The Impact of Weatherization on Unhealthy Indoor Temperature and Humidity

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ABSTRACT

This paper explores the impacts that weatherization may have on reducing episodes of unhealthy temperatures and relative humidity levels in single-family homes occupied by low-income occupants. Data are drawn from three studies conducted that collectively recorded sensor data on indoor temperature and humidity in approximately 200 homes across the four major cities in Tennessee. One study collected sensor data in homes just before and after receiving weatherization services modeled on the national Weatherization Assistance Program (WAP). A second study monitored temperature and humidity in both weatherized and unweatherized homes where at least one occupant had asthma or another chronic respiratory condition. The third study developed a system to alert elders when indoor temperatures combined with humidity levels began to pose risks to their health. Merged with local weather station data, these readings on Indoor Environmental Quality (IEQ) levels were used to analyze the impacts of weatherization on improving IEQ and reducing the emergence of hazardous indoor conditions, even when outdoor temperatures reach extremes. The team additionally estimated the degree to which weatherization may be able to reduce mortality attributable to indoor heat. Overall, the results suggest that weatherization leads to healthier indoor temperatures during both winter and summer, though indoor relative humidity may also increase in summer. These improvements in summertime home temperatures may be associated with lower mortality risk during summer months.

Introduction

Indoor temperature and relative humidity impact both the health and comfort of building occupants (Ormandy & Ezratty 2016; Edwards et al. 2025). At the extremes, exposure to cold and heat can lead to direct temperature-related health impacts from hypothermia or hyperthermia, respectively. Extreme temperatures and relative humidity levels can also impact human cardiovascular, respiratory, and immune systems (Head et al. 2018; World Health Organization 2018). High levels of relative humidity make it difficult for the body to cool down through evaporative cooling from sweat, which increases the risks associated with heat. Low relative humidity can exacerbate respiratory conditions such as asthma and increase susceptibility to airborne disease (Guarnieri et al. 2023). In low-income homes in particular, unhealthy indoor conditions can result from an inability to afford adequate fuel or adequate, energy-efficient housing (Ruse 2020). However, housing interventions such as insulation and adequate heating and cooling systems can provide a key strategy for protecting those most vulnerable to unhealthy indoor conditions (Kenny et al. 2024).

Climate in the Study Region

All four cities in the studies analyzed below—Nashville, TN, Memphis, TN, Knoxville, TN and Chattanooga, TN—have hot, humid summers and cool winters with occasional cold bursts and winter storms (Runkle et al. 2022). According to the National Oceanic and Atmospheric Administration, "Average high temperatures in the summer vary between 85°F and 90°F in western and central Tennessee and between 80°F and 85°F in the eastern portion of the state" (Runkle et al. 2022). During winter, Tennessee typically sees highs in the 40s °F and lows around 30°F (Hodges, Norrell & Howell 2026).

Importantly, heat can begin to affect mortality even when the temperature is in the 70s °F (Ai, Crago & Mullins 2026). Higher temperatures can aggravate pre-existing health conditions and lead to population-level rises in overall mortality (Dutchen 2021). Older adults, especially those with limited incomes, face compounded risk (Dutchen 2021). Even for those able to afford an air conditioning (AC) unit, the cost of using the AC or repairing it on failure may be too great: in the 2019 Arizona heat wave, 91% of people who died indoors from heat had AC units – however, 8% of the units were turned off, 87% were broken, and 5% of homes had no electricity (Maricopa County 2019).

Methodology

This paper analyzes data collected by indoor environmental quality (IEQ) sensors in weatherized and unweatherized homes across three studies conducted in the state of Tennessee, USA. Together with third-party weather data, these IEQ data are used to examine the impact of weatherization on potentially unhealthy indoor temperatures and relative humidity levels.

Data Collection

Home temperature and relative humidity data were collected as part of three separate studies taking place in the four major cities across Tennessee: Knoxville, Nashville, Chattanooga, and Memphis. The three studies and their data collection methods are summarized in the table and write ups below.

Table 1. Overview of Studies and Data Collection Methods

Study	Cities	House Types	Outdoor Data Source	What Was Measured
TDEC/TVA Home Uplift (Marincic & Rose 2023)	Nashville, Memphis, Knoxville, Chattanooga	Single-Family	Visual Crossing (official weather stations)	Temperature, RH
EASIER (Elders Alert System and POC)	Knoxville only	Single-Family (N=41); Small & Large Multifamily (N=9)	Purple Air (crowdsourced sensors)	Temperature, RH, $PM_{2.5}$, TVOCs, CO_2
HUD Home Environments & Asthma	Nashville, Memphis,	Single-Family;	Purple Air (crowdsourced sensors)	Temperature, RH, $PM_{2.5}$, TVOCs, CO_2

Study	Cities	House Types	Outdoor Data Source	What Was Measured
	Knoxville, Chattanooga	Small & Large Multifamily; Mobile Home		

