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Impact of meteorology on indoor air quality, energy use, and health in a typical mid-rise multi-family home in the eastern United States

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Abstract

Heating and cooling requirement differences across climates not only have carbon emissions and energy efficiency implications but also impact indoor air quality (IAQ) and health. Energy and IAQ building simulation models help understand tradeoffs or co-benefits, but these have not been applied to evaluate climate zone or multi-family home differences. We modeled a four-story multi-family home in six U.S. climate zones and quantified energy, IAQ, and health outcomes with EnergyPlus, CONTAM, and a pediatric asthma systems science model. Pollutant sources included cooking and ambient. Outputs were daily $PM_{2.5}$ and NO_2 indoor concentrations, infiltration, energy for heating and cooling, and asthma exacerbations, which were compared across climate zones, apartment units, and resident behaviors. Daily ambient-sourced $PM_{2.5}$ decreased and cooking-sourced $PM_{2.5}$ increased with higher ambient temperatures. Infiltration air changes per hour were higher on the first versus the fourth floor and in colder climates. Window opening during cooking led to decreases in total pollutant concentrations (11%–18% for $PM_{2.5}$ and 9%–15% for NO_2), 3%–4% decreases in asthma exacerbations within climate zones, and minimal impacts on cooling, but led to increased heating demand (4%–8%). Our results demonstrate the influence of meteorology, multi-family building characteristics, and resident behavior on IAQ, energy, and health, focused on multi-zone methodology.

KEYWORDS
climate zones, energy, indoor air quality, multi-family homes, multi-zone modeling, pediatric asthma

1 | INTRODUCTION

Energy demands for residential buildings vary by regional climate zone, with implications for climate action plans that seek to curb carbon emissions and meet reduction goals associated with fuel and electricity consumption.[1] Region-specific climate conditions, such as ambient temperature, influence pressure and temperature differentials across the building envelope, which in turn affect air exchange rates and the degree to which buildings must be heated or cooled to maintain thermal comfort. Improving energy efficiency in homes is often accomplished with measures that tighten the building envelope and increase insulation.[2] Such changes to the building envelope also influence indoor air quality (IAQ) via reduced infiltration and exfiltration of indoor- and outdoor-sourced pollutants, with resultant impacts on human health. Therefore, understanding region-specific energy and IAQ impacts of residential energy efficiency interventions is vital to maximizing human health benefits across climate zones.

In the United States, much of the information on the energy and IAQ implications of energy efficiency measures is derived from audits of single-family homes enrolled in savings programs.[3] However, single-family homes are not necessarily representative of all residential homes.[4] Housing with five or more units, or multi-family housing, comprises 18% of the 118.2 million housing units in the United States,[5] and residents often have lower socioeconomic status, are renters, or belong to a formally identified vulnerable population (e.g., children, older adults).[6] In the United States, multi-family houses represent a growing percentage of households, although the percentage of residential energy consumption attributable to multi-family housing has remained constant,[7] and a range of factors influence both energy and IAQ differently than in single-family homes. For example, common spaces and shared interior walls allow air pollutants to travel between units, and resultant exposures are magnified due to small living space volumes.[8,9] In spite of the importance of multi-family housing, there is a lack of comprehensive and representative data on inter-zone airflows and envelope leakiness for these building types,[4,10] parameters which are crucial to estimating energy and IAQ impacts of planned residential energy efficiency interventions.

Building simulation models can estimate energy and IAQ impacts of energy efficiency measures in the absence of available data. Such models have been used to assess regional variation in $PM_{2.5}$ infiltration in the U.S. housing stock,[11] infiltration differences across UK housing types,[12] and the effect of changing temperatures (due to climate change) on air exchange and indoor exposures in single-family U.S. homes.[13] One research group created a single-zone building modeling framework that assesses IAQ, energy, and health for the U.S. housing stock and found well-matched estimates of energy and indoor air pollutant concentrations, as well as the chronic health burden from air pollution.[14] However, these studies modeled all homes as a single zone, including multi-family apartment buildings, and did not capture the influence of regional climate and other key factors on both energy and IAQ.

In this study, we use a novel combination of models to provide insight about the influence of regional climate on energy, IAQ, and health in multi-family homes in the United States. This work builds on our previous research developing and applying IAQ-energy-health modeling frameworks to characterize NO_2 and $PM_{2.5}$ concentrations in multi-family homes for health-based intervention modeling,[15] assess indoor environmental quality and interventions for pediatric asthma and associated costs[16] and estimate the impact of residential behavior and retrofit actions on IAQ and energy.[17] We adapted these multi-family housing models to quantify the impact of regional climate on indoor air quality, energy use, and pediatric asthma health outcomes.

