A SOCIAL-ECOLOGICAL APPROACH FOR HEAT ADAPTATION

OF SENIOR LOW-INCOME HOUSING

by

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A dissertation submitted to the

School of Graduate Studies

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Doctor of Philosophy

Graduate Program in Planning and Public Policy

Written under the direction of

Clinton J. Andrews

And approved by

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New Brunswick, New Jersey

January, 2021

ABSTRACT OF THE DISSERTATION

A Social-Ecological Approach for Heat Adaptation of Senior Low-Income Housing

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As elevated summer temperatures increase in frequency and duration, they pose threats to human health and well-being that differentially affect the most vulnerable urban residents, including older adults in low-resource communities. The percentage of the senior population living in cities is projected to increase in the US and a high proportion are likely to live in poor housing conditions, which makes them more susceptible to environmental challenges. In the 1995 Chicago heat wave, it was found that most of the heat victims were low-income older adults living in highly urbanized neighborhoods, with no access to air-conditioning. More recently, during Hurricane Irma, several heat-related deaths in Florida were attributed to power outages that exacerbated an existing medical condition by depriving residents of cooling. Such cases highlight the strong institutional dimensions of heat adaptation at socially vulnerable sites and emphasize the need to provide integrated solutions across spatial scales.

This research is about the real experiences and exposures of seniors living in a low-income urban area in NJ, US during heat waves. The focus is on thermal and air quality conditions in multi-family public housing, and the availability of mitigating affordances. It employs a social-ecological systems framework that conceptualizes urban sites as complex interacting social, natural and built environments, in order to document and describe the relative roles of building systems, microclimate, social context and individual agency in heat adaptation.

The social-ecological systems approach is found to be helpful as a descriptive and diagnostic tool to guide study design, data collection and modeling, but also as a means to identify cost-effective, integrated heat adaptation strategies at nested scales. In particular, it is demonstrated that although indoor environments are critical in protecting seniors from heat, there is value in investing in outdoor environments, which can function as alternative shelters during heat wave periods. Furthermore, it is shown that heat adaptation is not only subject to built-environment characteristics indoors and outdoors, but also depends on how people interact with these resources and the extent to which they receive support from social networks and community organizations.

Eventually, this research leads to the realization that heat adaptation pathways are found at the very localized scales and inevitably include indoor-outdoor synergies, tied to individual users, local actors and institutions. It concludes with a list of concrete recommendations, through a set of behavioral and physical alterations for transforming built environments in order to improve the thermal experiences of low-income seniors.

ACKNOWLEDGMENTS

I would like to express my sincerest gratitude to the many individuals who have contributed to the completion of this dissertation. Starting with my advisor, Clinton J. Andrews, I am deeply grateful for his invaluable guidance and support throughout the years of the PhD, but also for his mentorship while pursuing my master's at Bloustein. From the first email I sent him back in 2012, he has trusted me and encouraged me in pursuing graduate studies. He has been a true mentor, who has fundamentally shaped my research development. I am also very grateful to my dissertation committee members, Lyna Wiggins (Bloustein), Frank Felder (Bloustein) and Anu Ramaswami (Princeton), as well as the Graduate Director Robert Noland for their valuable assistance, which substantially helped me improve the quality of this thesis.

Special thanks also go to the Rutgers Center for Green Building (RCGB) team, especially Jennifer Senick, Gediminas Mainelis, Deborah Plotnik and MaryAnn Sorensen Allacci for their support in pursuing this thesis and the opportunity to expand my research horizons and work in a variety of exciting projects over the years. I would also like to kindly thank the residents and managers of HACE, who welcomed me and the rest of the RCGB team in their community and fully supported this thesis. I further acknowledge the gracious support from National Science Foundation for pursuing this work. Thanks also to many colleagues from Bloustein, who made qualification exams and conferences fun!

A very special thanks goes to my friends and amazing people, Marilou, Anthi, Aretousa, Chrysa, Tolis, Tasos, Matina, Savvas, Alejandro, Anastasoula, Gabriel, Thanasis, Spencer, Giannis, Giannis and Giannis (!), Popi, Handi, Kostas, Miriam and Maria Sole, who may be living in different parts of the world now, but made my life wonderful over the years in NJ.

Final thanks go to my family with the hope that I have made them proud; thanks to my parents Kostantina and Vasilis and my brother Ted for a lifetime of support and inspiration, and thanks to my partner Dionysis for literally taking this journey together.

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LIST OF ABREVIATIONS

A/C: Air Conditioner

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

CAS: Complex Adaptive Systems

CO_2: Carbon Dioxide

HACE: Housing Authority of the City of Elizabeth

HI: Heat Index

HVAC: Heating, Ventilating and Air-Conditioning

HW: Heat Wave

IAQ: Indoor Air Quality

IEQ: Indoor Environmental Quality

IHI: Indoor Heat index

NOAA: National Oceanic and Atmospheric Administration

NO_2: Nitrogen Dioxide

OB: Occupant Behavior

OHI: Outdoor Heat index

OSHA: Occupational Safety and Health Administration

O_3: Ozone

PM: Particulate Matter

$PM_{2.5}$: Particulate Matter (diameter<2.5 micrometers)

PM_{10}: Particulate Matter (diameter<10 micrometers)

SEIS: Social-Ecological-Infrastructural System

SES: Social-Ecological System

UHI: Urban Heat Island

WO: Window Opening

Chapter 1 Introduction

This chapter discusses the impacts of heat waves on urban areas and populations and explores past research and current knowledge gaps on the social and physical factors affecting heat coping processes of low-income seniors. It then identifies the socio-ecological dimensions of heat adaptation, which leads to the initial premise of this research that senior public-housing sites can be conceptualized as social-ecological systems. Arguing that such an approach can be helpful in understanding the interactions between actors, infrastructure and the environment and eventually in identifying pathways for heat adaptation, it then lays out the research questions and associated hypotheses. It proceeds by presenting the case study and data collection process and concludes by summarizing the research contributions.

1.1 Research Background

Impacts of Heat Waves on Urban Areas and Populations

Our changing climate is increasing the frequency of extreme heat events, which cause both local and global impacts (IPCC, 2014; Horton et al., 2014; Stone, Vargo and Habeeb, 2012). Urban environments experience aggravated consequences of heat, due to high human population concentrations and ubiquitous heat absorbing surfaces, such as asphalt, concrete, metal and stone that cover cities, which produce higher surface air temperatures via the urban heat island effect (UHI) (Knowlton et al., 2007; Rosenthal, 2010). This in turn translates into higher energy demand and worsened air quality, so that ground-level ozone and particulate matter (PM) increase during heat waves (Kalisa et al., 2018; Steeneveld et al., 2018, Peterson et al., 2014; Jacob and Winner, 2009). Residents are exposed to health-associated risks related to both heat stress and air pollution’s effects on the respiratory tract, such as damage to the lungs, bronchitis, emphysema and asthma, which link to ozone and PM levels (EPA, 2012; EPA, 2015). This long causal chain is especially likely to affect those suffering from chronic, pre-existing heart and lung conditions, children and the elderly (EPA, 2015; Horton et al., 2014, Kovats and Hajat, 2008).

According to the Intergovernmental Panel on Climate Change, vulnerability to climate change includes both the sensitivity of socioeconomic and biophysical systems and their ability to cope with actual or expected impacts of climate change (He et al., 2019; IPCC, 2014). Heat vulnerability at the individual level is influenced by age, gender, health status, race, income, and educational levels (Bélanger et al., 2015; Bouchama et al., 2007) that are often linked to location attributes and built environment characteristics (Kenny et al., 2010; Phadke, Manning and Burlanger, 2015; Reid et al., 2009; Zanobetti et al., 2012). Access to resources, the condition of human settlements and indoor/outdoor living conditions like the absence of air-conditioning, may increase thermal discomfort and the health risk from heat (Reid et al., 2009). Lastly, indoor living conditions and the indoor environment are particularly important, considering that people, and especially seniors, spend about 90% of their time indoors (ASHRAE, 2011; Klepeis et al., 2001; Spalt et al., 2016).

The percentage of the senior population living in cities is projected to increase in the US and a proportion are likely to live in poor housing conditions (Arnberger et al., 2017; Joint Center for Housing Studies, Harvard, 2016), which makes them more susceptible to environmental challenges. Vandentorren et al. (2006) found that during the 2003 heat wave in France, lack of thermal insulation and being on the top floor were among the most important housing characteristics associated with mortality in elderly people. Diaz et al. (2018) showed that improvements in building systems, such as the installation of air-conditioning, can lower the impact of heat on senior mortality. More recently, Issa et al. (2018) found that during Hurricane Irma, several heat-related deaths in Florida, USA were attributed to power outages that exacerbated an existing medical condition by depriving senior residents of cooling. These findings suggest that vulnerable populations, such as the elderly, should be prioritized during heat events and that more research is needed to understand the thermal conditions experienced by seniors in low-income housing and the factors that affect them (Nahlik et al., 2017).

The Socio-Ecological Dimensions of Heat Adaptation

As governments engage in long-term climate planning to mitigate heat, local authorities and organizations strive to find immediate cost-effective ways to support their most vulnerable populations and infrastructure (Phadke, Manning and Burlager, 2015). Much research has recognized that when temperatures are up, low-income seniors are among the most vulnerable groups (see Bélanger et al., 2015; Horton et al., 2014, Kovats and Hajat, 2008; Phadke, Manning and Burlager, 2015). The indoor environment is particularly important and a better understanding of the actual indoor thermal conditions experienced by low-income seniors and occupant behavior can help forming realistic policies and interventions to reduce the risk of overheating (Klingsborough, Jenkins and Hall, 2017; Kuras et al., 2017).

Yet, different research communities offer their own perspectives in coping with heat and often, those efforts are not aligned among disciplines and only partly address heat vulnerability. Urban planning and public policy-oriented literature usually concentrates around the urban heat island (UHI) and related mitigation (see Hondula, Georgescu and Balling, 2014; McMichael et al., 2008; Parsaee et al., 2019; Steeneveld et al., 2018; Stone et al., 2014; Ziter et al., 2019), but does not focus on indoor living conditions. Likewise, building science research often focuses on building envelope modifications to improve the indoor thermal performance (see Bauwens and Roels, 2013; Mohammad and Shea, 2013; Nahilik et al., 2016), but may not include the occupants' comfort and behaviors, while cost-effective and easily accessible building retrofits are scarce. Lastly, thermal comfort-related studies, although advanced in occupant behavior and comfort models (see Escandon, Suarez and Sendra, 2019; Kim, Schiavon and Brager, 2018; Peng, Nagy and Schluter, 2019), do not often address the adaptive responses of seniors in low-income sites (see Giamalaki and Kolokotsa, 2019; Mendez et al., 2015; Terés-Zubiaga, Erkoreka and Sala, 2013).

Heat adaptation described as the adjustment process to heat and its effects (Hondula et al., 2015), is challenging at socially vulnerable sites, as there are fewer resources, guides and institutions to provide support (Carmin, Nadkarni and Rhie, 2012). The availability of residential air conditioning is recognized by many as one of the most effective adaptation measures (see Luber and McGeehin, 2008; Sailor et al., 2019) and based on past heat-disaster reports, it is argued that heat-related senior morbidity and mortality would be avoided with access to functioning A/C systems (Sailor et al., 2019). Yet, about 13% of the US households still lack A/C (EIA, 2015) and those households are disproportionately poor, while landlords are not required to provide cooling in most places (Fraser et al., 2017; HACE, 2017). Furthermore, even if low-income households have access to air conditioning, there may be additional limitations, such as the cost of running the A/C, as well as the effectiveness of it (e.g. small window units covering single rooms) (Belanger et al., 2015; Green et al., 2019). Lastly, A/C use may not be a preferred adaptation action, as it increases energy demand and greenhouse gas emissions (Kingsborough, Jenkins and Hall, 2017).

These limitations indicate that the heat problem has strong institutional dimensions and show that adaptation to heat goes beyond residential access to air conditioning, insights which are especially important in disadvantaged communities with significant financial restrictions (Belanger et al., 2015). The role of local organizations, such as community centers, non-profit and volunteer groups may be vital, as they can assist with small-scale initiatives like financial assistance programs to pay A/C bills (Yardley, Sigal and Kenny, 2011). Many studies also highlight the spatial scales of heat adaptation; Kingsborough, Jenkins and Hall (2017) suggest that land-use planning, building design, occupant behavior and community resilience should be considered together, as well as the relationships between them and their effects on health and residential comfort should be evaluated. Likewise, Yardley, Sigal and Kenny (2011) propose a socio-ecological approach that would help identify the various factors contributing to heat vulnerability and assist in formulating adaptation plans that fit the particular social and physical characteristics of communities. Lastly, Barnett et al. (2013) approach people, housing and neighborhood as a complex, social-ecological system and argue that heat-related health risk in social housing can be reduced through a combination of urban and building-level upgrades. They further show how different people at different scales can affect those upgrades and consequently heat adaptation outcomes.

1.2 Approach and Methodology

Forming an effective heat adaptation policy to reduce the risk of overheating for seniors living in low-income sites needs a focus on the very localized scales and a guiding framework to address the complex interactions among humans, infrastructure and the climate. The role of infrastructure systems is critical both indoors and outdoors, but different actors and institutions become important at each scale. Indoor environments can be highly influenced by resident behaviors and activities, while outdoor spaces involve additional actors, such as local authorities and organizations. At the same time, individual houses or buildings are nested within sites, which are in turn part of larger urban units, and residents and local organizations move across those scales.

This dissertation grasps on these issues and examines senior low-income sites and their real-time performance during heat waves, specifically impacts on thermal and air quality conditions, human health and well-being. It draws from an empirical study of a public housing community and its elderly residents in Elizabeth, NJ, USA.

The framework for this research stems from urban social-ecological systems (SESs) approaches that view cities as complex interacting social, natural and built environments. It conceptualizes senior, low-income sites as SESs, in order to document and describe the interactions among social-ecological factors, such as the local climate, infrastructure, social context and individual agency, on heat coping processes. It then seeks to better understand the relative roles of those factors in heat adaptation. Eventually, the aim is to provide an integrated policy that can guide interventions to assist low-income seniors in coping with heat.

This dissertation focuses on the site as a suitable unit of analysis, because it is a well-defined geographical entity that physically represents the indoor and immediate outdoor environments where seniors live. Therefore, it allows for a closer examination of their infrastructure characteristics. At the same time, the site serves as a good analogy of a SES, since it involves the interactions between multiple individuals at nested spatial scales, including residents, managers, operators, local authorities and organizations. In other words, it makes the role of human agency in heat adaptation visible.

Research Questions and Hypotheses

The research questions of this work are guided by the premise that senior low-income sites can be conceptualized as SESs. From that I ask:

1. **What social and ecological components become relevant in the case of senior low-income sites suffering from heat waves?**

This primary question is of particular importance, as it frames the remaining research. It seeks to connect SESs with heat waves and provide a descriptive social-ecological structure to the senior public housing community. This includes organizing the spatial scales (e.g. indoors and outdoors) in which seniors move and identifying the infrastructure characteristics (e.g. dwelling envelopes, site landscaping) that influence environmental conditions within the site boundaries, as well as the social actors (e.g. senior residents, managing authority, local organizations) and the ways in which they may affect heat coping processes. Once the SES framework is empirically derived, I aim to explore which of these social and ecological components have a higher influence to thermal and air quality conditions. The main hypotheses here are that 1) heat waves require actors to adapt and change key behaviors, and that 2) some SES parts (e.g.

resident activities, indoor affordances, outdoor amenities) give sites an advantage in increasing the chances of heat adaptation.

2. **What is the role of indoor environments in mediating heat and which social and ecological factors influence indoor environmental conditions?**

Drawing on the previous inquiry and the SES's spatial scales, this question attempts to document the indoor environmental conditions experienced by low-income seniors and examine variations across different dwellings. It further aims to identify the social-ecological factors contributing to those variations and explain their interactions, from the outdoor climate and occupant adaptive actions to the indoor and outdoor amenities, as well as their relative effects and trade-offs on indoor thermal and air quality performance. Here, I hypothesize that 1) outdoor environmental conditions can influence indoor environmental conditions, and certain site and apartment characteristics can moderate or strengthen this relationship, that 2) occupants engage in adaptive actions that can also influence indoor environmental conditions and are subject to personal characteristics, but also to the indoor and outdoor resources they have available, and that 3) certain occupant actions have a trade-off on indoor thermal and air quality performance.

3. **What is the value of outdoor environments in heat adaptation?**

Following the exploration of indoor environmental conditions, this question aims at investigating the extent to which, adjacent outdoor amenities (e.g. site landscaping) can support seniors in coping with heat. Therefore, it focuses on mapping the outdoor preferences and destinations of seniors within and outside the site boundaries, observing the temporal patterns of those activities and documenting how and why residents interact with them. The hypotheses here are that 1) if outdoor spaces are provided to them, seniors use them, assuming they are in close proximity, and that 2) these spaces may serve as alternatives in sites where indoor environments are inadequate in providing shelter from heat.

4. **How can we empirically inform policy towards heat adaptation through a social-ecological systems lens?**

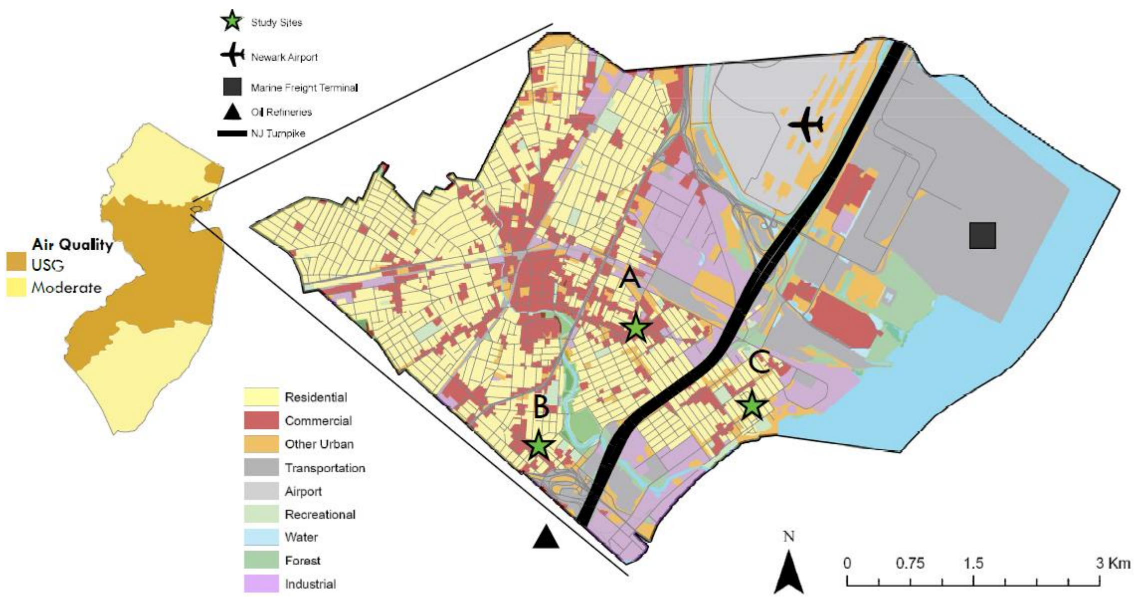
This last question concludes the dissertation by assessing the value of taking an integrated social-ecological systems approach towards heat adaptation. Through discussing the findings from the previous questions, it aims to translate them into a set of realistic policies that can guide cost-effective and easily accessible interventions to assist elderly low-income communities in adapting to heat. The main hypothesis here is that the heat waves problem needs integrated solutions across scales; from changes to residents' habits, to building envelope modifications and building operations, and to outdoor space alterations.

Methods

In order to examine the themes and issues raised in the research questions above, I undertake field work in Elizabeth, NJ, USA. The focus is on three public housing sites operated by the Housing Authority of the City of Elizabeth (HACE). Longitudinal environmental and behavioral data were collected between May - October 2017.

Elizabeth is among the areas with the most severe urban heat island and worst air quality levels in the state, based on high 24-hr average concentrations (29.1 $\mu g/m^3$), and the highest annual average (9.58 $\mu g/m^3$) ambient particulate matter ($PM_{2.5}$) concentration among NJ stations (NJDEP, 2017). As shown in Figure 1.1, the New Jersey Turnpike (I-95), the Bayshore petrochemical complex, the Port Elizabeth Marine Terminal, the Newark Liberty International Airport and a highly urbanized and industrialized profile, all contribute to the city's air pollution and thermal stresses, which can be exacerbated during extreme heat periods (Kalisa et al., 2018; Steeneveld et al., 2018, Peterson et al., 2014).

Figure 1.1: Pollution sources in Elizabeth, NJ and the location of study sites A, B, and C (NJGIN, 2016; AirNow, 2016).



Low-income neighborhoods, such as the public housing sites in Elizabeth, are even more likely to be affected by environmental challenges, considering their often poor housing conditions and limited access to resources (Phadke, Manning and Burlager, 2015; Rosenthal, 2010). Another consideration is that elderly populations may be socially isolated and physically frail (Gasparini et al., 2015; Clarke and Nieuwenhuijsen, 2009), which justifies my focus on senior apartments within the sites shown in Figure 1.2.

Figure 1.2: The three public housing sites (A, B and C) in Elizabeth, NJ.

A Site B Site C Site

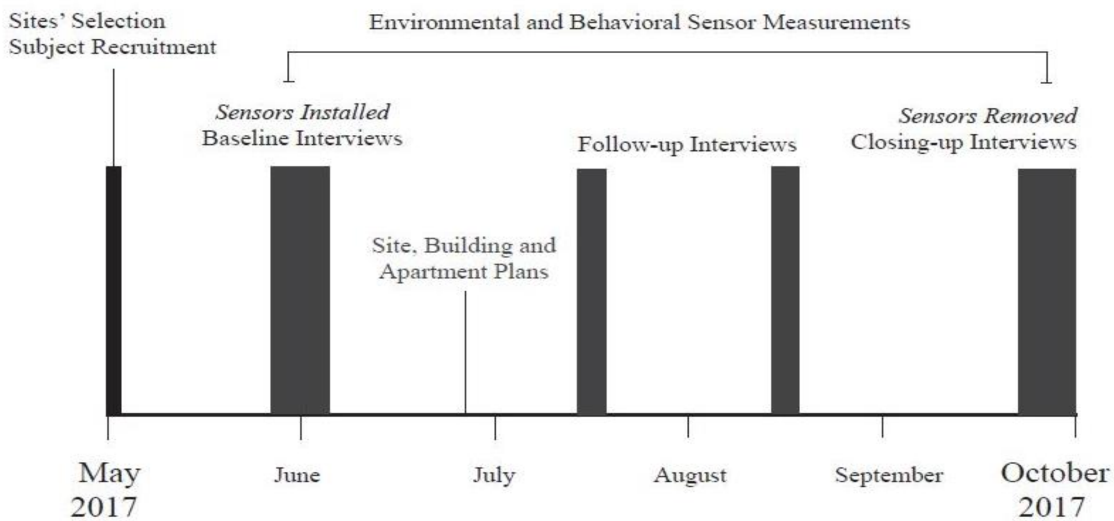
Lastly, the selection of 3 sites additionally maximizes variation by building characteristics and nearby outdoor amenities, summarized in Table 1.1. A is the largest and the oldest of the sites with a mix of families/senior residents, B consists of one high-rise senior building and C is a newly-built, LEED-certified, green structure with central A/C that is included in the rent.

Table 1.1: Building and site characteristics by study site.

Group	**Variable**	**A**	**B**	**C**
Site	Year Built	1938	1967	2011
	No. of Buildings	15	1	1
	Total Floor Area	36,790 m^2	6,875 m^2	3,575 m^2
	No. of Apartments	423	121	31
	Back/Front Yard	Yes	Yes	No
	Gardens	Yes	Yes	No
	Community Center	Yes	No	No
Building	No. of Stories	3	11	4
	Central A/C	No	No	Yes
	Lobby/Cooling Center	No	Yes	Yes
	Elevator	No	Yes	Yes

Data collection included three stages, described below (Figure 1.3): 1) subject recruitment and interviews; 2) sensor measurements; and 3) review of site, building and apartment plans.

Figure 1.3: The study timeline; collection of data from interviews, plans and sensor measurements across summer 2017.



Data Collection

Subject Recruitment and Interviews

In cooperation with HACE, three on-site information sessions were organized for subject recruitment (one for each study site), which included a general project description and scope, the research approach and the time frame of the study, both in English and in Spanish, and lunch was served. Recruitment included senior residents (>55 years) who were willing to participate. Rutgers University's Institutional Review Board protocol #14-327M (expedited approval per 45 CFR 46.110(b)(2)) governed my interactions with this vulnerable population. An agreement form was distributed to subjects, accompanied by a $50 gift card. In total, 24 residents agreed to participate in the study; 11 from site A, 9 from site B and 4 from site C. Each resident agreed to have sensors placed in their apartment and respond to a series of baseline, follow-up and closing-up interviews. Each apartment/resident in the sample was given a unique identifier to preserve anonymity and the interview data were stored online.

The baseline interviews were 50-min in-person, once for each participant during May-June 2017; sensors were installed at the same time. The baseline questionnaire included open and close-ended questions, related to:

- Demographics, general health and supportive social networks
- Apartment characteristics
- Environmental comfort and preferences
- Common behaviors and typical schedule

The baselines generated a total of 24 questionnaires; key statistics are summarized in Table 1.2. The Interview Protocol and coding can be found in Appendix A. Demographics show that the sample is dominated by females, and while gender is considered to have an insignificant effect on thermal preferences (see ASHRAE, 2017), one recent literature review suggested that female subjects may be preferred over males, due to their higher levels of dissatisfaction with the indoor thermal environments (Karjalainen, 2012).

Table 1.2: Resident sample characteristics (N=24). Demographics, health and social networks.

	All Sites	**A (N=11)**	**B (N=9)**	**C (N=4)**

Group	Variable	Category	% of Sample	% of Sample	% of Sample	% of Sample
Demographics	Gender	Female	84%	91%	66%	100%
		Male	16%	9%	34%	0%
	Age	55-64	34%	36%	34%	25%
		65-74	45%	45%	45%	50%
		75-84	21%	19%	11%	25%
	Education	< High School	33%	27%	44%	25%
		High school	63%	64%	66%	75%
		College	4%	9%	0%	0%
	Income	< 10,000	80%	73%	100%	50%
		> 10,000	20%	27%	0%	50%
Health	Overall Health	< Good	58%	64%	55%	50%
		> Good	42%	36%	45%	50%
	Condition Exacerbated by Heat	Yes	50%	54%	66%	25%
		No	50%	46%	34%	75%
Social Networks	Frequency of Relatives	< Often	50%	54%	44%	25%
		> Often	50%	46%	56%	75%
	Frequency of Neighbors/Friends	< Often	16%	27%	0%	25%
		> Often	84%	73%	100%	75%

	Frequency of Community Activities	< Often	60%	54%	55%	75%
		> Often	40%	46%	45%	25%
	Program Assistance in Paying Bills (Proceed, Social Security, SNAP, BPU)	Yes	70%	64%	66%	100%
		No	30%	36%	34%	0%

The follow-up interviews were 5-min phone or in-person, conducted during or after each heat wave period, for the five heat wave periods of summer 2017, further analyzed in chapter 3. Questions were open and close-ended, related to:

- Health and support during heat waves
- Behaviors and schedule during heat waves

The follow-ups generated 96 questionnaires in total. The Interview Protocol and coding can be found in Appendix A.

Lastly, the closing-up interviews were 10-min in person, conducted once at the end of the data collection period; sensors were removed at the same time and a $50 gift card was given to the participants. Questions were open-ended, related to:

- Comparison of summer 2017 with previous summers
- Outdoor activities
- Apartment, building and site improvement recommendations

The closing-ups generated 24 questionnaires. The Interview Protocol can be found in Appendix A.

Sensor Measurements

Consumer-grade sensors measuring thermal and air quality conditions (temperature, humidity, ozone (O_3), particulate matter (PM) and carbon dioxide (CO_2)) and occupant behaviors (occupant presence, window opening and air-conditioner (A/C) use) were purchased in Fall 2016 and calibrated during Spring 2017 against professional-grade instruments. In June 2017, and after arrangements with HACE, selected devices were installed in an outdoor location within site A and were enclosed in a box 1.5 meters from the ground that protected them against precipitation and heat radiation from outside sources, while still allowing air to circulate freely through it. Additional sensors were installed in an empty (control) apartment in site A. During the baseline interviews of June 2017, indoor sensors were placed in all 24 recruited households and remained until the end of summer 2017 (un-installed during closing-up interviews). All indoor sensors were located at a 0.4-08 meters height and at least 0.5 meters from the wall. The sensor names, detailed calibration procedure, network and the locations in sample apartments can be found in Appendix B. All pieces of equipment in each apartment connected and transmitted data to a mobile Wi-Fi hotspot. The resulting dataset contains time-variant data on hourly intervals over a 24-hour period for approximately 3 months on the variables shown in Table 1 of Appendix B. Table 1.3 below summarizes the measurements and their observed range for each variable during all summer and during heat waves.

Table 1.3: Summary of sensor measurements during all summer and during heat waves. *Based on Table 2.1. **Median, min and max values.

Group	Variable	Observed Range**	
		All Summer	Heat Waves*
Outdoor Environment	Ambient Temperature (C)	23 (6-34)	24 (20-34)
	Relative Humidity (%)	67 (30-97)	67 (37-95)
	$PM_{2.5}$ (ug/m^3)	7 (0-432)	8 (2-36)
	CO_2 (ug/m^3)	422 (392-538)	431 (397-538)
	O_3 (ppb)	18 (0-133)	19 (0-127)
Indoor Environment	Ambient Temperature (C)	25 (19-31)	25 (20-31)
	Relative Humidity (%)	57 (30-91)	57 (38-90)
	$PM_{2.5}$ (ug/m^3)	10 (0-1,726)	10 (0-1327)
	PM_{10} (ug/m^3)	11 (0-2,000)	11 (0-1595)
	CO_2 (ug/m^3)	517 (350-10,000)	517 (389-8119)
Behaviors	Occupancy (motion/no motion)	-	-
	Window State (open/closed)	-	-
	A/C Use (kwh)	0.04 (0-2.28)	0.04 (0-2.26)
	A/C State (open/closed)	-	-

After data acquisition, necessary clean-up processes took place, such as identification and removal of extreme/wrong values and deletion of missing values in Excel. In addition, measurements for behavioral variables were recorded in inconsistent time intervals, while several devices measured occupancy, window and A/C states for each sample resident. Lastly, although some variables' measurements were delivered in 24-hour intervals, the time stamps did not align. Therefore, the data management process (in MATLAB) included:

- Synchronize the time stamps of environmental variables across apartments,
- Produce consistent time stamps of behavioral variables for each apartment,
- Retime variables (behavioral) in hourly intervals,
- Generate new behavioral variables (e.g. total occupancy, % window opening % A/C on),
- Merge environmental and behavioral variables in 24 separate apartment datasets, and
- Concatenate all apartment datasets in one final database.

The final database covers from July to mid-September (7/1/17-9/15/17) in 24-hour intervals.

Site and Apartment Plans

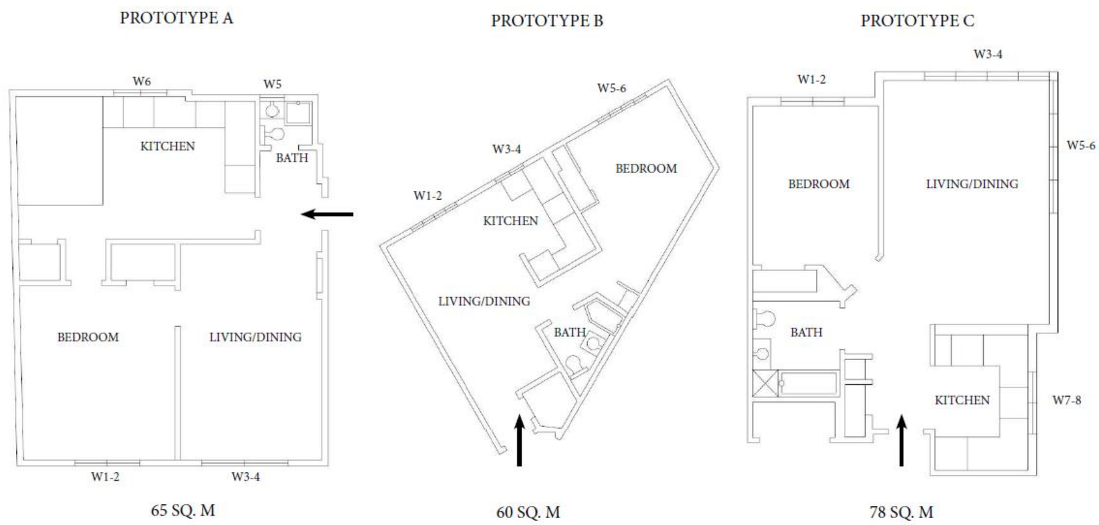
After the end of the baseline interviews and the sensor installation, hard copies of building and apartment plans were obtained from HACE and were digitized in AutoCAD and Sketchup. Alongside the plans, site maps were also prepared in Sketchup and InDesign, based on a series of site observations and with the help of Google Maps/Google Earth. Information from the maps and plans include neighborhood amenities and more detailed site landscaping characteristics and engineered building and apartment details. Table 1.4 summarizes key variables from the apartment plans and Figure 1.4 shows typical apartment layouts.

Table 1.4: Summary of key variables from apartment plans.

		All Sites	**A (N=11)**	**B (N=9)**	**C (N=4)**
Variable	**Category**	**% of Sample**	**% of Sample**	**% of Sample**	**% of Sample**

Area (m^2)	60-65	62.5%	54%	100%	0%
	69-78	17%	0%	0%	100%
	85	20.5%	46%	0%	0%
Bedrooms	1	80%	54%	100%	100%
	2	20%	46%	0%	0%
Orientation	South	54%	82%	34%	25%
(All M are	East	54%	64%	44%	50%
cross-ventilated)	West	46%	36%	55%	50%
	North	34%	18%	34%	75%
Location	Middle	29%	27%	34%	25%
	Corner	71%	73%	66%	75%
Floor	1-3	71%	100%	44%	50%
	4-7	21%	0%	34%	50%
	8-11	8%	0%	22%	0%
A/C Units	0	-	9%	0%	-
	1	-	27%	78%	-
	2	-	55%	22%	-
	3	-	9%	0%	-

Figure 1.4: Typical 1-bedroom apartment layouts from each study site A, B and C.



1.3 Research Contributions

This work offers contributions to several underexplored areas. First, while it is well recognized that low-income seniors are among the most vulnerable groups to extreme heat, missing are studies documenting their indoor and outdoor living environments and the thermal and air quality conditions they experience. Towards that end and guided by the social-ecological approach, this dissertation addresses indoor-outdoor synergies and their links to individuals and organizations.

On the theoretical side, the SES framing offers ways to better understand how different actors at different scales can influence heat adaptation in senior public housing sites. Methodologically, this fine-grained investigation guides the bridging of human behavior within buildings to outside of buildings, an area not usually explored in the urban planning and building science literature. Air quality is further added as an equally important consideration to the heat wave discussion. On the policy side, it is shown that heat adaptation needs an inventory of integrated solutions across scales. Lastly, the application of social-ecological systems to urban sites extends the SES literature by connecting a conceptual framework to an empirical study, which shows that natural and built environments are purely distinct. It also highlights that human agency, control and ownership vary from indoor to outdoor scales and that the SES approach can benefit from incorporating a behavior theory.

Taken as a whole, this study contributes to an integrative and interdisciplinary understanding for long-term resilience and adaptation of elderly low-income communities to heat. Stand-alone examination of either people or their built environment does not capture the significant interrelations developed in the urban context, because at every scale people can make choices and influence outcomes. Occupants can adjust thermostats, windows, and clothing, or relocate. In buildings, we can improve cooling systems, promote tighter envelopes, and manage solar gains; outdoors, we can redesign key infrastructure such as open and public spaces. The equity aspects of the story that are invisible at the global level become highly visible once we are able to focus on the human-scale urban form.

Focusing on a local, relatively homogenous public-housing community is less of a weakness and more of a strength of this research; each of the three study sites belongs to a different neighborhood and can be separated from the rest in terms of outdoor amenities, building characteristics, and the senior residents' profiles. In addition, the aim is to understand the role of human agency in heat adaptation, which can be succeeded through a focus on the very localized scales. Therefore, such an approach is primarily beneficial for communities who seek solutions on how to transform their built environments, assuming joint collaborations among residents, designers, and public officials.

