

Article

Sustainable and Health-Promoting Ventilation Optimization for Kindergarten Buildings Across Diverse Climate Zones

Chang Yi ¹, Mingrui Zhang ¹, Fei Gao ², Yiheng Liu ¹, Yin Zhang ^{3,*}, Jin Li ^{4,*} and Jialin Wu ⁴

¹ School of Architecture, Southwest Minzu University, Chengdu 610225, China; isyichang@163.com (C.Y.); 19836639583@163.com (M.Z.); ianno_0201@163.com (Y.L.)

² Sichuan Provincial Architectural Design and Research Institute, Chengdu 610000, China; sadigaofei@163.com

³ AI+Arch Lab, Southwest Minzu University, Chengdu 610225, China

⁴ School of Civil Engineering, Sichuan University of Science & Engineering, Zigong 643000, China; 18190389984@163.com

* Correspondence: cdzhangyin@swun.edu.cn (Y.Z.); jinli@suse.edu.cn (J.L.)

Abstract

HVAC systems account for a significant portion of building energy consumption, making them a critical factor in achieving energy efficiency and sustainable development in buildings. The thermal comfort environment within kindergarten buildings has a direct impact on children's health and learning performance while also being closely linked to building energy consumption. Natural ventilation serves as a fundamental passive technology for ensuring indoor air quality. It offers advantages such as energy savings and emissions reduction while improving thermal comfort, making it a key advancement in promoting sustainable building practices. Air change rate serves as a key indicator for measuring indoor air renewal. This study, based on the characteristics of young children being more sensitive to environmental changes and having weaker resistance, investigated the impact of different air change rates on indoor thermal comfort in kindergartens across three distinct climatic zones in China: hot summer and warm winter, hot summer and cold winter, and temperate areas. Thermal comfort was evaluated using the Temperature Humidity Index (THI) and temperature fluctuation rate. And the effects of air change rates on building energy consumption were further examined. Simulation results show that the influence of air change rates on indoor thermal comfort, temperature fluctuations, and energy consumption varies significantly across climate zones. Guided by the sustainable principles of prioritizing children's health and low-energy operation, the findings indicate that an air change rate of 1.5 is optimal in hot summer and warm winter areas, a rate of 0.5 is most suitable in hot summer and cold winter areas, and a rate of 0.5 is most suitable in temperate areas. This study aims to provide scientific evidence for achieving energy conservation and sustainable ventilation design through natural ventilation in kindergarten buildings across different climate zones, while ensuring children's health.

Keywords: kindergarten; passive sustainable design; air change rates; thermal comfort; temperature humidity index (THI); energy consumption

Academic Editor: Ali Bahadori-Jahromi

Received: 17 December 2025

Revised: 14 January 2026

Accepted: 29 January 2026

Published: 31 January 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Global surface temperatures continue to rise, posing challenges to human health and livelihoods [1], with children bearing 88% of the additional disease burden caused by

climate change [2]. During school hours, children spend approximately one-third of their time in academic buildings [3]. Research indicates that the thermal comfort provided by schools significantly impacts children's performance and health [4,5]. When thermal comfort is maintained within optimal ranges, student performance improves; conversely, failure to meet necessary environmental standards leads to decreased learning efficiency [6,7]. To investigate thermal comfort in building interiors, numerous evaluation indices and standards have been proposed. Previous studies indicate that students' thermal comfort levels fall outside the comfort ranges provided by these standards [8–10], and discrepancies exist between children's thermal comfort levels and predictions by the Predicted Mean Vote (PMV) model and current adaptive thermal comfort models. This primarily stems from differences in children's metabolic rates, activity levels, and their adaptability to environmental conditions. Therefore, investigating indoor thermal comfort specifically in kindergarten buildings is of great importance.