2 | METHODS

2.1 | Overview of the coupled energy and indoor air quality model

We applied a previously published building co-simulation model[18] to analyze indoor pollutant exposures and energy use in a four-story mid-rise multi-family home in several U.S. climate regions. The co-simulation model incorporates EnergyPlus (Department of Energy, Washington, DC), a whole building energy simulation program, and CONTAM (National Institute of Standards and Technology, Gaithersburg, MD), a multi-zone indoor air quality and ventilation analysis program. The advantages of this co-simulation model include dynamic temperature calculations from EnergyPlus and defined airflow pathways in CONTAM to perform multi-zone modeling for a multi-family home, rather than modeling it as a single zone. Building parameters and meteorology were modified to reflect the climate zone. We also examined the impact of human behavior (window opening during evening cooking time) on energy use and IAQ regionally. We analyzed building- and apartment-level indoor pollutant concentrations, energy used for heating and cooling for the whole building, and air changes per hour due to infiltration. Figure 1 shows the inputs and outputs of our modeling framework.

2.2 | Meteorology, climate zones, and building templates

We selected six climate zones in the eastern United States from the International Energy Conservation Code (IECC) guidelines[19] as shown in Figure 2; see Table 1 for summary metrics. These climate zones were chosen because they have similar levels of ambient moisture, but vary greatly in ambient temperature. Hourly meteorological data for each climate zone (using a medium-to-large city within each) was assigned based on the most recent Typical Meteorological Year (TMY3) file (National Renewable Energy Laboratory, Golden, CO), which approximates annual meteorology based on historical data from 1976 to 2005.[20,21] Meteorological parameters included dry and wet bulb temperatures, relative humidity, barometric pressure, direct and normal solar radiation, and wind speed and direction (see Table S1). We also modified ground temperatures to be region-specific.

The baseline multi-family building model has 32 apartment units, with four floors and eight units per floor (Figure 3). We modified this baseline model in EnergyPlus with building parameters that reflected region-specific construction practices for pre-1980 housing infrastructure in the United States,[22] including window properties and external wall and roof insulation. These building parameters (i.e., insulation and windows) were matched to pre-1980 building templates as our baseline for older, leakier, and less energy efficient buildings.[22] Additionally, building leakage rates were

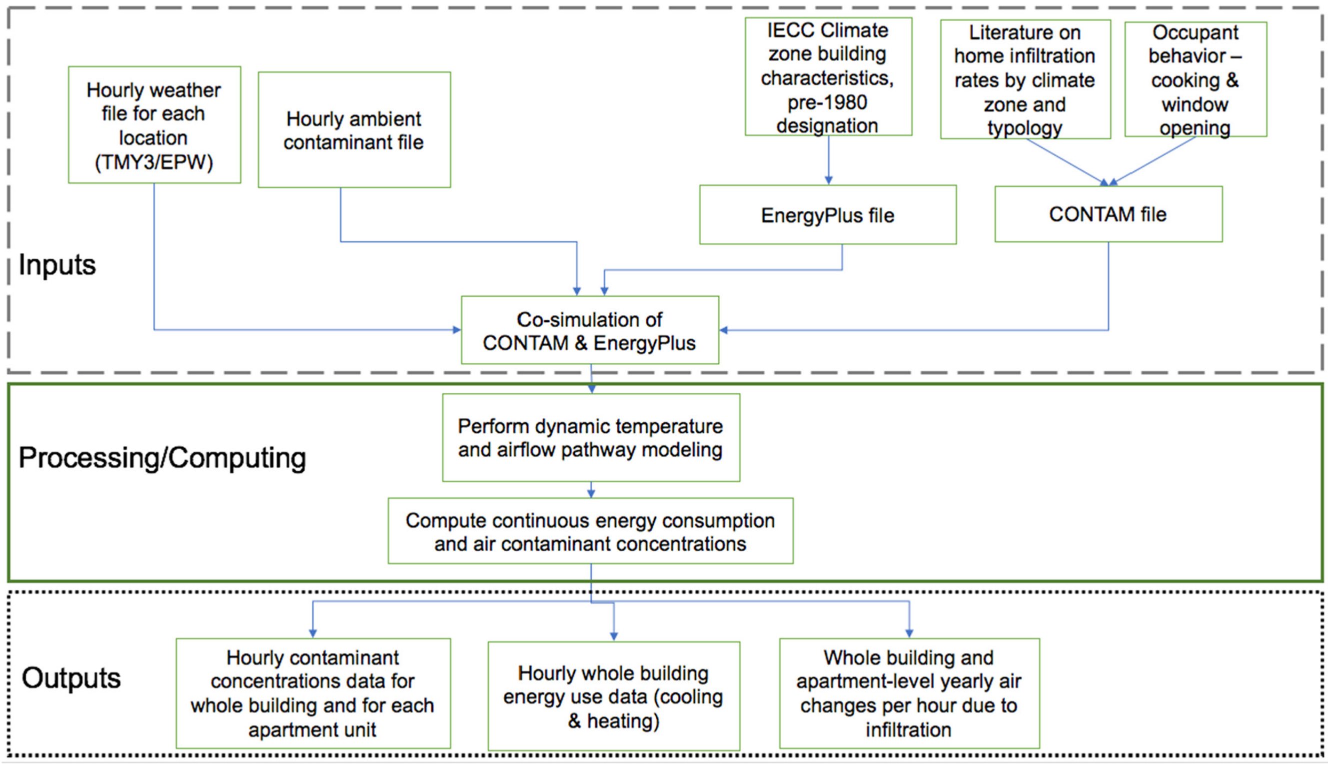
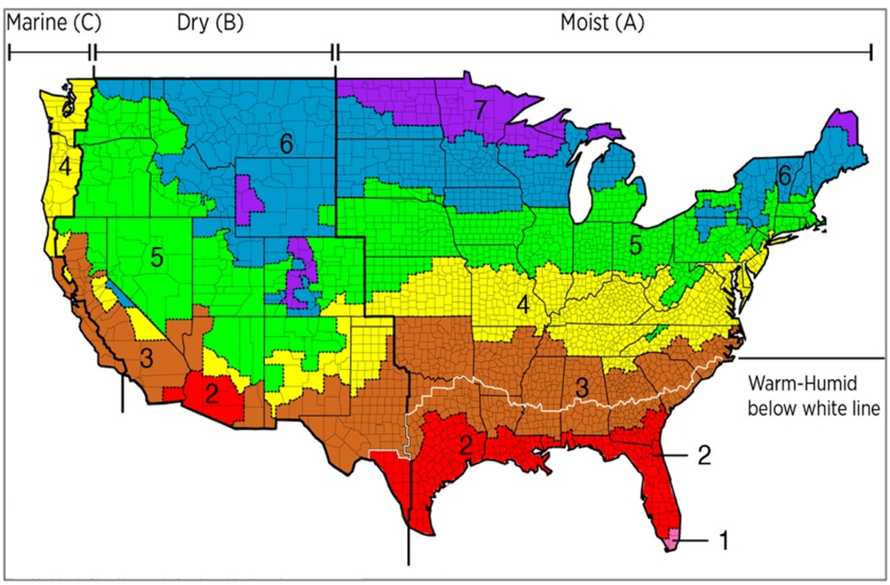


