

Article

Impact of Winter HVAC Use Patterns on Arthritis Symptoms in Young Older Adults Across Climate Zones

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Abstract

Environmental differences between climate zones may affect arthritis risk. This study aims to explore how winter HVAC use impacts arthritis symptoms in young older adults across four Chinese cities: Chongqing, Beijing, Guangzhou, and Kunming. We surveyed 3579 participants aged 60–74 and used partial least squares-structural equation modeling (PLS-SEM) to explore relationships between HVAC habits, indoor environmental exposure, and arthritis outcomes. Results reveal that distinct climate-specific HVAC usage patterns and their differing relationships with indoor environmental exposures and arthritis symptoms. In Beijing, widespread heating is linked to fewer symptoms (28.6%), while greater reliance on air conditioning or ventilation in humid southern cities corresponds to higher prevalence (33.3–44.9%). The favorable association between HVAC habits and arthritis outcomes was strongest in Beijing, whereas the adverse association between indoor environmental exposures and arthritis was strongest in Chongqing. Mediation analysis suggested that these associations were largely explained through indoor environmental conditions, particularly reduced cold exposure (72.32% in Chongqing) and reduced damp exposure (44.71% in Guangzhou). The strength of this indirect association varied across cities, ranking as Chongqing > Guangzhou > Beijing > Kunming. These findings highlight the importance of climate-responsive HVAC strategies and suggest that improving indoor environmental conditions may support healthier ageing in winter.

Keywords: multi-city; HVAC utilization habits; young older adults; arthritis; indoor environment



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1. Introduction

The aging population is accelerating in most countries worldwide, driven by notable rises in life expectancy. Arthritis is a common disease affecting the well-being of older adults. Global burden of disease data indicate that in 2021, among individuals aged more than 70 in China, there were 1237 cases of disability-adjusted life years due to osteoarthritis [1]. Future estimates suggest a substantial rise in osteoarthritis cases within China, with the

incidence and disability-adjusted life years (DALYs) expected to increase about 1.5-fold from 2020 to 2044 [2].

China is a large country with five main climate zones: Severe Cold (SC), Cold (C), Hot Summer and Cold Winter (HSCW), Hot Summer and Warm Winter (HSWW), and Mild (M). This climate diversity offers a good basis for multi-city research. Heating, ventilation, and air conditioning (HVAC) usage and indoor environments vary a lot across these zones. These differences are mainly caused by local climate and prevailing heating policies. The Qinling-Huaihe Line divides the country into the north and the south. People in the north and south use different heating methods in winter. This makes the indoor environment in homes more complex. Many studies have compared indoor thermal conditions between northern and southern cities [3–5]. In general, cities in the SC and C zones, like Beijing and Harbin, keep heating systems running almost all the time. This helps maintain indoor temperatures above 24 °C to keep residents comfortable [6]. A field study also found that indoor temperatures during sleep in northern cities were about 4 °C higher than in the south [7]. In warmer cities like Guangzhou and Hong Kong, indoor temperatures stay around 20 °C because the outdoor weather is mild [5]. But in HSCW cities like Shanghai and Chongqing, indoor temperatures can drop below 12 °C. This often happens when people only heat some rooms part-time using heaters or air conditioners [5]. A large study of more than 8000 households in the Yangtze River area confirmed this user-controlled heating style. It showed that air conditioners are the main source of heating in winter [8]. In HSCW areas, many people feel uncomfortable because the heating is not enough. Even when they use heating devices, over 30% still wish it were warmer indoors [9]. In this zone, HVAC use also changes with income, time of day, and season [10]. This shows how people adjust their habits based on local climate. These studies show that climate zones strongly affect how people use HVAC in winter. Multi-city research can help us better understand how HVAC use shapes indoor environments and how this might affect health.

The indoor environment of buildings can pose significant challenges to human health and comfort. Many studies have shown that chemical, biological or physical agents, commonly prevalent in residential environments, can be detrimental to human health [11–13]. Inhalable particles in the air can stimulate immune responses, potentially triggering or worsening inflammatory conditions [14]. In addition to exposure to particulate matter, the health risks associated with exposure to dampness are well documented. Severe dampness and mold damage in Finland costs an estimated annual healthcare expenditure of €2.01 billion [15]. An Australian study found a significant positive correlation between relative humidity and the incidence of joint swelling in older adults ($p = 0.032$) [16]. Furthermore, inappropriate indoor cold exposure can harm health. It is widely recognized that low temperatures can exacerbate arthritis symptoms. For young and middle-aged arthritis patients (aged 50–65), hospital visits typically occur at lower temperatures, suggesting that cold exposure may worsen arthritis symptoms [17]. In summary, these findings suggest that poor indoor environmental conditions in buildings significantly increase the risk of diseases such as arthritis.

HVAC systems play a vital role in regulating indoor temperature, humidity, and air circulation, thereby promoting a healthy and comfortable indoor environment [18,19]. In certain specific contexts, such as hospitals [20], schools [21,22], and restaurants [23], the installation of HVAC systems is mandated to safeguard human health. For patients with knee osteoarthritis, the use of localized heaters has been shown to significantly alleviate pain [24]. Additionally, installing HVAC systems helps reduce indoor mold and dampness, which, in turn, lowers the incidence of respiratory diseases [25]. Conversely, in buildings unable to afford air conditioning systems, inadequate indoor operating temperatures that

exceed physiological comfort limits can pose risks to physical and mental health, such as winter-related pain [26].

Previous research has explored the effects of HVAC systems on health [27,28] and numerous studies discussed how environmental factors—including temperature, precipitation, and barometric pressure—affect arthritis [16,29–31]. Also, our earlier work has established that HVAC utilization habits can indirectly improve health by adjusting indoor environmental conditions (i.e., reducing cold exposure, dampness, and air pollution) [32]. However, few studies have explored the comparative effects of HVAC utilization habits on arthritis symptoms across different climate backgrounds. The core focus of this study is to compare how variations in HVAC utilization habits—primarily through their influence on indoor temperature, humidity, and air quality—affect arthritis symptoms among the young older adults across different climate zones. Therefore, this study constructs a structural equation model encompassing variables such as HVAC utilization habits, indoor environment, and health status across four climate zones, focusing on the following two objectives:

- (1) To reveal how winter HVAC usage patterns differ across climate zones, and how these differences correspond to variations in arthritis prevalence among the young older adults.
- (2) To identify the pathways through which HVAC usage mitigates arthritis symptoms via indoor environmental exposures, and to assess how these pathways vary across different climate zones.

2. Materials and Methods

2.1. Cross-Sectional Survey

This study investigates the association between residential indoor environment characteristics and arthritis among young older adults across different climatic regions in China. The survey cities were purposively sampled, and Chongqing, Beijing, Guangzhou and Kunming were chosen to conduct the research. Among which, Beijing represents the C zone, Chongqing represents the HSCW zone, Guangzhou represents the HSWW zone, and Kunming represents the M zone. The survey was conducted from October 2021 to March 2023. Based on an arthritis prevalence (p) of 27.7% from GBD 2021, a confidence level of 95% ($u_{\alpha/2} = 1.96$), and a tolerance error (δ) of 3%, the minimum required sample size for each city was 855 participants, calculated by Formula (1) [33]. To ensure a sufficient response rate, 1000 questionnaires were distributed in each city.

$$n = [u_{\alpha/2}^2 \times p \times (1 - p)] / \delta^2 \quad (1)$$

A multi-stage cluster random sampling method was employed in this survey to obtain a representative sample of young older adult residents from each city. In the first stage, a complete list of all districts in each city was compiled, from which three districts were randomly selected. In the second stage, within each selected district, a list of parks and public squares was generated, and three sites were randomly chosen in each district. At each site, four professionally trained researchers handed out the questionnaires and clarified any questions for participants as needed. Inclusion criteria for the sample consisted of individuals aged 60 to 80 who had resided in the city for over ten years. Individuals outside these criteria or unwilling to participate were excluded. Details of the cross-sectional survey methodology have been described in prior studies [32,34]. The study protocol was approved by the Ethical Review Committee of the School of Life Sciences, Central China Normal University. All participants gave informed consent before joining the survey.

The questionnaire consisted of four sections: demographic characteristics, residential environment, lifestyles, and arthritis-related health status. The residential environment and HVAC habits were adapted from the Swedish Dampness in Buildings [35] and the China, Children, Homes, Health study [36]. The arthritis-related health outcomes were developed based on the Swedish Epidemiological Investigation of Rheumatoid Arthritis [30] and the European Symptoms in Persons At Risk of Rheumatoid Arthritis [37]. These internationally recognized large cohort studies have been validated in numerous publications [38,39], ensuring the reliability of the questionnaire. With assistance from professionally trained researchers, each participant completed the questionnaire in approximately 15–20 min.