1.4 Research Structure

The organization of this dissertation is as follows: The 2nd chapter links to the first research question and offers background and literature in support of the premise that senior low-income sites can be conceptualized as SESs. It extends this line of thinking to the public housing sites of Elizabeth, in order to identify the social and ecological factors that affect heat coping processes indoors and outdoors. Tied to the SES framing, chapters 3 and 4 link to the second research question and explore the seniors' indoor environments. The factors that affect thermal conditions are examined first, followed by indoor thermal and air quality trade-offs. Then, chapter 5 extends to outdoor environments and links to the third research question, which assesses the usefulness of outdoor spaces in heat adaptation. Lastly, chapter 6 links to the fourth research question and collects evidence from the previous chapters in support of an integrated approach to the heat waves problem. It revisits the SES framing and offers recommendations for improvement. Table 1.5 outlines the research questions, hypotheses and associated chapters.

Table 1.5: Overview of research questions, hypotheses and associated chapters.

Research Questions	Hypotheses	Chapter
1) What social and ecological components become relevant in the case of senior low-	1) Heat waves require actors to adapt and change key behaviors	2

income sites suffering from heat waves?	2) Some SES parts (e.g. resident activities, indoor affordances, outdoor amenities) give sites an advantage in increasing the chances of heat adaptation	
2) What is the role of indoor environments in mediating heat and which social and ecological factors influence indoor environmental conditions?	1) Outdoor environmental conditions can influence indoor environmental conditions, and certain site and apartment characteristics can moderate or strengthen this relationship 2) Occupants engage in adaptive actions that can also influence indoor environmental conditions and are subject to personal characteristics, but also to the indoor and outdoor resources they have available 3) Certain occupant actions have a trade-off on indoor thermal and air quality performance	3 & 4
3) What is the value of outdoor environments in heat adaptation?	1) If outdoor spaces are provided to them, seniors use them, assuming they are in close proximity 2) These spaces may serve as alternatives in sites where indoor environments are inadequate in providing shelter from heat	5
4) How can we empirically inform policy towards heat adaptation through a social-ecological systems lens?	1) The heat waves problem needs integrated solutions across scales; from changes to residents' habits, to building envelope modifications and building operations, and to outdoor space alterations	6

Chapter 2 Forming a Heat-Wave Social-Ecological Framework

This chapter offers background and a rationale for the initial premise of this work that conceptualizes senior public-housing sites as social-ecological systems[1]. The first section provides a literature review on the theory and urban applications of SESs. The next section extends this line of thinking to the study community and assembles a descriptive SES framework for heat waves that can guide future analysis. Drawing on information from sensors, interviews and site plans, the last part of the chapter concludes with identifying the key social and ecological dimensions of heat adaptation, in relation to thermal and air quality conditions.

2.1 Background

The Social-Ecological Systems Approach

The social-ecological systems approach has emerged as a research tradition among scholars concerned with the management of sustainable systems, including ecologists, biologists, economists, sociologists and others (Gadgil et al., 2003). A common unifying pool is the realization that phenomena with multiple and diverse causes cannot be fully understood without combining theories and practices from both the social and natural sciences (Berkes, Colding and Folke, 2003; Folke, 2006; Gadgil et. al, 2003). Therefore, a social-ecological system is an organized structure that includes human and non-human

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[1] The information presented in this chapter comes from a co-authored peer-reviewed conference paper. The citation is: *Tsoulou, I., Senick, J., Andrews, C. J., Mainelis, G., He, R., & Putra H.C. (2020). "Heat Waves and Seniors in Public Housing: A Social-Ecological Exploration in an Urban Context." In the 12th International Forum on Urbanism, Beyond Resilience, June 27-29, 2019, Jakarta, Indonesia.*

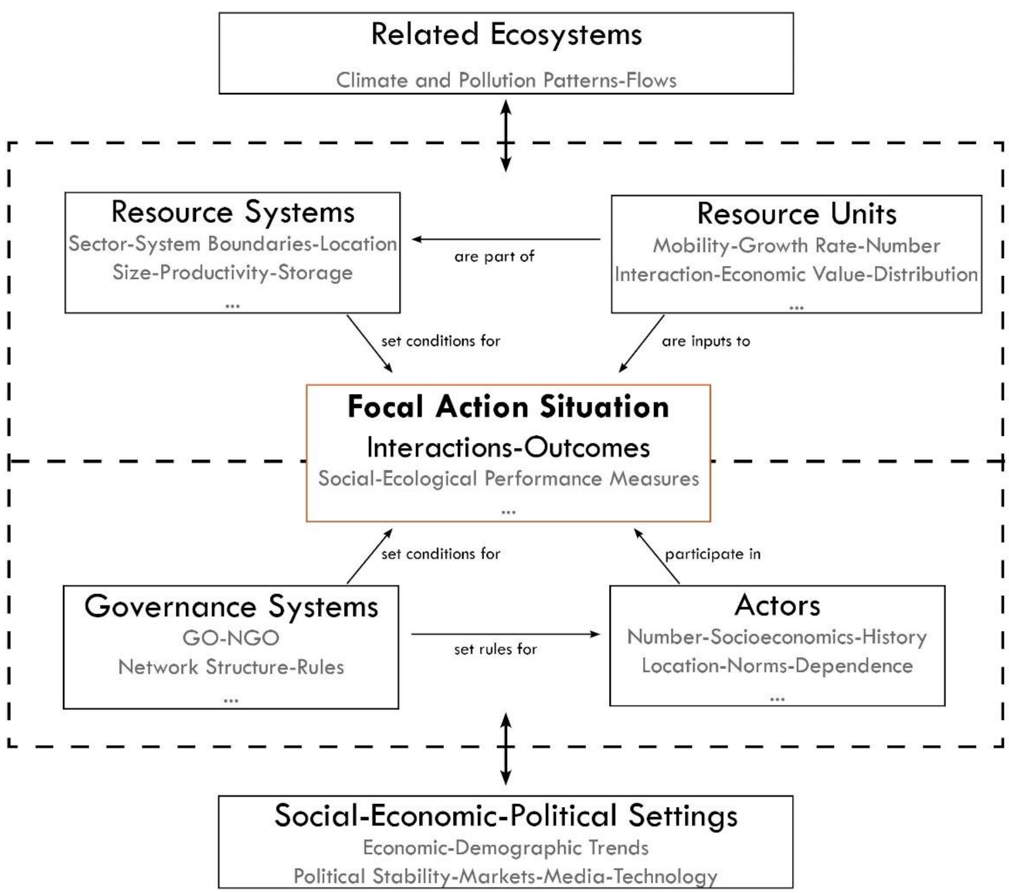
forms (e.g. natural, infrastructural or technical components) interacting with each other in a specific location (Halliday and Glaser, 2011).

SESs build upon complex adaptive systems (CAS), according to which, understanding of a system comes from the examination of how its parts operate together and not in isolation (Gadgil et.al, 2003). Therefore, they share all the CAS properties such as non-linearity that links to rules of interaction that change as the system evolves, emergence of behavior from the interaction of several parts, nestedness where each subsystem is nested within larger subsystems, and self-organization that relies on the idea that systems will reorganize at critical points of instability (Gadgil et.al, 2003).

Since the 1980s, social-ecological systems thinking has expanded in multiple interdisciplinary fields besides systems ecology, which explicitly incorporate nature and society interactions in their framing of issues; instances include ecological economics, environmental psychology, human geography, resource environmental management, anthropology and the social sciences (Folke, 2006; Gadgil et. al, 2003). Urban planning and policy is recently added on that list, as urban researchers increasingly identify links among social-ecological resilience and planning, especially those concerned with climate change impacts on the built environment, urban governance and cross-scale spatial dynamics in complex systems (Wilkinson, 2012).

Scholars like Elinor Ostrom have pushed the social-ecological metaphor beyond the conceptual level, through the development of frameworks as common modes of analysis. Her famous SES framework diagrammatically represents a system made up of social and ecological components interacting with each other in context of a disturbance, or, a focal action situation (McGinnis and Ostrom, 2014). Several frequently identified explanatory variables are found within each of these components and may be classified into first-level variables and their secondary attributes (adapted from Ostrom, 2009). As shown in Figure 2.1, the dashed line indicates a well-defined SES that is affected by exogenous ecosystems and social, economic and political settings operating at different scales. Within the SES boundaries, the social part includes governance systems and actors and the ecological part includes resource system(s) and units, and the corresponding explanatory variables help characterize them (Ostrom, 2009). The choice of those variables depends on the research questions, the type of SES and the spatio-temporal scales of analysis.

Figure 2.1: A SES conceptual framework (Adopted from McGinnis and Ostrom, 2014).



Ostrom's framework is flexible and can be applied to a wide range of research questions. Common applications involve cases where humans interact with resources in a particular location. The SES framework has been applied to phenomena in sectors as diverse as agriculture, fishing, forestry, tourism and resilience of coastal zones (Campbell and Gabriel, 2016; McGinnis and Ostrom, 2014; Ostrom, 2009; Stojanovic et al., 2016). In most cases, population groups (the social component) depend heavily on natural or community resources (e.g. forestry and tourism) for their survival. Resources represent the ecological component of the system.

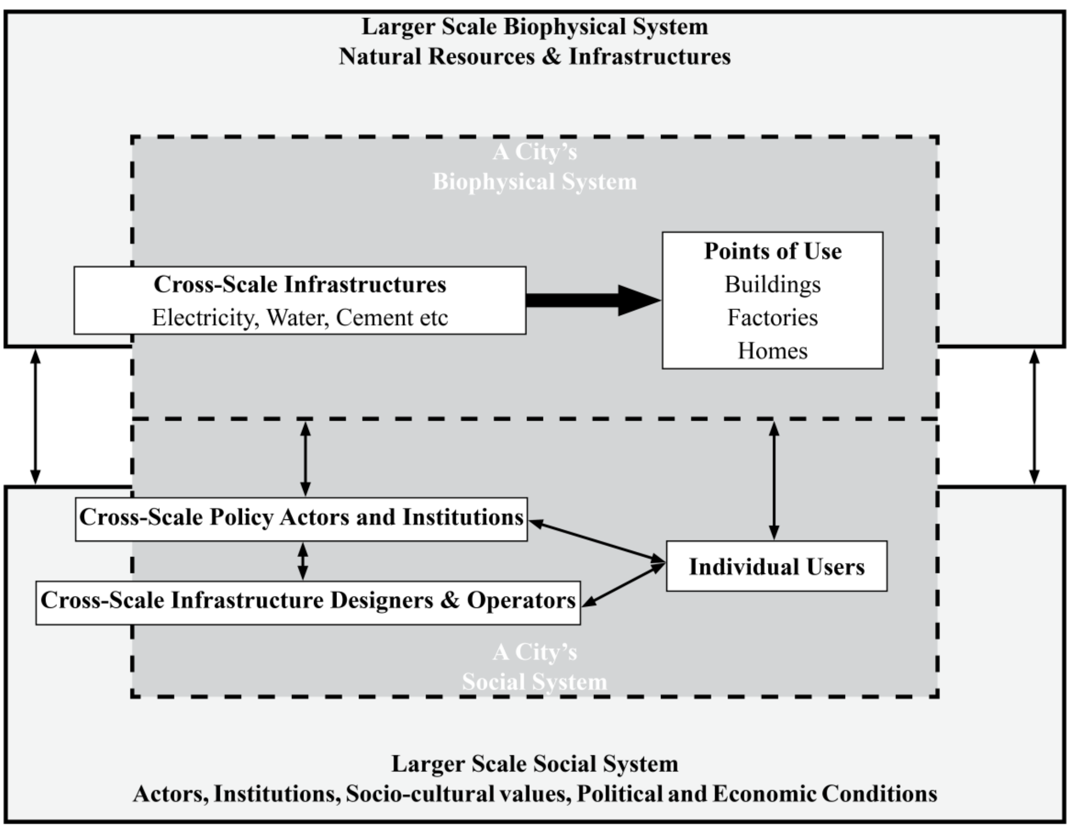
SES frameworks have also received some criticism. Stojanovic et al. point out to their tendency to operationalize "the social", disregarding sometimes questions of politics, power, inequity, and marginalization (Stojanovic et al., 2016). Likewise, Vogt et al. argue that absent from the framework are ecological considerations, such as ecological rules and processes (Vogt et al., 2015). Nevertheless, the SES framing provides an essential first step towards interdisciplinary research and can be valuable in describing a system's social-ecological structure (Alberti et al., 2011, Liu et al., 2007). The next step is to extend this line of thinking to theoretical and methodological analysis for empirical inquiry (Epstein et al., 2013, Ramaswami et al., 2012).

Cities as Social-Ecological Systems

In viewing cities as systems, urban ecological approaches identify infrastructural and technological components that draw from natural resources and are linked to social actors and institutions (McPhearson et al., 2016; Ramaswami et al., 2012). An understanding of the system derives from an examination of how its components operate conjointly (Gadgil et.al, 2003). The field of urban ecology explicitly adopts this view to advance cities' sustainability and resilience (McPhearson et al., 2016). Along those lines, it is argued that social-ecological systems thinking is very relevant for planning theory, since it responds directly to environmental and ecological considerations as a driving concern; however, a stronger theoretical basis is needed to address issues of power, conflict and culture (Wilkinson, 2012).

Urban scholars such as Ramaswami et al. (2012) have extended the applicability of the SES framework in urban environments, framing cities as coupled social-ecological-infrastructural systems (SEIS), where infrastructures feed from natural resources and provide continuous support to their users. The main parts of the SEIS framework are briefly summarized in Figure 2.2.

Figure 2.2: A SEIS conceptual framework (Adopted from Ramaswami et al., 2012).



A major distinction between the SES and the SEIS frameworks is that artificial systems have inherently different dynamics than ecological systems. Also, unlike in a fishing or forestry community, users of the resource system (e.g. buildings, transportation networks etc.) may not be able to maintain it, which introduces the role of additional human entities such as designers and operators (Ramaswami et al., 2012). These distinctions should be considered in the explanatory variables of each SEIS part and the guiding theory at later research stages.

2.2 Forming a Social-Ecological Framework for Heat Waves

To date, there are limited empirical studies applying a SES perspective to urban issues. Such an effort is presented in the remainder of this chapter. Drawing on the works of Ostrom and Ramaswami, I view urban sites as social-ecological systems and I argue that the SES framework is helpful for understanding and measuring key elements of how heat waves impact senior citizens living in public (low income) housing communities, and seniors' corresponding behavior and activities.

I commence with an 8-step process, premised on Ostrom (2009) and McGinnis and Ostrom (2014), for assembling a SES framework to serve as the basis for the remaining research:

- Define the focal action situation
- Locate the system boundaries
- Establish the ecological component
    - Identify the resource system and units
- Establish the social component
    - Identify the governance system and actors

- List the related social, economic and political settings
- List the related ecosystems

Define the Focal Action Situation

This first step is of primary importance, as it determines the selection of first and second-level variables and attributes. Here, the focal action situation is heat waves and their impacts on thermal and air quality conditions of urban sites. Therefore, resource systems, units, governance institutions and actors interact with each other and produce outcomes in relation to heat adaptation.

Locate the System Boundaries

The next step is to specify the study area that contains the resource systems and units and is the place where primary users spend most of their time before and during the focal action situation. Additional actors that link to governance systems can be located outside the system boundaries, although they may influence interactions, outcomes and the overall system performance during heat waves. The study area indicates a discrete whole, but exogenous influences from related social, economic and political settings, and ecosystems may affect any component of SES. In the case of heat waves, the system boundaries are the site boundaries.

Establish the Ecological Component- Identify the Resource System and Units

The resouce systems and the units nested in them are first-level variables and are further described and comprised by second-level attributes. In the case of heat waves, the resource systems are the sites and the units are the dwellings (buildings and apartments). Secondary attributes include the size and location of each, adjacent affordances, such as shade trees and benches (e.g., landscaping), the outdoor and indoor climate and the dwelling envelopes.

Establish the Social Component - Identify the Governance System and Actors

Actors and governance systems are first-level variables and are characterized by second-level attributes. Primary actors are the individual users of the system, while additional actors and governance institutions include the organization that manages the resource systems and units. In an urban site affected by heat waves, primary actors are the residents, and secondary actors and governance systems relate to the company that operates the sites and buildings along with its employees. Second-level attributes include the number of actors, their profiles (socio-demographics, culture, norms), their actions during heat waves, and, for governance institutions, the frequency of support and the type of services they provide.

List the Related Social, Economic and Political Settings

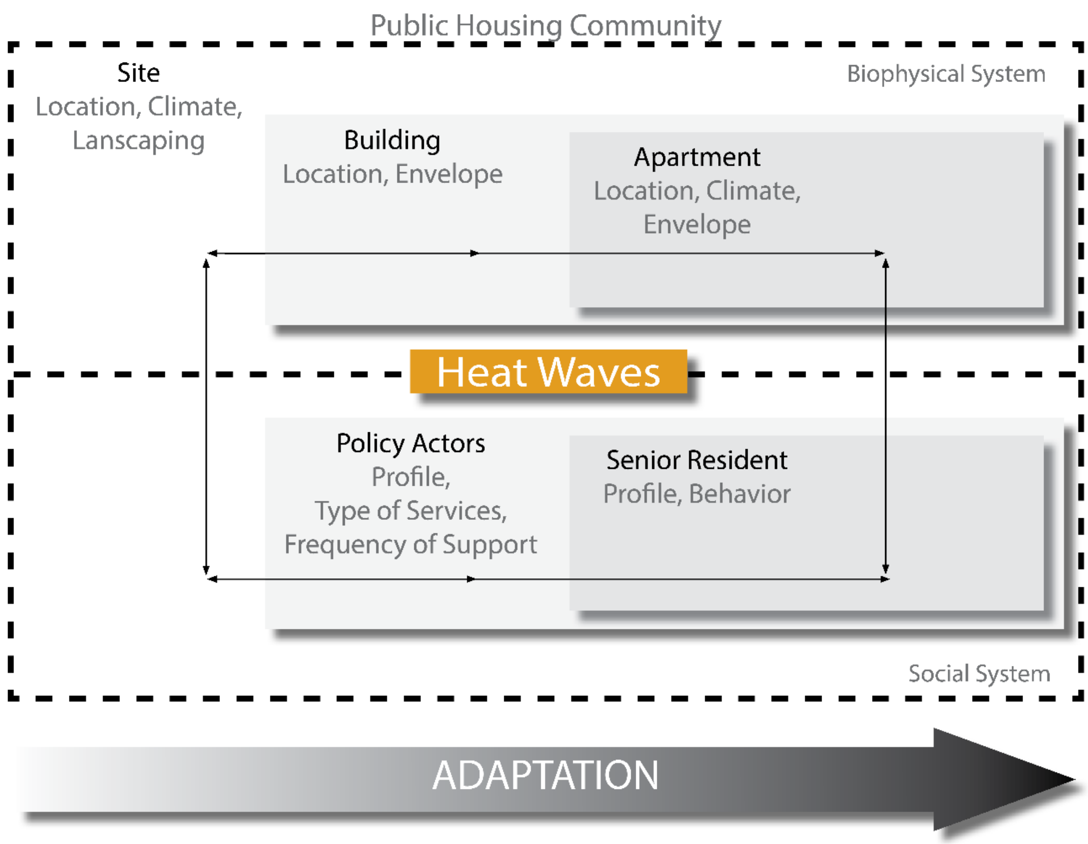
Social, economic and political settings indicate exogenous influences that may operate at different scales than that of the SES. In the case of urban sites, this category relates to the overall demographic, economic, political and technological trends shaping the wider area in which the sites are located.

List the Related Ecosystems

Lastly, related ecosystems are not within the immediate system boundaries and represent the overall climate and pollution patterns that may affect the study area characteristics. In the case of heat waves, this translates into the local climate attributes that relate to the urban heat island effects, and ambient air quality.

Figure 2.3 depicts SES components of a senior, public housing community in relation to a heat wave.

Figure 2.3: A SES framework for heat waves. (Adapted from Ostrom, 2009)



2.3 Applying the Social-Ecological Framework to the Study Community

The previous section established that senior low-income sites can be conceptualized as SESs and identified the key social and ecological parts that are fit and indicate applicability in the case of heat waves. Employing the SES framework in Figure 2.3 as guidance, this section examines the relative roles of local climate, building characteristics, landscaping and other site affordances, and human behavior in relation to thermal and air quality conditions and preservation of well-being in the study community during heat waves.

Starting with related ecosystems and socioeconomic settings, as described in section 1.2 of chapter 1, Elizabeth is a highly urbanized and polluted area, with low educational achievement and median household incomes, as well as high unemployment rates (US Census Bureau, 2015).

Within Elizabeth, resource systems correspond to the three public housing sites in the study (A, B and C). Those reside in proximate but distinct neighborhoods and include both conventional multi-family and LEED-rated residential buildings, thereby providing variation in surroundings, landscaping and building systems, as noted in Table 1.1 of chapter 1. Then, the resource units include differences among the 24 sample apartments (11 located in A, 9 in B and 4 in C), such as floor locations, orientation and other apartment characteristics that are potentially significant in influencing indoor environmental conditions (Klepeis et al., 2017; Urso et al., 2015).

Moving to the actors of the community, the primary system users are the 24 elderly residents occupying the 24 apartments, whose personal characteristics, such as age, gender, health and support from social networks vary by apartment and site, as shown in Table 1.2 of chapter 1. Additional actors include institutional staff at HACE, friends and family members who provide support to the seniors, and non-governmental organizations such as local churches and charities.

Results

According to the relative definition of the National Oceanic and Atmospheric Administration (NOAA), a heat wave is "*a period of abnormally and uncomfortably hot and usually humid weather*" (NOAA, 2009), with New Jersey specifying a heat wave as a maximum daytime temperature above 32 degrees C for two or three consecutive days, often along with elevated night-time temperatures (Robinson, 2009). As suggested by Robinson (2001), "*heat waves may be meteorological events, but cannot be assessed without reference to human impacts.*" Therefore, for a human-centric approach of heat waves, heat index may be a preferred measure over temperature.

Resource Systems: Outdoor Thermal and Air Quality Conditions

Figure 2.4 shows the outdoor heat index (OHI), as derived from the environmental sensors, during summer 2017. The OHI variable was created based on the formula found in Rothfusz (1990)[2], which combines outdoor ambient air temperature and relative humidity, and is utilized as a more representative measure of human stress (Steeneveld et al., 2018; Quinn et al., 2014). Black arrows indicate the hottest days, which, along with the definition of NOAA (2009), define the heat wave periods of summer 2017.

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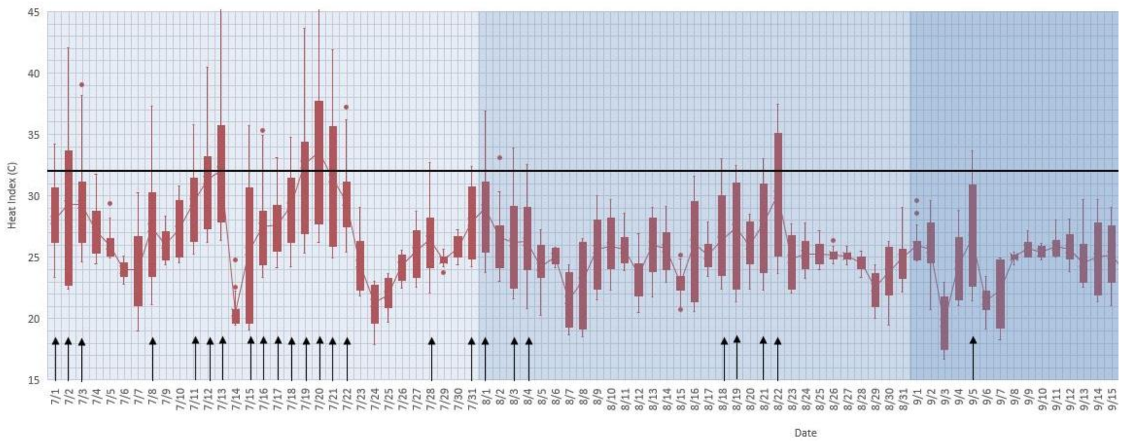
[2] The Heat Index equation as found in Rothfusz (1990) is: $HI = -42.379 + 2.04901523 \times T + 10.14333127 \times \mathrm{R} - 0.22475541 \times \mathrm{T} \times \mathrm{R} - 6.83783 \times 10^{-3} \times T^2 - 5.481717 \times 10^{-2} \times \mathrm{R}^2 + 1.22874 \times 10^{-3} \times \mathrm{T}^2 \times \mathrm{R} + 8.5282 \times 10^{-4} \times \mathrm{T} \times \mathrm{R}^2 - 1.99 \times 10^{-6} \times \mathrm{T}^2 \times \mathrm{R}^2$, where T is ambient temperature and R is relative humidity.

Figure 2.4: Calculated outdoor heat index (C) based on sensor measurements and the 5 heat wave periods of summer 2017.



Based on Figure 2.4, the heat wave periods of summer 2017 are shown in Table 2.1.

Table 2.1: Heat wave periods of summer 2017 based on sensor measurements of the calculated outdoor heat index.

Heat Waves	1st	2nd	3rd	4th	5th
Dates (2017)	7/1 - 7/3	7/11-7/13	7/15- 7/22	7/31-8/4	8/18-8/19 & 8/21-8/22

Figure 2.4 and Table 2.1 show that the neighborhood climate(s) indicated high heat index levels during the heat wave periods. This was also the case with outdoor air quality, specifically O_3, $PM_{2.5}$ and CO_2, shown in Figures 2.5 - 2.7.

Figure 2.5: Outdoor O_3 (ppb) based on sensor measurements of summer 2017.

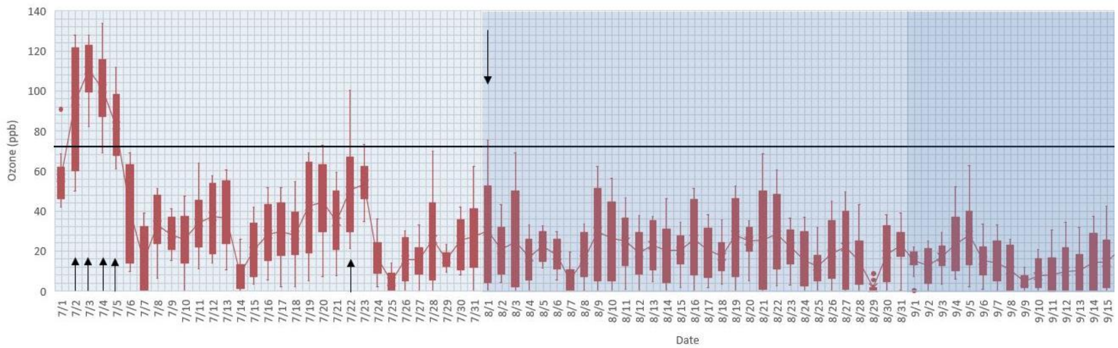


Figure 2.6: Outdoor $PM_{2.5}$ (ug/m^3) based on sensor measurements of summer 2017.

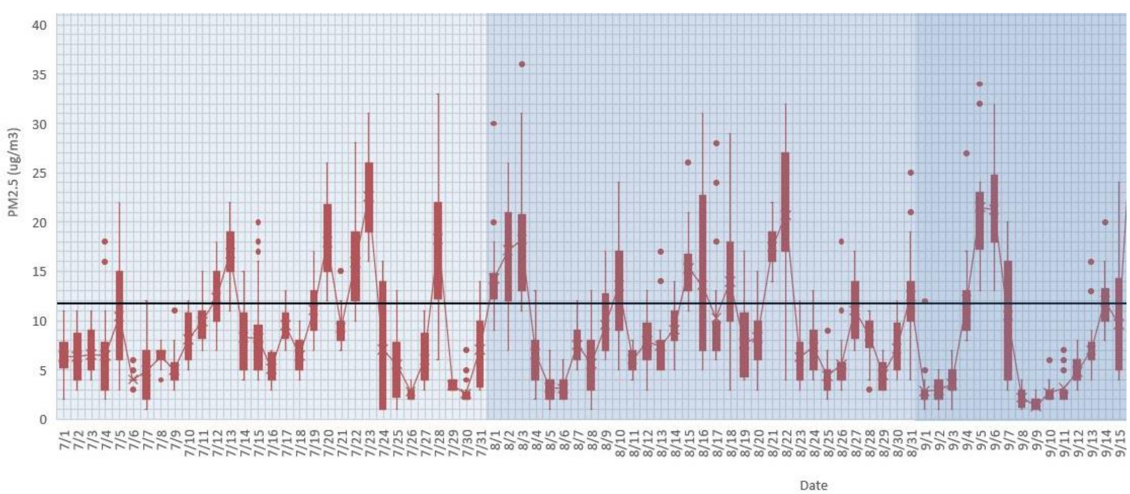


Figure 2.7: Outdoor CO_2 (ug/m^3) based on sensor measurements of summer 2017.

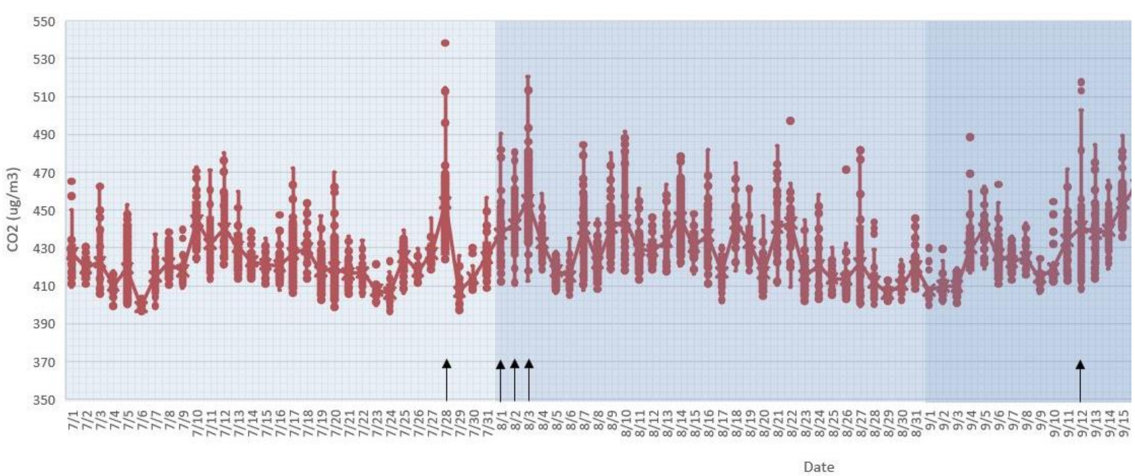
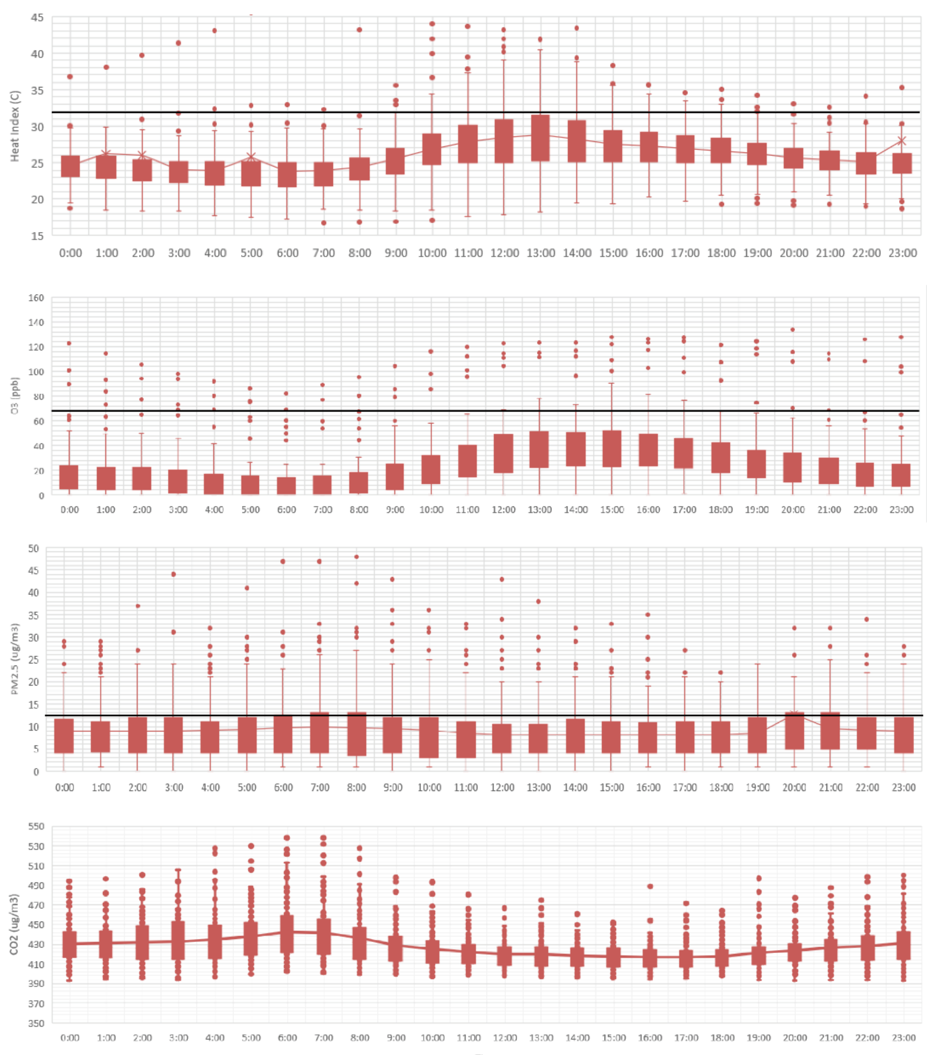


Figure 2.8 shows the hourly OHI, O_3, $PM_{2.5}$ and CO_2 variations. The highest heat index and ozone levels occurred during morning and afternoon between 9-5 pm, while $PM_{2.5}$ and CO_2 concentrations peaked in early morning (4-8 am). Ozone acceptable maximums (70 ppb) were exceeded in the 1st and 3rd heat waves (EPA, 2015). $PM_{2.5}$ concentrations were mostly above the accepted maximums (24-hr standard of 12 μg/m^3) (EPA, 2013).

Figure 2.8: Calculated outdoor heat index (C), O_3 (ppb), $PM_{2.5}$ (ug/m^3) and CO_2 (ug/m^3) based on sensor measurements of summer 2017: Hourly variations and peaks during morning and afternoon.



