Large-Scale and Long-Term Monitoring of the Thermal Environments and Adaptive Behaviors in Chinese Urban Residential Buildings

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Abstract:

Indoor thermal environments in residential buildings vary due to differences in the outdoor climates, the envelope thermal properties of the buildings, the types of heating and cooling systems, and adaptive behaviors such as the operation of air conditioners and windows by dwellers. This study comprehensively investigated the thermal environments in 46 apartments in nine cities across five climate zones in China via on-site monitoring of the indoor air temperature, the relative humidity, and the air conditioner and window use for one year. The results demonstrate large variations in the thermal environments among the cities. During the heating period, the interior air in Urumqi and Shenyang was overheated (>24 °C) 43% and 59% of the time, respectively, while the indoor air temperature in Chongqing can be lower than 10 °C. As the outdoor climate became warmer, the temperature difference between indoors and outdoors decreased due to the increased window-opening duration. In summer, the indoor humidity ratio was higher than 12 g/kg for a long time in all cities except Urumqi. A clear linear positive correlation between the indoor and outdoor humidity ratios was identified until the indoor humidity reached 18 g/kg, which was due to the increased use of air conditioners. The results of this study provide an updated overall picture of the thermal environments in Chinese residential buildings.

Keywords: Thermal environment; urban residential buildings; on-site measurement; human behaviors; thermal comfort

1. Introduction

In residential buildings, the indoor thermal environment, including both the air temperature and the humidity, is strongly associated with health [1-5], thermal comfort [6-9] and cognitive performance [10]. Researchers, such as Murray et al. [2] and Verhoeff et al. [3], found that damp houses increased the risks of dust mite allergies and childhood respiratory symptoms. High temperature and low humidity indoors in winter will make eyes more sensitive to airborne particulates and to other forms of pollution, thereby resulting in eye redness and chronic eye ache [4,5]. More importantly, the thermal environment strongly affects the heat balance of the human body and is vital to occupants' thermal comfort [6], which is important for occupants' productivity. Large amounts of energy are being used to create healthy and thermally comfortable indoor environments. According to Yang et al. [11], in developed countries, heating, ventilation, and air conditioning (HVAC) systems account for approximately half of the total energy consumption of buildings. Due to this large contribution, indoor thermal environments in residential buildings have been studied by many researchers around the world, such as in Korea [12], Africa [13], and Malaysia [14].

China, as a major developing country, has also contributed substantially to the global carbon emissions and many studies have been conducted in residential buildings in major cities such as Harbin [15-18], Beijing [19,20], Shanghai [19], Changsha [21-23], Guangzhou [21], and Shenzhen [21] in China to evaluate their indoor thermal environments. These studies provided valuable knowledge regarding the residential thermal environments in cities. As for free-running space, occupants' thermal sensations dynamically respond to the outdoor climate [23]. The study by Wang et al. [15] shows that the neutral temperature in Harbin is lower than neutral temperatures in warm climates during summer. During heating season, overheated environments were identified in residential buildings in Harbin [18]. But if people could control the amount of heating according to their personal demand, the indoor thermal condition would be different. A study in Beijing indicated that in individual heating apartments, the mean indoor temperature of individual spaces was 0.5~3.0 ºC lower than that of district heating spaces due to different control modes [20].

Since China is a large country that covers vast territory, large variations in climate conditions exist among regions. Due to the climatic variation, the thermal properties of buildings differ among regions and buildings are equipped with various forms of cooling and heating systems. Furthermore, studies have shown that residents from warmer climate regions tended to open windows for longer than the residents from cooler climates [24,25]. Opening windows had a major impact on the indoor thermal environment by introducing more outdoor air into the room. Due to the above factors, the features of the indoor thermal environments many differ among regions. Thus, it is important to provide an overall picture of the thermal environments in Chinese residential buildings.

Two important studies investigated the thermal environments in Chinese residential buildings across climate zones. During the period from 1998 to 2004, Yoshino et al. [26,27] conducted large-scale field studies on residential indoor thermal environments in nine major cities in China. After that, Li et al. [28] conducted monthly on-site field measurements in nine typical cities in the five climate zones from 2008 to 2011. Both studies demonstrated discrepancies in the indoor thermal environments among cities and a correlation between the indoor and outdoor thermal environments. However, these studies were conducted in limited and discrete periods of time. For example, Yoshino et al. [26,27] only measured the indoor air temperature and humidity for a week in winter and a week in summer. In the study by Li et al. [28], testers visited the studied apartments to collect data; hence, it was not possible to obtain continuous results and the thermal conditions at night were ignored. In addition, the window operation behavior was not recorded in either of the two studies. Almost all buildings in the study of Yoshino et al. [26,27] and over half of the buildings that were investigated by Li et al. [28] were constructed prior to 2000. However, with the rapid urbanization in China, many buildings were built after 2000, which satisfy higher thermal insulation requirements than the previous buildings.

To fully investigate the updated thermal environment, field measurements were conducted for one year in Chinese residential buildings that were constructed after the new millennium across five climate zones. The connections between the indoor thermal environment and climate, window-opening behaviors, and heating and cooling system use were explored. We also assessed the thermal comfort and humidity environment based on the obtained data.

2. Methods

2.1 Monitored cities and buildings

In this study, a one-year longitudinal measurement study (March 1st, 2017 to February 28th, 2018) was conducted in the main bedrooms of 46 apartments in nine cities in China, namely, Urumqi (Lon: 87.68°, Lat: 43.77°), Shenyang (123.38°, 41.80°), Tianjin (117.20°, 39.13°), Xi’an (108.95°, 34.27°), Shanghai (121.48°, 31.22°), Chongqing (106.54°, 29.59°), Kunming (102.73°, 25.04°), Shenzhen (114.07°, 22.62°) and Nanning (108.33°, 22.84°). Figure 1 presents the nine selected cities and the number of monitored apartments in each city. According to the thermal design code for civil buildings in China (GB50176-2016) [29], the nine cities belonged to five climatic zones: Severe Cold (SC), Cold (C), Hot Summer and Cold Winter (HSCW), Mild (M), and Hot Summer and Warm Winter (HSWW). The cities in the SC and C zones (Urumqi, Shenyang, Tianjin and Xi’an) are also regarded as northern cities and the remaining cities (Shanghai, Chongqing, Kunming and Shenzhen) are regarded as southern cities.