Individuals aged 75–80 years were excluded as they constituted less than 0.5% of the total sample. Additionally, samples with missing questionnaire data were excluded, resulting in a final inclusion of 3579 participants, distributed approximately equally across Chongqing, Beijing, Guangzhou, and Kunming at 25.1%, 24.7%, 25.1%, and 25.1%, respectively. In Chongqing and Beijing, the response rate was higher among men than among women. Over 70% of participants were concentrated in the 60–64 age group. They generally maintained a healthy weight, with only about 10% being underweight or obese. The prevalence of a family history of arthritis was higher in Chongqing than in the other three cities. Additionally, only 10.2–12.6% of participants retained smoking habits, and almost half had never smoked in their lives. The sample's statistical characteristics are shown in Table 1.

Table 1. Demographic information.

Item	Chongqing	Beijing	Guangzhou	Kunming
Sample	897 (25.1)	884 (24.7)	899 (25.1)	899 (25.1)
Gender				
Male	492 (54.8)	542 (61.3)	303 (33.7)	411 (45.7)
Female	405 (45.2)	342 (38.7)	596 (66.3)	488 (54.3)
Age				
60–64	768 (85.6)	658 (74.4)	775 (86.2)	764 (85)
65–69	114 (12.7)	176 (19.9)	117 (13)	124 (13.8)
70–74	15 (1.7)	50 (5.7)	7 (0.8)	11 (1.2)
BMI				
Underweight	27 (3)	78 (8.8)	87 (9.7)	87 (9.7)
Healthy weight	607 (67.7)	508 (57.5)	643 (71.5)	551 (61.3)
Over weight	229 (25.5)	255 (28.8)	157 (17.5)	233 (25.9)
Obesity	34 (3.8)	43 (4.9)	12 (1.3)	28 (3.1)
Family genetic history of arthritis				
Yes	277 (30.9)	212 (24)	233 (25.9)	242 (26.9)
No	620 (69.1)	672 (76)	666 (74.1)	657 (73.1)
Smoking				
current	113 (12.6)	106 (12)	92 (10.2)	104 (11.6)
ever	268 (29.9)	333 (37.7)	365 (40.6)	371 (41.3)
never	516 (57.5)	445 (50.3)	442 (49.2)	424 (47.2)
Income				
<5000	191 (21.3)	177 (20)	91 (10.1)	177 (19.7)
5000–10,000	265 (29.5)	331 (37.4)	363 (40.4)	290 (32.3)
10,000–50,000	280 (31.2)	226 (25.6)	200 (22.2)	205 (22.8)
>50,000	161 (17.9)	150 (17)	245 (27.3)	227 (25.3)
Education				
Primary school	48 (5.4)	57 (6.4)	21 (2.3)	43 (4.8)
Middle school	242 (27)	115 (13)	91 (10.1)	110 (12.2)
High school	306 (34.1)	280 (31.7)	166 (18.5)	214 (23.8)
Bachelor's degree	301 (33.6)	432 (48.9)	621 (69.1)	532 (59.2)

Table 1. *Cont.*

Item	Chongqing	Beijing	Guangzhou	Kunming
Professional prestige				
Heavy manual labor	311 (34.7)	272 (30.8)	65 (7.2)	84 (9.3)
Light manual labor	261 (29.1)	217 (24.5)	468 (52.1)	463 (51.5)
Non-manual labor	325 (36.2)	395 (44.7)	366 (40.7)	352 (39.2)

2.2. Research Variables

Five latent variables were identified from the survey items through factor analysis (see Table S1): HVAC utilization habits, indoor cold exposure, indoor damp exposure, indoor air pollution, and health status.

Independent variable. HVAC utilization habits regulate the indoor environment and may influence health. The survey items were adapted from the China, Children, Homes, Health study [36]. Lower usage frequency reflects a less favorable indoor environment for participants.

Dependent variable. Health status was measured by arthritis symptoms. Based on European studies [30,37], we included three indicators: joint pain, joint swelling, and joint stiffness. A higher frequency of these symptoms indicates greater severity.

Mediators. Indoor cold exposure (ICE), indoor damp exposure (IDE), and indoor air pollution (IAP) were included as potential mediators. Cold discomfort indicates poor thermal conditions. Damp exposure was assessed by mold spots, damp stains, and water damage. Lower scores indicate better indoor conditions. Air pollution was assessed using questionnaire-based proxy indicators for particulate matter (PM) and volatile organic compounds (VOCs), the most common indoor pollutants. PM exposure was represented by the frequency of cooking in the current dwelling, because residential cooking is a major indoor PM source, and cooking frequency has been reported to influence indoor PM exposure [40,41]. VOC exposure was represented by a recent furniture purchase or home renovation within the past 12 months, because building materials, interior finishes, and furniture are important indoor VOC sources, especially in newly renovated or newly furnished homes [42]. These items were used to capture potential indoor pollution sources rather than directly measured pollutant concentrations; therefore, the IAP construct may contain measurement error and may bias the estimated path coefficients involving IAP. Although VOC exposure did not differ significantly across cities, it was retained in the SEM because it showed a significant loading on the latent construct of IAP.

Covariates. Gender, age, BMI, family history of arthritis, smoking status, and socioeconomic status (income, education, professional prestige) were included, as these have been shown to correlate with arthritis in prior epidemiological studies [43,44].

Details of questionnaire items and rating scales are shown in Figure 1.

2.3. Statistical Analysis

This study first collected average monthly temperatures and relative humidity from December to February over the past five years for four cities, using data from the National Meteorological Science Data Center (<https://data.cma.cn/>).

To compare HVAC habits and health status across cities, we used the Kruskal–Wallis test, followed by Dunn’s post hoc tests. Pearson correlation analysis was conducted to explore relationships between indoor environment, HVAC usage, and health status. Correlation coefficients were used to rank influencing factors.

	Research variables	Definition/Measuring questions	Rating scales
 HVAC utilization habits	Heating	How often do you use floor heating/radiators in winter? ^a	4 often 3 sometimes 2 occasionally 1 never
	Air conditioner	How often do you use air conditioners in winter?	
	Ventilation	How often does your home use exhaust fans/fresh air systems?	
 Indoor cold exposure	Cold feeling in the living room	In the last 12 months, have you felt cold when you were in the living room in winter?	4 often 3 sometimes 2 occasionally 1 never
	Cold feeling in the bedroom	In the last 12 months, have you felt cold when you were in the bedroom in winter?	
 Indoor damp exposure	Mold spots	In the last 12 months, have you noticed any visible or apparent mold spots (on interior walls, ceilings, or floors) in your home?	3 massive 2 minor 1 none
	Wet stains	In the last 12 months, have you noticed any visible or apparent damp spots (on interior walls, ceilings, or floors) or condensation?	
	Water damage	In the last 12 months, have you experienced any water damage in your home? (such as flooding or leaks causing peeling, cracking, or flaking of floors, walls, or ceilings)	
 Indoor air pollution	Particular matter	In the last 12 months, how often have you cooked in your current dwelling?	3 often 2 occasionally 1 never
	VOCs	In the last 12 months, have you bought new furniture or renovated your current dwelling? ^b	
 Health status	Joint pain	In the last 12 months, how often have you experienced symptoms of joint pain?	4 often 3 sometimes 2 occasionally 1 never
	Joint swelling	In the last 12 months, how often have you experienced symptoms of joint swelling?	
	Joint stiffness	In the last 12 months, how often have you experienced symptoms of joint stiffness?	

^a A score of 1 indicates no use a week, 2 indicates HVAC use once or twice a week, 3 indicates use three to five times a week, and 4 indicates use six or seven times a week.
^b A score of 1 is assigned if no new furniture was purchased and no renovations were made in the past year; 2 is assigned if either new furniture was purchased or renovations were conducted; and 3 is assigned if both actions were carried out.

Figure 1. Questionnaire items and rating scales for research variables.

We built two binary logistic regression models using HVAC habits as independent variables and health status as the outcome. Health was classified based on arthritis symptoms (Yes/No). Model Formula (2) is shown as follows:

$$\text{logit}[P(Y = 1)] = \beta_0 + \beta_1 \text{HVAC} + \beta_2 \text{gender} + \beta_3 \text{age} + \beta_4 \text{family history} + \beta_5 \text{BMI} + \beta_6 \text{smoke} + \beta_7 \text{income} + \beta_8 \text{education} + \beta_9 \text{professional prestige} \quad (2)$$

where Y denotes the binary arthritis outcome (joint pain, joint stiffness, or joint swelling), and HVAC denotes the HVAC utilization habit (heating, air conditioning, or mechanical ventilation). Separate logistic regression models were fitted for each arthritis outcome and each HVAC utilization habit. Models adjusted for covariates listed in Section 2.2. Results are reported as adjusted odds ratios (AORs) with *p*-values.