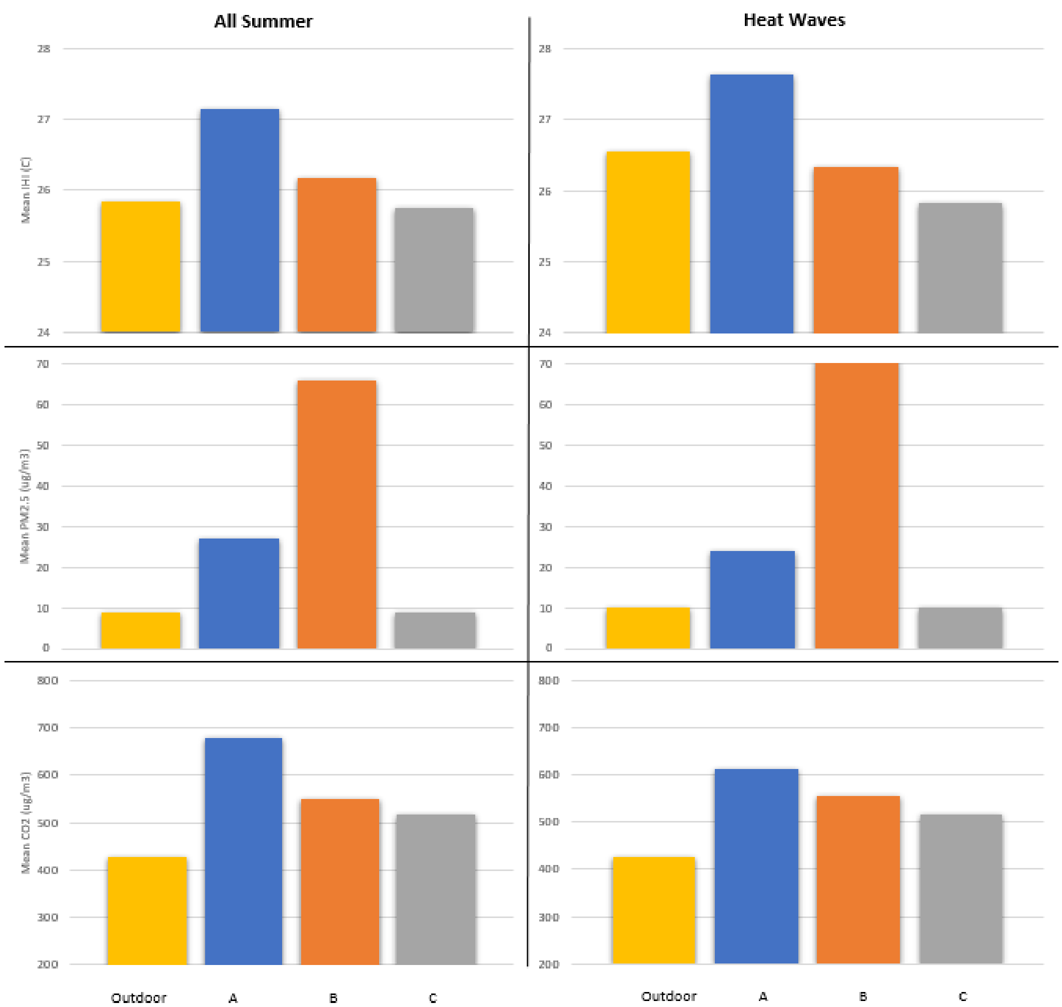
Resource Units: Indoor Thermal and Air Quality Conditions

Same as outdoors, air temperature and relative humidity sensor measurements were combined to produce indoor heat indexes (IHI) for the sample apartments. While no strict regulations exist for indoor temperature and humidity in residential settings, the Occupational Safety and Health Administration (OSHA) recommends office temperature control in the range of 68-76° F (20 - 24 C) and humidity control in the range of 20%-60% (OSHA, 2017). As a second source of guidance, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 recommends summer indoor temperatures for homes in the range of 75 to 80.5 F (24 - 27 C) and indoor humidity levels to be kept below 65%, considering standard clothing levels (ASHRAE, 2013).

During all summer 2017 and during the heat wave periods, indoor conditions in the resource units, the three buildings and 24 apartments, deteriorated, with some notable variations among the study sites. Specifically, as shown in Figure 2.9, A apartments were consistently the warmest, C were coolest and B were highly variable. Mean HI in A and B exceeded the OSHA guidelines; notably, building C has central A/C, while A and B apartments have either window A/C or no A/C, thereby constraining residents' adaptive actions.

The case of indoor $PM_{2.5}$ is different. B apartments registered the highest $PM_{2.5}$ concentrations and almost all of them exceeded the national 24-hr standard of 12 $\mu g/m^3$ (EPA, 2013). Four B apartments had excessively high $PM_{2.5}$ concentrations, all of which were due to indoor smoking, combined with lighting incense, cooking activity and poor apartment ventilation, as substantiated by resident interview. A apartments had the highest CO_2 levels. The highest CO_2 concentrations were in two A apartments, whose occupants reported keeping the windows closed to avoid noise and smells coming from outside, and also reported having several pets.

Figure 2.9: Average IHI, $PM_{2.5}$ and CO_2 by site, based on sensor measurements of summer 2017.



Governance Systems and Actors: Behaviors, Services and Support

The previous findings demonstrate effects of the seniors' behaviors and activities on their indoor environment. The interviews provided key information on varied adaptive (and maladaptive) actions in heat conditions. As shown in Table 2.2, more frequent use of fans, opening the windows, cooking avoidance and clothing adjustment -all adaptive actions - was reported in apartments located in buildings A and B, where some of the apartments have window A/C units and other apartments have none, as compared to apartments in building C where there is central A/C.

Table 2.2: Frequencies of adaptive actions taken during the heat wave periods of summer 2017 among each site's apartments. *Not necessarily in search for a cooler place.

Frequencies of Adaptive Actions Among Each Site's Apartments (N=96)			
	A (N=49)	**B (N=29)**	**C (N=18)**
Adjustable Fan	96%	66%	33%
Open Windows	80%	62%	39%
Close Windows	88%	90%	100%
A/C	78%	100%	55%
Clothing Adjustment	61%	41%	22%
Avoid Oven	69%	48%	6%
Avoid Stove	30%	21%	6%
Avoid Candles	19%	21%	0%
Avoid Smoking	19%	7%	0%
Leave Apartment*	61%	62%	67%

Data obtained from the indoor sensors were supported by seniors' interview statements that use of A/C and operating of windows were the most frequently taken actions, which mainly occurred during the afternoon and evening times when outdoor temperature peaked. Clothing adjustments and avoidance of oven or stove use were employed in A and B more frequently than in C.

Interviews with residents also revealed outdoor activities and preferences, shown in Table 2.3. About 63% of the seniors reported leaving their apartment at some point of the day. However, few of them left specifically in search of a cooler place; the majority performed their routine outdoor activities. In addition, while Table 2.2 shows that a similar percentage from the three sites left their apartments during heat wave conditions, from the interviews it was understood that seniors in A and B stayed outside for more hours during the weekdays and weekends and took more adaptive actions, while seniors in C mostly stayed within the building/community rooms.

Table 2.3: Residents' activities and preferences within sites and surroundings.

Sample (N=96)	
Outdoor Activities	
Within the Site	Lobby/Community Room-Center Outdoor Yard Community Gardens
Outside the Site	Visit Relative/Friend Shopping Store Senior/Cooling Center Park

	Library Public Pool Movie Theater Church Doctor/Hospital/Nursing Home/Pharmacy Work

Additional policy actors played two crucial roles during the summer 2017 heat waves. First, the HACE staff kept the buildings and grounds functioning, thereby ensuring that residents had appropriate shelter. Second, Proceed-a local non-profit- had previously put in place both window air conditioners where residents wanted them and arranged to pay the associated electric bills for their operation, in some apartments. This allowed residents to cope with the hot weather much more easily, generally within their own homes.

As reported in informal discussions with HACE, other community actors such as the facility managers (one manager per site) were responsible for the overall monitoring and functioning of the sites, both in terms of the systems operations and maintenance and the residents' well-being. An example is assigning floor captains at site C, who occasionally check on the residents' status or report any issues with the units. Also, the Community Service Staff provided free services to seniors such as flu shots, health and eye screenings and health education workshops. It also collaborates with Union County and City of Elizabeth Office of Aging to motivate the elderly to attend social, cultural and recreational activities, along with informing them about transportation to medical facilities, home aid, and day care programs (HACE, 2017).

Additional important governmental entities supporting seniors included actors representing the U.S. Social Security Administration for retirement benefits, US Food Nutrition Service (FNS-SNAP) in the form of food stamps, and lastly, Medicare for health insurance, all of which were reported by the residents during the baseline interviews. Other non-governmental actors were identified in the interviews, including nearby churches that organized food pantries once a month or checked on the elderly members; and Robert Wood Johnson Foundation (RWJF) programs including the Shaping Elizabeth Coalition (NJ Health Initiatives, 2017). Lastly, some residents reported receiving help from families/relatives (children, siblings) or social workers/nurses for cleaning the apartments or going shopping.

2.4 Discussion

The previous sections assembled a heat wave SES framework for seniors residing in public housing in low-income neighborhoods and demonstrated its effectiveness as a heuristic for evaluating inter-relationships among actors and infrastructure at different spatial scales. The Elizabeth, New Jersey, USA case study provides empirical evidence on how and to what effect SES components are involved in heat coping processes. When the heat waves occur, variations among the three study sites are reflected in the specific actions residents from each site take. These actions depend on the indoor and outdoor resources available to them and on the extent to which they receive support from social networks and community services. The results indicate that a stronger focus on the interactions among resident activities and apartment characteristics is needed, followed by an examination of the role of outdoor environments.

A primary conclusion of this chapter concerns the role of human activities, which were notable in their (positive and negative) mediating influences on measured indoor thermal and air quality conditions, and well-being. Measured $PM_{2.5}$ and CO_2 concentrations were influenced by behaviors such as window closing, smoking, lighting candles or incense and having pets, in addition to the local climate. On the other hand, indoor heat index was impacted more by the outdoor climate and building systems, especially the type of air-conditioning systems. Yet, it was shown that residents in apartments with poor building envelopes engaged in more adaptative actions, such as operating windows and fans, cooking less, drinking extra water and adjusting clothing. Such actions have also been positively linked to lower heat risks elsewhere (Bouchama, 2007; Zanobetti, 2012). Additional factors, such as outdoor amenities appeared to affect the residents' thermal experience; seniors spent more time outside in sites with better landscaping (shaded yards, community gardens etc.), substantiating the influence of these affordances.

As further empirical analysis emerges, a restructuring of the heat wave SES framework to emphasize and further elaborate second-level attributes, especially human behavior, may prove fruitful. Documenting the heat wave experiences of low-income seniors in the urban environment of Elizabeth, NJ indicated that, while the role of infrastructure systems is vital, in the end, heat adaptation depends on individual behavior and actions, and the extent to which they receive support from area organizations and institutions. Adaptation to heat waves, comprising individual, interpersonal, community-based, institutional, environmental and public policy interventions lowers the percent increase in heat wave-related deaths. The SES framework is a tool through which to characterize the empirical pathways of adaptation and correspondingly how to improve upon them.

Chapter 3 Indoor Environments: Thermal Conditions and Senior Resident Behaviors

Drawing on findings from chapter 2 and the community of Elizabeth, NJ, USA, this chapter closely examines the role of indoor environments in mediating heat, which corresponds to the 2nd research question of this dissertation[3]. It investigates the summertime thermal performance of apartments within the 3 public housing sites and the seniors' adaptive responses, based on data from sensors, interviews and plans. It adopts an occupant-centric approach based on multi-level regression that utilizes the indoor heat index as a proxy for heat stress, against site and building characteristics, and environmental and personal variables. The chapter concludes with a discussion of the results and next steps.

3.1 Background

Indoor Environment and Heat Vulnerability

Ongoing research on the thermal performance of residential housing aims to improve energy efficiency and thermal comfort, both in new design and in building retrofits. But building energy efficiency often appears as a separate design and operational objective from building comfort, which aims at thermal comfort and improved indoor environmental quality, despite their many interrelationships (Park and Nagy, 2018). In both cases, an integrated design approach is preferred that considers several factors,

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[3] The information presented in this chapter comes from a co-authored peer-reviewed research paper published in the Journal of Building and Environment. The citation is: *Tsoulou, I., Andrews, C. J., He, R., Mainelis, G., & Senick, J. (2020). Summertime thermal conditions and senior resident behaviors in public housing: A case study in Elizabeth, NJ, USA. Building and Environment, 168, 106411.*

including the climate, building characteristics and technology, occupant behaviors and operational practices (Li, Hong and Yan, 2014).

Regarding a building's thermal performance, most emphasis is typically given on how the heating, ventilating and cooling (HVAC) systems perform under specific climatic conditions, while accounting for building envelope characteristics, including age and geometry (Bauwens and Roels, 2013; Mohammad and Shea, 2013; Nahlik et al., 2017). However, research directly investigating the summertime indoor thermal performance is scarce and building control strategies rarely target cost-effective and easily accessible retrofits that could improve the thermal conditions in low-income households (Nahlik et al., 2017). In addition, common practice largely ignores aspects of occupant behavior and their effect on a building's thermal conditions and related energy use (Andrews et al., 2016; Azar and Menassa, 2012; O'Brien and Gunay, 2014).

Research focusing on thermal comfort adopts instead an occupant-centric approach that aims at understanding the effect of human behavior (Park and Nagy, 2018), since occupants are the end-users of energy in buildings (D'Oca et al., 2017). Thermal comfort is generally perceived as the human perception of satisfaction with the thermal environment based on external and internal stimuli (ASHRAE 55, 2013). More recently, several studies have started approaching a building's comfort and efficient operation in an integrated fashion (Langevin, Wen and Gurian, 2016; Marinakis et al., 2013; Park and Nagy, 2018; Veselý and Zeiler, 2014), and the contribution of occupants' adaptive behaviors is well recognized (Hong and Lin, 2013; Langevin, Wen and Gurian, 2016). However, it is still quite challenging to formally include multiple aspects of those behaviors in building performance simulation (BPS) tools (Andrews et al., 2016; O'Brien and Gunay, 2014).

Perhaps the most dominant model of thermal comfort is the Predicted Mean Vote (PMV) by Fanger (1970), which has been incorporated in the ASHRAE-55 and ISO 7730 standards (ASHRAE 55, 2013; ISO 7730, 2005). It combines environmental factors - temperature, humidity, and air speed - with personal factors - metabolic rate and clothing levels – to produce a 7-point scale of thermal sensations (Kim, Schiavon and Brager, 2018; Park and Nagy, 2018). An alternative to the PMV is the adaptive model, which is also part of the ASHRAE 55 and ISO 7730 standards (ASHRAE 55, 2013; ISO 7730, 2005), and linearly connects indoor operative temperature and satisfaction with the outdoor temperature (Escandon, Suarez and Sendra, 2019; Kim, Schiavon and Brager, 2018; Park and Nagy, 2018). PMV is generally used in mechanically-ventilated buildings, and the adaptive model is preferred in naturally-ventilated buildings (ASHRAE 55, 2013).

Due to recent advances in data collection and methods, there is a shift towards personal comfort models, where the focus is on understanding the behavior and comfort of individuals instead of groups and related models are more dynamic compared to the traditional PMV and adaptive approaches, as they get updated based on continuous data input (Kim, Schiavon and Brager, 2018; Peng, Nagy and Schluter, 2019). Yet, there are limited studies on the adaptive responses of vulnerable groups, such as the elderly, despite the need to improve the health and welfare of those populations.

3.2 Methods

After the preliminary exploration of the SES components in chapter 2, this chapter focuses on the seniors' indoor environments and examines the summertime thermal performance of apartments within the public housing sites in Elizabeth, NJ, USA and the residents' adaptive responses to this performance.

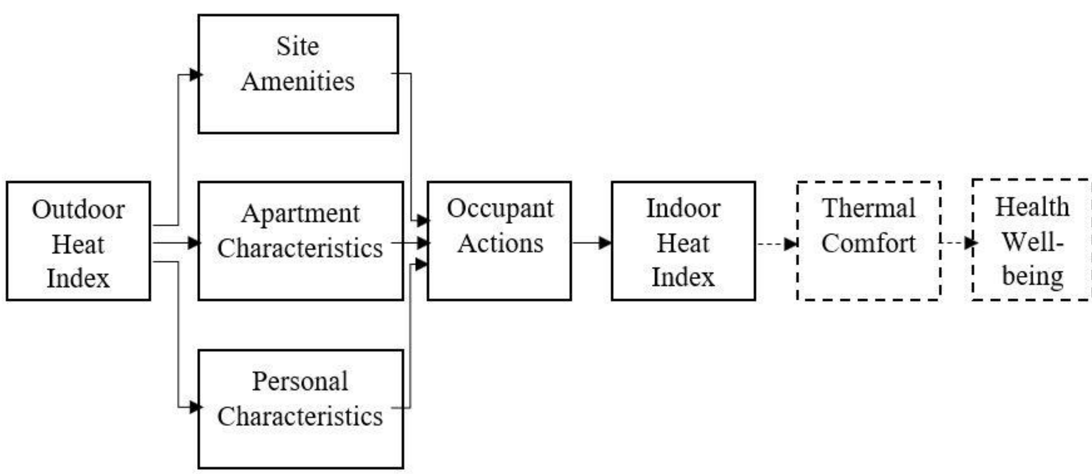
Based on hypotheses 1 and 2 of the 2nd research question, outlined in Table 1.5, the objectives of this chapter are:

- To examine the relative effects of the outdoor climate, the site and apartment characteristics and the residents' actions on the indoor thermal performance.
- To investigate thermal variations in apartments across and within sites with different indoor and outdoor characteristics.
- To identify behavioral variations and temporal patterns among seniors residing in different sites.
- To identify cost-effective and easily accessible strategies that depend on individual behaviors and outdoor amenities to help seniors in public housing communities cope with heat.

Data Analysis

The data analysis is guided by the premise that since seniors spend about 90% of their time indoors (ASHRAE, 2011; Klepeis et al., 2001; Spalt et al., 2016), indoor environmental quality is particularly important for their health and well-being (Arif et al., 2016). When summer temperatures are up, the focus is on indoor heat stress, which, here, is approximated by the indoor heat index. Therefore, IHI outcomes are examined against site and apartment characteristics, and personal and behavioral variables. The literature cited earlier has shown that the indoor thermal conditions are affected by the outdoor climate and building envelope characteristics but has not jointly investigated them along with occupant behaviors, which, in turn, are subject to personal variables and the indoor and outdoor resources available to the residents. The schematic representation in Figure 3.1 illustrates this causal chain affecting the health and well-being of low-income seniors during heat waves.

Figure 3.1: Conceptual framework explaining the factors affecting health and well-being of seniors in public housing sites during heat waves. Indoor heat index that approximates thermal comfort or discomfort becomes the most important aspect of indoor environmental quality and links to the outdoor heat index, site amenities, apartment characteristics, personal characteristics and occupant actions. Occupant actions are subject to personal characteristics and the indoor/outdoor resources available to the residents.



The analysis zooms into the indoor thermal conditions and shows variations within sites and within apartments during all summer 2017 and during heat wave periods. Next, variations in occupants' behaviors, such as occupancy, window opening and use of A/C are observed across and within sites. Lastly, each of the above predictor variables is entered into a panel regression analysis that examines their relative effect on the indoor heat index.

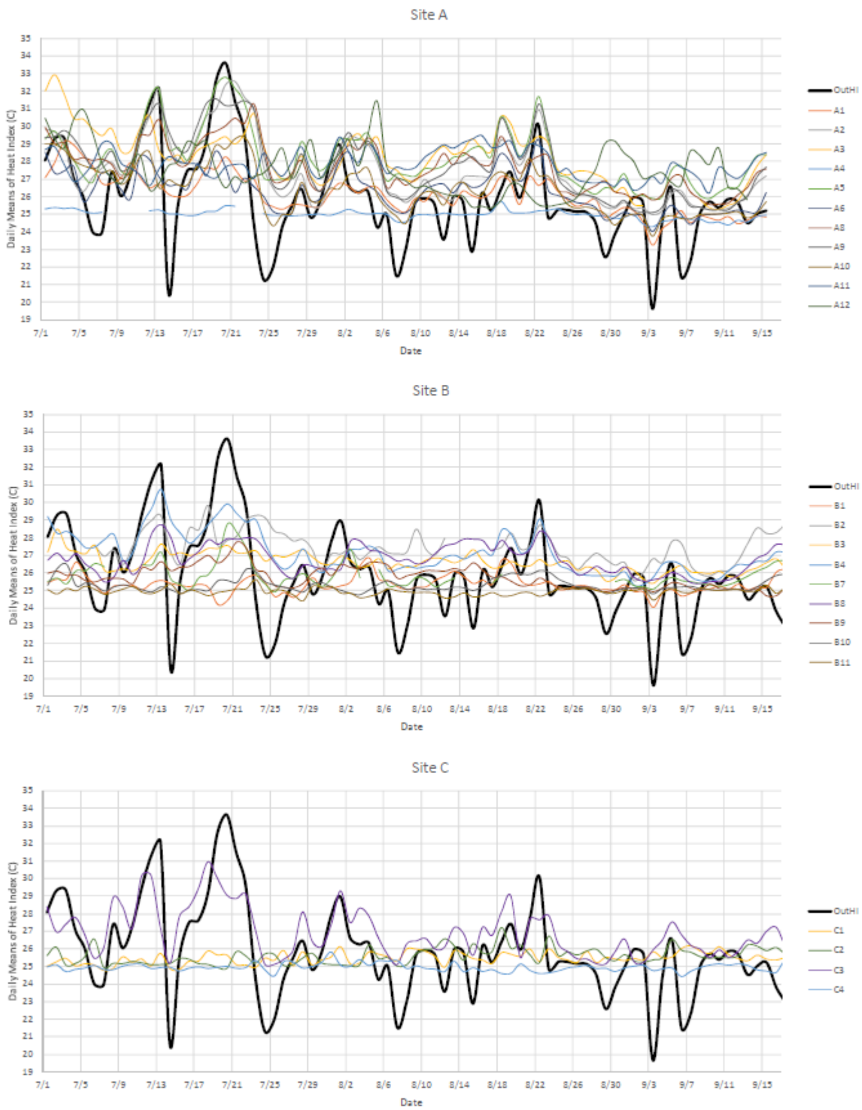
3.3 Results

Indoor Thermal Performance

Variations Across and Within Sites

When comparing IHIs among sites and with the OHI during all summer (Figure 3.2), it is evident that most A apartments have higher indexes in the ranges of 25-30 Celsius, followed by B apartments that range within 25-28 Celsius, and those from C that are in the range of 25-26 Celsius. It is also shown that many A apartments have the same trend with the OHI, especially in the highest peaks that occur during heat waves. This is expected, since they are all cross-ventilated and have poor wall insulation, as documented in the baseline interviews. Some other A apartments follow their own trend (e.g. A3), while there are few apartments, such as A4, which, have relatively invariant trends with very low median values. In the case of B apartments, about half of them follow the OHI peaks during the heat wave periods, while the rest have relatively invariant trends and lower daily averages. Lastly, only one of the C apartments (C3) follows the OHI variations, both during the heat wave and the non-heat wave periods; the rest have low daily averages and no significant peaks.

Figure 3.2: Daily averages of calculated indoor heat index (C) based on sensor measurements by site during summer 2017.



The significant IHI variations between the 3 sites are additionally confirmed through a 1-way ANOVA test (F = 4,318.96, p = .000), found in Table 3.1. Specifically, IHI is shown to be statistically significantly higher in the A site compared to the C site (1.38 ± 0.017 packages, p = .000) based on a Turkey post-hoc test.

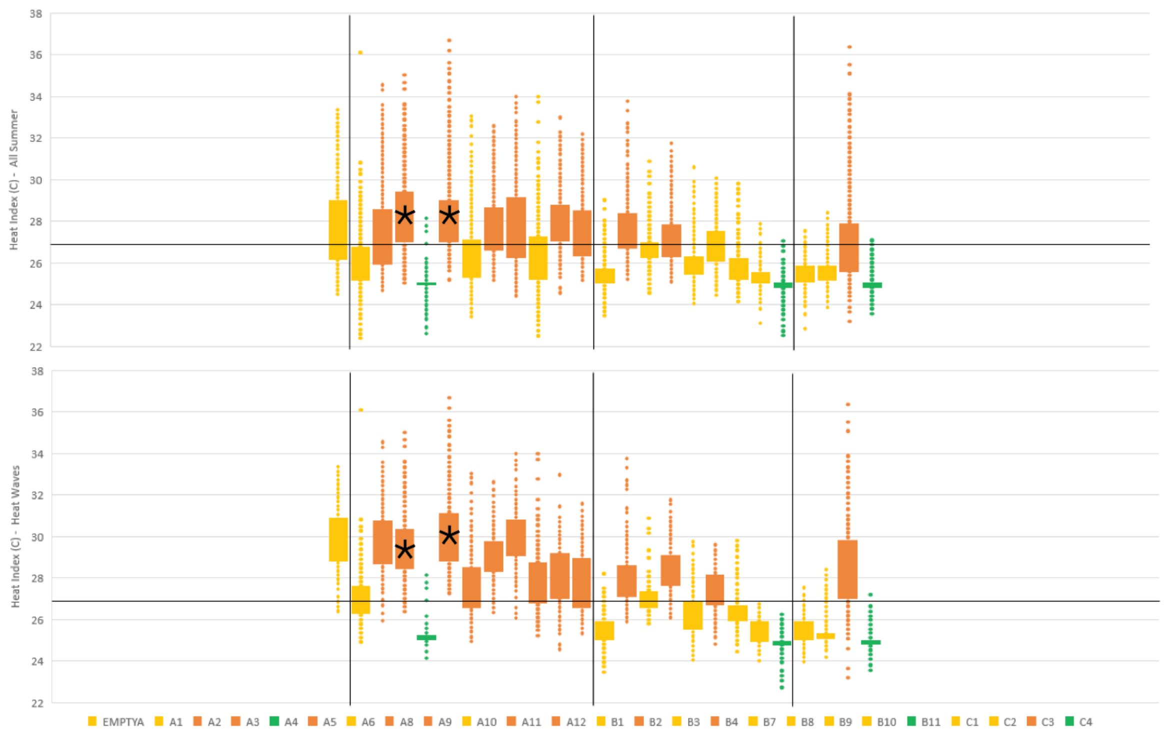
Table 3.1: 1-way ANOVA tests for statistical differences in indoor heat index means among sites.

1-way ANOVA of Heat Index by Site					
	SS	df	MS	F	p
Between groups	20124.9743	2	10062.4871	4318.96	0.00
Within groups	142330.073	61090	2.32984241		
Total	162455.047	61092	2.65918691		
Bartlett's test for equal variances: chi2(2) = 4.9e+03 Prob>chi2 = 0.000					

When comparing indoor heat indexes among apartments within each site (Figure 3.3), it is evident that, indeed, apartments in the A site have considerably higher values than those in B and C. Specifically, the medians of 7 A apartments reach or exceed the threshold of 27 C, which is also the case with 2 B apartments. This pattern repeats during heat waves, where the median HIs of 9 A, 3 B and 1 C apartments also exceed 27 C, which is more than half of the sample.

The wider IHI range and the highest peak is found in apartment A5, which is the only apartment without a functioning A/C unit. A very similar IHI pattern is also evident in apartment A3, which, as reported in the baseline interviews, has 1 operating A/C unit. On the other hand, A4 also has one A/C unit, but its HI is considerably lower than both A3 and A5, as well as the rest of the A apartments. Within site B, B11 has the lowest ranges, while B2 has the highest IHI values, all of which have 1 window A/C unit. It also appears that there is a similarity among the IHI ranges of A4, B11 and C4.

Figure 3.3: Calculated indoor heat index (C) based on sensor measurements during summer and during heat waves of 2017. Green indicates apartments with the lowest IHIs, yellow corresponds to mid values and orange to high IHIs that exceed 27 C. 13 apartments exceed the threshold of 27 C during the heat wave periods. Apartments A3 and A5 (highlighted with asterisk) have considerably higher heat indexes compared to apartments A4, B11 and C4 (highlighted in green).



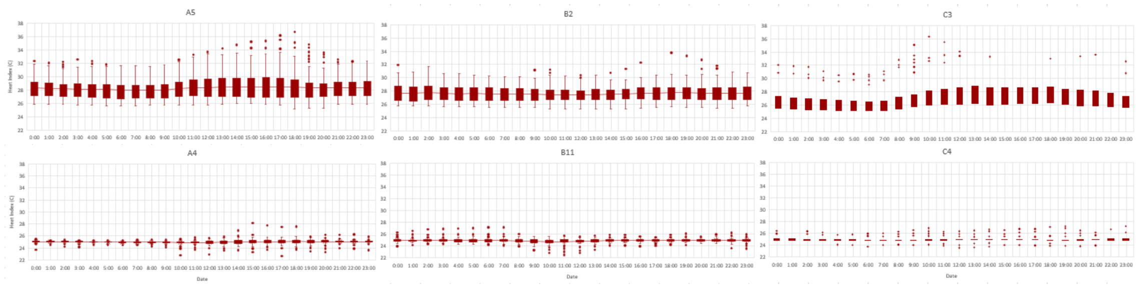
1-way ANOVA test further confirms the statistically significant IHI variations between the sample apartments (F = 1,892.58, p = .000), found in Table 3.2. Based on a Turkey post-hoc test, it is further shown that the IHI is statistically significantly higher in apartments A3 and A5 compared to apartments A4, B11 and C4.

Table 3.2: 1-way ANOVA tests for statistical differences in indoor heat index means among apartments.

1-way ANOVA of Heat Index by Apartment					
	SS	df	MS	F	p
Between groups	67606.8084	23	2939.42645	1892.58	0.00
Within groups	94848.2386	61069	1.55313234		
Total	162455.047	61092	2.65918691		
Bartlett's test for equal variances:		chi2(23) = 2.6e+04	Prob>chi2 = 0.000		

Lastly, time variations in the heat indexes of selected apartments can be found in Figure 3.4, which indicates that in all sites, the apartments with low heat index values have no significant peaks, few hourly variations and the median value is around 25 Celsius. On the other hand, in apartments with high heat indexes, the hourly IHI trends may follow the outdoor hourly HI trend (indicates no use or effect of A/C), or they may be lower during the morning and afternoon times and peak during the night times (indicates use of A/C during the day and no use or effect of A/C during the night). The median values in those apartments range from 27 to 29 Celsius, and there are more variations in each hourly lag.

Figure 3.4: Calculated indoor heat index (C) based on sensor measurements in selected apartments during summer 2017: Hourly variations.



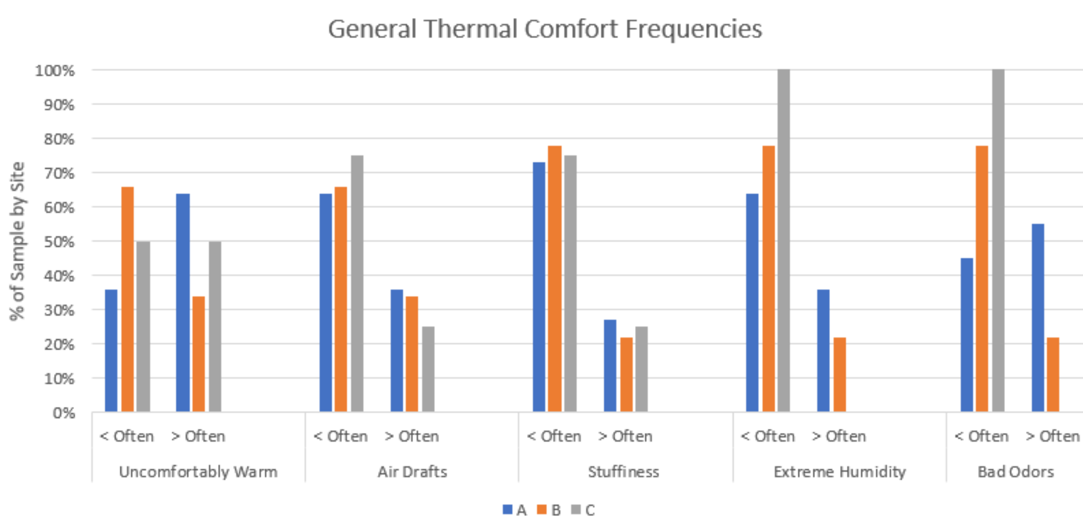
Indoor Thermal Comfort and Adaptive Behaviors

As seen previously, there are significant thermal variations in apartments located in different sites, which is expected, considering differences in building envelope characteristics, including HVAC systems, age and geometry. For instance, as shown in Tables 1 and 4 of Appendix C, only apartments in the green building (site C) have central A/C and good insulation. Apartments located in A are old, cross-ventilated, with poor insulation (e.g. no double-glazing) and no central A/C. Similarly, apartments in B have no central A/C, but are newer and with better insulation. Some apartments in both A and B have only 1-3 small window A/C units.

Results show significant thermal variations among apartments located in the same sites, while some apartments from A and B have similar IHI trends with apartments from the green building. To some extent, those variations can be attributed to additional apartment characteristics, such as orientation, floor, size, number of windows etc. But certain occupants' behaviors, such as occupancy rates, window and A/C operation, may highly affect the indoor thermal performance and consequently, the overall thermal comfort of residents.

As documented in the baseline interviews, the overall self-reported comfort of seniors across sites shows a consistent story with the sensors (Figure 3.5). There are high percentages of dissatisfaction in all sites regarding the indoor air drafts, feeling of stuffiness and extreme humidity, while half of the sample also reported feeling uncomfortably warm during summer. As expected, the percentage of occupants complaining that they are uncomfortably warm is higher in site A, but it is unexpected to see a similar percentage of dissatisfaction in site C.

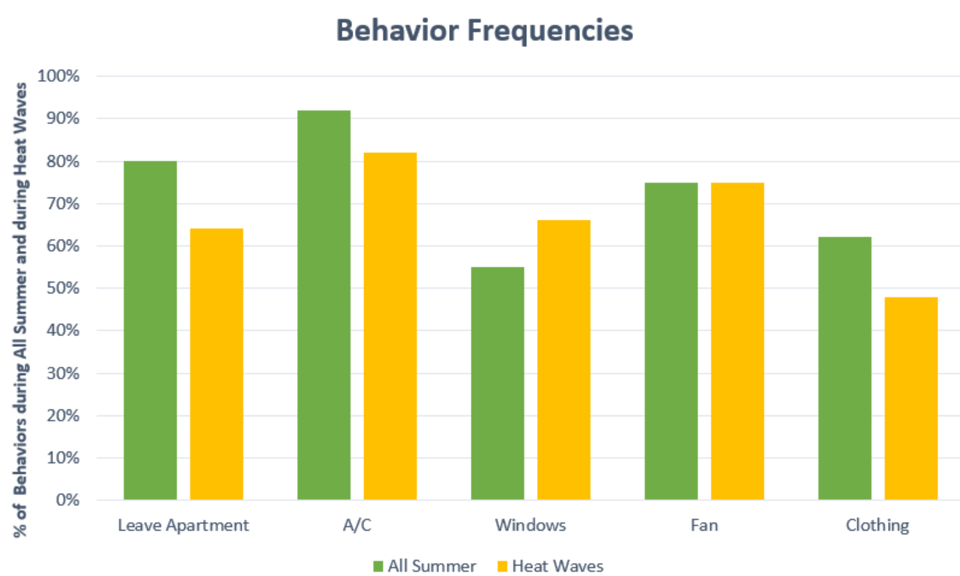
Figure 3.5: Self-reported general thermal comfort during summer of 2017 from the baseline interviews. A high percentage of residents located in site A report thermal discomfort, followed by residents in C and B.



Adaptive Behaviors Across and Within Sites

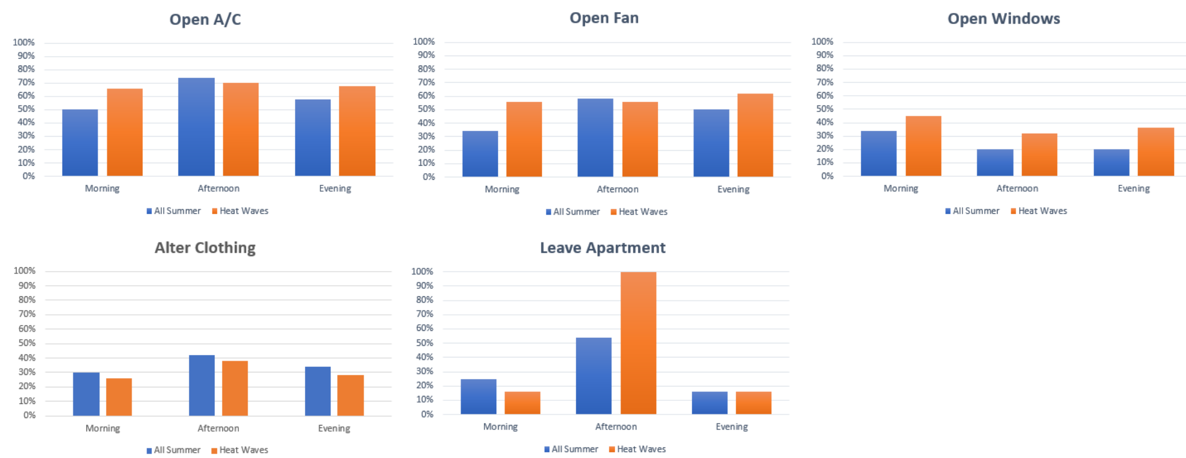
The most frequently reported behaviors in the baseline (all summer) and follow-up (heat waves) interviews shown in Table 2.2, include the use of air-conditioning as the most popular action, followed by fans, window opening (WO) and clothing adjustment. Leaving the apartment is another consideration, although, as mentioned in chapter 2, it is not necessarily due to indoor heat stress. Surprisingly, as shown in Figure 3.6, residents reported using less A/C during heat waves and more WO, while the use of fans remained the same. Leaving the apartment happens less, as expected, and the same counts for clothing adjustment.