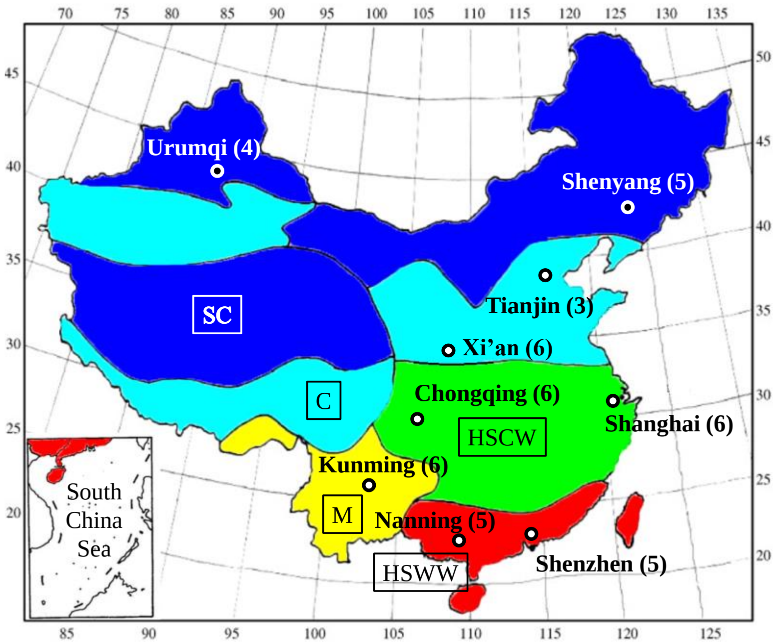

Figure 1: Monitored cities in a map of China, with the number of studied apartments in each city

2.2 Data collection

2.2.1 Monitoring instruments

During the monitoring period, both environmental and nonenvironmental parameters were collected, such as the indoor air temperature and humidity, the outdoor air temperature and humidity, the states of windows and the states of air-conditioners. These data were gathered and stored on a central cloud for downloading and analysis by researchers [30-32]. Figure 2 depicts the monitoring instruments that were used in the study.

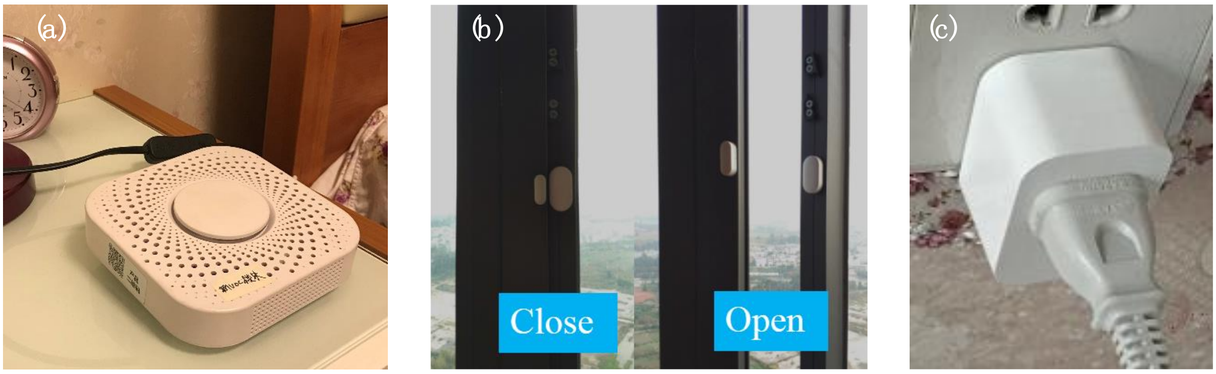

Figure 2: Monitoring instruments: (a) An environmental monitoring kit for indoor air temperature, humidity and CO_2 concentration; (b) Magnetic contactors for monitoring window states; (c) A socket for monitoring air-conditioner power consumption

In this study, the indoor air temperature (°C) and the relative humidity (%) were monitored and recorded every minute using an Ikair environmental monitoring kit (Figure 2a), which has measurement ranges of -40~125 °C for the air temperature and 0~100% for the relative humidity. The measurement accuracies for the parameters were ±0.3 °C and ±3%, respectively. The environmental monitoring kit was placed on a bedside table in the bedroom. Outdoor meteorological data, such as the outdoor temperature (°C) and the outdoor relative humidity (%), were obtained from nearby public weather stations (www.weather.com.cn) on the basis of a two-hour average. Magnetic contactors were used to detect the states of windows, from which occupants' window opening/closing actions could be deduced, as shown in Figure 2b. Each set of contactors had two magnetic induction devices, namely, one on the window casement and another on the window frame, which were used for both casement and sliding windows. If the distance between the two devices exceeded 2.2 cm, the window was regarded as open. Otherwise, it was regarded as closed. Occupants' use of air conditioners was recorded by power monitoring sockets, as shown in Figure 2c. If the detected power usage exceeded 100 W (to exclude stand-by cases), the air conditioner was regarded as turned on. In addition to the above parameters, the indoor environmental monitoring kit also recorded the indoor CO_2 concentration, which was used in the study to determine the occupancy of rooms. A room was deemed unoccupied for a period if the monitored CO_2 concentration never exceeded 460 ppm, with no change of the window states and no use of air-conditioners. The threshold of 460 ppm was calculated by summing the typical outdoor CO_2 concentration, which is 420 ppm [24,25], and the instrument uncertainty, which is 40 ppm. Data that were collected from unoccupied rooms were excluded from the subsequent analysis.

In addition to onsite monitoring, questionnaires were distributed to all participants at the beginning of this investigation to collect relevant information about all monitored apartments, namely, the year of construction, the types of heating systems and the types of cooling systems.

2.2.2 Data preprocessing

Four types of data were collected, namely, air-conditioner power, window open/close action, indoor air temperature and relative humidity, outdoor air temperature and relative humidity. In order to clearly present the results through charts, the raw data needs to be preprocessed according to the following methods:

Based on monitored data, the proportion of days when air conditioner was used can be summarized for each room per month. Then, the monthly average proportion of all monitored apartments was calculated for each city. As for window behaviors, the daily window-open duration was calculated for each household. Thereafter, the monthly average value of the daily window-open duration was obtained for each monitored city.

When it comes to environmental parameters, the humidity ratio can be derived from air temperature and relative humidity. And then the monthly average value of air temperature and humidity ratio from all monitored apartments were calculated. Since weather data and indoor environmental parameters were record on the basis of different time interval, in order to analyze their relationship, both of them should be integrated in the same time axis. The weather data was on the basis of a two-hour average, the interval of indoor temperature and humidity was converted from one value per minute to a two-hour mean accordingly. Finally, the average indoor temperature was calculated for every 1 °C interval of outdoor temperature. The average indoor humidity ratio was calculated for every 0.5g/kg interval of outdoor humidity ratio.

2.3 Evaluation criteria for the thermal environment

As the main objective of this study was to evaluate the current thermal environments of buildings in various climatic zones in China, several criteria, as described in this section, were used to judge their thermal and humidity conditions.