To further assess the effects and pathways linking HVAC habits, indoor exposures, and arthritis outcomes, we developed a structural equation model with multiple mediators. Five latent variables were extracted using factor analysis, explaining 65.09% of the total variance. Indoor cold exposure and health were treated as reflective measurement models; HVAC habits, air pollutants, and dampness were formative.

We used partial least squares SEM (PLS-SEM), which suits models combining reflective and formative indicators and does not require multivariate normality. HVAC habits were assumed to affect both the indoor environment and health, directly and indirectly. These hypotheses are summarized in Table 2 and modeled in Figure 2. The model structure is shown in Formula (3).

#Regressions between latent variables

$$\text{IAP} \sim \text{HVAC} + \text{IDE} + \text{ICE}$$

$$\text{IDE} \sim \text{HVAC} + \text{ICE}$$

$$\text{ICE} \sim \text{HVAC}$$

(3)

#Regression between latent variables and dependent variable

$$\text{Health status} \sim \text{HVAC} + \text{IAP} + \text{IDE} + \text{ICE} + \text{HVAC} * \text{IAP} + \text{HVAC} * \text{IDE} + \text{HVAC} * \text{ICE}$$

Table 2. Hypotheses of relationships between latent variables.

Code	Hypothesis	Code	Hypothesis
H1	HVAC utilization habits positively affect health status	H6	Indoor damp exposure is associated with poor health status
H2	HVAC utilization habits negatively affect indoor cold exposure	H7	Indoor damp exposure correlates with indoor pollutant exposure
H3	HVAC utilization habits negatively affect indoor damp exposure	H8	Indoor cold exposure is associated with poor health status
H4	HVAC utilization habits negatively affect indoor pollution exposure	H9	Indoor cold exposure correlates with indoor damp exposure
H5	Indoor pollution exposure is associated with poor health status	H10	Indoor cold exposure correlates with indoor pollutant exposure
H11	HVAC * ICE moderates the impact of the ICE on health status	H12	HVAC * IDE moderate the impact of the IDE on health status
H13	HVAC * IAP moderates the impact of the IAP on health status		

Note: The asterisk * denotes the interaction between HVAC utilization habits and ICE/IDE/IAP, representing their joint moderating effect on health status.

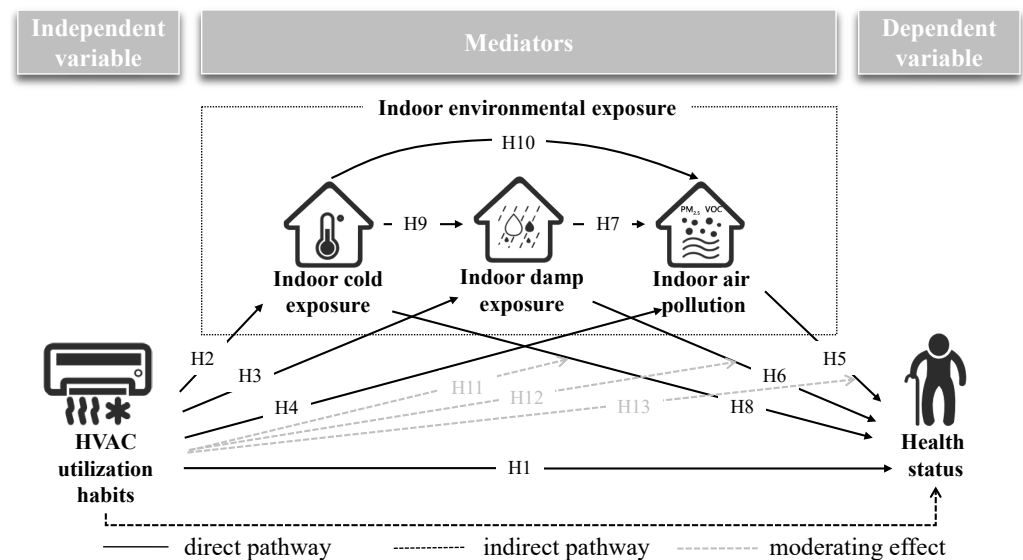


Figure 2. Path relationship between HVAC utilization habits and indoor environmental exposure on health status. Note: Solid arrows represent direct pathways, black dotted arrows represent indirect pathways, and gray dotted arrows represent moderating effects.

Measurement model reliability was confirmed with Cronbach's alpha and composite reliability (>0.7). Most item loadings exceeded 0.7, and AVE values were >0.5. Discriminant validity was supported by the Fornell–Larcker test. Some indicators were not significant but retained for completeness. VIF values were mostly <3. Analyses were performed using IBM SPSS Statistics 25 (IBM, Armonk, NY, USA) and the cSEM package in R v4.1.0 (R Core Team, Vienna, Austria).

3. Results

3.1. Climatic Features

Figure 3 illustrates the winter (December to February) outdoor temperature and humidity characteristics over the past five years in four cities. Guangzhou records the highest dry bulb temperatures, with winter minimums above 11 °C, reducing the likelihood of young older adults experiencing cold. Chongqing and Kunming share similar temperature ranges (7.9–13.5 °C), though Kunming's distribution is more concentrated. Beijing, by con-

trast, is significantly colder, with temperatures from -3.6°C to 2.8°C . In terms of humidity, Chongqing maintains consistently high levels (70–80%). Guangzhou's peak winter relative humidity occasionally surpasses that of Chongqing, although its average relative humidity remains slightly lower, with a broader range from 61.5% to 86.1%. Kunming's humidity remains within a comfortable range (52.2–75.0%), and Beijing has the lowest humidity, with markedly lower levels and a minimum as low as 30.2%. ANOVA results confirm significant differences in winter temperature and humidity across the four cities ($p < 0.001$). For temperature, all pairwise comparisons show significant differences ($p < 0.001$) except between Chongqing and Kunming. For humidity, all cities differ significantly ($p < 0.001$) except Chongqing and Guangzhou. These findings highlight clear climatic contrasts: Chongqing experiences relatively cold and humid winters, Guangzhou is warm but humid, Beijing exhibits typical cold and dry northern climate characteristics, and Kunming's moderate meteorological environment remains neutral among the four cities.

Winter Outdoor Climate Psychrometric Chart of four major cities

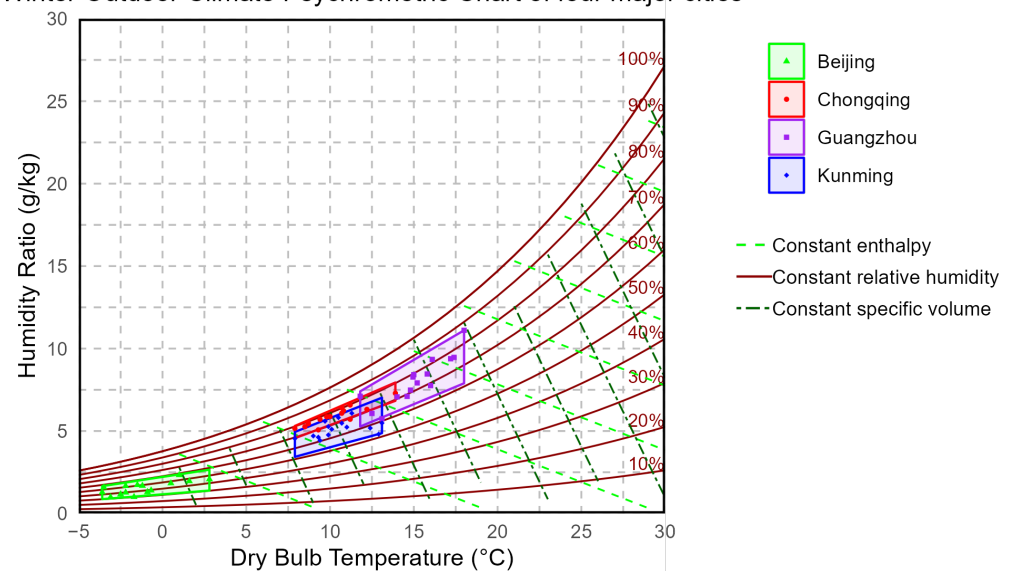


Figure 3. Winter temperature and relative humidity in four cities.