Figure 3.6: Self-reported key adaptive behaviors during summer and during heat waves of 2017. Windows indicates window opening.



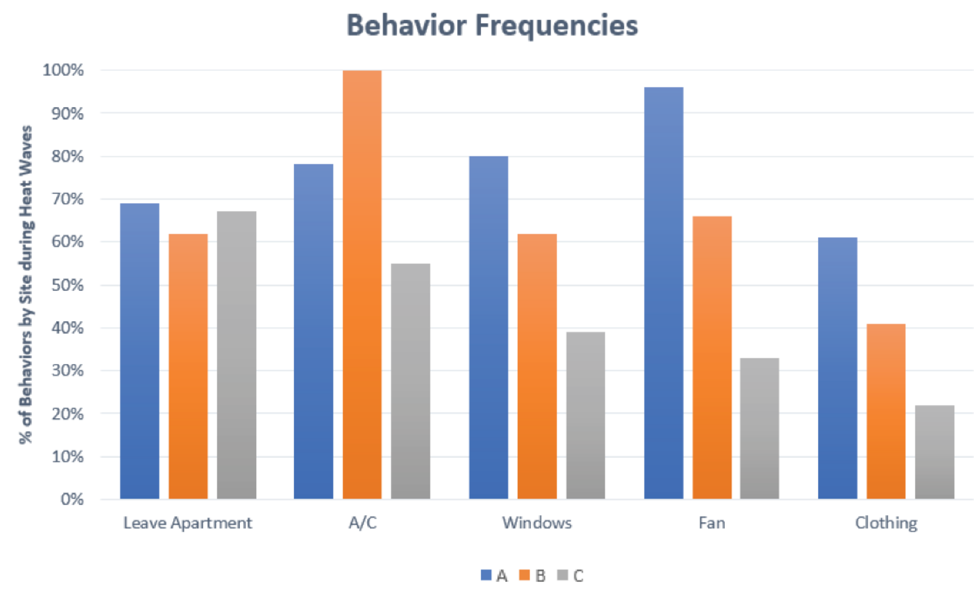
Regarding the time of day they took each action, as shown in Figure 3.7, there is a consistent use of A/C and fans throughout the day. Then, there is more window opening in the morning, which was explained in the interviews as being part of their everyday routine. Clothing adjustment happens more in the afternoon, which is expected considering higher temperatures at those times. Perhaps the most unexpected finding is leaving the apartment in the afternoon, when outdoor temperatures are at their peak. It also contradicts with the residents' statement that they don't usually leave the apartment because of the indoor heat.

Figure 3.7: Self-reported time of day variations in behaviors during all summer 2017 and during heat waves. Windows indicates window opening.



There are also interesting variations in the residents' key behaviors across different sites during heat waves, based on the follow-up interviews (Figure 3.8). Leaving the apartment has similar prevalence across all sites. Then, A/C is a consistent action throughout all sites, although B residents reported that they used it more, followed by A and C. It should be noted however, that this may be due to differences in envelopes; A and B residents operate small window A/C units, while C residents operate thermostats. Perhaps the most interesting observation relates to the differences in the use of fans, WO and clothing adjustment among residents of A and C; there is a higher percentage of fan, window activity and clothing adjustment in A than in C, which indicates that residents in sites with poor envelopes engage in a wider range of adaptive actions during heat waves.

Figure 3.8: Comparison of self-reported key adaptive behaviors among sites during heat waves of 2017 from the follow-up interviews. (Windows indicates window opening).



These behavioral variations across sites are lastly confirmed through Pearson correlations among site fixed effects and binary variables of window activity, A/C opening and occupancy, taken from the sensor database (Table 3.3). Specifically, residents in site A are more likely to open the window than the residents of C, while the opposite happens with operating the A/C. This is different from what was reported in the interview. Lastly, occupancy levels are higher among A residents and lower for B and C residents. The strongest coefficients are those of window opening in sites A and C.

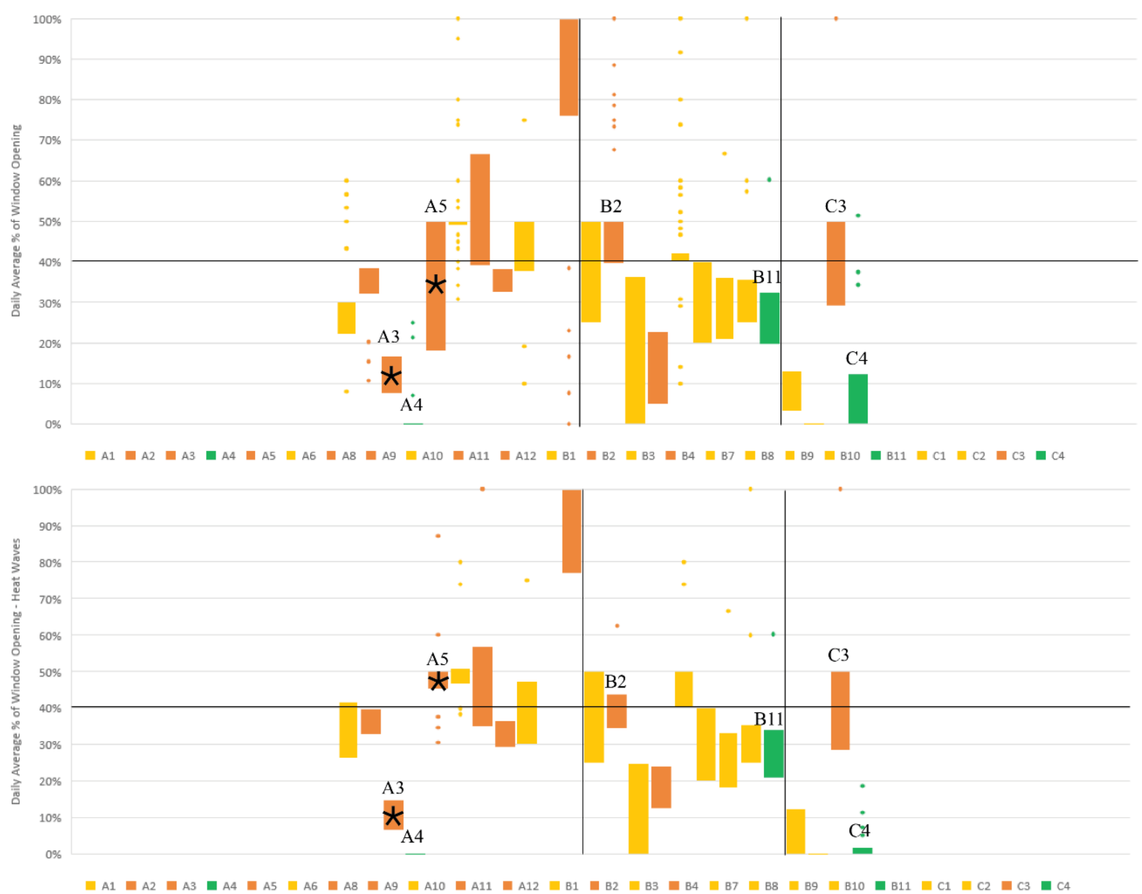
Table 3.3: Pearson correlations between sites and behaviors. *Significant at the p=0.05 level.

	Site A	**Site B**	**Site C**
Occupancy	0.09*	-0.02*	-0.09*
Window Open	0.20*	0.03*	-0.30*
A/C On	-0.02*	0.00	0.03*

Figure 3.8 and Table 3.3 showed interesting behavioral patterns among a site with mostly passive cooling and a green building with central A/C; A residents have window A/C units that do not operate very well and this can possibly explain their frequent use of WO, fans and clothing adjustments. On the other hand, C residents mostly rely on adjusting the thermostats and don't engage much in other adaptive actions. Access to functioning air conditioning is important in reducing the indoor heat stress, however, those behavioral variations indicate that some residents choose alternative paths for heat adaptation, especially when combined with results from Figures 3.2 and 3.3 that show selected A and C apartments having similar heat index trends.

Considering the significant correlation and variation of window opening among sites, Figure 3.9 zooms into the particular WO patterns of the sample apartments during all summer and during heat waves of 2017, based on sensor data. Window opening percentages and ranges are higher in A apartments, followed by B and C and this pattern repeats during heat waves. Within site A, apartment A5 that has no A/C unit has the widest range of window opening percentages, which indicates that the resident's WO routine may be highly affected by weather patterns. In contrast, A4, which has the lowest indoor HI, has the smallest percentage and range. However, apartment A3 also has a quite high IHI, despite its low window activity. Within B, B11 has the lowest heat index based on Figure 3.3, but has a medium window opening activity, while B2 with the highest IHI also has the highest percentage of WO among all B. Lastly, only C3 has a high window opening activity, which also coincides with the highest IHI among all C, while C4 that has the best IHI has a relatively low WO activity. In sum, it is evident that in buildings with tighter envelopes, such as in C, window opening may indeed affect the indoor thermal performance, but this relationship may be more complex in sites with more passive cooling.

Figure 3.9: Calculated daily average percentage of window opening based on sensor measurements by apartment during all summer and during heat waves of 2017. Green indicates apartments with the lowest IHIs, yellow corresponds to mid values and orange to high IHIs that exceed the threshold of 27 C. WO percentages and ranges are higher in A apartments and this pattern repeats during heat waves. Apartment A5 (highlighted with asterisk) that has no A/C unit has the widest range of window opening percentages. In contrast, apartment A4 (highlighted in green), which has the lowest indoor HI, has the smallest percentage and range.



1-way ANOVA test further confirms the statistically significant window opening variations between the sample sites (F = 1,941.39, p = .000) and apartments (F = 1,067.94, p = .000), found in Table 3.4. Based on a Turkey post-hoc test, it is further shown that WO is statistically significantly higher in site A compared to C, and in apartments A6, B2 and B7 compared to apartments A4 and C2.

Table 3.4: 1-way ANOVA tests for statistical differences in window opening means among sites and among apartments.

1-way ANOVA of Window Opening by Site					
	SS	df	MS	F	p
Between groups	778.193879	2	389.096939	1941.39	0.00
Within groups	7249.44268	36171	.200421406		
Total	8027.63656	36173	.221923439		
Bartlett's test for equal variances: chi2(2) = 266.6150 Prob>chi2 = 0.000					
1-way ANOVA of Window Opening by Apartment					
	SS	df	MS	F	p
Between groups	3162.12302	22	143.732865	1067.94	0.00
Within groups	4865.51354	36151	.134588629		
Total	8027.63656	36173	.221923439		
Bartlett's test for equal variances: chi2(21) = 9.4e+03 Prob>chi2 = 0.000					

Lastly, to better understand window opening activity and examine whether it is used for cooling purposes, Table 3.5 shows the regression results of percent windows open by apartment examined against the indoor/outdoor heat index ratio 1 hour earlier. I/O HI ratio is statistically significant in 2/3 of the sample and explains little of the variance in window opening.

Table 3.5: 24 Models of regression parameters for percent of windows open for during summer 2017. *Significant at the p=0.05 level.

Percent of Windows Open				
Site	**Apartment**	**I/O Heat Index Ratio (1 hour early)**	**F**	**R2**
A	A1	-0.25*	11.96	0.01
		(0.07)	(0.00)	
	A2	-0.33*	50.50	0.03
		(0.04)	(0.00)	
	A3	0.13*	5.73	0.00
		(0.05)	(0.01)	
	A4	0.19*	12.88	0.01
		(0.05)	(0.00)	
	A5	-0.75*	116.33	0.06
		(0.07)	(0.00)	
	A6	0.02	0.48	0.00
		(0.03)	(0.48)	
	A8	0.33*	27.70	0.02
		(0.06)	(0.00)	
	A9	0.13*	9.16	0.00
		(0.04)	(0.00)	
	A10	0.03	0.33	0.00
		(0.06)	(0.56)	
	A11	-	-	-
	A12	0.24*	8.20	0.00
		(0.08)	(0.00)	
B	B1	-0.10	0.06	0.00

		(0.42)	(0.81)	
	B2	0.34*	46.83	0.03
		(0.05)	(0.00)	
	B3	0.23*	12.84	0.00
		(0.06)	(0.00)	
	B4	-0.00	0.03	0.00
		(0.05)	(0.86)	
	B7	-0.05	0.83	0.00
		(0.05)	(0.36)	
	B8	0.03	0.20	0.00
		(0.06)	(0.65)	
	B9	0.32*	19.00	0.01
		(0.07)	(0.00)	
	B10	-0.16*	6.69	0.00
		(0.06)	(0.00)	
	B11	0.15*	4.88	0.00
		(0.06)	(0.02)	
C	C1	0.13*	4.72	0.00
		(0.06)	(0.03)	
	C2	-	-	-
	C3	0.03	0.20	0.00
		(0.07)	(0.65)	
	C4	0.53*	106.34	0.06
		(0.05)	(0.00)	

Regression Analysis of Indoor Heat Index

The previous section investigated how the summertime thermal comfort and adaptive behaviors of seniors change across sites with different building envelopes and outdoor amenities. This section examines statistical associations of the indoor heat index with 5 distinct groups of variables:

- Outdoor environment, through the time-variant, outdoor heat index,
- Site characteristics expressed through fixed effects for each site,
- Apartment characteristics that are fixed effects for orientation, floor number, corner or middle etc.,
- The residents' personal characteristics that include fixed effects for community active, having pets, being an indoor smoker, and lighting candles or incense indoors, and
- The residents' adaptive behaviors, such as being present in the apartment, and window and A/C opening that are binary and time-variant.

The time-variant variables are taken from the sensor database and the fixed effects are constructed based on the interviews and the apartment plans.

Pearson Correlations of Indoor Heat Index

Table 3.6 shows Pearson correlations among the indoor heat index and selected variables related to the outdoor climate, site and apartment characteristics, the residents' behaviors and the residents' personal characteristics. More detailed correlations can be found in Tables 2 - 6 of Appendix C, based on which, the final set of variables was selected for the analysis.

First, there is a statistically significant correlation among the indoor and outdoor heat indexes; as expected, with increases in the outdoor temperature and humidity, the indoor heat index goes up. Then, there are significant correlations among all sites and the IHI;

specifically, indoor heat index increases if apartment belongs to site A and decreases otherwise. In addition, HI goes down if the apartment is located in a higher floor, and goes up with south orientation, corner exposure and increase in the number of windows. Elsewhere it has been found that higher floors may have exposure to higher indoor temperatures, here, most floor variations can be found in high-rise site B. It is also interesting to see the HI's connection with the residents' personal characteristics. Being community active, which, for some residents means lower occupancy, connects to a lower IHI, which is also the case with having pets. This makes sense, considering that most pet owners in the sample reported engaging in more community activities. Lastly, indoor heat goes up with occupancy and window opening and goes down if the A/C is on, as expected.

While most of these correlations are statistically significant, the highest magnitudes are those of site A, outdoor heat index, being community active, and opening the windows. These results indicate that while the outdoor climate and site-apartment characteristics have a strong effect on the indoor thermal performance, personal variables and adaptive actions may also play an important role. The same pattern repeats during heat waves, where magnitudes increase for site and behaviors.

Table 3.6: Pearson correlations between the indoor heat index and selected variables during all summer and during heat waves of 2017. *Significant at the p=0.05 level.[4]

	IHI	
	All Data	**Heat Waves**
OHI	0.21*	0.11*

[4] IHI and OHI are continuous variables. The rest are dummy variables.

Site A	0.34*	0.50*
Floor	-0.07*	-0.19*
Community Active	-0.21*	-0.19*
Occupancy	0.04*	0.05*
Window Open	0.19*	0.31*
A/C On	-0.02*	-0.08*

Panel Regressions of Indoor Heat Index

The following paragraphs examine statistical associations among the indoor heat index and the variables presented in Table 3.6, through panel regression analysis. Panel regression with random effects and robust standard errors is suitable, as the database is two-dimensional and has spatial variations (across apartments) and temporal variations (24-hour intervals for approximately 3 summer months). The use of random instead of fixed effects is appropriate here, as the focus is on differences among spatial units, while random effects more clearly show the impact of fixed effects on the dependent variable. Lastly, the use of robust standard errors allows valid inference, especially in cases where serial correlation and heteroscedasticity issues arise.

Table 3.7 presents the results of 5 models; the first examines a simple, indoor-outdoor heat index relationship, and the rest progressively add site fixed effects, selected apartment attributes, personal characteristics and behaviors. Panel regression for the last model (M5) is repeated only for the heat wave periods, as well as for all summertime data only when apartments are occupied. The table shows the regression coefficients and standard errors for each predictor variable, in addition to their statistical significance and the models' explanatory power based on R^2 within and between groups, and overall.

In model 1 (M1), regression coefficients indicate that as the outdoor heat index goes up, so does the indoor heat index. When the fixed effect for site A is added in model 2 (M2), the OHI coefficient remains the same, but it clearly shown that the site has a stronger effect; apartments in site A experience higher indoor heat indexes, which is expected considering results from Figures 3.3 and 3.5. Model 3 (M3) adds the floor variable, which shows an effect over the IHI, although this effect is weaker than this of site A. Here, the floor's direction indicates that IHI is higher for apartments located in higher floors, which is expected, but contradicts with the results of Table 3.6. Since most floor variations are found in site B, this finding mostly applies to its apartments. Moving forward, model 4 (M4) adds a fixed effect related to the residents' personal characteristics. It shows that if the residents engage in community activities several times per week, it is likely that their apartment will have a lower heat index. This coefficient also has implications for apartment occupancy, assuming that community active residents spend more time outside of the apartment. The magnitude is not very strong, but it still higher than the OHI and floor number.

The last model (M5) adds binary variables for occupant behaviors and interaction terms related to the indoor heat index and those behaviors. Evident in the last model is that the effect of the outdoor heat index becomes even smaller, although still statistically significant. The same happens with the effect of site A, the floor and the community active variables. Now, there are statistically significant and very strong effects of occupancy, window and A/C opening on the indoor heat index. Specifically, when apartment is occupied, with at least a window open and the A/C on, the indoor heat index goes down. This is expected for A/C and to a certain extent for occupancy, considering that when residents are indoors, may turn on their A/C. Perhaps the most surprising coefficient is the window opening, which contradicts with the correlation shown in Table 3.6. It further indicates that IHI and WO is not a straight-forward relationship but gets highly affected by the interaction with the earlier indoor heat index, which is also the case with the remaining occupant actions. Lastly, the comparison among R^2 statistics shows that the model explains more of the variation in the data when behaviors and interactions among behaviors and indoor heat index are added, compared to models that only included environmental and site/apartment related variables.

The two additional models for heat wave data and for occupied apartments are based on model 5. Evident in the model with the heat wave data is that the effect of the OHI becomes not statistically significant and the same counts for community active. This can be probably explained by the fact that during heat wave periods most seniors stay in, as reported in the follow-up interviews. The same happens with the use of A/C, but since the observations are reduced, the sample mostly relies on the behaviors of the residents located in sites A and B. Lastly, the final model selects only data from the occupied hours based on occupancy sensor data where motion was reported (see Table 1.3 of chapter 1) and assumes that residents aren't engaging in adaptive actions when they are not indoors. Compared to the full model, the coefficients have the same directions but higher magnitudes, especially in the case of behaviors, which confirms their strong effect over the indoor HI.

Table 3.7: 5 Models of panel regression parameters for indoor heat index during summer 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

IHI (1 hour late)[5]		**M1**	**M2**	**M3**	**M4**	**M5**	**M5** (Heat Waves)	**M5** (Occupied)
Outdoor Env.	OHI	0.09* (0.01)	0.09* (0.01)	0.09* (0.01)	0.09* (0.01)	0.02* (0.00)	0.01 (0.00)	0.04* (0.00)
Site	Site A		1.04* (0.38)	1.62* (0.50)	1.85* (0.40)	0.56* (0.21)	1.26* (0.49)	0.88* (0.39)
Apartment[6]	Floor			0.17* (0.06)	0.27* (0.05)	0.07* (0.02)	0.12* (0.04)	0.13* (0.04)
Personal Char.[7]	Com. Active				-0.97* (0.30)	-0.31* (0.13)	-0.23 (0.29)	-0.50* (0.24)
Personal Behaviors	Occupancy					-11.39* (2.01)	-8.63* (1.59)	-
	Wind. Open					-13.47* (1.89)	-12.15* (1.09)	-19.83* (0.97)
	A/C On					-2.62* (0.78)	-1.41 (0.93)	-4.76* (1.09)
Interaction:	IHI early * Occupancy					0.43* (0.07)	0.31* (0.05)	-

[5] The dependent variable is the indoor heat index one time-step later (1 hour later) than the independent variables, as this more clearly shows cause and effect.
[6] Orientation (south and east) and corner were excluded, as they did not yield statistically significant coefficients. Number of windows was excluded, due to collinearity issues with the window opening behavior.
[7] Gender was excluded due to limited variability in the dataset. Similarly, income, age and education were excluded, as the focus is only on senior, low-income residents. In addition, having pets is part of being community active, while smoking and lighting candles did not yield statistically significant coefficients.

Indoor Env. (1hr early) and Behaviors	IHI early * Wind. Open					0.51* (0.07)	0.45* (0.07)	0.75* (0.03)
	IHI early * A/C On					0.09* (0.03)	0.05 (0.03)	0.18* (0.04)
	Constant	24.03* (0.42)	23.55* (0.45)	22.72* (0.49)	22.87* (0.54)	25.18* (0.24)	25.91* (0.58)	24.59* (0.34)
	R^2							
	Within	0.08	0.08	0.08	0.08	0.71	0.46	0.60
	Between	0.00	0.24	0.35	0.53	0.93	0.88	0.79
	Overall	0.04	0.16	0.20	0.26	0.80	0.75	0.68

Another round of regressions is presented in Table 8 of Appendix C, where IHI outcomes are examined against the same variables of model 5, by site. As expected, outcomes in site C (green building with central A/C and a tighter envelope) are not sensitive to the outdoor heat index, unlike the 2 conventional sites. Then, Table 9 of Appendix C presents IHI outcomes against the same variables of model 5 for night vs day times, for all data and for data where apartments were occupied. Community active becomes not statistically significant and window opening has a higher magnitude during the night, while adaptive behaviors explain much of the IHI variation. Lastly, Table 10 of Appendix C shows results of factor analysis for selected apartment characteristics (2 factors produced with eigenvalues=2.39/1.21 and Kaiser-Meyer-Olkin test=0.54) and Table 17 presents the regression results of indoor heat index against the same variables of model 5 using the 2 factors. The factor analysis confirms the importance of the explanatory role of adaptive behaviors in predicting indoor heat index.

3.4 Discussion

This chapter utilized a multi-level approach to identify the relative roles of sites, buildings and the seniors' actions in managing heat stress. It was observed that besides apartment characteristics, occupant behaviors have a significant effect on indoor thermal performance and that those behaviors vary significantly based on the resources available to the residents. Indoor heat index distributions showed significant variations across sites with different outdoor amenities and building envelopes, as well as across apartments located within the same sites. The same pattern was also repeated in the residents' behaviors. These findings, along with results from Pearson correlations and panel regressions, suggest that heat adaptation is not only subject to built-environment characteristics, but also depends on how people interact with their resources. This level of agency should be part of heat adaptation strategies.

Considering that certain heat wave definitions that rely only on thresholds may ignore significant findings from "non-heat wave" periods (Diaz et al., 2018), the approach was based both on a whole summertime period and on selected heat wave periods. The comparative analysis of three public housing sites with different characteristics indoors and outdoors, further showed how built-environment variations can alter the residents' behaviors and in turn, how those behaviors may significantly affect the indoor thermal conditions.

Results from Tables 3.6 and 3.7 showed that selected variables related to the outdoor environment, site and apartment attributes, personal characteristics and individual behaviors all significantly affect the indoor thermal conditions, and should all be part of regression analysis, considering improvements in the models' explanatory power. More specifically, the first hypothesis is supported, as an increase in the outdoor heat index results in higher indoor heat index, and certain site and apartment characteristics strengthen this relationship. However, the coefficient magnitudes are small, indicating that other influences are more important in explaining indoor thermal variations. In addition, the analysis approaches sites as bundles that include outdoor amenities and buildings with certain envelope characteristics but does not distinguish between the two. This is a ripe area for future work. Regarding the second hypothesis, it is confirmed that individual behaviors have the strongest influence on the indoor heat index and their coefficients show that they explain much of its variation, but this is not the case with the occupants' personal characteristics, although they may mediate occupant behaviors. Furthermore, while it is shown that those behaviors vary by indoor/outdoor resources (by site), only window and A/C opening can be considered adaptive behaviors, because interviews indicate that non-occupancy/leaving the apartment is exogenous, that is, not related to thermal conditions.

I find that the most interesting relationships are those of individual behaviors and the effect of site on the IHI, since they are consistently stronger than the rest. Therefore, the 2 main findings are:

Site is a strong determinant of indoor thermal conditions, but there is still substantial variation in IHI across apartments within each site.

Residents of site A do not have access to central air conditioning and some apartments have 1-3 small window A/C units, which, as reported in the baseline interviews, became available to them by Proceed, one local non-profit, identified in chapter 2. Their buildings have mainly passive cooling options and are surrounded by shady yards with sitting. Site

B characteristics are quite similar, although the building is younger, and apartments are not cross-ventilated. In contrast, residents of site C live in a LEED-rated building with a tight envelope and central A/C that is included in the rent, but with limited outdoor amenities. Overall, living in A translates to a higher indoor HI, while living in C means a lower HI, however, this is not a one-to-one relationship. Upon a closer examination of the indoor thermal performance by site, it is evident that within A and B, there are 2 different groups of apartments; the first follow the same trends as the outdoor heat index and have quite high values, which indicates that the indoor environments are inadequate in providing shelter. The second have a less variant trend and do not follow the OHI peaks, while having considerably lower values. Lastly, most of the C apartments belong to the second group, except for one.

In the case of sites A and B, it is logical to assume that the apartments with a "good" HI may have more window A/C units, better orientation or other apartment attributes that contribute to thermal comfort. However, comparisons between HI and apartment attributes show that while certain characteristics may partly explain those variations, they cannot provide the full picture, as they don't consider interactions among those attributes. For example, in the case of A4, the IHI trend was very good, but the apartment has only 1 window A/C unit, south-east orientation, and is not located in the corner. Those characteristics are similar to apartment A3 that had the worst HI of all A. Therefore, there is a clear implication of behavioral contributions to the IHI. This is further confirmed, when the seniors' adaptive responses are shown in Figure 3.8; there were differences in the use of windows, fans and clothing among residents of A, B and C. This makes intuitive sense: C residents do not need to engage in a wide range of actions, since the building envelopes can provide adequate support during heat, and when variations in the IHI are observed, this may be attributed to the personal characteristics of the occupant. Likewise, A residents don't have as much access to A/C, which makes them more adaptive. While convenient and affordable access to cooling is extremely important for low-income seniors during heat waves, as shown in the literature, power outages often coincide with heat waves, therefore, being adaptive and having nearby cooling options is equally important.

Window opening serves multiple purposes, only one of which is heat management.

Among the residents' behaviors examined in the regression analysis, window opening coefficients had the highest magnitude. The strength of this relationship makes sense, however, the direction may vary depending on the building type, the number and size of windows and the temporal pattern. Model 5 of Table 3.7 showed that in general, when at least one of the windows is open, the indoor heat index goes down, which was unexpected considering the opposite direction shown in the correlations of Table 3.6. First, the above considerations were not taken into account in the regression analysis and in addition, interaction terms were present. The interaction term referring to WO indicates that when the earlier IHI goes up, it significantly affects the occupant's window opening response, and when this interaction happens, it means an increase to the later indoor heat index. Same as with the site, this is not a straight-forward relationship, and it may better be examined along with other behavioral actions, such as A/C opening and apartment characteristics. Further analysis indicated that window opening for cooling purposes (proxied by increased opening when I/O ratio for HI is high) was only a statistically significant behavior in 2/3 of apartments, and it explained very little of the variance in window opening.

Figure 3.9 provided some additional insights for the WO patterns across and within sites, especially when combined with Figure 3.8. In general, occupants in site A opened their windows more than in site C. Within A, the apartment with the most WO variations was A5, which is the only one in the sample without any A/C unit, while the least window opening activity was seen in A4 that had the best IHI among all A. The same happened in the case of C3; it had the highest daily averages of WO and the highest IHI among all C. However, there were cases such as B11 and A1 with a medium WO activity and a relatively good HI. In simplified terms, it can be assumed that if windows are continuously open, this translates into a higher HI, but in some cases, if there is medium WO, it can indeed benefit the indoor thermal conditions. In addition, while it is generally recommended to close the windows during heat, some amount of daily ventilation is required for improved indoor air quality. Therefore, the focus should not be on the total percentage of WO, but on the particular time of day windows should remain open. To that end, it is clear that based on their IHIs, certain apartments, such as A4, A1 and B11, open their windows in an effective manner; however, it cannot be answered whether this effectiveness also applies to thermal comfort, as this would require closer attention to personal characteristics, such as the residents' thermal preferences.

As seen in the previous paragraphs, the question of reducing indoor heat stress and consequently improving health and well-being is complicated and includes multiple dimensions, from outdoor amenities, to building envelopes and to the residents' individual behaviors. Therefore, a multi-level approach is preferred. Overall, it is shown that access to proper cooling is beneficial, but it is not enough, as adaptation to heat involves multiple scales, within which, different individuals can affect the outcomes. It is also shown that more adaptive residents have higher chances of surviving the heat, which the literature confirms. To that end, Table 3.8 shows the senior residents' recommendations for apartment, building, site and neighborhood improvements, as reported in the interviews. It is once again shown that C residents are mostly satisfied with their indoor environments and do not consider site improvements important. In contrast, A and B residents provide a variety of indoor and outdoor recommendations, and while it makes intuitive sense for indoors, it also shows their recognition of the importance of outdoor amenities.

Table 3.8: Self-reported resident recommendations for apartment/building, site and neighborhood improvements.

	Elements	**A (N=11)**	**B (N=9)**	**C (N=4)**
Apartment	A/C	More storage for units	More and better units	
	Windows	Better insulation/reduce air drafts	More windows	
Building	Lobby/Cooling Room	Include more food events since there is kitchen available, so that occupants can use	Close it later	

		the space more frequently		
Site	Back/Front Yards	More greenery/ Make them safer	Add BBQ/More greenery Decrease dust More sitting/Bigger space	
	Gardens	Strengthen them with more flowers and plants		
Neighborhood	Park	Make them safer/reduce humidity-bugs	Make them safer/provide shady paths to reduce heat/provide better transportation/access	
	Shopping Stores		Add more and bigger in walking distance	
	Library	Provide a new one close by	Make them safer	
	Pool			Better access through transportation

Overall, this chapter has particularly important implications for long-term resilience and adaptation of elderly low-income communities to heat; it identifies pathways for local action that are cost-effective and easily accessible, such as promoting passive cooling techniques through a combination of site landscaping and amenities and related behavioral patterns. Further analysis should investigate the behavioral sequencing and its effect on indoor thermal conditions during heat waves. Study of links to indoor air quality would also be valuable, as it is also important for occupant health and well-being during heat waves and it may affect occupant behaviors such as window opening.

Chapter 4 Indoor Environments: Behaviors and Indoor Thermal and Air Quality Trade-offs

In response to the 2nd research question of this thesis, this chapter extends previous analysis on indoor environments and the seniors' summertime thermal experiences to examine the effectiveness of natural ventilation and window operation on simultaneously mitigating indoor heat while maintaining good indoor air quality[8]. The analysis is based on environmental and behavioral monitoring data from all apartments within the 3 public housing sites of Elizabeth, NJ, USA. Besides site characteristics and individual behaviors, such as smoking, mixed linear models highlight window opening as an important modifying factor of indoor thermal and air quality conditions. However, comparisons across apartments reveal that within "smoking" apartments, there is a thermal and air quality trade-off. The chapter concludes with a discussion of findings and implications for the interdependencies among (1) technological and behavioral dimensions of efforts to improve occupant comfort, and (2) thermal comfort and IAQ outcomes.

4.1 Background

Heat, Pollution and Health in Urban Environments

While extreme heat events are among the deadliest environmental hazards (Habeeb, Vargo and Stone, 2015; IPCC, 2014), degrading air quality is also a top threat to human health and welfare (IEA, 2019; WHO, 2014), with a documented relationship to

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[8] The information presented in this chapter comes from a co-authored research paper that is submitted for publication. The citation is: *Tsoulou, I., Andrews, C. J., Senick, J., He, R., & Mainelis, G. (Under Review). Summertime Thermal Comfort, Air Quality and Natural Ventilation in Senior Public Housing Residences.*

increased temperatures. Much research has shown that ground-level ozone (O_3), particulate matter (PM) and nitrogen dioxide (NO_2) increase with heat waves (HWs) (see Analitis et al., 2018; Kalisa et al., 2018; Meehl et al., 2018; Papanastasiou, Melas and Kambezidis, 2015; Patel et al., 2019; Yim et al., 2019). During the extreme European HW of 2003, Tressol et al. (2008) identified O_3 anomalies coinciding with higher temperature and humidity levels, while Mues et al. (2012) showed correlations among PM_{10} concentrations and high daily maximum temperatures all over Europe. Furthermore, several studies have linked heat-related mortalities to elevated pollutants (see Fischer, Brunekreef and Lebret, 2014; Patel et al., 2019; Scortichini et al., 2018).

The concurrent impacts of heat and air pollution on health and well-being are more evident in urban areas and populations due to urban heat island effects and multiple sources of pollutants (Habeeb, Stone and Vargo, 2015; Lenick et al., 2019; Sarrat et al., 2006; Steeneveld et al., 2018). In a cross-country study, Sera et al. (2019) found that heat-related mortality can be higher in cities with increased air pollution and limited green spaces, but also in places with higher inequality levels and lower access to health services. Neighborhoods with racial-ethnic minorities and socially isolated groups like low-income older adults are at higher risk from overheating (see Analitis et al., 2018; Bélanger et al., 2015; Kaiser et al., 2007; Semenza et al., 1996; Klinenberg, 2015) and are also more likely to be close to pollution sources, like factories and highways (see Hajat, Hsia and O'Neill, 2015; Miranda et al., 2011; Tessum et al., 2019).

City-level action plans in response to hot weather may include immediate responses, such as community engagement and emergency preparedness for vulnerable groups or weather advisories with warning alerts, but also long-term adaptation strategies, such as changes in the built environment, including reduction of impervious surfaces and urban greening (Harlan and Ruddell, 2011; He et al., 2019). Yet, urban-level strategies can only partly assist in reducing heat and air pollution exposures, considering that people spend about 90% of their time indoors (ASHRAE, 2016; Klepeis et al., 2001; Spalt et al., 2016) and that they may experience different conditions indoors from outdoors (Tsoulou et al., 2020). In fact, findings from past heat wave disasters indicate that the majority of heat-related deaths have occurred indoors (Quinn et al., 2014).

Determinants of Thermal Comfort and Air Quality in Indoor Environments

While there are close links between indoor and outdoor environmental conditions, (see Challoner and Gill, 2014; Lundgren Kownacki et al., 2019; Srivastava and Jain, 2003; Walikewitz et al., 2018), the strength of this relationship, and consequently much of individual exposure to indoor heat and pollutants, depends heavily on building characteristics and occupant activities. These factors are in turn, subject to social, economic and demographic considerations in residential environments.

Building characteristics such as dwelling size, the type of heating, ventilating and air-conditioning (HVAC), building tightness and insulation, floor, orientation, shading, and the existence of carpets, can modify indoor environmental quality (IEQ) (Adamkiewicz et al., 2011; Becher et al., 2018; Ben-David and Warling, 2018; Lundgren Kownacki et al., 2019; Thomas et al., 2019). However, these features may be different for low-income residents, who often live in less tight, naturally ventilated multi-family buildings with lower construction standards and with more occupants/area (Baxter et al., 2007; Challoner and Gill, 2014; Klepeis et al., 2017).

IEQ is also affected by occupant behaviors (OB) such as time spent at home (occupancy), and operating windows, fans and air-conditioning (A/C) (Hong et al., 2017; Quinn et al., 2014; Tsoulou et al., 2020). Cleaning practices, smoking, cooking with gas, lighting candles/incense and having pets have further been linked to indoor pollutants (see Baxter et al., 2007; Klepeis et al., 2017; Urso et al., 2015; Ye et al., 2017). But these activities also depend on the availability of resources and the degree of problem conceptualization, as well as on personal factors, such as habitual behaviors (Lundgren Kownacki et al., 2019; O'Brien and Gunay, 2014).