2.3.1 Evaluation criteria for the thermal environment

Two main approaches are widely used by researchers to assess indoor thermal comfort, namely, the static “comfort zone” and the adaptive model, both of which are available for ASHRAE Standard 55 [6]. The former approach is based on the classic human heat balance model that was developed by Fanger [6,33]. According to this approach, thermal comfort can only be realized within limited ranges of operative temperature and humidity. In contrast to the lab-based approach that was used by Fanger, the adaptive model was developed using field data that were collected from real buildings [34]. The adaptive model shows changes in the acceptable indoor operative temperatures according to outdoor temperature conditions. Which approach is more accurate for evaluating indoor thermal comfort for residential buildings has yet to be determined; hence, in this study, both were used.

2.3.2 Evaluation criteria for the humidity environment

To evaluate the humidity level indoors, two criteria, namely, 0-12 g/kg humidity ratio [6] and 40%-60% relative humidity [1], were adopted. The former criterion considers impact of humidity on thermal comfort and the latter criterion mainly considers the health effect. The 0-12 g/kg humidity ratio is defined in the ASHRAE static comfort zone as an upper limit on the humidity ratio of 12 g/kg, as high humidity will increase the moisture on the skin, thereby affecting people’s thermal comfort. The 40%-60% relative humidity was suggested by Arundel et al. [1], which focuses on the impact of humidity on human health. They investigated people’s health conditions under various relative humidity levels and suggested that maintaining the indoor relative humidity between 40% and 60% could minimize most relevant adverse health effects.

2.4 Basic characteristics of the monitored apartments

The construction years of all monitored apartment buildings were obtained from the questionnaire survey. In 2010, the Residential Building Energy Efficiency Design Standard of China was updated by the Chinese Ministry of Housing and Urban-Rural Development (MOHURD). Therefore, whether the investigated buildings were built according to the new standard or to the old standard has been considered in this study and according to this, all apartment buildings in each climate zone were classified into two groups. Table 1 lists the new and old standards for each climatic region, except the mild region, as no such standard is available yet for this zone. According to the statistics that are presented in Figure 3, approximately half of the monitored apartment buildings were constructed after 2010.

Table 1: Old and new residential building energy efficiency design standards for the climatic regions in China [35-40]

	SC	C	HSCW	M	HSWW
Before	JGJ26-1995 [35]		JGJ134-2001 [37]	N/A	JGJ75-2003 [39]
After	JGJ26-2010 [36]		JGJ134-2010 [38]		JGJ75-2012 [40]

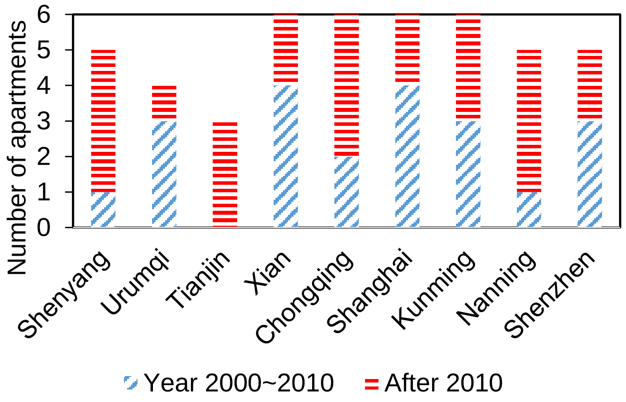

Figure 3: Number of apartments built according to the old or new standards in each monitored city

The buildings constructed after 2010 generally have a higher requirement for envelope insulation than the older buildings. As an example, Figure 4 presents the changes in the maximum allowable heat transfer coefficient of exterior wall for normal shaped residential buildings in different cities. Buildings in northern cities generally have a higher thermal insulation than those in southern cities. It can also be observed that maximum allowable heat transfer coefficients dropped after the update of building energy efficiency standards in some cities, such as Shenyang, Tianjin, Xi’an, Shenzhen and Nanning.

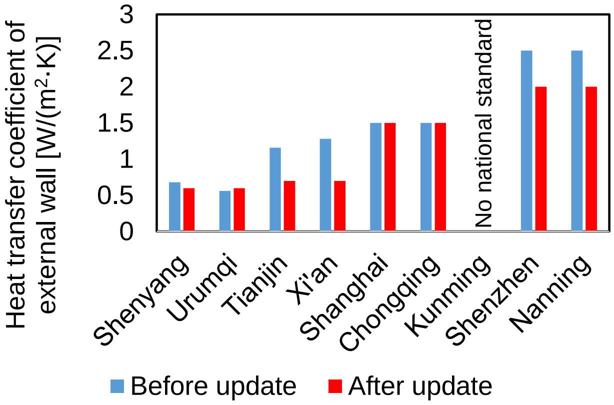

Figure 4: The maximum allowable heat transfer coefficients of exterior wall for buildings constructed before and after the update of residential building energy efficiency design standards in the studied cities.

Additionally, the information about the number of floors and volume of bedrooms as well as the number of residents has been summarized in Table 2. It can be seen that monitored apartments are distributed at different number of floors, meeting the requirement for diversity of samples. As for the bedroom volume, there is little discrepancy among different climate regions, the mean value of which varied between 36 and 44 m^3. More than half of the bedrooms have two users (65%), follow by those with one user (22.5%). When there are 3 users in the bedroom, households usually include a couple and a child.

Table 2: The basic information about apartments and residents

Climate zones	Number of floors				Volume of bedrooms mean ± SD (m^3)	Number of residents in bedroom		
	⩽3	4~6	7~9	⩾10		1	2	3
SC	4	1	1	3	37 ± 12	2	7	0
C	2	1	1	5	38 ± 12	1	6	2
HSCW	3	3	0	0	44 ± 5	2	4	0
M	0	2	2	2	40 ± 13	1	5	0
HSWW	2	2	2	4	36 ± 12	3	4	3

Figure 5 presents data on the available heating and cooling systems in all monitored apartments. The apartments in the northern cities all had central heating systems; most had radiant floor heating systems and only one, which was in Tianjin, used radiator heating. In contrast, most monitored apartments in southern cities did not have any heating system, except for one apartment in Chongqing, which had an electric radiator system. A major exception for southern cities was Shanghai, in which four out of six monitored apartments had either floor heating or radiator heating systems. This is probably due to its higher level of economic development.