FIGURE 1 Conceptual model schematic of inputs and outputs in our co-simulation modeling framework

FIGURE 2 Adapted from the International Energy Conservation Code map of the U.S. regional climate zones. Our analysis focuses on the Moist (A) climate zones in the eastern United States



modified in the CONTAM housing templates, based on building construction across different climate zones.[10,23,24] External wall leakage rates were all calculated at an ambient pressure of 75 Pa (a standard pressure for larger multi-zone buildings) with 20.3 m^3/h-m^2 for zones 5A and 6A (the coldest zones), 25.6 m^3/h-m^2 for zones 3A and 4A, and 33.3 m^3/h-m^2 for zones 1A and 2A (the warmest zones) and reflected varying external wall leakiness based on climate zones. Building parameters (i.e., insulation, windows, and external wall leakage rates) were modified to be region-specific (Table S2). Heating, ventilation, and air conditioning (HVAC) systems were automatically sized by EnergyPlus to meet heating and cooling requirements for the extreme temperatures according to the respective weather files. Building models were representative of older housing stock in which infiltration was the primary way in which outdoor air entered the building unintentionally through openings, no supply of outdoor air is provided from the HVAC system, and recirculation within units is the heating and cooling mechanism.[17]

Climate zone	Zone type	Yearly mean (range) ambient dry bulb temperature (°C)	Classification
1A	Very hot-humid	24.5 (5 to 35.6)	Warm
2A	Hot humid	20.4 (−6.1 to 39.4)	Warm
3A	Warm humid	16.7 (−12.8 to 36.7)	Warm
4A	Mixed humid	12.8 (−13.9 to 36.7)	Cold
5A	Cool humid	10.6 (−20 to 37.2)	Cold
6A	Cool humid	7.9 (−27.8 to 37.2)	Cold

TABLE 1 International Energy Conservation Code (IECC) climate zones and regional yearly parameters from typical meteorological year (TMY3) files