3.2. Variations in HVAC Utilization Habits, Indoor Environment, and Arthritis Symptoms Across Climate Zones

Figure 4 presents the disparities in winter HVAC utilization habits, indoor environmental exposures, and the incidence of arthritis attacks among young older adults in the four cities. A total of 64.9% of participants in Beijing frequently use floor heating or radiators, whereas only about 3% of participants in the southern cities report using these heating systems. The small proportion in the southern cities represents households equipped with individual floor-heating systems or radiators rather than centralized district heating. Instead, most households in the southern cities rely on air conditioners (52.1–71.7%). Half of these individuals employ these devices occasionally or sometimes. Mechanical ventilation like exhaust fans or fresh air systems is widely adopted ($\geq 85\%$ any use), with 43.6–56.2% using it regularly in Beijing, Guangzhou, and Kunming. These patterns are statistically robust (Kruskal–Wallis $p < 0.001$, see Figure 5). Dunn's tests show that heating use in Beijing $>$ Chongqing/Guangzhou/Kunming (all $p < 0.001$). Air conditioning use in Guangzhou/Kunming $>$ Beijing (all $p < 0.001$), highlighting the need for heating through air conditioners in milder southern climates. Ventilation use also varied significantly. Guangzhou showed the highest frequency, and residents in Kunming were most likely to report "frequent ventilation," while Beijing had the lowest ($p < 0.001$). These patterns reflect the stronger reliance on natural ventilation in warm-humid or temperate climates.

For mechanical ventilation, Guangzhou showed a significantly higher frequency than the other three cities (all $p < 0.001$).

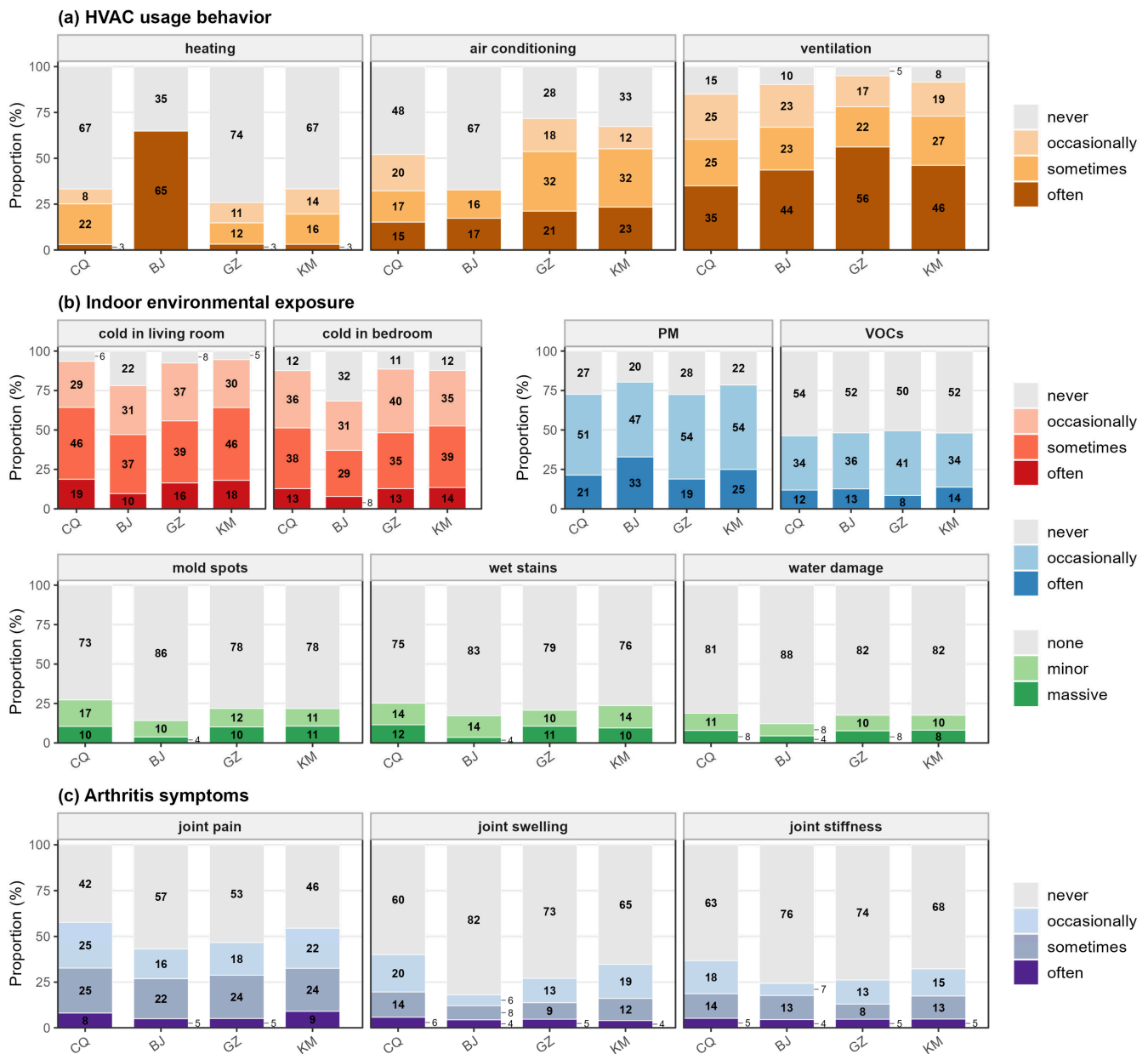


Figure 4. Distribution characteristics of HVAC utilization habits, indoor environment, and health status in four cities.

Cities differ strongly in cold sensations reported in living rooms and bedrooms (Kruskal–Wallis both $p < 0.001$). Fewer than 10% of participants in Beijing complain about feeling cold indoors, while most participants in Chongqing, Guangzhou, and Kunming report indoor cold exposure in winter (all $p < 0.001$). Among the southern cities, complaints about cold discomfort in Chongqing living rooms are significantly higher than in Guangzhou ($p = 0.002$). Beijing's standardized mean is 0 for cold exposure, whereas Chongqing and Kunming are higher (0.95–1.00), with Guangzhou intermediate (0.71–0.90), confirming a north–south contrast aligned with heating availability.

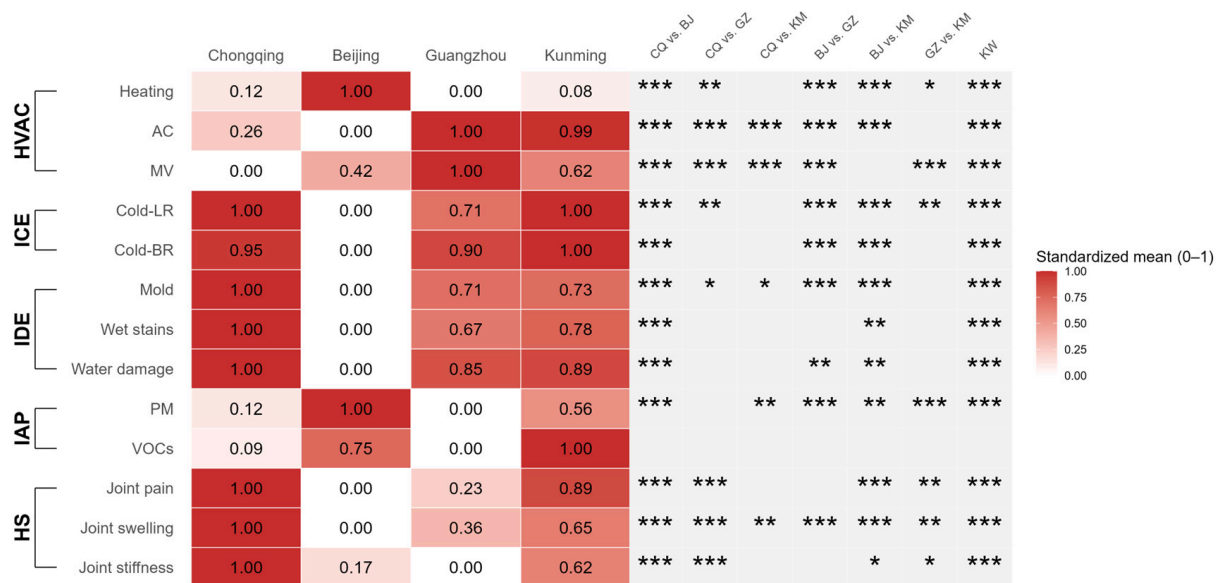


Figure 5. City-wise normalized means and between-city significance for HVAC utilization habits, indoor exposures, and arthritis symptoms. Note: Colors show normalized means (0–1) computed within each variable across the four cities (min–max scaling of the city-level mean frequency/proportion). Darker/red = higher value (e.g., higher HVAC use or heavier disease/exposure burden); lighter/white = lower value. Left brackets group variables by domain: HVAC (Heating, AC = air conditioning, MV = mechanical ventilation); ICE (indoor cold exposure: Cold-LR = cold feeling in living room; Cold-BR = cold feeling in bedroom); IDE (indoor damp exposure: Mold, Wet stains, Water damage); IAP (indoor air pollution: PM, VOCs); HS (health status: Joint pain, Joint swelling, Joint stiffness). The right panel reports between-city significance: six Dunn pairwise contrasts (CQ vs. BJ, CQ vs. GZ, CQ vs. KM, BJ vs. GZ, BJ vs. KM, GZ vs. KM) using Holm-adjusted p -values; the KW column shows the overall Kruskal–Wallis test across the four cities. Asterisks denote: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Also, humidity-related problems are more serious in the south. Chongqing showed the heaviest burden, with 26.3% of participants affected, with significantly higher mold prevalence than in Beijing ($p < 0.001$), Guangzhou ($p = 0.011$) and Kunming ($p = 0.011$). Guangzhou and Kunming also exhibit high incidences, both above 20%, yet no significant difference was observed between the two cities. In Beijing, only 3.9% of people report damp-related issues, significantly less than in the south ($p < 0.001$). Water damage is the least reported among all three issues, but still higher in southern cities ($p = 0.002$).