According to statistics, building energy consumption accounts for approximately 40% of global energy use, with HVAC systems contributing 40–50% of this total [11,12], making them a critical focus for building energy efficiency. Natural ventilation stands as one of the fundamental techniques for ensuring good indoor air quality [13,14], safeguarding occupant health and comfort while advancing sustainable building practices [15]. Compared to mechanical ventilation, natural ventilation conserves energy, reduces emissions, and lowers noise levels and maintenance costs while improving indoor environments [16]. Therefore, passive optimization strategies, specifically natural ventilation, are preferred for achieving more comfortable indoor thermal conditions. Air change rate (ACR), also known as ventilation rate, refers to the number of times air is replaced within a given time period. It is calculated by dividing the volume of air entering a room per unit time by the room's volume. ACR is a key factor influencing building energy consumption and indoor air quality [17]. Increased attention to thermal comfort in kindergarten buildings has also spurred research on air change rates in these facilities. Numerous studies have examined air change rates in buildings. Wang et al. [18] monitored bacterial and fungal concentrations in multiple building types across five climate zones in China and examined the effects of temperature, relative humidity, and air change rate on indoor bioaerosols. They found that higher air change rates were associated with lower indoor airborne bacterial concentrations and could mitigate the influence of occupant density on bacterial levels, indicating that the air change rate is a key factor affecting indoor microbial loads. Park et al. [19] investigated the impact of unintentional door-opening events caused by occupant movement on air change rates in naturally ventilated office spaces. They observed that such door-opening events significantly increased the air change rate (by 11.5–41%) and were strongly correlated with the number of people entering or leaving, indicating that occupant-induced door openings constitute a major source of air exchange in naturally ventilated environments. Peng et al. [20] simulated hourly infiltration air change rates for residential buildings across 10 cities in five climate zones, examining the influence of building characteristics and climatic factors. They found that residential air change rates nationwide follow a log-normal distribution with an annual average of 0.338 h^{-1} . Building type, floor level, and construction era significantly affect air change rates. In warm regions, wind pressure dominates, while in cold regions, buoyancy and wind jointly influence air change rates. Deshko et al. [21] compared the energy use under natural ventilation when using experimentally obtained air change rates versus the standardized values, and developed hourly air change rate schedules based on occupancy patterns. They found that, during weekends, adopting a scheduled ventilation approach aligned with occupancy resulted in approximately 25% lower energy use compared with maintaining a constant air change rate. This indicates that an appropriate ventilation strategy can significantly influence heating energy consumption as well as indoor air quality. Liu

et al. [22] evaluated the air exchange efficiency, air change rate, and influencing factors of single-sided window opening in air-conditioned rooms through field experiments and CFD simulations. They found that window opening effectively removed indoor contaminants but increased cooling losses. The air exchange efficiency was most significantly affected by the position of the air-supply register (accounting for about 46% of the influence), and intermittent window opening was shown to improve indoor air quality with relatively lower energy consumption. Alhindawi et al. [23] monitored indoor pollutant concentrations and air change rates in highly airtight, naturally ventilated dwellings during both winter and summer. They found that the bedroom air change rates ranged only from 0.08 to 0.35 h⁻¹, and that CO₂ concentrations remained above 1000 ppm for most of the sleeping period in winter, indicating that natural ventilation failed to meet the intended design performance and that a significant performance gap exists. Chiesa et al. [24] developed a low-cost smart ventilation system based on multisensor and Internet of Things technologies, which employs data-driven control to balance indoor air quality and energy consumption. Experimental results demonstrate that the system can effectively maintain satisfactory indoor air quality and show strong potential for integration and practical application. Cai et al. [25] monitored CO₂, PM_{2.5}, and air change rates in school classrooms in Beijing under both natural and mechanical ventilation conditions. They found that the air change rate in naturally ventilated classrooms was relatively low (about 1.9 L/s·person), and during periods of severe ambient pollution, the air change rates decreased by as much as 58%, with CO₂ concentrations frequently exceeding recommended limits. These findings indicate that insufficient air exchange is a major contributor to poor indoor air quality in classrooms. Rizzo et al. [26] evaluated CO₂ sensor-based demand-controlled ventilation in classrooms, showing that while winter natural ventilation can meet IAQ standards, it causes energy losses. The demand-controlled system maintains CO₂ below recommended levels year-round, and combining it with passive strategies further improves efficiency, highlighting the feasibility of integrating mechanical and passive ventilation for healthy, energy-efficient indoor environments. Lee et al. [27] investigated the effects of different operating scenarios of mechanical ventilation systems and air purifiers on indoor CO₂ and PM_{2.5} concentrations in kindergartens using numerical simulations. The results indicated that, to maintain acceptable indoor air quality, the required ventilation rate per child was approximately 20.4 m³/h. However, increasing the ventilation rate alone led to an increase in indoor PM_{2.5} concentrations, whereas the use of a high-efficiency MERV 13 filter effectively mitigated this issue. Munckton et al. [28] conducted field measurements in five kindergartens in Melbourne to monitor indoor air quality (IAQ) and thermal conditions during the COVID-19 pandemic, using CO₂ concentration as an indicator of ventilation performance. The results showed that CO₂ levels exceeded recommended maximum limits in several kindergartens under normal operation, with the highest concentration reaching 1908 ppm during class time. Kindergartens employing a combination of mechanical and natural ventilation exhibited lower CO₂ concentrations than those relying solely on mechanical ventilation; however, thermal comfort was compromised. However, most of these studies have been conducted in office buildings and residential structures, with very few focusing on educational buildings, particularly kindergarten facilities. Moreover, studies on educational buildings have primarily concentrated on variations in indoor pollutant concentrations, with comparatively less attention paid to thermal comfort. Therefore, investigating air change rates in kindergarten buildings is both necessary and feasible.