Indoor-level strategies to reduce the risk of overheating range from a focus on mechanical ventilation and the use of A/C to passive measures that emphasize the importance of natural ventilation and the operation of windows (Jeong et al., 2016; Nahlik et al., 2017). Along with other passive strategies, natural ventilation has been shown to have a positive impact on reduced summer energy use and thermal comfort (see Bayoumi, 2017; Du and Pan, 2019; Van Hoof et al., 2016). With regard to window operation, Jeong et al. (2016) and Park and Kim (2012) have further shown that it may be the most preferred way for residents to control thermal conditions even in mechanically ventilated buildings. Lastly, it may be the only available option for households dealing with affordability issues (Kingsborough et al., 2017; Tsoulou et al., 2020).

While the operation of windows for natural ventilation can be a potentially effective indoor strategy to mitigate overheating, it is also an important determinant of indoor air quality (IAQ) (Mavrogianni et al., 2015) and these relationships are often conflicting. In some instances, it has been shown that window opening (WO) to improve thermal comfort may increase indoor $PM_{2.5}$ concentrations coming from outdoor sources (see

Taylor et al., 2014). Inversely, opening the windows to reduce pollutant concentrations from indoor sources may also lead to increased heat coming from outdoors. Residential activities, such as WO, may be driven by a range of environmental stimuli that happen at the same time. Yet, most observational studies of IEQ focus on single and not multi-domain influences on WO (Schweiker et al., 2020).

4.2 Methods

This chapter extends the analysis of chapter 3 on the seniors' indoor thermal experiences, to focus on the relationship between natural ventilation and indoor thermal and $PM_{2.5}$ performance, and on the potential of WO in mitigating indoor heat while maintaining good IAQ. The selection of $PM_{2.5}$ as the pollutant of interest is due to its multiple adverse health effects, as well as its documented connection to elevated temperatures (Analitis et al., 2018; US EPA, 2020).

Based on hypothesis 3 of the 2nd research question, outlined in Table 1.5, this chapter's objective is to improve understanding about the relationship between thermal comfort, air quality and the operation of windows. To this end, it seeks to:

- document and evaluate indoor thermal and $PM_{2.5}$ levels experienced by low-income seniors in parallel,
- observe variations across and within sites and identify indoor sources of overheating and pollutants,
- examine closely the effect of natural ventilation and related WO behaviors on these variations and identify thermal comfort and air quality trade-offs, and

- suggest suitable ventilation strategies to reduce overheating and $PM_{2.5}$ exposures for different types of buildings and occupants.

Data Analysis

The analysis starts by simultaneously exploring the indoor thermal conditions and $PM_{2.5}$ concentrations inside senior residences and evaluates exceedances of certain thermal and air quality thresholds according to known standards and guidelines summarized below. Then, variations and potential sources of overheating and pollutants across and within sites are analyzed, followed by an identification of the “natural clusters” through ANOVA. Next, natural ventilation patterns for different clusters are observed and the effect of window opening behaviors on each unit through mixed linear models is examined, while thermal comfort and air quality trade-offs are analyzed. The last part takes a closer look at certain apartments through time-series analysis, in order to suggest effective passive ventilation strategies for reducing indoor overheating and $PM_{2.5}$ exposures.

Criteria for Indoor Overheating and Pollution

Same as in the previous chapters, the analysis of indoor thermal performance and the assessment of overheating is based on the heat index (HI) and on the ASHRAE Standard 55 recommendation for residential summer temperatures in the range of 24 - 27 C (75 - 80.5 F) and indoor humidity less than 65%. In the case of indoor air quality, the focus is on $PM_{2.5}$, which is defined as one of the criteria air pollutants by US EPA (2020). Currently there are no specified thresholds for indoor $PM_{2.5}$ concentrations. Therefore, the analysis relies on recommendations from US EPA (2020) for outdoor $PM_{2.5}$ levels, based on which the annual mean of 12 ug/m^3 and daily mean of 35 ug/m^3 shall not be exceeded.

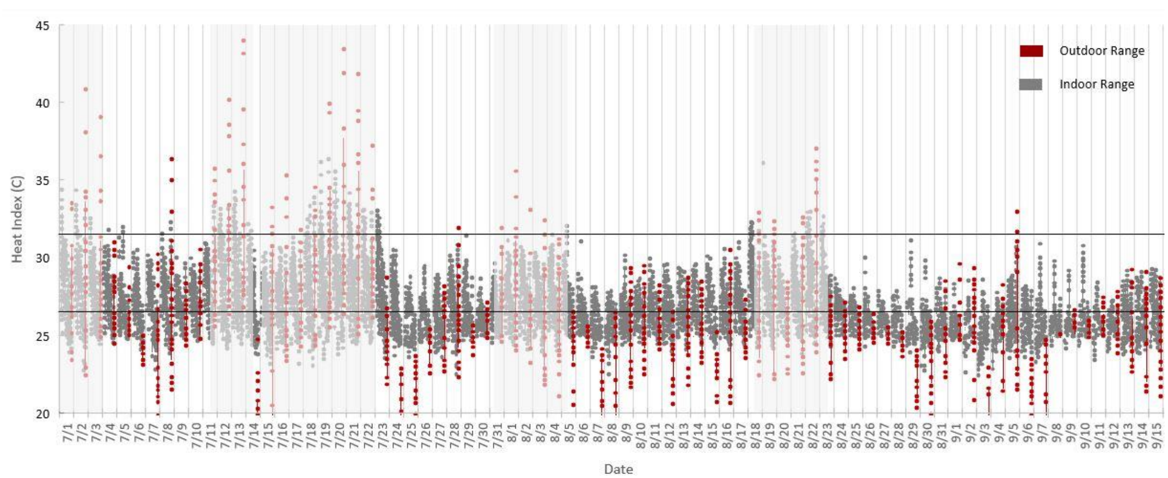
As a second source of guidance, WHO (2013) recommends an annual mean of no more than 10 ug/m^3 and a daily mean of less than 25 ug/m^3.

4.3 Results

Indoor Thermal and Air Quality Conditions

Figure 4.1 summarizes the indoor HI range for all apartments (with the 5 HW periods highlighted) and shows the ASHRAE threshold of 27 C. 32% of all measurements exceeded 27 C, while 99% exceeded 24 C and this happened both during HW periods and on regular summer days. Results from Figure 4.1 and Table 4.1 suggest that while higher outdoor HI results in higher indoor HI, exposure to indoor overheating may also be subject to additional factors, such as building characteristics and occupant behaviors.

Figure 4.1: Outdoor and indoor HI ranges during summer 2017 based on environmental monitoring with HW periods highlighted.



As shown in Figure 4.2, outdoor $PM_{2.5}$ levels were also elevated in Elizabeth during the monitoring period. Concentrations exceeded the US EPA threshold of 12 ug/m^3 in several instances and this coincided with 4 out of the 5 HW periods. Yet, there appears to be no direct link to the extremely elevated indoor $PM_{2.5}$ concentrations. Specifically, 45% of all measurements were found to be above 12 ug/m^3, 21% above 35 ug/m^3 and more than 50% above 10 ug/m^3. Table 4.1 further shows that the average and maximum outdoor $PM_{2.5}$ levels were considerably lower than the corresponding indoor $PM_{2.5}$, which is a strong indicator that indoor sources may play a role.

Figure 4.2: Outdoor and indoor $PM_{2.5}$ ranges during summer 2017 based on environmental monitoring with HW periods highlighted.

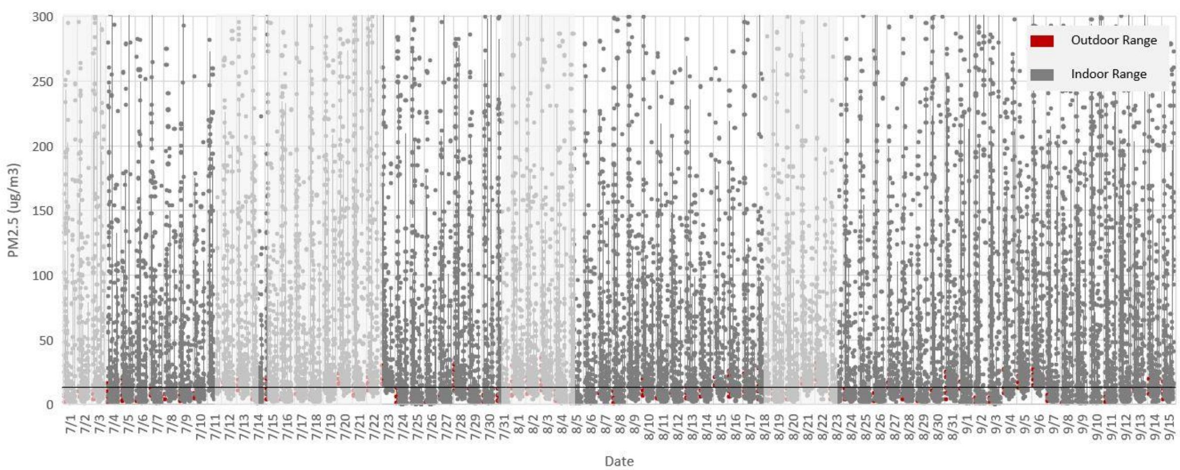


Table 4.1: Summary of HI and $PM_{2.5}$ measurements (average, minimum and maximum values) during summer 2017.

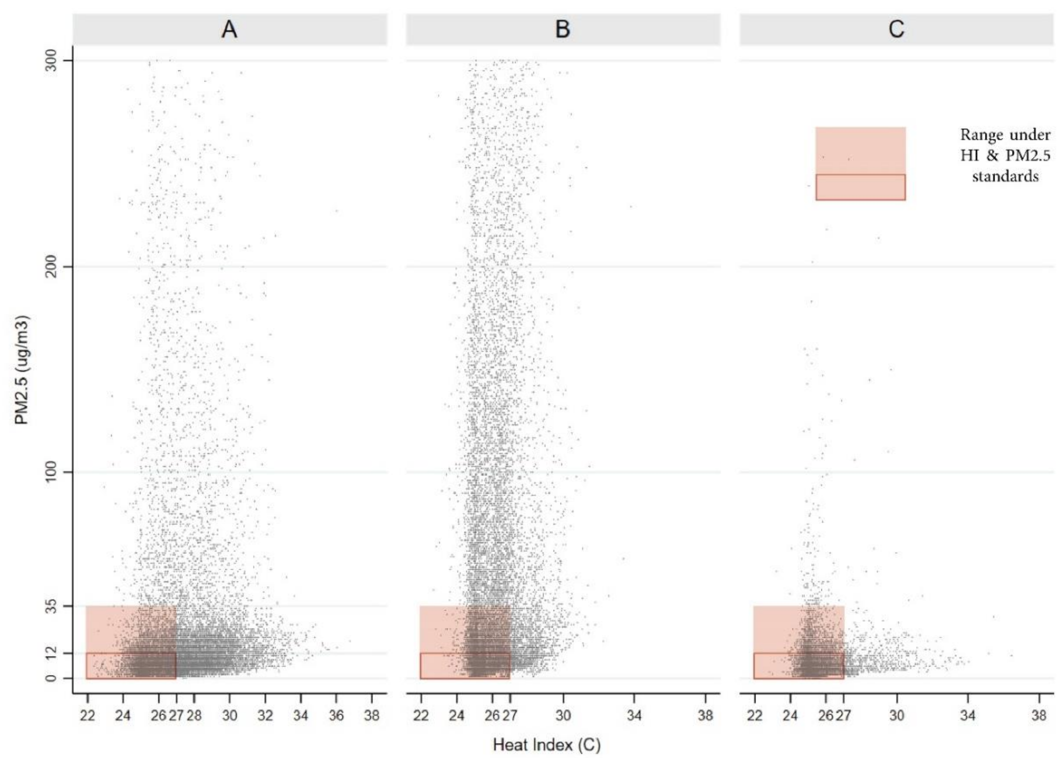
Heat Index (C)		$PM_{2.5}$ (ug/m^3)	
Outdoor Range	Indoor Range	Outdoor Range	Indoor Range
26 (17-49)	27 (22-37)	9 (1-36)	39 (0-1726)

Variations Across and Within Sites

In order to identify differences in indoor thermal and air quality performance and potential sources of variation, sensor measurements were grouped by site. As shown in

Figure 4.3, apartments of site C experienced the best indoor conditions based on HI and $PM_{2.5}$ ranges, with 35% of measurements falling within the 1^{st} acceptable area[9] and 43% within the 2^{nd}[10].The worst ranges can be seen in site B, with only 13% of measurements within the 1^{st} area and 24% within the 2^{nd}, followed by site A that had slightly better performance, mostly due to lower $PM_{2.5}$ concentrations (23% of measurements were under the 1^{st} area and 34% within the 2^{nd}).

Figure 4.3: Indoor HI and $PM_{2.5}$ ranges during summer 2017 based on environmental monitoring grouped by site. Shaded areas indicate the 1^{st} and 2^{nd} acceptable areas constructed based on ASHRAE and US EPA thresholds for HI and $PM_{2.5}$.



[9] 1^{st} acceptable area based on the ASHRAE threshold for HI<27 C and the US EPA threshold for $PM_{2.5}$<12 ug/m^3.
[10] 2^{nd} acceptable area based on the ASHRAE threshold for HI<27 C and US EPA 2^{nd} threshold for $PM_{2.5}$<35 ug/m^3.

1-way ANOVA tests (through pairwise comparisons with Tukey post-hoc test and 95% confidence level) further confirmed statistically significant variations between the 3 sites both in terms of HI (F (2, 3,373), p=0.00) and $PM_{2.5}$ (F (2, 1,756), p=0.00). Table 4.2 shows that the biggest difference in HI was between sites A and C, with A being significantly warmer. In the case of $PM_{2.5}$, the biggest difference was between B and C, with B having the highest $PM_{2.5}$ concentrations.

Table 4.2: 1-way ANOVA tests for statistical differences in indoor HI and $PM_{2.5}$ means among sites.

1-way ANOVA of HI by Site

Site	Mean	St.Dev.	Freq.
A	27.21	1.87	19,773
B	26.11	1.20	15,536
C	25.74	1.29	7,333

	SS	df	MS	F	p
Between groups	16,418.01	2	8,209.00	3,373.51	0.00
Within groups	103,756.58	42,639	2.43		

Bartlett's test for equal variances: chi2(2) = 3.8e+03 Prob>chi2 = 0.00

1-way ANOVA of $PM_{2.5}$ by Site

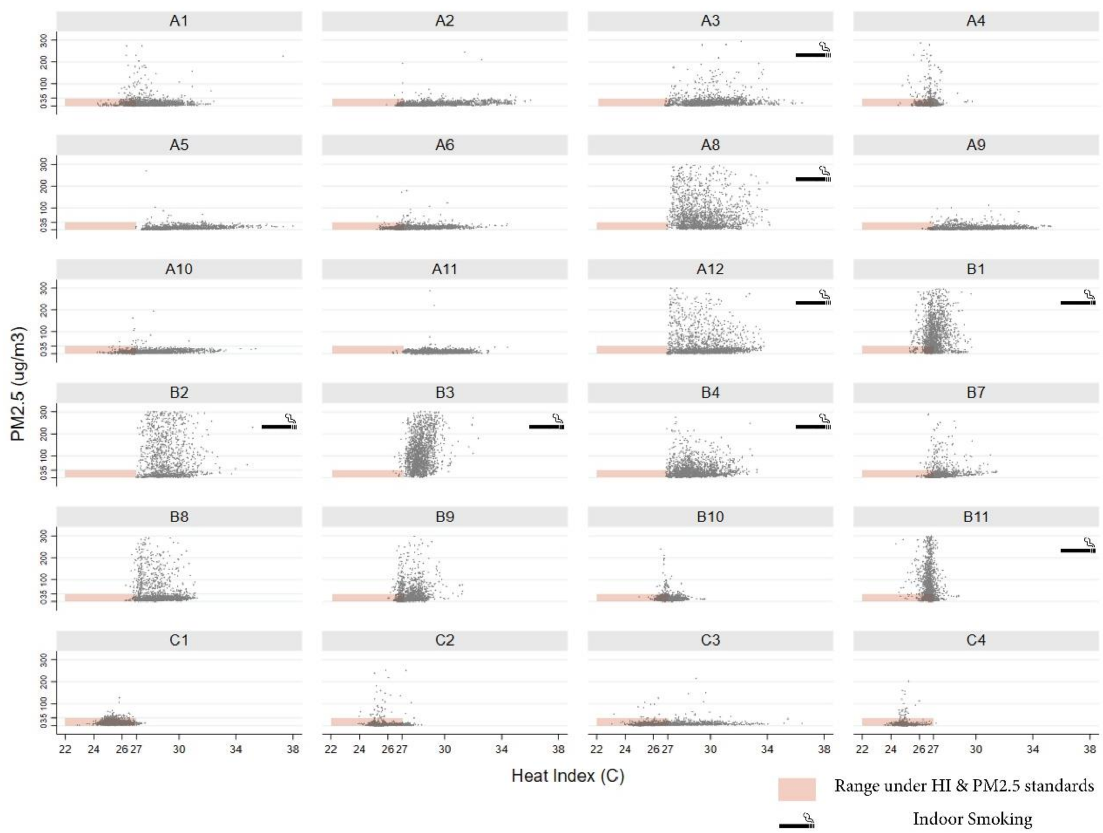
Site	Mean	St.Dev.	Freq.
A	25.82	71.02	19,344
B	69.05	108.38	15,542
C	9.42	19.09	7,126

	SS	df	MS	F	p
Between groups	23,641876.80	2	11,820938.40	1,756.31	0.00
Within groups	282,750819	42,010	6,730.56		
Total					
Bartlett's test for equal variances: chi2(2) = 1.8e+04 Prob>chi2 = 0.00					

As described in earlier chapters, the low HI performance of apartments within site A is not surprising and it can be explained by the absence of central A/C and the poor building fabric, but it may also link to cross-ventilation and the occupants' window opening patterns. Likewise, the extreme $PM_{2.5}$ concentrations of apartments in site B can be attributed to indoor sources and the occupants' behaviors, such as indoor smoking. Specifically, and as shown in Table 13 of Appendix C, residents smoke in more than half of the sample apartments in B, while indoor smoking is prohibited in site C. Yet, the poor IAQ levels in B may also indicate limited ventilation.

While some differences in indoor HI and $PM_{2.5}$ can be explained by site-specific characteristics, Figure 4.3 additionally suggests that there is some unexplained variation within each study site. Figure 4.4 and Table 4.3 aim to provide additional insights by zooming into each sample apartment to investigate its indoor thermal and IAQ performance. Table 4.4 further presents statistically significant differences for $PM_{2.5}$ between "smoking" and "nonsmoking" apartments through a 1-way ANOVA test (through pairwise comparisons with Tukey post-hoc test and 95% confidence level).

Figure 4.4: Indoor HI and $PM_{2.5}$ ranges during summer 2017 based on environmental monitoring grouped by apartment. Shaded areas indicate the 1st and 2nd acceptable areas constructed based on ASHRAE and US EPA thresholds for HI and $PM_{2.5}$.



As previously, Figure 4.4 suggests much better thermal and IAQ levels for all apartments within site C, with the exception of C3 that had a high HI median and range. Since this cannot be attributed to poor building characteristics, it may be an indicator of window opening (below).

Within site A, most apartments had good $PM_{2.5}$ levels except from A8 and A12 (where indoor smoking occurred), but this was not the case with HI, where almost all apartments exceeded the threshold of 27 C regularly. A5, which is the only apartment in the sample without an A/C unit (see Table 14 of Appendix C), had a median HI of 28 C and, along with apartment A3, experienced the hottest conditions of all 24 units. Yet, A4 is an exception to these findings (although, based on Table 14 of Appendix C, apartment characteristics such as orientation and number of A/C units are similar to A3 and A5), with the percentage of measurements within the 1st and 2nd acceptable areas being close to those of apartments within C. Another interesting observation concerns units A3 and A12, whose $PM_{2.5}$ levels were lower than other "smoking" apartments (with medians of 15 and 16 ug/m^3 respectively). For A3, this may be partly attributed to passive smoking as was indicated from the resident in the interviews.

A reverse trend can be observed in apartments of site B. Most apartments had a better HI (except B2, which is located on the 11th floor) but considerably worse $PM_{2.5}$ levels compared to apartments in A. While this can be explained by indoor smoking in B1, B2, B3, B4 and B11, this is not the case with B8 and B9 that had relatively small medians but a wide range of $PM_{2.5}$ concentrations. This is an interesting finding and it may relate to additional indoor sources and/or the units' ventilation patterns. Lastly, an exception is apartment B10, which had the best HI and $PM_{2.5}$ performance among all Bs, based on the percentage of measurements within the 1st and 2nd acceptable areas.

Table 4.3: Descriptive statistics and percentage of HI and $PM_{2.5}$ measurements by apartment during summer 2017 that fall within the 1st and 2nd acceptable areas.

	Combined HI and $PM_{2.5}$ Performance		**HI (C)**	**$PM_{2.5}$ (ug/m^3)**
	1st acceptable area (%)	2nd acceptable area (%)	Median (Min-Max)	Median (Min-Max)
A1	25	36	26 (22-36)	9 (1-866)
A2	21	25	27 (24-35)	8 (0-246)

A3	5	9	28 (25-35)	15 (0-1530)
A4	38	46	25 (23-28)	7 (0-966)
A5	8	9	28 (25-37)	8 (0-482)
A6	27	35	26 (23-33)	8 (1-179)
A8	2	6	28 (25-33)	51 (0-772)
A9	17	20	28 (24-34)	7 (0-171)
A10	27	33	26 (22-34)	7 (0-533)
A11	8	12	28 (25-33)	7 (0-467)
A12	9	12	27 (25-32)	16 (1-756)
B1	8	17	25 (24-29)	62 (1-1325)
B2	5	7	27 (25-34)	81 (1-1726)
B3	1	6	27 (25-31)	91 (2-491)
B4	9	19	27 (25-32)	22 (1-346)
B7	23	40	26 (24-31)	11 (0-923)
B8	15	23	27 (24-30)	13 (0-742)
B9	24	36	26 (24-30)	13 (0-641)
B10	24	48	25 (23-28)	11 (0-357)
B11	11	23	25 (23-27)	42 (0-1716)
C1	28	48	25 (23-28)	10 (1-126)
C2	43	46	25 (24-28)	4 (0-538)
C3	24	28	27 (23-36)	6 (0-634)
C4	44	49	25 (24-27)	5 (0-352)

Table 4.4: 1-way ANOVA tests for statistical differences in indoor $PM_{2.5}$ means among smoking and nonsmoking apartments.

1-way ANOVA of $PM_{2.5}$ by Smoking-Nonsmoking Apartments

Site	Mean	St.Dev.	Freq.		
Nonsmoking	16.78	49.62	29,420		
Smoking	91.00	121.34	12,593		
	SS	df	MS	F	P
Between groups	48,584626.40	1	48,584626.40	7,917.09	0.00
Within groups	257,808070	42,011	6,136.68		

Bartlett's test for equal variances: chi2(2) = 1.6e+04 Prob>chi2 = 0.00

Window Opening Patterns: Thermal and Air Quality Trade-Offs

The analysis so far has shown that overall site characteristics and related building fabric play an important role for indoor overheating, while smoking can highly impact indoor pollutant levels. Yet, there remains some unexplained variation in selected apartments from each site, both for HI and $PM_{2.5}$, which may be related to occupant activities, such as window operation. Instances include apartments A4 and B10, which had among the best indoor HI and $PM_{2.5}$ levels, A3 and C3 with surprisingly high HIs, B8 and B9 that had elevated $PM_{2.5}$ without any indoor smoking reported and A12 with somewhat low $PM_{2.5}$ levels for a “smoking apartment”. The analysis that follows examines the potential effect of passive ventilation and window opening on indoor thermal and air quality performance.

Figure 4.5 presents window opening patterns for each study site. As expected, residents of the green building with central A/C in site C relied much less on WO than those residing in A and B. Percentages by room further suggest that within site A, kitchen and living room windows were more open than in bedrooms, while the reverse happened in site B. This may indicate temporal variations, as bedroom WO might have been used for night cooling, while kitchen and living room WO for daytime cooling.

Figure 4.5: Percentage of window opening during summer 2017 based on behavioral monitoring grouped by site.

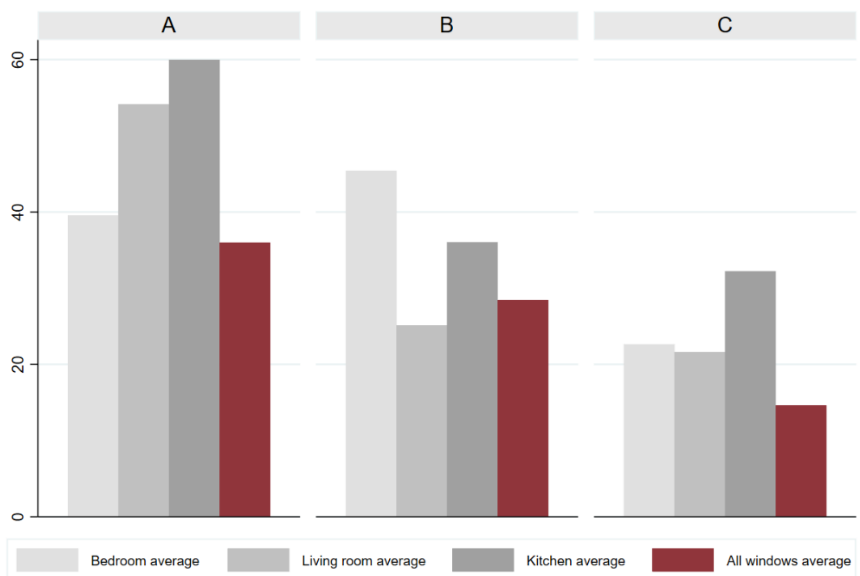
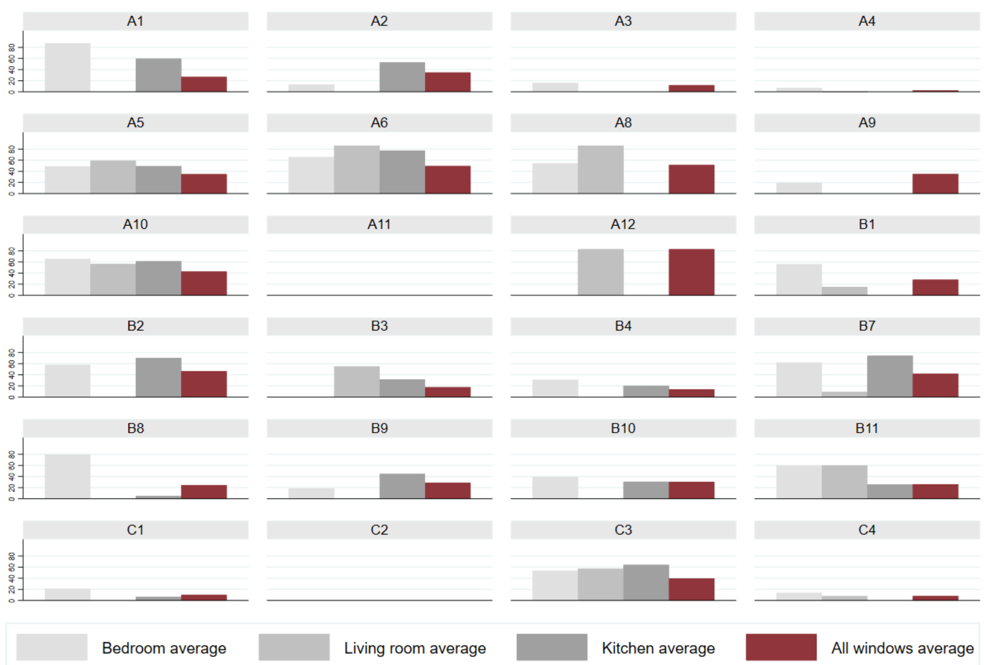


Figure 4.6 presents window opening patterns by apartment. If we are to examine the effect of WO on $PM_{2.5}$ alone, we can conclude that in the absence of significant outdoor sources, natural ventilation generally benefits IAQ and this can explain the lower $PM_{2.5}$ levels of apartment A12 compared to other "smoking" apartments (median of 16 ug/m^3 based on Table 4.3) or the higher $PM_{2.5}$ levels of apartments B8 and B9 compared to other "non-smoking" apartments. Yet, when considering HI as well, we can see that this

is a not straight-forward relationship. In some cases, frequent WO can benefit indoor HI, such as in apartments A6 and A10 (with a median of 26 C based on Table 4.3) or limited WO can result in a higher HI, such as in A3. However, in some other cases, a reverse trend is observed; more WO means a higher HI for apartment C3, and less WO means a better HI for apartment A4. Therefore, for selected units, there is a thermal and air quality trade-off with natural ventilation and the way residents operate their windows that needs to be examined more closely.

Figure 4.6: Percentage of window opening during summer 2017 based on behavioral monitoring grouped by apartment.



To explore further the relationship between window opening, thermal comfort and IAQ, a 3-level mixed model with random effects was fitted (with level 3 the site and level 2 the apartment, since apartments are nested within sites). The model shows the effect of WO on indoor HI and $PM_{2.5}$, while accounting for the outdoor HI, as well as the effect of WO on indoor $PM_{2.5}$, while accounting for the outdoor $PM_{2.5}$. Based on the results shown in Table 4.5, overall, there is indeed a thermal and air quality trade-off with natural ventilation, but this does not relate to bedroom window opening. Only the percentage of kitchen and living room WO had a significant positive effect on indoor HI and a significant negative effect with a much higher magnitude on indoor $PM_{2.5}$.

Table 4.5: 3-level mixed models (linear regression with random effects) for indoor HI and $PM_{2.5}$ during summer 2017.

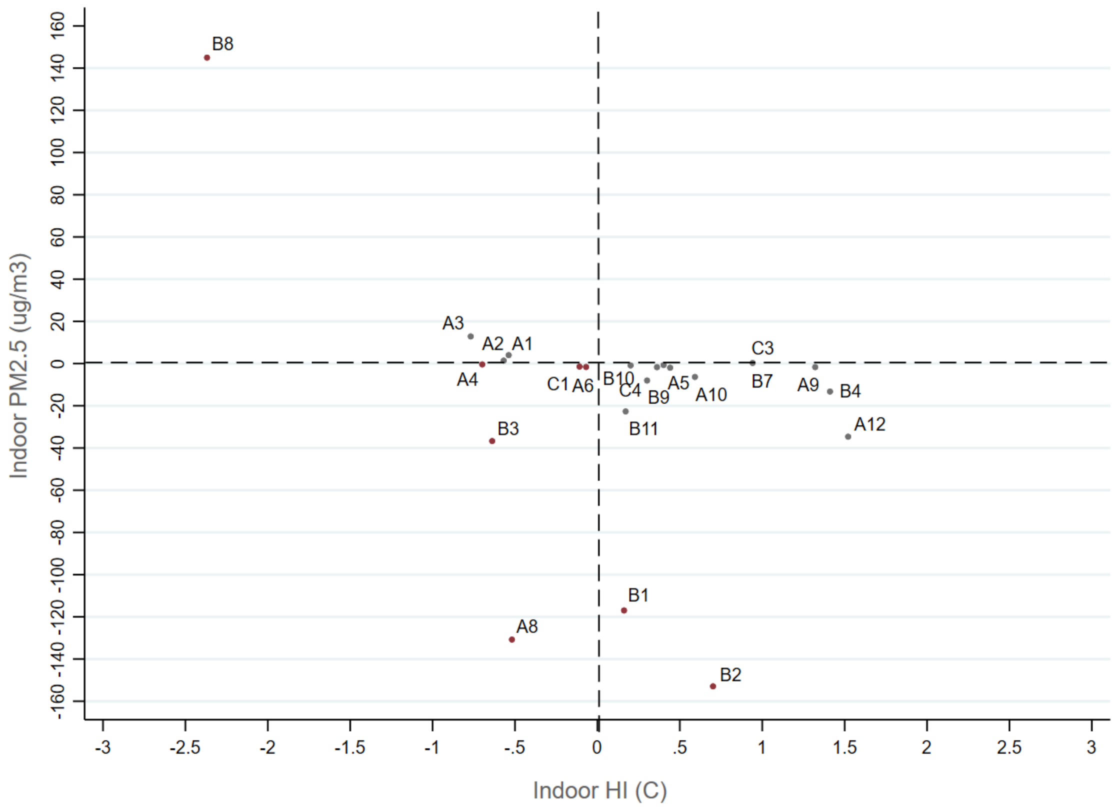
		Coefficient (Standard Error) * statistically significant at the p=0.05 level.
HI (1 hour later[11])	Outdoor HI	0.13* (0.0)
	% of Bedroom WO	0.13* (0.03)
	% of Kitchen and Living Room WO	0.30* (0.03)
	Constant	22.79* (0.31)
	Log Likelihood	-30,523.89
	P	0.00
$PM_{2.5}$ (1 hour later[12])	Outdoor $PM_{2.5}$	0.79* (0.07)
	% of Bedroom WO	0.47

[11] In order to better understand the effect of the outdoor HI and WO on indoor HI, the dependent variable is at one time step later (1 hour later).
[12] In order to better understand the effect of the outdoor $PM_{2.5}$ and WO on indoor $PM_{2.5}$, the dependent variable is at one time step later (1 hour later).

		(1.55)
	% of Kitchen and Living Room WO	-29.60*
		(1.83)
	Constant	37.24
		(14.48)
	Log Likelihood	-101,724.46
	P	0.00

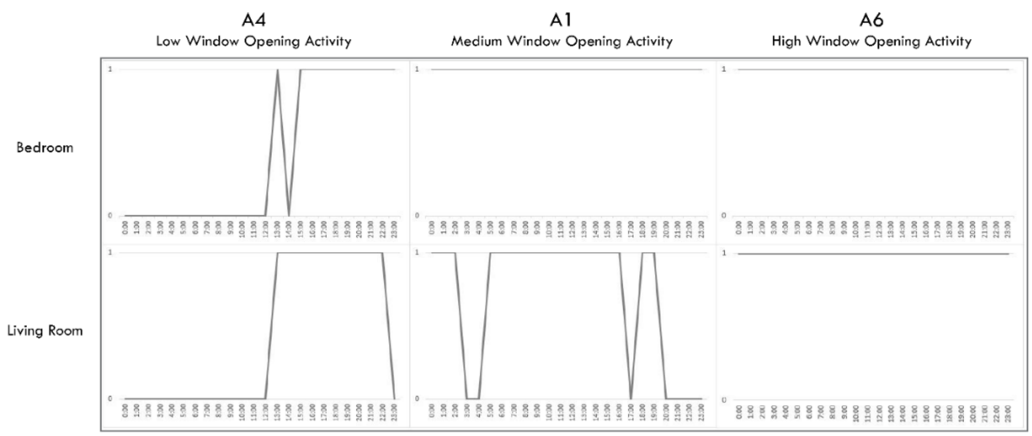
However, as seen previously, certain WO patterns may improve both thermal comfort and IAQ. In order to better understand where these trade-offs occur, indoor HI and $PM_{2.5}$ of each apartment were regressed against the corresponding WO, as well as the outdoor HI and $PM_{2.5}$. The results shown in Figure 4.7 (and in Table 13 of Appendix C) suggest that in the case of the green building apartments of site C, when an active window opening pattern occurred (see unit C3), it resulted in higher indoor thermal performance, but did not significantly affect IAQ. In apartments with a poorer building fabric, such as those of A and B, WO had a more significant impact on both thermal comfort and IAQ. Within these sites, the thermal and air quality trade-off was more pronounced in apartments of B and in the "smoking" units (especially B1 and B2) and was experienced by 50% of all sample apartments. On the other hand, WO benefited both HI and PM2.5 in 5 apartments (A4, A6, A8, B3 and C1).

Figure 4.7: Percentage of kitchen and living room WO coefficients for indoor HI and $PM_{2.5}$: linear regression results.



