Summer Indoor Thermal Conditions in Chicago Residences without Central Air Conditioning

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ABSTRACT

Earth's warming climate necessitates increased understanding of indoor thermal conditions as extreme heat exposure is the leading weather-related cause of death in the U.S. and heat waves are projected to become more severe and frequent. Existing research in the U.S. shows that places with historically cooler climates like Chicago face particular health risks from rising temperatures since the prevalence of central air conditioning is much lower than the national rate, their residential buildings were designed to retain heat, and the population is less acclimatized and prepared for extreme heat. This study measured summer indoor temperature and humidity in ten homes with building characteristics that are common among Chicago's older residential building stock, including a lack of a central air-conditioning system.

The paper describes the measured spatial and temporal temperature variations within residences as well as temperature differences across buildings with different characteristics, such as frame and masonry construction. The paper also explores participants' heat adaptation behaviors and perception of risk from extreme heat. It was observed that, during extreme heat events, temperature and humidity in all home types exceeded thermal comfort thresholds. The results indicate that heat waves in places such as Chicago with low prevalence of central air-conditioning can cause extreme indoor overheating in typical residential buildings. The findings of this study increase our understanding of predictors of building overheating and necessitate increased access to affordable cooling systems within homes, along with other strategies that mitigate the harmful effects of extreme heat.

Introduction

Extreme heat is the leading cause of weather-related death in the U.S., and exposure to extreme temperatures is a growing public health concern as temperatures and humidity increase globally (NWS 2022). Acute and chronic heat exposure can inhibit the body's ability to regulate its core temperature and can result in heatstroke, reduced cognitive function, respiratory problems, and can exacerbate existing medical conditions like cardiovascular disease (WHO 2018a). Much of the research on the health effects of extreme heat has used outdoor temperatures to estimate human heat exposure and heat stress, though indoor temperatures provide a more accurate representation of heat exposure as people in the U.S. spend, on average, 69% of their time at home (Klepeis et al. 2001). There is substantial variation in indoor temperatures across residential building types, and susceptibility to overheating varies based on the building's characteristics (White-Newsome et al. 2012; Larsen et al. 2022). Additionally, many of the residential buildings in cold climates, like Chicago's, lack central cooling and were designed to retain heat in cold weather which can result in these buildings also retaining heat during extreme heat events. Our study seeks to better understand the associations between building characteristics and indoor thermal conditions during extreme heat.

Heat waves in Chicago are projected to become more frequent, intense, and prolonged (Hayhoe et al. 2010). In August 2023, Chicago's heat index (HI) reached 120°F, the highest ever recorded at Chicago's official climate observation site.[1] The use of mechanical cooling like central air conditioning (AC) protects people against heat-related morbidity and mortality, but access to AC varies considerably across geography and demographics. Nationally, 76% of single family buildings have a central cooling system, but in Chicago only 30% of single family buildings and 9% of 2-4 unit buildings have a central cooling system (Elevate and NREL 2022). Previous research on disparities in AC prevalence across four cities, including Chicago, found that central AC among Black households was less than half that among White households (O'Neill, Zanobetti, and Schwartz 2005). Another study of AC prevalence in the US found that census tracts with the lowest AC prevalence were tracts that had the lowest median income and high percentages of residents with less than high school education (Romitti et al., 2022).

The temperature threshold for heat-related mortality is lower in cooler climates, and epidemiological studies show that populations in colder climates face greater health risks from heat in comparison to warmer climate populations that are more acclimatized and prepared for warm weather (Anderson and Bell 2011; Howe et al. 2019; Kenny et al. 2018). Populations with limited acclimatization to extreme heat, along with less adaptive capacity to respond to heat events, are increasingly at risk for negative health issues as extreme heat events become more severe and long-lasting (Diffenbaugh et al. 2017). These elevated environmental hazards are coupled with the trait that Midwest populations have relatively low concern and risk perception around extreme heat, making for a potentially dangerous scenario in which the population does not adequately perceive the danger of extreme heat and is unable to sufficiently respond during extreme heat events (Howe et al. 2022). This study further investigates risk perception by surveying participants about the perceived safety of their home's indoor temperature.

Research indicates that heat-mitigating strategies and behaviors can effectively reduce heat exposure during extreme heat events (Georgescu, Broadbent, and Krayenhoff 2023). The use of heat adaptation behaviors varies widely (White-Newsome et al. 2011; Quinn, Kinney, and Shaman 2017). Previous studies indicate there may be a geographic or demographic component to the relative utilization of each of these behaviors, and this study's sample of ten Chicago residents provides a better understanding of how Chicago residents may respond and adapt to high indoor temperatures.

The study team collected indoor temperature and humidity data in ten homes in Chicago without central cooling for approximately four weeks during July and August 2023. Examining the interior temperatures of homes that do not have a central cooling system provides insight into the conditions of many households across Chicago and exposes opportunities for heat mitigation strategies and investment. This research focused on the five most common housing types in Chicago, representing over 333,000 homes citywide, or over 75% of the city's total residential building stock, allowing for a better understanding of how these building types perform during

[1] August 23-24, 2023: Late Summer Heat Wave Results in Consecutive Days With 115+° Heat Indices: https://www.weather.gov/lot/2023_08_23-24_Heat#:~:text=Chicago%20officially%20observed%20a%20high%20t

extreme heat events. We also collected data about participants' perceptions of extreme heat and heat adaptation strategies to inform future programs and policies. This study is part of a larger body of work led by Northwestern's Defusing Disasters Working Group to reduce the harmful impacts of extreme weather. Their development of a Heat Vulnerability Index, along with Chicago's Heat Watch campaign,[2] and the results of this study seek to understand various dimensions of vulnerability to inform the development of climate resilience policies.

Methods

Findings presented in this study rely on two primary data sources: (1) data collected from 40 sensors in ten homes that measured indoor temperature and relative humidity (RH) at high temporal and spatial resolution; and (2) survey data collected from ten residents focusing on risk perception, heat adaptation, and AC usage. The study was conducted during summer 2023. Participants were recruited by Elevate via a convenience approach using outreach to personal contacts. Eligibility for participation included the following criteria: own and reside in a 1-4 unit home in the City of Chicago that is one of the five prevalent home types,[3] reside in a home without central air conditioning or heat pumps but can have window or portable AC units or ceiling and portable fans, and reside in a home in which no members of the household were vulnerable to heat stress. Participants were required to have Wi-Fi in their home since some of the sensors needed a Wi-Fi connection to operate. The study was approved by the Institutional Review Board (IRB) of the Illinois Institute of Technology (IRB-2024-4).