China can be divided into five climatic zones: hot summer and warm winter, hot summer and cold winter, temperate, cold, and severe cold. The climatic variations within each climate zone are quite pronounced. The impact of ventilation on the indoor environment varies under different climatic conditions. To better understand the effects of air

change rates on thermal comfort in kindergartens and to ensure children's health, this study first modifies the THI index for children to more accurately assess thermal comfort levels in kindergarten buildings, and then proposes optimal ventilation strategies for different climatic characteristics. This study is structured as follows: (1) modification of the THI index; (2) investigate the impact of air change rates on thermal comfort in kindergartens under different climatic conditions; (3) understand the impact of different air change rates on kindergarten energy consumption across various climate zones; (4) determine the optimal air change rate by comprehensively considering thermal comfort and energy consumption in kindergartens.

2. Materials and Methods

2.1. Illustrative Case

This study selected a pre-designed kindergarten located in Haikou City, Hainan Province as its research subject. The kindergarten comprises three floors, each featuring four children's activity units interconnected by external corridors. Key functional rooms, teachers' offices and children's activity units, were selected from each floor for simulation analysis and assigned sequential identification numbers, as illustrated in Figure 1.



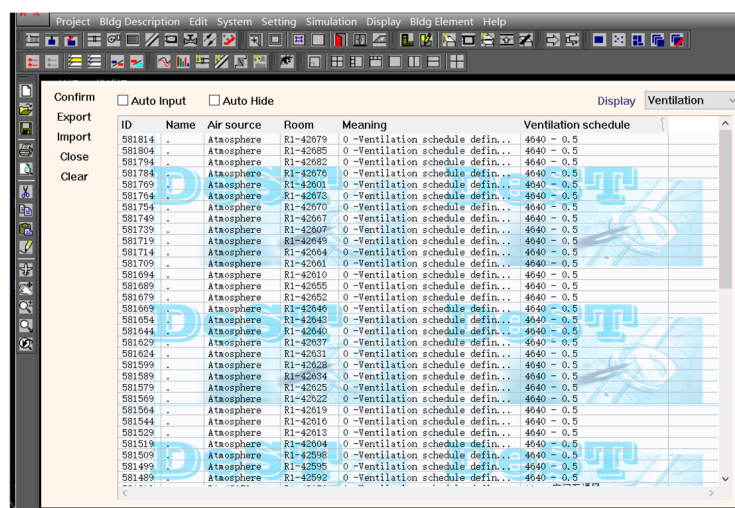
Figure 1. Kindergarten Floor Plan.

This study employed DeST (Version: 20230713) software to simulate indoor ventilation and energy consumption, conducting simulation analyses based on DeST's typical annual data. Since the kindergarten design incorporates an external corridor, which is unsuitable for cold and severe cold areas, but is commonly used in southern China, this

