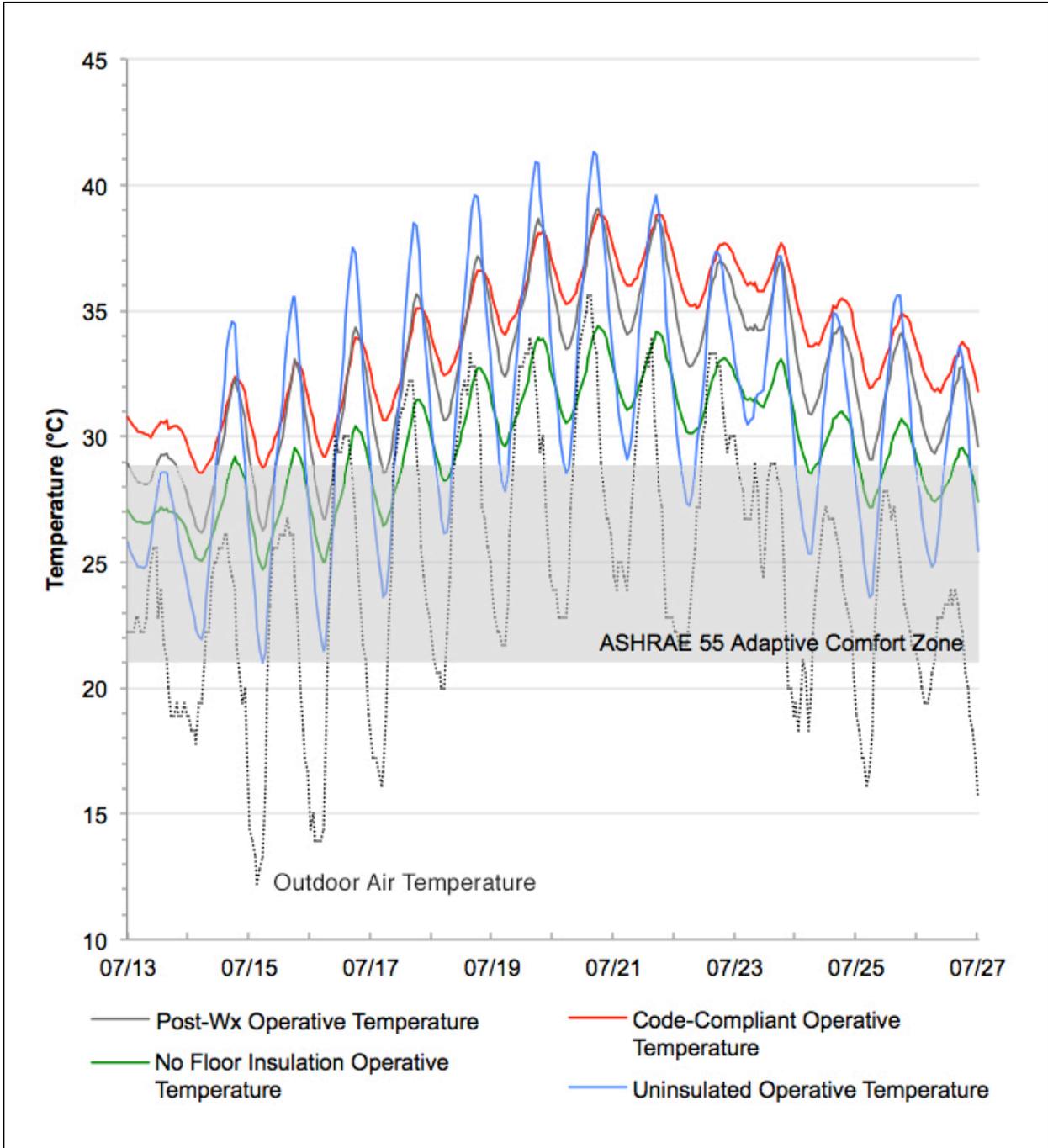


Figure 3.2: Comparison of summer indoor operative temperatures for a wood framed home with a full basement for four configurations of energy efficiency upgrades

## 5. Discussion

This chapter was structured around three research questions. First, what is the effect of wintertime weatherization on thermal comfort and energy usage during a heat wave? Second, what additional weatherization measures would improve thermal comfort and decrease electrical demand during a heat wave? Finally, what is the effect of other housing characteristics on thermal comfort and energy usage during a heat wave? While the last section discussed the results generated by the energy models, this section discusses the implications of the results for policy, program design, and program management.

### 5.1 *Impact of wintertime weatherization*

Wintertime weatherization measures (e.g., insulation, air sealing) reduce exposure to low temperatures in the winter, but these same strategies may increase exposure to temperatures above the upper boundary of the comfort zone in the summer. Weatherization measures currently employed in Ohio reduce energy usage in a home for both the heating and cooling seasons. In situations where it is necessary to install air-conditioning (e.g., residents have limited mobility that prevents them from accessing a cooling center), heating season weatherization measures reduce the required cooling capacity of the air-conditioning system, reducing both electrical demand and operating costs.

If an air-conditioning system is necessary for a home, weatherization should be completed before the system is installed. Using a smaller cooling system will draw less power from the local electrical distribution system and cost a resident less to operate the system. In addition, if power is lost during a heat wave, an insulated house should remain cooler for a longer period of time, though the energy modeling did not explore this effect.

Because the WAP and direct install air-conditioning programs are frequently done by two different entities, such as a community action agency and a public health department, it is important to improve coordination between these entities so that energy efficiency work is completed before a cooling system is installed. If increased coordination improved both winter and summer energy performance, the protocols could then be incorporated into the WAP, national initiatives such as Weatherization Plus Health ([www.wxplushealth.org](http://www.wxplushealth.org)), program notices from the U.S. Department of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control, or city-level programs operated by the Green and Healthy Homes Initiative ([www.greenandhealthyhomes.org](http://www.greenandhealthyhomes.org)).

## 5.2 *Impact of warm climate weatherization measures*

Warm climate weatherization measures (e.g., radiant barriers, white roof coating, solar window films) are not effective in lowering interior temperatures in single-family houses in Greater Cleveland and will likely increase wintertime energy usage. To keep a house from overheating during periods of hot weather, it is better to ensure that the windows are operable since results showed that natural ventilation could reduce interior temperatures by more than 10°C and had a negligible impact on annual energy performance.

Opening windows on the windward and leeward side of a house encourages cross ventilation, though opening windows on the ground floor and in an upper story in a multistory home will also help to cool a home by inducing a chimney effect to draw warm air out of the interior. In temperate climates where there is a low prevalence of air-conditioning, it is important for at least some of the windows to be operable if the house is air sealed during weatherization.

Improving cross and stack ventilation in weatherized homes will require at least five modifications to existing fenestration. First, it is important to release windows that are painted shut. Second, inoperable windows with damaged locks and/or balancing mechanisms must be repaired. Third, screens should be installed, since residents may be reluctant to open windows if doing so would allow insects or other pests into the house. Fourth, any lead paint should be mitigated as older windows have some of the highest concentrations of lead-based paints and coatings (Jacobs et al. 2002). Finally, to alleviate fears about burglaries or a child falling out of an upper-story window, it may be necessary to install security screens or window bars. While these adverse conditions may represent significant barriers to opening a window on a hot day (White-Newsome et al. 2011, Sampson et al. 2013), they can all be addressed through inexpensive and simple repairs.

The WAP recently moved to a set of national standards to govern energy efficiency upgrades in homes. These Standard Work Specifications (SWS) outline procedures to be followed by staff in the field if a project receives federal funding (U.S. Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) 2013). While the SWS mention egress windows, lead abatement, weather stripping, locking mechanisms, and repairing windows that leak, they do not currently discuss procedures to ensure that windows are operable to prevent overheating. This may be a topic to include in future versions of the specifications or distributed to states as part of a Weatherization Program Notice (WPN).

### 5.3 *Impact of foundation configuration*

Houses with less ground contact, like manufactured/mobile homes on post foundations, are subject to higher operative temperatures during a heat wave. Insulating the floor between an unconditioned crawlspace or basement and conditioned living spaces above increases interior temperatures in the summertime but improves wintertime energy performance and indoor comfort during cold weather.

Instead of having to choose either coolth in the summer or warmth in the winter, it may be possible to insulate the ground floor and then to develop new technologies based on traditional ways of operating a home. In Cleveland, a unique configuration of ductwork is found in many pre-war homes. In the Cleveland Drop, the return air ducts from living spaces are not connected to the furnace; instead, they are open to the basement air. In many homes, the open return air ductwork was placed at all four corners of a house, the maximum distance from the heating element, to ensure that the air had to travel across the basement. While no literature describes why contractors installed this configuration in Northeast Ohio homes, local weatherization officials speculated that it may have been a way to keep basements dry near Lake Erie, that it was less expensive, or that it was a way to provide low-cost cooling in summer.

In the low-cost cooling scenario, if the fan on a furnace were run without turning on the heating element, cool air tempered by ground contact in the basement would then be circulated throughout the house. While it may have been a good strategy for low-cost conditioning of air, there were many unintended side effects, including poor wintertime performance and contamination of the air with mold and moisture from the basement. In fact, the Cleveland Drop configuration was implicated in a cluster of idiopathic pulmonary hemosiderosis in infants, which resulted in 16 pediatric deaths in 1993 and 1994 (Jacobs et al. 2007).

Current healthy housing practices in Cleveland include returning the open ductwork in the basement to the furnace to prevent contamination of the air. However, if a low-cost heat exchanger that did not allow cross-contamination were installed on this return air ductwork in the basement, it might be possible to draw on the cooling effect of the basement while still protecting indoor air quality. Other options might include creating a closed loop cooling coil that has direct contact with the ground to temper the air in the summer without installing a full air-conditioning system. Both options should use less energy than a conventional compressor-based air-conditioning system.

#### 5.4 *Limitations of the study*

While results related to energy savings and energy costs were back-checked against program evaluations of the Ohio weatherization program (Khawaja et al. 2006) and the Residential Energy Consumption Survey (2009) to ensure that the modeling results were consistent, the BEopt/EnergyPlus software has several issues that are currently being investigated by the DOE. For example, according to a NREL report (2011), the EnergyPlus model overestimates energy usage in poorly insulated residential buildings. These errors may include variations in the operation of homes, differences in the amount and type of appliances in a house, or other factors related to neighborhood configuration. Since the models in this analysis are not representative of any single home in Cleveland, it is not possible to validate the results in the field.

For this reason, the energy and temperature profiles presented in this chapter should be viewed as only one perspective on the issue of heat-related morbidity and mortality; they should not be seen as a surrogate for reality (Williamson 2010). While great care was taken to ensure reliability and validity by back checking the results against energy efficiency evaluations and other data, the five models are meant only to convey the general condition of housing typically found in Cleveland.

In addition, the results of this research are intended to illustrate potential issues that might arise during the weatherization of a home and how energy efficiency might be used to reduce exposure to extreme temperatures. While the strategies selected are common during weatherization work and part of standard lists of energy efficiency measures, they are not a substitute for professional judgment in the field. Frequently, auditors and installers modify the levels of insulation or include non-standard measures in response to site conditions.

Finally, the energy and temperature modeling in this study is based on TMY data from Cleveland Hopkins International Airport. The TMY data are an average of fifteen years of weather data; they do not represent the conditions from any single year. If a major heat wave were to hit Cleveland, with temperatures more intense or of longer duration than calculated normals, one might expect conditions in homes to be worse than the current study represents. On the other hand, variations in the local microclimate due to vegetated land cover or proximity to Lake Erie might improve interior conditions by reducing incoming solar radiation or moderating air temperature. Further work is necessary to localize the results from this study and potentially to explore future conditions using downscaled climate models.

## 6. Conclusions

This research fills an important gap in the literature by quantifying temperature exposure in single family detached housing and identifying strategies to improve both comfort and energy use. Using a building energy model, I found that wintertime weatherization measures reduce exposure to low temperatures in the winter, and decrease annual energy usage, but these same strategies may increase exposure to temperatures in the summer. To keep a house from overheating, it is therefore critical that windows are operable since natural ventilation can reduce interior temperatures by more than 10°C and has a negligible impact on energy performance.

If an air-conditioning system is necessary for a home, weatherization should be completed before the system is installed because it lowers the yearly cost to heat and cool a house by a minimum of \$260, decreases electricity usage associated with air-conditioning by more than 35%, and reduces the required size of air-conditioning equipment by more than 40%. However, weatherizing a home before installing a cooling system requires closer coordination between public health and energy efficiency programs.

While warm climate weatherization measures show promise in lowering interior temperatures in single-family houses, they currently cannot be included in the DOE WAP because they increase wintertime energy usage. These strategies could be installed by another program, like a heat island reduction effort by a city. They also suggest that the benefit-cost tests used by DOE should be reviewed to account for health impacts.

Finally, houses with less ground contact, like manufactured/mobile homes on post foundations, are subject to higher temperatures indoors during periods of hot weather. While additional research is needed to understand the full relationship between indoor thermal environments, building configuration, and urban form, this finding potentially allows for the identification of an overheated home based on its configuration. This adds a new layer to our understanding of temperature exposure in cities, extending it to begin to include the indoor environment.

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## CHAPTER 4

### A System of Professions Approach to Reducing Heat Exposure

#### 1. Introduction

In many temperate cities, exposure to high temperatures is increased because of the poor quality of housing stock and the urban heat island effect (Huang 1996, Semenza et al. 1996, Luber and McGeehin 2008, White-Newsome et al. 2012). Although strategies to reduce heat-related illness should incorporate insights from the environmental health sciences (Luber and McGeehin 2008), building science (Guy and Shove 2000), and urban climate (Oke 2005), there remains limited connections among these three disciplines and the policies they propose to reduce heat-related vulnerability. Drawing on each of these three literatures, this chapter assesses how health, building science, and urban environmental professionals in Cuyahoga County, Ohio work to reduce heat exposure.

After a literature review, the chapter describes the results from twenty-eight semi-structured interviews with health, building science, and urban environmental professionals. These professionals define issues related to temperature differently, which results in barriers to collaboration. Only three strategies—energy efficiency, air-conditioning, and indoor air quality protection—were mentioned by the majority of interviewees; other important interventions like cooling centers, cool roofs, or an increase in the tree canopy were only discussed by participants from one of the other sectors. The qualitative approach used in this chapter is in the tradition of communicative planning theory (Innes and Booher 2014); the results from this research are intended to improve coordination and collaboration among local organizations as they look for innovative strategies to reduce exposure to elevated temperatures.

#### 2. Literature Review

To date, there have been few efforts to describe how professionals define, implement, and evaluate strategies to reduce heat exposure, though several authors have claimed that such a taxonomy might support cross-disciplinary collaboration and communication (Oke 2006, Blanco

et al. 2009, O'Neill et al. 2009, Maller and Strengers 2011). To address this gap, this chapter discusses the system of professions involved in reducing heat-related exposure in Cuyahoga County. A system of professions approach links professionals (e.g., public health officials, architects, urban planners) to the work they consider their jurisdiction, such as providing cooling centers, weatherizing homes, or developing plans (Abbott 1988, Janda and Killip 2013).