Interestingly, this trade-off was absent in about half of the A apartments, where the indoor HI benefited from the residents' window opening strategies. The results of Figure 4.7, when combined with the WO patterns of each apartment shown in Figure 4.6, illustrate that natural ventilation in certain rooms and at certain times of the day can improve the heat index and consequently increase thermal comfort. Whether a conservative approach through a low WO activity throughout the day (see unit A4), a medium one with frequent WO changes (see unit A1), or a more active WO strategy (see unit A6) with continuous bedroom ventilation and WO in the kitchen and living room at early mornings and late afternoons can result in ranges within the acceptable areas with avoidance of overheating and air pollution indoors. Then, natural ventilation can be adjusted based on an apartment's specific characteristics, such as the existence of cross ventilation and number of windows, the façade(s) orientation and the floor number. As an illustration of different yet successful WO patterns, Figure 4.8 shows the hourly variations for 3 apartments within site A.

Figure 4.8: Temporal patterns of bedroom and living room WO in 3 apartments of site A. [1 indicates window opening and 0 indicates window closing.]



4.4 Discussion

The findings of this chapter suggest that indoor environmental conditions and consequently exposure to overheating and pollutants highly depend on building characteristics and the building fabric, but are also subject to the residents' individual behaviors, such as indoor smoking. Natural ventilation and associated window opening patterns can significantly alter these exposures, either by reducing both indoor $PM_{2.5}$ concentrations and the heat index or through resulting in a thermal and air quality trade-off.

In the case of IAQ, the results, specifically Figures 4.2, 4.4 and Tables 4.1, 4.4, showed that when certain indoor sources are present, such as smoking, they drive elevated $PM_{2.5}$ concentrations, while outdoor sources and the associated role of building fabric are of secondary importance. As shown in Table 4.5 and Figure 4.7, overall, opening the windows has a positive impact on $PM_{2.5}$ exposures, and this effect becomes much higher in magnitude within "smoking" apartments. Therefore, there is a clear distinction between smokers and non-smokers, and based on Table 4.3 and Figures 4.4 and 4.6, for "smoking" apartments, a high WO activity is recommended, while in the absence of indoor smoking, a medium WO activity, such as kitchen ventilation in the afternoon, which may coincide with cooking activities, can result in lower indoor $PM_{2.5}$ levels.

With regard to indoor thermal comfort, results from Figures 4.1, 4.3 and Tables 4.2, 4.3 showed that outdoor heat and the role of building fabric as a protective measure are of primary importance, which suggests a distinction of the sample apartments by site (older versus newer buildings). Overall, natural ventilation has a significant impact on the indoor HI (see Table 4.5 and Figure 4.6), but the WO time of day and the selection of particular windows to be opened are key considerations. Based on the results shown in Table 4.3 and Figures 4.4-4.8, for a newer building and given that the residents can afford to operate the A/C, a lower WO activity in the common spaces (kitchen and living room) is recommended for improved thermal comfort, complemented by medium bedroom WO for night ventilation. For older buildings with a poorer building fabric without central A/C, an effective WO strategy may depend on additional considerations, such as the existence of cross ventilation and the number of windows, the floor number and the façade(s) orientation; either a low WO activity with bedroom ventilation in the night time or a more active WO strategy with ventilation in the bedroom and common spaces (with avoidance during the hottest hours - noon) can be effective.

When examining natural ventilation in the context of both thermal comfort and IAQ, results from Figure 4.7 showed that often there is a thermal and air quality trade-off that needs to be considered. The type, amount and timing of window opening and the extent to which it can be effective in simultaneously reducing overheating and pollutant concentrations heavily depend on the existence of indoor pollutant sources, the outdoor environment and building characteristics. In the absence of significant indoor pollutant sources, a medium WO strategy can be beneficial for both indoor HI and $PM_{2.5}$ in older buildings, while limited WO is recommended for newer buildings with advanced building standards and mechanical ventilation options. However, when indoor sources such as smoking cannot be avoided either in new or older buildings, a very active WO strategy appears to be necessary for reducing $PM_{2.5}$ concentrations, even if this translates into a higher indoor HI.

Overall, this chapter stresses the importance of exploring cost-effective interventions such as natural ventilation, but also presents associated complexities when examining effects on more than one IEQ domain. Additionally, results support the position that city-level policy making for housing should incorporate indoor strategies to reduce environmental exposures. This emphasis on residential environments and on ventilation strategies also comes in response to the global COVID-19 pandemic, which requires immediate action for the protection of vulnerable groups and especially older adults. This work suggests that natural ventilation for improved IEQ should be part of a spectrum of policies that can be addressed by municipal and state officials, as well as by building code professionals. Undoubtedly building homes with sufficient ventilation should be a requirement, since window opening can work well as a means to cool off and clean the indoor air for a regular “non-smoking” dwelling on a regular summer day. It is also very suitable in an affordable residential housing context.

Yet, as this chapter illustrated, there are limitations in the effectiveness of window opening during extreme heat conditions and when there are significant indoor pollutant sources, such as smoking. It is therefore best when it is coupled with educational and technological interventions. For example, while it is intuitive to operate the windows in response to heat, this is not necessarily the case with indoor pollutants. Educating residents about the importance of indoor air quality and effective ways to open their windows has minimal cost and can be useful in the long term. Then, WO can be coupled with technological interventions, such as using air purifiers and installing high-efficiency filters, which can also work well in the long term and have faster results, however, they may require higher capital and electricity costs.

Chapter 5 Outdoor Environments: Site Amenities and Senior Activities

Already from the preliminary findings of chapter 2, it is established that both indoor and outdoor resources are important in assisting low-income seniors cope with heat. The exploration of indoor environments in chapters 3 and 4 further highlighted that among other factors, site characteristics, such as landscaping and other nearby affordances may affect indoor environmental conditions, through altering the residents' activities, such as indoor occupancy patterns. This chapter grasps on these findings and extends outdoors to investigate the role of adjacent amenities for heat adaptation in the 3 public housing sites of Elizabeth, NJ, USA, which corresponds to the 3rd research question of this dissertation[13]. The analysis examines how and why residents interact with their immediate outdoor environments, through documenting outdoor destinations and associated temporal patterns. Pearson correlations and logistic regressions illustrate the relative effect of outdoor and indoor thermal conditions and site characteristics on indoor occupancy. The chapter concludes with a discussion of findings.

5.1 Background

Outdoor Environments: Landscape Design and Amenities

The literature, analysis and findings presented in previous chapters of this work have already established the importance of indoor environments and household characteristics for older adults coping with high summertime temperatures. The availability of functioning air-conditioning has been deemed essential; yet, in the case of low-resource

[13] The analysis presented in this chapter is prepared for a journal submission.

communities, it was shown that A/C is neither an accessible affordance nor enough to ensure seniors' thermal comfort, considering cost and effectiveness constraints, as well as possible power outages during heat waves. Towards that end, more accessible alternative building adaptations have been examined, such as passive cooling and natural ventilation, which further highlighted that importance of occupant behaviors in heat adaptation.

Besides indoor-level approaches, researchers and practitioners have also turned their efforts to less traditional, outdoor-level modifications and the effectiveness of features related to landscaping and greening to improve thermal comfort at local spatial scales. A vast body of literature focuses on the effects of urban green spaces on microclimate conditions, including the reduction of ambient temperatures, UHI effects and urban energy, and the improvement of ambient air quality. It has been shown that trees, grass, shrubs and vegetation can be effective cooling strategies particularly at local scales, and yield energy savings for residential buildings through shading (see Akbari et al., 2001; Bowler et al., 2010). High tree coverage can further contribute to lower ambient PM levels in urban settings (see Chen et al., 2016; Chen et al., 2019; Nowak, Crane and Stevens, 2006). Similar outcomes have been shown for additional urban green strategies, such as parks, green walls and green roofs, which have been linked to lower levels of pollutants and summer temperatures (see Currie and Bass, 2008; Qin et al., 2019; Yin et al., 2011).

Epidemiological research has further examined health benefits of urban greening, ranging from recreation and physical activity to social cohesion and reduced heat-related mortality. Hartig et al. (2014) discussed pathways to link nature-based solutions with human health, including stress recovery, physical activity and social contacts. Likewise, Fong et al. (2018) summarized literature on the relationship between greenness and health in general and found strong evidence of associations for higher greenness with improvements in physical activity and lower depressive symptoms and mortality rates.

Some studies have also focused on the extent to which urban green spaces and an overall supportive neighborhood environment can improve health outcomes specifically for older adults, including how to cope with elevated summer temperatures and reduce heat stress. These studies have repeatedly underlined the importance of additional features for seniors compared to younger adults, such as providing a variety of destinations in addition to green spaces that are safe, within walking distance, well-connected to the street and with social cohesion (see Arnberger and Eder, 2011; Carlson et al., 2012; Engel et al., 2016; Klinenberg, 2015; Sugiyama and Thompson, 2007; Van Holle, 2014). Van Holle et al. (2014) highlighted the need to provide a variety of outdoor options within walking distance from the seniors' residences and Arnberger et al. (2017) emphasized sitting options, like benches along routes to destinations such as green spaces.

In sum, a diverse body of literature has demonstrated the benefits of outdoor landscape design and green spaces for improved environmental conditions, but also for better health outcomes. Welcoming neighborhood environments with trees, parks and a variety of destinations can also function as shelters from heat, when indoor environments are inadequate in doing so (Arnberger et al., 2017; Kabisch, 2017). Research in the use of such spaces has shown that besides traditional urban design features, personal factors, such as sociodemographics and health, as well as additional considerations, such as safety and social cohesion are important (Gehl and Svarre, 2013; Whyte, 1980). Yet, there is a dearth of literature on the summertime use of outdoor spaces by low-income older adults and on the value of outdoor environments in assisting them to cope with heat.

5.2 Methods

After the exploration of indoor environments in chapters 3 and 4, this chapter focuses on the seniors' outdoor environments and examines the role of landscape design and adjacent amenities for heat adaptation in the 3 public housing sites in Elizabeth, NJ, USA.

Based on hypotheses 1 and 2 of the 3rd research question, outlined in Table 1.5 of chapter 1, the objectives of this chapter are:

- To map the outdoor preferences and destinations of seniors within and outside the site boundaries.
- To observe variations in the temporal patterns of those activities across sites and apartments.
- To examine the relative effect of site characteristics, and indoor and outdoor heat on indoor occupancy, and consequently, the degree to which they may affect outdoor activities.
- To identify whether adjacent outdoor amenities can provide additional heat adaptation possibilities.

Data Analysis

The analysis is based on the premise that seniors who live in sites with poor indoor environments but rich outdoor amenities in close proximity, may spend less time in their apartments and more time in outdoor spaces, especially during prolonged periods of heat.

When summer temperatures are up, the focus is on indoor and outdoor heat stress, which, here, are approximated by the indoor and outdoor heat index respectively. Therefore, guided by the conceptual framework presented in Figure 3.1, indoor occupancy outcomes are examined against site characteristics, IHI and OHI, while accounting for a number of key personal variables.

5.3 Results

Outdoor Activities and Temporal Patterns

Table 2.3 of chapter 2 briefly presented outdoor activities of seniors during the heat wave periods of 2017, within and outside the sites' boundaries. To some extent, these activities and associated variations across the three study sites may relate to differences in outdoor amenities and landscaping, such as the existence of yards and gardens. For instance, as it is shown in Table 1.1 of chapter 1, sites A and B may have poor building envelopes compared to site C, but are richer in outdoor amenities, within and outside the site boundaries, further explained in the site plans of Figures 5.1 - 5.3.

Specifically, site A has 3 playground areas with plenty of benches and trees for shading. The community center provides good thermal comfort and sitting options but is not always open and accessible to the residents, which may explain why it is not used during heat waves. In the surrounding area, a public pool and a park are within about a 3-4-minute walk. Limited grocery stores exist in the area, but there are numerous houses of worship. Then, B incorporates a front yard with plenty of shading and sitting options and a back yard with community gardens, both of which, are accessible 24/7 and may explain why residents use them during heat waves. Within a 3-minute walk, there is a church and a pharmacy, and within a 10-minute walk, there exist two grocery stores, a senior center, and a small park. Lastly, in C, there are no open/green space options within the site. Some houses of worship are within a 5-minute walk, but a grocery store and a park are more than a 10-minute walk away.

Figure 5.1: Study Site A and its Surroundings ((NJGIN), 2016; Maps, 2017).

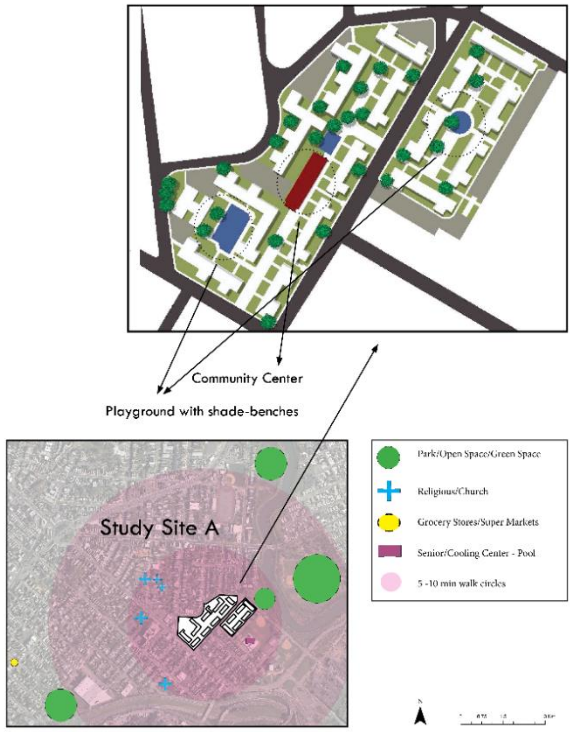


Figure 5.2: Study Site B and its Surroundings ((NJGIN), 2016; Maps, 2017).

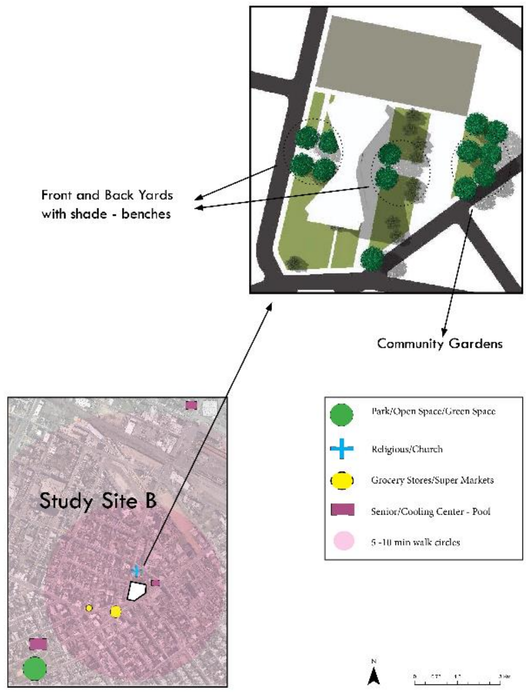


Figure 5.3: Study Site C and its Surroundings ((NJGIN), 2016; Maps, 2017).

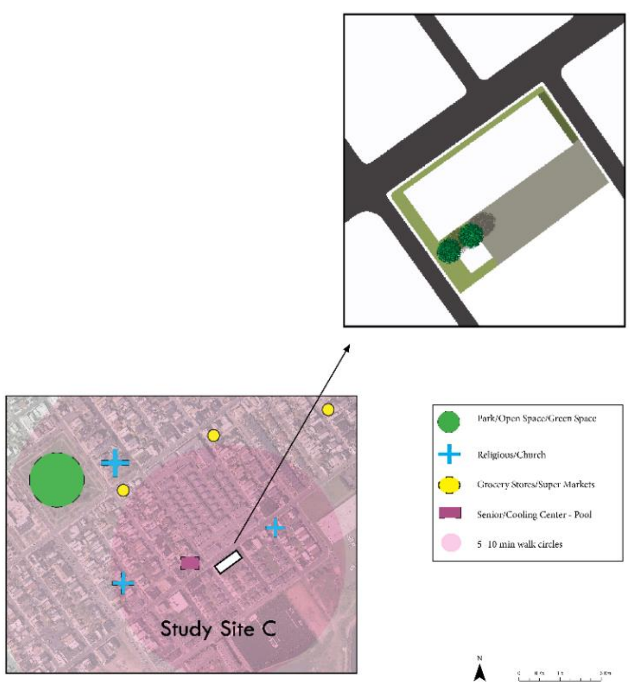


Figure 5.4 shows where each resident reported going during all summer of 2017. Within the site boundaries, the most frequently visited places were the lobby/cooling room or community center and the shady back or front yards, but only from residents in sites A and B, where they were available. The most popular destinations outside the site boundaries were shopping store, senior or cooling center, doctor, pharmacy or hospital and church, while library, movie theater and trips were less frequently preferred. Interestingly, the most frequently visited destinations are all places that allow social interactions, which has also been highlighted in the literature (see Klinenberg, 2015). Lastly, it appears that residents from sites A and B reported a higher number of outdoor activities compared to those in site C, which complies with findings from chapters 2 and 3, while the most active residents were from apartments B1, B2, B3, B9, A1, A6, A9 and C4.

Figure 5.4: Visual network of self-reported outdoor destinations of seniors during summer of 2017 from the baseline and follow-up interviews. The most popular destinations are highlighted with green on the left and the most active residents are highlighted with green on the right.

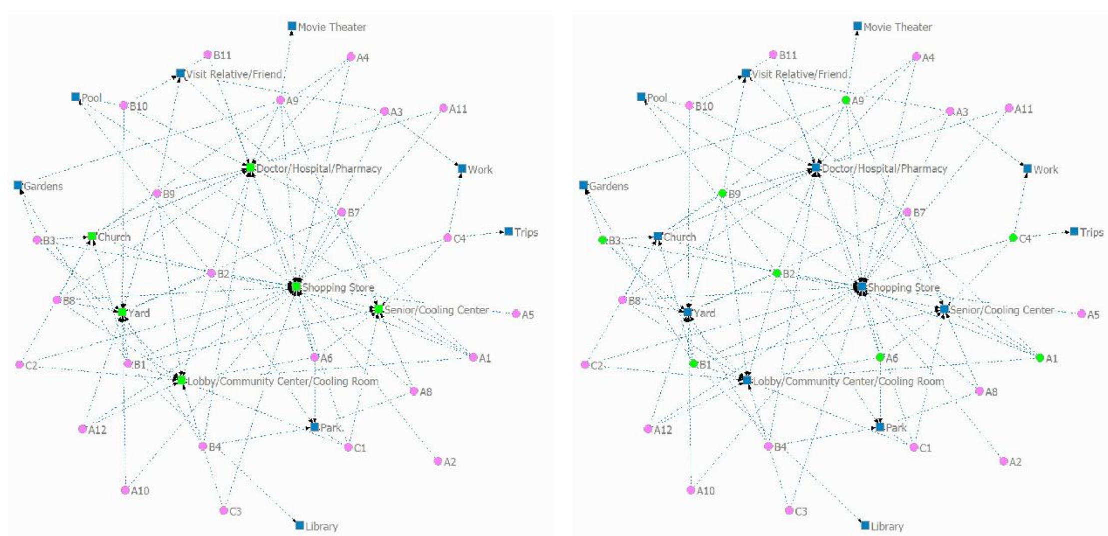
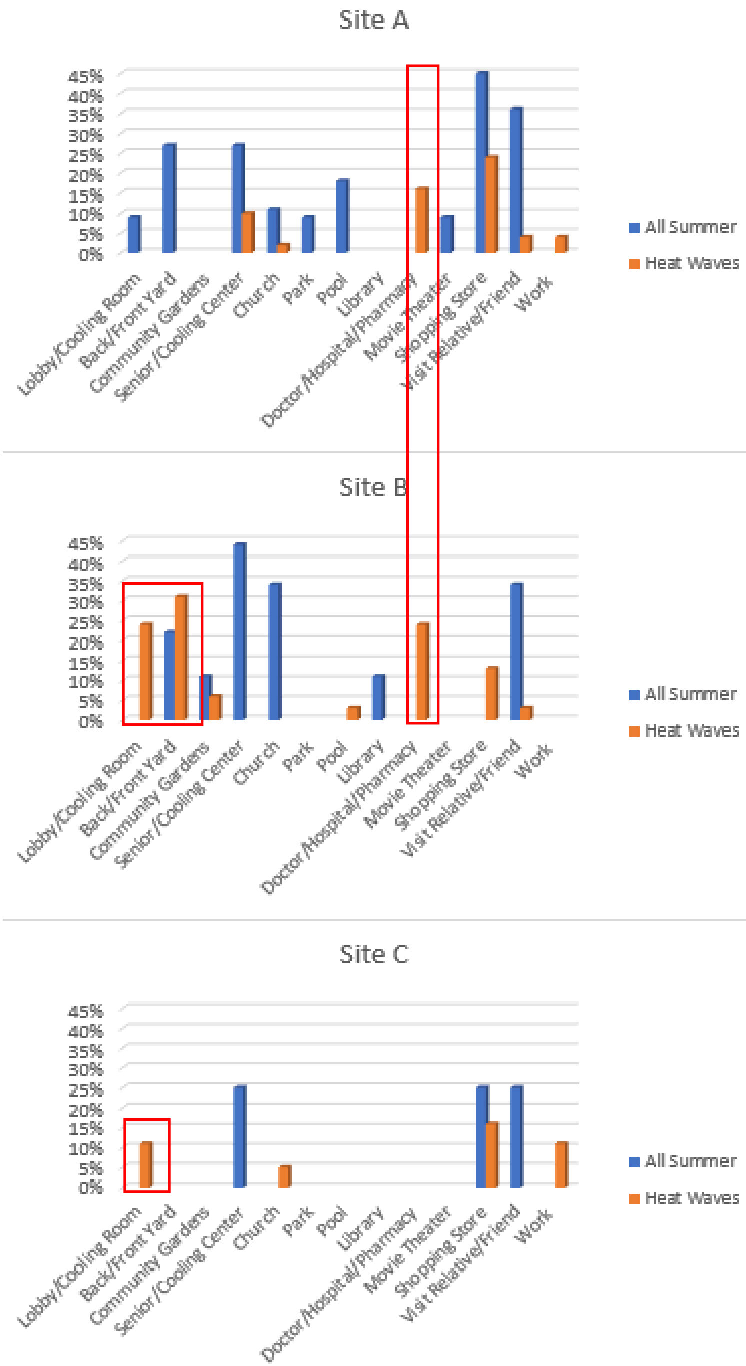


Figure 5.5 compares visits to outdoor destinations across the three sites, which confirms previous findings that A and B residents had a higher percentage of visits and more outdoor activities reported than those in C. Furthermore, five destinations were reported by residents from all sites: lobby, cooling room or community center, senior or cooling center, church, shopping store, and visit to relative or friend.

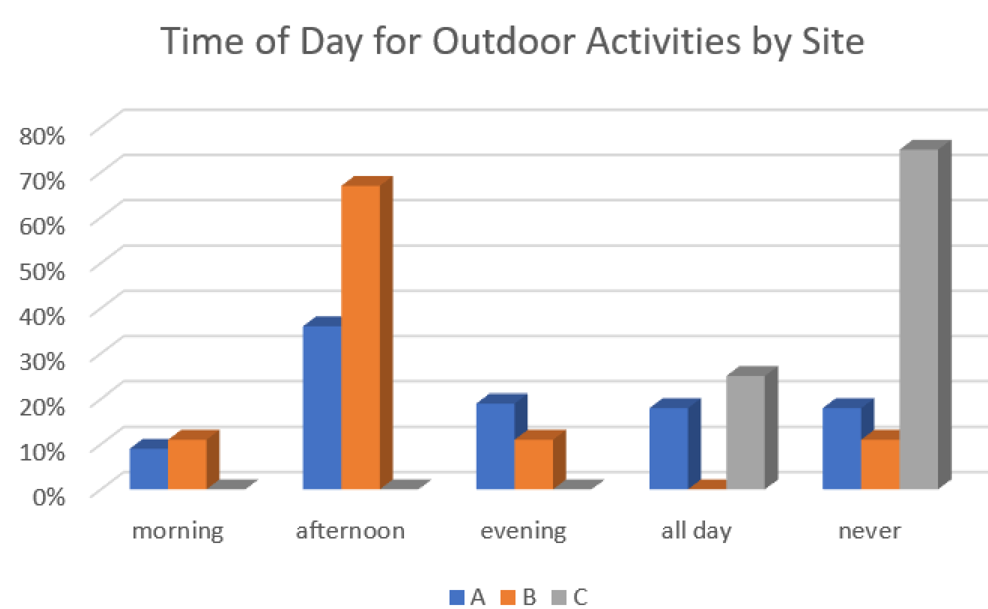
Variations were also observed between all summer and the heat wave periods. Within the site boundaries, residents in A reduced their outdoor visits during heat waves, residents in B increased their visits in the lobby and yard, and residents in C only visited the lobby. This, to some extent, may relate to the common perception that outdoor spaces are always hotter than the apartment (Arnberger et al., 2017), regardless of whether this is accurate. In fact, as it is shown in Figure 3.2 of chapter 3, many apartments in sites A and B were warmer than outdoors.

Figure 5.5: Self-reported outdoor destinations of seniors during summer and during heat waves of 2017 from the baseline and follow-up interviews: variations by site.



The previous paragraphs indicated that the number of summertime outdoor activities of older adults depends to some extent on the number of options available to them and on particular features, such as shading, sitting and walking accessibility. Another consideration relates to the environmental conditions, which, in turn, links to when seniors engage in outdoor activities. Figure 3.6 of chapter 3 briefly showed that residents reported leaving their apartments less during heat waves, but when they did, they mostly went out during the afternoon times (see Figure 3.7 of chapter 3). Upon a closer examination of the time of day variations in outdoor activities, Figure 5.6 shows that only residents of sites A and B left their apartments in the afternoon. This is surprising, since at this time, summertime temperatures were at their peak, but may also relate to the indoor thermal conditions experienced by residents living in apartments within sites A and B.

Figure 5.6: Self-reported time of day variations in outdoor activities by site during summer 2017. Residents in sites A and B mostly went out in the afternoon.



Regression Analysis of Indoor Occupancy

The previous sections investigated how the outdoor preferences and destinations of seniors, as well as the temporal patterns of those activities change across sites with different building envelopes and outdoor amenities. This section examines statistical associations of indoor occupancy with environmental conditions across all apartments, through the time-variant, indoor and outdoor heat index, while accounting for site and personal characteristics, such as being community active, having pets, being an indoor smoker, and general health. The time-variant variables were taken from the sensor dataset and the fixed effects were constructed based on the interviews and the apartment plans.

Pearson Correlations of Indoor Occupancy

Table 5.1 shows Pearson correlations among indoor occupancy and selected variables related to the outdoor and indoor climate, site characteristics and some key personal variables.

First, there is a statistically significant correlation among indoor occupancy and indoor and outdoor heat indexes. This indicates that the occupant was indoors when outdoor and indoor temperature and humidity went up. Then, there are significant correlations among all sites and occupancy; specifically, occupancy increases if apartment belongs to site A and decreases otherwise. This is somewhat expected based on findings of Figures 5.5 and 5.7. In addition, it is also interesting to see how occupancy links to the residents' personal characteristics; a smoker was more likely to be indoors than a non-smoker. Then, as expected, being community active and having pets translates into lower occupancy, which makes sense, as most pet owners in the sample reported being involved in more community-based activities. Finally, a more healthy resident is more likely to be outdoors, which is also expected, since it relates to senior mobility.

The highest magnitudes are those of site A, general health and indoor and outdoor heat index, which indicates that the decision of leaving (or not) the apartment can be affected by the indoor and outdoor environmental conditions, site characteristics and personal constraints. The same patterns repeat during daytime and during heat waves, where coefficient magnitudes remaining similar.

Table 5.1: Pearson correlations between indoor occupancy and selected variables during all summer 2017, daytime only and heat waves only. *Significant at the p=0.05 level.[14]

	Indoor Occupancy		
	All Data	**Daytime**	**Heat Waves**
OHI	0.04*	-0.03*	0.05*
IHI	0.04*	0.07*	0.08*
Site A	0.10*	0.12*	0.10*
Site B	-0.03*	-0.04*	-0.02*
Site C	-0.09*	-0.10*	-0.10*
Having Pets	-0.03*	-0.02*	-0.02
Smoking	0.09*	0.07*	0.10*
Community Active	-0.05*	-0.08*	-0.04*
General Health	-0.10*	-0.08*	-0.11*

Logistic Regressions of Indoor Occupancy

The following paragraphs examine statistical associations among indoor occupancy and selected variables of Table 5.1, through panel logistic regression analysis. Same as in

[14] IHI and OHI are continuous variables. The rest are dummy variables.

previous chapters, panel regression with random effects and robust standard errors is suitable, due to the two-dimensional database (spatio-temporal variations).

Table 5.2 presents the results of 3 models; the first examines a simple, heat-occupancy relationship, the next adds the effect of site characteristics, and the last examines the influence of personal attributes, such as the occupant's general health. The last model (M3) is repeated only for daytime data and for the heat wave periods. The table shows the odds ratios and standard errors for each predictor variable, as well as their statistical significance and the models' explanatory power based on Log Likelihood.

In model 1 (M1), regression coefficients indicate that indoor occupancy is 9% less likely if the indoor heat index goes up, which contradicts to the correlation shown in Table 5.1. Then, it is 3% more likely as the outdoor heat index goes up. In other words, if outdoor heat increases, the occupant remains indoors and if indoor heat increases, the occupant leaves the apartment. Both coefficients make sense, however, their magnitudes are small. When the fixed effect for site A is added in model 2 (M2), IHI and OHI coefficients remain the same, and it becomes clear that the site characteristics have a stronger effect; occupants in site A are 103% more likely to remain indoors. Lastly, model 3 (M3) adds the health variable, which shows a significant effect over indoor occupancy and indicates that if the occupant's health goes down, the occupant is about 31% less likely to leave the apartment. The magnitude is somewhat strong and still higher than the influence of IHI and OHI.

The two additional models for daytime and heat wave data are based on model 3. The model with the heat wave data follows the odds of M3, both in terms of directions and magnitudes. In the model with the daytime data, it is shown that the site's effect becomes higher (192%), which indicates that seniors in site A mostly remained indoors during the day. There is also a change in the OHI direction, indicating that outdoor heat may also refrain seniors from going out, however, its magnitude is very small (1%).

Table 5.2: 3 Models of panel logistic regression parameters for indoor occupancy during summer 2017, daytime only and heat waves only. Random effects with robust standard errors. Coefficients in odds ratios. *Significant at the p=0.05 level.

Indoor Occupancy		**M1**	**M2**	**M3**	**M3** (Daytime)	**M3** (Heat Waves)
Environment	IHI (1 hr early)	0.91* (0.00)	0.91* (0.00)	0.91* (0.00)	0.95* (0.01)	0.94* (0.01)
	OHI (1 hr early)	1.03* (0.00)	1.03* (0.00)	1.03* (0.00)	0.99* (0.00)	1.04* (0.00)
Site	Site A		2.03* (0.69)	2.07* (0.64)	2.92* (1.13)	2.19* (0.69)
Personal Characteristics	Health			0.69* (0.12)	0.76 (0.16)	0.64* (0.11)
	Constant	27.19* (8.66)	19.91* (6.82)	101.56* (82.95)	74.94* (77.45)	39.56* (37.62)
	Log Likelihood	-19,785	-19,783	-19,781	-11,199	-6,001

The last table (5.3) zooms into the effects of IHI and OHI on indoor occupancy for each apartment in the sample. Overall, indoor and outdoor heat have a statistically significant effect on indoor occupancy for 60% and 67% of the apartments in the sample respectively. This changes during heat waves, where indoor conditions become less important. Upon a closer look on site variations, it is shown that indoor heat is a more important determinant of occupancy for residents located in sites A and B, compared to those located in site C, and indicates that indoor environmental conditions may drive residents outside of their apartments. In other words, it is shown that occupancy in A and B may be driven more by the indoor and outdoor heat index, whereas in site C, other factors may become more important, as there is functioning A/C available. However, this changes during daytime and it is shown that seniors in site B get affected more by indoor conditions. Another interesting finding is that half of the residents may stay indoors with a higher indoor heat index, which can be partly explained by their health condition, as explained in the interviews (e.g. blood thinners).

Table 5.3: 24 Models of logistic regression parameters for indoor occupancy during summer 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

		All Data		**Daytime**		**Heat Waves**	
Indoor Occupancy		**IHI (1 hr early)**	**OHI (1 hr early)**	**IHI (1 hr early)**	**OHI (1 hr early)**	**IHI (1 hr early)**	**OHI (1 hr early)**
		Odds ratios		*Odds ratios*		*Odds ratios*	
A	A1	0.70*	1.05*	0.66*	1.05*	0.92	1.01*
	A2	0.92*	1.13*	1.31*	0.93	1.01	1.20*
	A3	0.93	1.09*	1.04	1.04	1.10	1.12*
	A4	0.96	0.94*	0.81	0.97	1.54	0.89*
	A5	0.87*	1.17*	0.86	1.12*	1.09	1.20*
	A6	0.93	1.01	1.08	0.92*	0.94	1.01
	A8	0.74*	1.10*	0.83*	1.07*	0.65*	1.08*
	A9	0.88*	1.17*	1.02	1.03	0.68*	1.26*

	A10	0.69*	1.09*	0.73*	1.06*	0.81*	1.07*
	A11	0.67*	1.19*	0.66	1.07	0.55*	1.25*
	A12	0.91*	1.01	1.03	0.97	0.99	0.99
B	B1	0.78*	0.99	0.83	1.00	0.34*	0.99
	B2	1.12	1.00	1.41*	0.98	0.98	0.94
	B3	1.39*	0.97	1.94*	0.92*	6.09*	0.90*
	B4	0.92	1.10*	0.89*	1.07*	1.00	1.11*
	B7	0.66*	1.11*	0.75*	1.05*	0.67*	1.16*
	B8	0.99	0.98	1.27*	0.96*	0.95	1.04
	B9	1.33*	0.93*	2.04*	0.90*	1.22	0.96
	B10	0.50*	1.02	0.51*	0.99	0.49*	1.05*
	B11	0.84	1.01	0.79	0.91*	1.11	1.02
C	C1	0.88	0.96*	0.86	0.96*	1.09	0.93*
	C2	1.20*	1.12*	1.46*	1.06*	1.16*	1.21*
	C3	0.98	1.06*	0.94	1.01	0.99	1.08*
	C4	1.15	0.90*	0.93	0.91*	0.74	0.87*

5.4 Discussion

This chapter examined the value of outdoor environments in heat adaptation, through identifying the seniors' outdoor destinations and preferences, the temporal pattern of these activities, and the drivers behind going (or not) outdoors. The analysis evaluated the extent to which environmental, site-specific and personal variables may affect the residents' decision to leave the apartment. Same as in previous chapters, to avoid missing important findings, the approach was based both on heat wave periods and on the whole summer of 2017. Comparisons among three public housing sites with different indoor and outdoor amenities revealed variations in the residents' indoor occupancy patterns and outdoor activities, which suggests that built-environment characteristics, such as outdoor landscape design and amenities may alter occupant behaviors and offer additional heat adaptation options.

Specifically, results from Figures 5.4 and 5.5 combined with Table 2.3 of chapter 2 support the first hypothesis that seniors indeed use outdoor spaces, assuming they are available in close proximity. As shown in Figures 5.1 - 5.3, in contrast to C, sites A and B have gardens and shady yards with sitting, and are surrounded by numerous additional amenities, such as shopping stores, pharmacies, religious places and senior centers, within walking distance. The existence of these options explains to some extent why the number of outdoor activities is higher among A and B residents. This is further supported by Table 3.8 of chapter 3, where it is shown that seniors from these two sites provided a variety of recommendations for outdoor space improvements, which additionally indicates their recognition of the importance of outdoor amenities. Yet, besides walking accessibility, a number of additional considerations are highlighted; safety, more greenery, shading, and sitting options, as well as better transportation access, all are considered important features that may increase outdoor activities of older adults and their use of outdoor spaces, which the literature confirms.

Moving forward, results from Figure 5.6 show that residents from sites A and B mostly engaged in outdoor activities in the afternoon, and this increased during heat wave periods. Since summer temperatures were at their peak during this time (see Figure 2.8 of chapter 2), this finding supports the second hypothesis that outdoor spaces may serve as alternatives in sites where indoor environments are inadequate in providing shelter from heat. Tables 5.1 – 5.3 further show a statistically significant relationship between indoor heat and occupancy. Specifically, as the indoor heat index increased, the occupant was more likely to leave the apartment, especially if he/she was in good health. Yet, the coefficient magnitude is small, which indicates that the relationship between indoor heat and occupancy is not straight-forward and is likely influenced by additional factors, such as the outdoor climate and individual preferences or constraints. Somewhat contradictory results come from the overall effect of site A on indoor occupancy, which means that A residents were more likely to stay indoors. However, this result was overturned in a zoomed-in investigation of individual apartments, through logistic regressions of occupancy-heat (Table 5.3); coefficients show that most A residents were more likely to leave the apartment when the indoor heat index went up.