A visit was conducted to each home to install temperature and RH monitors and to collect data on the location and number of window air conditioning units, most and least-often occupied rooms, warmest and coolest rooms, and number of floors. Building age, type (i.e., single family or 2-4 unit), and exterior construction were collected from the Cook County Property Assessor database. All participants completed a survey about extreme heat concerns, risk perception, strategies and behaviors to mitigate heat exposure, and reasons for not having central cooling.

This study uses two sets of instruments to collect indoor data: (1) custom wet bulb globe temperature (WBGT) loggers with onboard storage and (2) Wi-Fi temperature and RH loggers. The custom WBGT loggers consisted of a custom-made plastic enclosure serving as a base for exterior Onset MX-1104 temperature and RH loggers[4] connected to an Onset TMC20-HD external temperature probe with the tip inserted inside a black sphere to measure globe temperature (Ali et al. 2020).[5] All measured parameters were recorded at one-minute time intervals. The Wi-Fi logger was a TempStick[6] which was set to record temperature and RH at 15-

[2] Heat Watch is a community-guided urban heat island mapping campaign sponsored by the National Oceanic and Atmospheric Administration (NOAA), CAPA Strategies, Chicago Department of Public Health, Chicago's Office of Climate and Environmental Equity, and Defusing Disasters. Chicago Heat Watch report: https://www.chicago.gov/content/dam/city/depts/cdph/environment/heat_watch/Summary-Report-Heat-Watch-Chicago_CAPA-12.15.2023.pdf
[3] Details on the five most prevalent home types in Chicago: https://www.elevatenp.org/publications/achieving-50-energy-savings-in-chicago-homes-a-case-study-for-advancing-equity-and-climate-goals/
[4] Air/Water/Soil Temperature Sensor: https://www.onsetcomp.com/sites/default/files/resources-documents/6679-L%20TMC-HD%20Manual.pdf
[5] HOBO MX1104 Data Logger: https://www.onsetcomp.com/datasheet/MX1104
[6] TempStick specifications: https://tempstick.com/manuals/setup-guide-temp-stick-th.pdf

minute intervals (the highest resolution of time interval available for the instrument). The data were sent via 2.4 GHz Wi-Fi to an online dashboard for real-time visualization and data download.[7] Table 11 summarizes the sensor information and specifications.

Table 1. Sensors installed in participating homes

Name	Time interval	Parameter	Range	Accuracy	Resolution
WBGT logger	1-minute	Globe temperature	-40°F to 212°F	±0.27	0.003° at 77°F
		Air temperature	-4°F to 158°F	±0.36°F from 32° to 122°F	0.004°F at 77°F)
		Relative humidity	0% to 100% at -4°F to 158°F	±2.5% from 10% to 90% (typical) to a maximum of ±3.5%	0.01%
		Light level	0 to 167,731 lux (15,582 lum/ft^2)	±10% typical for direct sunlight	-
Wi-Fi logger	15-minute	Air temperature	-40°F to 125°F	±0.27	-
		Relative humidity	0-100%	±2%	-

For each home, we installed four loggers, including two WBGT loggers and two Wi-Fi loggers. For homes with two stories, one WBGT logger and one Wi-Fi logger were installed per floor. For homes with one floor, all four loggers were installed on the same floor and, when possible, some of them were co-located to evaluate consistency between the two logger types. To ensure Wi-Fi sensors could effectively transmit data, they were located near the Wi-Fi router.

To assess potential impacts of summer extreme heat, several metrics were analyzed: (1) indoor atmospheric properties such as air temperature (i.e., dry bulb temperature), relative humidity (RH), dew point temperature, and wet bulb temperature, (2) standard effective temperature (SET), (3) heat index, and (4) wet bulb globe temperature.[8] The findings here will focus on temperature and heat index. We focused on these two metrics because they are commonly used by different stakeholders for communications and are easier to understand.

For the purpose of this study, an air temperature (i.e. dry bulb temperature) of 80°F is used as a threshold for high temperature since this is a temperature at which indoor conditions are considered potentially unsafe (WHO 2018b). This study also reports on heat index, which accounts for temperature and humidity, and a heat index of over 103°F is used to indicate danger. The National Weather Service (NWS) classifies a heat index threshold of 103°F as dangerous since prolonged exposure is likely to result in heat cramps or heat stroke.[9,10]

Findings – Building Characteristics

The five housing types included in the study were: single family frame construction 1-2 stories built pre-1942; single family masonry construction 1-2 stories built pre-1942; 2-4 flat

[7] TempStick dashboard: https://mytempstick.com/dashboard

[8] Refer to "Summer Indoor Thermal Conditions and Heat Adaptation in Chicago Residences," to be posted to Elevate's website in summer 2024, for analysis of each of these metrics.

[9] National Weather Service Heat Index Chart: https://www.weather.gov/media/unr/heatindex.pdf

[10] National Weather Service heat index ranges, classification, and effect on the body: https://www.weather.gov/ama/heatindex#:~:text=If%20you%20are%20exposed%20to,physical%20activity%20in%20the%20heat.

frame construction built pre-1942; 2-4 flat masonry construction built pre-1942; and single family masonry construction built 1943–1978. Table 2 shows detailed building characteristics for each home and the dates of sensor installation and removal for each.[11] These five housing types were selected due to their prevalence in Chicago, as these homes make up over 75% of the total residential building stock, including homes with and without central cooling (Elevate and NREL 2022). Additionally, these home types are common in Chicago's low-income neighborhoods, environmental justice communities, and communities that have experienced disinvestment (Elevate and NREL 2022).