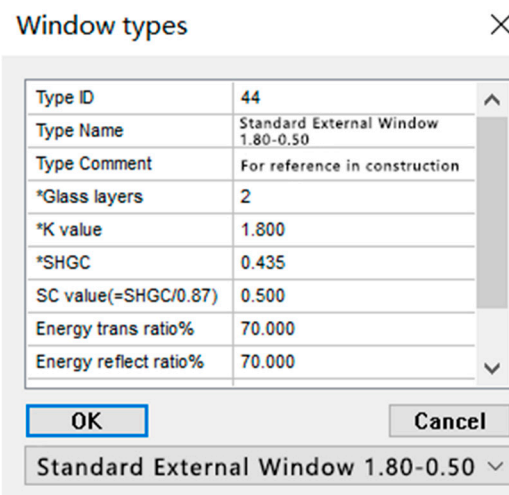
study therefore focuses on hot summer and warm winter, hot summer and cold winter, and temperate areas. The original design location for this kindergarten was in Haikou City, Hainan Province, which is classified as a hot summer and warm winter area. Therefore, Haikou City was selected as the representative case for this climate zone in the study. For the hot summer and cold winter area and the temperate area, Changsha City in Hunan Province and Kunming City in Yunnan Province were chosen, respectively, for the research. According to typical annual data from DeST, Haikou City has an average annual temperature of 24.34 °C. The hottest month, July, has an average temperature of 28.86 °C, while the coldest month, January, has an average temperature of 17.98 °C. The average annual humidity is 16.42%. Changsha City has an annual average temperature of 17.06 °C. The hottest month, July, has an average temperature of 28.54 °C, while the coldest month, January, has an average temperature of 5.54 °C. The annual average humidity is 11.20%. Kunming City has an average temperature of 15.46 °C. The hottest month, June, has an average temperature of 20.07 °C, while the coldest month, December, has an average temperature of 8.42 °C. The annual average humidity is 9.85%. For the building envelope, the exterior wall construction consists of 20 mm cement mortar + 200 mm red clay bricks + 50 mm polystyrene foam + 20 mm cement mortar. The interior wall uses 20 mm cement mortar + 180 mm lightweight aggregate concrete + 20 mm cement mortar. The roof employs 80 mm slag concrete + 25 mm extruded polystyrene board + 100 mm reinforced concrete, with thermal conductivities of 0.58, 1.52, and 0.81, respectively. The windows utilize double-glazed glass with PVC frames, featuring a thermal transmittance coefficient of 1.80. And three air change rates were selected: 0.5, 1.0, and 1.5 (Table 1, Figure 2).

Table 1. Model Boundary Condition Settings.

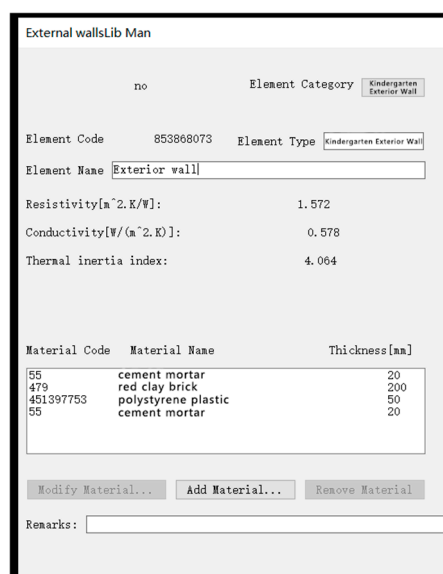
Boundary Conditions		Setting	Heat Transfer Coefficient
Climate Conditions	Haikou	Average temperature	24.34 °C
		Average humidity	16.42%
	Changsha	Average temperature	17.06 °C
		Average humidity	11.20%
	Kunming	Average temperature	15.46 °C
		Average humidity	9.85%
Envelope	Exterior wall	20 mm cement mortar + 200 mm red clay brick + 50 mm polystyrene plastic + 20 mm cement mortar	0.58
	Interior wall	20 mm cement mortar + 180 mm expanded clay aggregate concrete + 20 mm cement mortar	1.52
	Roof	80 mm slag concrete + 25 mm extruded polystyrene board + 100 mm reinforced concrete	0.81
	Window	Insulated glass + PVC windows	1.80
Air change rates		0.5, 1.0, 1.5	/