Table 2. Description of Households Included in IAQ Data

Study	N Homes in Study	N Homes with Complete IAQ Data	N Weatherized During the Study	N Weatherized Prior to Study
TDEC/TVA Home Uplift (Marincic & Rose 2023)	101	101	101	0
HUD Home Environments & Asthma (Includes 20 homes recruited from the EASIER study; 17 Single-Family and 3 Small Multifamily)	67	64	0	36

Impacts of Weatherization on Temperature, Humidity, and Occupant Well-Being in the Tennessee Valley (Marincic and Rose, 2023). Following on a broad evaluation of the Tennessee Valley Authority's Home Uplift weatherization program, the research team conducted a further study to measure the impacts of weatherization on indoor temperature and relatively humidity in addition to occupant comfort, health, and well-being. Funded by the Tennessee Department of Environment and Conservation (TDEC), the study included both a qualitative phone survey with program participants and in-home IEQ monitoring in the period leading up to and following weatherization. Pre- and post-weatherization surveys captured occupant's subjective feeling of comfort in the home in addition to outcomes such as seeking medical care for exposure to extreme temperatures, asthma, chronic obstructive pulmonary disease (COPD), or arthritis. The survey also explored physical conditions and energy-related hardships in the home, such as whether:

- Heating, Ventilation, and Air Conditioning (HVAC) equipment functioned properly prior to weatherization,
- Mold and moisture were present in the home, and
- Energy bills imposed financial burden.

IEQ monitoring was conducted by placing loggers in program homes to measure indoor temperature and relative humidity one month before and one month after weatherization. The results of this evaluation indicate that weatherization programs could provide meaningful benefits for occupants by reducing indoor exposures to extreme hot and cold temperatures, particularly for those with a chronic health condition that is exacerbated by extreme temperatures, such as asthma, COPD, or arthritis. IEQ sensor readings were merged with hourly weather data from Visual Crossing to obtain outdoor temperature and relative humidity readings for each of the four major cities. Indoor and outdoor data were merged by location, day, and hour. The type and prevalence of weatherization measures installed in homes that participated in the Home Uplift evaluation are summarized in Table 3.

Table 3. Mix of Measures Installed through Home Uplift in Study Participant Homes

Measure Type	Percent of Homes Receiving Measure
HVAC Repair or Replace	76%
Air Sealing	60%
Attic Insulation	63%
Wall Insulation	3%
Duct Sealing and Repair, Insulate or Replace	67%
Hot Water Heater	17%
Lighting	20%
Windows	21%

Alerting Elders and Trusted Social Networks Living in Environmental Justice Communities About Indoor and Outdoor Risks to Their Health. This project designed, developed, deployed, and evaluated the Elders Alert System for Imminent Environmental Risks (EASIER). The system uses inputs from Indoor Air Quality (IAQ) sensors to generate alerts to elders about current and imminent indoor environmental risks (e.g., home has been too hot for too long). In addition to temperature and humidity, the sensors measured fine particulate matter ($PM_{2.5}$), total volatile organic compounds (TVOCs), and carbon dioxide (CO_2). Measurements were recorded every five minutes. EASIER was installed in 50 elders' homes located in historically disadvantaged neighborhoods of Knoxville, TN. Convenience sampling was used to select the homes. Single-family, small multifamily, and large multifamily homes were included in this project. All participating homes were required to have thermostats operatable by occupants. Because EASIER was deployed in phases over an 18-month period, temperature and humidity data were collected for 18 to 6 months for each home.

Examining Home Environments & Asthma Interventions in the Tennessee Valley. Three[3] was provided a grant by the U.S Department of Housing and Urban Development (HUD) to study why evaluations of weatherization have produced mixed results regarding asthma impacts, with some indicating positive outcomes and some finding no impact, despite improvements in common asthma triggers such as dust and mold in the home (Tonn et al. 2014; Rose et al. 2022). One hypothesis tested during the project was whether weatherization leads to worse indoor air quality. Homes for this project were drawn from a major non-energy impacts evaluation of the Tennessee Valley Authority's (TVA) low-income weatherization program called Home Uplift (HU). This program enrolled homes in Knoxville, Chattanooga, Memphis, and Nashville, TN, including 20 homes that had also participated in the above EASIER study in Knoxville, TN. For homes that participated in both the EASIER and HUD projects, IAQ monitoring and weather data were combined from both studies. Treatment and control homes where at least one occupant reported having asthma and/or another chronic respiratory disease were recruited into the project. A total of 67 homes participated, which included single-family, mobile, small multifamily and large multifamily homes. IAQ sensors that measured temperature, humidity, $PM_{2.5}$, TVOC, and CO_2 were installed in these homes for up two years. During the second year of the project, portable air cleaners (POCs) were installed to test their effectiveness and acceptability to occupants.