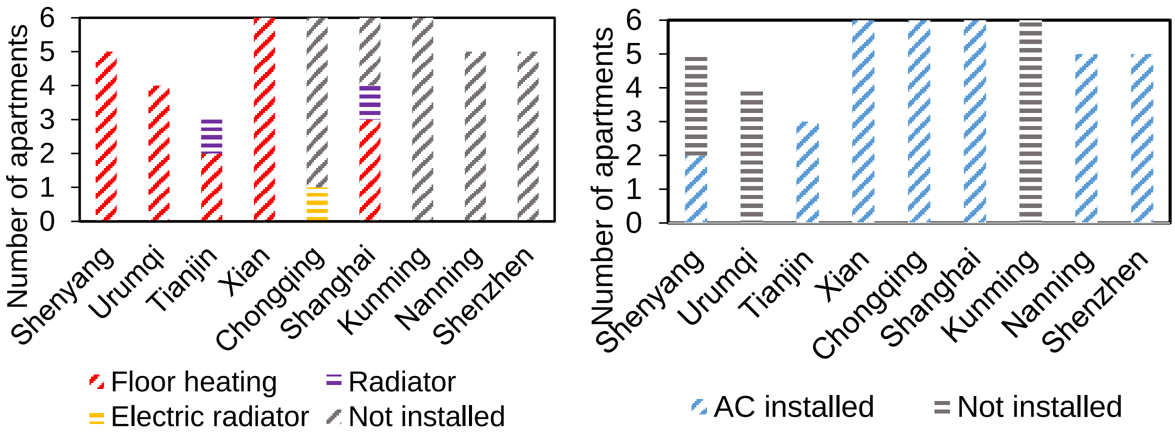

Figure 5: Available heating (a) and cooling (b) systems in all monitored apartments in nine cities

In terms of the available cooling systems, all apartments that had air-conditioning systems used split-type air conditioner (AC) units. As shown in Figure 5(b), all monitored apartments from the C, HSCW, and HSWW climate regions had AC systems. As both the SC and M regions have mild summers, cooling systems were not needed. Therefore, only two apartments in Shenyang used AC systems.

3. Results

3.1 Occupant use of heating, AC and window systems

Occupant behavior has been widely acknowledged as having substantial impacts on buildings' indoor thermal environments [41-43]. This section explores occupants' major behaviors, namely, heating, AC and window behaviors, in the monitored apartments.

3.1.1 Use of heating systems

Table 3 lists the heating periods of Urumqi, Shenyang, Tianjin and Xi'an, together with the ranges of their five-day average outdoor temperatures in the heating season. According to the data, the five-day average outdoor air temperatures for all four cities were mostly lower than 10 °C. Additionally, the length of the heating period decreased from north to south (Urumqi > Shenyang > Tianjin > Xi'an).

Table 3: Heating schedules and the 5-day averaged outdoor air temperatures of the studied northern cities

City	Heating schedule	5-day averaged outdoor temperature in the heating season (of 5%, 95% accumulative frequency)
Urumqi	October 10 to April 10	(-16.5, 8.3)
Shenyang	November 1 to March 31	(-13.7, 5.7)
Tianjin	November 5 to March 31	(-2.8, 11.1)

Xi’an	November 15 to March 15	(-2.2, 10.0)

3.1.2 Use of AC systems

According to the field measured data, Figure 6 plots the average operation ratios (cooling time over total time) of air conditioners in all monitored cities. Since air conditioners are mainly designed for cooling, their usage times were found to increase from north to south due to the warmer/hotter climate in southern China than in northern China. The operation ratio was the highest in July for the C region; for the HSCW region, it was highest in July and August. For the two cities in the HSWW region, the usage of air conditioners remained at a high level from June to September. According to the study, for intensive cooling periods with an AC operation ratio that exceeds 40%, the outdoor monthly mean air temperature was higher than 28 °C. In addition to using air conditioners for cooling, some residents in Shanghai, Chongqing, Shenzhen and Nanning also used air conditioners for heating in the winter. However, the operation ratios were less than 20%.

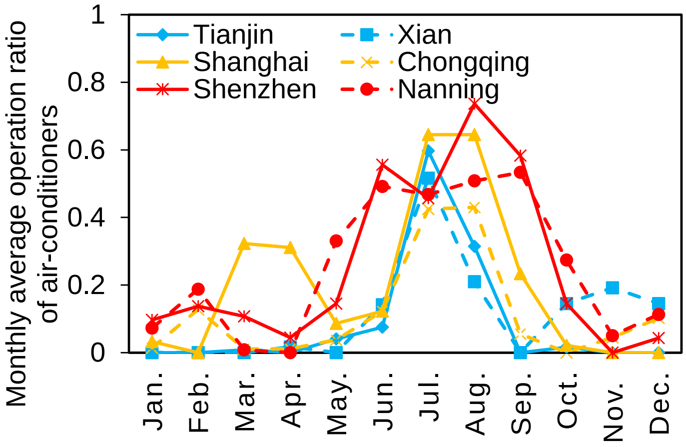

Figure 6: Operation ratios of air conditioners for six cities in each month

3.1.3 Use of window systems

Window states, namely, opened/closed windows, have a key impact on air exchange between indoor and outdoor environments. Figure 7 summarizes the monthly average daily window-opening durations. According to the comparison, the daily window opening duration increased from north to south [24,25]. Among these cities, residents in Chongqing were more likely to keep their windows open, comparing to residents in other cities. To remove excessive heat and moisture from dwellings in Chongqing, residents must promote the ventilation of their buildings to maintain healthy indoor thermal environments. In addition, larger differences in monthly window-opening durations across the year are observed among the cities in northern China than among those in southern China, which is due to larger climate variations among seasons.

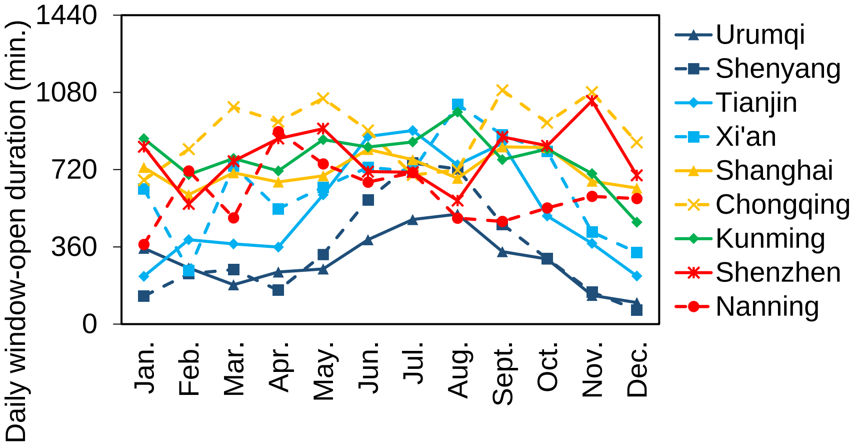

Figure 7: Monthly average daily window-opening durations in nine cities

3.2 Indoor and outdoor temperatures

The main objective of this study is to investigate the indoor thermal environments of apartments in the five climate regions. This section begins by exploring their indoor and outdoor temperature conditions.