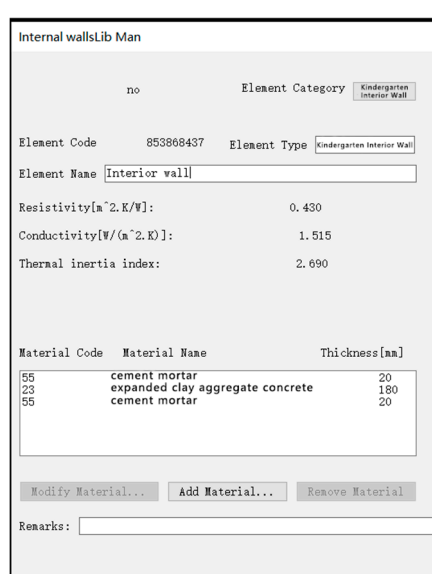
(a) Air Change Rate Setting



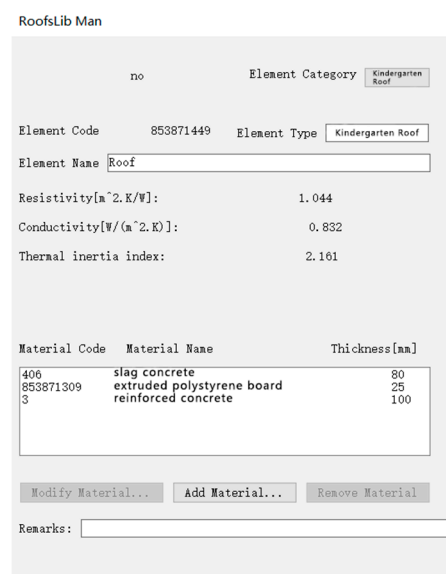
(b) Window Setting



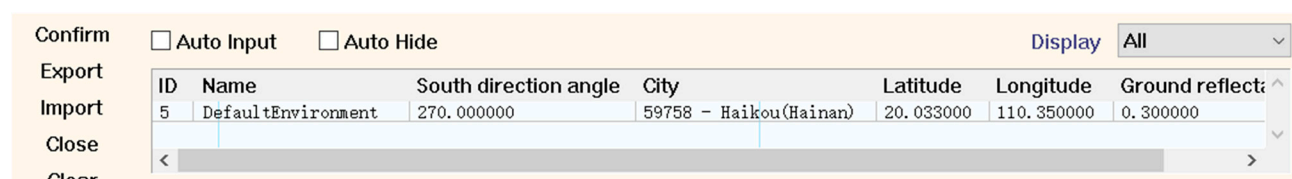
(c) Exterior Wall Setting



(d) Interior Wall Setting



(e) Roof Setting



(f) Geographical Location Settings

Figure 2. Model Parameter Settings.

2.2. Evaluation Indicators

According to the “Climatic suitability evaluating on human settlement” (GB/T 27963-2011), the temperature humidity index (*THI*) refers to an index describing the human body’s overall perception of environmental temperature and humidity. Climate comfort is classified into five levels based on the *THI*: cold, chilly, comfortable, hot, and muggy. The classification is shown in Table 2. The calculation method for *THI* is shown in Equation (1).

$$THI = T - 0.55 \times (1 - RH) \times (T - 14.4) \quad (1)$$

where THI is the thermal humidity index, rounded to one decimal place, T is the room temperature in degrees Celsius, and RH is the relative humidity in percent. According to research by Nam and Yun, preschool children (aged 4–6)’s comfort temperature is approximately 3 °C lower than that of adults [29,30], and the subjects of this study are also preschool children. Additionally, research indicates that children’s humidity preferences remain consistent. Since the THI evaluation criteria are based on adult standards, children’s assessments differ somewhat from those of adults. Substituting the 3 °C difference into the THI calculation formula yields the difference shown in Equation (2).

$$\Delta THI = -3 \times (0.45 + 0.55RH) \quad (2)$$

This temperature difference is uniformly applied across all climate zones but is only applicable to preschool children. While the use of a 3 °C temperature deviation here introduces some uncertainty, the objective of this study is to explore the relative impact of ventilation on indoor thermal comfort under different climatic conditions rather than to predict precise comfort temperatures. Therefore, although this uncertainty affects absolute values, it does not alter the comparative trends observed under different ventilation schemes. Using DeST for simulation, hourly room temperature and humidity data were obtained for each test subject under different conditions. Hourly and average temperature differences were calculated, yielding the average temperature differences across different floors of the studied kindergarten under varying air change rates across three distinct climate zones, as shown in Table 3. Data reveals that under identical air change rates and climate zones, the average differences between different floors are relatively small. However, the average differences between varying air change rates are significantly pronounced, and the differences across different climate zones are also markedly distinct. Therefore, we calculated the average difference across all floors under various climate and ventilation conditions, then averaged these differences to obtain the overall building average. This adjusted THI evaluation standard, which is suitable for children, is presented in Table 4.

Table 2. Comfort Level Classification.