IEQ sensor readings from both the HUD and EASIER studies were combined into one dataset and joined with outdoor weather data from Purple Air to obtain hourly outdoor temperature and relative humidity readings. Purple Air was chosen over Visual Crossing for these projects because it also provided air pollution metrics, which were of interest to the projects overall but are not used in the current analysis. Indoor and outdoor data were merged by location, day, and hour. Indoor and outdoor temperature and RH data from the TDEC, HUD, and EASIER projects were combined into one dataset with variables for location, date, time, and weatherization status (0 = unweatherized, 1 = weatherized).

Statistical Analysis

Estimating weatherization impacts on temperature and relative humidity. The hourly datasets of indoor and outdoor temperature and relative humidity (RH) were summarized into a dataset of daytime and nighttime averages (hereafter, "12-hour averages") for each household in the three studies to allow for differences in impacts during the day versus night that can result from solar radiance, for example; daytime was defined as 6:00AM-5:59PM and nighttime from 6:00PM-5:59AM based on average sunrise and sunset times in the state. The dataset was then separated into winter and summer datasets, where winter includes December, January, and February and summer includes June, July, August, and September, modelled after O'Lenick et al. 2020.

Using the winter dataset, the team constructed a fixed effects linear model regressing 12-hour average indoor temperature on (1) weatherization status alone and (2) outdoor temperature, weatherization status, and an interaction term of outdoor temperature and weatherization status. Both models included a unique household identifier ("ID") as a fixed effect and clustering variable for the errors. Fixed effect models were estimated using feols() from the 'fixest' package and reported using summary() from base R (Bergé, Butts & McDermott 2026). The same fixed effect models were performed for (1) relative humidity in winter; (2) temperature in summer; and (3) relative humidity in summer.

The team then created a factor variable sorting 12-hour average outdoor temperature into 5-degree bins to examine indoor temperatures under groups of similar outdoor temperature levels. Average indoor temperature readings for each household were calculated within each outdoor temperature bin, and the pre-weatherization averages were subtracted from the post-weatherization averages to estimate changes in indoor temperature following weatherization for each outdoor temperature bin. Both the pre-weatherization averages and the change in averages were plotted using ggplot() from the 'ggplot2' package (Wickham 2016). Bin analyses were performed for both winter and summer data. Across all analyses, the winter data were restricted to heating days (outdoor 12-hour average temperatures under 65°F) and the summer data were restricted to cooling days (outdoor 12-hour average temperature greater than or equal to 65°F).

Estimating preventable heat-related deaths among elders. To estimate the possible protective effects of weatherization against heat-related mortality, the team adapted the methodology from O'Lenick et al. 2020, which estimated deaths attributable to excess indoor heat in Houston, TX and the surrounding county (Harris County, TX) for people ages 65 and over. In the paper, the team developed an indoor heat discomfort index (DI) defined as the average between indoor dry bulb temperature and indoor wet bulb temperature. The paper also used conditional logistic regression to estimate associations between a 3-day moving average of daily maximum DI and heat-related mortality for various demographic groups; the groups of interest for this paper for ages 65-74 and age 75+ (Table 4 in O'Lenick et al. 2020). Using this association, the paper estimated deaths attributable to excess indoor heat on any given day in a given location as:

*Attributable Deaths = (1 – exp(-log(odds) * DI)) * Number of Potentially Heat-Related Deaths*

DI here represents the difference between the maximum DI on the given day and a reference value of 20°C (68°F). Total Number of Potentially Heat-Related Deaths is a count of all deaths for the given day and location with a reported cause linked either directly to heat exposure (e.g. heat stroke) or to the respiratory or cardiovascular systems, which are especially susceptible to heat impacts. O'Lenick et al. 2020 defined potential heat-related deaths as those with an underlying cause of one of the following ICD-10-CM (International Classification of Diseases, 10th Revision, Clinical Modification) codes: I00-I99[1]; J00-J99[2]; N00-N20[3]; T67.0-T67.9[4]; and X30[5]. The paper also modelled cardiovascular deaths alone. The team adapted this methodology for the current study through the following steps:

1) using the hourly data, calculated indoor wet bulb temperature using wetbulb() from the 'heatindex' package in R along with sensor readings for indoor dry bulb temperature and relative humidity and a standard pressure of 101,000 Pa;
2) calculated DI as 0.5 * (dry bulb temperature + wet bulb temperature);
3) summarized the hourly data at the daily level, taking the maximum DI, outdoor temperature, and outdoor relative humidity reading for each day;
4) calculated a 3-day moving average of maximum daily DI, using forward fill to impute missing values.

