



Summertime thermal conditions and senior resident behaviors in public housing: A case study in Elizabeth, NJ, USA

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ABSTRACT

As heat waves become more extreme, there is a growing concern for the health of elderly city dwellers who have poor living conditions and limited access to resources. Much research has documented socioeconomic links to heat vulnerability, but limited studies have investigated the detailed living conditions of vulnerable populations, despite increasing requests from local communities. In this paper, we examine the summertime thermal performance of 24 senior apartments within 3 public housing sites (2 conventional multifamily and 1 LEED-rated building), and the seniors' adaptive responses in Elizabeth, NJ, USA. Time-series data were collected from sensors, interviews and observations on the thermal environment and behavior, from May–October 2017. Our multi-level, occupant-centric approach utilizes the indoor heat index as a proxy for heat stress, against site and building characteristics, and environmental and personal variables. Panel regressions show thermal variations among sites/apartments and illustrate the significant effect of actions, such as window opening and air conditioner use. Results also show how the seniors' adaptive responses vary by site; residents with central air-conditioning use it, while residents from the two older sites engage in a wider range of adaptive actions, and in some cases achieve similar indoor heat indexes as apartments from the green building. Indoor heat stress experienced by low-income seniors can be greatly reduced through cost-effective strategies that target individual behaviors and outdoor amenities. This implies the need for integrated solutions to the heat waves problem across scales; including changes to residents' habits, building envelopes, building operations, and outdoor spaces.

1. Introduction

Our changing climate is increasing the frequency of extreme heat events, which cause both local and global impacts [35,36,76]. 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) [47,71]. 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 [39,41,65,75]. 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 [19,20]. This long causal chain is especially likely to affect those suffering from chronic, pre-existing heart and lung conditions, children and the elderly

[20,35,48].

According to the Intergovernmental Panel on Climate Change, vulnerability to climate change includes both the sensitivity of socio-economic and biophysical systems and their ability to cope with actual or expected impacts of climate change [24,36]. Heat vulnerability at the individual level is influenced by age, gender, health status, race, income, and educational levels [10,12] that are often linked to location attributes and built environment characteristics [43,66,68,83]. 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 [68]. Lastly, indoor living conditions and the indoor environment are particularly important, considering that people, and especially seniors, spend about 90% of their time indoors [7,46,73].

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

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conditions [4,40], which makes them more susceptible to environmental challenges [80]. 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 [16]. showed that improvements in building systems, such as the installation of air-conditioning, can lower the impact of heat on senior mortality. More recently [38], 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 indoor thermal conditions in senior, low-income housing and the factors that affect them [56].

In this article, we examine the summertime indoor heat conditions experienced by senior residents who live in public housing sites in Elizabeth, NJ, USA. We monitor indoor and outdoor thermal conditions and occupant behaviors and document apartment and site amenities, in order to understand the relative significance of those variables in determining variability in the residents' experiences. We find great variability in adaptive actions due to the influence of site, building, apartment and occupant-specific factors. The following sections briefly review past research and current knowledge gaps on the social and physical factors affecting indoor thermal environments.

1.1. 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 [63]. In both cases, an integrated design approach is preferred that considers several factors, including the climate, building characteristics and technology, occupant behaviors and operational practices [51].

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 [9,55,56]. 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 [56]. In addition, common practice largely ignores aspects of occupant behavior and their effect on a building's thermal conditions and related energy use [2,8,60].

Research focusing on thermal comfort adopts instead an occupant-centric approach that aims at understanding the effect of human behavior [63], since occupants are the end-users of energy in buildings [17]. Thermal comfort is generally perceived as the human perception of satisfaction with the thermal environment based on external and internal stimuli [6]. More recently, several studies have started approaching a building's comfort and efficient operation in an integrated fashion [50,53,63,81], and the contribution of occupants' adaptive behaviors is well recognized [34,50]. However, it is still quite challenging to formally include multiple aspects of those behaviors in building performance simulation (BPS) tools [2,60].

Perhaps the most dominant model of thermal comfort is the Predicted Mean Vote (PMV) by Ref. [30]; which has been incorporated in the ASHRAE-55 and ISO 7730 standards [6,37]. 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 [44,63]. An alternative to the PMV is the adaptive model, which is also part of the ASHRAE 55 and ISO 7730 standards [6,37], and linearly connects indoor operative temperature

and satisfaction with the outdoor temperature [29,44,63]. PMV is generally used in mechanically-ventilated buildings, and the adaptive model is preferred in naturally-ventilated buildings [6].

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 [44,64]. 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.

1.2. 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 infrastructures [66]. Much research has recognized that when temperatures are up, low-income seniors are among the most vulnerable groups (see Refs. [10,35,48,66]). 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 [45,49].

Yet, as seen previously, 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 Ref. [26]; McMichael et al., 2008; [62,75,78,84], 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 Refs. [9,55,56], 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 Refs. [29,44,64], do not often address the adaptive responses of seniors in low-income sites (see Refs. [33,54,79].

Heat adaptation described as the adjustment process to heat and its effects [25], is challenging at socially vulnerable sites, as there are fewer resources, guides and institutions to provide support [13]. The availability of residential air conditioning is recognized by many as one of the most effective adaptation measures (see Refs. [52,77] 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 [77]. Yet, about 13% of the US households still lack A/C [28] and those households are disproportionately poor, while landlords are not required to provide cooling in most places [22,31]. 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) [11,21]. Lastly, A/C use may not be a preferred adaptation action, as it increases energy demand and greenhouse gas emissions [45].

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 [11]. 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 [82]. Many studies also highlight the spatial scales of heat adaptation [45]; 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 [82],

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 [9], approach people, housing and neighborhood as a complex, social-ecological system (SES) 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 the heat adaptation outcomes.

1.3. Research objectives

In this work, we adopt a multi-level perspective to examine the joint contributions of social-ecological factors, such as the local climate and the site characteristics including building systems, social context and individual agency, on the heat coping processes. Our focus is on the summertime thermal performance of senior apartments within public housing sites in the US with varied characteristics indoors and outdoors, and the seniors' adaptive responses to this performance. Our data come from interviews with the residents, field visits to apartments and sites, and sensors documenting the thermal environment and occupant behaviors during the summer of 2017. Our research question asks *how do poor urban seniors cope with summer heat waves and what are the relative roles of neighborhoods, buildings and occupants in managing hot conditions*. Our occupant-centric approach to indoor thermal comfort examines heat index, as a proxy for heat stress, against site and building characteristics, and environmental and personal variables. We expect that seniors spend most of their time indoors, especially when summer temperatures are up. Therefore, we hypothesize that:

- Outdoor thermal conditions can influence indoor thermal conditions, and certain site and apartment characteristics can moderate or strengthen this relationship.
- Occupants engage in adaptive actions that can also influence indoor thermal conditions and are subject to personal characteristics, but also to the indoor and outdoor resources they have available. Their responses are particularly important in sites where indoor environments are inadequate in providing shelter.