Rank	Level of Perception	Temperature Humidity Index
1	Cold	<14.0
2	Chilly	14.0~16.9
3	Comfortable	17.0~25.4
4	Hot	25.5~27.5
5	Muggy	>27.5

Table 3. Average ΔTHI between floors.

Climate Areas	ΔTHI											
	0.5				1.0				1.5			
	1st Floor	2nd Floor	3rd Floor	Average	1st Floor	2nd Floor	3rd Floor	Average	1st Floor	2nd Floor	3rd Floor	Average
Hot summer and warm winter	2.09	2.04	2.04	2.1	1.36	1.36	1.36	1.4	1.36	1.36	1.36	1.4
Hot summer and cold winter	1.93	1.89	1.90	1.9	2.04	2.01	2.03	2.0	2.06	2.03	2.05	2.1
Temperate	2.02	2.02	2.03	2.0	2.03	2.01	2.03	2.0	2.04	2.02	2.04	2.0

Table 4. THI Evaluation Criteria Suitable for Children.

	Haikou			Changsha			Kunming		
	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
Cold	<11.9	<12.6	<12.1	<12.0	<11.9		<12.0		
Chilly	11.9~14.8	12.6~15.5	12.1~15.0	12.0~14.9	11.9~14.8		12.0~14.9		

Comfortable	14.9~23.3	15.6~24.0	15.1~23.5	15.0~23.4	14.9~23.3	15.0~23.4
Hot	23.4~25.4	24.1~26.1	23.6~25.6	23.5~25.5	23.4~25.4	23.5~25.5
Muggy	>25.4	>26.1	>25.6	>25.5	>25.4	>25.5

Because young children have weaker resistance compared to adults, temperature fluctuations affect them more significantly. Therefore, we introduced the hourly temperature difference rate to assess temperature fluctuations, calculated as shown in Equation (3):

$$\Delta T_h(t) = T(t) - T(t - 1) \quad (3)$$

where $\Delta T_h(t)$ represents the hourly temperature difference rate, $T(t)$ denotes the room temperature at hour t , and $T(t - 1)$ denotes the room temperature at hour $(t - 1)$. The hourly temperature difference rate is smaller, indicating less temperature fluctuation, which is more beneficial for young children.

3. Results

3.1. Hot Summer and Warm Winter Area

Calculate the hourly THI values for kindergartens in hot summer and warm winter areas, and evaluate them using the scoring method in Table 4. Determine the percentage of comfortable hours for each primary functional room under different air change rates. Analysis of Figure 3 reveals that in a hot summer and warm winter area, the comfort ratio of each room increases as the air change rate rises. At an air change rate of 1.5, the room comfort ratio reaches its peak. Overall, increasing the air change rate significantly enhances the proportion of comfortable hours. However, the resulting increase in the percentage of comfortable hours remains relatively low, peaking at only 50.91%. This indicates that the air change rate has limited effectiveness in optimizing the duration of comfortable hours. At the same air change rate, the first floor offers superior comfort compared to the second and third floors, while the second floor provides slightly better comfort than the third. Overall, comfort levels follow a trend where the first floor is optimal, the third floor is next best, and the second floor is the least comfortable.

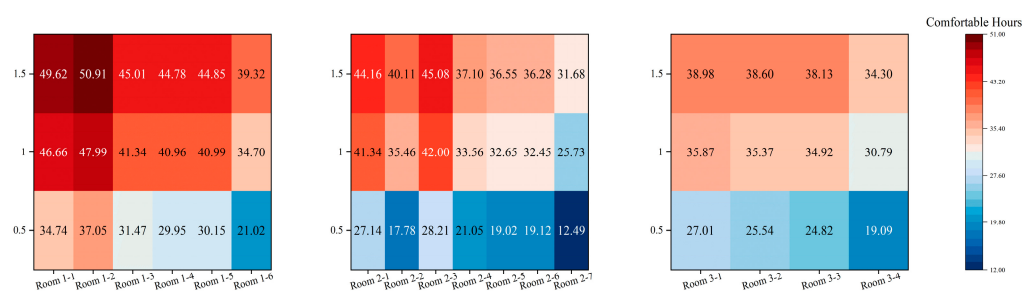


Figure 3. Percentage of Comfort Hours in Key Functional Rooms at Different Air Change Rates in Hot Summer and Warm Winter Areas.