### *2.1 Disjointed Policy Responses*

A number of authors have advocated for increased access to air-conditioning as a way to reduce heat-related morbidity and mortality (Semenza et al. 1996, Keatinge 2003). This is because cities with higher air-conditioning prevalence have lower levels of heat-related mortality (Chestnut et al. 1998, Braga et al. 2002, Anderson and Bell 2009). However, this quick fix creates other problems like waste heat, air pollution, and increased greenhouse gas emissions (O'Neill et al. 2009). Air-conditioning also stresses electrical distribution systems, causing brownouts or blackouts during heat waves when the protective cooling is most needed (Stone 2012).

Instead of a simple, technical solution, Strengers and Maller (2011) maintain that we need a better understanding of cooling practices, including the processes that drive adoption of certain technologies. In a study of Australian households, they found that policy responses to high temperatures have become locked in; this keeps policymakers from considering alternatives like natural ventilation and urban heat island management (Ibid.).

They also state that differences in definitions leads to conflicts among the health, housing, and energy sectors:

For health policymakers, heat involves issues of life and death and requires urgent solutions such as immediate access to cooling services. For the housing sector, there is an imperative to improve the thermal performance of buildings to reduce greenhouse gas emissions and adapt to climate change. In the energy sector, the rapidly increasing demand for residential air-conditioning on hot summer days threatens continuity of supply (Ibid., 155).

They find that issues of heat-related illness, energy security, and climate change are interconnected, but policy responses are not; in fact, efforts to reduce heat-related morbidity and mortality frequently contradict one another (Ibid.). To overcome these divisions, they argue that more work is required to understand what role policymakers play in shaping cooling practices, and a new theoretical framework is needed to understand the interconnections of the problem

across policy sectors (Ibid.). This chapter builds on their work and takes an initial step toward describing a new framework.

## 2.2 *Policy sectors*

A *policy sector* is defined as a broad group of individual, organizational, and institutional entities that focus on improving the health, housing, or urban environments of their constituents. A policy sector is similar in concept to an advocacy coalition (Sabatier and Weible 2007) or a discourse coalition (Hajer 1995), but it is broader in scope. While this paper focuses primarily on efforts in Cuyahoga County, policy sectors can span multiple levels of government to include local, state, and federal efforts.

Three policy sectors are engaged with the issue of heat stress in cities: health, building science, and the urban environment. While the three sectors I selected vary slightly from those examined in Strengers and Maller's (2011) work on the health, housing, and energy sectors of Australia, this chapter combines housing and energy into a building science policy sector because most energy efficiency programs in the United States are targeted at the household level. In addition, their research focused exclusively on residences and did not discuss the role of the urban heat island in exacerbating exposure to heat stress (Strengers and Maller 2011).

While heat stress reduction efforts could be divided into two large sectors (health and urban environment), or four smaller sectors (health, housing, urban environment, and energy), preventative programs in the United States generally fall under the direction of a single federal agency like the U.S. Department of Health and Human Services (HHS), the U.S. Department of Energy (DOE), or the U.S. Environmental Protection Agency (EPA).

While some institutions like the U.S. Department of Housing and Urban Development (HUD) have crosscutting missions, individual programs under these agencies still tend to align with health, building science, or the urban environment. For example, federal programs tasked with reducing heat-related stress include the Low Income Home Energy Assistance Program (LIHEAP), the Weatherization Assistance Program (WAP), or the Heat Island Program, even though each parent agency (HHS, DOE, EPA) has a broader mission related to health, energy, or the environment.

The three policy sectors selected also align with the allied professions of public health, architecture, and urban planning. Although these professions emerged from a common historical root (Dagenhart and Sawicki 1992, Corburn 2009), they take very different approaches to

improving the public's quality of life. While a number of authors have used these three professions as examples to describe the sequence of professionalization (Wilensky 1964), or the monopoly they may hold over decision-making processes (Fischer 2000, Larson 2013), this chapter focuses exclusively on their current interrelations to identify the gaps, barriers, and conflicts that may limit coordination and collaboration around the issue of reducing exposure.

The focus is on professionals because they are experts who operate within the “hidden hierarchies of policy communities” and have a significant influence on policy definition and implementation of solutions (Fischer 2000, 22). Janda and Parag (2013) believe that the importance of professionals is often overlooked in the social sciences; they argue that professionals have an important role in the “middle” as mediators between the government and the public. In their article, they claim that professionals are “middle-out” actors who work upstream to government, downstream to clients and customers, and sideways among other groups and organizations working in their area of expertise (Ibid.).

Because my goal is not to understand how a profession emerges, or to construct a complete sociology of these three professions, I broadly define a *profession* as an occupational group that has an abstract skill requiring extensive training. These abstract skills are not applied in a routine fashion; they require application on a case-by case-basis depending on the situation (Abbott 1988, 7). This definition avoids a discussion of codes of ethics, professional organizations, and licensure; instead, it focuses on the knowledge systems used to define a problem and on the constitution of professional work (Ibid., 9).

### 2.3 *The System of Professions Framework*

A system of professions approach (Abbott 1988) describes how professional groups define their work and establish jurisdictions over a problem; it is an ecological model that attempts to explain how professions interact (Henn 2013). To define his framework, Andrew Abbott uses three terms to label key processes: diagnosis, treatment, and inference (Ibid., 40).

*Diagnosis* is the analysis of the cause of a condition, situation, or problem. *Treatments* are the techniques or actions customarily applied in a specified situation. *Inference* is the act of passing from one proposition, statement, or judgment considered as true to another. The following example illustrates how diagnosis, inference, treatment are related in the health policy sector.

In the 1950s, U.S. Navy physicians used data from hospitalizations at the Parris Island Marine Corps Recruit Depot in South Carolina to model combinations of temperature, humidity, wind speed, and solar radiation that could lead to heat stroke during training exercises (Minard 1957). Using their medical knowledge, these doctors determined that outdoor thermal environmental conditions caused symptoms of heat-related illness. This analysis eventually became the basis for the wet-bulb globe temperature (WBGT) heat warning system still used today (Budd 2008).

Many U.S. cities use similar heat warning systems to decide when to open cooling centers or provide air-conditioning to vulnerable populations (O'Neill et al. 2009, White-Newsome et al. 2014). These treatments generally target vulnerable populations like the elderly, low-income residents, those living alone, or people with preexisting conditions like diabetes or heart disease (Reid et al. 2009). These treatments are inferred from case control studies of extreme heat events like the July 1995 heat wave in Chicago that killed over 700 people (Semenza et al. 1996). These ex-post studies established odds ratios that direct the selection of treatments.

In the Chicago heat wave study, Semenza et al. (1996) found that access to air-conditioned environments had the greatest protective effect, consistent with the diagnosis that exposure to high temperatures leads to heat-related illness. In this way, diagnosis, treatment, and inference of heat stress are interrelated; this work is all based on a system of *academic knowledge* that formalizes these professional skills (Abbott 1988, 52). According to Abbott:

Academic knowledge legitimizes professional work by clarifying its foundations and tracing them to major cultural values. In most modern professions, these have been the values of rationality, logic, and science. Academic professionals demonstrate the rigor, the clarity, and the scientifically logical character of professional work, thereby legitimating that work in the context of larger values (54).

The academic, abstract knowledge system is important to all professions; assaults on the jurisdiction of a profession to treat an issue are often directed at the academic level (Ibid., 55).

For example, after the 1995 heat wave in Chicago, a building scientist at Lawrence Berkeley National Laboratory argued that ventilation, insulation, and roof color were just as important as air conditioning in reducing exposure (Huang 1996). One sociologist blamed the deaths on social isolation, marginality, and neglect in American cities (Klinenberg 2002), while

another used an ethnographic approach to understand how drug and alcohol addiction played a role in individual deaths (Duneier 2006). The authors of all three studies agreed that extended high temperatures contributed to the deaths; however, each author interpreted this observation relative to other factors using his or her own base of academic knowledge.

The differences in diagnosis, inference, and treatment are explored in greater detail in Table 4.1, which outlines differences among the health, building science, and urban environment policy sectors.

Table 4.1: From Academic Knowledge to Preventative Programs

	Academic Knowledge <sup>2</sup>	Example Authors/Studies	Diagnoses <sup>2</sup>	Methods of Inference <sup>2</sup>	Treatments <sup>2</sup>	Preventative Programs <sup>3</sup>
Health Policy Sector <sup>1</sup>	Medicine, Industrial Hygiene, Public Health, Social Work, Health Geography, Health Sociology, Epidemiology	(Minard 1957, Kilbourne 1982, Semenza et al. 1996, Budd 2008)	Exposure to high temperatures causes illness. Socioeconomic status, age, education, health, and environmental factors are associated with increased exposure.	Case control studies investigate the socioeconomic, demographic, and environmental factors associated with increased morbidity and mortality.	Reduce exposure in vulnerable populations by tempering the thermal environment.	Heat health warning systems, messaging, cooling centers, neighborhood watch programs, air-conditioning installation
Building Policy Sector <sup>1</sup>	Mechanical and Electrical Engineering, Building Science, Economics, Environment and Behavior, Behavioral Psychology	(Fanger 1972, Nicol and Humphreys 1973, de Dear and Schiller Brager 1998, Hoppe 1999)	Building occupants require a certain range of indoor thermal environmental conditions to achieve thermal comfort.	Studies investigate the thermal environmental and personal variables that predict comfortable conditions.	HVAC or passive systems provide comfortable indoor conditions for the occupants.	Emerging technologies, energy efficiency, weatherization, low-income energy assistance
Urban Policy Sector <sup>1</sup>	Civil and Environmental Engineering, Urban Climate, Landscape Architecture, Urban and Regional Planning, Urban Sociology	(Oke 1982, Klinenberg 2002, Harlan et al. 2006, Reid et al. 2009, Santamouris et al. 2011)	The urban heat island effect increases energy consumption, pollutes air, compromises human health, and impairs water quality.	Experimental and quasi-experimental field studies investigate the biophysical variables that cause the urban heat island effect.	Improvements in land cover, urban geometry, heat capacity, and anthropogenic heat sources mitigate the urban heat island effect.	Street tree planting, zoning, architectural standards, paving specifications, energy efficiency

1. Concept of policy sectors adapted from Strengers and Maller (2011).
2. Concept of academic knowledge, diagnosis, inference, and treatment adapted from Abbott (1988).
3. Preventative programs are city, county, state, federal and non-governmental programs that provide services such as air-conditioning installation, energy efficiency, street tree planting, or public education/outreach.

This matrix informed the creation of semi-structured interview questions to explore whether the concepts of diagnosis, inference, treatment and academic knowledge could be used to explain differences among the professionals reducing heat exposure in Cuyahoga County.

#### *2.4 Communicative Planning Theory*

The qualitative approach of this chapter is in the tradition of communicative planning theory (CPT). CPT refers to the work of scholars in planning and related fields who conduct fine-grain, interpretive research on planning processes using concepts from social theorists like Abbott (1988) to describe observations and develop normative perspectives (Innes and Booher 2014).

By promoting “communicative action among scientists, planners, and laymen, all can learn and take advantage of what the other does best, and the resulting knowledge can be both more accurate and more meaningful” (Ibid., 7). CPT has been effective in solving other difficult policy problems, most notably in Sacramento, California, where members of the Sacramento Water Forum spent five years in an intensive consensus-building process to manage their limited water supply (Innes and Booher 2003).

In the Sacramento example, a collaborative group was convened that included local, state, and federal agencies with jurisdiction over California’s water supply. The collaborative planning process allowed agencies to make collective decisions that were defensible to the larger public, reduced conflict among parties, and were comprehensible among parties.

Comprehension among parties is important because collective deliberation on a problem is necessary for the formation of a collaborative rationale. Innes and Booher state that, for a project team to form a collaborative rationality, three conditions are required: a full diversity of interests among participants, interdependence of the participants, and engagement in face-to-face dialogue (2010, 35). Collaborative rationality results in reciprocity among agents, stronger interpersonal relationships, collective learning, and shared heuristics that transcend disciplinary boundaries (2010, 37).

While there is some concern over the amount of resources participants need to contribute to such a process, the concept may be transferrable to the issue of heat exposure in Cuyahoga County and other cities (Innes and Booher 2004). Research that supports communicative action—such as the research presented in this chapter—can lead to new identities, meanings, heuristics, and innovation that may help communities adapt to future challenges like extreme heat events or other climate-related surprises (Schneider 2004, Innes and Booher 2010).

## 2.5 *Research Questions and Hypotheses*

I structured this chapter around three research questions. The first question was “How do professionals define issues related to temperature in the built environment?” I generated two hypotheses consistent with the system of professions to address this question. First, professionals in the health, building science, and urban environment policy sectors have different sets of academic knowledge. Second, professionals have different diagnoses, methods of inference, and treatments of temperature-related issues in the built environment.

My second research question was “How do professionals act on issues related to temperature in the built environment?” I created two hypotheses, derived from the system of professions approach and from Janda and Parag (2013), to answer this question. First, professionals simplify treatments to increase program efficiency. Second, professionals are middle-out actors who work upstream by participating in the policy process, downstream to assist program implementation, and sideways to influence local decision-making.

After investigating how professionals define and address issues, I asked, “What are the barriers to collaboration among these professionals?” I explored two hypotheses in the interviews. First, differences in priorities cause conflict among programs, but recent efforts have successfully integrated programs at the local level. Second, a major event or a change in program funding can alter how professionals address thermal environmental issues in the built environment. This is based on the observation that events like the 1995 heat wave in Chicago or the 2003 extreme heat event in Europe brought global attention to the problem of elevated temperatures in urban environments.

## **3. Methods**

I used two primary methods to collect data. The first was a review of official documents from the weatherization, urban environment, and heat health programs at the city, county, state, and federal levels. I also participated in a week-long, hands-on weatherization training program, attended two national weatherization and health conferences, and observed a sustainability summit sponsored by the City of Cleveland.

Drawing on these experiences, I then developed a schedule of questions for semi-structured interviews with program staff. The questions were based on concepts from the system of professions and focused on five areas: (1) career and educational background, (2) agency

structure, (3) collaboration, (4) innovation, and (5) program evaluation. I also developed recruitment emails, consent forms, and an interview checklist to ensure consistency among all of the interviews. The University of Michigan Institutional Review Board (IRB) reviewed and approved the questions and procedures; copies of all of the forms and the IRB exemption letter appear in Appendix B.

Beginning with the names of city staff I had identified from the program documentation, I began to schedule and interview program managers. Interviews ranged from approximately 45 minutes to more than two hours in length. In two instances, there was more than one participant in the interview: one interview had two participants, and the other had three participants. All interviewees gave their written consent for the interviews; a second form gave permission to audio record the conversation for transcription and analysis. Only one interviewee asked me not to audio record the interview.

At the end of each interview, I asked the participant for contact information for additional interview participants; this snowball sampling method is commonly used in qualitative interviewing (Weiss 1994). In total, I conducted twenty-eight semi-structured interviews with 32 people from the health, building science, and urban/neighborhood policy communities who work on temperature-related issues. All of the interviews were conducted between August 19 and October 25, 2013. Because the interviews were related to their profession, and because public employees are generally prohibited from receiving gifts, participants did not receive any compensation for their participation.