Based on the above, the objectives of this study 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.

2. Methods

2.1. Data collection

Longitudinal environmental and behavioral data were collected between May–October 2017 at three public housing sites operated by the Housing Authority of the City of Elizabeth (HACE) in Elizabeth, NJ, USA. 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 $\mu\text{g}/\text{m}^3$), and the highest annual average (9.58 $\mu\text{g}/\text{m}^3$) ambient particulate matter (PM_{2.5}) concentration among NJ stations [57]. As shown in Fig. 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 [41,65,75].

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 [66,71]. Another consideration is that elderly populations may be socially isolated and physically frail [14,32], which justifies our focus on senior apartments within the sites shown in Fig. 2. Lastly, the selection of 3 sites additionally maximizes variation by building characteristics and nearby outdoor amenities, summarized in Table 1 of Supplementary Material, Appendix C. 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.

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

2.1.1. Subject recruitment and interviews

In cooperation with HACE, the research team organized three on-site information sessions 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. During each session, English and Spanish-speaking team members attended and lunch was served. Recruitment included senior residents (> 55 years) who were willing to participate. XXXX University's Institutional Review Board protocol #14-327 M (expedited approval per 45 CFR 46.110(b)(2)) governed our 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 team members stored the interview data 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 2 of Supplementary Material, Appendix C. 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 Ref. [23], 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 [42]).

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, shown in section 3.1. 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

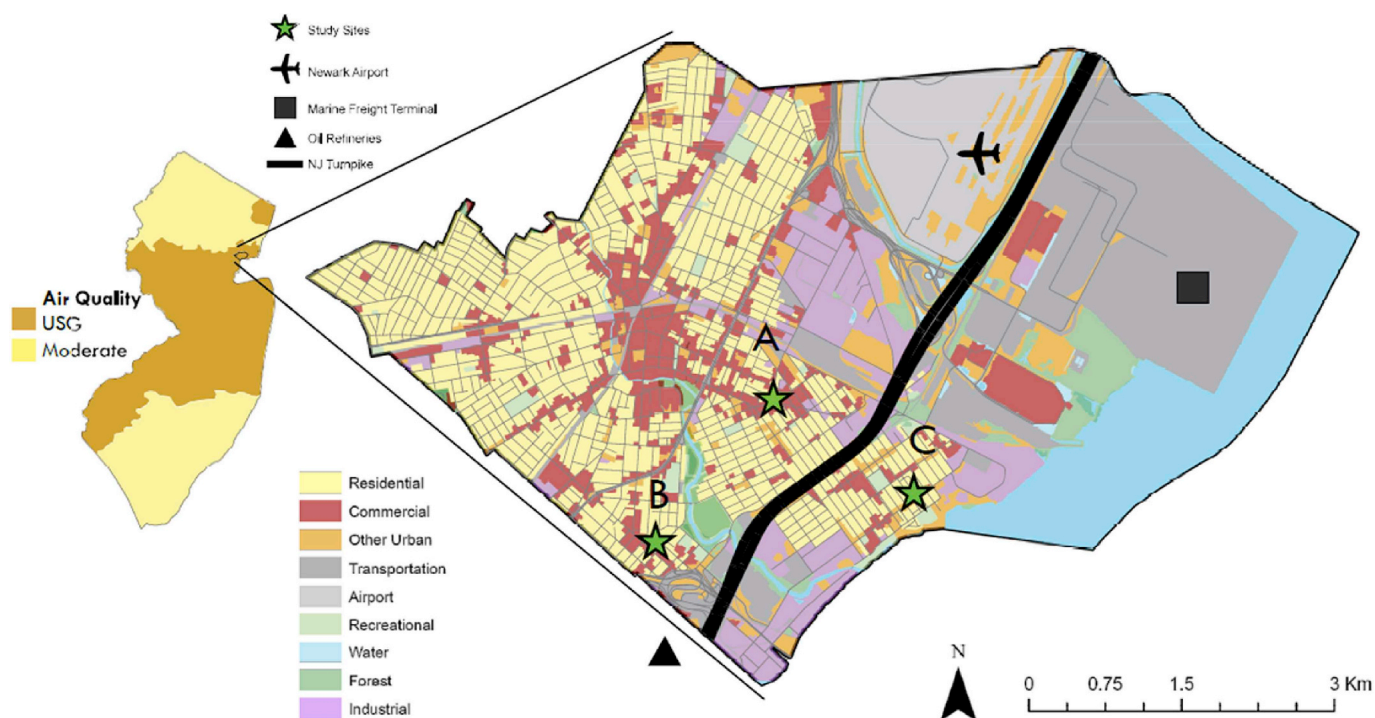


Fig. 1. Pollution sources in Elizabeth, NJ and the location of study sites A, B, and C [1,59].

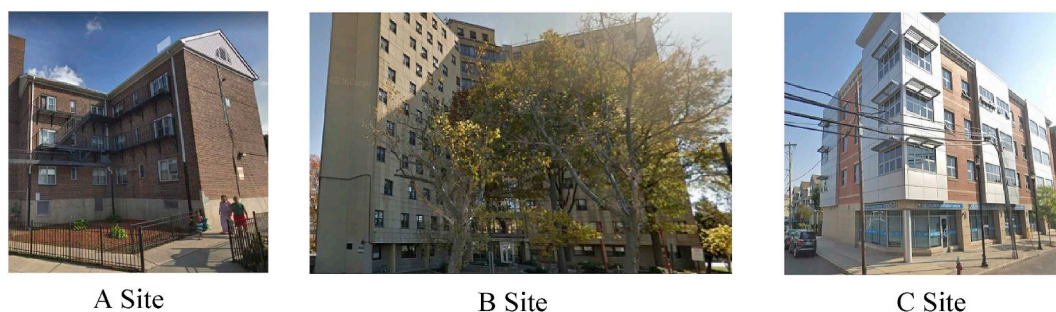


Fig. 2. The three public housing sites (A, B and C) in Elizabeth, NJ.