We then acquired mortality data from the Centers for Disease Control and Prevention (CDC) Wide-ranging ONline Data for Epidemiologic Research (WONDER) system (Centers for Disease Control and Prevention 2026). WONDER allows users to query mortality data by geography (county), time period (months), demographics, and underlying causes. The team downloaded data for the counties surrounded each of the four Tennessee metros: Davidson County (Nashville, TN); Hamilton County (Chattanooga, TN); Knox County (Knoxville, TN); and Shelby County (Memphis, TN). We limited results to the age groups 65 and over and the heat-related underlying causes for all months in the study samples that were available (January 2021 – December 2024); mortality data were not yet available for 2025. Mortality data were then joined to the daily indoor IEQ data by location, month, and year; because mortality data were only available as monthly totals, the team divided the mortality counts by the number of days in each month, then calculated deaths attributable to indoor heat using the equation above for each day and household. The team constructed fixed effects linear models regressing number of attributable deaths on weatherization status and the daily maximum of outdoor temperature and

[1] Diseases of the circulatory system
[2] Diseases of the respiratory system
[3] N00-N09 Glomerular diseases; N10-N16 Renal tubulo-interstitial diseases; N17-N19 Acute kidney failure and chronic kidney disease; N20 Calculus of kidney and ureter
[4] Effects of heat and light
[5] Exposure to excessive natural heat

relative humidity to control for differences in weather and climate. Models included a unique household identifier ("ID") as a fixed effect and clustering variable for the errors. Fixed effect models were estimated using feols() from the ‘fixest’ package and reported using summary() from base R (Bergé, Butts & McDermott 2026).

Results

Winter Impacts on Temperature and Relative Humidity

Results of modeling weatherization’s impact on wintertime indoor temperatures in Table 4 indicate a statistically significant increase in indoor temperatures of 2.4°F when controlling for outdoor temperature. Additionally, prior to weatherization, homes show a positive association between indoor and outdoor temperature (coef = 0.08; p = 0.0002), meaning indoor temperatures fell as outdoor temperatures dropped. The interaction term was negative but not statistically significant.

Table 4. Fixed Effects Models of Weatherization Impacts on Average Indoor Temperature, Winter Heating Days

Variable	Model 1	p-value	Model 2	p-value	Model 3	p-value
Weatherization Status	1.31	0.02	1.25	0.02	2.43	0.03
Outdoor Temperature (12-Hour Average)			0.06	<0.0001	0.08	0.0002
Interaction Term					-0.03	0.16
Adjusted R^2	0.64		0.65		0.66	
AIC	75,683		75,112		75,077	

Note: Model 1 included weatherization status only; Model 2 included weatherization status and outdoor temperature; Model 3 included weatherization status, outdoor temperature, and an interaction term. Household ID was included as the fixed effect and cluster variable for errors. Analysis was limited to heating days (i.e., outdoor temperatures under 65°F).

The average indoor relative humidity (RH) in unweatherized homes was 40% compared to 37% in weatherized homes. Fixed effect models for the impact of weatherization on RH also initially indicated weatherization may lower indoor RH, even when controlling gfor outdoor RH (Table 5). However, when adding an interaction term in Model 3, the impact of weatherization on RH was no longer statistically significant. Similar to temperature, indoor RH also showed a positive association with outdoor RH (coef = 0.29, p < 0.0001) prior to weatherization that was partially attenuated following weatherization (coef = -0.08, p = <0.0001), indicating weatherization may have acted as a protective factor against dry outdoor air.

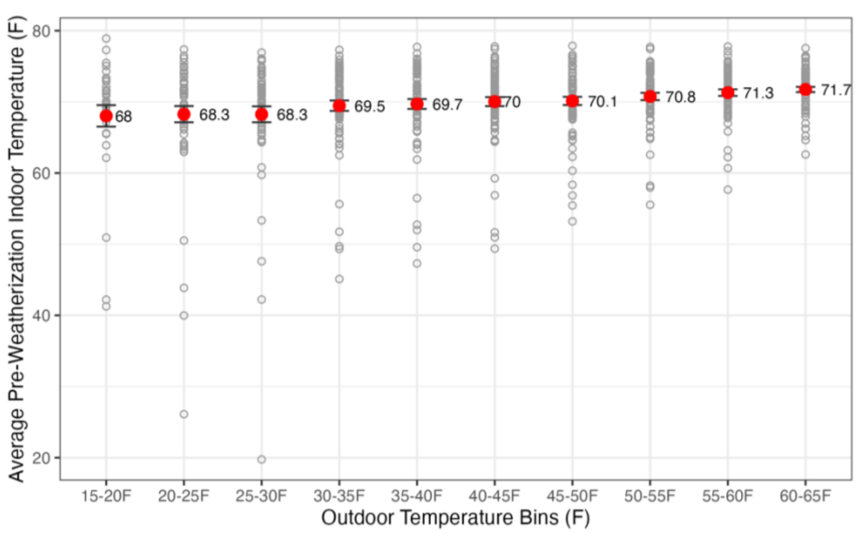
Table 5. Fixed Effects Models of Weatherization Impacts on Average Indoor Relative Humidity, Winter Heating Days

Variable	Model 1	p-value	Model 2	p-value	Model 3	p-value
Weatherization Status	-4.98	0.0002	-4.46	0.0008	2.34	0.24

Variable	Model 1	p-value	Model 2	p-value	Model 3	p-value
Outdoor Relative Humidity (12-Hour Average)			0.24	<0.0001	0.29	<0.0001
Interaction Term					-0.08	<0.0001
Adjusted R^2	0.49		0.58		0.59	
AIC	100,163		97,202		97,114	

Note: Model 1 included weatherization status only; Model 2 included weatherization status and outdoor relative humidity; Model 3 included weatherization status, outdoor relative humidity, and an interaction term. Household ID was included as the fixed effect and cluster variable for errors. Analysis was limited to heating days (i.e., outdoor temperatures under 65°F).