Table 4.2: Interviewee Characteristics by Sector

Characteristic	Health	Building Science	Urban Environment	Row Total
Male	5 (15.6%)	7 (21.9%)	8 (25.0%)	20 (62.5%)
Female	6 (18.8%)	3 (9.4%)	3 (9.4%)	12 (37.5%)
Column Total	11 (34.4%)	10 (31.2%)	11 (34.4%)	32 (100%)

City/County	Health	Building Science	Urban Environment	Row Total
State	0	2 (6.2%)	0	2 (6.2%)
Federal	1 (3.1%)	2 (6.2%)	1 (3.1%)	4 (12.5%)
Non-Governmental	4 (12.5%)	3 (9.4%)	4 (12.5%)	11 (34.4%)
Column Total	9 (28.1%)	12 (37.5%)	11 (34.4%)	32 (100%)

Table 4.2 presents the characteristics of the interviewees by sector. Twenty of the interviewees were male (62.5%) and twelve were female (37.5%). Eleven of the interviewees were from the

health sector (34.4%), ten were from the building science sector (31.2%), and eleven were from the urban environment sector (34.4%). The majority of the professionals worked at the city and county levels (46.9%), though I also interviewed professionals at the state (9.4%) and federal (9.4%) levels. Roughly a third of the interviewees (34.3%) were from non-governmental organizations that worked at all three levels.

I taped the interviews using a digital recorder. The audio files were transcribed by a professional transcriptionist; I checked the transcripts against the audio recording for accuracy and entered them into the cloud-hosted Dedoose software for analysis (Lieber and Weisner 2010, SocioCultural Research Consultants 2014). The primary advantage of using a computer is that it streamlines the coding and analysis process. However, the software does not perform the analysis; it merely reduces the amount of time it takes to code and helps with the creation of matrices to explore relationships among codes.

In qualitative analysis, coding is the process by which transcribed narrative data are organized and assigned meaning; the codes are tags or labels assigned to segments of text (Miles et al. 2014). I began coding with a provisional list of codes related to the five categories of questions. Once I had coded all of the interviews using this initial list, I then coded the text line-by-line using an open coding approach (Saldaña 2009). Using Dedoose, I then generated coding reports to understand how frequently a code occurred within each policy sector. These reports were also helpful in identifying representative quotations to illustrate a concept and to triangulate answers to improve the validity of my conclusions.

#### **4. Results**

The results section follows the order of the six hypotheses presented at the end of the literature review. First, I describe the academic knowledge base used by professionals in each sector. Second, I discuss the diagnoses, methods of inference, and treatments used by each policy sector. Third, I explore how professionals simplify their processes to increase program efficiency. Fourth, I explain how professionals work as middle-out actors to influence policy, affect program implementation, and influence decision-making. Fifth, I discuss conflicts that can arise among policy sectors. In the sixth and final subsection, I describe how a major event can lead to a change in program structure.

#### 4.1 Academic knowledge

An analysis of the interviews revealed that professionals in the health, building science, and urban policy sectors have different sets of academic knowledge. For example, the thirty-two interviewees had earned post-secondary degrees in twenty different fields from three different branches of science (Table 4.3).

Table 4.3: Highest Degree Earned by Sector

Branch of Science	Highest Degree Earned	Health	Building Science	Urban Environment	Row Total
Health Sciences	Master of Public Health	3 (9.4%)	0	0	3 (9.4%)
	Master of Nutrition	1 (3.2%)	0	0	1 (3.2%)
	PhD in Industrial Hygiene	1 (3.2%)	0	0	1 (3.2%)
	PhD in Medical Anthropology	1 (3.2%)	0	0	1 (3.2%)
Natural Sciences	Bachelor in Environmental Studies	0	2 (6.3%)	0	2 (6.3%)
	Bachelor of Landscape Architecture	0	0	1 (3.2%)	1 (3.2%)
	PhD in Forest Biology and Wood Science	0	0	1 (3.2%)	1 (3.2%)
	PhD in Systems Ecology	0	0	1 (3.2%)	1 (3.2%)
	PhD in Climatology	0	0	1 (3.2%)	1 (3.2%)
Social Sciences	Juris Doctor	1 (3.2%)	0	0	1 (3.2%)
	PhD in History of Sociology & Science	1 (3.2%)	0	0	1 (3.2%)
	Master of Business Administration	0	1 (3.2%)	0	1 (3.2%)
	Master of Regional Planning	0	1 (3.2%)	0	1 (3.2%)
	Master of Public Administration	0	1 (3.2%)	1 (3.2%)	2 (6.3%)
	PhD in Urban and Regional Planning	0	1 (3.2%)	1 (3.2%)	2 (6.3%)
	Master of City/Urban and Regional Planning	0	0	1 (3.2%)	1 (3.2%)
	Master of Energy Policy and Economics	0	0	1 (3.2%)	1 (3.2%)
	Master of Public Policy	0	0	1 (3.2%)	1 (3.2%)
	Master of Urban Studies	0	0	1 (3.2%)	1 (3.2%)
PhD in Geography	0	0	1 (3.2%)	1 (3.2%)	
Other	Some College Experience	2 (6.3%)	4 (12.6%)	1 (3.2%)	7 (21.9%)
Column Total		11 (34.4%)	10 (31.2%)	11 (34.4%)	32 (100%)

Only four degrees were earned by more than one professional: a Master of Public Health (n=3), a Bachelor of Environmental Studies (n=2), a Master of Public Administration (n=2), and a PhD in Urban and Regional Planning (n=2).

The majority of the interviewees had earned doctoral degrees (31.3%) or a master's degree (37.5%). The rest had either earned a bachelor's degree (9.4%) or had some college experience (21.9%). The degrees were all related to the health sciences, natural sciences, or the social sciences, though several of the professionals also mentioned undergraduate degrees in arts-related fields like English Literature. The professionals I interviewed remained connected to the local academic community; half (50%) stated that they regularly collaborated with local universities on teaching, research, or service learning projects.

The highest degree earned was generally related to the interviewee's professional career, though the majority of interviewees (56.3%) described additional state or federal government training that was required for their work. Most of the interviewees (75%) regularly attended professional conferences, though the economic downturn had limited recent opportunities. Slightly less than a third (31.3%) had professional registrations; these included Registered Sanitarian, LEED Accredited Professional, and Registered Landscape Architect.

Because the professionals were educated in twenty different fields, with limited overlap among their educational backgrounds, they draw on different sets of scientific knowledge to accomplish their work. This affects how they diagnose, test, and reduce heat exposure in the built environment.

#### 4.2 *Diagnoses, inference, and treatments*

Consistent with Abbott's system of professions framework (Abbott 1988), I found that professionals have different diagnoses, methods of inference, and treatments of temperature-related issues in the built environment. These differences are aligned along the health, building science, and urban environment policy sectors.

In the health sector, risk factors correlate with increased morbidity and mortality during extreme heat events (*diagnosis*). Epidemiological studies investigate these factors with the goal of identifying patterns of morbidity and mortality (*inference*). Preventative programs attempt to reduce morbidity and mortality in vulnerable populations by reducing exposure, creating public awareness campaigns, or providing social services like a cooling center (*treatment*).

Public health officials use epidemiological studies to diagnose local health problems and inform the design of their programs to prevent heat-related illness:

Our epidemiologists at the city and the county take a look at heat-related illness, what kind of issues we're running into, not just the heat-related illness, but all of the issues. And then we break out what the healthy actions and healthy choices are that people can be making. And, that includes how you prepare for them, how you respond to disasters or issues. (Interview #5)

For professionals in the building science policy sector, climate, house configuration, and behavior are associated with thermal comfort and energy use in a home (*diagnosis*). Field studies by building scientists investigate these factors with the goal of creating cost-effective energy efficiency strategies and standardized analysis tools like the blower door (*inference*).

Weatherization and energy efficiency programs improve thermal comfort and reduce energy use by using these tools to select cost-effective energy efficiency treatments for a house (*treatment*).

A weatherization program manager discussed how their organization borrowed energy efficiency research from building scientists in Canada to improve the diagnostic procedures used by the weatherization program:

When I got into this over here 27 years ago, of course there were no diagnostics really, a blower door type or combustion analysis or anything like that. And building science was more like folklore I'd say, 'cause a lot of things that were done were not good. But it was, I guess, a learning lab for people... And at the same time I think the Canadians were starting to do their actual research. They were a little more organized, I think. Of course, it's a little colder there. But, the blower door type testing I think was—that was the first research I started doing, is what they were doing in Canada and a few scattered places. (Interview #15)

For urban environmental professionals, low albedo and high levels of impervious surface are associated with increased temperatures and greater stormwater runoff (*diagnosis*). Field studies by urban climatologists and natural resource managers investigate and statistically define these relationships (*inference*). Cool roofs, pervious paving, and open space reduce the urban heat island effect by increasing albedo and stormwater infiltration (*treatment*). A policy analyst described how their non-governmental organization promotes certain strategies to reduce the urban heat island effect in cities:

I would say on the code side we do try to promote inclusion of reflective roof standards, reflective coatings for re-roof jobs, replacements, and new roofs. That's sort of at the one end of the spectrum. We're also interested in—beyond the white roofs—we're looking at permeability measures. So, whether that's preferential permitting or FAR [floor area ratio] ratio changes, things like the program in [Washington] D.C. that they just launched, a stormwater mitigation credit program. We do look at utility programs, both in terms of the incentives but also in terms of how the utility—the cost effectiveness tests that are applied to cool roof projects—and how that can be done in a way that's a little bit more preferential to cool roofing. (Interview #18)

While diagnoses and methods of inference are different for each of the policy sectors, there are some overlaps in the treatments discussed during the interviews. Professionals described thirteen different treatments that are effective in reducing exposure to temperature (Figure 4.1).

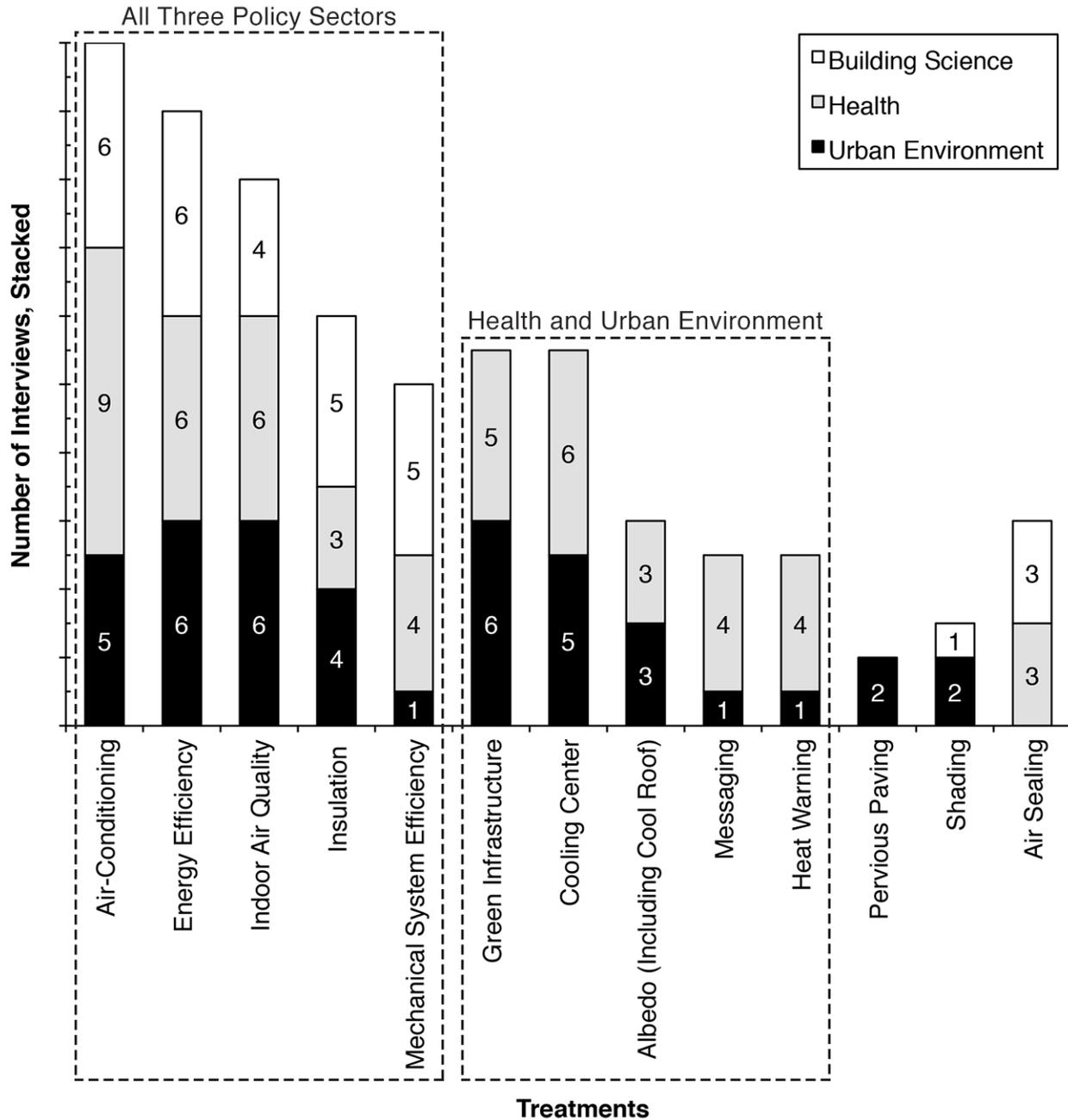


Figure 4.1: Treatments Discussed by Sector (Note: Treatments were counted only once per interviewee. Treatment types were narrowly coded; interviewees had to mention that the strategy was used by their program or that they felt it might be an effective way to reduce exposure.)

Air-conditioning, energy efficiency, indoor air quality, insulation, and mechanical system efficiency were mentioned by all three policy sectors. Green infrastructure, cooling centers, increases in albedo, messaging, and heat warning systems were discussed in interviews only in the health and the urban environment policy sectors. Finally, pervious paving, shading, and air sealing were only discussed by a small number of professionals from one or two of the sectors.

Air-conditioning, energy efficiency, and indoor air quality protection were the only treatments discussed by a large fraction of interviewees from all three sectors. In addition, several strategies like pervious paving, shading, and air sealing were mentioned by only one or two of the sectors. In general, professionals from the urban environment sector discussed the widest range of strategies, and building scientists mentioned the narrowest number.

An unexpected result was that no one from building science mentioned albedo increases as part of their interview; cool roofs are a well known strategy for reducing summertime air-conditioning loads. This may be because the Ohio Home Weatherization Assistance Program primarily targets wintertime energy savings.

#### 4.3 *Simplification of treatments*

Abbott (1988) describes the conversion of professional knowledge into a commodity that can be bought and sold without the direct involvement of a profession. Abbott provides examples from law, architecture, and the social sciences; these professional commodities include fixed legal forms, house plans, and statistical analyses (Ibid., 146). Because professionals in Cuyahoga County did not actively sell their professional knowledge in a condensed form, I use the term “simplify” instead of “commodify”.

In the interviews in Greater Cleveland, I found that professionals simplify treatments to increase program efficiency and to aid in evaluation. Across all three of the policy sectors, the process used to simplify treatments was similar; it was described as the creation of a template or tool for use by others (35.7%), as the standardization of treatments (50%), or as the sharing of data among organizations (14.3%).