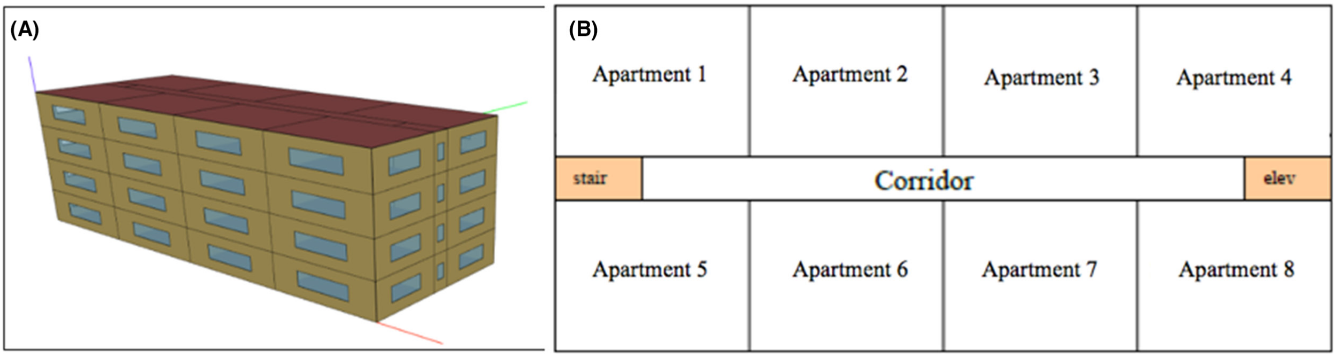


FIGURE 3 (A) EnergyPlus building model and (B) CONTAM floor plan for mid-rise multi-family building

2.3 | Air pollutant modeling and residential behavior

We used a single ambient pollution dataset for all models to allow us to compare IAQ effects across climate zones while controlling for ambient concentrations. The ambient pollution dataset included monitored fine particulate matter with an aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$) and nitrogen dioxide (NO_2) from the US EPA AirData database for 2009 to 2019 for Suffolk County, MA.[25] Measurements below the limit of detection or missing were excluded (15% of the overall data). We calculated mean hourly concentrations by month and weekday to create a file of hourly concentrations for a full year, similar to our previous work.[15] The resulting mean concentration (and standard deviation) for $PM_{2.5}$ was 11.5 (1.7) μg/m^3 and for NO_2 was 14.9 (4.5) ppb. $PM_{2.5}$ and NO_2 emitted during cooking was modeled by turning on the gas stove for breakfast at 7:00–7:10 AM and for dinner at 18:00–18:20 every day in all apartment units.[17] $PM_{2.5}$ and NO_2 emission and decay/deposition values are listed in Table S3. Windows were modeled as closed at all times or open during evening cooking time from 18:00–18:20 every day. Window opening during this cooking time was based on guidance to reduce indoor air pollution and improve ventilation when possible given housing design and safety with window opening.[26,27]

2.4 | Asthma discrete event simulation model

Health outcomes related to IAQ were generated using our previously published discrete event simulation (DES) model for pediatric asthma.[16] In short, the DES simulates the effect of daily modeled indoor NO_2, $PM_{2.5}$, and allergen exposure on lung function of a child with asthma, measured by forced expiratory volume for one second expressed as a percentage of the forced vital capacity (FEV1%). The DES then uses predicted FEV1% to estimate the total number of serious adverse asthma events (clinic visits, emergency department visits, and hospitalizations), prescription medicine use, and related health care costs per child with asthma. For each climate zone, we ran the DES for 1000 children with asthma over the course of five years and analyzed the number of serious asthma events per simulation.

2.5 | Analysis

We created a total of 12 co-simulation models (6 climate regions × 2 window scenarios), and ran each for a full year. We examined the changes in IAQ, energy use, and health outcomes by climate zones, building floor, and apartment unit. Energy consumption totals for site energy, electricity used for cooling, and gas used for heating were checked for anticipated values and trends based on mean yearly ambient temperatures and related cooling and heating demands. We evaluated the relationship between daily ambient- and cooking-sourced pollutant levels and mean daily ambient temperature across climate zones by fitting a locally estimating scatterplot smoothing, or LOESS, function with a 95% confidence interval and calculated R^2 values. We assessed percent differences for window opening and between climate zones for pollutant concentrations, energy consumption totals, and predicted asthma events. All data compilation and statistical analyses were performed in the statistical software R Version 3.5.2. Whole building results are reported to describe overall IAQ-energy trends while multi-zone results describe within-building differences and the impact of occupant behavior.

3 | RESULTS

3.1 | Impact of climate on IAQ and energy consumption

Differences in meteorology by climate zone were reflected in overall trends in IAQ. As mean ambient temperature increased, daily ambient-sourced $PM_{2.5}$ concentrations decreased and cooking-sourced $PM_{2.5}$ increased (Figure 4) with LOESS R^2 of 0.61 and 0.67, respectively. We observed similar trends for ambient- and cooking-sourced NO_2 (data not shown). Colder climates had more days with larger indoor–outdoor temperature differences, in which more infiltration occurred and increased the concentration of ambient pollutants entering the multi-family home. Differences in meteorology by climate zone were also reflected in overall trends in energy consumption, with anticipated patterns. Cooling energy consumption was higher in warmer climate zones, while heating energy consumption was higher in colder climate zones (Table 2).

3.2 | Impact of stack effect on ACH and IAQ

Differences in air exchange rates by climate zone explain some of the energy and IAQ dynamics, with variable effects across floors of the multi-family building. Colder climates had greater values for whole-building ACH due to higher infiltration on the first floors compared to warmer climates (Figure 5). These building dynamics reflected the stack effect, the physical phenomenon in which heat affects the movement of air upward in a building with more replacement air entering on the first floor. In the warmest climate zone (1A), there was an indication of the reverse stack effect, with the fourth floor having higher infiltration rates compared to the lower floors, a result of more space cooling in the building throughout the year.