After averaging 12-hour indoor temperature readings within each 5-degree bin of outdoor temperatures, we find again that wintertime pre-weatherization indoor temperatures were positively associated with outdoor temperature (Figure 1). At the coldest outdoor temperatures (15-20°F), indoor temperatures averaged 68.0°F, while at the warmest outdoor temperatures (60-65°F), indoor temperatures averaged 71.7°F. Weatherization had the greatest impacts on the when outdoor temperatures were between 20-50°F, with average indoor temperatures rising between 1.2-1.9°F from the pre- to post-weatherization period. When the outdoor temperature was between 15-20°F and also between 60-65°F, average indoor temperatures actually lowered slightly from before to after weatherization, though sample sizes were limited in both bins. Results are more modest than in Table 4 due to averaging across greater spans of time. As a comparison, Panel (c) indicates that average outdoor temperatures remained fairly stable within each temperature bin (difference of 0.5°F or less), other than at the lowest and highest bins, which had the fewest data points and greatest uncertainty. This further supports the hypothesis that changes in the indoor temperature were attributable to weatherization rather than differences in outdoor temperature between the pre- and post-intervention periods.



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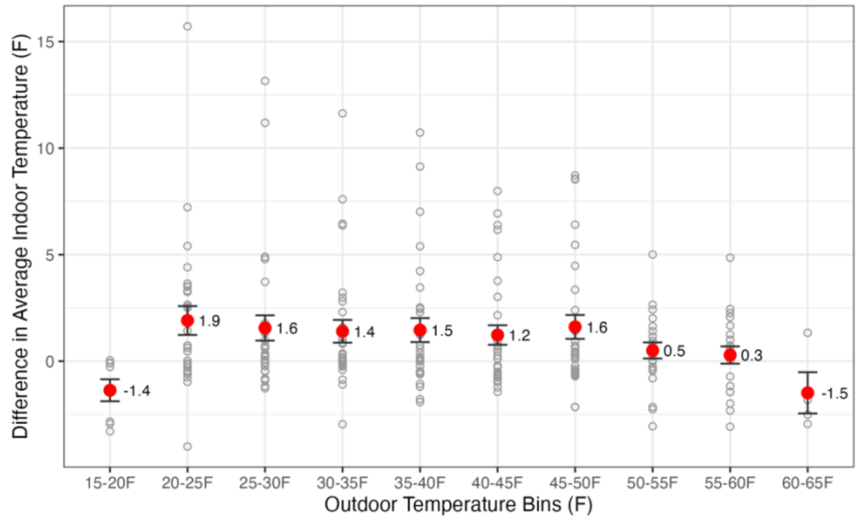

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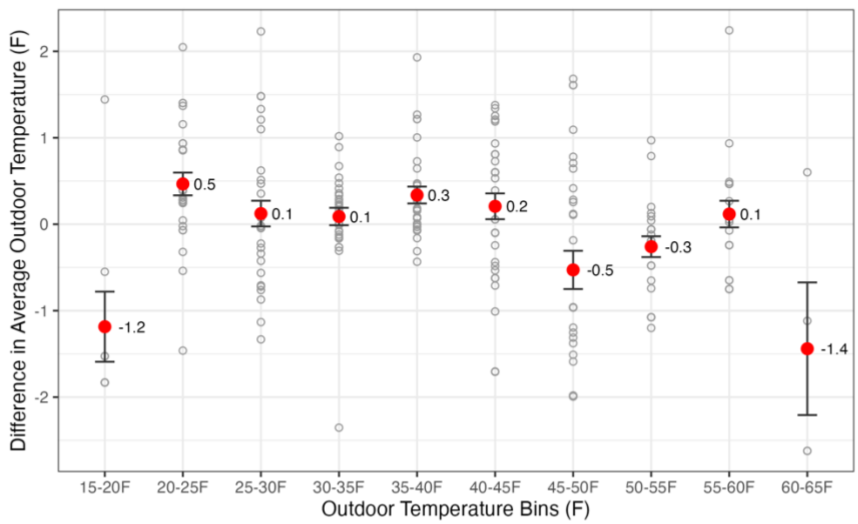


(c)

Figure 1. Analysis of winter indoor temperatures with 5-degree bins of outdoor temperature. Panel (a) summarizes average indoor temperatures prior to weatherization for each household. Panel (b) summarizes changes in indoor temperature from before to after weatherization, where positive numbers indicate an increase in indoor temperature. Analysis was limited to heating days (i.e., outdoor temperatures under 65°F). Panel (c) summarizes changes in average outdoor temperature within each temperature bin.