For example, rather than allowing each local jurisdiction to develop heat warning messages, federal health professionals provide templates to local agencies to ensure consistency in public messaging about heat waves; local professionals in turn coordinate and share these announcements with the public:

A lot of what we do that reaches the public is coordinated through our public information officers, and shared messaging, and shared templates of responses. We'll take federal guidance and federal programs and bring them down to the local level and share the messages. We'll work with our partner agency, the public information officers, to make sure that we're all talking about the same things at the same time. (Interview #5)

In a similar way, the weatherization program initially provided services on a case-by-case basis, leaving selection and implementation of strategies to local building professionals. Over time, research borrowed from Canada defined insulation and air sealing as two of the most important strategies to improve energy efficiency and comfort in a home. To reduce errors during installation, state officials created standards to guide the renovation of homes:

We have what is called the Ohio Weatherization Program Standards. It's 536 or so pages of everything you can think of from HVAC [heating, ventilation, and air-conditioning], to how to blow insulation, to combustion analysis, and just about anything you can think of. There's guidelines for all of it and exactly how you do it. (Interview #3)

In the urban environment sector, data sharing among organizations facilitates coordination among agencies. Several interviewees mentioned an effort by Case Western Reserve University called the Northeast Ohio Community and Neighborhood Data for Organizing (NEO CANDO). According to the NEO CANDO (2012) website, staff at the university compile data from a wide variety of federal, state, and local organizations, clean the data, create consistent formatting, and upload it to a password-protected website. In this case, data created by professionals is open for public interpretation; their professional judgment is no longer needed to create a map to analyze trends in the region.

#### *4.3.1 Evaluation*

The health, building science, and urban environment sectors all evaluate the performance of their programs; simplification assists in this process because it breaks down professional knowledge into units for analysis. For example, in the health sector, professionals use epidemiological surveillance to determine current health risks in the community. If more people are being admitted to the hospital than usual due to high temperatures, they can increase or target messages to stem the rate of heat morbidity.

Residential efficiency programs conduct ex-post evaluations to understand how standardized treatments like insulation or air-sealing perform; they also calculate cost-benefit ratios based on the number of kilowatt-hours and therms of natural gas used to ensure that the programs are saving more money than they cost. Without standardization of the treatments and evaluation metrics, it would not be possible to measure across programs and from year to year.

However, very formal procedures may create institutional inertia that makes it more difficult to introduce new strategies; this is discussed in greater detail in the conclusions section.

Finally, the urban environment policy sector tends to rely on broad sustainability indicators, metrics that signal if progress is being made on environmental issues (Sustainable Cleveland 2014). The process urban environment professionals use is less formal than those of either the health or building science sectors, but one advantage is that program managers monitor a wide range of outcomes and can adjust their strategies accordingly.

#### *4.4 Professionals as middle-out actors*

Consistent with Janda and Parag (2013), I found that professionals in all three policy sectors are middle-out actors, and that they work upstream by participating in the policy process, downstream to assist program implementation, and sideways to influence local decision-making. The interviews indicate that all three of the sectors use similar tactics; there are no significant tactical differences among health, building science, and urban environment professionals. The following three subsections describe these upstream, downstream, and sideways processes.

##### *4.4.1 Upstream*

In working upstream to influence policy formation, more than two-thirds of the professionals interviewed (71.4%) participated in advocacy efforts, served on a policy committee, or had a direct advisory role for their program. Slightly more than a quarter of the interviewees (28.6%) provided data to help formulate policy. Others (7.1%) participated in regularly scheduled meetings to discuss program management with policymakers.

For example, a series of pediatric deaths in Cleveland led to changes in how the U.S. Department of Housing and Urban Development (HUD) addresses environmental hazards across the United States. As early as 1993, local hospital officials noticed that there was a cluster of infant mortality occurring in low-income and minority households. They received permission from parents to autopsy the children to determine the cause and found a rare condition of the lungs called pulmonary hemosiderosis (Jacobs et al. 2007). Hypothesizing that the children had been exposed to something in the air in their homes, they visited their houses and discovered a unique configuration of ductwork called the “Cleveland Drop.”

In the Cleveland Drop, the return air ducts from living spaces are not connected to the furnace; instead, they are open to the basement air. In many homes, the open return air ductwork

was placed at each of the four corners of a house, the maximum distance from the heating element, to ensure that the return air had to travel across the basement. While no literature describes why contractors installed this configuration in Northeast Ohio homes, local weatherization officials speculated that it may have been a way to keep basements dry near Lake Erie, that it was less expensive, or that it was a way to provide low-cost cooling in summer.

Unfortunately, this unique ductwork configuration appears to have caused the pulmonary hemosiderosis by contaminating the indoor air with moisture and mold from the basement. One of the interviewees described the testing they used to determine whether the Cleveland Drop was causing air contamination in homes:

We had moisture. We had mold. We had a Cleveland Drop. And the numbers were perfect. When that furnace ran I mean our spore counts, phew... And then when the furnace kicked down it went down. And, it was what you'd expect to find. (Interview #16)

In testimony before the U.S. House of Representatives (1998), two local health officials asked Congress to provide additional funding to address environmental hazards in homes. One of the members of Congress, Louis Stokes, was the representative for the City of Cleveland and was aware of the pediatric deaths. Louis Stokes then worked with Congress to restructure the HUD Office of Lead Hazard Control into a new organization with a broader focus on health issues in the home (U.S. Congress 1998).

Although this example of professionals working upstream is only indirectly related to temperature exposure, it is a clear example of how professionals can influence the policy process. In addition, the Office of Lead Hazard Control and Healthy Homes initiated by Louis Stokes at HUD is responsible for reducing common health-related issues in the home; one of the major risk factors recently identified is a lack of indoor temperature control (Federal Healthy Homes Work Group 2013). Similar examples occurred in the building science and urban environment sectors, though none of the other cases had as dramatic of an impact on federal policy.

#### *4.4.2 Downstream*

In working downstream, more than half of the professionals interviewed participate in community meetings (60.7%), collaborate on research (32.1%), or serve as a consultant to projects (7.1%). In one example, urban designers are working with neighborhoods to find new purposes for vacant properties, a significant problem for Greater Cleveland (Dewar 2006).

In this example, urban environment professionals are interpreting a consent decree agreed to by the Northeast Ohio Regional Sewer District (NEORS) and the U.S. Environmental Protection Agency (2011) to reduce combined sewer overflows into Lake Erie. Their goal is to reutilize vacant land to increase resiliency:

It's really about understanding the best ways to redevelop the city in light of the current population realities and anticipated opportunities for regeneration and new development. So, we have this moment in time where we have surplus real estate like crazy... So we can begin, not necessarily how we use vacant land, but how we redevelop city neighborhoods, where the developments should go and where it shouldn't. That shouldn't part is really important because right now is the moment when the market demand is so weak that we can set aside land through deed restrictions or public covenants of one kind or another so we don't develop that. In which case, we can build resiliency in the neighborhoods. We can build resiliency into the city and the region. And so, that's where it connects to climate change, and also hydrology, and all kinds of other things that we're interested in. (Interview #11)

Working with local non-profits, they are using their professional knowledge to show how vacant land can be repurposed for stormwater capture and rain gardens to reduce combined sewer overflows into Lake Erie. They are also developing pilot projects in distressed neighborhoods to increase the amount of tree canopy in the city. While their primary goals are to reutilize the large number of vacant properties and to reduce the discharge of sewage into the lake, they said in the interviews that their efforts will have environmental co-benefits like climate resiliency. This example shows how professionals can interpret policy and work with local organizations downstream to implement the policy process. All three policy sectors engaged in similar efforts.

#### *4.4.3 Sideways*

Education and training (39.3%) and tool kits (21.4%) were the two primary ways that professionals worked sideways to influence other professionals in their work. For example, the Office of Emergency Management in Cuyahoga County recently held a “table top” training exercise to examine heat-related vulnerability. The exercise emphasized collaboration among professionals from local agencies:

What happened was they invited a variety of different response partners that would be involved in a heat type of response and we actually had the exercise here. What they did was they set up some tables in the room and each table had a multidisciplinary group. And so they started out with a scenario and described a situation where it's forecasted that it's going to be an extreme heat event. And

then they pose questions to the group. And as a small group you work through those questions and following that small group discussion, there's a larger group. They reconvene and then report out. And so you—it's nice because you get different perspectives from other groups and then you're also able to find things you maybe hadn't thought of, gaps in your plan that maybe would be beneficial to add. (Interview #7)

After the exercise, the county emergency management staff sent sample policies and procedures prepared by other cities as a tool kit to help each agency prepare its strategy. The hope was that in the event of an actual emergency, the new professional networks created during the table top exercise would expedite communication and the sample documents would create some consistency among jurisdictions. This example shows how professionals can work sideways to influence the work of other organizations; all three policy sectors engaged in similar efforts.

#### *4.5 Conflicts among sectors*

Although efforts like table-top exercises can help to promote collaboration among policy sectors, I found that differences in priorities can cause conflict among programs. In all three policy sectors, the differences in priorities are caused by siloed funding (50.0%) or a perception that health, building science, and urban environment issues are unrelated (25.0%). Only one direct conflict between two sectors emerged in the interviews, a disagreement between the health and building science professionals over the distribution of air-conditioners (25.0%).

The following subsection describes how siloed funding and a perception that health, building science, and urban environment issues are unrelated can create an indirect conflict among policy sectors. The second subsection then discusses the direct conflict between the health and building science policy sectors.

##### *4.5.1 Siloed funding*

Siloed funding is a result of how federal agencies organize programs in the health, building science, and urban environment sector. One non-governmental organization program administrator described the funding landscape of Washington as follows:

D.C. is an interesting place in that there are a lot of pots of money to do things—and it can be very siloed—in that I'm doing thing one, and this other group is doing thing two, and this other group is doing thing three. (Interview #17)

However, these “pots of money” often do not align with the needs of residents and community organizations.

For example, if eligible homeowners want their house to be cooler in the summer, they can apply to the Council for Economic Opportunities in Greater Cleveland for an air-conditioner. If they are having trouble making their utility payments after the air-conditioner is installed, they can apply to the State of Ohio for LIHEAP assistance. If the electric bill becomes a long-term problem, they can apply to the City of Cleveland for weatherization underwritten by the DOE. If the weatherization creates asthma triggers, they can apply to HUD for help with improving the air quality in their home. Unfortunately, each of these programs has different eligibility requirements, authorizations, and service queues; the resulting bureaucracy can be very frustrating for both residents and local community action agencies. The siloes can also give the mistaken impression that issues of health, building science, and the urban environment are unrelated.

To adjust for the mismatch between needs and federal funding, and to begin to relink these issues, a weatherization program administrator described how local program managers are drawing on funding from multiple sources:

They're like maestros and they pull from multiple programs. "Okay, we've got this house. They qualify for this, this, and this. We're gonna pay for this with this, that with that." They pull all these things together and make it work. The more programs you have, the better equipped you are. (Interview #14)

For each house, the local program manager determines which federal programs the resident qualifies for, applies the funding from the correct source to the project, and then attributes results to each of the federal programs. While this results in more administrative work for the local agency, it streamlines the process for residents. Local foundations have been instrumental in funding pilot projects supporting this type of integration.

For example, the St. Luke's Foundation provided funding in the 1990s to start the Greater Cleveland Lead Advisory Council (GCLAC). The goal of the GCLAC was to end childhood lead poisoning in Cuyahoga County. Working with the Cuyahoga County Board of Health, GCLAC meetings became a forum where local organizations could discuss the challenges they faced in renovating homes and find ways to work together to address common health issues. In 2010, the organization merged with the Greater Cleveland Asthma Coalition (GCAC) to become the Healthy Homes Advisory Council of Greater Cleveland (HHAC). The new organization has a broad mission to "assess, reduce and prevent illnesses and unintentional injuries associated with indoor environments – including childhood lead poisoning and respiratory illness" (Reifsnyder

2014). Efforts to coordinate health, building science, and urban environmental issues that were piloted by this council are now being replicated across the country (Bingham 2013).

#### *4.5.2 Direct conflict between the health and building science sectors*

Two direct conflicts were specific to the health and building science sectors: whether weatherization programs should prioritize energy savings or indoor air quality in homes (19.4%) and whether Ohio's weatherization program should provide air-conditioners to residents (6.4%).

Regarding the first conflict, recent changes to the Department of Energy (DOE) Weatherization Assistance Program (WAP) require the adoption of a new standard, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2, which sets stricter guidelines regarding indoor air quality in homes. It also requires the use of electrical fans to provide a constant supply of outdoor air to a house after it has been air sealed. Weatherization program managers view this as an unfunded mandate by the DOE that is based on limited evidence; they feel that the weatherization program has done a good job of saving energy while preserving indoor air quality. In contrast, health professionals view the use of fans to flush contaminants out of the home as important to protect health. They argue that the required ventilation systems will not reduce energy performance if alternate technologies are employed:

We've been able to show that you can dramatically improve health and ventilation rates and also have huge energy cost savings. I think one housing development... had a 46 percent improvement in energy costs in the first year and that's 'cause they put in a pretty efficient geothermal system. And the building had no ventilation, it was just through leakage through windows and doors. I think if we're smart about it, but it does mean training HVAC contractors and others to make sure that we are using our best technology to preserve health—or support health, I should say—as well as pay attention to the energy thing. (Interview #24)

There is likely a middle ground related to energy use and indoor air quality in homes, but because each policy sector is dedicated to either houses or health, it may set standards that conflict with another sector's. For example, the cost-effectiveness tests for the weatherization program do not currently include health impacts, though recent studies indicate that the health benefits of a warmer home may be larger than the value of the energy saved (Schweitzer and Tonn 2002, Howden-Chapman et al. 2005).

The second conflict, also between building science and health, was related to the installation of air-conditioning in weatherized homes (6.4%). On the weatherization side,

officials felt that their program should focus primarily on keeping residents warm in the winter. They also thought that Cleveland did not have a hot enough climate to warrant the installation of air-conditioning, and they expressed concern that installing air-conditioning would reduce the cost effectiveness of their weatherization programs by increasing annual energy usage. On the health side, professionals viewed air-conditioning as a cost-effective solution that could prevent heat-related morbidity and mortality:

One of our grantees...does have a program where they hand out air conditioners. They've done a cost benefit analysis and have determined that a \$500 air conditioner is a whole lot cheaper than a \$6,000 or \$8,000 ED [emergency department] visit for heat stroke. And they're right. (Interview #30)

While it might be possible to begin to include air-conditioning installation into residential efficiency programs, the definition of Cleveland as a heating-dominated climate is unlikely to change in the near future. This means that DOE would need to authorize the addition of air-conditioning to the Ohio weatherization program.

#### 4.6 Major changes in funding levels

Interviewees in all three policy sectors cited major events that had dramatically changed their program's focus and levels of funding. Table 4.4 presents the major events the interviewees discussed.