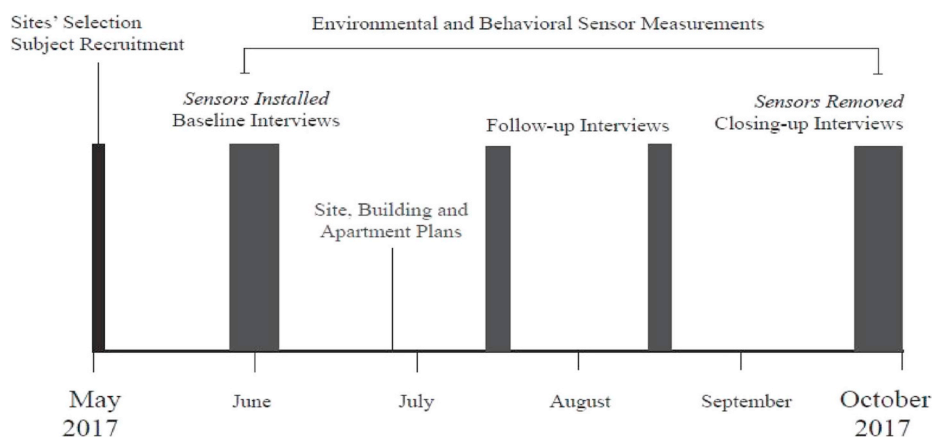


Fig. 3. The study timeline; collection of data from interviews, plans and sensor measurements across summer 2017.

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](#).

2.1.2. Sensor measurements

The research team purchased consumer-grade sensors measuring thermal conditions (temperature, humidity) and occupant behaviors

(occupant presence, window opening and air-conditioner (A/C) use) in Fall 2016 and calibrated them 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 m 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 0.4–0.8 m height and at least 0.5 m from the wall. The sensor names, detailed calibration procedure, network and the locations in sample apartments can be found in Supplementary Material, [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-h period for approximately 3 months on the variables shown in Table 1 of [Appendix B](#). Table 3 of [Appendix C](#) summarizes the measurements and their observed range for each variable during all summer and during heat waves.

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-h 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-h intervals.

2.1.3. Site, building and apartment plans

After the end of the baseline interviews and the sensor installation, the research team obtained hard copies of building and apartment plans from HACE and digitized them in AutoCAD and Sketchup. Alongside the plans, team members also prepared site maps 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 4 of Supplementary Material, [Appendix C](#) summarizes key variables from the apartment plans and [Fig. 4](#) shows typical apartment layouts.

2.2. Data analysis

The data analysis in this paper is guided by the premise that since seniors spend about 90% of their time indoors [7,46,73], indoor environmental quality is particularly important for their health and well-being [3]. When summer temperatures are up, the focus is on the indoor heat stress, which, here, is approximated by the heat index (HI), calculated from the combination of temperature and humidity measurements as a more representative measure of human stress [67,75]. Therefore, we adopt a multi-level, occupant centric approach that examines HI outcomes 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 [Fig. 5](#) illustrates this causal chain affecting the health and well-being of low-income seniors during heat waves.

The analysis that follows starts with descriptions of the outdoor thermal performance during the summer of 2017 and identifies periods of extreme heat and hourly variations. It then zooms into the indoor thermal conditions and shows variations within sites and within apartments during all summer and during heat waves. 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. Results

3.1. Outdoor thermal performance

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” [58], with New Jersey specifying a heat wave as a maximum daytime temperature above 32° C for two or three consecutive days, often along with elevated night-time temperatures [70]. As suggested by Ref. [69]; “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. [Fig. 6](#) shows the outdoor heat index (OHI), as derived from the environmental devices, during summer 2017. The OHI variable was created based on the formula found in Ref. [72],¹ which combines outdoor ambient air temperature and relative humidity. Black arrows indicate the hottest days, which, along with the definition of [58]; define the heat wave periods of summer 2017. Figure 0 of Supplementary Material, [Appendix C](#) shows the hourly OHI variations; values increase during morning and afternoon.

Based on [Fig. 6](#), the heat wave periods of summer 2017 are:

- 1st: 7/1–7/3
- 2nd: 7/11–7/13
- 3rd: 7/15–7/22
- 4th: 7/31–8/4
- 5th: 8/18–8/19 & 8/21–8/22.

3.2. Indoor thermal performance

Indoors, air temperature and relative humidity sensor measurements are 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% [61]. 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 75–80.5 °F (24–27 °C) and indoor humidity levels to be kept

¹ The Heat Index equation as found in Ref. [72] is:

$$HI = -42.379 + 2.04901523 \times T + 10.14333127 \times R - 0.22475541 \times T \times R - 6.83783 \times 10^{-3} \times T^2 - 5.481717 \times 10^{-2} \times R^2 + 1.22874 \times 10^{-3} \times T^2 \times R + 8.5282 \times 10^{-4} \times T \times R^2 - 1.99 \times 10^{-6} \times T^2 \times R^2$$
 where T is ambient temperature and R is relative humidity.

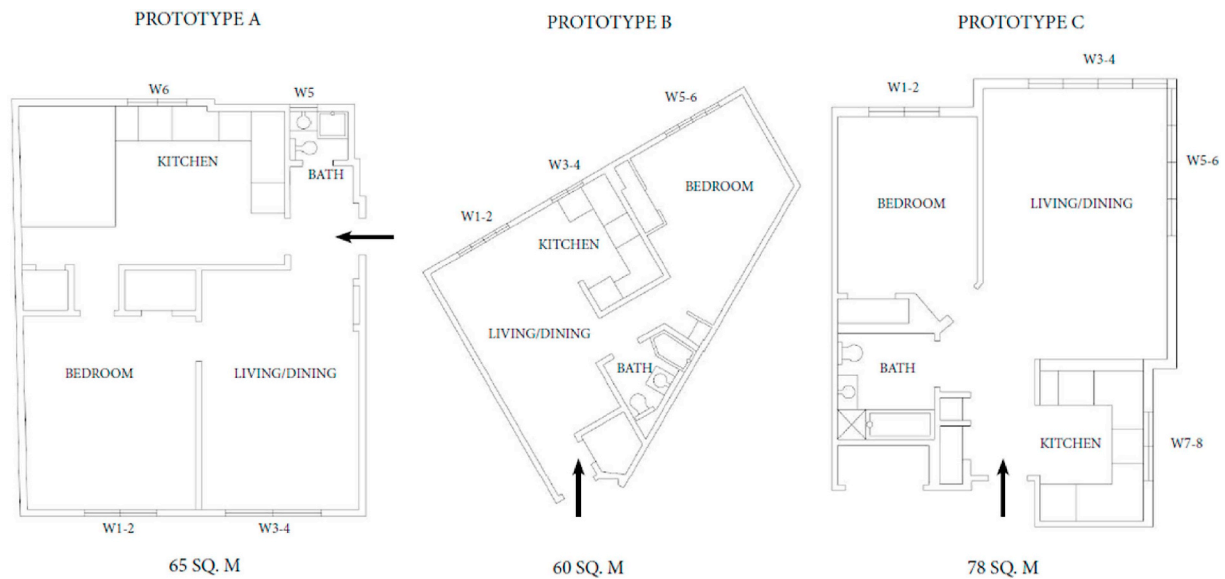


Fig. 4. Typical 1-bedroom apartment layouts from each study site A, B and C.