Table 2. Building characteristics and data collection periods for each home

Home #	Data Collection Start Date	Data Collection End Date	Duration (Days)	Exterior	Home Type	Year Built	No. of Occupied Floors	No. of Sensors in Unconditioned Spaces	No. of Sensors in Semi-conditioned Spaces*
1	8/2/23	8/28/23	26	Frame	Single Family	1894	2	4	0
2	7/25/23	8/28/23	34	Frame	Single Family	1899	2	2	2
3	7/27/23	9/8/23	43	Masonry	Single Family	1964	1	2	2
4	7/25/23	8/28/23	34	Masonry	Single Family	1931	3	3	1
5	7/25/23	8/28/23	34	Masonry	Single Family	1899	2	3	1
6	7/31/23	10/3/23	64	Frame	2-4 unit	1899	2	4	0
7	8/2/23	9/8/23	37	Masonry	2-4 unit	1879	2	4	0
8	8/3/23	8/29/23	26	Masonry	2-4 unit	1917	1	2	2
9	7/25/23	8/28/23	34	Masonry	2-4 unit	1928	2	4	0
10	7/25/23	8/29/23	35	Masonry	2-4 unit	1924	2	3	1

*Most sensors were installed in unconditioned spaces, but some spaces utilized simple cooling systems in the form of window AC or portable AC—these spaces are categorized as semi-conditioned.

Findings – Temperature and Heat Index Distributions

Table 3 and Table 4 provide the distribution of the heat index and temperature values for two different time periods: (1) monitoring period excluding the extreme heat days of 7/28/2023, 8/23/2023, and 8/24/2023; (2) the extreme heat day of 8/24/2023.[12] For each home and floor, the minimum, maximum, average, and the maximum differential between floors are reported. In some cases, there is no differential between floors because the home only has one floor. Differentials between floors were calculated to better understand the risk of extreme heat within

[11] Refer to "Summer Indoor Thermal Conditions and Heat Adaptation in Chicago Residences," to be posted to Elevate's website in summer 2024, for details on home layout and sensor locations.

[12] During the monitoring period, temperatures were generally moderate and similar to historic averages. However, Chicago Office of Emergency Management issued a heat advisory for July 28 and an excessive heat warning for August 23-24. August 24, having the highest temperatures, is highlighted here. Refer to "Summer Indoor Thermal Conditions and Heat Adaptation in Chicago Residences" (forthcoming, available on Elevate's website in summer 2024) for additional information on the extreme heat days of 7/28 and 8/23.

the homes and to determine which areas are safer. For the heat index, the value of 103°F is used as the danger threshold and the number of hours in danger are shown. For the temperature, the number of hours over 80°F are reported.

Table 3 shows heat index values for each home's unconditioned spaces. All ten homes met or exceeded the NWS heat index caution thresholds (80°F-90°F) and extreme caution (91°F-103°F) on 8/24/2023. On the same day, seven homes met or exceeded the danger threshold for 2-23 hours. The maximum heat index shows extreme conditions in many of the homes, with 120°F being the highest heat index recorded in the study. Table 3 shows a maximum heat index differential of 36.8°F (Home 4: basement to second floor). Heat index differentials on heat wave days were large, with multiple homes having differentials greater than 20°F, suggesting high variability within the home itself. The heat index differential is highest for single family masonry homes, and generally, frame homes show less fluctuation in heat index differential while masonry houses show higher fluctuations. The average heat index differentials from Table 3 for each home are: single family frame: 11.5°F; 2-4 unit frame: 5.9°F; single family masonry: 18.9°F; 2-4 unit masonry: 12.0°F.

Table 3. Distribution of the heat index values for each home and floor

Heat Index for Unconditioned Spaces											
		Monitoring period (excluding 7/28, 8/23, 8/24)					8/24/2023				
Home #	Floor	Min.	Max.	Avg.	Max HI Differential	HI>103 (Danger)	Min	Max	Avg.	Max HI Differential	HI>103 (Danger)
1	1	70.4	90.5	77.7	19.9°F 8/3/23 19:59	00:00	88.9	105.2	97.7	8.1 F 06:16	05:45
	2	69.3	92.9	78.4		00:00	85.9	113.2	93.1		06:00
2	1	69.4	95.3	78.1	10.7 F 8/4/23 16:39	00:00	95.1	107.1	101.4	15.9 F 15:57	09:00
	2	68.4	99.5	77.9			93.8	120.1	105.7		11:45
3	1	73.8	98.0	80.8	-	00:00	90.9	99.5	93.7	-	00:00
4	0	69.2	85.8	75.2	36.8 F 8/1/23 20:56	00:00	81.4	85.9	83.1	30.8 F 14:41	00:00
	1	71.1	93.5	78.3		00:00	81.4	88.8	84.3		00:00
	2	66.1	93.5	79.5		00:00	83.6	116.1	100.8		11:00
5	1	71.1	88.5	78.7	8.0 F 7/27/23 23:29	00:00	81.6	86.8	84.6	26.7 F 19:00	00:00
	2	69.8	88.4	80.0		00:00	92.3	110.5	99.5		07:30
6	1	61.4	99.3	75.8	6.4 F 8/5/23 7:37	00:00	94.6	114.6	103.2	7.0 F 03:03	22:00
	2	65.0	99.7	76.9		00:00	97.4	111.0	105.5		22:00
7	1	70.6	93.1	77.6	2.7 F 8/8/23 16:52	00:00	93.6	110.6	103.6	19.9 F 17:49	21:45
	2	66.2	98.6	79.4		00:00	87.6	117.1	106.9		22:36
8	1	70.6	88.4	77.7	-	00:00	82.1	91.4	86.1	-	00:00
9	1	66.8	91.5	76.8	17.6 F 8/20/23 18:36	00:00	88.5	105.3	98.1	13.4 F 08:01	02:00
	2	66.4	91.5	76.7		00:00	75.5	104.2	92.0		06:00
10	1	71.2	87.2	77.3	8.4 F 8/4/23 6:22	00:00	80.0	87.3	83.9	16.9 00:03	00:00
	2	72.2	93.4	79.3		00:00	83.7	100.3	93.9		00:00

To better assess the indoor thermal conditions, Table 4 shows temperature values for each home's unconditioned spaces. Table 4 shows a maximum temperature of 108°F (Home 6) and a maximum temperature differential of 16.6°F (Home 4: basement to second floor). Most unconditioned spaces regularly exceeded the 80°F threshold throughout the study, during both moderate weather and extreme heat events. The number of hours above 80°F in the unconditioned spaces ranged from 1% of the time (five hours) to 34% of the time (354 hours). On 8/24/2023, all homes exceeded the 80°F threshold and nearly all unconditioned spaces were over 80°F for 24 hours.