Table 4.4: Major Events by Sector

Major Event	Health	Building Science	Urban Environment	Row Total
American Recovery and Reinvestment Act	0	5 (17.9%)	0	5 (17.9%)
Heat Waves (1995 Chicago, 2003 Europe)	3 (11.7%)	0	2 (7.1%)	5 (14.2%)
Indoor Air Quality (Lead, Asthma, Mold)	1 (3.6%)	2 (7.1%)	0	3 (11.7%)
Hurricane Sandy	0	1 (3.6%)	2 (7.1%)	3 (11.7%)
Vacant Land	0	0	3 (11.7%)	3 (11.7%)
Anthrax Attacks After 9/11	2 (7.1%)	0	0	2 (7.1%)
Climate Change	0	1 (3.6%)	1 (3.6%)	2 (7.1%)
New County Executive	0	0	2 (7.1%)	2 (7.1%)
Affordable Care Act	1 (3.6%)	0	0	1 (3.6%)
Cleveland Health Disparity Study	1 (3.6%)	0	0	1 (3.6%)
1969 Cuyahoga River Fire	0	0	1 (3.6%)	1 (3.6%)
Column Total	8 (28.6%)	9 (32.1%)	11 (39.3%)	28 (100%)

The major events included the American Recovery and Reinvestment Act (17.9%), heat waves in Chicago and Europe (14.2%), Hurricane Sandy (11.7%), lead and asthma problems in homes

(11.7%) and the vacant land problem in Cleveland. Other events included the anthrax attacks after 9/11 (7.1%), climate change (7.1%), and a new County Executive (7.1%). Professionals also mentioned the 1969 Cuyahoga River fire, the Affordable Care Act, and the Cleveland Health Disparity Study. Each of these major events led to changes in how health, building science, and urban environment programs were structured; two notable examples are discussed below.

#### *5.6.1 American Recovery and Reinvestment Act*

From the early 1970s until 2009, the DOE WAP spent approximately \$5 billion to improve wintertime energy performance and comfort in low-income homes. As part of the American Recovery and Reinvestment Act (ARRA) of 2009, Congress authorized a one-time payment of an additional \$5 billion to the DOE, all to be spent by mid-2012. This dramatic increase in funding required local weatherization agencies to scale up their efforts quickly to meet the new federal targets. Ohio was the first state to meet the production goals, and was one of the few states to complete all of its weatherization work by the deadline.

When ARRA ended, the programs had additional staff and equipment that could no longer be totally supported by DOE WAP funding. Several of the local program managers asked other energy efficiency organizations, like gas and electric utilities, to support their energy efficiency work. Unlike the DOE WAP, this new source of funding allowed the programs to look at both heating and cooling system energy usage, making them responsible for thermal exposure in both winter and summer.

#### *4.6.2 Anthrax Attacks after September 11, 2001*

In a second example, anthrax attacks after September 11, 2001 changed how the region approached emergency management:

Basically, the emergency preparedness program started out of the events following September 11th with the anthrax attacks. And we had what we affectionately called “white powder awareness month” here because we were bombarded with white powder calls. So, that was the initial beginning—that was the beginning of our emergency preparedness program here. Prior to that, it really wasn’t—we had information on cleaning up after a flood and some general sanitation stuff, but there was nothing out there that we had done to prevent someone from getting sick. (Interview #7)

Funding from the federal government created a network of professionals who met regularly to discuss potential issues, including heat waves. This funding continues to support activities like table top events and functional exercises with first responders:

I guess the main thing that's been instrumental in the last eleven years that we've been doing this is the networking and the planning. So it's really not the plan that's going to get us through it, it's the planning process and meeting all those people and developing all those relationships with the multiple partners that we never—we hardly ever dealt with emergency management prior to September 11th. We didn't work with police and fire like we do now. And so when—we have kind of one leg up now because when we have a heat event, we have all these community partners that we've been working with for the last ten years that know who we are and know what we do and will help push out the message.  
(Interview #7)

In this example, an unrelated terrorist attack affected funding levels at local health organizations. This influx of funding allowed the organizations to begin to address a larger set of issues than the initially authorized; the result is a sustainable change in how these agencies work together to address potential health issues in the region.

## **5. Conclusions**

In addition to contributing to the literature on heat wave exposure and responses, a goal of this project has been to assist local planning efforts. I hope that this work, in the tradition of collaborative research (Fischer 2000), will help to bring practitioners from the three sectors together to address exposure to extreme temperatures in Cuyahoga County. In addition, results from this research may be used to help structure ongoing climate adaptation planning efforts (for example, the City of Cleveland recently completed its first climate action plan).

This chapter was structured around three research questions. First, how do professionals define issues related to temperature in the built environment? Second, how do professionals act on issues related to temperature in the built environment? Finally, what are the barriers to collaboration among these professionals? While the last section discussed the results from the semi-structured interviews, this section discusses the implications of the results for policy, program design, and program management.

### 5.1 *Definitions and conflicts*

The interviews confirmed that professionals in the health, building science, and urban environment policy sectors define issues related to temperature in the built environment differently. Each of the sectors has different sets of academic knowledge; this results in different diagnoses, methods of inference, and treatments of temperature-related issues in the built environment. Only air-conditioning, energy efficiency, and indoor air quality protection were discussed by the majority of interviewees from all three sectors. In addition, strategies like cooling centers, cool roofs, and green infrastructure were only discussed by one or two sectors; this indicates a disconnect among policy sectors regarding strategies.

Air-conditioning, energy efficiency, and indoor air quality protection all target exposure at the household level. It not surprising, then, that interviews revealed conflicts only between the health and building science sectors over ASHRAE Standard 62.2 and the installation of air-conditioning in homes. However, although they were not discussed in the interviews, I found that other conflicts arise among policy sectors, like between health and the urban environment, or the urban environment and building science. It is likely that these conflicts were not highlighted in the interviews either because professionals in Cuyahoga County do not see this part of heat exposure as being interrelated or because funding is siloed among their programs. Figure 4.2 explores these additional conflicts.

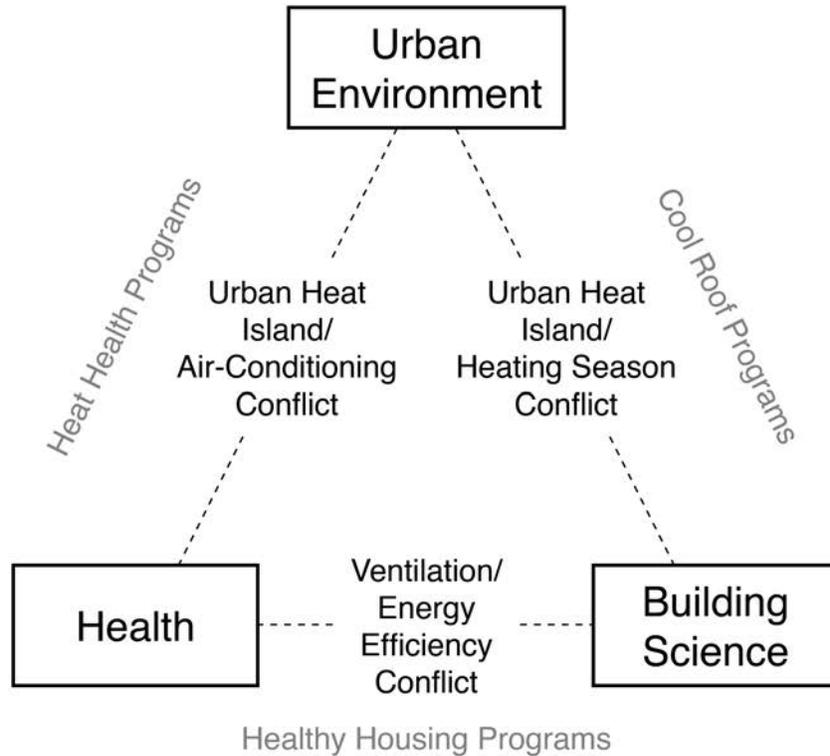


Figure 4.2: Conflicts among the Health, Building Science, and Urban Environmental Sectors (adapted from Campbell 1996)

For example, in a temperate climate like Northeast Ohio, installing a treatment like a light-colored roof on a house to mitigate the urban heat island effect might reduce indoor and outdoor temperatures, but it might also increase wintertime energy use. (This conflict was discussed and explored in Chapter 3.) Because the weatherization programs deal only with improving heating season energy performance, installing this treatment creates a conflict between the urban environment and building science policy sectors.

Other potential conflicts may arise between the health and urban environment sectors around the installation of air-conditioning. While air-conditioning may help to reduce temperature inside buildings, the waste heat produced by the compressor contributes to the urban heat island effect. (This conflict was discussed and explored in Chapter 2.) In addition, in much of the United States, the electricity used to power air-conditioning equipment is generated by combusting fossil fuels; this contributes to the broader issue of global warming. Although these issues represent two additional conflicts, they may also offer opportunities to bring professionals together to discuss how to address heat exposure in cities. The last section of the discussion explores this idea in greater detail.

## 5.2 *Addressing issues*

The interviews confirmed that professionals address heat exposure differently, though the processes they use are similar. For example, the professionals in all three policy sectors described ways that they simplify treatments to increase program efficiency and to aid in evaluation (Abbott 1988). Professionals also described working as middle-out actors who work upstream by participating in the policy process, downstream to assist program implementation, and sideways to influence local decision-making (Janda and Parag 2013).

Although simplification improves the efficiency of programs, it also appears to create barriers among programs. For example, the weatherization program has a very specific set of metrics to evaluate program performance: kilowatt-hours and therms of natural gas usage. These two metrics are used to compute cost effectiveness and to demonstrate the program's ability to reduce wintertime heating costs. However, these metrics do not capture the effect of the programs on summertime electrical demand, typically measured by utilities as a reduction in total kilowatts. Because the weatherization program omits kilowatts as part of its program evaluation, it does not count the positive benefits of weatherization on peak loads, a potential co-benefit of the weatherization program.

If weatherization programs collected this data, they could not only take credit for these benefits but also facilitate coordination around the issue of heat exposure. For example, planting of deciduous trees by an urban environment program would have limited effect on wintertime heating performance in homes, but it should help to reduce summertime electrical demand from air-conditioning. Using a common metric, the two programs could then work together to achieve mutually beneficial goals, though attributing the results to either program might be challenging.

To make such coordination possible, professionals need to be willing to regularly revisit how they define treatments. Weatherization programs have not changed the treatments or the metrics they use because their strategies and evaluation protocols have been extremely successful from the perspective of cost-effectiveness. However, given recent variability in funding, it might be prudent for programs to engage in experimentation and limited pilot projects that could lead to new directions (Sullivan 2009). These efforts could be supported by local foundations, which have already accepted this role for issues related to healthy housing and vacant land.

However, the simplification of professional knowledge can have positive benefits for a profession. For example, many professionals create data specifically for policymakers, provide

“tool kits” to peer organizations to assist decision-making, or use their professional skills to help local agencies achieve their goals. Although it may take a major event like the cluster of pulmonary hemosiderosis to catalyze changes in policy, these proactive efforts by local professionals encourage these dialogues to occur. The following section describes how a regular dialogue might promote communication and collaboration.

### *5.3 Overcoming barriers*

The interviews confirmed that differences in priorities can cause conflict among programs; however, these conflicts were limited to the health and building science sectors. Although Abbott (1988) might argue that conflicts are the primary way that professionals compete with one another to protect their jurisdictions, I found that there is significant interest among the professionals in working together to address issues related to climate change.

For example, the City of Cleveland hosts an annual sustainability summit to define goals for the region; local foundations also provided funding for a recent health and land use summit. The tabletop exercises initiated after September 11, 2001 have continued for more than 10 years although the threat of anthrax attacks is now low; these regular meetings have increased coordination among agencies and fostered communication networks critical for emergency management.

Professionals may be willing to work together in the sectors of health, building science, and urban environment because they do not regularly come into conflict over resources. However, this very lack of open competition may actually impede regular collaboration, because these professionals may not view their work as interdependent. Just as foundation support helped to bridge the health and building science sectors to address lead poisoning, and to bridge the building science and urban environment sectors to address stormwater management and vacant land, it may be possible to use foundation support in Cuyahoga County to create new programs to engage multiple sectors around heat exposure. These programs could form the basis for local collaborative planning.

Innes and Booher (2010) state that three conditions are required for collaborative planning: a diversity of interests among participants, engagement in face-to-face dialogue, and interdependence among the participants (35). The first and second conditions already appear to be met in Greater Cleveland. However, interdependence around the issue of heat exposure remains an open issue. If a new program included representatives from each of the three policy

sectors, collaborative dialogues and planning could create reciprocity among agents, stronger interpersonal relationships, collective learning, and shared heuristics that transcend disciplinary boundaries (Ibid., 37).

This process would be different from typical collaborative planning efforts, which seek to elevate underrepresented communities to stakeholder status using participatory approaches. Rather than direct participation in the formation of crosscutting heat exposure policy, which is unlikely to draw much interest from the general public, these professionals from the health, building science, and urban environment policy sectors might work downstream to encourage public input for each of their programs individually, and then mediate relationships sideways with other sectors (Figure 4.3). Using official channels, they might then influence policymakers upstream to reduce siloes among programs, and have more leverage for their claims because they have initiated a public process to substantiate their policy recommendations.

Working sideways, these professionals might also use their professional expertise and participate as a member of the public in the work of another sector; for example, several professionals from the health and urban environment sectors indicated that they recently had their houses weatherized by local contractors. After the energy efficiency improvements were completed, they had informally talked with local energy efficiency program managers about potential improvements to their processes, and were interested in making durable links between their professional work and residential energy efficiency programs.

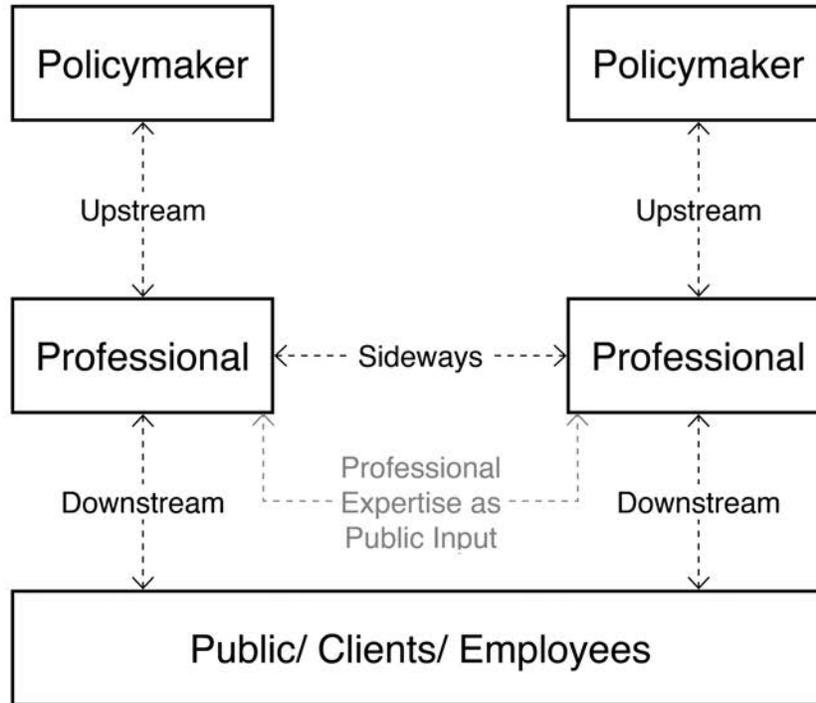


Figure 4.3: Professionals Collaborating Through Middle-Out Actions  
(adapted from Janda and Parag 2013)

While the system of professions framework (Abbott 1988) is useful for understanding differences in how health, housing, and urban environment professionals diagnose, analyze, and treat heat stress, and builds on the work of Strengers and Maller (2011), a modified collaborative planning approach may be a useful way to bring these policy sectors back together to reduce heat-related morbidity and mortality. This work is timely given concerns about an increase in the intensity, frequency, and duration of extreme heat events. Although professional communities could wait for a major extreme heat event like the 1995 Chicago heat wave to catalyze new program structures and reduce barriers among programs, they should be proactive and work to collaborate among policy sectors before such a crisis occurs.