3.2.1 Monthly indoor and outdoor air temperatures

Figure 8 plots the monthly average outdoor and indoor air temperatures in all studied cities. According to the data, there were large differences in the monthly outdoor temperatures among cities from various climate regions, especially during the winter period, namely, December, January and February. For Urumqi, Shenyang, Tianjin, Xi'an, Shanghai, Chongqing, Kunming, Shenzhen and Nanning, the minimum monthly mean outdoor temperatures were -14.5 °C, -11.1 °C, -1.8 °C, -0.8 °C, 4.8 °C, 6.8 °C, 8.8 °C, 20.9 °C and 14.4 °C, respectively. However, due to the use of central heating systems, the average indoor temperatures in the northern cities were much higher than those in the southern cities in winter. During the heating season, the monthly average indoor temperature varied from 23 °C to 25 °C in Urumqi and Shenyang and from 20 °C to 24 °C in Tianjin and Xi'an. According to the latest Chinese design code for the heating, ventilation and air conditioning of civil buildings [44], the heating setpoint should not exceed 24 °C, in consideration of both thermal comfort and energy conservation. However, based on the obtained winter indoor air temperatures from apartments in northern cities, temperatures exceeded the threshold for 43%, 59%, 19% and 29% of the studied period for Urumqi, Shenyang, Tianjin and Xi'an, respectively. In the HSCW region, despite having similar outdoor climates, the monthly mean interior temperature (from 17.0 °C to 19.1 °C) of Shanghai in winter well exceeded that (from 8.8 °C to 10.4 °C) in Chongqing, which may be due to the higher prevalence of individual heating systems in Shanghai than in Chongqing. Although no monitored apartments in Kunming had heating systems, their monthly average indoor temperatures were still 6 °C higher than the outdoor temperatures, which be partly due to internal heat gains from occupants and electronic equipment. In the HSWW region, due to its warm outdoor climate, the indoor air temperature was maintained between 18 °C and 22 °C in winter.

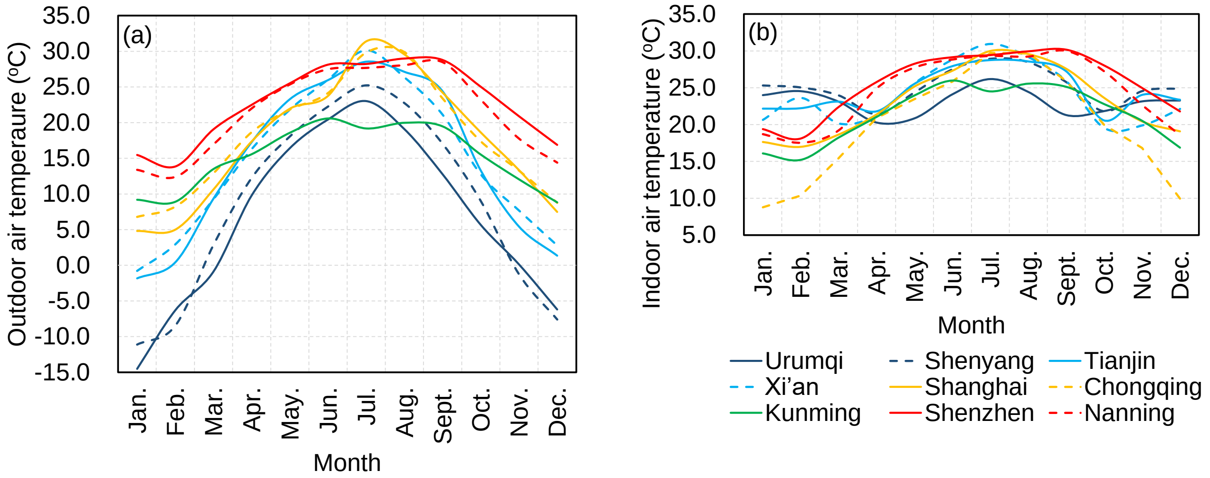

Figure 8: Summary of (a) the monthly outdoor air temperatures in all studied cities and (b) the monthly indoor air temperatures in all monitored apartments in each city

In summer (June, July and August), the indoor air temperature was greatly influenced by both the outdoor climate and the use of air-conditioners. For cities in which air conditioner use is not popular, such as Urumqi, Shenyang and Kunming, due to internal heat gains from both occupants and electronic equipment, the monthly average indoor temperature was 3 °C to 6 °C higher than the outdoor temperature. By contrast, all monitored dwellings in the C, HSCW and HSWW regions had air-conditioners, thereby resulting in much better controlled indoor environments despite the changing outdoor weather conditions. The monthly average indoor temperature varied from 27.9 °C to 28.8 °C in Tianjin, 28.8 °C to 30.9 °C in Xi'an, 27.3 °C to 30.0 °C in Shanghai, 25.8 °C to 29.7 °C in Chongqing, 29.1 °C to 29.9 °C in Shenzhen and 28.8 °C to 29.3 °C in Nanning during the summer time.

The remaining months, namely, March to May and September to November, were regarded as transition seasons in China. During these periods of the year, residents were more likely to regulate their indoor thermal environments by opening/closing windows due to the relatively moderate outdoor air temperature. Due to differences in the outdoor climate conditions, the indoor temperatures rose from north to south, varying from 20.3 °C to 23.1 °C in Urumqi, 21.4 °C to 25.8 °C in Shenyang, 20.6 °C to 27.1 °C in Tianjin, 19.5 °C to 25.9 °C in Xi'an, 18.7 °C to 27.6 °C in Shanghai, 15.5 °C to 25.9 °C in Chongqing, 18.2 °C to 25.1 °C in Kunming, 22.4 °C to 30.2 °C in Shenzhen and 19.2 °C to 30.0 °C in Nanning. In addition, a slight decrease in the indoor air temperature of approximately 3 °C was observed in cities with central heating systems at both the beginnings and the ends of the transition seasons, when outdoor air temperature remained as low as approximately 10 °C.