Regarding indoor air quality, 32.9% of Beijing households report frequent PM exposure, significantly higher than in the southern cities, ranging from 18.9% to 25.0% ($p = 0.003$). Kunming also reports more PM exposure than Chongqing and Guangzhou ($p = 0.003$). Standardized mean results show PM exposure is highest in Beijing (1.00), followed by Kunming (0.56), and lowest in Chongqing (0.12) and Guangzhou (0.00). VOCs show no significant differences among cities (Kruskal–Wallis $p = 0.777$; all pairwise comparisons non-significant).

Arthritis symptoms are more common among young older adults in the southern cities, especially in Chongqing (36.8–57.5%), followed by Kunming (40.5%), Guangzhou (33.3%) and Beijing the lowest (28.6%). All three symptoms differ significantly across cities (pain $p < 0.001$; swelling $p < 0.001$; stiffness $p < 0.001$). The proportion of participants in Chongqing reporting joint symptoms “often” or “sometimes” was significantly higher than in Guangzhou ($p < 0.001$) and Beijing ($p < 0.001$). Beijing consistently showed the lowest symptom burden, with significantly fewer reports compared to Kunming ($p < 0.01$) and Chongqing ($p < 0.001$).

3.3. Associations Between HVAC Utilization Habits and Arthritis Across Climate Zones

3.3.1. Correlation Analysis

Figure 6 compares the correlations between HVAC utilization habits, indoor environmental and health factors in four cities. Although using HVAC systems is negatively correlated with arthritis symptoms, the associations are generally weak. In Chongqing, there is no significant connection between HVAC habits and arthritis, while in Beijing, heating and ventilation use are negatively correlated with joint swelling ($r = -0.10$ to -0.08 , $p < 0.05$). In Guangzhou, heating and air conditioning use are negatively correlated with joint pain ($r = -0.10$ to -0.08 , $p < 0.01$), while in Kunming, they are negatively correlated with joint stiffness ($r = -0.08$ to -0.07 , $p < 0.05$). These findings indicate that the HVAC–arthritis associations differ across cities. Ranking of the three HVAC behaviors further shows that heating generally exhibited the strongest negative correlations with arthritis symptoms in Beijing and Guangzhou, as it appears first in the order of protective effects. Indoor environmental factors consistently show a positive correlation with arthritis symptoms. All indoor factors in Chongqing are significantly linked to arthritis ($r = 0.12$ to 0.27 , $p < 0.001$). In Beijing and Kunming, they are mostly associated with joint stiffness ($r = 0.08$ to 0.22 , $p < 0.050$) and joint pain ($r = 0.14$ to 0.22 , $p < 0.001$), respectively. In Guangzhou, indoor cold and damp exposure shows relatively stronger positive correlations with arthritis ($r = 0.18$ to 0.29 , $p < 0.001$). Particularly, mold, damp spots, and water damage are most strongly correlated with arthritis symptoms, with coefficients nearing 0.30 in Guangzhou and Chongqing, and around 0.22 in Beijing and Kunming.

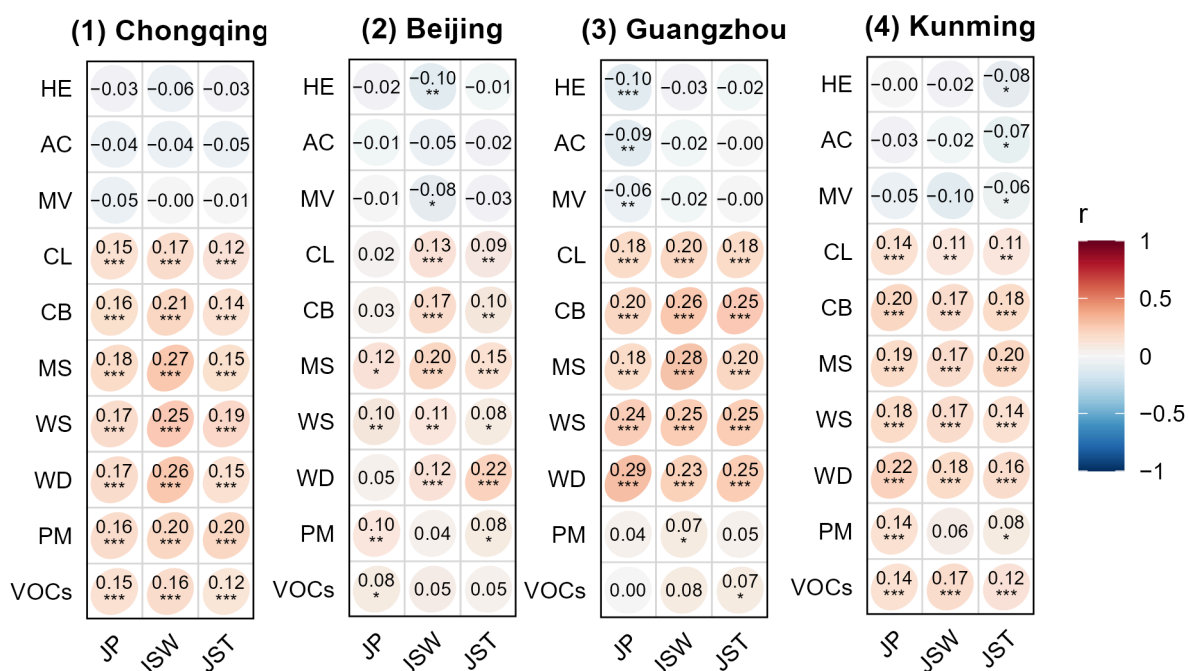


Figure 6. The correlation between HVAC utilization habits, indoor environment, and arthritis symptoms in four cities. Note: JP—joint pain; JSW—joint swelling; JST—joint stiffness; MS—mold spots; WS—wet stains; WD—water damage; CL—cold in the living room; CB—cold in bedroom; AC—air conditioning; HE—heating; MV—mechanical ventilation; the shapes and asterisks represent the strength of the correlations between variables. Asterisks denote statistical significance: * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$.

3.3.2. Logistic Regression

Figure 7 presents the associations between HVAC utilization habits and arthritis symptoms among young older adults, showing clear differences across cities. In Beijing,

heating (AOR = 0.76, 95% CI: 0.60–0.97, $p = 0.028$) and mechanical ventilation (AOR = 0.74, 95% CI: 0.57–0.94, $p = 0.017$) are significantly associated with lower odds of joint swelling, while air conditioning is significantly associated with lower odds of joint pain (AOR = 0.80, 95% CI: 0.65–0.98, $p = 0.032$). All three HVAC behaviors in Guangzhou are significantly associated with lower odds of joint pain, with similar effect sizes (AOR = 0.74–0.75, 95% CI: 0.60–0.94, $p < 0.050$). Chongqing shows a protective link between heating and joint swelling (AOR = 0.82, 95% CI: 0.70–0.95, $p = 0.015$), and between ventilation and joint pain (AOR = 0.81, 95% CI: 0.66–0.99, $p = 0.011$). In Kunming, only heating is significantly associated with a lower risk of joint stiffness (AOR = 0.85, 95% CI: 0.74–0.96, $p = 0.009$). Overall, significant associations between HVAC utilization habits and arthritis symptoms were more frequently observed in Beijing and Guangzhou, fewer in Chongqing, and only one significant association was identified in Kunming.