Similar to the heat index results shown in Table 3, the largest temperature differential occurred in the home with the basement (Home 4) and the temperature differential was greatest among single family masonry homes. However, while the maximum heat index differential occurred on a moderate summer day, the maximum temperature differential occurred on an extreme heat day (8/24/23). Comparisons between Table 3 and Table 4 illustrate that some variation exists when humidity is accounted for, as there are some differences in which types of homes experience the highest values and lowest values.

Table 4. Distribution of the temperature values for each home and floor

Temperature for Unconditioned Spaces											
		Monitoring Period (excluding 7/28, 8/23, 8/24)					8/24/2023				
Home #	Floor	Min.	Max.	Avg.	Max T Differential	Hours >80°F	Min	Max	Avg.	Max T Differential	Hours >80°F
1	1	71.1	88.6	76.9	8.1°F 8/25/23 0:10	121:00	84.1	90.1	87.8	3.6°F 06:16	24:00
	2	69.8	87.6	77.5		117:00	83.1	90.4	86.6		24:00
2	1	69.9	88.0	77.2	6.9°F 8/2/23 16:06	157:00	86.1	92.2	88.9	9.7°F 15:49	24:00
	2	68.5	91.8	77.1		257:00	84.7	100.4	92.2		24:00
3	1	73.7	89.1	79.3	-	354:00	85.3	89.4	87.4	-	24:00
4	0	69.4	84.6	74.7	13.6°F 7/25/23 16:41	05:00	78.9	81.1	79.8	16.6°F 15:41	9:30
	1	71.4	87.9	79.3		77:00	80.8	85.7	83.0		24:00
	2	66.7	91.3	78.7		280:00	80.9	99.2	90.1		24:00
5	1	71.6	85	77.4	5.9°F 7/29/23 09:32	116:00	80.3	82.3	81.7	11.5°F 20:03	24:00
	2	70.3	89.3	78.4		258:00	86.6	93.2	89.1		24:00
6	1	62.5	90.8	75.3	5.5°F 8/5/23 07:22/23 8/17/23 02:37	247:00	85.0	107.9	96.7	3.4°F 06:57	24:00
	2	66.0	90.9	76.4		301:00	89.9	94.3	91.4		24:00
7	1	70.7	87.1	76.8	6.7°F 8/25/23 01:01	105:00	86.3	94.9	90.1	3.6°F 12:48	24:00
	2	67.2	92.2	78.4		190:00	83.6	98.5	92.5		24:00
8	1	71.3	84.0	77.0	-	46:00	81.9	85.8	82.8	-	24:00
9	1	67.2	87.9	76.1	13.9°F 8/20/23 18:36	93:00	83.3	89.3	86.8	4.4°F 05:45	24:00
	2	67.6	85.5	76.7		63:00	75.4	90.3	84.3		19:30
10	1	70.5	90.3	77.1	8.7°F 8/4/23 08:52	44:00	78.7	82.9	70.9	7.6°F 20:33	17:00
	2	72.4	87.3	78.2		210:00	77.3	90.0	85.8		21:00

For a better understanding of how temperature varies between the single family versus 2-4 unit homes and between different floors and their enclosure, Figure 1 and Figure 2 compare indoor temperature (dry bulb) and indoor dew point temperature for semi-conditioned and unconditioned spaces using box and whisker plots. Figure 1 shows that unconditioned spaces reach higher temperatures than semi-conditioned spaces. Additionally, masonry homes show a lower range of variation compared to frame homes, this is especially evident on first floors. In addition, second floors experience a higher range of temperature variation when compared with first floors. Figure 2 depicts high dew point temperatures among both unconditioned and semi-conditioned spaces. The median dew point temperature for most home types and floors is between 60°F and 65°F,[13] and some spaces reached dew point temperatures near 80°F. In the boxplot figures, the upper and lower whiskers represent the Q1-1.5×IQR and Q3+1.5× IQR, and Q1, Q3, and IQR are the 25% percentiles, 75% percentile, and the interquartile range. Outliers are shown as red dots.

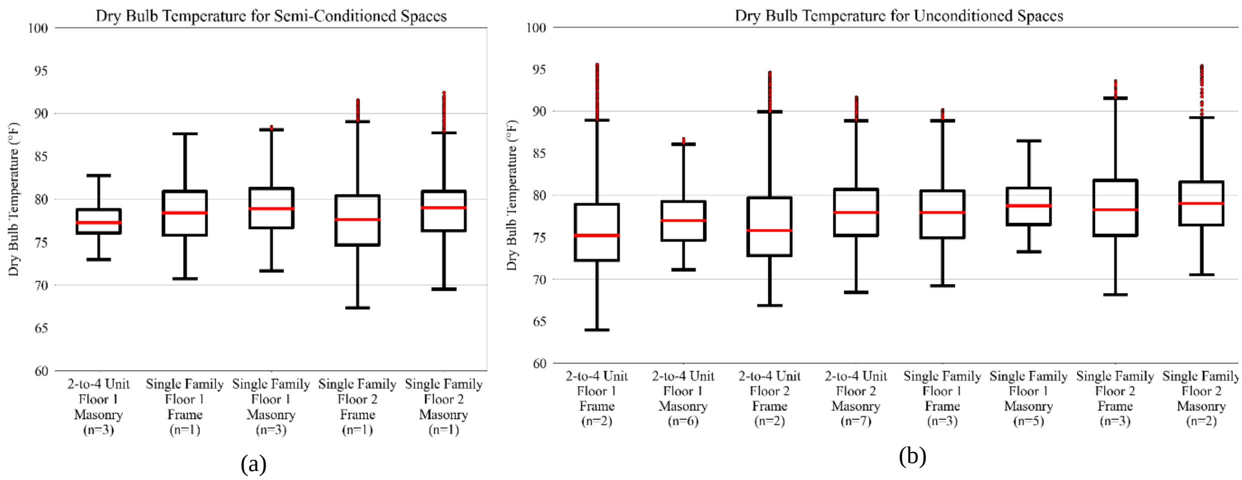


Figure 1. Variation of indoor temperature for different building types and floors: (a) semi-conditioned and (b) unconditioned