In almost all climate zones, ACH was higher on the first floor compared with the fourth floor, yielding higher ambient-sourced air pollutant concentrations, but lower cooking-sourced air pollutant concentrations on the first floor. For example, in the coldest climate zone (6A), yearly mean cooking-sourced $PM_{2.5}$ was 11 μg/m^3 for an apartment unit on the first floor, compared to 19 μg/m^3 for the fourth floor, and ambient-sourced $PM_{2.5}$ was 8.4 μg/m^3 for a unit on the first floor and 6.0 μg/m^3 on the fourth floor, corresponding to a percent increase of 73% (cooking) and a percent decrease of 29% (ambient) for the fourth versus the first floor, respectively. In contrast, for the warmest climate zone (1A), there was a higher cooking-sourced $PM_{2.5}$ concentration on the first floor (23 μg/m^3) compared to the fourth floor (14 μg/m^3), with lower ambient-sourced $PM_{2.5}$ on the first floor (5.0 μg/m^3) compared with the fourth floor (7.3 μg/m^3), corresponding to a percent decrease of 39% (cooking) and a percent increase in 46% (ambient) for the fourth versus the first floor, respectively.

3.3 | Impact of window opening on ACH and IAQ

When windows were opened during dinner cooking time for 20 minutes, we found that overall site energy (i.e., total energy consumed by the building) increased between 0.20% and 2.55% across climate regions, with colder regions having greater increases associated with heating requirements (Table 3). In contrast, total indoor $PM_{2.5}$ and NO_2 both decreased considerably across all climate zones. Yearly $PM_{2.5}$ averages decreased between 11% and 17% with the largest decreases in colder climate regions. Yearly, NO_2 averages decreased between 9.2 and 14.7%, with similar decreases in all but the coldest climate zone. In general, window opening decreased indoor-sourced air pollutant concentrations indoors more than it increased ambient-sourced pollutant concentrations indoors.

Opening windows also had larger decreases in total $PM_{2.5}$ and total NO_2 for fourth floor apartments compared to first floor apartments in all but the warmest climate zone (1A). For climate zones 2A through 6A, the fourth-floor decreases ranged from 3.1 to 3.9 μg/m^3 for total $PM_{2.5}$ (13%–16% decreases for open vs. closed windows) and 1.1–1.4 ppb for total NO_2 (12%–16%). The first-floor decreases were 2.8–3.0 μg/m^3 (12%–14%) and 1.0–1.2 ppb (11%–13%), respectively. In contrast, the warmest climate zone (1A) showed larger decreases on the first floor of 2.8 μg/m^3 for $PM_{2.5}$ and 0.9 ppb for NO_2 (11% and 10%) compared with decreases in 2.5 μg/m^3 for $PM_{2.5}$ and 0.8 ppb (9.8% and 10%) for NO_2 on the fourth floor for open versus closed windows.

3.4 | Impact of climate and window opening on asthma exacerbations

The incidence of serious asthma events was similar among climate zones (Table 4). Window opening for 20 minutes during evening cooking reduced serious asthma events by 3.5%–4.1% across climate zones, with no clear trend as a function of temperature. Asthma events followed from the difference (or similarity) in IAQ as described above. Using climate zone 5A as an example, an apartment unit on the first floor had 1.2% lower predicted serious adverse events compared to a unit on the fourth floor with windows closed. With windows open during cooking, serious adverse events were reduced by 3% for the fourth-floor unit and 2.6% for the first-floor unit, reducing the difference between floors to 0.4%.

4 | DISCUSSION

In this analysis, we leveraged a building co-simulation model framework and incorporated meteorological impacts and building characteristics from six eastern U.S. climate zones on a four-story mid-rise