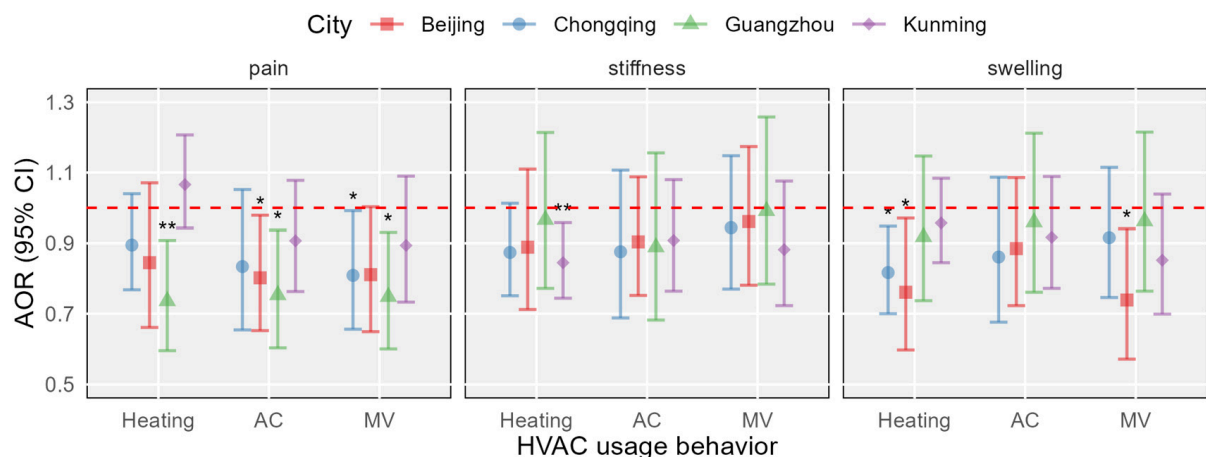


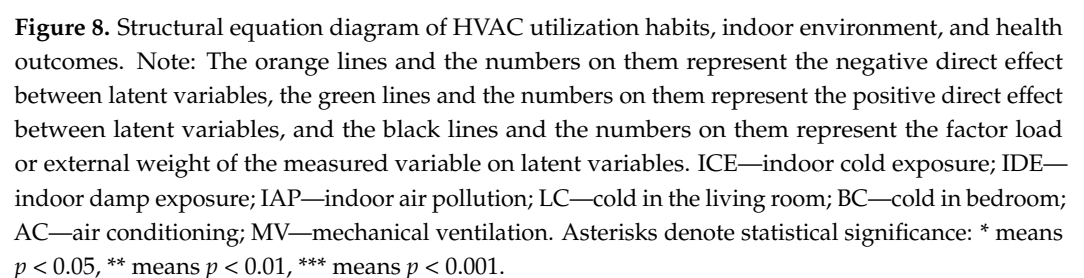
Figure 7. Protective effect of HVAC utilization habits on arthritis symptoms. Note: AC means air conditioning; MV means mechanical ventilation; the scatter points represent AOR values, and the error bars indicate the 95% confidence intervals. Asterisks denote statistical significance: * means $p < 0.05$, ** means $p < 0.01$. The red dashed reference line corresponds to AOR = 1, which represents no association between HVAC usage behaviors and arthritis symptoms.

3.4. Effectiveness of HVAC Utilization Habits on Arthritis via Mediators Across Climate Zones

After fitting the SEM, the model evaluation showed that the R^2 values for indoor exposure were below 0.20, while those for health status were around 0.21. These relatively low R^2 values are expected in a cross-sectional population-based study, because indoor exposures and arthritis symptoms are influenced by multiple unmeasured factors, including physiological conditions, disease history, medication use [29,45], short-term weather variability [46], housing operation, and behavioral adaptations [36,47]. The positive Q^2 values suggested that the models retained some predictive relevance. The NFI values approached 0.90 in Chongqing and Kunming, but were lower in Beijing and Guangzhou, at around 0.70. Overall, these results indicate acceptable measurement reliability and validity, but limited predictive capability. Therefore, the SEM results should be interpreted as partial evidence for theoretically specified HVAC–indoor environment–health pathways.

3.4.1. Direct Effects

Figure 8 depicts the direct effect between HVAC habits, indoor environment, and health status across the four cities. The direct impact of HVAC habits on health is weak and not significant in all four cities. Although Beijing shows the largest path coefficient ($\beta = -0.048$), this effect is not statistically significant, indicating HVAC habits do not directly alleviate arthritis symptoms.



However, HVAC habits are associated with lower indoor environmental risks. The strongest effect on reducing indoor cold is seen in Chongqing ($\beta = -0.372$, 95% CI: -0.431 to -0.310 , $p < 0.001$), followed by Beijing ($\beta = -0.301$, $p < 0.001$) and Kunming ($\beta = -0.104$, $p = 0.040$). For indoor damp, Guangzhou shows the highest effect ($\beta = -0.180$, 95% CI: -0.257 to -0.164 , $p = 0.021$), while Kunming shows a smaller one ($\beta = -0.092$, $p = 0.040$). HVAC habits are associated with lower indoor air pollution only in Beijing ($\beta = -0.196$, $p < 0.001$). Overall, HVAC habits show the strongest association with reduced cold exposure, followed by air pollution, and the least for dampness. Among cities, its impact on mitigating an unfavorable indoor environment is strongest in Beijing, followed by Chongqing, Guangzhou, and Kunming.

Indoor cold, damp, and air pollution are all associated with poorer health. Dampness shows the largest effect, especially in Guangzhou ($\beta = 0.263$, 95% CI: 0.187 to 0.341 , $p < 0.001$). Cold exposure ($\beta = 0.233$, $p < 0.001$) and air pollution ($\beta = 0.182$, $p < 0.001$) have the strongest impact in Chongqing. Residents in Chongqing appear to be most affected, while Beijing residents are least impacted.

3.4.2. Indirect and Total Effects

SEM results indicate that the relationship between HVAC habits and health status (HS) is mainly reflected through indoor environmental mediators (see Table 3). In Chongqing, HVAC habits are linked to lower cold exposure, which then corresponds to better health (HVAC $\rightarrow$ ICE $\rightarrow$ HS: $\beta = -0.087$, 95% CI: -0.116 to -0.062 , $p < 0.001$). This is the strongest mediation effect overall. The same pathway is also seen in Beijing ($\beta = -0.033$, $p = 0.011$), along with HVAC $\rightarrow$ IAP $\rightarrow$ HS ($\beta = -0.031$, $p = 0.009$), although the cold-related pathway is stronger. In Guangzhou, HVAC habits are mainly connected with lower damp exposure, which was further related to better health status (HVAC $\rightarrow$ IDE $\rightarrow$ HS: $\beta = -0.047$, $p = 0.031$). Kunming shows weaker but still significant indirect associations through both cold and damp exposure (ICE: $\beta = -0.014$, $p = 0.043$; IDE: $\beta = -0.019$, $p = 0.041$). These findings suggest different dominant indirect pathways across cities: HVAC $\rightarrow$ ICE $\rightarrow$ HS in Chongqing and Beijing, HVAC $\rightarrow$ IDE $\rightarrow$ HS in Guangzhou and Kunming, and HVAC $\rightarrow$ IAP $\rightarrow$ HS as a secondary pathway in Beijing.

Table 3. Mediation strength of HVAC utilization habits on health status through indoor environment.

Pathways	Chongqing	Beijing	Guangzhou	Kunming
HVAC $\rightarrow$ ICE $\rightarrow$ HS	72.32%	24.09%	14.27%	18.67%
HVAC $\rightarrow$ IDE $\rightarrow$ HS	4.11%	3.65%	44.71%	25.33%
HVAC $\rightarrow$ IAP $\rightarrow$ HS	4.11%	22.63%	16.17%	5.33%
HVAC $\rightarrow$ ICE $\rightarrow$ IAP $\rightarrow$ HS	3.29%	1.46%	1.90%	1.33%
HVAC $\rightarrow$ ICE $\rightarrow$ IDE $\rightarrow$ HS	9.04%	10.95%	4.76%	8%
HVAC $\rightarrow$ IDE $\rightarrow$ IAP $\rightarrow$ HS	0.82%	0.73%	2.85%	2.67%
HVAC $\rightarrow$ ICE $\rightarrow$ IDE $\rightarrow$ IAP $\rightarrow$ HS	1.64%	1.46%	0%	1.33%

Note: HVAC means heating, ventilation, and air conditioning; ICE means Indoor Cold Exposure; IDE means Indoor Damp Exposure; IAP means Indoor Air Pollution; HS stands for Health Status. The data in the table represents the value of VAF (Variance Accounted For), which indicates the mediating effect strength of the corresponding path across the four cities.

Among all mediators, indoor cold exposure shows the largest indirect association. The VAF values further confirm this pattern. In Chongqing, 72.32% of the total HVAC–health association is mediated by cold exposure. In Beijing, cold exposure and air pollution contribute 24.09% and 22.63%, respectively. Guangzhou’s main mediator is damp (44.71%), while Kunming shows a weaker damp-related mediation (25.33%). Comparing the overall strength of indirect associations, the cities rank as follows: Chongqing > Guangzhou > Beijing > Kunming.