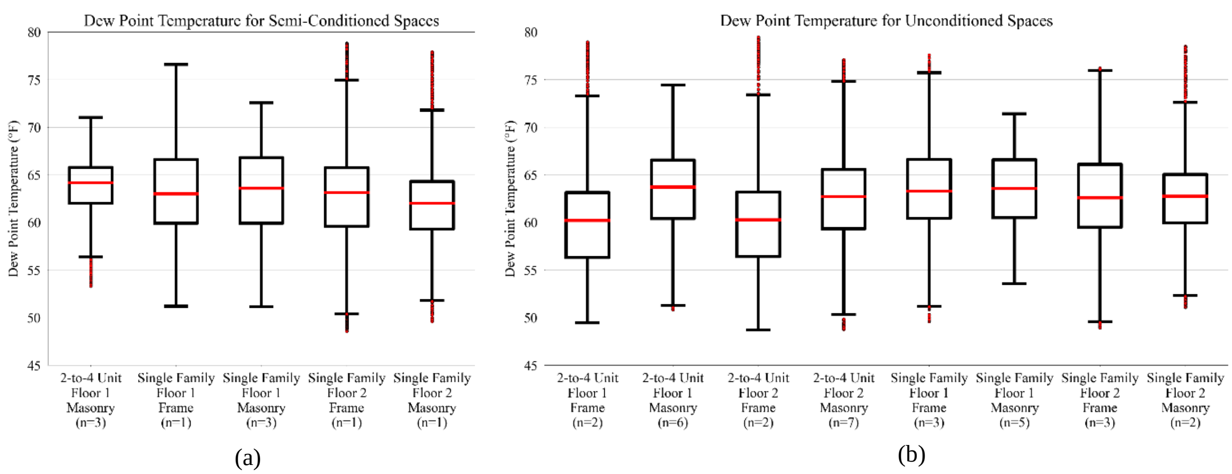
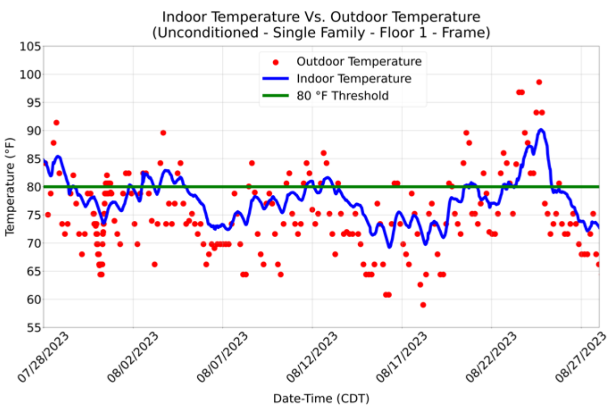


Figure 2. Variation of indoor dew temperature for different building types and floors: (a) semi-conditioned and (b) unconditioned

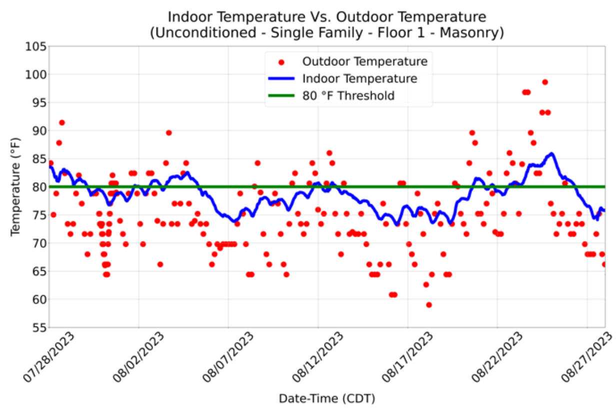
Figure 3 shows the temperature time series for the duration of the study for unconditioned spaces in single family homes of both frame and masonry construction. The green line represents

[13] NWS classifies dew point temperature of 65°F or greater as “lots of moisture in the air and becoming oppressive.”

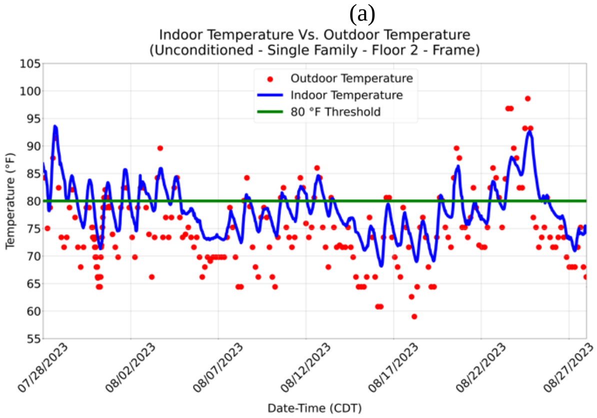
the 80°F threshold for indoor air temperature, and the figures show that during the extreme heat days of August, all homes and spaces had a temperature exceeding 80°F. The second-floor temperatures also exceed the 80°F threshold throughout the study. Figure 3 illustrates the indoor temperature patterns for unconditioned spaces between the first and second floors. The overall results show that the upper floors generally experienced higher heat index and temperature than lower floors. This finding is consistent with other research showing that upper floors are more likely to have higher temperatures (Quinn, Kinney, and Shaman 2017). This finding also suggests the importance of occupants remaining on lower floors and basements on heat wave days, when possible. Additionally, the diurnal outdoor temperature variations appear to have more impact on frame homes than masonry homes.



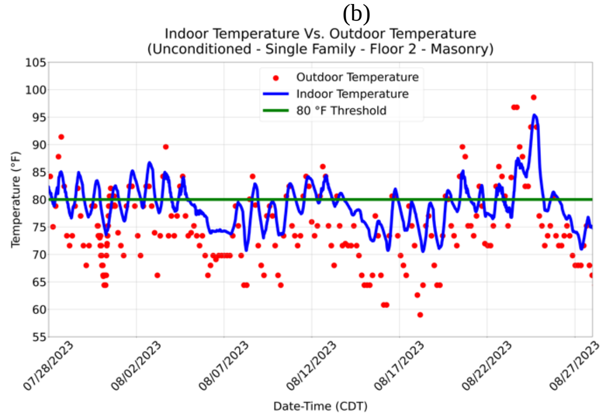
(a)



(b)



(c)



(d)

Figure 3. Indoor dry bulb vs outdoor dry bulb temperature for unconditioned single family homes: (a) Floor 1 – Frame (n=3), (b) Floor 1 – Masonry (n=5), (c) Floor 2 – Frame (n=3), and (d) Floor 2 – Masonry (n=2)