Overall, findings confirm the value of outdoor affordances in assisting low-income seniors coping with heat. A multi-level approach examining the relative roles of social, physical and environmental factors in heat adaptation is beneficial, as it highlights pathways for local action that extend beyond access to air-conditioning. A poor indoor environment with high levels of temperature and humidity pushes older adults to seek outdoor alternatives, assuming they are in good health and/or have some social network supporting their decision to go out. An adjacent neighborhood environment that is safe, cooler, attractive, with social ties and with green spaces, shading, and sitting can function as a refuge during heat periods. The above suggest that housing policies for heat adaptation can highly benefit from the users' perspectives and that investing in outdoor amenities and landscape design interventions can be valuable and cost-effective, especially when complemented by indoor-level modifications.

Chapter 6 Heat Adaptation Policy through a Social-Ecological Framework

This dissertation has tested the idea that urban sites can be conceptualized as social-ecological systems, aiming to understand the relative roles of social, physical and environmental factors in heat adaptation. Drawing from a study of a senior public housing community in Elizabeth, NJ, USA, a heat-wave SES framework was empirically derived that links indoor to outdoor environments and to social actors and organizations. Subsequently, the role of indoor environments was examined, followed by the exploration of the value of outdoor environments in assisting older adults coping with heat. This chapter concludes the work by synthesizing an inventory of integrated policy for heat adaptation through a social-ecological systems lens, which corresponds to the last question of the dissertation. It starts with a summary of the thesis' key outcomes, and critically reflects on the usefulness of the SES approach. It then translates the thesis findings into a set of cost-effective and easily accessible interventions to assist older adults and low-income communities in adapting to heat. The final section provides an overall discussion of the thesis contributions with suggestions for future development of the work.

6.1 Summary of Findings

The starting point of inquiry for this work was the view of urban sites as social-ecological systems, where actors interact with infrastructure during heat waves and produce outcomes related to heat adaptation. With this premise as guidance, the first research question asked, "*what social and ecological components become relevant in the case of senior low-income sites suffering from heat waves*." Chapter 2 addressed this question by extending the SES framing to the study community in Elizabeth, NJ and by assembling a descriptive SES framework for heat waves to guide subsequent analysis. The framework, shown in Figure 2.3, organizes the indoor and outdoor scales in which seniors move, and identifies the infrastructure characteristics that influence environmental conditions, as well as the social actors that become important at each scale.

Chapter 2 further tested the first question associated hypotheses. Specifically, in regard to the first hypothesis, which states that "*heat waves require actors to adapt and change key behaviors*," preliminary analysis showed that indeed, when summer temperatures went up, the primary actors of the study community - senior residents - engaged in a range of adaptive actions, including operating windows and A/C and leaving the apartment (indoor occupancy); yet, these actions varied based on the indoor and outdoor resources available to them and the potential of receiving support from the community. To that end, the role of additional policy actors was proactive. A local non-profit had previously installed window A/C units and covered the associated bills in some apartments. Similarly, facility staff of the managing authority monitored the operations and maintenance of the sites and the residents' well-being during heat waves. Therefore, the above suggests that there is merit in the first hypothesis, yet, further analysis is needed to assess the extent to which some behaviors can be fully attributed to heat waves.

Another important finding of chapter 2 relates to the second hypothesis, which states that "*some SES parts give sites an advantage in increasing the chances of heat adaptation*." Preliminary results indicated that the outdoor climate and infrastructure characteristics (indoor affordances, outdoor amenities) highly affected the indoor environmental conditions experienced by low-income seniors, yet, the influence of resident activities was also deemed important. This finding suggests a stronger focus on the interactions among resident activities and dwelling characteristics, followed by an examination of the role of outdoor environments. Given this analysis, the hypothesis was well supported and revealed that the focus should be on behavior-infrastructure synergies to be further explored in subsequent chapters.

In response to findings from chapter 2, the second research question asked "*what is the role of indoor environments in mediating heat and which social and ecological factors influence indoor environmental conditions*." Chapter 3 addressed this question by taking a multi-level regression approach to identify the relative roles of site and apartment characteristics, environmental and personal variables and the seniors' actions on indoor heat, diagrammatically represented in the framework of Figure 3.1. The framework shows how occupant actions are subject to personal characteristics and the indoor/outdoor resources available to the residents, which are highly varied across the three study sites. Since the focus was on indoor environments, the main occupant behaviors investigated here were operation of windows and A/C.

Results from chapter 3 partly supported the first hypothesis and showed that an increase in outdoor heat resulted in higher indoor heat, while certain site and apartment attributes strengthened this relationship. However, the small magnitude of regression coefficients indicated that additional influences could be more important in explaining indoor thermal conditions. Indeed, occupant actions had the strongest influence on indoor heat, which confirms the second hypothesis. In fact, some apartments located in sites with poor building envelopes had similar indoor thermal performance with apartments from the green building that had central air-conditioning, which was due to the way residents operated windows and the small A/C units. Specifically, it was shown that when there was medium WO activity and at certain times of day, it reduced indoor heat. Therefore, it became clear that the operation of windows, which relates to the operation of A/C, was directly related to indoor environmental conditions. This finding is very important because it establishes window opening as an effective adaptive action and shows that passive cooling can be valuable in mediating indoor heat. Furthermore, in accordance with the findings of chapter 2, it was shown that the residents' actions varied by indoor/outdoor resources, and specifically by site. A zoomed-in investigation of behavioral variations revealed that the absence of proper A/C systems combined with the existence of rich outdoor amenities promoted a wide range of additional heat coping behaviors, such as leaving the apartment (indoor occupancy), further explored in subsequent analysis.

Chapter 4 grasped on the first finding of chapter 3 to focus on another aspect of the 2^{nd} research question and explore further indoor environmental conditions by examining thermal comfort in parallel to indoor air quality. Analysis zoomed into the concurrent impact of natural ventilation and window opening on mitigating indoor heat and pollutant concentrations through mixed linear models and time series.

Results from chapter 4 confirmed chapter's 2 findings and showed that building characteristics played an important role for indoor heat exposure, but not for indoor $PM_{2.5}$ pollution, which was mostly driven by indoor sources related to occupant behaviors, such as smoking, while WO was an important modifying factor for both aspects. A deeper investigation of the effect of WO on thermal and air quality performance supported the third hypothesis based on which, "*certain occupant actions have a trade-off on indoor* *thermal and air quality performance*." Yet, it was found that this trade-off was not evident in all apartments, but mostly within those with indoor smokers. This finding is important, as it suggests that overall, while a low-to-medium window opening activity of certain windows and at certain times per day is effective for both cooling and improved IAQ, the interdependencies among IEQ aspects need to be considered in housing policies for improved health outcomes.

Moving forward, in response to the last finding of chapter 3, chapter 5 investigated the third research question that asks about "*the value of outdoor environments in heat adaptation*." Given variations in outdoor amenities and landscaping among the three study sites, the chapter focused on answering where do seniors go when they leave the apartment, what time of day do they take these actions and what are the drivers behind going outdoors. Since the focus was on outdoor environments, the main occupant behavior investigated here was indoor occupancy/leaving the apartment, and the analysis was guided by the framework presented in Figure 3.1.

Results of chapter 5 supported the first hypothesis, which stated that "if outdoor spaces are provided to them, seniors use them, assuming they are in close proximity." Specifically, it was shown that residents in sites and neighborhoods with rich outdoor landscaping and a variety of possible destinations for seniors reported a higher number of outdoor activities. However, besides walking accessibility, a number of additional criteria were highlighted by the residents in regard to the use of outdoor spaces, such as adequate transportation options, safety, sitting, shading and greenery.

Further analysis in the temporal pattern of those activities as well as in regressions, revealed that indoor heat can drive seniors outdoors, which supports the second hypothesis of chapter 4 that "*outdoor spaces may serve as alternatives in sites where indoor environments are inadequate in providing shelter from heat*." This finding was more pronounced for seniors residing in sites with poor building envelopes, which was further established by those residents' interest and recommendations for outdoor space improvements. However, in explaining indoor occupancy, additional considerations were found to be important, such as the outdoor climate and individual constraints, especially health and mobility, as well as the residents' everyday routine. In other words, the extent to which the decision to leave the apartment/indoor occupancy is driven by heat waves seems to hold true, but it deems further investigation.

In sum, findings from the previous chapters highlighted two areas for further discussion, which are explored in the following sections. The first area concerns the view of urban sites as social-ecological systems, which is the theoretical umbrella of this work. Section 6.2 critically reflects upon the SES approach and offers recommendations for improvement. The second area concerns the last research question of the dissertation, which asks "how can we empirically inform policy towards heat adaptation through a social-ecological systems lens." Its aim is to organize and translate the thesis findings into a set of cost-effective and easily accessible interventions to assist elderly low-income communities in adapting to heat, which is the conclusive goal of this work. This effort is presented in Section 6.3.

6.2 Revisiting the Social-Ecological Systems Approach

As argued in earlier chapters, the social-ecological systems approach utilized in this dissertation addresses the challenge of bringing together the key social (human) and ecological (non-human) dimensions that shape urban landscapes as equally important considerations into a coherent framework. This framework successfully connects interdisciplinary knowledge needed to describe the complex, dynamic and multi-scalar interactions among these dimensions, out of which, heat adaptation pathways emerge.

Certainly, the SES approach has been useful in identifying and quantifying the relative contributions of humans, infrastructure and the climate in the heat coping processes and in expanding knowledge for related disciplines. It has further revealed that the long causal chain, which contributes to heat vulnerability can reversely lead to successful heat adaptation outcomes. Exposure to elevated ambient temperatures is higher for low-income seniors living in sites with poor landscaping and few outdoor amenities; this is further aggravated when combined with poor building envelopes and the absence of support from community services and social networks, as residents are left without enough options to improve their thermal experience. However, empirical analysis guided by the SES framework has shown that the seniors' options are increased if one or more of these components are advanced. Older adults living in sites with good building envelopes, but few outdoor amenities mostly rely on indoor environments and the operation of A/C to improve comfort. Contrariwise, residents living in sites with rich outdoor amenities, but poor building envelopes consider both indoor and outdoor environments and rely on the operation of windows and the alteration of occupancy patterns. In both cases, support from community actors (e.g. managing authority, supportive organizations and social networks) is necessary for infrastructure operations, maintenance and improvement, and to ensure the residents' well-being.

The above findings suggest one important take-away from the application of the SES approach to the empirical study of Elizabeth, NJ and an area for further inquiry, which is the realization of the importance of human agency in heat adaptation. Rather than an explanatory theory, the SES framework is better thought of as a descriptive, and often diagnostic, theory-free tool that guides study design, data collection and modeling; therefore, it could benefit from incorporating a theory of adaptive behavior. In its current form, the framework does not clearly problematize the production of human behaviors linked to built-environment characteristics, which is central in characterizing heat coping processes. Thus, a behavioral theory could provide guidance on how organization-level actions facilitate infrastructure alterations, which in turn, influence individual-level actions and eventually adaptation outcomes. This is critical because it can improve our understanding of the multiple spatial and institutional levels of agency that shape residents' choices within urban landscapes.

6.3 Synthesizing an Inventory of Integrated Policy for Heat Adaptation

Already from the first chapter of this dissertation, a recurring notion is that the heat-waves problem requires integrated solutions across indoor-to-outdoor scales that link to local actors and institutions. The idea behind this integration lies in the fact that although indoor environments are critical in assisting seniors coping with heat, they are not isolated entities and therefore, they cannot be separated from the wider urban context they belong to. This has been repeatedly demonstrated in earlier literature and in the outcomes of the previous chapters. In response to the last research question of this dissertation, the following paragraphs conclude this work by attempting to expand the SES framework beyond its diagnostic capability in guiding analysis and facilitate policy development.

Translating modeling outcomes into sets of policies is unarguably challenging, as social-ecological systems are characterized by non-linear dynamics, feedback loops between social and ecological processes and emergence of behavior that changes across space and time. However, a part that stands out in this dissertation is the importance of the institutional dimension in policy making, which is well-established in the SES framework. In particular, the focus is on local actors and institutions and it is shown that their involvement is critical for successful heat adaptation policy development and implementation. Yet, missing is an in-depth identification of each actor's and institution's role at specific scales and the likely effects of their actions for different policy interventions.

In response to the above and drawing from the heat waves SES framework presented in Figure 2.3, Tables 6.1and 6.2 translate findings from the previous chapters as outlined in section 6.1 into two different groups of heat adaptation policies; each group is linked to the spatial scale (indoors and outdoors) and the associated sub-scale, as well as the actor(s) involved, further explained below.

Implications for Heat Adaptation Policy Addressing Behavioral Alterations

The importance of emphasis on behaviors is already evident from the outcomes of chapter 2, also listed as findings one and two in Table 6.1. Related to that are two strategies that the current study highlights, both of which address changes in the residents' behavioral habits and can assist older adults cope with extended periods of hot and humid weather.

The first strategy concerns the operation of certain windows at certain times of day, as demonstrated in the third finding of Table 6.1, and encourages investment in efficient cooling, such as effective natural ventilation. Due to its focus on the real indoor environmental exposures experienced by seniors inside public housing, an important consideration that this study stresses is that thermal-comfort decision-making should not be done in isolation, but within the context of indoor environmental quality. This is directly relevant to behavioral interventions, such as window operation, given the associated complexities when examining effects on more than one IEQ domain. This emphasis on ventilation also comes in response to the global COVID-19 pandemic, which requires immediate action for the protection of vulnerable groups and especially older adults. Therefore, the main take-away is that sufficient natural ventilation for improved IEQ should be enforced, since window opening can work well as a means to cool off and clean the indoor air at the same time. Yet, it is best when it is coupled with educational and technological interventions. For example, while it is intuitive to operate the windows in response to an indoor environmental stimulus, it is not easy to weight multiple criteria simultaneously (e.g. decide on the optimal window opening based on both thermal and air quality conditions). Educating residents about the importance of indoor air quality and effective ways to open their windows can be very valuable in the long term. Then, WO can be coupled with technological interventions, such as using air purifiers and installing high-efficiency filters, which can also work well in the long term and have faster results (see physical alteration policy 1 of Table 6.1).

The second strategy relates to reduced indoor occupancy and the opportunity to leave the apartment at certain times of day, which is related to the fourth finding of Table 6.1. When combined with outdoor landscape design to provide adequate amount of shading, as well as a variety of adjacent amenities based on seniors' preferences (see physical alteration policies three and four of Table 6.1), these strategies can be important protective factors from indoor heat-related discomfort, especially for those not having access to A/C or not being able to afford running it. These features also help maintain well-being during power outages, which often coincide with heat waves. Leaving the apartment and visiting outdoor destinations further responds to the need for achieving additional health goals, such as mobility and socializing for older populations.

Heat adaptation policy that goes beyond access to air-conditioning and re-examines cost-effective options at the apartment-level is urgently needed. In addition, the above protective strategies integrate human agency into the heat-wave stories, which is not clearly established in the literature. While a large body of studies focus on indoor strategies to improve thermal performance and many incorporate occupant behaviors, such as window opening, most often occupants are treated as powerless actors without ownership of their own actions. Therefore, empowering key actors is an additional aim of this group of policies, which present the potential for long-term adaptation to heat waves. Lastly, an additional benefit includes the non-existent cost of implementation; however, there is a knowledge barrier that needs to be overcome, which can be achieved through educating residents. This requires attention on collaboration among residents and organizations (see Table 6.2), such as the managing authority and additional supportive institutions, which can be time consuming and complicated, as it involves several human entities.

Implications for Heat Adaptation Policy Addressing Physical Alterations

Chapter 2 outcomes, and findings one and two of Table 6.1 respectively, have further demonstrated the critical role of infrastructure, especially the extent to which it may affect the residents' adaptive options. Chapters 3, 4 and 5 revealed how the physical characteristics of indoor environments may drive certain occupant actions, and the extent to which outdoor environments can enhance such activities.

Starting with physical alterations of indoor environments, and in relation to finding three from Table 6.1, an important policy implication that emerges from this study is that all renters should have access to cooling and rental housing regulations should include that as a requirement. Therefore, the two related interventions concern investing in 1) optimal size, location and type windows for better passive ventilation performance coupled with high-efficiency filters and air purifiers, and in 2) central air-conditioning. In general, the more comfortable indoor environments are, the less action is needed by occupants to improve their comfort. Outcomes from chapters 3 and 4 clearly show that residents who either live in air-conditioned apartments or follow a "smart" window opening routine, overall enjoy heat index ranges that fall within the ASHRAE standards. The above strategies aim to enhance these findings. Cooling options should not be a luxury, but a necessity that could significantly reduce morbidity and mortality rates during heat disasters, especially among socially isolated and physically frail low-income seniors.

Incorporating apartment and building-level retrofits is critical for heat adaptation policy, since indoor spaces are the first protective environments for aged occupants. The notion of investing on envelopes is not new and is well-established in the literature, for both existing and new building stock. But the cost involved may be a significant barrier for low-income communities, who often struggle to distribute a small annual budget across several different sites. Collaboration among human entities is again vital here, as collective efforts to spread associated costs between several institutions (e.g. between managing authority and local non-profits) could overcome this barrier (see Table 6.2).

The last group of interventions corresponds to the fourth finding of Table 6.1 and relates to physical alterations of outdoor environments. The first related strategy concerns investing in site landscape design and greening, such as sitting, vegetation and increased tree canopy for shading. Besides creating additional protection from heat for indoor environments, these features are frequently used by seniors, as shown in the outcomes of chapter 5. In addition, literature focusing on nature-based solutions, has repeatedly demonstrated links to physical activity, social contact and stress recovery, all of which are particularly important considerations for older adults. Related to that is also the final strategy to invest in connections to adjacent neighborhood amenities, such as community and cooling centers, shopping stores, places of worship, and swimming pools, whose importance is addressed by limited studies.

Chapter 5 showed the value of investing in outdoor environments, especially because certain outdoor features may provide alternative options for older adults during extended periods of hot weather and this can be particularly helpful in cases where indoor environments cause thermal discomfort. Same as with indoor physical alterations, cost presents a significant barrier here. When it comes to site landscaping, in a large-scale implementation, the cost may be higher, but greening the immediate building surroundings with small trees and shrubs can still be cost-effective, assuming close collaboration among local institutions and organizations (see Table 6.2). Such collaborations are also essential in the case of promoting connections to neighborhood amenities. The existence of such spaces and their proximity to existing public housing communities moves beyond local organizations to city authorities. Yet, related interventions should invest in safety, free transportation options and providing walkable and shady paths to these destinations.

Besides managing authorities and local institutions, the spectrum of strategies guiding heat adaptation policy for senior public housing can be addressed by municipal and state officials, as well as building code professionals and highlight four key take-outs. First, both knowledge and cost barriers present significant challenges. In response to that, the empirical study of Elizabeth, NJ presented in this thesis suggests filling the knowledge gap through education and addressing financial limitations through the involvement of and distributions across several local actors and institutions. Second, there are important trade-offs when it comes to the implementation of policies; interventions that are zero or low-cost, require attention on the scale and time of implementation, and on the complexities of involving several human entities. Third, while one thing is to enforce behavioral and physical interventions, the other is to maintain them and ensure proper operations, which is especially important for long-term heat adaptation. Fourth, the last and perhaps most high-level theme established in this work, is that an integrated set of actions are needed to ensure heat adaptation. Policymaking is characterized by uncertainty, but the risk becomes lower when recognizing the importance of human agency and promoting a diverse range of options across scales.

Table 6.1: Translating dissertation findings into an inventory of integrated policy for heat adaptation.

	Finding		Policy
			Behavioral Alterations
1	Actors change key behaviors in response to heat waves, which can be either proactive or reactive. The first relate to policy actors linked to the managing authority (HACE) and local non-profits. The second relate to the primary system users, which are the residents, as well as to supportive social networks, such as the seniors' family members, nurses and managers of HACE.	1	**Operation of Windows:** operating windows at certain times of day links to finding 3 and can be an effective natural ventilation measure, especially for those not having access to A/C or not being able to afford it. Passive ventilation performance can be improved when combined with optimal size, location and type of windows (physical alterations policy 1).
2	Heat adaptation possibilities are increased once behavior-infrastructure synergies are identified. This is a non-linear relationship, since occupant behavior links to both indoor and outdoor built-environment characteristics at nested scales. It also emphasizes that the adaptation process depends not only on infrastructure and the physical environment, but also how people end up using it.	2	**Reduced Indoor Occupancy/Leaving Apartment:** reduced indoor occupancy and the opportunity to leave the apartment at certain times of day links to finding 4 and can help maintain thermal comfort, especially during power outages. When combined with rich outdoor landscaping and amenities (physical alterations policies 3 and 4), it further promotes

			mobility and socializing for older populations.
			Physical Alterations
3	Higher outdoor heat translates into higher indoor heat; poor building envelopes strengthen this relationship, while good building envelopes mediate it. Occupant actions related to the operation of windows and A/C also affect this relationship and their influence is higher than that of building envelopes. Specifically, if central A/C is available and functioning, it translates into lower indoor heat, assuming that the resident operates it along with closed window(s) at certain times of day. Then, if there is/are small window A/C unit(s) available, or if no A/C at all, window operation is the main adaptive action in response to heat. Leaving windows either open or closed all day generally means higher indoor heat. But a medium window opening activity at certain times of day (e.g. early morning, late evening) translates into lower indoor heat, and indoor thermal performance may be similar to apartments with central A/C. Yet, when examining indoor thermal and air quality performance in parallel, there is a thermal and IAQ trade-off when indoor sources, such as smoking, are present. In that case, a very active WO strategy is necessary, even if this translates into less cooling.	1	**Ventilation and Windows:** improving the size, location and type of windows as well as adding air purifiers and high-efficiency filters links to finding 3 and can improve ventilation performance and therefore promote a more comfortable indoor environment during periods of hot weather. However, this is also subject to the way residents operate windows and the extent to which, they follow a "smart" window opening routine that relates to the type of window, the time of day and the duration.
		2	**Air-Conditioning:** investing in central air-conditioning links to finding 3 and is a very important cooling strategy. Same as with ventilation and windows though, it depends on how residents operate it, especially the time of day.

4	Residents' behaviors vary based on the indoor and outdoor resources provided to them. Limited access to A/C combined with rich outdoor landscaping and amenities promotes heat coping behaviors, such as reduced indoor occupancy/leaving the apartment, in addition to higher rates of visits to outdoor destinations and more appreciation of outdoor spaces. Limited A/C links to higher indoor heat and this can drive seniors outdoors. Additional considerations are also important, such as outdoor heat, occupant characteristics and everyday routine, and the state of outdoor spaces. In relation to the latter, residents value proximity (walkability or free transport), safety, sitting, shading and greenery.	3	**Landscape Design:** investing in site landscaping and greening links to finding 4 and involves strategies, such as sitting, vegetation and increased tree canopy for shading. These features protect indoor environments from heat and promote physical activity, social contact and stress recovery.
		4	**Amenities:** providing connections to adjacent neighborhood amenities links to finding 4 and involves investing in safety, free transportation options and providing walkable and shady paths to these destinations. These places can serve as alternatives in cases where indoor environments are inadequate in providing shelter from heat.

Table 6.2: Inventory of integrated policy for heat adaptation; Linking policies with actors and spatial scales.

	Policy	**Scale**		**Actor**
	Behavioral Alterations			
1	Window Operation	Indoors	Apartment	Resident-Organization
2	Indoor Occupancy/ Leaving Apartment	Indoors - Outdoors	Apartment/Site/ Neighborhood	Resident-Organization
	Physical Alterations			

1	Ventilation and Windows	Indoors	Apartment	Organizations
2	Air-Conditioning	Indoors	Apartment/Building	Organizations
3	Landscape Design	Outdoors	Site	Organizations
4	Amenities	Outdoors	Neighborhood	Organizations

6.4 Contributions and Future Directions

In conceptualizing urban sites as SES, this dissertation contributes to a new way of understanding and studying the complex interrelationships between social and ecological processes that shape urban landscapes. This new approach leads to the realization that heat adaptation pathways are found at the very localized scales and inevitably include indoor-outdoor synergies, tied to individual users, local actors and institutions. Therefore, the central merit of this work lies in the value of integrating theoretical themes and methodological tools from various disciplines, in order to advance knowledge collectively on how to improve environmental conditions and consequently, human health and well-being of low-income seniors.

As the starting point of this dissertation, urban ecological literature has guided the development of a social-ecological framework. The SES framework has in turn directed the collection of studies drawing from public health and epidemiology, building science, thermal comfort and occupant behavior, urban planning and public policy, and landscape architecture. Theoretical discourses have been discussed in the context of heat waves and the thermal and air quality conditions in senior public housing. Furthermore, and in line with the SES framework, this work has utilized a multi-level approach to identify the relative roles of humans, infrastructure and the environment in heat adaptation, through a number of methods, such as analysis of time-series, panel and mixed linear regression, factor analysis, mapping and graphical communication. This investigation has guided the bridging of human behavior within buildings to outside of buildings, which has been further useful for policy communication. In attempting to take the SES framework one step further, this thesis has lastly derived integrated strategies for heat adaptation of low-income seniors, by translating modeling findings into policy outcomes.

The view of urban sites as SES has been well-established in this work through literature and related empirical analysis, various aspects of which, may be extended to similar urban settings beyond Elizabeth and NJ. There are several public housing projects federally managed throughout the Northeast United States, who struggle with funding and have similar resident profiles and building stock as in NJ; those could benefit directly from this research project. Then, as the impacts of a warming climate accelerate throughout the world, more and more urban communities seek for integrated strategies linking indoor to outdoor scales; this is an area that could offer indirect benefits to those communities and the central idea behind this research.

An investigation of additional applications from real urban settings with larger sample sizes and exploring alternative data collection and modeling techniques can be proven useful. First, additional sources of IEQ variations can be captured in larger samples, which may be helpful in offering more concrete policy recommendations. Then, collecting data from consumer-grade sensors inevitably presents several limitations, such as resolution biases, despite calibration. In addition, behavioral sensors that are stationary, only partly capture the range of human activities, especially as they relate to indoor occupancy patterns, and outdoor visits and preferences. Additional uncertainty in the study relates to the selection of criteria for assessing indoor overheating and pollution. For both the HI and PM2.5, the study relied on thresholds from ASHRAE and the US

EPA respectively, which have relatively conservative standards compared to guidelines from the OSHA and WHO, which recommend lower thresholds. Therefore, a suggestion for future research is to assess the sensitivity of recommendations to selected thresholds. Lastly, approaching the heat wave problem through a multi-level analysis is definitely complicated, as it connects inherently different phenomena, each with its own logic and dimensions. Regression analysis is practically useful, as it enables combining diverse variables and showing direct effects of predictors on the dependent variable. However, it is also a reductionist approach that does not capture the nested hierarchy among many variables of interest. More empirical studies on heat waves in senior, low-income housing can address these methodological challenges and offer new explorations to extend this work.

APPENDIX A INTERVIEWS

Baseline Interview Protocol

DATE__ Interviewer___ CODE__

<u>Baseline survey:</u> Subjects will participate in 1 60-minute session during which a baseline questionnaire will be administered in-person and during which time air quality sensors and power meters will be installed in the apartment by other members of the research team. The function of this equipment will be explained to the subject also during this time.

1/ Use of apartment/occupancy

The next few questions ask about how the apartment is used.

1.1 When did you first move to this apartment?

Please fill approximate month and year: __ __/__ __

1.2 How many people including yourself live or stay in your apartment on a regular basis (more than 2-3 days/week, including family, roommates)?

Starting from the youngest, can you tell us their ages, gender, and an identifying name (for future reference-we may ask about them again later on)?

Person	**Age**	**Gender (M/F)**	**Identifier (1st[t] or middle name)**
Interviewee			
Person 2			

Person 3			
Person 4			
Person 5			
Person 6			

1.3 On an average weekday, your apartment is unoccupied (no one at home)…

1. <1 hour/day
2. 1-3 hours/day
3. 3-6 hours/day
4. 6-12 hours/day
5. >12 hours/day

1.4 On an average Saturday or Sunday your apartment is unoccupied (no one at home)…

1. <1 hour/day
2. 1-3 hours/day
3. 3-6 hours/day
4. 6-12 hours/day
5. >12 hours/day

1.5 Approximately how many weeks in the past year was this apartment unoccupied (no one was there including sleeping somewhere else)?

1. 0-2
2. 3-5
3. 4-6

4. 7-9
5. >9

2.A/ Environmental Conditions/Comfort

The next few questions are about how comfortable the conditions are in the apartment ***during the typically warmer months (May-October).***

2.A.1 How frequently do you feel uncomfortably warm in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1 day/week)
4. Often (>1 days/week)
5. Daily

2.A.2 How frequently do you feel uncomfortably cold in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1 day/week)
4. Often (>1 days/week)
5. Daily

2.A.3 How frequently do you experience air drafts in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1 day/week)
4. Often (>1 days/week)
5. Daily

2.A.4 How frequently do you experience stuffiness in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1 day/week)
4. Often (>1 days/week)
5. Daily

2.A.5 How frequently do you experience extreme humidity in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1 day/week)
4. Often (>1 days/week)
5. Daily

2.A.6 How frequently do you experience extreme dryness in the apartment?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

2.A.7 How you would rate the overall air quality in the apartment?

1. Extremely bad
2. Somewhat bad
3. Neither bad nor good
4. Somewhat good

5. Extremely good

2.A.8 Have you ever experienced any bad odors in the apartment (e.g. chemical or garbage smells from hallway?

1. Yes
2. No

9. Don't know/refuse

2.A.8.a If yes, how often?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

2.A.9 Have you ever noticed any mold in the apartment?

1. Yes
2. No

9. Don't know/refuse

2.A.9.a If yes, how often?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

___In what circumstances? ____

2.A.10 Have you ever noticed rodents, cockroaches or other insects in the apartment?

1. Yes
2. No

9. Don't know/refuse

2.A.10.a If yes, how often?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

___In what circumstances? ____

2.A.11 How would you rate the temperature of the hallway compared to the temperature in the apartment?

1. Much colder
2. Somewhat colder
3. Neutral (no noticeable difference)
4. Somewhat warmer
5. Much warmer

2.A.12 On a scale of 1-7 on the hottest day of the year, what are the conditions in your apartment? (1=completely comfortable; 7= completely unbearable)

- 1
- 2

- 3
- 4
- 5
- 6
- 7

2.A.13 How do you find air quality outside between May-October?

1. Very polluted
2. Somewhat polluted
3. Neutral (not particularly polluted or clean)
4. Somewhat clean
5. Very clean

2.A.13.a Does it vary by season? If yes, how?

1. Yes
2. No

9. Don't know/refuse

If yes: ____

2.A.14 Is your breathing different when you are outside?

1. Made better
2. Made worse
3. Made neither better or worse

9. Don't know/refuse

2.A.15 How often are you outside between May-October (hours/per day)?

1. 1-2 hours

2. 3-4 hours
3. 5-7 hours
4. 8-10 hours
5. 10-12 hours

2.B/ Environmental Actions

The next few questions are about the actions taken to improve comfort in the apartment ***during warmer months (May-October).***

2.B.1 What actions do you routinely take to feel more comfortable in terms of environmental conditions (temperature, humidity and air)?

2.B.1.a Dress in layers/adjust clothing

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.a.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.b Use portable fan

1. Never/Option not available

2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.b.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.c Open/close windows

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.c.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.d Use air purifier

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.d.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.e Use window air conditioning unit

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.e.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.f Adjust thermostat *(for central AC building/s only*)

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.f.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.g Use portable heater

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.g.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)

- Night (8:00 pm – 8:00am)

2.B.1.h Use dehumidifier

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.h.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.1.i Notify landlord/supervisor

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

2.B.1.i.1 Which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)

- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2.B.2 Does anyone ever smoke in the apartment (cigarette, cigar, or pipe)?

1. Yes
2. No
9. Don’t know/refuse

2.B.2.a If yes, how often is there someone in the apartment smoking?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

2.B.3 Do you use candles, air fresheners, or incense?

1. Yes
2. No
9. Don’t know/refuse

2.B.3.a If yes, how often are any of these used?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

2.B.4 Does anyone in the apartment have any pets?

1. Yes
2. No
9. Don't know/refuse

2.B.5 How do you clean carpets in the apartment (if any)?

1. Vacuum cleaner
2. Broom
3. Washing machine
4. Other. Please specify: ______
9. Don't know/refuse

2.B.6 How do you clean the floors that have hard surfaces-no carpets in the apartment (if any)?

1. Vacuum cleaner
2. Broom
3. Mop
4. Dusters or dusting wipes, such as Swiffer
5. Other. Please specify: ____
9. Don't know/refuse

2.B.7 What cleaning products do you use for kitchen, bathrooms, floors (these can be liquids or powders)?

3/ Response to Heat Waves-Electricity Use

The next few questions ask about the electricity use in the apartment and the specific actions taken during heat waves that is extended periods of excessively hot weather, which may be accompanied by high humidity from May to October.

3.1 How many times have you experienced extreme heat waves while living in this apartment?

1. 0-2
2. 3-5
3. 6-8
4. >8

3.2 What actions would/do you take during heat waves to feel more comfortable (check all that apply)?

3.2.a Use adjustable fan

1. Yes
2. No

9. Don’t know/refuse

3.2.a.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

3.2.b Use window air conditioning unit

1. Yes
2. No

9. Don’t know/refuse

3.2.b.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

3.2.c Adjust thermostat

1. Yes
2. No

9. Don’t know/refuse

3.2.c.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

3.2.d Use air purifier

1. Yes
2. No

9. Don’t know/refuse

3.2.d.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.2.e Use dehumidifier

1. Yes
2. No

9. Don’t know/refuse

3.2.e.1 If yes, which time of day do you usually take this action? (check all that apply)

○ Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.2.f Open windows

1. Yes
2. No

9. Don’t know/refuse

3.2.f.1 If yes, which time of day do you usually take this action? (check all that apply)

○ Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.2.g Close windows

1. Yes
2. No

9. Don't know/refuse

3.2.g.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

3.2.h Adjust clothing

1. Yes
2. No

9. Don't know/refuse

3.2.h.1 If yes, which time of day do you usually take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

3.2.i Refrain from using oven or stove

1. Yes
2. No

9. Don't know/refuse

3.2.i.1 If yes, which time of day do you usually take this action? (check all that apply)

○ Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.2.j Avoid hallways/stairs

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month
4. 1-3 times/week
5. Daily

3.2.j.1 If yes, which time of day do you usually take this action? (check all that apply)

○ Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.2.k Drink extra water

1. Never/Option not available
2. Not in the last month
3. 1-3 times/month

4. 1-3 times/week
5. Daily

3.2.k.1 Which time of day do you usually take this action? (check all that apply)

- ○ Morning (8:00 am - 12:00 pm)
- ○ Afternoon (12:00 pm – 4:00 pm)
- ○ Evening (4:00 pm – 8:00 pm)
- ○ Night (8:00 pm – 8:00am)

3.2.l If you leave your apartment in search of a cooler place, where do you go? (*Check all that apply, and apply the following question to each affirmative action. Then have respondent indicate locations on a map.*)

1. Cooling center
2. Sit in the shade (where?)
3. Movie theatre
4. Shopping mall
5. Visit relative or friend
6. Library
7. Community center
8. Public pool
9. Other: please describe

3.2.l.1 If yes, which time of day do you usually take this action? (check all that apply)

- ○ Morning (8:00 am - 12:00 pm)

○ Afternoon (12:00 pm – 4:00 pm)

○ Evening (4:00 pm – 8:00 pm)

○ Night (8:00 pm – 8:00am)

3.3 Are there any places you would prefer to go to cool down, but you cannot get there?

1. Yes
2. No

9. Don't know/refuse

3.3.a What prevents you from accessing these cooler destinations? (e.g., physical constraints, lack of affordable transportation, other)

____

3.4 What other actions do you take to make yourself feel more comfortable when room temperatures are not desirable?

____

____

3.4.a Which time of day do you usually take this action? (check all that apply)

- ○ Morning (8:00 am - 12:00 pm)
- ○ Afternoon (12:00 pm – 4:00 pm)
- ○ Evening (4:00 pm – 8:00 pm)

- Night (8:00 pm – 8:00am)

3.5 Have you experienced a power outage during a period of extreme heat?

1. Yes
2. No

9. Don’t know/refuse

3.5.1 If yes, how did you cope?

____

_

____

_

3.6 Do you participate in any programs that assist you with paying your utility bills?

1. Yes
2. No

9. Don’t know/refuse

4/ Demographics and Health

The next few questions are about some basic demographics and health.