Coupled exposures also show significant sequential mediation. The path HVAC→ICE→IDE→HS is observed in Chongqing ($\beta = -0.011$, $p = 0.002$), Beijing ($\beta = -0.015$, $p < 0.001$), and Kunming ($\beta = -0.006$, $p = 0.006$). Longer paths such as HVAC→ICE→IDE→IAP→HS are also identified in Chongqing and Beijing ($\beta = -0.002$, $p < 0.05$).

Although the direct pathway from HVAC habits to health status is not significant, the total indirect associations are significant, especially in Beijing (total $\beta = -0.137$, $p < 0.001$). Moderation effects (HVAC use * indoor environmental exposure) are not significant in any city. Therefore, hypotheses H2–H10 are supported, except for the moderation paths.

4. Discussion

This study developed an SEM to show that HVAC usage patterns, shaped by regional climate zones, significantly influence indoor environmental conditions and thereby impact arthritis symptoms among young older adults during winter. To better understand these relationships, this section discusses the regional differences in HVAC habits, the mediating path coefficients and the implications for tailored HVAC strategies.

4.1. Differences in HVAC Usage Habits Across Climate Zones

Significant regional differences exist in HVAC usage habits between northern and southern Chinese cities. In Beijing, 64.9% of participants frequently used floor heating or radiators, whereas only about 3% of participants in the southern cities reported using these heating systems. By contrast, households in Chongqing, Guangzhou, and Kunming relied more on air conditioners, with reported use ranging from 52.1% to 71.7%. These HVAC patterns may be shaped by climatic conditions, heating policies, building envelope thermal properties, and residents' thermal adaptability. Northern cities like Beijing have long, dry winters but benefit from centralized heating, keeping the average indoors ~ 18 – 22 °C [4,5,48]. In Chongqing, Guangzhou, and Kunming (southern climates with cold, damp winters and no district heating), homes rely on individual heaters or ACs, with limited use [5,47], so indoor temperatures drop much lower (~ 12 °C on average vs. ~ 18.6 °C in the north [4]). This explains why our survey found high heating use in Beijing but much lower direct heating use in the southern cities.

Regarding the impact of building insulation, in cold and severe cold zones, buildings employ higher insulation materials, resulting in lower U-values for exterior walls ($0.45 \text{ W}/(\text{m}^2 \cdot \text{K})$) and windows ($2.0 \text{ W}/(\text{m}^2 \cdot \text{K})$) [49], effectively reducing heat transfer. Conversely, U-values are higher in HSCW [50], HSWW [51], and M [52] regions (walls: 1.2 – $2.5 \text{ W}/(\text{m}^2 \cdot \text{K})$; windows: 2.3 – $3.5 \text{ W}/(\text{m}^2 \cdot \text{K})$), which can increase heat loss and reduce the effectiveness of intermittent heating.

Additionally, northern residents are accustomed to warmer indoor conditions, while southern residents tolerate cooler homes [53], potentially lowering their demand for active heating. However, the present results show that this behavioral adaptation does not necessarily eliminate health-related exposure: most participants in Chongqing, Guangzhou, and Kunming still reported indoor cold exposure in winter, and arthritis symptoms were more prevalent in these cities than in Beijing. Therefore, climate-specific HVAC habits should be understood as adaptive behaviors that are closely linked to indoor environmental inequalities and health-related outcomes.

4.2. Mechanistic Differences in HVAC–Health Pathways Across Climate Zones

Our SEM indicates that HVAC affects health mainly by improving indoor environmental quality rather than through a direct path. This pattern is consistent with the broader evidence. Previous osteoarthritis studies have reported that weather conditions, particularly cold and dampness, are associated with joint pain severity and inflammation [29,54–58],

while heating, dehumidification, and clean ventilation reduce these exposures [59–62]. Specifically, low indoor temperatures and persistent dampness are well-established risk factors for exacerbating arthritis symptoms and general health deterioration [56]. The World Health Organization recommends a minimum indoor temperature of 18 °C in winter to minimize cold-related risks [55]. A recent systematic review further suggested that weather conditions are statistically associated with osteoarthritis pain, although the magnitude and direction of effects vary across studies [29]. These outdoor-weather findings are not identical to our indoor exposure results, but they support the broader plausibility that thermal and moisture-related environments may be linked to arthritis symptoms. Our results extend this evidence from outdoor meteorological exposure to residential indoor environmental exposure. Indoor cold, dampness, and source-related air pollution all showed positive relationships with poorer health status in the SEM.

City-specific mediating pathways demonstrate that the health impacts of HVAC usage are determined by the predominant indoor environmental exposure concerns in each corresponding climate zone. In Chongqing, winters are cold and damp, and household heating is limited. Any increase in HVAC use shortens cold-damp exposure, so the indirect benefit is the strongest among the four cities. Guangzhou has milder temperatures but very high humidity. Ventilation is frequent—over 85% of homes report using it to reduce moisture—yet high indoor humidity still contributes to arthritis risk when air exchange rates are insufficient, or filters are absent, and when maintenance is poor [54]. This aligns with our findings that the humidity-related mediation path was significant in Guangzhou ($\beta = -0.047, p = 0.031$). Beijing, characterized by cold winters and centralized heating, is the only city in which HVAC usage was significantly associated with lower indoor air pollution ($\beta = -0.196, p < 0.001$). This likely reflects the widespread use of mechanical ventilation systems with integrated filtration [60,63]—necessary adaptations in a context where natural ventilation is limited by outdoor pollution. Kunming has a mild climate for most of the year, and HVAC use is minimal, so the indirect pathway via indoor environment quality is the weakest.

The lack of a clear direct effect is also plausible biologically and operationally. Health responses depend on the achieved temperature, humidity, and pollutant levels, which in turn depend on ventilation rates, airflow distribution, and filtration efficiency [54,60,61,64]. When these parameters are adequate, HVAC reduces exposure and symptoms; when they are not, benefits may be limited then.

Beyond environmental exposures, socio-economic differences also shape arthritis risk. In Chongqing and Kunming, a larger share of participants had physically demanding occupations, which may aggravate symptoms. Conversely, higher income in Guangzhou and better education in Beijing provide some protection [65–67]. These contextual variables may potentially modulate the relationship between HVAC use and health outcomes.

In summary, multiple factors shape the differences in path coefficients across cities, including local climate conditions, heating policies, building envelope performance, residents' thermal adaptability, HVAC utilization habits, and other non-environmental factors (Figure 9).

4.3. HVAC Adaptation Policies Across Different Climate Zones

The city-specific mediation results have direct implications for HVAC adaptation policies. Because the dominant indoor environmental pathway differed across cities, a uniform HVAC strategy is unlikely to be effective across climate zones. In Beijing, the main advantage of HVAC use was reflected in lower indoor cold exposure and lower source-related IAP scores, and avoiding secondary problems such as excessive dryness or pollutant accumulation. This is consistent with ongoing clean heating programs in northern

China, which aim to replace coal-based heating with cleaner centralized systems or heat pumps [68,69].

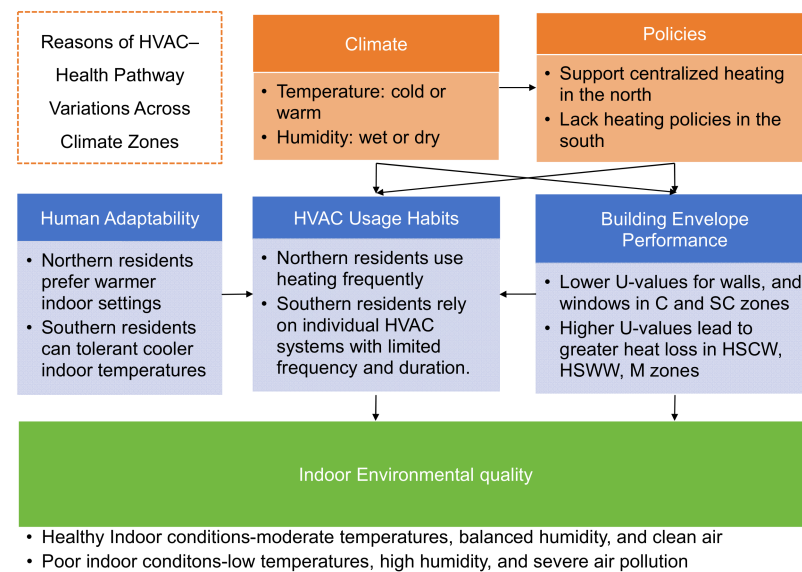


Figure 9. Reasons for HVAC–Health Pathway Variations Across Climate Zones.