3.2.2 Correlation between the indoor and outdoor air temperatures

The adaptive theory has suggested a high correlation between the indoor temperature and the outdoor temperature, especially for non-air-conditioned buildings [34]. This section investigates the correlations between the measured indoor and outdoor air temperatures from the monitored apartments. Figure 9 presents a scatter plot with both parameters, for every 1 °C interval of outdoor temperature. The dashed line corresponds to identical indoor and outdoor temperatures. For cities with central heating systems, the indoor temperature was within the narrow range of 20 °C and 25 °C when outdoor temperature was lower than 10 °C. However, for other cities, the indoor temperature increased with the outdoor temperature for most of the year. Moreover, with the increase of the outdoor temperature, since the proportion of open windows increased, the temperature difference between indoors and outdoors decreased until the indoor temperature reached approximately 30 °C [24,25]. When the outdoor air temperature exceeded 30 °C, the indoor temperature was much lower than the outdoor temperature because more residents from southern cities began to use air conditioners. Additionally, the high thermal inertia of walls of buildings in northern cities reduced the peaks of outdoor temperature waves. Under the same outdoor temperature, the variation in the indoor temperature among cities may be attributed to the diversity in window use, as described in Section 3.2.3. For example, the monitored indoor temperature in Chongqing was very close to the local outdoor temperature due to its long window-opening duration, as shown in Figure 7.

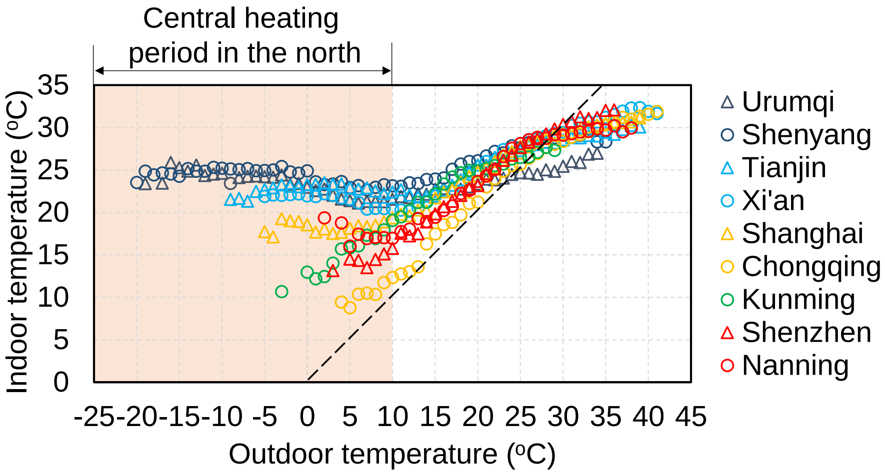

Figure 9: Correlation between indoor and outdoor air temperatures in nine cities

This study also analyzed the indoor air temperatures in the nine cities during extreme outdoor temperature conditions. A detailed analysis is presented in the Supporting Information in Section S1.

3.3 Indoor and outdoor humidities

3.3.1 Monthly indoor and outdoor humidity ratios

Figure 10 plots the monthly outdoor and indoor humidity ratios of all studied cities, in which substantial seasonal differences in the humidity ratios are observed. Both the outdoor and indoor humidity ratios reached their peaks in summer and dropped to relatively low levels in winter. The indoor average humidity ratio was in a narrower range of 4.3 g/kg to 16.9 g/kg and the outdoor average humidity ratio varied from 0.9 g/kg to 19.0 g/kg. Comparing differences among cities, both the indoor and outdoor humidity ratios increased from north to south. Descriptive results for both the outdoor and indoor relative humidities are presented in Supporting Information Section S2.

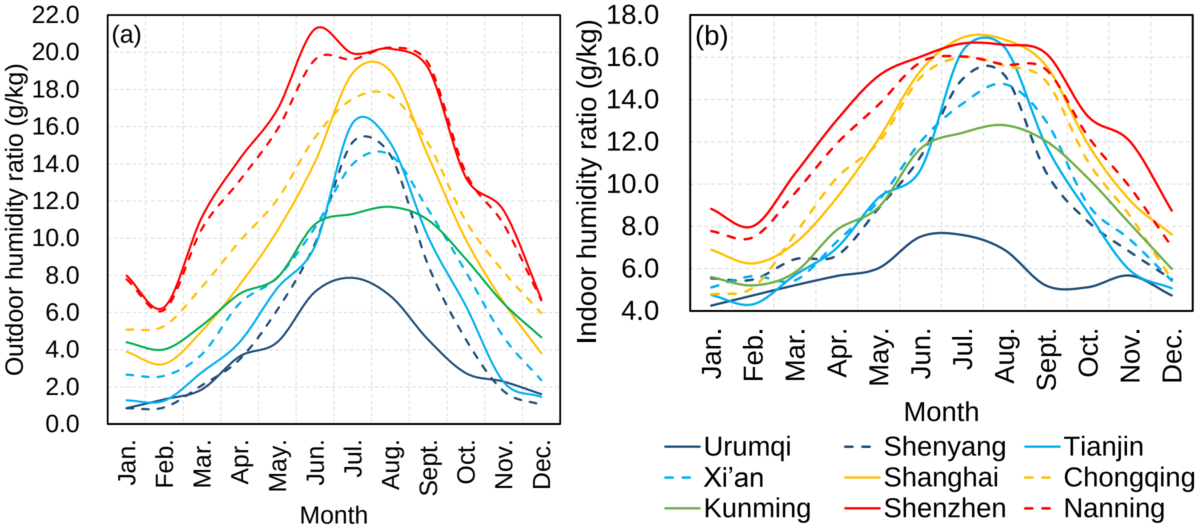

Figure 10: Summary of (a) the monthly outdoor humidity ratios and (b) the monthly indoor humidity ratios in the monitored apartments in the studied cities

3.3.2 Correlation between indoor and outdoor humidities

This section analyzed the correlation between the indoor and outdoor humidities via the same method as for Figure 9. In Figure 11, the dashed line represents the conditions when the indoor humidity is equal to the outdoor humidity. When the outdoor humidity ratio was lower than 5 g/kg, the indoor humidity ratio was much higher than the outdoor ratio due to moisture being generated indoors, such as from human bodies and food, and to low ventilation volume, especially in northern cities, such as Urumqi, Shenyang, Tianjin and Xi'an. According to Figures 8 and 10, low outdoor humidity ratios were generally accompanied by low outdoor temperatures, at which residents preferred to keep their windows closed to avoid cold discomfort. When the outdoor humidity ratio was between 5 g/kg and 18 g/kg, the indoor humidity ratio closely followed its outdoor counterpart. This may be due to satisfactory ventilation under such circumstances. When the outdoor humidity ratio exceeded 18 g/kg, the indoor humidity ratio became relatively stable at 18 g/kg due to dehumidification by air conditioners.