4.1 What is your age?

1. 55-64
2. 65-74
3. 75-84
4. 85+

(check Census & PH categories)

4.2 What is your gender?

1. Female
2. Male

4.3 What is your educational level?

1. Elementary school
2. Secondary school
3. High school
4. Bachelor’s degree
5. Graduate degree

4.4 What was the total household income for the past year (in $)?

1. < 10,000
2. 10,000-19,999
3. 20,000-39,999
4. 40,000-49,999
5. =>50,000

4.5 In general, how would you characterize your health?

1. Very poor
2. Somewhat poor
3. Poor
4. Fair
5. Good
6. Somewhat good
7. Very good

9. Don’t know/refuse

4.5.1 What about other household members and their overall health?

1. Very poor
2. Somewhat poor
3. Poor
4. Fair
5. Good
6. Somewhat good
7. Very good

9. Don't know/refuse

4.6 Do you have a chronic medical condition that is exasperated by heat? (asthma, diabetes, COPD, emphysema, hypertension, etc.)

1. Yes
2. No

9. Don't know/refuse

4.7 Does anybody else in this household have a pulmonary or cardiovascular disease that is exasperated by heat?

1. Yes
2. No

9. Don't know/refuse

4.8 Have you ever sought out medical care because of the heat?

1. Yes
2. No

9. Don't know/ refuse

4.9 Do you have any relatives or friends nearby that you can call when in need?

1. Yes
2. No

9. Don’t know/refuse

4.9.1 In general, how often do you see your friends/relatives?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

4.10 Do you participate regularly in any community groups, religious groups, clubs, or other social groups?

1. Yes
2. No

9. Don’t know/refuse

4.10.1 How often do you participate in these groups or clubs?

1. Never
2. Rarely (1-3 days/month)
3. Sometimes (1day/week)
4. Often (>1 days/week)
5. Daily

4.11 How often do you interact with your neighbors (in person, by phone, other)?

1. Never

2. Rarely (1-3 days/month)

3. Sometimes (1day/week)

4. Often (>1 days/week)

5. Daily

5/ Catch All

5.1 Is there anything else you would like to add?

____

______

____

______

Follow-up Interview Protocol

DATE__ Interviewer___ CODE__

<u>Brief follow-up interviews:</u> Subjects will be engaged in brief follow-up interviews on days when heat wave advisories are in effect. These interviews most likely will be conducted by phone but it is possible that they will be conducted in person if circumstances permit (e.g., they are home and willing to meet us in person and if we can get there in a timely fashion to meet with multiple participants on the same day). The number of these interviews will depend on incidence of heat wave advisories and success rate in reaching the participant by phone or in person. Each brief follow-up interview will last approximately 10 minutes.

1/ Response to Heat Waves-Electricity Use

The next few questions ask about the electricity use in the apartment and the specific actions taken during heat waves that is extended periods of excessively hot weather, which may be accompanied by high humidity from May to October.

1.1 What actions did/do you take during the heat wave to feel more comfortable while in the apartment (check all that apply)?

1.1.a Use adjustable fan

1. Yes
2. No

9. Don't know/refuse

1.1.a.1 If yes, which time of day did/do you take this action? (check all that apply)

- o Morning (8:00 am - 12:00 pm)
- o Afternoon (12:00 pm – 4:00 pm)
- o Evening (4:00 pm – 8:00 pm)
- o Night (8:00 pm – 8:00am)

1.1.b Use window air conditioning unit

1. Yes
2. No

9. Don't know/refuse

1.1.b.1 If yes, which time of day did/do you take this action? (check all that apply)

- o Morning (8:00 am - 12:00 pm)
- o Afternoon (12:00 pm – 4:00 pm)

- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.c Adjust thermostat

1. Yes
2. No

9. Don't know/refuse

1.1.c.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.d Use air purifier

1. Yes
2. No

9. Don't know/refuse

1.1.d.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.e Use dehumidifier

1. Yes
2. No

9. Don’t know/refuse

1.1.e.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.f Open windows

1. Yes
2. No

9. Don’t know/refuse

1.1.f.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.g Close windows

1. Yes
2. No

9. Don’t know/refuse

1.1.g.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.h Adjust clothing

1. Yes
2. No

9. Don't know/refuse

1.1.h.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.1.i Refrain from using oven

1. Yes
2. No

9. Don't know/refuse

1.1.i.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)

- o Afternoon (12:00 pm – 4:00 pm)
- o Evening (4:00 pm – 8:00 pm)
- o Night (8:00 pm – 8:00am)

1.1.j Refrain from using stove

1. Yes
2. No

9. Don't know/refuse

1.1.j.1 If yes, which time of day did/do you take this action? (check all that apply)

- o Morning (8:00 am - 12:00 pm)
- o Afternoon (12:00 pm – 4:00 pm)
- o Evening (4:00 pm – 8:00 pm)
- o Night (8:00 pm – 8:00am)

1.1.k. Refrain from burning candles or incense?

1. Yes
2. No

9. Don't know/refuse

1.1.k.1 If yes, which time of day did/do you take this action? (check all that apply)

- o Morning (8:00 am - 12:00 pm)
- o Afternoon (12:00 pm – 4:00 pm)
- o Evening (4:00 pm – 8:00 pm)
- o Night (8:00 pm – 8:00am)

1.1.l Refrain from smoking inside

1. Yes
2. No non smoker

9. Don’t know/refuse

1.1.l.1 If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.2. Did you leave your apartment during the heat wave?

1. Yes
2. No

9. Don’t know/refuse

1.2.a If yes, where did you go?____________________________

1.3 Did you leave your apartment <u>specifically</u> in search for a cooler place?

1. Yes
2. No

9. Don’t know/refuse

1.3.a If yes, where did/do you go? (*Check all that apply, and apply the following question to each affirmative action. Also, indicate relevant locations on the provided map.*)

1. Cooling center

2. Sit in the shade
3. Movie theatre
4. Shopping mall
5. Visit relative or friend
6. Library
7. Community center
8. Swimming pool
9. Other: please describe

1.3.b If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.4 Are there any places you would prefer to go to cool down, but you couldn't/cannot get there?

1. Yes
2. No

9. Don't know/refuse

1.5 What prevented/prevents you from accessing these cooler destinations? (e.g., physical constraints, lack of affordable transportation, other)

____

1.6 Did/do you experience a power outage during the period of extreme heat?

1. Yes
2. No

9. Don't know/refuse

1.6.a If yes, how did/do you cope?____

____

____

1.6.a.1 Called a friend, relative, neighbor or community organization for help *<u>(circle all which apply</u>*)

1. Yes
2. No

9. Don't know/refuse

1.6.a.1.a If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.6.a.2 Left the apartment

1. Yes
2. No

9. Don't know/refuse

1.6.a.2.a If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

1.6.a.3 Other-Specify what:____

____

1.6.a.3.a If yes, which time of day did/do you take this action? (check all that apply)

- Morning (8:00 am - 12:00 pm)
- Afternoon (12:00 pm – 4:00 pm)
- Evening (4:00 pm – 8:00 pm)
- Night (8:00 pm – 8:00am)

2/ Health

The next few questions are about your health today.

2.1 How would you characterize your health today?

1. Very poor
2. Somewhat poor
3. Poor
4. Fair

5. Good

6. Somewhat good

7. Very good

9. Don't know/refuse

2.1.1 What about other household members and their health today?

1. Very poor

3. Somewhat poor

4. Poor

5. Fair

6. Good

7. Somewhat good

8. Very good

9. Don't know/refuse

2.2 Did the heat today affect any specific health conditions such as diabetes, hypertension, asthma or any other cardiovascular or pulmonary disease?

1. Yes

2. No

9. Don't know/refuse

3/ Catch All

3.1 Would you like to add anything?

Thank you for your time.

Closing-up Interview Protocol

DATE____________________ Interviewer________________

CODE__________

Brief closing-up interviews: Subjects will be engaged in one-time closing-up interviews on the day equipment gets uninstalled from their apartment. These interviews most likely will be conducted in person but it is possible that they will be conducted by phone if circumstances do not permit (e.g., they are not willing to meet us in person). Each brief closing-up interview will last approximately 10 minutes.

1. How would you compare the heat waves you experienced this summer (2017) to previous summers' heat waves while living here? (mainly in terms of temperature)

____

____

____

____

2. Actions:

2a) What did you do differently during the heat waves of this summer compared to in previous years?

- **In terms of air conditioning use?**
- **In terms of window activity?**
- **In terms of fan use?**
- **Other?**

____

2b) Did you take advantage of community cooling centers or other neighborhood places more or less this summer than in previous ones? (e.g. church, grocery store, movie theatre) [indicate in map]

2c) Did you go out to friends or relatives to escape the heat more / less this summer than in previous ones?

---

3. Here, there will (or not) be a question based on data anomalies detected in the sensors (mainly WEMO for apartments in M and F).

---

4. Devices:

4a) Did you notice a colored-light in one of the devices installed in your apartment? (here show them the Air Visual-if respondent says yes, explain to them what it was and what the color classification means)

1 = Yes

0 = No

9 = Don't know/refuse

4b) If yes,

Did you use the Air Visual to help you make decisions about closing or opening windows, going outside? or other actions?

1 = Never

2 = Rarely (1-3 days/month)

3 = Sometimes (1day/week)

4 = Often (>1 days/week)

5 = Daily

5. In the next spring (spring 2018), we will have some results from our study and we intend to visit the community and share them. Would you like to be informed of the presentation date? If yes, how would you like to be contacted?

6. Would you like to add anything? Is there something we should have asked you about heat waves but didn't?

7. Would you like to comment on any other aspect of your experience with this project?

e.g. better apartments, better outdoor areas, both of them? And if so, why?

Thank you for your time.

APPENDIX B SENSORS

Figure 1: The sensor network.

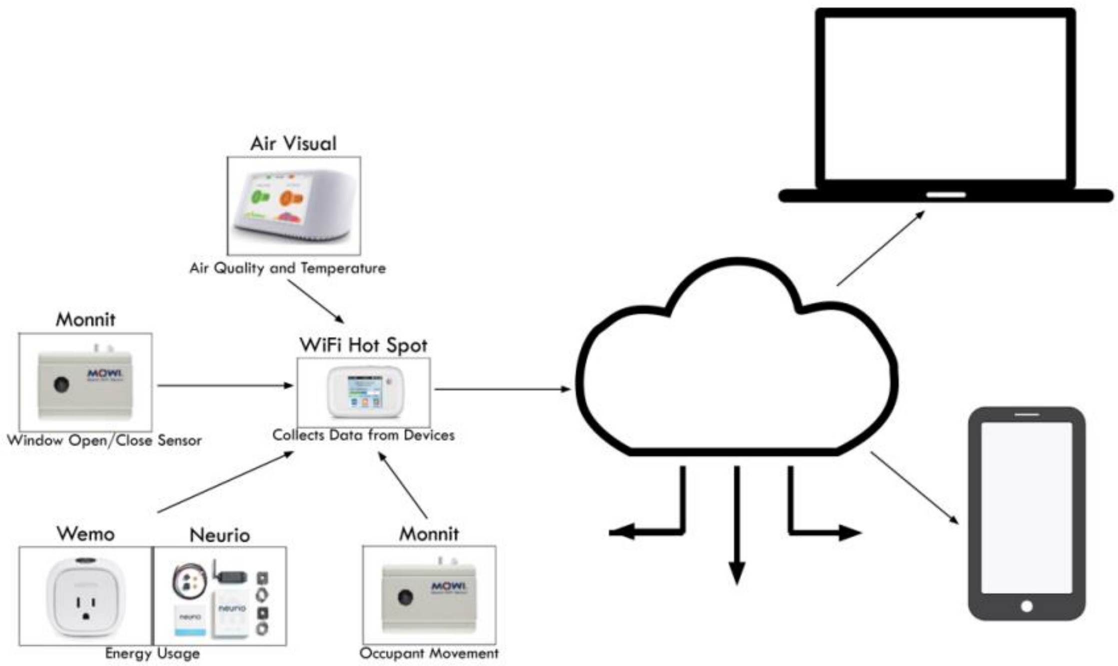
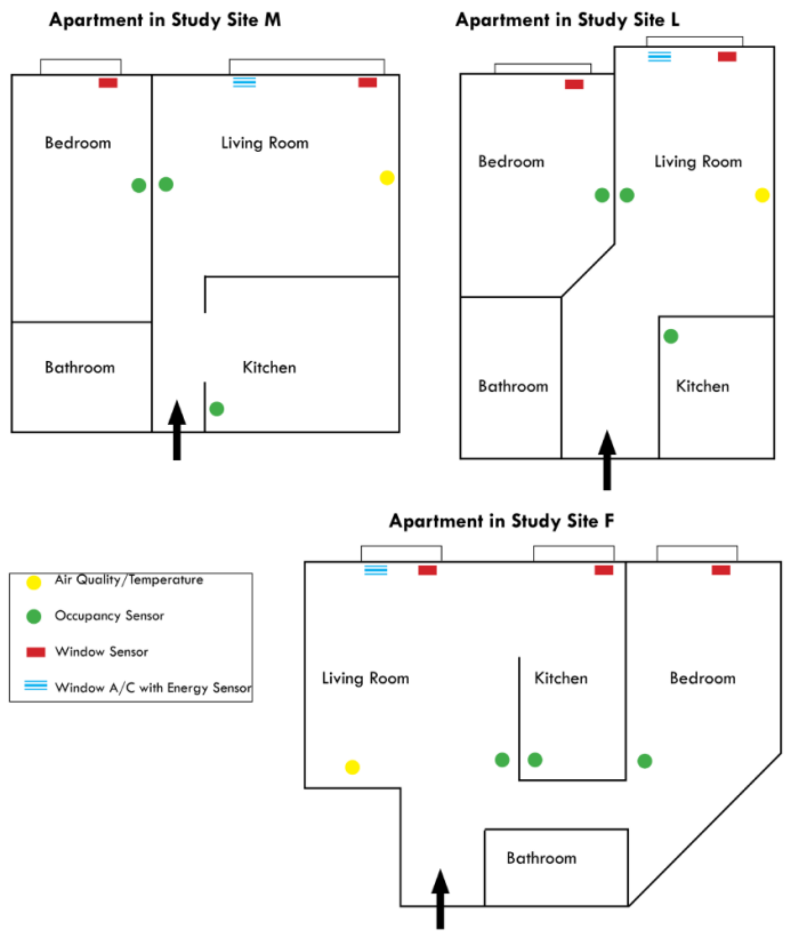


Figure 2: Sensor locations in typical sample apartments.



To calibrate the temperature and relative humidity data, three consumer-grade AirVisual Nodes (AirVisual, Hong Kong, China) and a professional-grade Indoor Air Quality Meter (IAQ 7545, TSI Inc., MN, USA) were put side-by-side in a 0.6 m wide x 1.2 m deep x 1.2 m high Aerosol Exposure Chamber (Lab Products, Inc., Aberdeen, MD, available from CH Technologies, Westwood, NJ, USA). The calibration experiment ran for 2.5 hours and 5-min average temperature and relative humidity data were measured by all sensors. The result showed that temperature readings from AirVisual Nodes had a nearly perfect linear correlation with the IAQ Meter readings with $R^2 > 0.98$, and the biases of temperature measured by AirVisual and IAQ Meter are within ±7%. All AirVisual Nodes either overestimated or underestimated the relative humidity, but they all showed good correlation with the IAQ Meter with R2 > 0.74, and the bias of the relative humidity by AirVisual and IAQ Meter are within ±7%. More information can be found at: *Ruikang He, Daniel Bachman, Dominick J Carluccio, Rudolph Jaeger, Jie Zhang, Sanjeevi Thirumurugesan, Clinton Andrews, and Gediminas Mainelis (2019). Evaluation of two low-cost sensors under different laboratory and indoor conditions*. *Submitted to Aerosol Science & Technology*. Several calibration tests were also conducted for the occupancy, window opening and A/C use data for two days (3 hours/day), where the Monnit (Monnit, Midvale, Utah, USA), WEMO (Belkin International, Los Angeles, CA, USA) and Neurio (Neurio Technology Inc., Vancouver, BC, Canada) devices were placed in an empty apartment and were compared with Ubisense SmartSpace (Cambridge, UK) to ensure they operated properly.

Table 1: Sensors' environmental and behavioral variables.

Group	**Variable**	**Data Period (2017)**	**N (Sensors/Apt)**	**Measure Interval**	**Data Acquisition**
Outdoor Environment	Ambient Temp. (C)	6/30 – 10/6	-	1 h	Device
	Relative Hum. (%)	6/30 – 10/6	-	1 h	Device
	PM2.5 (ug/m^3)	6/30 – 10/6	-	1 h	Device
	CO2 (ug/m^3)	6/30 – 10/6	-	1 h	Device
	O3 (ppb)	7/1 – 9/30	-	30 min	Device
Indoor Environment	Ambient Temp. (C)	6/30 – 10/6	1	1 h	Device
	Relative Hum. (%)	6/30 – 10/6	1	1 h	Device
	PM2.5 (ug/m^3)	6/30 – 10/6	1	1 h	Device
	PM10 (ug/m^3)	6/30 – 10/6	1	1 h	Device
	CO2 (ug/m^3)	6/30 – 10/6	1	1 h	Device

Behaviors	Occupancy (motion/no motion)	7/1 – 9/15	2 - 4	On state change	Cloud
	Window State (open/closed)	7/1 – 9/15	1 - 8	On state change	Cloud
	A/C Use (kwh)	7/1 – 9/30	1	30 min/1 h	Cloud/Device
	A/C State (open/closed)	7/1 – 9/30	1	30 min/1 h	Cloud/Device

APPENDIX C ANALYSIS

Table 1: Sensor measurements of indoor heat index (C) during summer 2017; Summary statistics.

		All Summer			**Heat Waves**		
Site	**Apartment**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
	Outdoor	25.22	16.72	49.29	25.77	17.86	49.29
	Empty A	27.44	24.50	33.39	28.69	25.93	33.39
A	A1	25.84	22.39	36.10	26.44	24.37	36.10
	A2	26.95	24.04	34.55	27.73	24.04	34.55
	A3	28.10	25.02	35.02	28.84	25.87	35.02
	A4	25.01	22.63	28.13	25.02	23.60	28.13
	A5	27.95	25.19	36.68	28.44	25.19	36.68
	A6	26.01	23.34	33.05	26.64	23.85	33.05
	A8	27.56	25.15	32.73	28.17	25.89	32.73
	A9	27.57	24.42	33.98	28.55	25.17	33.98
	A10	26.09	22.35	33.99	26.85	22.35	33.99
	A11	27.85	24.54	32.97	28.17	24.54	32.97
	A12	27.20	25.15	32.19	27.24	25.15	32.19
B	B1	25.27	23.47	29.02	25.35	23.47	28.21
	B2	27.42	25.22	33.75	27.63	25.32	33.75
	B3	26.53	24.57	30.87	26.76	25.63	30.87
	B4	26.88	25.06	31.76	27.40	25.83	31.76
	B7	25.75	23.97	30.59	25.77	23.97	29.89
	B8	26.79	24.44	30.08	27.00	24.44	29.63
	B9	25.66	24.13	29.81	26.04	24.47	29.81

	B10	25.19	23.11	27.99	25.21	23.11	27.99
	B11	24.95	22.51	27.15	24.89	22.51	27.15
C	C1	25.34	22.83	27.54	25.24	22.83	27.54
	C2	25.42	23.88	28.42	25.23	23.88	28.42
	C3	26.53	23.11	36.35	26.95	23.11	36.35
	C4	24.93	23.57	27.28	24.93	23.57	27.21

Table 2: Pearson correlations between the indoor and outdoor heat index. **Significant at the p=0.05 level.

	Indoor HI	
	All Data	**Heat Waves**
Outdoor HI	0.21*	0.11*

Table 3: Pearson correlations between the indoor heat index and the sites. *Significant at the p=0.05 level.

	Indoor HI	
	All Data	**Heat Waves**
Site A	0.34*	0.50*
Site B	-0.17*	-0.29*
Site C	-0.22*	-0.29*

Table 4: Pearson correlations between the indoor heat index and apartment characteristics. *Significant at the p=0.05 level.

	Indoor HI	
	All Data	**Heat Waves**

South	0.22*	0.27*
East	0.00	0.07*
Corner	0.05*	0.04*
Floor	-0.07*	-0.19*
Windows	0.13*	0.19*

Table 5: Pearson correlations between the indoor heat index and personal characteristics. *Significant at the p=0.05 level.

	Indoor HI	
	All Data	**Heat Waves**
Smoke	0.06*	0.01
Candles	0.13*	0.21*
Pets	-0.01*	0.12*
Community Active	-0.20*	-0.19*

Table 6: Pearson correlations between the indoor heat index and behaviors. *Significant at the p=0.05 level.

	Indoor HI	
	All Data	**Heat Waves**
Occupancy	0.03*	0.05*
Window Open	0.19*	0.31*
A/C On	-0.01*	-0.08*

Table 7: 5 Models of panel regression parameters for indoor heat index for all sites during heat waves of 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

Indoor HI (1 hour later)		M1	M2	M3	M4	M5
Outdoor Environment	Outdoor HI	0.04* (0.01)	0.04* (0.01)	0.04* (0.01)	0.04* (0.01)	0.01 (0.00)
Site Characteristics	Site A		2.00* (0.56)	2.59* (0.78)	2.66* (0.71)	1.26* (0.49)
Apartment Characteristics	Floor			0.18 (0.10)	0.24* (0.08)	0.12* (0.04)
Personal Characteristics	Community Active				-0.86 (0.57)	-0.23 (0.29)
Personal Behaviors	Occupancy					-8.63* (1.59)
	Window Open					-12.15* (1.09)
	A/C On					-1.41 (0.93)
Interaction Terms: Indoor Environment (1 hour earlier) and Behaviors	Indoor HI early * Occupancy					0.31* (0.05)
	Indoor HI early * Window Open					0.45* (0.07)
	Indoor HI early * A/C On					0.05 (0.03)
	Constant	25.99* (0.35)	25.07* (0.42)	24.21* (0.63)	24.61* (0.74)	25.91* (0.58)
	R2					
	Within	0.03	0.03	0.03	0.03	0.46
	Between	0.00	0.35	0.40	0.45	0.88

	Overall	0.01	0.26	0.29	0.32	0.75

Table 8: 3 Models of panel regression parameters for indoor heat index by site during summer 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

Indoor HI (1 hour later)		**A**	**B**	**C**
Outdoor Environment	Outdoor HI	0.02* (0.00)	0.02* (0.00)	0.01 (0.01)
Apartment Characteristics	Floor	-0.25 (0.17)	0.04 (0.00)	-0.12 (0.20)
Personal Characteristics	Community Active	-0.41 (0.22)	-0.11 (0.09)	-0.14 (0.21)
Personal Behaviors	Occupancy	-14.66* (2.99)	-13.55* (2.16)	-9.62* (3.11)
	Window Open	-12.73* (2.50)	-9.74* (2.06)	-17.07* (1.22)
	A/C On	-1.14 (0.69)	-3.37* (0.56)	-5.66 (3.45)
Interaction Terms: Indoor Environment (1 hour earlier) and Behaviors	Indoor HI early * Occupancy	0.54* (0.11)	0.52* (0.08)	0.37* (0.12)
	Indoor HI early * Window Open	0.47* (0.09)	0.37* (0.08)	0.67* (0.04)
	Indoor HI early * A/C On	0.04 (0.02)	0.13* (0.02)	0.22 (0.14)
	Constant	26.84* (0.68)	24.99* (0.18)	25.81* (0.89)

	R2			
	Within	0.77	0.68	0.65
	Between	0.95	0.98	0.98
	Overall	0.82	0.83	0.76

Table 9: 4 models of panel regression parameters for indoor heat index by nighttime and by daytime hours during summer 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

Indoor HI (1 hour later)		**M5 Night (10pm-6am)**	**M5 Day (7am-9pm)**	**M5 Night (Occupied Apt)**	**M5 Day (Occupied Apt)**
Outdoor Environment	Outdoor HI	0.03* (0.00)	0.02* (0.00)	0.04* (0.01)	0.04* (0.00)
Site Characteristics	Site A	0.58* (0.24)	0.57* (0.20)	0.88* (0.40)	1.00* (0.41)
Apartment Characteristics	Floor	0.07* (0.02)	0.08* (0.02)	0.13* (0.04)	0.15* (0.04)
Personal Characteristics	Community Active	-0.27 (0.15)	-0.35* (0.15)	-0.41 (0.26)	-0.61* (0.24)
Personal Behaviors	Occupancy	-10.46* (1.97)	-12.52* (2.36)	-	-
	Window Open	-15.62* (2.08)	-11.25* (2.23)	-20.28* (1.22)	-19.43* (0.91)
	A/C On	-2.62* (1.00)	-2.23* (0.93)	-4.09* (1.09)	-5.05* (1.39)
Interaction Terms:	Indoor HI early *	0.40* (0.07)	0.48* (0.09)	-	-

Indoor Environment (1 hour earlier) and Behaviors	Occupancy				
	Indoor HI early * Window Open	0.59* (0.08)	0.43* (0.08)	0.77* (0.04)	0.73* (0.03)
	Indoor HI early * A/C On	0.09* (0.03)	0.08* (0.03)	0.15* (0.04)	0.19* (0.05)
	Constant	24.90* (0.21)	25.14* (0.26)	24.37* (0.33)	24.49* (0.36)
	R^2				
	Within	0.71	0.72	0.58	0.60
	Between	0.93	0.93	0.82	0.76
	Overall	0.80	0.80	0.69	0.67

Table 10: Factor analysis results for apartment characteristics.

Factor	Eigenvalue
Factor 1	2.39
Factor 2	1.21
Factor 3	0.92
Factor 4	0.68
Factor 5	0.61
Factor 6	0.17

LR test: independent vs. saturated: chi2(15) = 1.2e+05 Prob>chi2 = 0.00

Variable	Factor 1	Factor 2	Uniqueness
Number of Bedrooms	0.90	0.02	0.18
South	0.51	-0.17	0.70
East	0.38	-0.69	0.37

Corner	0.53	0.60	0.36
Floor	-0.49	0.49	0.52
Number of Windows	0.80	0.32	0.25

Kaiser-Meyer-Olkin measure of sampling adequacy

Number of Bedrooms	0.54
South	0.39
East	0.68
Corner	0.70
Floor	0.77
Number of Windows	0.51
Overall	0.54

Rotated factor loadings (pattern matrix) and unique variances

Variable	**Factor 1**	**Factor 2**	**Uniqueness**
Number of Bedrooms	0.80		0.18
South	-	-	0.70
East		0.79	0.37
Corner	0.75		0.36
Floor		-0.66	0.52
Number of Windows	0.86		0.25

Table 11: 4 models of panel regression parameters for indoor heat index with apartment characteristics-related factors 1 and 2 during summer 2017. Random effects with robust standard errors. *Significant at the p=0.05 level.

Indoor HI (1 hour later)	**M5** **All Data** **2 Factors**	**M5** **All Data** **1 Factor**	**M5** **Occupied Apt** **2 Factors**	**M5** **Occupied Apt** **1 Factor**

Outdoor Environment	Outdoor HI	0.02* (0.00)	0.02* (0.00)	0.04* (0.00)	0.04* (0.00)
Site Characteristics	Site A	0.32* (0.14)	0.22 (0.16)	0.46 (0.24)	0.29 (0.28)
Apartment Characteristics	Factor 1	0.13 (0.08)	0.14 (0.09)	0.23 (0.15)	0.25 (0.16)
	Factor 2	-0.08 (0.08)	-	-0.14 (0.13)	-
Personal Characteristics	Community Active	-0.22 (0.14)	-0.16 (0.13)	-0.34 (0.24)	-0.23 (0.23)
Personal Behaviors	Occupancy	-11.45* (2.01)	-11.40* (2.01)	-	-
	Window Open	-13.47* (1.88)	-13.50* (1.88)	-19.84* (0.96)	-19.84* (0.96)
	A/C On	-2.64* (0.78)	-2.64* (0.78)	-4.76* (1.09)	-4.76* (1.09)
Interaction Terms: Indoor Environment (1 hour earlier) and Behaviors	Indoor HI early * Occupancy	0.44* (0.07)	0.44* (0.07)	-	-
	Indoor HI early * Window Open	0.51* (0.07)	0.51* (0.07)	0.75* (0.03)	0.75* (0.03)
	Indoor HI early * A/C On	0.09* (0.03)	0.09* (0.03)	0.18* (0.04)	0.18* (0.04)
	Constant	25.49*	25.50*	25.12*	25.13*

		(0.22)	(0.23)	(0.27)	(0.29)
	R^2				
	Within	0.71	0.71	0.60	0.60
	Between	0.93	0.94	0.80	0.80
	Overall	0.80	0.80	0.67	0.67

Table 12: Behavioral changes-comparison of summer 2017 with previous summers.

			All Sites	**A (N=11)**	**B (N=9)**	**C (N=4)**
	Variable	**Category**	**% of Sample**	**% of Sample**	**% of Sample**	**% of Sample**
	Heat of 2017	More	12%	9%	22%	0%
	Vs	Same	34%	36%	22%	75%
	Heat before 2017	Less	54%	45%	56%	25%
Indoor Behaviors	A/C	More	16%	19%	34%	0%
		Same	45%	54%	11%	100%
		Less	39%	27%	55%	0%
	Windows	More	25%	9%	55%	0%
		Same	75%	91%	45%	100%
		Less	-		-	-
	Fan	More	25%		34%	0%
		Same	42%	54%	32%	100%
		Less	33%		34%	-
Outdoor Activities	Lobby/Cooling Room	More	0%	0%	0%	0%

		Same	100%	100%	100%	100%
	Yards/Gardens	More	25%	9%	9%	-
		Same	75%	91%	91%	-
	Visit Relative/Friend	More	9%	0%	22%	0%
		Same	91%	100%	78%	100%

Table 13: Percentage of kitchen and living room WO coefficients for indoor HI and PM2.5: linear regression results.

% of Kitchen and Living Room WO Coefficients		
s indicates smoking	**Indoor HI** * statistically significant at the p=0.05 level.	**Indoor $PM_{2.5}$** * statistically significant at the p=0.05 level.
A1	-0.54* (0.15)	4.09 (3.54)
A2	-0.57* (0.17)	1.51 (1.01)
A3 s	-0.77* (0.27)	12.94 (22.11)
A4	-0.70* (0.15)	-0.29 (13.00)
A5	1.32* (0.00)	-1.57 (1.62)
A6	-0.11 (0.11)	-1.34 (0.78)
A8 s	-0.52* (0.14)	-130.67* (10.39)
A9	0.44* (0.18)	-1.86* (0.89)
A10	0.59* (0.13)	-6.23* (2.27)
A11	-	-
A12 s	1.52* (0.12)	-34.55* (6.90)
B1 s	0.16 (0.39)	-116.87* (46.63)
B2 s	0.70* (0.09)	-152.84* (15.27)

B3 s	-0.64* (0.04)	-36.60* (5.83)
B4 s	1.41* (0.18)	-13.15* (5.64)
B7	0.36* (0.07)	-1.59 (5.68)
B8	-2.37* (0.29)	145.08* (21.54)
B9	0.30* (0.05)	-7.91 (4.51)
B10	0.40* (0.03)	-0.60 (1.73)
B11 s	0.17* (0.03)	-22.57 (12.39)
C1	-0.07 (0.07)	-1.52 (1.10)
C2	-	-
C3	0.94* (0.10)	0.39 (2.20)
C4	0.20* (0.04)	-0.78 (1.92)

Table 13: Residents' key behaviors (N=24) as derived from the interviews.

	Indoor Smoking[15]	**Pets**	**Lighting Candles**
A1	No	Yes	Sometimes
A2	No	No	Sometimes
A3	Yes[16]	No	Daily
A4	No	Yes	Daily
A5	No	No	Daily
A6	No	Yes	Daily
A8	Yes	No	Often
A9	No	Yes	Often
A10	No	Yes	Often
A11	No	No	Daily
A12	Yes	Yes	Often
B1	Yes	No	Daily

[15] Indoor smoking is not allowed in site C.
[16] A3 is a passive smoker.

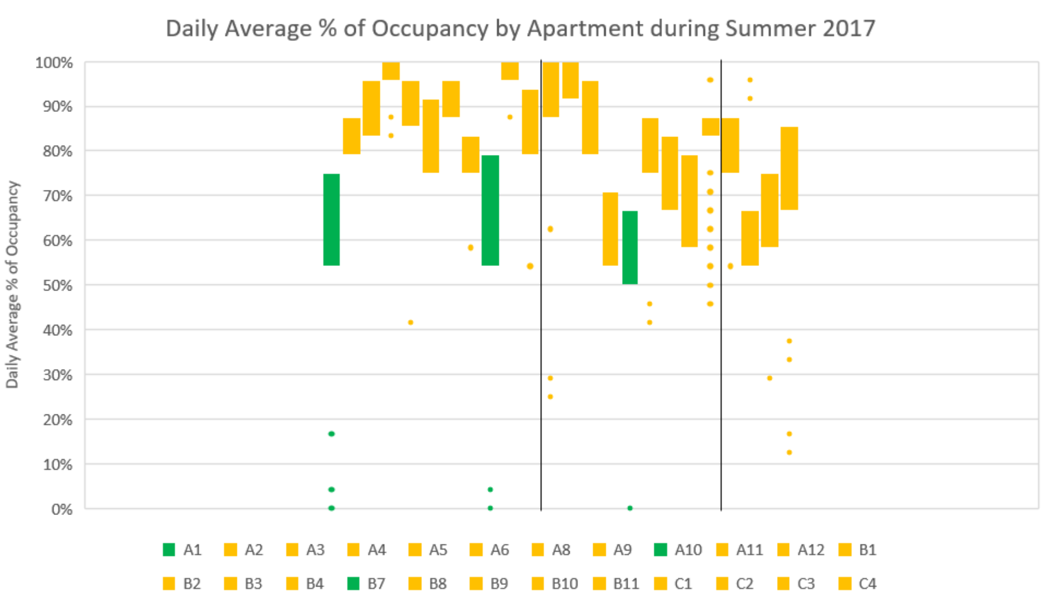
B2	Yes	No	Daily
B3	Yes	No	Never
B4	Yes	No	Daily
B7	No	No	Rarely
B8	No	No	Daily
B9	No	No	Often
B10	No	No	Daily
B11	Yes	No	Daily
C1	No	No	Daily
C2	No	No	Rarely
C3	No	No	Rarely
C4	No	No	Never

Table 14: Key apartment characteristics (N=24) as derived from the interviews and apartment plans.

	Number of Bedrooms	**Façade Orientation**	**Story**	**No. of Windows**	**No. of Window A/C Units**	**Cross ventilation**
A1	1	South-west	1	6	2	Yes
A2	2	South-east	1	8	1	Yes
A3	2	South-east	2	8	1	Yes
A4	1	South-east	3	6	1	Yes
A5	1	South-east	1	6	0	Yes
A6	2	South-east	2	8	2	Yes
A8	1	South-west	1	6	2	Yes
A9	2	South-east	2	8	3	Yes
A10	1	North-west	1	6	2	Yes
A11	2	South-west	2	8	2	Yes

A12	1	North-west	1	6	2	Yes
B1	1	East	2	6	1	No
B2	1	West	11	6	1	No
B3	1	South-east	8	6	2	Yes
B4	1	West	3	6	1	No
B7	1	North-west	5	6	1	Yes
B8	1	South-west	7	6	1	Yes
B9	1	South-west	6	6	2	Yes
B10	1	North-east	3	6	1	Yes
B11	1	North-east	2	6	1	Yes
C1	1	South-east	3	6	N/A	No
C2	1	North-west	3	8	N/A	Yes
C3	1	North-east	4	8	N/A	Yes
C4	1	North-west	4	8	N/A	Yes

Figure 1: Calculated daily average % of occupancy by apartment during summer 2017. Only apartments A1, B7 and A10 have 0% occupancy for limited days.



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