For HSCW cities such as Chongqing, the strongest mediation pathway was HVAC→ICE→HS, with cold exposure accounting for 72.32% of the total HVAC–health association. This suggests that winter heating access remains the most important adaptation target in cold-damp southern climates. Because centralized heating is generally absent, individual heating devices and air conditioners currently dominate winter space heating [70]. However, community-scale heating pilots in cities such as Wuhan and Shanghai indicate that shared heating systems may be feasible in selected southern urban areas [3]. Low-temperature fan coil systems combined with heat pumps may also provide a technical pathway for residential heating in these climates [71].

For humid southern cities such as Guangzhou, damp exposure accounts for 44.71% of the total HVAC–health association. This indicates that heating alone may be insufficient unless combined with moisture control. Air-source heat pumps may be suitable in these milder winters because they can provide both heating and humidity control with relatively high efficiency [70].

Kunming’s climate is relatively mild, and the indirect associations between HVAC habits and health are weaker than in the other cities. Previous studies have suggested that passive solar heating can meet a large proportion of winter heating needs in temperate climates [72].

Therefore, HVAC adaptation policies must be tailored to the specific climatic and infrastructural conditions of each region to ensure both environmental sustainability and thermal comfort.

4.4. Physiological Factors Influencing HVAC Use and Health Status

The findings of this study should also be interpreted in relation to the physiological vulnerability of young older adults. Although this study focused on individuals aged 60–74 years rather than the entire elderly population, this age group may already experience reduced thermoregulatory capacity, altered thermal perception, and increased susceptibility to musculoskeletal discomfort. First, aging is associated with diminished thermal sensitivity. Older adults have higher temperature thresholds for feeling warmth or cold [73,74]. This blunted perception can lead to underestimating indoor cold and delaying heating use. In

milder winter climates, older adults might remain in an uncomfortably cool home without realizing the health problems.

The musculoskeletal system may also be sensitive to cold and damp exposure. Experimental evidence suggests that environmental cold exposure can affect pain sensitivity in arthritic joints through biological pathways such as TRPA1-related mechanisms [45,75]. In particular, synovial fluid in joints becomes more viscous in the cold, reducing lubrication and mobility [31]. In our study, indoor cold and damp exposure were positively related to arthritis symptoms, and the dominant mediation pathways differed by climate zone. The strong cold-related pathway in Chongqing and the damp-related pathway in Guangzhou are therefore consistent with previous evidence that thermal and moisture-related stressors may aggravate musculoskeletal symptoms.

Lifestyle factors amplify these risks. On average, retirees spend the vast majority of their time indoors [76]. Limited mobility and exercise further reduce metabolic heat production and flexibility, compounding cold sensitivity. For example, the U.S. National Institute on Aging cautions that even mildly cool home temperatures of 15–18 °C can cause hypothermia in seniors over time [75], which may precipitate not only arthritis flare-ups but also risks like high blood pressure and respiratory issues.

These physiological and behavioral factors help explain why climate-responsive HVAC strategies are important for this population. Our findings suggest that climate-responsive HVAC strategies are essential for promoting healthy indoor environments for young older adults across different climate zones.

4.5. Psychological Factors Influencing HVAC Use and Health Status

Psychological factors may also help explain part of the unexplained variance in the HVAC–indoor environment–health pathway. In this study, indoor cold, dampness, and air pollution were assessed through self-reported residential exposure indicators. Previous thermal comfort studies have shown that thermal sensation is not determined only by air temperature and humidity, but is also affected by psychological and contextual factors, including mood state, perceived control, past experience, and individual sensitivity [77,78]. Recent studies introduced the Mood State Correction Factor, also known as the Turhan and Özbey coefficient, to adjust predicted thermal sensation according to occupants' mood states, usually using psychological measures such as the Profile of Mood States [79,80]. However, this study did not measure psychological status, so this coefficient could not be directly incorporated into the SEM. Future studies should add psychological scales to examine whether mood-related correction factors can improve the explanatory power of HVAC–health models among young older adults.

4.6. Strengths and Limitations

The study highlights differences in HVAC habits between cities. Using the PLS-SEM method, it shows how HVAC use to control indoor conditions like heat, humidity, and air quality affects the health of young older adults. The findings help identify key mediators and give advice on how to use HVAC equipment properly in different regions.

However, the study has some limitations. It does not include data from cities in China's extreme cold regions. Since Beijing uses centralized heating like these colder places, the results from Beijing can partly reflect those areas. Also, like many similar studies, this one is cross-sectional. So, it cannot prove that HVAC use causes health changes. Even though SEM helps to show links between factors, it cannot confirm direct cause and effect. Third, the study focused on adults aged 60–74. Caution is needed when extrapolating to older age groups. A further limitation is the use of questionnaire-based proxies for indoor PM and VOC exposures (cooking frequency and recent renovation/furniture purchase).

These proxies do not capture ventilation rates, filtration, outdoor air quality, or product use patterns. This limitation may bias the estimated path coefficients involving IAP. Therefore, IAP-related pathways were interpreted cautiously as source-related exposure associations rather than direct effects of measured indoor pollutant concentrations. In addition, the climatic comparison was based on long-term winter conditions rather than daily weather fluctuations, as the study focused on climate-zone differences instead of short-term weather effects. Future research will adopt randomized controlled trial methods to test whether more HVAC use in southern cities during winter can ease arthritis symptoms in young older adults. This will help to validate the causal links between HVAC use and arthritis.

Regarding generalizability, although this study was conducted in four Chinese cities, its main contribution lies in the proposed framework linking climate characteristics, HVAC adaptation behaviors, indoor environmental exposures, and health outcomes. The specific HVAC patterns and mediation strengths reported here may vary across regions because of differences in climate, building design, and occupant behavior. Nevertheless, the framework may provide a useful basis for investigating climate-specific HVAC strategies in other countries.

5. Conclusions

This study suggests that climate zones are related to differences in HVAC utilization habits, indoor environmental exposures, and arthritis symptoms among young older adults during winter.

- (1) HVAC practices differed across climate zones and showed distinct relationships with arthritis. In Beijing, widespread heating use is associated with lower indoor cold and dampness and the lowest prevalence of arthritis symptoms. By contrast, Chongqing and Guangzhou rely more on air conditioning and ventilation and show higher levels of cold discomfort, damp problems, and arthritis symptoms. Kunming, with its mild climate, depends mainly on ventilation, but this pattern is linked to limited health benefits. These findings suggest that climate-specific adaptation behaviors are closely related to indoor environmental conditions and arthritis outcomes.
- (2) Mediation analysis indicates that the relationship between HVAC habits and arthritis symptoms is partially explained by indoor environmental exposures. The indirect effect through reduced cold exposure accounts for 72.32% of the total effect in Chongqing and 24.09% in Beijing. Damp exposure accounted for 44.71% in Guangzhou and 25.33% in Kunming. A partial indirect association through indoor air pollution is observed only in Beijing (22.63%). Overall, the indirect associations are greatest in Chongqing, followed by Guangzhou and Beijing, and weakest in Kunming, suggesting that the relative importance of indoor environmental pathways differs across climate zones.
- (3) These findings suggest that climate characteristics, HVAC adaptation behaviors, and indoor environmental conditions are closely interconnected and may help explain regional differences in arthritis symptoms among young older adults. The observed patterns support the potential value of climate-responsive HVAC strategies. Optimizing heating systems in northern regions while avoiding excessive dryness, and expanding access to winter heating in cold-damp southern regions, may help improve indoor thermal conditions. Future longitudinal and intervention studies are needed to verify whether these strategies can reduce arthritis symptoms and improve healthy ageing.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16142898/s1>, Table S1: Factor analysis results; Table S2:

Evaluation results of measurement model and structural model in Chongqing; Table S3: Evaluation results of measurement model and structural model in Beijing; Table S4: Evaluation results of measurement model and structural model in Guangzhou; Table S5: Evaluation results of measurement model and structural model in Kunming.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethical Review Committee of the School of Life Sciences, Central China Normal University (protocol code: CCNU-IRB-2019-002 and date of approval: 8 October 2019).

Informed Consent Statement: Oral informed consent was acquired from every participant prior to the survey. This anonymous questionnaire only collects general thermal comfort feedback from elderly volunteers. No identifiable personal data is collected, and the survey causes no potential harm to participants, complying with the institution’s exemption criteria for low-risk human subject research.

Data Availability Statement: The data presented in this study are not publicly available due to privacy and ethical restrictions involving human participant data. Data may be available from the corresponding author upon reasonable request and subject to applicable ethical approvals.

Conflicts of Interest: Author Wei Yu was affiliated with the General Research Institute of Architecture & Planning Design Co., Ltd., Chongqing University. Author Haizhu Zhou was affiliated with the China Academy of Building Research Co. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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