In general, the results show that masonry homes experience a lower range of temperature variation compared to the frame homes, especially for the first floor spaces. Frame homes were able to cool down more during the nighttime while the masonry homes were unable to cool down as quickly and appeared to retain heat for longer than the frame homes. Generally, the temperature and heat index in masonry homes was more uniform while the frame homes showed more impact from diurnal (i.e. daytime) outdoor temperature variations. This aligns with White-

Newsome et al.'s (2012) study of indoor temperature in Detroit homes that found homes with frame construction were more sensitive to outdoor temperature than masonry homes. These findings may be explained by the higher heat capacity of masonry homes helping to keep the home cooler during high outdoor temperatures; however, a different study of indoor temperature found that masonry construction exacerbated the effect of increasing outside temperatures (Larsen et al. 2022), suggesting the need for additional targeted investigations.

In this study, masonry homes showed higher temperature and heat index differentials between floors. Among the unconditioned spaces, the single family, one story masonry home experienced the longest duration over 80°F while the basement of the masonry single family home experienced the least amount of time over 80°F. As noted, there is substantial variation within different spaces in the home, especially among the masonry homes.

Findings – Heat Adaptation Strategies, Risk Perception, and Concerns

As part of our indoor heat assessment study, all ten participants completed a survey whose questions and the responses are described below in three sections: adaptive behaviors and cooling strategies, risk perception and safety, and opinions on central cooling systems.

Adaptive Behaviors and Cooling Strategies

To assess heat adaptation behaviors and strategies, participants were provided a list of 17 behaviors and asked to select which ones they use on the hottest days of summer (Table 5). All participants reported using three of these strategies: using fans to cool down, using curtains/blinds/shades, and wearing lighter clothing. Sixteen of the 17 strategies were used by at least 50% of respondents. This is consistent with findings from Portland, OR where public housing residents without AC employed many strategies to keep cool like keeping blinds closed all day and turning lights off (CAPA Strategies 2023). Participants in this study reported opening windows and doors at a slightly lower rate than some other studies. This difference may be explained by a trend of persistent overnight heat which lowers the effectiveness of window opening at nighttime, particularly because the survey asked about strategies used on the hottest days of summer and nighttime radiative cooling is often reduced on extremely hot days. Other less-utilized coping strategies were: reducing sources of electronic and electrical heat in the home (50%), using a cool cloth to cool off while inside (50%), and eating light or iced foods to cool off (50%).

The least utilized coping strategy was leaving the home, with only three people (30%) choosing this option. Though leaving the home was the least-used strategy, 60% of respondents reported going to an outdoor space of the home (e.g., porch or yard) when the indoor space is too uncomfortable. Among those who leave the home when it is too warm, most go to an air-conditioned business (e.g., grocery store) rather than an air-conditioned public place like a community center or library (one person) or a park or area with tree shading (one person). This result may indicate that participants utilize their home as the main place of refuge during extreme heat events and remain inside despite high temperatures. Studies from other areas of the U.S. show that leaving the home is one of the least utilized strategies in a heat wave. Madrigano et al. (2018) found that most people stay home during hot weather, with only 12% of people leaving home to go to a public place with AC while Lane et al. (2023) found that most people prefer to stay home during extreme heat events, with the main reason being that the home was comfortable. This preference to stay home during extreme heat demonstrates the importance of efforts to reduce exposure to extreme indoor heat within the home.

Some participants wrote about additional strategies they use that were not captured in our list. These responses included strategies like using a portable dehumidifier since reducing humidity helps improve comfort. Another person noted, “Our main cooling strategy is keeping good airflow in the house. Most every room has a ceiling fan, we leave the windows open, without screens and can create a chimney effect with different combinations of open upstairs windows, depending on wind direction.”

Table 5. Heat adaptation strategies reported by participants

Strategies used on the hottest days of summer	**Percent**
Wear lighter clothes	100%
Turn fan(s) on	100%
Use curtains, blinds, or window shutters	100%
Turn air conditioner unit(s) on	90%
Drink beverages to cool off	80%
Close doors of warmer spaces	80%
Move to cooler areas of the home	70%
Use thinner bedding	70%
Open windows or doors	70%
Try to create airflow in spaces with window opening, AC(s), fans(s), and closing doors	70%
Check weather reports and base behaviors on this information	60%
Move to an outdoor space of the home	60%
Take a shower or bath	60%
Eat fresh, light, or iced foods to cool off	50%
Use a cool, wet cloth to cool off while inside	50%
Reduce sources of electrical and electronic heat in the home	50%
Leave the house	30%

The participants who reported using fans or AC units were asked to estimate how many hours and during which parts of day they use fans or AC units on the hottest days of summer. Of the nine people who had AC units in their homes, the average number of hours of AC use was 16.7 hours, with a range of 8 to 24 hours a day. The AC usage was highest at night (10:00 pm to 8:00 am) and lowest in the morning (8:00 am to12:00 pm). All participants used fans and the average number of hours of use per day was 19.2 hours, ranging from 10 to 24 hours a day. Similar to AC use, fans were most utilized at night and least used during morning and early afternoon. The survey also asked about passive cooling strategies used to reduce heat in the home. The most commonly reported passive cooling strategies were insulation (70%) and tree canopy (70%) while reflective cooling (e.g., cool roof coating) was the least reported strategy (30%).

Risk Perception and Safety

When asked if their homes reached unsafe temperatures during the summer, five people (50%) reported that they believe their home reached unsafe temperatures. When asked where in the home reached unsafe temperatures, most reported the second floor or attic as considerably hotter than other areas in the home. Three respondents wrote about hazardous temperatures at night and sleep disruption, with one saying, "Our second floor is unbearable when the outside temps hit 100 degrees. We have a window unit that cools the sleeping areas, but it's not enough." Another reported, "My daughter sleeps on the top floor in the finished attic. It can get really hot up there. We do have AC but it has to run all the time just to keep it bearable. Sometimes she sleeps in the basement [to keep cool]." Additionally, there was some uncertainty about what temperature qualifies as unsafe, with three people answering "unsure" if their home reach unsafe temperatures and two people stating that they don't know what temperature threshold qualifies as unsafe.