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## CHAPTER 5

### Conclusions and Directions for Future Work

#### 1. Introduction

From 1979 to 2003, more people in the United States died from heat waves than from hurricanes, lightning, tornadoes, floods, and earthquakes combined (CDC 2009). Extreme heat events are projected to increase in intensity and duration over the next century due to global warming (Melillo et al. 2014). Because heat-related morbidity and mortality occurs primarily in cities (Luber and McGeehin 2008), planning efforts will need to address both exposure to high temperatures indoors and the urban heat island effect. However, while issues of health, thermal comfort, and elevated outdoor temperatures are interconnected, the responses are often not coordinated (Strengers and Maller 2011). This disconnect leads to an inefficient use of resources and efforts that contradict one another.

This dissertation drew on insights from the environmental health sciences, building science, and urban climate literatures to understand exposure in Cuyahoga County, Ohio. Cleveland and its suburbs were the focus of the study because several national-level assessments of heat vulnerability identified the region as being susceptible to high temperatures (Reid et al. 2009, Staudt and Inkley 2009, Altman et al. 2012). The results from this research quantify exposure, test adaptation strategies in housing, reduce greenhouse gas emissions, help to mitigate the urban heat island effect, and promote coordination among professions. In addition, because healthy housing and environmental planning programs developed in Greater Cleveland have been used as templates by other cities in the United States (Jacobs et al. 2007, EPA 2012), the results of this research may eventually inform policy in other states or at the federal level.

This final chapter of the dissertation presents the major findings from Chapters 2 through 4: the structure of the urban heat island, thermal comfort and energy use in houses, and how professions confront heat-related morbidity and mortality. These three sections also outline possible directions for future work based on the results. Immediately following these summaries, a final section describes broader conclusions that can be drawn from the dissertation as a whole.

## 2. Locating the “Hotspots” in Cuyahoga County

Higher global temperatures caused by climate change combined with the urban heat island (UHI) effect are likely to increase heat-related morbidity and mortality over present levels (Luber and McGeehin 2008). Chapter 2 investigated the distribution of the UHI effect in Cuyahoga County by adapting the use of mobile measurement platforms from the building science and urban climate communities. Building on the work of others (Heusinkveld et al. 2010, Brandsma and Wolters 2012, Coseo 2013), I designed a mobile measurement bicycle to assess the ground and air temperatures under the urban canopy layer. While techniques like remote sensing and airport weather stations can provide estimates of neighborhood-level temperatures, having detailed information on district- or block-level temperatures can help to plan responses to heat wave events (White-Newsome et al. 2013).

Results from four rides along the Canal Towpath in Cuyahoga County indicate that for a  $600 \text{ W/m}^2$  reduction in incoming solar radiation, roughly equivalent to being in the shade instead of the full sun, there is a  $8.4^\circ\text{C}$  drop in the ground surface temperature. Solar radiation ranged from approximately  $100$  to  $900 \text{ W/m}^2$  on the towpath transects. For every 10% increase in albedo, roughly the difference between asphalt paving and concrete, there was a corresponding  $3.4^\circ\text{C}$  drop in the ground surface temperature. Although sky view factor is frequently mentioned in studies of the UHI effect, it was not found to be statistically related to ground surface temperature in my model. This may be due to the unique nature of the towpath route, which passes through low-rise commercial/ industrial spaces and natural areas. On the towpath rides, variations in solar radiation and albedo led to greater-than- $30^\circ\text{C}$  shifts in the ground surface temperature.

Results also indicate that for a  $10^\circ\text{C}$  increase in the ground surface temperature, there is a  $0.2^\circ\text{C}$  increase in the local air temperature. This demonstrates a link between local ground surface temperatures and air temperature; the selection of paving materials has a significant effect on both surface and atmospheric UHIs. However, this may also indicate that waste heat from industrial facilities or highways plays a larger role than expected in warming local air temperatures because the link is not as strong as other studies have found (Coseo 2013). Therefore, in a place like Cuyahoga County, where a number of neighborhoods are located immediately adjacent to industrial sites, waste heat may cause a significant increase in exposure to elevated temperatures.

Finally, temperatures recorded downwind from a forested area were 0.25°C cooler than those recorded over impervious, bare soil, or grass land covers. Water also provided a cooling effect that was roughly 2.7 times stronger than that of a forest. However, very large areas of forest or water were necessary to achieve a drop in the local air temperature; roughly 11.8 hectares of water (29.16 acres) produced only a 0.67°C drop in the local air temperature.

### *2.1 Directions for Future Work*

While the data gathered by bicycle is helpful in understanding the physical characteristics of microclimates and the extent of the UHI effect, additional rides in Cuyahoga County are needed before a complete picture of the urban heat island effect can begin to emerge. If enough data were taken with the bicycle, it could be compared to airport weather data to create localized inputs for the thermal load modeling used to analyze weatherization strategies in Chapter 3. This approach would help to “localize” the modeling results to specific neighborhoods within the county; since temperatures can vary by several degrees in a short distance, this method might then result in efforts tailored to the warmest locations within the county.

Because the bicycle is a lower-cost method, it may be possible to create a multi-city or county-level study using bicycles to broadly examine the urban heat island effect. If the design of these vehicles were standardized, then the results could be compared from multiple climate zones to make better generalizations about the role of land cover.

Other configurations of the bicycle could also be explored, trading depth for breadth. In the last few years, a number of do-it-yourself computer prototyping platforms have entered the market. Using one of these systems, it may be possible to build a microdatalogger that can take GPS, air temperature, and ground surface temperature measurements for a fraction of the cost of a research-grade weather station. While calibrating this equipment would be a complex task, I can imagine handing out multiple copies of such system to a city’s bicyclists to gather data.

If the device were small and portable, it could also be used to develop personal profiles of temperature exposure both indoors and out-of-doors. In this way, health, building science, and urban planning professionals would have a single dataset that documented how people are exposed to temperature everyday in urban and suburban environments.

### **3. Protective Effects of Housing**

Research indicates that weatherization can improve indoor thermal comfort, reduce heating bills, and reduce health risks associated with exposure to low temperatures in winter (Howden-Chapman et al. 2005), and passive systems can reduce interior temperatures in summer (Givoni 2011). However, what remains relatively unknown is how to link these cold- and warm-climate treatments to combat heat-related morbidity and mortality. Addressing a knowledge gap between the environmental health sciences and building science, Chapter 3 described the effects of weatherization on indoor thermal environmental conditions and energy use.

In winter months, the model indicates that in houses before weatherization, occupants are exposed to low air temperatures even if they have an operational furnace. Total hours of exposure below a 21.1°C threshold range from 8 to 59 hours per year, depending on wall and foundation type. This is because during the coldest part of the winter, typically the end of January and early February in Northeast Ohio, there is significant conductive and radiative heat loss from the interior to the exterior walls in homes without insulation. Insulating and air sealing a house reduces the rate of heat loss, and a furnace is then able to maintain an acceptable interior temperature.

To keep a weatherized house from overheating during hot weather, it is important to ensure that the windows are operable. This is because wintertime weatherization measures reduce exposure to low temperatures in the winter but may trap warm air indoors in the summer, raising temperatures above the upper boundary of the ASHRAE comfort zone (ASHRAE 2010). For all five housing types modeled, ensuring that the windows were operable for natural ventilation reduced the number of hours a home exceeded 28.9°C to a range of 1 to 51 hours. This corresponds to a 96.3% to 99.9% reduction from the baseline pre-weatherized homes with sealed windows. In addition, none of the homes had operative temperatures above 37°C, and there was an average 10.6°C reduction in the maximum operative temperature.

Because the heat health literature frequently mentions air-conditioning as a treatment to reduce heat-related morbidity and mortality, and public health programs often advocate for the installation of compressor-based cooling, additional modeling investigated the impact of weatherization on summertime energy usage, energy costs, and air-conditioning system size. Weatherization reduced the total amount of electricity used by an air-conditioning system; energy savings ranged from 35.7% to more than 45% of operating costs. However, the most

significant result was related to the air-conditioning system size required to maintain comfortable conditions within the home. For all home types, the required size dropped by at least 40%, representing a significant reduction in electrical demand (kW) associated with running a compressor.

According to the State of Ohio, in 2012, 2,932 homes were weatherized in Cuyahoga County. According to the modeling, the weatherization work would have reduced air-conditioning bills for low-income customers by more than \$220,000 each year. In addition, if two-thirds of these homes were wood frame houses (1960 homes) with a full basement, and only half of these homes had air-conditioning, weatherization may have reduced total electrical demand associated with air-conditioning by more than 2,600 kW (2.6MW). This is roughly the equivalent of taking the demand associated with 260 to 463 single-family homes off the electrical distribution system.

Other important findings included an observation that warm climate weatherization measures (e.g., radiant barriers, white roof coating, solar window films) are not effective in lowering interior temperatures in single-family houses in Greater Cleveland. Their primary impact was a moderate reduction in the number of hours the interior of a house was over 37°C. In addition, these strategies increase wintertime energy usage, making it unlikely that the current DOE WAP could be used to install them. However, if the DOE expanded how it defines cost effectiveness for its program by including the heat health benefits of these approaches, perhaps such strategies could be included in future program cycles.

An important but unexpected finding is that houses with less ground contact are subject to higher temperatures indoors during a heat wave. Insulating the floor between an unconditioned crawlspace or basement and conditioned living spaces above increases interior temperatures in the summertime. This finding suggests potential ways to identify houses with a tendency to overheat; it may be possible to use housing data from the Cuyahoga County tax roll to identify which homes have this type of foundation and to use that information as the basis for an exposure map.

### *3.1 Directions for Future Work*

The DOE regularly undertakes an evaluation of the WAP to ensure that it is cost effective and that energy savings match assumptions made in the design of the program. To date, most of the work on temperature in weatherized homes has focused on the issue of “take back,” that is,

whether or not homeowners set their thermostats to a higher indoor air temperature after energy efficiency measures are installed (Ternes and Stovall 1988). These studies typically measure only air temperature in the home, usually by placing a datalogger near a thermostat.

While the issue of take back is important, additional studies could investigate thermal environmental conditions in homes pre- and post-weatherization, perhaps following the example of Howden-Chapman et al. (2005), who conducted a randomized control trial in homes in New Zealand to determine the effect of insulation on temperature, moisture, and associated illnesses. Measurements of air temperature could be expanded to include mean radiant temperatures, humidity, and air speed to get a more complete picture of thermal comfort in low-income homes.

In addition, weatherization evaluations do not discuss the impact of weatherization on electricity demand (kW), an issue that is becoming more important as utilities consider time-of-use rates. Electrical demand could be measured before and after weatherization either by installing measurement equipment on air-conditioning equipment and electrical panels, or by mining data from smart/time-of-use meters in locations where they are available. These studies might set the stage for weatherization programs to include air-conditioning system operation in their cost-effectiveness calculations, or to target energy efficiency work in neighborhoods where the electric grid is strained by summertime peak loads.

Another neighborhood-level approach would be to create maps based on housing configuration to identify which blocks have houses that tend to overheat. To do this, the State of Ohio maintains a database of all homes that have received weatherization assistance; this data has been used by Sherman and Matson (1997) to develop county-level maps of air leakage rates in homes. Similar data is used by the Case Western Reserve University Center on Urban Poverty and Community Development (2012) to help coordinate activities in Cleveland neighborhoods experiencing high rates of foreclosure.

It may be possible to combine data from the Ohio weatherization program, data from the neighborhood stabilization web application, and other public health tracking data to estimate neighborhood- or parcel-level vulnerability to extreme temperatures; this would significantly improve current research that aims to create temperature vulnerability maps. It could also be used to estimate which houses have air-conditioning or other cooling systems.

Such a study would fill a gap in our current understanding of the geographies of heat-related vulnerability. While air-conditioning is frequently mentioned as an important protective

factor during a heat wave, to date there have been no maps showing how air-conditioning prevalence varies across a city or county. In cities like Detroit, Toledo, Cleveland, and Buffalo, the percentage of homes with air-conditioning likely varies with housing type, housing age, income, race, distance from industrial heat sources, and distance from heat sinks like Lake Erie. The modeling could be validated in the field with a short survey, and the results would be extremely useful to the health community for the siting of cooling centers, to the housing community for the prioritization of energy efficiency programs, and to the urban planning community in targeting interventions to reduce the urban heat island effect.

#### **4. Improving Mitigation Efforts Across Policy Sectors**

While better monitoring can help create tailored strategies to reduce exposure at both the house and urban scale, significant differences exist in the approaches used by the health, building science and urban environment sectors. Authors like Strengers and Maller (2011) argue that while issues of heat-related mortality, energy security, and climate change are interconnected, policies regarding access to air-conditioning, energy efficiency, and greenhouse gas emissions reductions are typically not coordinated and sometimes even contradict one another. To bridge these gaps, Chapter 4 described the system of professions involved in reducing exposure to heat stress in Cuyahoga County (Abbott 1988).

Interviews with thirty-two officials at the local, state, and federal levels confirmed that professionals define issues related to temperature in the built environment differently. This results in different diagnoses, methods of inference, and treatments of temperature-related issues in the built environment. Only three strategies—energy efficiency, air-conditioning, and indoor air quality—were mentioned by the majority of interviewees from all three sectors. Other strategies, like cooling centers, improving heating/cooling system efficiency, or green infrastructure were mentioned by a majority of professionals in either the health, building science, or urban environment policy sectors; this indicates a disconnect among professions related to other important approaches like cooling centers, cool roofs, or an increase in the tree canopy.

The interviews also revealed ways that professionals simplify treatments to increase program efficiency and facilitate evaluation (Abbott 1988). Professionals used language that was consistent with working as a middle-out actor (Janda and Parag 2013); they work upstream by participating in the policy process, downstream to assist program implementation, and sideways

to influence local decision-making. Chapter 2 described a notable example in which Cleveland medical researchers lobbied Congress (1998) to create a new federal healthy housing program.

Interviews confirmed that differences in priorities can cause conflict among policy sectors. However, in the interviews, direct conflicts were limited to the health and housing sectors over the issue of air sealing versus indoor air quality in homes. Although this conflict could be considered an example of how professionals compete with one another to protect their jurisdictions over the issue of heat stress, I found that the professionals were interested in working together to address issues related to climate change.

These professionals may be willing to work together because they do not regularly come into conflict over resources. However, this very lack of open competition may actually impede regular collaboration, because these professionals may not view their work as interdependent. Because charitable foundation support helped Greater Cleveland to overcome several issues related to health, housing, and the urban environment, it may be possible to work with these organizations to create new programs to engage multiple sectors around heat exposure. These programs could form the basis for local planning efforts. For example, professionals regularly participated in tabletop exercises and sustainability summits to coordinate important health and environmental issues.

#### *4.1 Directions for Future Work*

While the results from the semi-structured interviews can help professionals to reduce heat stress in Greater Cleveland, I would like to expand my research to incorporate insights from other cities as part of a mixed-methods project. As part of this research, I would combine additional interviews with professionals and an online survey to determine what barriers impede the reduction of heat stress in different regions of the United States. This study would complement recent multi-city studies by White-Newsome et al. (2014) and would reveal whether issues related to heat stress vary by climate zone or city size.