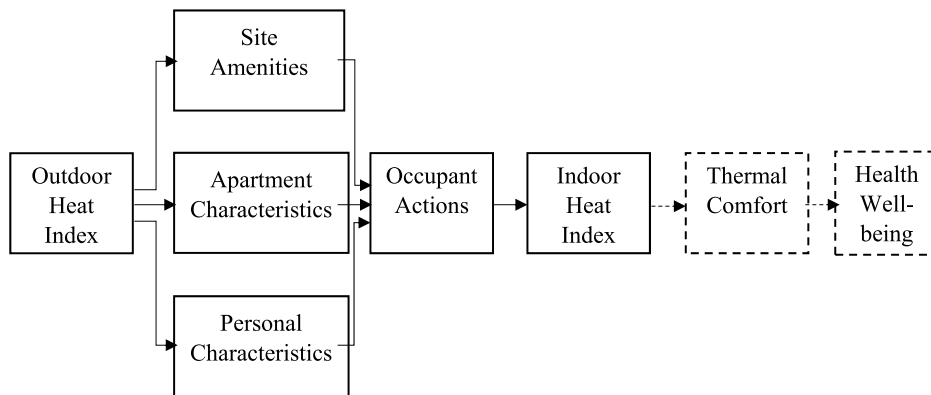


Fig. 5. Conceptual framework explaining the factors affecting health and well-being of seniors in public housing sites during heat waves. Indoor heat index that approximates thermal comfort or discomfort becomes the most important aspect of indoor environmental quality and links to the outdoor heat index, 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.

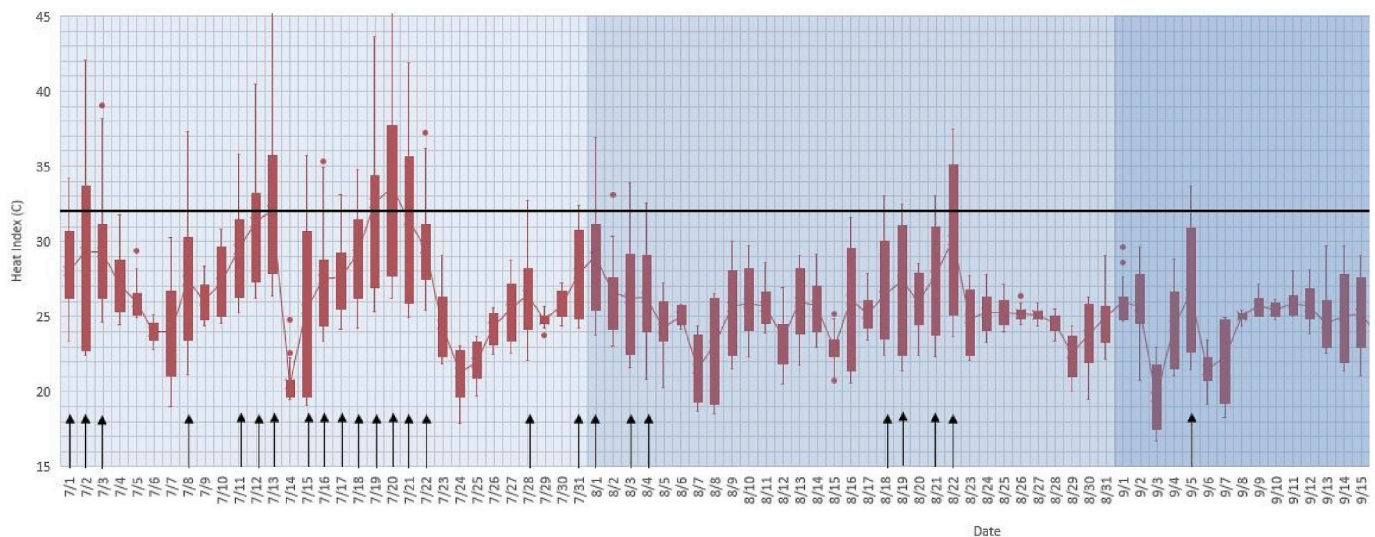


Fig. 6. Calculated outdoor heat index (C) based on sensor measurements and the 5 heat wave periods of summer 2017.

below 65%, considering standard clothing levels [6].

3.2.1. Variations across and within sites

When comparing indoor HIs among sites and with the outdoor HI during all summer (Fig. 7), 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 outdoor HI, especially in the highest peaks that occur during heat waves. This is expected, since they are all cross-