The survey results show that all ten participants were at least somewhat concerned about facing heat waves this summer, with 10% being "extremely concerned", 80% "moderately concerned", and 10% "somewhat concerned." In addition to general concern about heat waves, most participants (70%) expressed extreme concern about the wellbeing of their friends, family, and community during extreme heat events (Figure 4). One individual shared, "I am mostly concerned about others who are sensitive to heat. I never had AC growing up so I'm used to using fans, opening windows at night etc. And we do have one room with an AC we can retreat to." Other concerns included changes in sleep quality and duration due to increased temperatures as well as financial concerns from higher electric bills due to increased energy use for cooling. Despite these concerns around extreme heat, the majority (90%) of participants reported that they did not believe this summer was warmer than previous years.

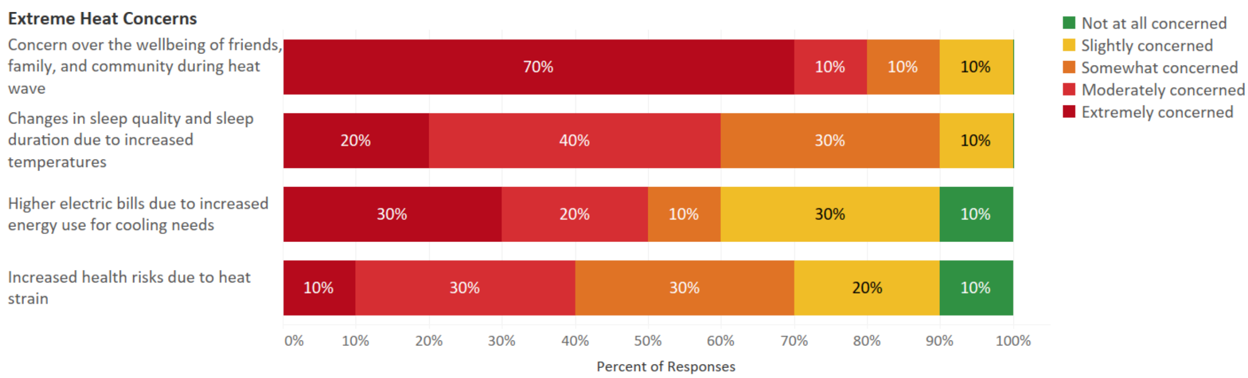


Figure 4: Participant ranking of extreme heat concerns (n=10)

Opinions on Central Cooling Systems

Participants were asked about the reasons for not having a central cooling system in their home. Three people (30%) selected "I am environmentally conscious and do not think all homes should have a central cooling system in Chicago", while another 30% reported, "I never lived in a home with a central AC system growing up, and I do not feel the need for it now." Five people (50%) indicated that they plan to install a heat pump that they would use for cooling in the summer. Several people added written responses that addressed their financial concerns for installing central cooling. One person stated, "[Getting central cooling] would be an invasive, expensive project and there typically are not that many brutal days. Having a window AC in a room or two is sufficient." Another added, "I do have environmental concerns about getting central air, but I don't see any good alternative so I would probably get some kind of AC if it was affordable."

Recommendations

The findings of this pilot study quantify the occurrence and severity of high indoor temperatures in archetypal Chicago homes and underscore the importance of policies and programs to protect people from high ambient temperatures and prevent future heat-related morbidity and mortality. The results presented here highlight a need for preventative measures and solutions that address the indirect and direct consequences of extreme heat. We conclude with four themes of recommendations to lessen heat vulnerability and increase resilience: increased access to safe conditions, additional risk assessment, additional research, and improved risk communication and education.

Recommendation 1: Access to safe conditions

Increase access to affordable cooling in homes. Access to safe conditions is critical to reducing the hazards of extreme heat exposure. Our results and others' show that people tend to stay home despite the indoor heat and generally do not leave home for public places with AC (e.g., cooling centers). Future efforts should focus on improving thermal comfort within homes so that residents are able to stay home in safe, comfortable, and affordable conditions during extreme weather. Nature-based solutions like increased tree canopy can help cool homes and reduce energy burden by lessening the need for AC usage, thereby lowering electric bills. Another method of improving thermal resilience is to combine weatherization with heat pumps. Research shows that heat pumps are more effective and efficient at providing comfortable indoor conditions on extreme heat days, in comparison to standard air conditioners (Tan and Fathollahzadeh 2021). All building electrification programs should prioritize homes without central cooling as part of their recruitment, assessment, and deployment strategy.

Recommendation 2: Need for additional risk assessment

Implement community conversations about adaptive capacity to assess community risks and hyper-local mitigation strategies. A community risk assessment that accounts for heat vulnerability at the community, individual, and building-level would help in identifying people who are at increased risk during extreme heat events. This assessment could highlight community assets and identify specific strategies to mitigate risk. Though this study is limited by its sample size, the results indicate that more information is needed to better understand community adaptive capacity, effective interventions, adaptive behaviors and cooling strategies, risk perception and safety, and access to and use of (or not) cooling, and community needs, assets, and solutions. Community residents have the hyper-local knowledge and experience with the climate, landscape, and strategies for achieving cooler indoor temperatures. The outcomes of such a risk assessment should be used to prioritize investment into efforts that reduce heat exposure and increase resilience for those who are at greatest risk.

Recommendation 3: Improved education and communication

Our third theme of recommendations are for improved education and communication regarding heat-related risks. Some participants in our sample did not know if they were at risk for unsafe temperatures, though they acknowledged uncomfortable temperatures in their homes and expressed extreme concern for others during heat waves. Participants expressed limited knowledge on dangerous temperature thresholds, so we recommend improved communications about risk, specifically public communication for heat events. Communications could aim to be more specific with messaging and danger warnings, and education on the most effective strategies for cooling the body and the home would make it easier to recognize danger and take appropriate caution and steps to reduce exposure. Additional recommendations include (1) utilizing networks of hyper-local partners to disseminate health and safety information about extreme weather events and (2) exploring opt-in push alerts from two-way communicating thermostats via utility smart meters when indoor air temperatures exceed certain thresholds.