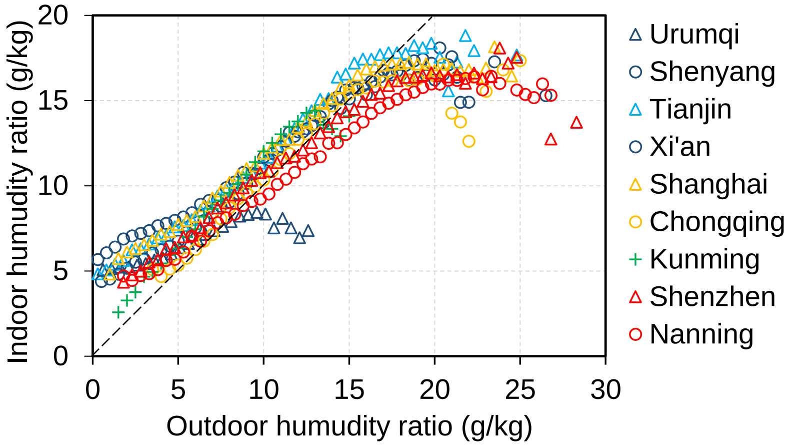

Figure 11: Correlation between the indoor and outdoor humidity ratios

For extreme outdoor conditions, this study has explored the indoor humidity ratios in both the driest and wettest months of the year; details are provided in Supporting Information Section S3.

4. Discussion

4.1 Evaluation of indoor thermal comfort

In this study, the indoor thermal environment has been further evaluated using both the static thermal comfort zone model and the adaptive thermal comfort model. According to the static comfort zone, most collected data are unsatisfactory. However, this method seems to be too strict for evaluating the indoor thermal environments of residential buildings due to the neglect of occupants' thermal adaptability [34]. For naturally ventilated buildings, occupants' comfort temperature would increase substantially in warmer climatic contexts and decrease in colder climate zones [45]. This change is not reflected in Fanger's heat balance equation.

For non-air-conditioned buildings, an adaptive thermal comfort model was developed. Compared with the static comfort zone model, it is more applicable to naturally ventilated spaces [34,45]. Using the adaptive model, the annual average acceptable proportion varied between 0.60 and 0.88 among the studied cities. The adaptive model was developed using data that were collected from an office environment. According to a recent study [46], the comfort zone width for 80% acceptability is 9 °C in residential buildings, which is 2 °C wider than in office buildings. Occupants of residential buildings typically have more "adaptive opportunities" than those in office buildings, e.g., to adjust their clothing levels and activities [46]. Hence, they may have higher satisfaction in indoor thermal environments than was estimated by the adaptive model. A detailed evaluation of indoor thermal comfort based on two methods is presented in the Supporting Information in Section S4.

4.2 Evaluation of the indoor humidity

In terms of indoor thermal comfort, an upper limit of the humidity ratio of 12 g/kg is suggested in the ASHRAE standard [6]. According to this limit, the acceptable proportions in all cities except Urumqi and Kunming were lower than 0.2 in summer. However, in winter, the acceptable proportions exceeded 0.8. In a study by Arundel [1], an optimum relative humidity of between 40% and 60% was suggested for minimizing adverse health effects. According to this criterion, over 80% of cases that were collected from northern cities had proportions of humidity that were below the lower limit in winter. For the HSCW and HSWW regions, the indoor humidity was likely to exceed 60% for more than half of the year. More details about evaluation of indoor humidity environment is provided in the Supporting Information in Section S5.

4.3 Evolution of the indoor air temperature in winter in the climate zones in China

Combining data that were collected in other studies with the data of this study, the evolution of the indoor air temperature in residential buildings in winter is plotted in Figure 12, with gradually increasing average indoor temperatures in both the SC and C zones. This might be associated with their improved building thermal insulation and airtightness. According to previous studies, the indoor temperatures in residential buildings in winter also showed upward trends in the UK, the US and Japan [47-51]. However, residential buildings with central heating systems tended to be overheated, especially in recent years, which can lead to excessive waste of energy. In addition, exposure to high temperature is associated with increases in mortality and morbidity, especially for elderly people [52]. In contrast, a temperature drop of 2~3 °C might double the perceived air quality [53]. Therefore, the heating supply could be suitably reduced to compensate for the impact of improved thermal insulation in both the SC and C zones. The average indoor temperature was approximately constant in the M and HSWW zones. In this study, residential buildings in the HSCW region were divided into two groups, namely, those with individual heating systems (HSCW-1) and those without (HSCW-2). HSCW-2 showed similar average indoor temperature to previously published results; the average indoor temperature for HSCW-1 was 6 °C higher. However, the winter indoor air temperature of HSCW-1 was much lower than that in apartments with central heating systems.

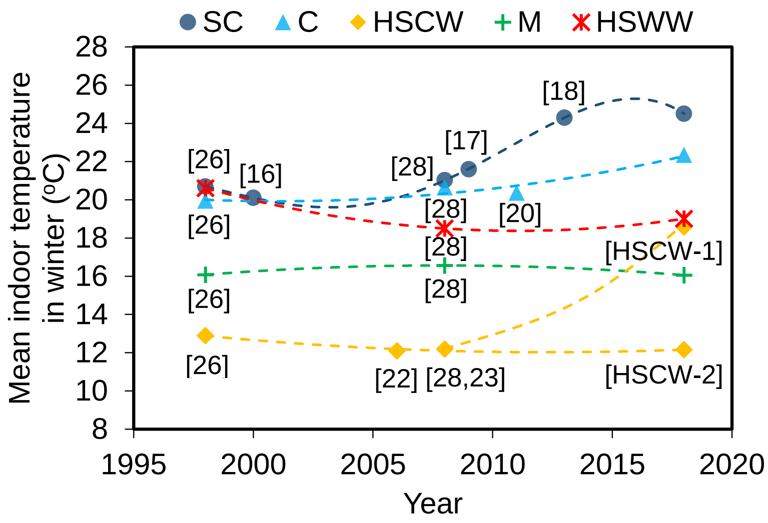

Figure 12: Evolution of the indoor air temperature in residential buildings in winter [16-18,20,22,23,26,28]

4.4 The impact of adaptive behaviors on thermal condition

Figure 13 presented how daily temperature difference between indoor and outdoor changed with daily window-open duration in monitored cities. Generally, as daily window-open duration increased, the temperature difference decreased, especially in northern cities including Urumqi, Shenyang, Tianjin and Xi'an. It may related to interior heat supply as well as good thermal insulation of building envelope. But in Chongqing, Shenzhen and Nanning, regardless of changing window behaviors, indoor temperature was about 2 K higher than outdoor.