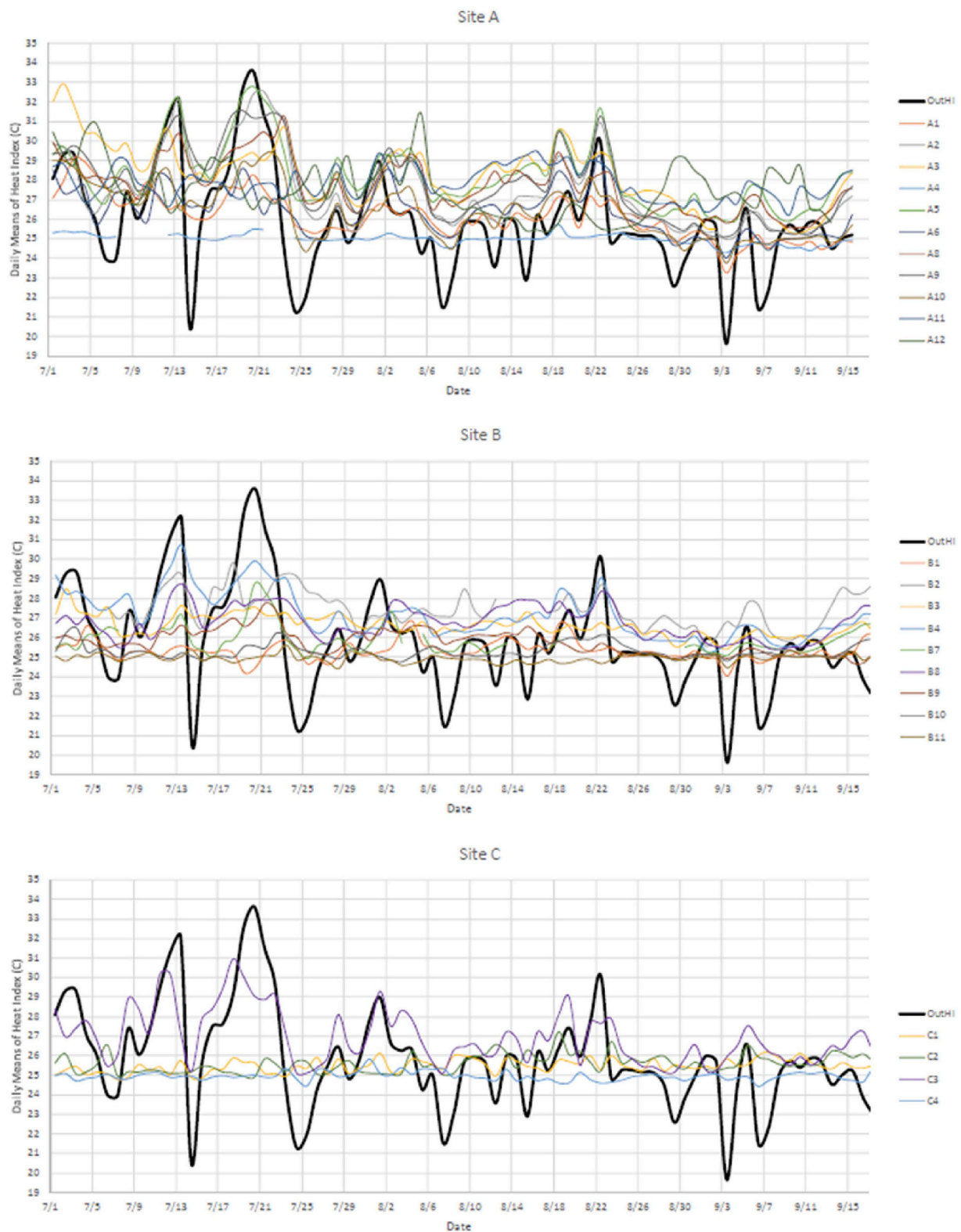


Fig. 7. Daily averages of calculated indoor heat index (C) based on sensor measurements by site during summer 2017. Apartments in A have the highest indexes, while many of them follow a similar trend with the outdoor HI.

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 outdoor HI 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 outdoor HI variations, both during the heat wave and the non-heat wave periods; the rest have low daily averages and no significant peaks.

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 0 of Supplementary Material, [Appendix C](#). Specifically,

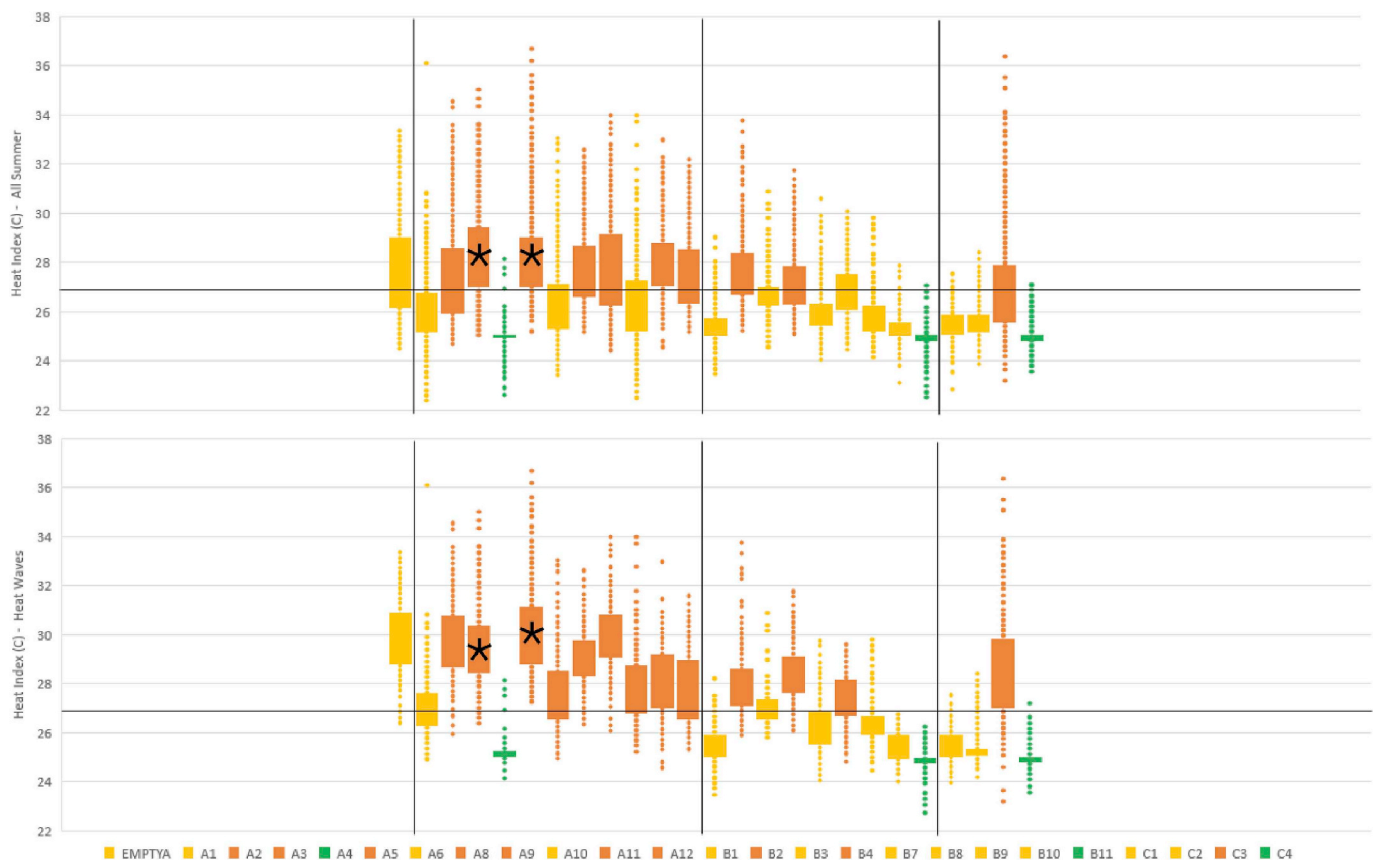


Fig. 8. Calculated indoor heat index (C) based on sensor measurements during summer and during heat waves of 2017. Green indicates apartments with the lowest IHIs, yellow corresponds to mid values and orange indicates high IHIs that exceed 27 C. 13 apartments exceed the threshold of 27 C during the heat wave periods. Apartments A3 and A5 (highlighted with asterisk) have considerably higher heat indexes compared to apartments A4, B11 and C4 (highlighted in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

indoor HI 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.