Summer Impacts on Temperature and Relative Humidity

The average indoor temperature among unweatherized homes was 74.3°F in the summer, compared to 73.8°F for weatherized homes. In a simple model regressing indoor temperature on weatherization status, homes were 1.59°F cooler following weatherization (Table 6; $p < 0.0001$). However, when controlling for outdoor temperature, the coefficient for weatherization status became positive and no longer statistically significant; only outdoor temperature remained significant (coef=0.06, p=0.02).

Table 6. Fixed Effects Models of Weatherization Impacts on Average Indoor Temperature, Summer Cooling Days

Variable	Model 1	p-value	Model 2	p-value	Model 3	p-value
Weatherization Status	-1.59	<0.0001	-1.53	<0.0001	0.51	0.78
Outdoor Temperature (12-Hour Average)			0.04	0.0095	0.06	0.02
Interaction Term					-0.03	0.27
Adjusted R^2	0.58		0.59		0.59	
AIC	71,040		70,876		70,861	

Note: Model 1 included weatherization status only; Model 2 included weatherization status and outdoor temperature; Model 3 included weatherization status, outdoor temperature, and an interaction term. Household ID was included as the fixed effect and cluster variable for errors. Analysis was limited to cooling days (i.e., outdoor temperatures at or above 65°F).

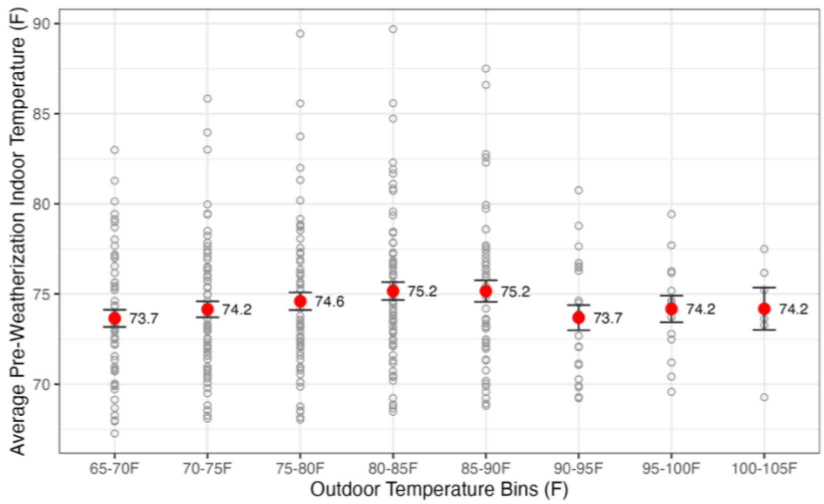
Fixed effect models also indicated that weatherization may raise indoor relative humidity levels, even when controlling for outdoor humidity (Table 7; coefs = (4.31, 5.16); p = (0.0001, 0.02)). The model indicated that indoor and outdoor RH remain positively associated following weatherization (coef=0.09, p=0.0001).

Table 7. Fixed Effects Models of Weatherization Impacts on Average Indoor Relative Humidity, Summer Cooling Days

Variable	Model 1	p-value	Model 2	p-value	Model 3	p-value
Weatherization Status	4.31	0.0001	4.04	0.0003	5.16	0.02
Outdoor Relative Humidity (12-Hour Average)			0.08	<0.0001	0.09	0.0001
Interaction Term					-0.01	0.64
Adjusted R^2	0.54		0.56		0.56	
AIC	95,906		95,385		95,383	

Note: Model 1 included weatherization status only; Model 2 included weatherization status and outdoor relative humidity; Model 3 included weatherization status, outdoor relative humidity, and an interaction term. Household ID was included as the fixed effect and cluster variable for errors. Analysis was limited to cooling days (i.e., outdoor temperatures at or above 65°F).

Looking at indoor summertime temperatures by outdoor temperature bins, indoor temperature demonstrated rising steadily alongside outdoor temperature until a discontinuity at the 90-95°F that may be due to smaller sample sizes and greater variation at the highest outdoor temperature bins (Fig. 2). Alternatively, the drop in temperatures at 90°F may reflect households turning on their air conditioning, indicating a type of comfort threshold beyond which households are no longer willing to tolerate the heat. Contrary to the mixed results in the fixed effect regression models, when analyzed by bins of outdoor temperature, weatherization had a consistently positive impact on average indoor temperatures, with greater reductions in indoor temperature occurring at hotter outdoor temperature bins from 70-90°F. There was not sufficient pre- and post-intervention data to estimate changes above 90°F. Panel (c) indicates that while outdoor temperatures were somewhat lower in the post-weatherization period specifically for the 65-70°F temperature bin, they were otherwise stable (difference of 0.3°F or less) across the pre- and post-intervention periods. Improvements in indoor temperatures consistently outpace reductions in outdoor temperatures and persist even at the 85-90°F temperature bin, which saw no change in average outdoor temperatures.