For example, are some cities large enough to have professional staff to coordinate efforts among the health, housing, and urban climate communities? Does having a full-time heat stress coordinator have an impact on local rates of heat morbidity and mortality? Do professionals assume different roles based on the structure of the local health, housing, and urban climate programs? The results of such a study could address some of the conflicts among policy sectors. The study might also promote sharing of information and best practices among U.S. cities.

## **5. Conclusions**

In the past, planning in Cuyahoga County has focused on disinvestment and declining municipal budgets. While these economic drivers will continue to threaten the stability of Northeast Ohio, the threat posed by climate change presents a significant challenge. Public officials will have less funding available to reduce exposure in low-income neighborhoods. In addition, strategies borrowed from other cities like Chicago or New York may not be applicable; fewer resources will be available to open cooling centers, to construct new energy efficient housing, or to plant street trees.

Local policymakers and practitioners are acutely aware of these challenges, and are leading efforts to reach more people with fewer dollars, to weatherize older homes, and to reconfigure vacant land. However, the research community has been slow to recognize and support this shift. Future work in cities like Detroit, Toledo, Cleveland, and Buffalo needs to first engage with local leaders to understand their day-to-day fiscal challenges before proposing a solution. Researchers also need to advocate for flexibility in national policies because “one size fits all” approaches may limit the success of local adaptation efforts.

Although this dissertation focused on Greater Cleveland, the issue of heat stress is not limited to Northeast Ohio, or even to the Great Lakes region. Adapting to a changing climate in the United States will require communities to advance public health, improve housing stock, and mitigate the urban heat island effect. If local public health officials, architects, and urban planners are willing to work together, they can make heat-related illness less of a threat than hurricanes, lightning, tornadoes, floods, or earthquakes; the natural disasters over which humans have far less control.

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## APPENDIX A

### Supplemental Material for Chapter 2

After acquiring and reviewing the data collected by the bicycle, I determined whether or not to use the data in my air and ground temperature analyses, using the following criteria:

1. The data was gathered within +/-5 days of a Landsat 7 image acquisition.
2. No precipitation was recorded at Cleveland Hopkins International Airport (KCLE).
3. Daily average cloud cover was 3/10 or less (clear conditions) at KCLE.
4. No record low temperatures were recorded at KCLE.
5. There were no onboard equipment or sensor failures.
6. I completed a full ride of a transect with only minimal interruptions for breaks.
7. I completed more than one ride on each section of the transect; for example, I had to abandon riding in the Bedford Reservation because of steep terrain.
8. All data gathered were within expected ranges (e.g., albedo between 0 and 1).
9. For air temperature analyses, the measured air temperature was above 27°C so that I could isolate effects on the hottest days.
10. For individual air temperature data points, there was a forward speed of at least 3.5 m/s to aspirate the thermocouple and prevent heat buildup under the solar radiation shield (Oke, 1973).

These rules limited the number of rides analyzed; I concentrated on results from four rides on the Ohio and Erie Canal Towpath. The four rides are shaded in gray in Table A-1.

Table A-1: Summary of Bicycle Transects in Cuyahoga County, Ohio

Ride <sup>†</sup> (#)	Date (M/Y)	Route	Direction/ Portion of Route	Daily High Temp. <sup>1</sup> (°C)	Daily Low Temp. <sup>1</sup> (°C)	Average Daily Temp. (°C)	Daily Rainfall (mm) <sup>1</sup>	Daily Average Cloud Cover <sup>1</sup>	Ride Time (GMT)
	6/24			30.6	16.7	23.9	0.0	8/10	
1	6/25*	Valley Pkwy.	N to S/All	22.8	16.7	20.0	Trace	5/10	15:00–20:10
2/3	6/26	Big Creek Pkwy.	S to N to S/All	25.6	11.1	18.3	0.0	2/10	18:12–20:51
4	6/27	Canal Towpath	N to S/Harvard Ave. to Lock #32	30.0	13.3	21.7	0.0	3/10	20:08–22:15
	6/28			36.1	21.7	28.9	0.0	3/10	
	7/10			27.2	18.9	23.3	0.0	3/10	
5/6	7/11*	Big Creek Pkwy.	N to S to N/All	28.3	15.6	22.2	0.0	2/10	20:26–23:04
7/8	7/12	Bedford Reservation <sup>2</sup>	S to N to S/ Alexander Rd. to Solon Rd.	31.7	20.6	26.1	0.0	4/10	15:45–18:50
9/10	7/13	Canal Towpath	S to N to S/ Rockside Rd. to Cleveland	31.1	20.0	25.6	0.0	5/10	22:10–23:48
	7/14			27.8	18.3	23.3	0.0	7/10	
	7/23			34.4	23.3	28.9	Trace	5/10	
11/12	7/25	Canal Towpath	S to N to S/ Lock #32 to I-480	31.7	16.1	25.0	0.0	1/10	16:06–18:39
13/14	7/26	Valley Pkwy.	S to N to S/ I-80 to Cedar Point Rd.	33.9	22.2	23.9	8.9	8/10	14:45–16:00
	7/27*			29.4	21.1	28.3	17.0	7/10	
	8/28*			25.6	18.9	22.2	0.0	5/10	
15/16	8/29	Valley Pkwy.	N to S to N/ Lake Erie to Cedar Point Rd.	23.3	14.4	18.9	0.0	3/10	18:47–21:29
17/18	8/30	Canal Towpath	N to S to N/I-480 to Lock #32	29.4	11.7	20.6	0.0	0/10	17:58–19:52
	8/31			33.3	16.7	25.0	0.0	0/10	
	9/13*			28.3	16.7	22.8	0.0	5/10	
	9/14			21.7	11.7	16.7	5.8	7/10	
19/20	9/15	Big Creek Pkwy.	S to N to S/All	20.0	10.0	15.0	0.00	3/10	16:47–18:37
21/22	9/16	Canal Towpath	N to S to N/ Steelyard Commons to Rockside Rd.	23.3	7.2	15.6	0.00	2/10	17:36–19:19
	9/17			23.9	10.0	17.2	0.5	6/10	

Italics indicate the four Canal Towpath transects (6/27, 7/25, 8/30, 9/16) used in the statistical analysis. The data from the fifth Canal Towpath (7/13) was dropped due to cloud cover.

<sup>†</sup> Gray shading indicates data used in the final analysis.

\* Indicates Landsat 7 acquisition date. Rides occurred during the solar summer from the summer solstice (June 21) through the fall equinox (September 21). August 9 through 14, 2012 had high cloud cover and rainfall across Cuyahoga County; no transects were recorded during that period.

<sup>1</sup> Data recorded at the Cleveland Hopkins International Airport (KCLE) and reported by the National Weather Service (NWS) Forecast Office in Cleveland, Ohio on the Preliminary Monthly Climate Data (CF6) form available from

<http://www.nws.noaa.gov/climate/index.php?wfo=cle>.

<sup>2</sup> Only one complete transect in the Bedford Reservation was completed; steep terrain made additional rides infeasible.

## APPENDIX B

### Supplemental Material for Chapter 3

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Supplemental Material, Table B-1:  
Wood Frame Home, Full Basement: Annual Natural Gas Usage (therms/year)

Distance to Neighbor	North	Northeast	East	Southeast	South	Southwest	West	Northwest	Average	
None	1,794	1,803	1,803	1,811	1,812	1,816	1,804	1,800	1,805	No A/C, Windows Sealed
at 6.1m (20')	1,755	1,755	1,751	1,773	1,774	1,768	1,752	1,762	1,761	
at 4.6m (15')	1,764	1,763	1,761	1,783	1,784	1,777	1,762	1,772	1,771	
at 3m (10')	1,777	1,777	1,777	1,798	1,797	1,790	1,778	1,786	1,785	
Average	1,773	1,774	1,773	1,791	1,792	1,788	1,774	1,780	1,781	
None	1,800	1,809	1,808	1,817	1,818	1,821	1,809	1,806	1,811	No A/C, Natural Ventilation Year-Round
at 6.1m (20')	1,760	1,759	1,756	1,778	1,779	1,772	1,757	1,767	1,766	
at 4.6m (15')	1,769	1,768	1,766	1,788	1,788	1,781	1,767	1,776	1,775	
at 3m (10')	1,781	1,781	1,782	1,802	1,801	1,794	1,783	1,790	1,789	
Average	1,778	1,779	1,778	1,796	1,796	1,792	1,779	1,785	1,785	

1. Heating set point of 21.1°C.
2. Average pre-weatherization natural gas usage of 1,811 therms for "high savers" per Khawaja et al., 2006.
3. 1 therm = 100,000 Btu. A therm is a common unit of measurement for natural gas and is frequently used by United States utilities for billing.
4. Cells with darker shading indicate higher natural gas usage and were used to identify patterns within the data.

Supplemental Material, Table B-2:  
Wood Frame Home, Full Basement: Annual Electricity Usage (kWh/year)

Distance to Neighbor	North	Northeast	East	Southeast	South	Southwest	West	Northwest	Average	
None	7,339	7,346	7,346	7,353	7,354	7,357	7,347	7,345	7,349	No A/C, Windows Sealed
at 6.1m (20')	7,309	7,308	7,305	7,323	7,324	7,319	7,306	7,314	7,313	
at 4.6m (15')	7,316	7,315	7,313	7,331	7,332	7,325	7,314	7,322	7,321	
at 3m (10')	7,326	7,325	7,326	7,343	7,342	7,337	7,327	7,333	7,333	
Average	7,323	7,324	7,323	7,337	7,338	7,334	7,324	7,329	7,329	
None	7,344	7,352	7,352	7,359	7,359	7,361	7,352	7,349	7,353	No A/C, Natural Ventilation Year-Round
at 6.1m (20')	7,312	7,312	7,309	7,326	7,327	7,322	7,310	7,318	7,317	
at 4.6m (15')	7,319	7,319	7,317	7,334	7,334	7,329	7,318	7,325	7,324	
at 3m (10')	7,330	7,329	7,330	7,346	7,345	7,339	7,331	7,337	7,336	
Average	7,326	7,328	7,327	7,341	7,341	7,338	7,327	7,332	7,333	

1. EER 13 A/C system adds ~3000 kWh to annual electricity usage with cooling set point of 22.2°C, per Tonn et al., 2011.
2. Average pre-weatherization electricity usage of 9,635 kWh for houses in Ohio, per Khawaja et al., 2006.
3. Cells with darker shading indicate higher electricity usage and were used to identify patterns within the data.

Supplemental Material, Table B-3:  
Wood Frame Home, Full Basement: Number of Hours with Air Temperature above 28.9°C Indoors (hours/year)

Distance to Neighbor	North	Northeast	East	Southeast	South	Southwest	West	Northwest	Average	
None	1,212	1,211	1,114	1,145	1,141	1,143	1,114	1,201	1,160	No A/C, Windows Sealed
at 6.1m (20')	1,106	1,176	1,116	1,130	1,025	1,117	1,113	1,182	1,121	
at 4.6m (15')	1,030	1,142	1,100	1,100	964	1,075	1,100	1,148	1,082	
at 3m (10')	943	1,042	1,054	1,009	884	994	1,066	1,065	1,007	
Average	1,073	1,143	1,096	1,096	1,004	1,082	1,098	1,149	1,093	
None	878	875	815	839	840	842	811	869	846	No A/C, Natural Ventilation Year-Round
at 6.1m (20')	830	885	847	863	789	847	837	888	848	
at 4.6m (15')	789	864	833	834	751	819	828	863	823	
at 3m (10')	721	796	802	769	678	762	806	812	768	
Average	805	855	824	826	765	818	821	858	821	

1. TMY3 for Cleveland, Ohio has 254 hours (of 8,760 hours) with an outdoor air temperature above 28.9°C.
2. Natural ventilation algorithm assumes that occupants will open windows when the humidity ratio and relative humidity of the air outside are less than the specified maximum values.
3. Cells with darker shading indicate greater number of hours above 28.9°C and were used to identify patterns within the data. A house with no neighbors with the front of the house facing north was selected for additional analysis because it had the highest number of hours above 28.9°C.

Supplemental Material, Table B-4:  
Wood Frame Home, Full Basement: Number of Hours with Air Temperature above 28.9°C Indoors (hours/year)

		Attic	R=Ø			R=19			R=38			
		Crawl Space	R=Ø	R-19	R-30	R=Ø	R-19	R-30	R=Ø	R-19	R-30	
Single Pane (U=0.84, SHGC=0.63)	Wall Cavity Insulation	Ø	1,212	1,355	1,371	1,153	1,355	1,387	1,160	1,361	1,391	20.0
			1,293	1,458	1,481	1,256	1,478	1,513	1,243	1,492	1,528	13.3
			1,392	1,579	1,601	1,383	1,647	1,671	1,387	1,653	1,690	7.0
		13	1,154	1,383	1,413	1,063	1,431	1,475	1,064	1,446	1,491	20.0
			1,267	1,563	1,601	1,225	1,643	1,698	1,221	1,673	1,729	13.3
			1,422	1,755	1,790	1,436	1,924	1,987	1,445	1,963	2,030	7.0
		13+5	1,155	1,435	1,471	1,068	1,493	1,537	1,057	1,506	1,564	20.0
			1,271	1,612	1,642	1,233	1,736	1,790	1,235	1,774	1,824	13.3
			1,440	1,801	1,846	1,489	2,041	2,109	1,501	2,075	2,160	7.0
Single Pane w/ Storm (U=0.48, SHGC=0.56)	Wall Cavity Insulation	Ø	1,140	1,297	1,322	1,048	1,272	1,302	1,043	1,268	1,308	20.0
			1,227	1,412	1,439	1,149	1,411	1,448	1,143	1,415	1,453	13.3
			1,319	1,538	1,561	1,296	1,608	1,647	1,294	1,621	1,658	7.0
		13	1,051	1,330	1,366	918	1,338	1,402	913	1,350	1,418	20.0
			1,180	1,509	1,543	1,085	1,588	1,653	1,071	1,619	1,694	13.3
			1,338	1,715	1,751	1,333	1,908	1,983	1,332	1,956	2,031	7.0
		13+5	1,053	1,379	1,414	894	1,395	1,477	878	1,419	1,492	20.0
			1,176	1,560	1,590	1,083	1,699	1,767	1,083	1,732	1,816	13.3
			1,358	1,767	1,825	1,369	2,058	2,124	1,383	2,101	2,176	7.0
Double Pane Low-e (U=0.35, SHGC=0.35)	Wall Cavity Insulation	Ø	1,094	1,246	1,274	963	1,203	1,232	947	1,199	1,225	20.0
			1,171	1,359	1,384	1,073	1,350	1,377	1,060	1,344	1,375	13.3
			1,281	1,504	1,535	1,202	1,534	1,580	1,192	1,541	1,580	7.0
		13	967	1,253	1,297	765	1,231	1,283	742	1,228	1,287	20.0
			1,101	1,442	1,476	935	1,480	1,554	914	1,498	1,583	13.3
			1,257	1,645	1,696	1,174	1,829	1,905	1,164	1,858	1,943	7.0
		13+5	941	1,305	1,347	721	1,245	1,323	696	1,264	1,342	20.0
			1,078	1,486	1,521	911	1,554	1,647	899	1,587	1,691	13.3
			1,268	1,705	1,756	1,175	1,949	2,033	1,176	1,988	2,081	7.0

1. Cells with darker shading indicate higher values and were used to identify patterns within the data. In this example, installing insulation in the floor between an unconditioned basement and a conditioned first floor leads to an increase in hours with an air temperature over 28.9°C indoors.