When comparing indoor heat indexes among apartments within each site (Fig. 8), 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 IHIs 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.

1-way ANOVA test further confirms the statistically significant IHI variations between the sample apartments ($F = 1,892.58$, $p = .000$), found in Table 0 of Supplementary Material, Appendix C. Based on a Turkey post-hoc test, it is further shown that the indoor HI is statistically significantly higher in apartments A3 and A5 compared to apartments A4, B11 and C4.

Lastly, time variations in the heat indexes of selected apartments can be found in Fig. 1 of Supplementary Material, Appendix C and 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 indoor HI 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.

3.3. 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 Supplementary Material, 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 indoor heat index 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 the residents.

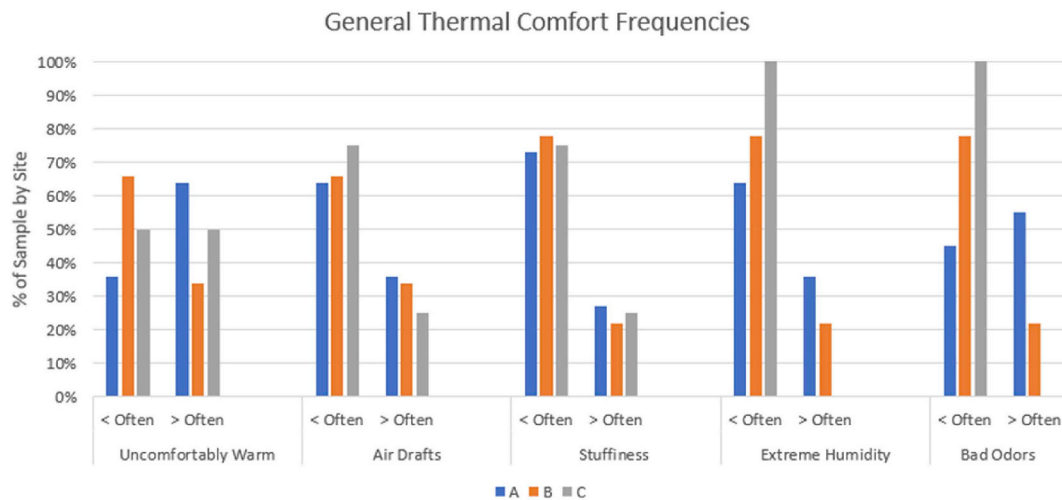


Fig. 9. Self-reported general thermal comfort during summer of 2017 from the baseline interviews. A high percentage of residents located in site A report thermal discomfort, followed by residents in C and B.

3.3.1. Indoor thermal comfort

As documented in the baseline interviews, the overall self-reported comfort of seniors across sites shows a consistent story with the sensors (Fig. 9). 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 (see Fig. 10).

3.3.2. Adaptive behaviors across and within sites

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

Regarding the time of day they take each action, as shown in Fig. 2 of Supplementary Material, [Appendix C](#), 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.

There are also interesting variations in the residents' key behaviors across different sites during heat waves, based on the follow-up interviews. 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, window opening 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

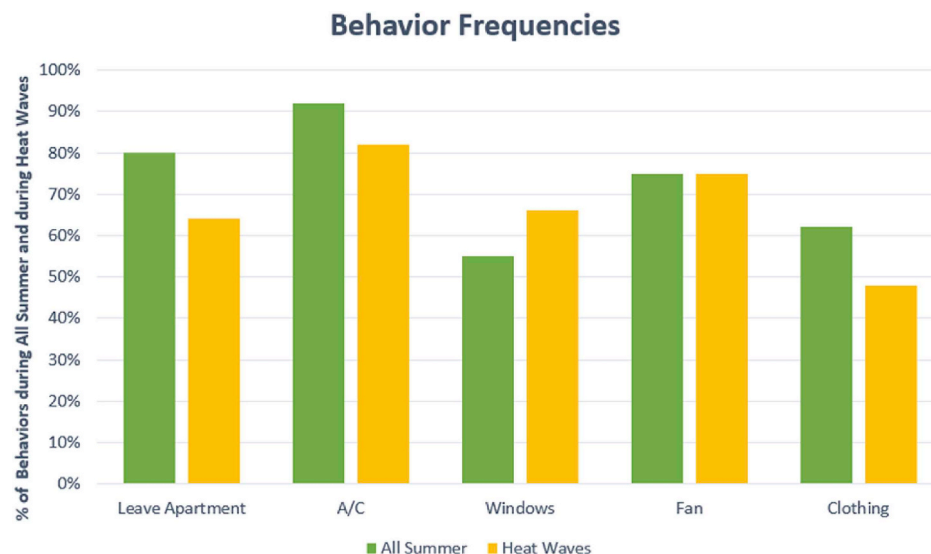


Fig. 10. Self-reported key adaptive behaviors during summer and during heat waves of 2017. (Windows indicates window opening.) During heat waves, A/C use and leaving the apartment go down and window opening goes up.

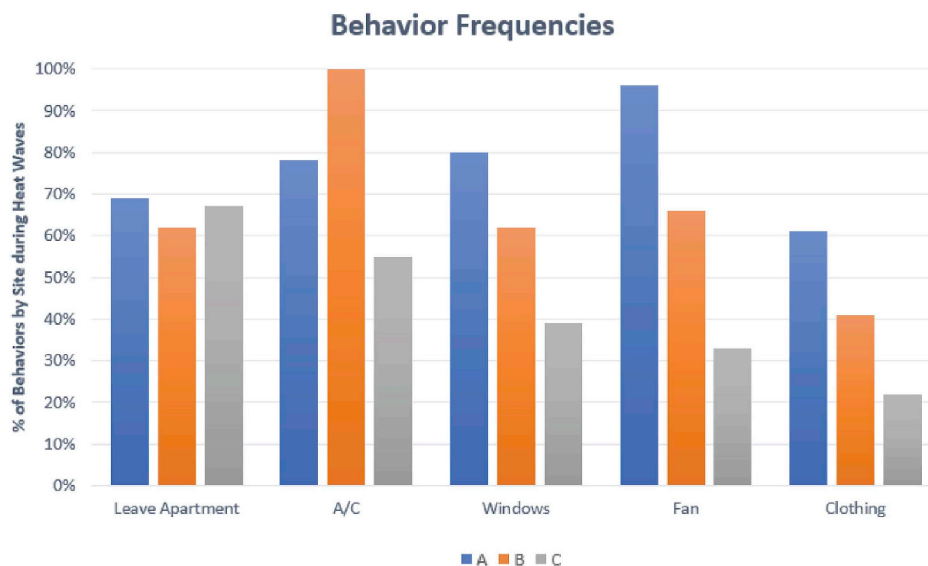


Fig. 11. Comparison of self-reported key adaptive behaviors among sites during heat waves of 2017 from the follow-up interviews. (Windows indicates window opening). There is a higher percentage of fan, window activity and clothing adjustment in site A than in site C.

indicates that residents in sites with poor envelopes engage in a wider range of adaptive actions during heat waves.