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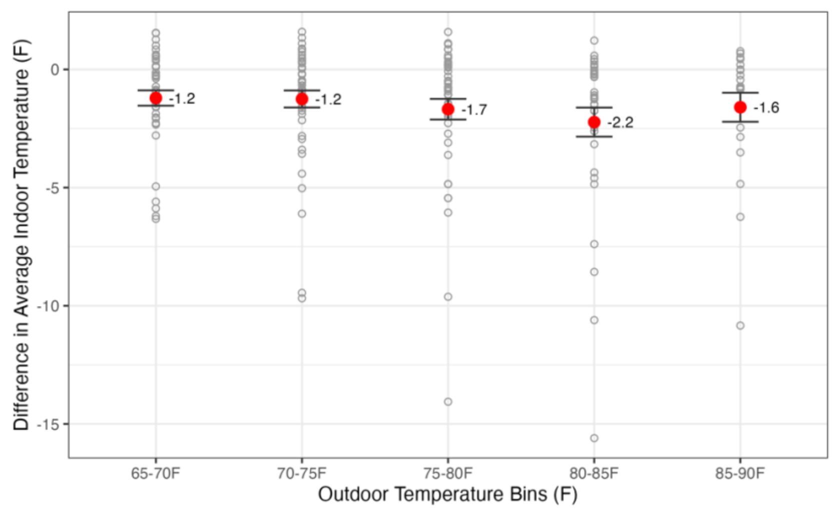

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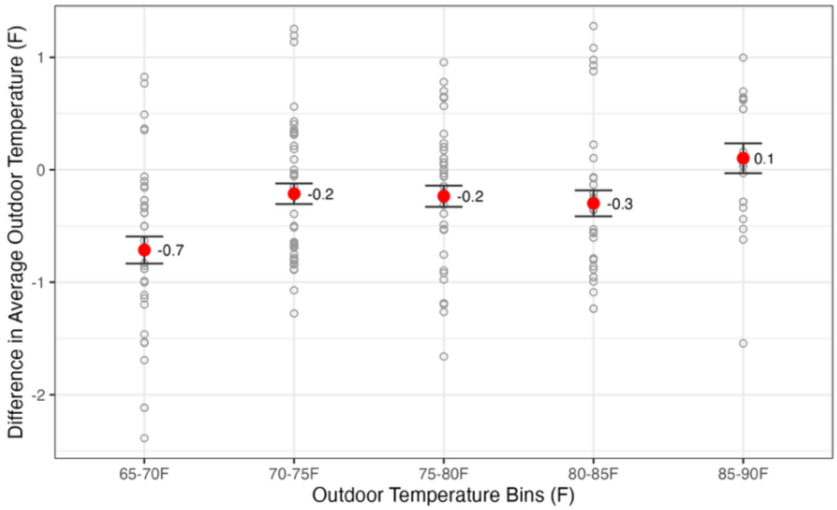

(c)

Figure 2. Analysis of summer indoor temperatures with 5-degree bins of outdoor temperature. Panel (a) summarizes average indoor temperatures prior to weatherization for each household. Panel (b) summarizes changes in indoor temperature from before to after weatherization, where negative numbers indicate a reduction in temperature. Analysis was limited to cooling days (i.e., outdoor temperatures at or above 65°F). There were insufficient data to calculate pre-post changes in indoor temperature for the following outdoor temperature bins: 90-95°F; 95-100°F; 100-105°F. Panel (c) summarizes changes in average outdoor temperature within each temperature bin.

Estimating Preventable Heat-Related Deaths Among Elders

Table 8 presents the results of modeling weatherization's impact on the indoor discomfort index (DI) when controlling for outdoor temperature and relative humidity (RH) during summer months. Despite the increases in indoor RH indicated in Table 7, the average DI, which is affected by both temperature and RH, fell by 0.7°F and the daily maximum DI fell by 1.08°F following weatherization. These improvements in DI directly affect the proportion of deaths considered attributable to indoor heat ("attributable deaths").