Supplemental Material, Table B-5:

Wood Frame Home, Full Basement: Number of Hours with Air Temperature below 21.1°C Indoors (hours/year)

		Attic	R=Ø			R=19			R=38			
		Crawl Space	R=Ø	R-19	R-30	R=Ø	R-19	R-30	R=Ø	R-19	R-30	
Single Pane (U=0.84, SHGC=0.63)	Wall Cavity Insulation	Ø	51	45	43	33	30	30	33	30	29	20.0
			39	34	34	28	25	24	26	23	22	13.3
			31	28	27	22	18	18	22	15	14	7.0
	13	27	23	23	12	5	4	8	3	1	20.0	
		19	12	12	0	0	0	0	0	0	13.3	
		9	3	3	0	0	0	0	0	0	7.0	
	13+5	17	13	12	1	0	0	0	0	0	20.0	
		10	5	4	0	0	0	0	0	0	13.3	
		1	0	0	0	0	0	0	0	0	7.0	
Single Pane w/ Storm (U=0.48, SHGC=0.56)	Wall Cavity Insulation	Ø	44	37	36	31	28	28	31	27	27	20.0
			32	31	30	26	22	22	24	21	18	13.3
			29	24	24	17	13	12	15	11	10	7.0
	13	25	18	18	6	1	0	3	0	0	20.0	
		13	9	8	0	0	0	0	0	0	13.3	
		6	0	0	0	0	0	0	0	0	7.0	
	13+5	14	10	9	0	0	0	0	0	0	20.0	
		6	1	0	0	0	0	0	0	0	13.3	
		0	0	0	0	0	0	0	0	0	7.0	
Double Pane Low-e (U=0.35, SHGC=0.35)	Wall Cavity Insulation	Ø	44	37	35	32	30	30	31	27	27	20.0
			32	30	30	26	23	21	25	18	17	13.3
			30	25	25	17	12	11	14	10	9	7.0
	13	24	18	18	7	1	1	3	0	0	20.0	
		13	8	8	0	0	0	0	0	0	13.3	
		5	0	0	0	0	0	0	0	0	7.0	
	13+5	15	10	8	0	0	0	0	0	0	20.0	
		6	1	0	0	0	0	0	0	0	13.3	
		0	0	0	0	0	0	0	0	0	7.0	

1. Cells with darker shading indicate higher values and were used to identify patterns within the data. In this example, installing insulation reduces the number of hours with an air temperature below 21.1°C indoors.

## APPENDIX C

### Supplemental Material for Chapter 4

#### Table of Contents:

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## **Script for Recruitment Email for Local Government & Community Leaders**

Dear (name):

You are invited to be a part of a research study that is trying to understand temperature-related preparedness in cities. As part of our study, we will be conducting interviews of about thirty people from all levels of government and community organizations. The purpose of these interviews is to understand how different professions and agencies address the issue of temperature-related exposure. Your knowledge and experience will be very useful for improving prevention programs including, but not limited to, green infrastructure, weatherization, and cooling centers.

If you agree to be part of the research study, we will schedule a face-to-face interview at the location of your choice. The interview should take about one hour. With your permission, the interview will be audio recorded so that we may accurately document everything that is said during the interview. Please note that the audio recorder can be turned off at any time during the interview per your request.

If you would be willing to participate in this study, please respond to this email. We will follow up with either an email or a telephone call to schedule the interview.

We hope that you will choose to participate in our research.

Sincerely,

Nicholas B. Rajkovich  
Urban and Regional Planning Program  
University of Michigan

**Consent to Participate in a Research Study**  
**Understanding the issue of thermal stress in Cuyahoga County, Ohio**

---

Principal Investigator:        Nicholas B. Rajkovich  
   PhD Candidate, Urban and Regional Planning  
   University of Michigan

You are invited to be a part of a research study that is trying to understand temperature-related preparedness in Cuyahoga County, Ohio. We will be conducting interviews of about thirty people from all levels of government and community organizations. The purpose of these interviews is to understand how different professions and agencies address the issue of temperature-related exposure. Your knowledge and experience will be very useful for improving prevention programs including, but not limited to green infrastructure, weatherization, and cooling centers.

If you agree to be part of the research study, you will be asked to participate in a face-to-face interview at the location of your choice. The interview should take about one hour. With your permission, the interview will be audio recorded so that evaluation staff may accurately document everything that is said during the interview. *Please note that the tape recorder can be turned off at any time per your request.*

The recorded interview session will be transcribed verbatim. The researchers will enter study data on a computer that is password-protected; only evaluation staff will have access to the audio file and transcripts. The discussion topics will include personal opinions and experiences working as a professional in a program or agency that deals with the issue of temperature. The findings from this study will be reported for the entire group of people we interview. Your exact words may be used but you will not be identified in any way. What you say may be included in the group report and in written or oral presentations. However, at any time during the interview, you may ask that anything you say today not be included in such reports. Upon completion of the study, the data will be retained for at least 10 years and then destroyed.

If you have questions about this research, including questions about the scheduling of your interview Nicholas Rajkovich, PhD Candidate in Urban and Regional Planning, University of Michigan. Phone: (415) 441-4251, email [rajkovic@umich.edu](mailto:rajkovic@umich.edu)

If you have any questions about your rights as a research participant, please contact the University of Michigan Institutional Review Board, (734) 936-0933, 540 E. Liberty St., Suite 202 Ann Arbor, MI 48104-2210, [irbhsbs@umich.edu](mailto:irbhsbs@umich.edu).

By signing this document on the following page, you are agreeing to be part of the study. Participating in this research is completely voluntary. Even if you decide to participate now, you may change your mind and stop at any time. You will be given a copy of this document for your records and one copy will be kept with the study records. Be sure that questions you have about the study have been answered and that you understand what you are being asked to do. You may contact the researcher if you think of a question later.

Interview # \_\_\_\_\_

*I agree to participate in the study.*

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
Name (please print)

\_\_\_\_\_  
Date

*I agree to be audiotaped as part of the study.*

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
Interviewer Signature

\_\_\_\_\_  
Date

Interview # \_\_\_\_\_

### Interview Checklist

#### *Pre-Interview:*

- The day before the interview, either call or email the interviewee at their office to confirm the date, time, and location of the interview. Be sure to remind them that we need a quiet space to conduct the interview because the interview will be audio recorded.

Confirmed interview date: \_\_\_\_\_

Confirmed interview time: \_\_\_\_\_

Confirmed interview location: \_\_\_\_\_

Special instructions from the interviewee:

- Arrive at least a half an hour early, review the questions, and be sure that all of the paperwork is in order. (If you are conducting your interview over the phone or via Skype, set time aside before the call to review the questions and then call the person you are interviewing at the agreed-upon time.)
- Test the audio equipment, and if necessary, replace the batteries.

#### *During the interview:*

- Review the informed consent form with the interviewee. Get signed consent to perform the interview and to record the interview (two signatures). Explain why you are conducting the interview.
- Set up the audio recorder and select the appropriate question checklist.
- Ask all of the questions on the script and be ready to respond with follow-up questions. Check off the questions asked during the interview.
- Take notes. A set of handwritten notes will serve as a backup in case of technical glitches and will help you remember ideas you had during the interview.
- Be alert for related sources mentioned in the interview. If you learn about specific sources that might be relevant to the research, ask for copies of those sources or followup via email.

#### *Post-interview:*

- Leave your business card when the interview is over. Tell the interviewee to feel free to reach you directly to change or add anything to their comments.
- Immediately after the interview, dictate notes on the interview into the audio recorder. Use Dragon Dication to transcribe the notes, and then edit the notes into a research memo. Research memos should be completed the same day of the interview.
- If certain questions were not answered, follow up with an email.
- Send a written thank-you note.

Interview # \_\_\_\_\_

### **Interview Schedule for Program Officials**

As mentioned in the informed consent and introductory letter, the objective of this study is to understand temperature-related preparedness in Cuyahoga County, Ohio. I will be conducting interviews of about 30 people. The purpose of these interviews is to understand how different professions and agencies address the issue of temperature-related exposure. Your knowledge and experience will be very useful for improving prevention programs including, but not limited to green infrastructure, weatherization, and cooling centers.

But, before we begin:

1. Did you receive a copy of the informed consent page? Do you have any questions about it? Could you please sign a copy of the informed consent form?
2. <Acquire signed consent before starting interview>
3. I would like to audio record this interview so that I can accurately recall our discussion. Participation in this interview is completely voluntary and you are free to withdraw your consent at any time. If there are any topics you prefer not to comment on or questions you would prefer not to answer, you are under no obligation to do so. In addition, you can ask me to turn off the recording anytime during the interview. May I turn on the audio recorder?
4. <Turn audio recorder on>

### **Interview questions and prompts:**

#### *Career and educational background:*

- What are your primary job responsibilities?
- How long have you worked here?
- Where did you work prior to working here?
- What is your educational background?
- What education, training, or conferences do you regularly attend for your job?
- Do you have any licenses or certifications related to your job?

#### *Agency structure:*

- Can you tell me a little bit about <this agency> and what it does?
- What are the primary issues <this agency> addresses?

- How is the <insert name> program designed to address these issues?
- How do you develop strategies for the <insert name> program?
- What strategies do you find to be the most effective for the <insert name> program?
- How do you evaluate strategies for the <insert name> program?
- Are there issues related to the <insert name> program that we didn't discuss that you feel are important?

*Policy, research, and collaboration:*

- What information or feedback do you provide to policymakers?
- What information or feedback do you provide to staff that have direct client contact?
- What kind of research do you use to support the <insert name> program?

*Collaboration and innovation:*

- Does <this agency> collaborate with any colleges or universities?
- Does <this agency> collaborate with any other agencies or programs?
- How do you introduce new ideas, technologies, or techniques into the <insert name> program?

*Evaluation:*

- Do you formally evaluate the <insert name> program?
  - If yes, how do you evaluate the <insert name> program?
- How do the results of the evaluation inform future versions of the <insert name> program?

*Wrapup:*

- Are there any additional things related to temperature-related preparedness in Cuyahoga County that we did not discuss today that you feel are important?
- Are there other policymakers, program managers, officials, or researchers you feel I should talk to for this research project?

Interview # \_\_\_\_\_

### **Interview Schedule for Researchers**

As mentioned in the informed consent and introductory letter, the objective of this study is to understand temperature-related preparedness in Cuyahoga County, Ohio. I will be conducting interviews of about 30 people. The purpose of these interviews is to understand how different professions and agencies address the issue of temperature-related exposure. I am also very interested in talking to people conducting research in this area. Your knowledge and experience as a researcher will be very useful for my study and for improving prevention programs.

But, before we begin:

5. Did you receive a copy of the informed consent page? Do you have any questions about it? Could you please sign a copy of the informed consent form?
6. <Acquire signed consent before starting interview>
7. I would like to audio record this interview so that I can accurately recall our discussion. Participation in this interview is completely voluntary and you are free to withdraw your consent at any time. If there are any topics you prefer not to comment on or questions you would prefer not to answer, you are under no obligation to do so. In addition, you can ask me to turn off the recording anytime during the interview. May I turn on the audio recorder?
8. <Turn audio recorder on>

### **Interview questions and prompts:**

#### *Career and educational background:*

- What is your primary area of research?
- How long have you worked here?
- Where did you work prior to working here?
- What is your educational background?
- What education, training, or conferences do you regularly attend for your job?
- Do you have any licenses or certifications related to your job?

#### *Research structure:*

- Can you tell me a little bit about your research and how it is connected to temperature-related morbidity and mortality?

- What are the primary issues your research addresses?
- How is your research designed to address these issues?
- In your research, do you develop strategies for reducing temperature-related morbidity and mortality?
- What strategies do you find to be the most effective in reducing temperature-related morbidity and mortality?
- How do you evaluate the effectiveness of these strategies?
- Are there issues related to your research that we haven't talked about that you feel are important?

*Policy, research, and collaboration:*

- What information or feedback do you provide to policymakers?
- What information or feedback do you provide to programs or program managers dealing with the issue of temperature-related morbidity and mortality?
- What sources of information do you use to support your research?

*Collaboration and innovation:*

- Do you collaborate with any other departments or fields outside your own?
- Do you collaborate with any other colleges or universities?
- Do you collaborate with any local agencies or programs designed to reduce temperature-related morbidity and mortality?

*Evaluation:*

- Do you participate in any evaluations of programs dealing with temperature-related morbidity and mortality?
  - If yes, how did you evaluate the program?
- How do the results of the evaluations inform future versions of the program or your research?

*Wrapup:*

- Are there any additional things related to temperature-related morbidity and mortality that we did not discuss today that you feel are important?
- Are there other policymakers, program managers, officials, or researchers you feel I should talk to for this research project?



Health Sciences and Behavioral Sciences Institutional Review Board • 540 East Liberty Street,  
Suite 202, Ann Arbor, MI 48104-2210 • phone (734) 936-0933 • fax (734) 998-9171 •  
irbhsbs@umich.edu

---

**To:** Nicholas Rajkovich

**From:**

Richard Redman

**Cc:**

Larissa Larsen  
Nicholas Rajkovich

**Subject:** Notice of Exemption for [HUM00078533]

**SUBMISSION INFORMATION:**

Title: A system of professions approach to understanding the issue of thermal stress  
Full Study Title (if applicable): A system of professions approach to understanding the issue of thermal stress  
Study eResearch ID: [HUM00078533](#)  
Date of this Notification from IRB: 7/17/2013  
Date of IRB Exempt Determination: 7/17/2013  
UM Federalwide Assurance: FWA00004969 (For the current FWA expiration date, please visit the [UM HRPP Webpage](#))  
OHRP IRB Registration Number(s): IRB00000246

**IRB EXEMPTION STATUS:**

The IRB HSBS has reviewed the study referenced above and determined that, as currently described, it is exempt from ongoing IRB review, per the following federal exemption category:

**EXEMPTION #2 of the 45 CFR 46.101.(b):**

Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Note that the study is considered exempt as long as any changes to the use of human subjects (including their data) remain within the scope of the exemption category above. Any proposed changes that may exceed the scope of this category, or the approval conditions of any other non-IRB reviewing committees, must be submitted as an amendment through eResearch.

Although an exemption determination eliminates the need for ongoing IRB review and approval, you still have an obligation to understand and abide by generally accepted principles of responsible and ethical conduct of research. Examples of these principles can be found in the Belmont Report as well as in guidance from professional societies and scientific organizations.

**SUBMITTING AMENDMENTS VIA eRESEARCH:**

You can access the online forms for amendments in the eResearch workspace for this exempt study, referenced above.

**ACCESSING EXEMPT STUDIES IN eRESEARCH:**

Click the "Exempt and Not Regulated" tab in your eResearch home workspace to access this exempt study.

A handwritten signature in black ink that reads "Richard W. Redman". The signature is written in a cursive style with a large initial 'R'.

**Richard Redman**  
Chair, IRB HSBS