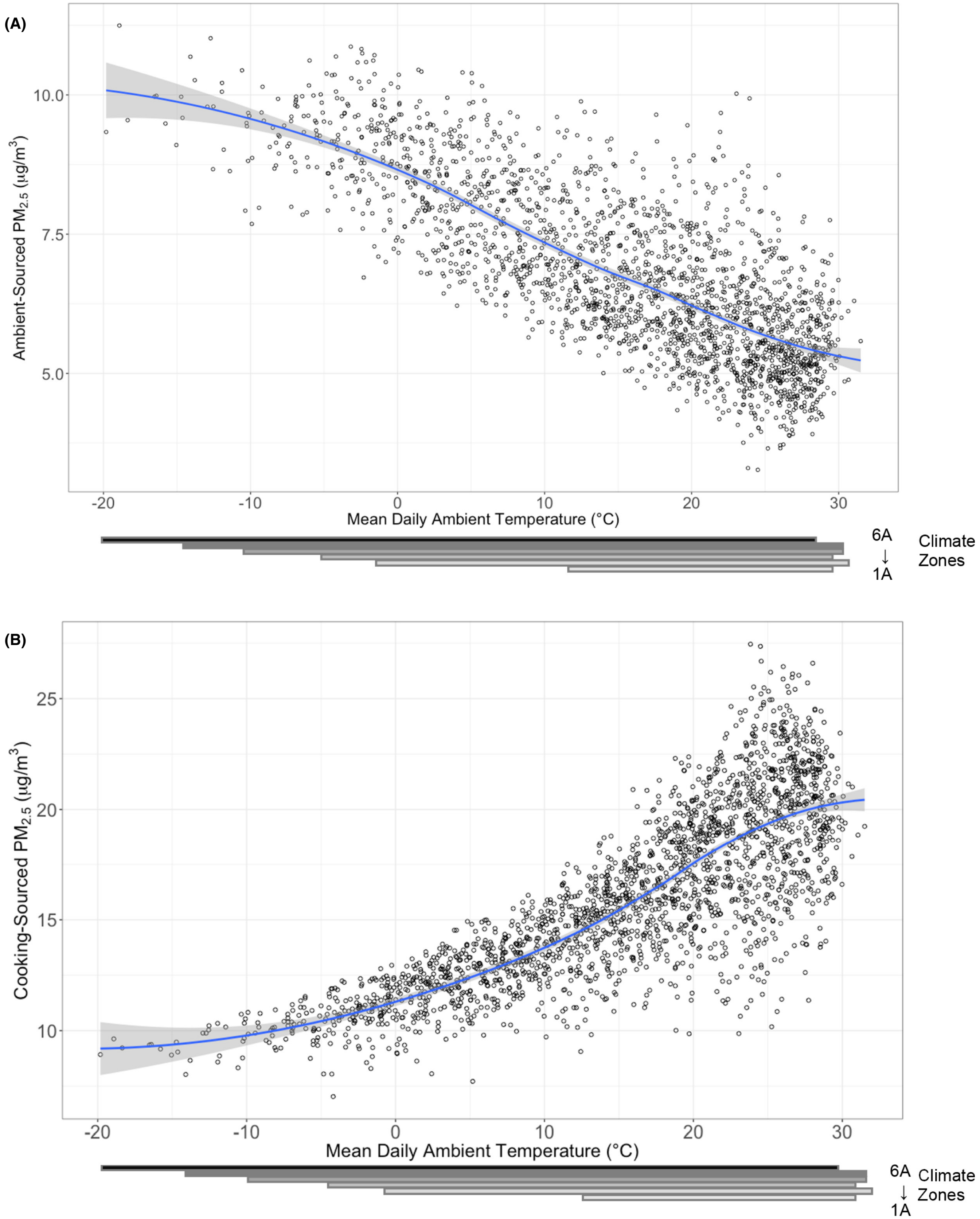


FIGURE 4 (A) Whole building daily ambient-sourced $PM_{2.5}$ as a function of daily mean ambient temperature across all six climate zones for one year. Each horizontal bar shows the range of mean daily ambient temperatures in each climate zone from 6A to 1A. (B) Whole building daily cooking-sourced $PM_{2.5}$ plotted as a function of mean ambient temperature across all six climate zones for one year. Each horizontal bar shows the range of mean daily ambient temperatures in each climate zone from 6A to 1A

TABLE 2 Yearly total site, cooling, and heating energy consumption in six climate zones

Climate zone	Total site energy (thousand kWh)	Electricity cooling (thousand kWh)	Gas heating (thousand SCF)
1A	423	107	0.9
2A	410	78	81
3A	426	54	227
4A	486	52	414
5A	431	26	354
6A	478	22	528

Site energy is total energy used on site by the building, including for HVAC, lighting, and water use.

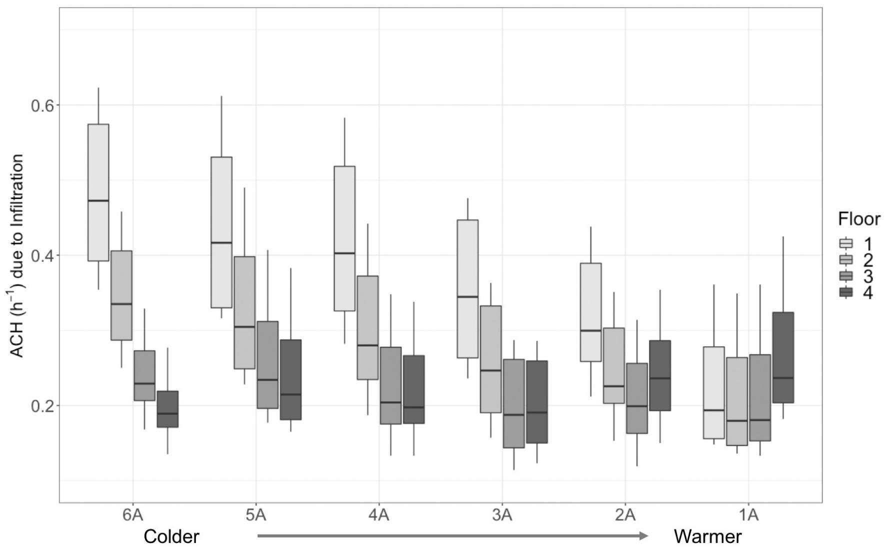


FIGURE 5 Building infiltration in ACH (h^{-1}) by floor and across six climate zones. Box and whisker plots indicate median (the solid black line in middle of each box), 25th to 75th percentiles (bottom and top of each box), and the upper and lower whiskers extend to 1.5 times inter-quartile range