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. 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.

Fig. 11 and Table 1 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 window opening, 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 Figs. 7 and 8 that show selected A and C apartments having similar HI trends.

Considering the significant correlation and variation of window opening among sites, Fig. 12 zooms into the particular window opening 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 window opening 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 Fig. 8, but has a medium window opening activity, while B2 with the highest IHI also has the highest percentage of window opening 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 window opening 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.

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 11 of Supplementary Material, Appendix C. Based on a Turkey post-hoc test, it is further shown that window opening is statistically significantly higher in site A compared to C, and in apartments A6, B2 and B7 compared to apartments A4 and C2. Lastly, to better understand window opening activity and examine whether it is used for cooling purposes, Table 12 of Appendix C shows the regression results of percent windows open by apartment examined against the indoor/outdoor heat index ratio 1 h earlier. I/O HI ratio is statistically significant in 2/3 of the sample and explains little of the variance in window opening.

3.4. 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

Table 1

Pearson correlations between sites and behaviors. *Significant at the $p = .05$ 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*

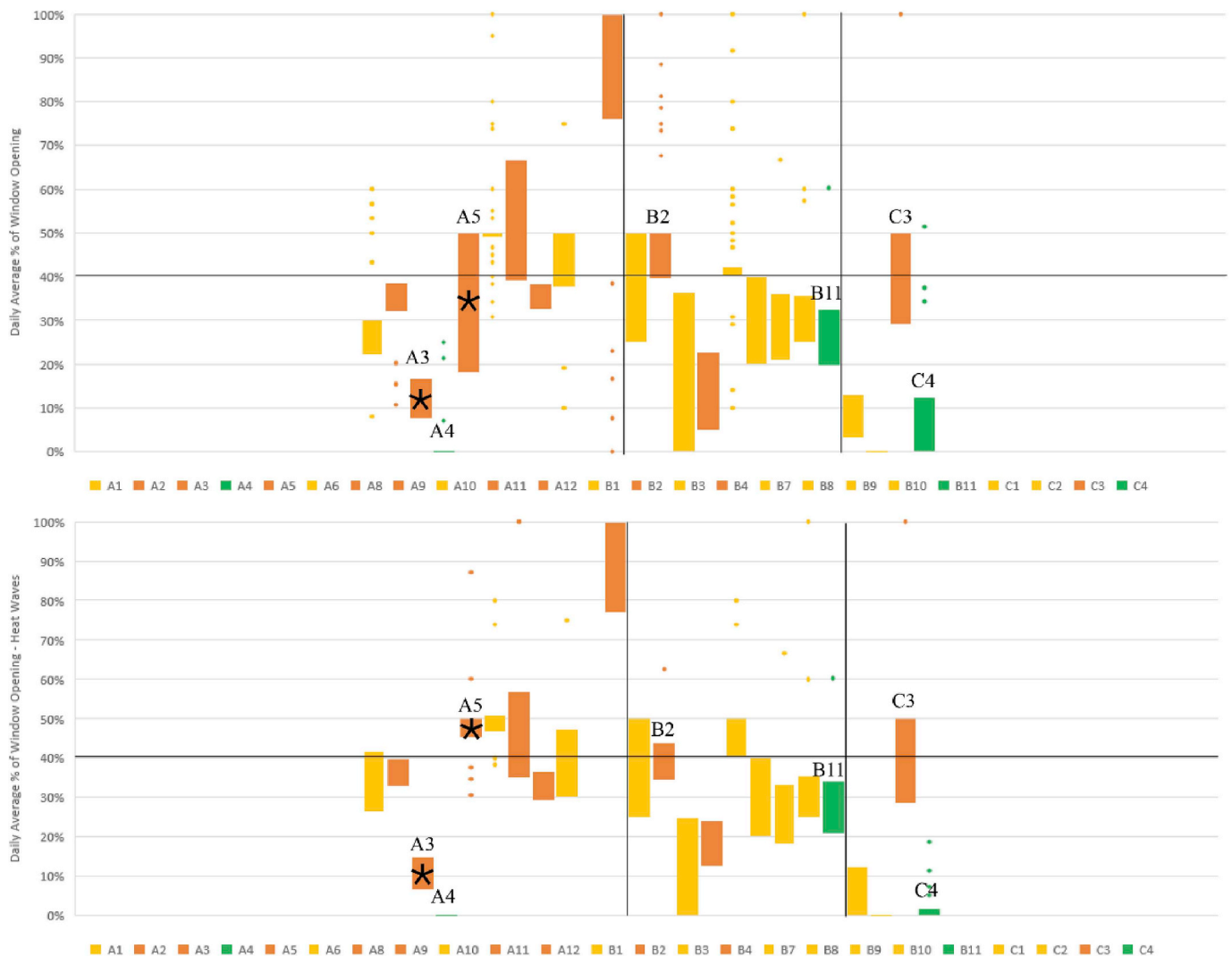


Fig. 12. Calculated daily average percentage of window opening based on sensor measurements by apartment during all summer and during heat waves of 2017. Green indicates apartments with the lowest IHIs, yellow corresponds to mid values and orange indicates high IHIs that exceed the threshold of 27 °C. Window opening 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the fixed effects are constructed based on the interviews and the apartment plans.

3.4.1. Pearson correlations of indoor heat index

Table 2 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 6–10 of Supplementary Material, 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 indoor HI; 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

Table 2

Pearson correlations between the indoor heat index and selected variables during all Summer and during heat waves of 2017. *Significant at the $p = .05$ level.¹

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

¹ Indoor and Outdoor HI are continuous variables. The rest are dummy variables.

characteristics. Being community active, which, for some residents means lower occupancy, connects to a lower indoor HI, 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.

3.4.2. Panel regressions of indoor heat index

The following paragraphs examine statistical associations among the indoor heat index and the variables presented in Table 2, 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-h 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 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 outdoor HI 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 Figs. 8 and 9. Model 3 (M3) adds the floor variable, which shows an effect over the indoor HI, although this effect is weaker than this of site A. Here, the floor's direction indicates that indoor HI is higher for apartments located in higher floors, which is expected, but contradicts with the results of Table 3. Since most floor variations are found in site B, we understand that this finding mostly applies to the B 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 the community active residents spend more time outside of the apartment. The magnitude is not very strong, but it still higher than the outdoor HI and the 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

Table 3

5 Models of panel regression parameters for indoor heat index during summer 2017. Random effects with robust standard errors.