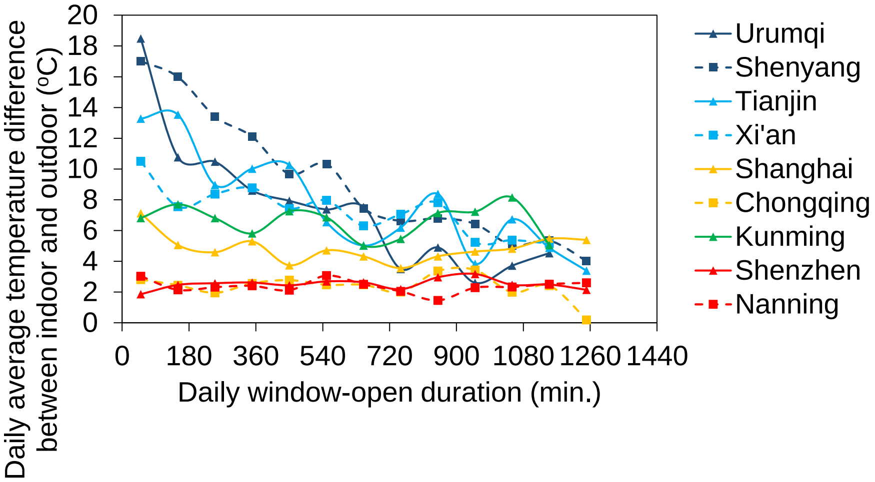

Figure 13: The impact of window behaviors on temperature difference between interior and exterior

In order to investigate the influence of air-conditioners on thermal condition, Figure 14(a) shows the box plots of the interior and exterior temperature of monitored apartments when air-conditioners was used for cooling. It can be seen that the mean value of indoor temperature varied from 26.6 to 29.1 °C, which was about 1.7 K lower than outdoor due to the usage of air-conditioners. In most cases, the indoor temperature was in a more narrow range than the outdoor temperature. Besides, worthy of attention is that outdoor temperature of 25% accumulative frequency was below that of indoor in Tianjin and Xi'an. Large temperature difference between day and night in these two cities may explain such phenomenon. By using the similar method, the summary of interior and exterior humidity was presented in Figure 14(b). Due to dehumidification of air conditioning, the mean value of indoor humidity ratio varied between 12.6 and 14.4 g/kg, which was lower than the corresponding average outdoor humidity ratio (15.5 ~ 19.9 g/kg). However, even if the air-conditioners were running, the indoor humidity ratio was over 12g/kg, the upper limit in ASHRAE [6], for about half of the time.

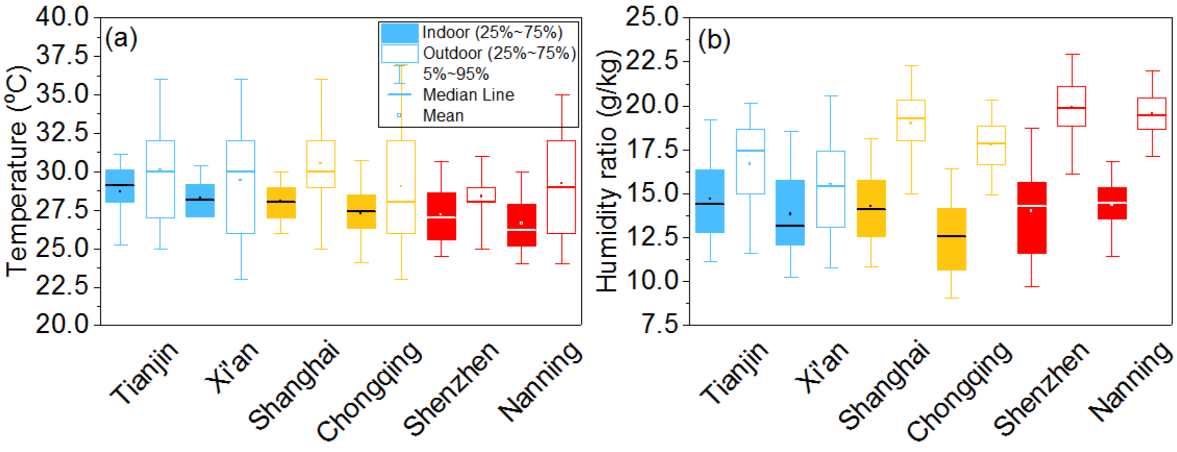

Figure 14: Box plots of (a) the interior and exterior temperature; (b) the interior and exterior humidity ratio when AC was used for cooling

4.5 Limitations

A comprehensive summary of the indoor thermal environments in Chinese residential buildings was presented in this study. However, this study has several limitations: first, although we monitored 46 apartments in total, the number of residential buildings that were monitored in each city is insufficient for obtaining statistically significant results. Moreover, human's subjective perceptions are not considered in this survey. The current data only describe the thermal environments under which the occupants live; it is not clear how they judge their thermal environments. Finally, the time that is spent sleeping accounts for a large percentage of the time at home and the sleeping thermal environment is vital to occupants' sleep quality [54,55]. Nevertheless, this study did not separately analyze the thermal environment during sleep.

5. Conclusions

This study investigated the indoor thermal environments in Chinese residential buildings across five climate zones based on a one-year monitoring campaign. From the obtained information, the following conclusions are drawn:

In winter, the overheated period (>24 °C) in Urumqi and Shenyang accounted for 43% and 59% of the entire heating season. The indoor temperature in the SC region was higher than that in the C region. Despite having similar outdoor climates, interior temperature of Shanghai in winter was well above that in Chongqing due to the operation of individual heating systems. In summer, the monthly mean interior temperature was lower than 30 °C in most dwellings. In addition, slight decreases are observed in cities with central heating in the beginnings and ends of the transition seasons.

The indoor temperature increased with the outdoor temperature in the cities without central heating. As the outdoor temperature increased, the temperature difference between indoors and outdoors decreased until the indoor temperature reached approximately 30 °C, which was due to the increase in the window-opening duration. When the outdoor air temperature exceeded 30 °C, the indoor temperature was lower than the outdoor temperature, which was due to the use of air-conditioners.

The outdoor and indoor humidity ratios peaked in summer and dropped to relatively low values in winter. The outdoor mean humidity ratio was in the range of 0.9 to 19.0 g/kg, while the indoor ratio varied in the narrower range of 4.3 to 16.9 g/kg. The interior and exterior humidity ratios increased from north to south. Low humidity was a serious problem in Urumqi.

When the outdoor humidity ratio was below 5 g/kg, the indoor humidity ratio was higher than the outdoor ratio due to indoor moisture sources and a low ventilation rate. The interior humidity ratio was close to the exterior ratio when the outdoor humidity ratio was between 5 g/kg and 18 g/kg. When the outdoor humidity ratio was higher than 18 g/kg, the indoor humidity ratio became relatively stable at 18 g/kg due to the dehumidification of air conditioning.

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