TABLE 3 Whole building percent change[a] in yearly total indoor pollution and yearly energy use between windows closed and windows open scenarios

Climate zone	Total indoor $PM_{2.5}$ (%)	Total indoor NO_2 (%)	Total site energy (%)	Electricity cooling (%)	Gas heating (%)
1A	−11.2	−10.1	0.20	0.63	4.13
2A	−13.3	−11.1	0.64	0.77	7.06
3A	−13.6	−9.20	1.17	0.55	5.78
4A	−13.3	−10.4	1.86	0.47	6.51
5A	−13.9	−11.3	2.02	−0.75	7.99
6A	−17.7	−14.7	2.55	−0.90	7.54

[a]Percent change = Total indoor pollutant concentration or energy use for windows open − energy/pollution for windows closed divided by windows closed multiplied by 100%.

TABLE 4 Average number of asthma exacerbations per 1000 children in all climate zones and across window opening scenarios

Climate zone	Average # of exacerbations (windows closed)	Average # of exacerbations (windows open)	% Difference[a] in window opening within climate zone
1A	9.44	9.09	−3.69
2A	9.44	9.05	−4.12
3A	9.42	9.09	−3.49
4A	9.42	9.03	−4.11
5A	9.39	9.03	−3.75
6A	9.41	9.03	−4.07

[a]Window opening calculation: (# of events in climate zone for windows open—# of events in climate zone for windows closed)/# of events in climate zone for windows closed) × 100%.

multi-family home. Regional differences in ambient conditions drove IAQ differences in residential settings. Daily $PM_{2.5}$ and NO_2 ambient-sourced concentrations decreased with increasing mean daily ambient temperature. Conversely, daily cooking-sourced indoor $PM_{2.5}$ and NO_2 concentrations increased with higher mean daily ambient temperatures across all climate zones. Apartment units with higher infiltration had lower overall pollutant levels due to the influx of outdoor air, especially on colder days. We found that cooking-sourced pollutants accumulated without the infiltration and subsequent dilution of outdoor air. Across all climate zones, daily window opening during dinner cooking time resulted in a decrease in total indoor pollutant levels of 10%–18%, while energy consumption yielded differences by only a few percentage points at the building level. Finally, asthma exacerbations were lower for apartments with daily window opening compared with no daily window opening and for apartments on the first floor compared with the fourth floor. These findings are important for home owners and residents of multi-family homes because of the implications from climate change and climate action planning on energy, IAQ, and health.

Multi-family homes with dozens of units represent unique logistical challenges in both modeling and monitoring in field studies. These types of homes have been understudied compared with single-family homes and have complex layouts that may not be well-represented by single-zone modeling.[23] While multi-family apartments may be twice as leaky as single-family homes per unit of building envelope area, indoor environments of multi-family apartments may still lack adequate ventilation, in part due to compartmentalization, thus emphasizing the need to model the multiple zones within these buildings.[4] A comprehensive review of inter-zonal airflow in multi-unit residential buildings has shown the multitude of factors related to indoor environmental quality including wind, ventilation, window opening, exterior and interior building leakiness, climate, and occupant behavior practices, while highlighting the need for continued research on these types of homes.[28] Building compartments (i.e., corridors, elevators, stairways) increase the influence of stack effect, wind effect, and the resulting pressure differentials on indoor environmental quality.[29,30] Interior flow between units on higher floors of high-rise apartment buildings were higher than on lower floors in multi-family homes with average leakiness, and, even with tighter building envelopes (i.e., reduced air leakiness), inter-air transfer between apartments occurred in housing energy models.[31] Temperature differentials are also important factors based on climate region and season with subsequent impacts on infiltration and pollutant buildup indoors.[32] In our analysis, we found differences in infiltration by floor and by climate zone as well as corresponding differences in mean yearly pollutant concentrations. Our four-story mid-rise building allowed us to capture the impacts of meteorological conditions on the indoor environment, which has implications for the health of residents in multi-family housing.