Recommendation 4: Additional research needed

This study relies on data collected from ten homes, and a larger and more diverse sample size would enable more robust conclusions. Monitoring temperature and heat index in additional home types like multi-family buildings and manufactured housing could help further identify housing types most vulnerable to heat. Further research into the impact of weatherization (e.g., insulation and air sealing) and other envelope measures is needed to better understand the impact of adding mechanical versus envelope upgrades for cooling. Also, further research could help better understand how indoor heat metrics compare to local outdoor heat metrics to improve our ability to map indoor heat risk. Additional data collection of heat index and survey data would allow for more accurate assessment of the most vulnerable home types, individual's responses to and perceptions of extreme heat events, and help shape overall extreme heat risk assessments.

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References

Ali, A. S., Riley, C., Acton, E., Ali, A., Heidarinejad, M., and Stephens, B. 2021. "Development and evaluation of an automatic steam radiator control system for retrofitting legacy heating systems in existing buildings." *Energy and Buildings*, 251, 111344. https://doi.org/10.1016/j.enbuild.2021.111344

Anderson, G. B. and Bell, M. L. 2011. "Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities." *Environmental Health Perspectives*, 119(2), 210–218. https://doi.org/10.1289/ehp.1002313

CAPA Strategies. (2023). *Home Forward Indoor Temperature Assessment*. https://www.portland.gov/pbem/documents/home-forward-indoor-temperature-assessment-report/download

Diffenbaugh, N. S., Singh, D., Mankin, J. S., Horton, D. E., Swain, D. L., Touma, D., Charland, A., Liu, Y., Haugen, M., Tsiang, M., and Rajaratnam, B. (2017). "Quantifying the influence of global warming on unprecedented extreme climate events." *Proceedings of the National Academy of Sciences*, 114(19), 4881-4886. https://doi.org/10.1073/pnas.1618082114

Elevate and NREL (National Renewable Energy Laboratory). 2022. *Achieving 50% Energy Savings in Chicago Homes: A Case Study for Advancing Equity and Climate Goals*. https://www.elevatenp.org/publications/achieving-50-energy-savings-in-chicago-homes-a-case-study-for-advancing-equity-and-climate-goals/

Georgescu, M., Broadbent, A. M., and Krayenhoff, E. S. 2023. "Quantifying the decrease in heat exposure through adaptation and mitigation in twenty-first-century US cities." *Nature Cities*, *1*(1), 42-50. https://doi.org/10.1038/s44284-023-00001-9

Hayhoe, K., Sheridan, S., Kalkstein, L., and Greene, S. 2010. "Climate Change, Heat Waves, and Mortality Projections for Chicago." *Journal of Great Lakes Research - J GREAT LAKES RES*. 36. https://doi.org/10.1016/j.jglr.2009.12.009

Howe, P. D., Marlon, J. R., Wang, X., and Leiserowitz, A. 2019. "Public perceptions of the health risks of extreme heat across US states, counties, and neighborhoods." *Proceedings of the National Academy of Sciences of the United States of America*, 116(14), 6743–6748. https://doi.org/10.1073/pnas.1813145116

Kenny, G. P., Flouris, A. D., Yagouti, A., and Notley, S. R. 2018. "Towards establishing evidence-based guidelines on maximum indoor temperatures during hot weather in temperate continental climates." *Temperature (Austin, Tex.)*, 6(1), 11–36. https://doi.org/10.1080/23328940.2018.1456257

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., and Engelmann, W. H. 2001. "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants." *Journal of Exposure Analysis and Environmental Epidemiology*, 11(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Lane, K., Smalls-Mantey, L., Hernández, D., Watson, S., Jessel, S., Jack, D., Spaulding, L., and Olson, C. 2023. "Extreme heat and COVID-19 in New York City: An evaluation of a large air conditioner distribution program to address compounded public health risks in summer 2020." *Journal of Urban Health*, 100(2), 290-302. https://doi.org/10.1007/s11524-022-00704-9

Larsen, L., Gronlund, C.J., Ketenci, K. C., Harlan, S. L., Hondula, D. M., Stone, B., Lanza, K., Mallen, E., Wright, M.K., and O'Neill, M.S. 2022. "Safe at home?" *Journal of the American Planning Association*, 1-13. https://doi.org/10.1080/01944363.2022.2087724

Madrigano, J., Lane, K., Petrovic, N., Ahmed, M., Blum, M., and Matte, T. 2018. "Awareness, Risk Perception, and Protective Behaviors for Extreme Heat and Climate Change in New York City." *International Journal of Environmental Research and Public Health*, 15(7), 1433. MDPI AG. Retrieved from http://dx.doi.org/10.3390/ijerph15071433

NWS (National Weather Service). 2022. *Weather related fatality and injury statistics*. https://www.weather.gov/hazstat/

O'Neill, M. S., Zanobetti, A., and Schwartz, J. 2005. "Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence." *Journal of urban health: bulletin of the New York Academy of Medicine*, *82*(2), 191–197. https://doi.org/10.1093/jurban/jti043

Quinn, A., Kinney, P., and Shaman, J. 2017. "Predictors of summertime heat index levels in New York City apartments." *Indoor Air*, 27(4), 840–851. https://doi.org/10.1111/ina.12367

Romitti, Y., Sue Wing, I., Spangler, K. R., and Wellenius, G. A. 2022. Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, *1*(4). https://doi.org/10.1093/pnasnexus/pgac210

Tan, L., and Fathollahzadeh, M. 2021. *Why heat pumps are the answer to heat waves*. RMI. https://rmi.org/why-heat-pumps-are-the-answer-to-heat-waves/#:~:text=The%20heat%20pump%20was%20more,over%2010%

White-Newsome, J. L., Sánchez, B. N., Parker, E. A., Dvonch, J. T., Zhang, Z., and O'Neill, M. S. 2011. "Assessing heat-adaptive behaviors among older, urban-dwelling adults." *Maturitas*, 70(1), 85–91. https://doi.org/10.1016/j.maturitas.2011.06.015

White-Newsome, J. L., Sánchez, B. N., Jolliet, O., Zhang, Z., Parker, E. A., Dvonch, J. T., and O'Neill, M. S. 2012. "Climate change and health: indoor heat exposure in vulnerable populations." *Environmental Research*, 112, 20–27. https://doi.org/10.1016/j.envres.2011.10.008

WHO (World Health Organization). 2018a. *Heat and health*. https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health

WHO (World Health Organization). 2018b. *WHO housing and health guidelines*. https://www.who.int/publications/i/item/9789241550376