Table 8. Fixed Effects Models of Weatherization Impacts on Indoor Discomfort Index (DI), Summer Months

Variable	Hourly Average Discomfort Index				Daily Maximum Discomfort Index			
	Model 1	p-value	Model 2	p-value	Model 3	p-value	Model 4	p-value
Weatherization Status	-0.70	0.04	-0.64	0.06	-1.08	0.003	-1.02	0.004
Outdoor Temperature			0.16	<0.0001			0.06	0.002
Outdoor Relative Humidity			0.06	<0.0001			0.02	0.002
Adjusted R^2	0.30		0.42		0.54		0.57	
AIC	1,652,974		1,595,173		44,491		37,783	

Note: The dependent variable in Models 1 and 2 was an hourly average of the indoor discomfort index (DI). The dependent variable in Model 3 and 4 was the maximum DI value among the hourly averages within a given day ("1-hour maximum"). The independent variables in Model 2 were weatherization status, hourly average outdoor temperature, and hourly average outdoor RH. The independent variables in Model 4 were weatherization status, daily 1-hour maximum outdoor temperature, and daily 1-hour maximum RH. Household ID was included as a fixed effect and cluster variable for standard error in all models.

CDC WONDER data indicated there were 4,616 summertime deaths associated with heat, cardiovascular, or respiratory health conditions (ICD-10-CM codes I00-I99, J00-J99, N00-N20, T67.0-T67.9, X30) across Davidson, Hamilton, Knox and Shelby Counties from 2021-2024 for people ages 65 and over. When controlling for total number of heat-related deaths, outdoor temperature, and outdoor RH, the daily number of deaths attributed to indoor heat showed a statistically significant decline in three of the four models (Table 9). When looking at all causes of mortality that may be affected by heat, daily deaths attributed to indoor heat declined by 0.136 for the 65-74 age group and 0.05 for the 75+ age group ($p = 0.008$ and $p = 0.005$, respectively). Among deaths linked to the cardiovascular system, deaths attributed to indoor heat declined by 0.075 per day in the 75+ age group. Across the four months of summer (122 days), the results for all heat-related deaths (Models 1 and 2) would translate to 22.7 fewer deaths among those age 65+ living in weatherized versus unweatherized homes in each location.

Table 9. Fixed Effects Model of Weatherization Impacts on Deaths Attributed to Indoor Heat; Davidson, Hamilton, Knox and Shelby Counties, 2021-2024

Variable	Daily Deaths Attributed to Indoor Heat, Ages 65-74		Daily Deaths Attributed to Indoor Heat, Ages 75+		Cardiovascular Deaths Attributed to Indoor Heat, Daily, Ages 65-74		Cardiovascular Deaths Attributed to Indoor Heat, Daily, Ages 75+	
	Model 1	p-value	Model 2	p-value	Model 3	p-value	Model 4	p-value
Weatherization Status	-0.136	0.008	-0.050	0.005	-0.100	0.35	-0.075	0.01
Total Daily Heat-Related Deaths	0.402	<0.0001	0.166	<0.0001	0.369	0.08	0.264	<0.0001
Daily Maximum Outdoor Temperature	0.008	0.005	0.004	0.0004	0.010	0.001	0.007	0.0002
Daily Maximum Outdoor Relative Humidity	0.002	0.06	0.0009	0.06	0.003	0.01	0.002	0.006
Adjusted R^2	0.67		0.58		0.69		0.60	

Limitations and Future Work

Primary limitations of this study include the small sample size, which is then extrapolated to county-wide populations. Future work should look to collect temperature and humidity data in a larger sample of homes both before and after weatherization and across a larger geography.

Further work will aim to improve modeling of summertime weatherization impacts, such as testing quadratic terms to capture the U-shaped relationship between indoor and outdoor temperature. Additional near-term work (Spring 2026) will include summarizing the alert rules base used in the EASIER system for elders and estimating the degree to which home weatherization measures could reduce alerts related to unsafe temperature and relative humidity levels in the home. Estimates of weatherization's impact on heat-related mortality could also be adjusted to account for rising outdoor temperatures.

Conclusion

In this paper, we find that home weatherization for low-income households in a hot-humid climate can substantially increase indoor temperatures the winter and reduce indoor temperatures but increase relative humidity during the summer. Results regarding wintertime impacts on indoor relative humidity were mixed. During both winter and summer, the interaction term between weatherization and outdoor temperature was not statistically significant, while the absolute improvements in temperature were highly significant, indicating that weatherization improves indoor temperatures but may not have a large impact on the relationship between indoor and outdoor temperatures.

In a simulation of mortality impacts for people ages 65 and over, models indicated weatherization served as a protective factor against mortality from causes affected by heat. Despite higher summertime relative humidity inside the weatherized homes, the discomfort index (DI), which is impacted by both temperature and humidity, improved both on average and at its maximum daily value. When looking at days where the maximum DI reached above 20°C, indicating a potential risk to health, this translated to statistically significant reductions in modelled mortality both among all heat-related health conditions and specifically for disease of the cardiovascular system, which can be exacerbated by heat.

Together, the results of the indoor environmental quality modelling and heat-related mortality simulation indicate that income-qualified weatherization programs can serve as an important mitigation strategy against both cold and hot temperatures, which are expected to become more severe due to climate change. While further work with a larger household sample size and more detailed mortality data is needed to verify the findings regarding prevented deaths, this paper provides important evidence that weatherization can save lives during summer heat and improve comfort year-round.

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