We compared the results of our modeling analysis to field studies of homes with similar ages and number of floors. Analyses of infiltration or natural ventilation air change rates in two- to three-story multi-family homes have found values ranging from 0.14 to 0.6 h^{-1}.[33–35] In Villi et al.,[36] researchers calculated an average air change rate due to infiltration at 0.1 h^{-1} during the heating season in Italy. This housing study also found decreasing infiltration rates (from 0.11 to 0.04 h^{-1}) for apartment units on higher to lower floors of three-story multi-family apartments during the heating season.[36] The range of average ACH due to infiltration in our analysis was 0.25 to 0.32 h^{-1}, which lined up well with these studies of similar home types. Our findings and these field studies of similar home types and ages show that air exchanges from natural ventilation of the older housing stock are still not sufficient to provide fresh and filtered air to residents.[28,36] Consideration of infiltration and movement between apartment units has great implications for multi-family housing residents. Monitoring studies investigating the effect of environmental tobacco smoke on neighboring units in apartments has shown that older, less well-insulated housing is more susceptible to the sharing of this polluted air than newer housing.[8,37] Given the higher rates of smoking in affordable and public housing,[38] increasing our understanding of IAQ dynamics in multi-unit apartment buildings is essential to minimize resident health impacts.

Many studies have modeled indoor particulate matter, NO_2, and other indoor pollutants (e.g., VOCs) through a variety of methodologies involving box models and building modeling software. In a study focused on modeling population-adjusted $PM_{2.5}$ across the entire U.S. housing stock, researchers compared modeled studies to largescale field studies and calculated air exchange rates, concentrations, and infiltration of $PM_{2.5}$.[11] Compared with our results, those from the $PM_{2.5}$ population dynamic model found higher mean air exchange rates (approximately 1.5 h^{-1}) but did not distinguish between infiltration versus total ACH. Also, these data were primarily sourced from single-family homes, which have simpler constructions (as noted above). In a home modeling study for the entire U.S. housing stock, researchers developed a framework to simultaneously assess IAQ ($PM_{2.5}$, ultrafine particles, NO_2, ozone, VOCs), energy consumption, and health (disability-adjusted life years).[14] Their results showed infiltration ACH with a mean = 0.37 h^{-1} (SD = 0.13) for housing for 1970–1989, similar to our results (0.25–0.32 h^{-1}). These studies used single-zone modeling, including for multi-family houses, which could lead to differences with our work since accounting for multiple zones within an apartment building may reveal lower air change rates due to less well-ventilated indoor spaces.

Climate change will affect residential settings with significant impacts on IAQ, indoor allergens, and indoor temperatures from increased ambient temperatures and anticipated building updates. In a review of the impacts of climate change on the domestic indoor environment, researchers detailed the large number of consequences expected for IAQ, indoor allergens, and indoor temperatures.[39] One study has also considered the impact of increasing ambient temperatures for infiltration and pollutants and found that air exchange decreased in single-family U.S. homes due to anticipated smaller outdoor-indoor temperature differentials.[13] As with many modeling studies, this study primarily considered single-family homes and questions remain about the impacts on multi-family home residents. With expected retrofits to the existing housing stock and new home construction built to be more energy efficient, airtightness of the external walls will increase, thereby potentially leading to the buildup of pollutants inside without proper ventilation balance. Therefore, the proposed decarbonization and energy efficiency upgrades of the building sector should take into account the potential changes to both energy use and IAQ. By focusing primarily on reduced energy consumption and associated carbon emissions, indoor air pollutant concentrations could increase without and adversely affect residents.

We addressed the nexus of occupant behavior, IAQ, and energy in our analysis by considering residents who open their windows during an evening cooking time. This action resulted in decreases of average $PM_{2.5}$ and NO_2, with slight percentage increases in cooling and heating. Window opening could simulate the effects of an exhaust fan or filters inside the home that may be part of planned retrofits in which government agencies and stakeholders consider IAQ and health along with energy efficiency measures to combat climate change. With tighter buildings being built, research must consider the impacts on the indoor environment for our aging homes to benefit these residents. Future work in this area could expand the number of climate zones studied in the United States. or around the world, including more region-specific building types for multi-family homes and potential regional variability in air pollution or occupant behaviors. In a warming climate, the impact on older buildings will be realized in changing heating and cooling demand, especially in traditionally colder regions. Further analyses of multi-zone buildings could investigate these interactions and analyze more closely the impacts on energy, IAQ, and health for residents.

5 | CONCLUSION

Policy interventions to reduce carbon emissions (e.g., building energy efficiency updates) may leave multi-family housing residents vulnerable to the impacts of these decisions if the necessary steps to prioritize health are not taken, such as adequate ventilation and filtration of indoor residential air. Modeling studies allow us to evaluate housing types and climate zones given limitations with measured housing data which remain resource-intense to obtain. Our modeling framework can evaluate IAQ, energy, health, and climate simultaneously given the interconnectedness of these factors in affecting the indoor environment and human health. Results showed varying air exchange rates and pollutant concentrations across apartments in the same building, demonstrating the heterogeneity in multi-family housing not captured in single-family studies. Since millions of people reside in multi-family homes in the United States, research in this field is needed as government agencies and partners implement energy efficiency goals for the building sector to reduce carbon emissions.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST

The authors declare no conflict of interest for this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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