Indoor HI (1 h later) ¹		M1	M2	M3	M4	M5	M5 (Heat Waves)	M5 (Only for Occupied Apt)
Outdoor Environment	Outdoor HI	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 Characteristics	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 Characteristics ²	Floor			0.17* (0.06)	0.27* (0.05)	0.07* (0.02)	0.12* (0.04)	0.13* (0.04)
Personal Characteristics ³	Community 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)	−
	Window 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 Terms: Indoor Environment (1 h earlier) and Behaviors	Indoor HI early *					0.43* (0.07)	0.31* (0.05)	−
	Occupancy					0.51* (0.07)	0.45* (0.07)	0.75* (0.03)
	Indoor HI early *					0.09* (0.03)	0.05 (0.03)	0.18* (0.04)
	Window Open					0.09* (0.03)	0.05 (0.03)	0.18* (0.04)
	Indoor HI early *					0.09* (0.03)	0.05 (0.03)	0.18* (0.04)
	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

*Significant at the $p = .05$ level.

¹ The dependent variable is the indoor heat index one time-step later (1 h later) than the independent variables, as this more clearly shows cause and effect.

² 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.

³ 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.

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. It further indicates that indoor HI and window opening 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 outdoor HI 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 3 of Supplementary Material, Appendix C) 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.

Another round of regressions is presented in Table 14 of Supplementary Material, Appendix C, where indoor HI 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 15 of Appendix C presents indoor HI 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 indoor HI variation. Lastly, Table 16 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.

4. Discussion

Results from Tables 2 and 3 show 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, our 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, in our analysis we approach sites as bundles that include outdoor amenities and buildings with certain envelope characteristics, but we do not distinguish between the two. This is a ripe area for future work. Regarding our second hypothesis, we confirm 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 we show 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. Therefore, we leave for future research occupant behavior modeling that will include personal characteristics as drivers and will be constrained by apartment and building attributes.

We find that the most interesting relationships are those of individual behaviors and the effect of site on the indoor HI, since they are consistently stronger than the rest, which is also shown in the HI distributions and behavioral variations of sections 3.2 and 3.3. 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 a local non-profit. 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 outdoor HI 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 indoor HI trend is 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 has the worst HI of all A. Therefore, there is a clear implication of behavioral contributions to the indoor HI. This is further confirmed, when the seniors' adaptive responses are shown in Fig. 11; there are important 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 indoor HI 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 (WO) coefficients have 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 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 2. 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 window

opening indicates that when the earlier indoor HI 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 indicates that window opening for cooling purposes (proxied by increased opening when I/O ratio for HI is high) is only a statistically significant behavior in 2/3 of apartments, and it explains very little of the variance in window opening.

Fig. 12 provides some additional insights for the window opening (WO) patterns across and within sites, which can provide additional information when combined with Fig. 11. In general, occupants in site A open their windows more than in site C. Within A, the apartment with the most WO variations is A5, which is the only one in the sample without any A/C unit, while the least window opening activity is seen in A4 that has the best indoor HI among all A. The same happens in the case of C3; it has the highest daily averages of WO and the highest indoor HI among all C. However, there are 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 indoor HIs, certain apartments, such as A4, A1 and B11, open their windows in an effective manner; however, we cannot answer 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 4 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.

4.1. Limitations

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. Using a panel regression analysis is useful, as it allows us to combine time-variant with time-invariant variables and clearly shows the effect of each predictor on the dependent variable. But there is a nested hierarchy among many variables of interest, such as the relationship between behaviors and the outdoor heat index, which cannot be fully captured in a single regression. In addition, it is not suggested to include multiple fixed effects in a panel regression, as it would significantly reduce the value of time-variant variables, which excludes additional relationships of interest. Then, all the time-variant variables included in the present analysis were derived from consumer-grade sensors, which, although calibrated, may still contain several resolution biases. Lastly, the regression was based on variables, such as window opening and occupancy that were produced by synchronizing and retiming multiple sensors, thereby resulting in missing values.

5. Conclusions

In this paper, we presented findings from a summer-long study of senior apartments located in three public housing sites and examined the thermal performance of those apartments and the residents' adaptive responses to this performance. To answer how do poor urban seniors cope with summer heat waves, we utilized a multi-level approach to identify the relative roles of neighborhoods, buildings and the seniors' actions in managing heat stress. We 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. Our mixed data collection approach included information from interviews with the residents, apartment, building and site plans, and sensor measurements

Table 4
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 the space more frequently	Close it later	
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/ transportation

of behavior and the indoor and outdoor thermal environment.

The focus was on indoor heat index, which was used as a proxy to the seniors' indoor heat stress. Indoor HI 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 [16], our 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 allowed us to clearly show how built-environment variations can alter the residents' behaviors and in turn, how those behaviors may significantly affect the indoor thermal conditions.

The first 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. While this study did not determine health effects from thermal discomfort, the results of the analysis showed that residents who live in air-conditioned apartments overall enjoy heat index ranges that fall within the ASHRAE standards. 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. Then, building design should account for those not able to afford running the A/C even if they have it, and invest in efficient passive cooling, such as effective natural ventilation, combined with outdoor landscaping to provide adequate amount of shading. These features also help maintain comfort during power outages which often coincide with heat waves. Lastly, city authorities should invest in nearby amenities, such as trees and shading combined with sitting, cooling centers and swimming pools, because those amenities are frequently used by seniors, as long as they are safe and in walking distance.

Our work has particularly important implications for long-term resilience and adaptation of elderly low-income communities to heat, as 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. It further shows the need for integrated solutions to the heat waves problem across scales; from changes to residents' habits, to building envelope modifications and building operations, and to outdoor space alterations.

Future research should more deeply explore the interactions among indoor thermal conditions and resident behaviors and further investigate the behavioral sequencing during heat waves, while modeling occupant behavior as endogenous. 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at [https://](https://doi.org/10.1016/j.buildenv.2019.106411)

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPS	Building Performance Simulation
EPA	Environmental Protection Agency
HI	Heat Index
HVAC	Heating, Ventilating and Cooling
IEQ	Indoor Environmental Quality
IHI	Indoor Heat Index
NOAA	National Oceanic and Atmospheric Administration
OHI	Outdoor Heat Index
OSHA	Occupational Safety and Health Administration
PM	Particulate Matter
PMV	Predicted Mean Vote
SES	Social-Ecological Systems
UHI	Urban Heat Island

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