Analysis of Figure 4 reveals that in hot summer and warm winter areas, the proportion of time spent feeling muggy is significant. Particularly at an air change rate of 0.5, the percentage of hours spent feeling muggy exceeds 50%, and on the second and third floors, it approaches 60%. However, in this area, there are no instances of feeling cold or chilly at all. As the air change rate increases, the number of hours during which the room feels muggy and hot decreases significantly. This indicates that in hot summer and warm winter areas, increasing the air change rate can markedly improve indoor thermal discomfort. Although the proportion of muggy conditions has decreased significantly, the improvement in perceived comfort has not been particularly noticeable. Therefore, further

improvement in comfort levels cannot be achieved by increasing air change rates alone, and active optimization strategies, such as the use of air-conditioning or other mechanical systems, are required when necessary.

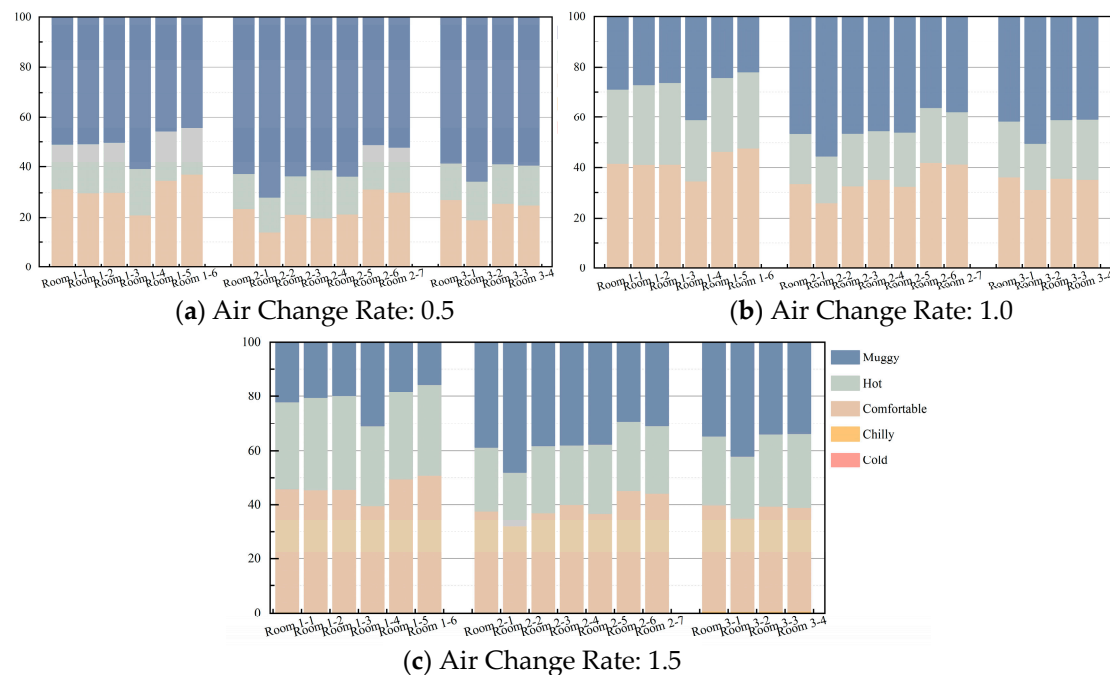


Figure 4. Percentage of Comfortable Conditions in Each Room at Different Air Change Rates in Hot Summer and Warm Winter Areas.

Analysis of Figure 5 reveals that under different air change rates, the temperature fluctuation patterns across all rooms are consistent. Furthermore, the temperature fluctuation patterns in the children's activity units and teacher offices remain identical regardless of their respective floor levels. The periods of significant temperature fluctuations in the children's activity unit primarily occur between the 1200th and 4500th hours of the year, and between the 6000th hour of the year and the 300th hour of the following year, that is, from February to June and from August to January of the subsequent year. These correspond to the spring and fall semesters. The temperature fluctuations in the teachers' office are generally lower overall and exhibit smaller variations. When the air change rate increased from 0.5 to 1.0, the peak temperature fluctuation decreased significantly, with the activity unit for young children decreasing by nearly 1 °C. However, when the air change rate increased from 1.0 to 1.5, the temperature fluctuation remained unchanged. Additionally, temperature fluctuations in the same room across different floors are nearly identical.

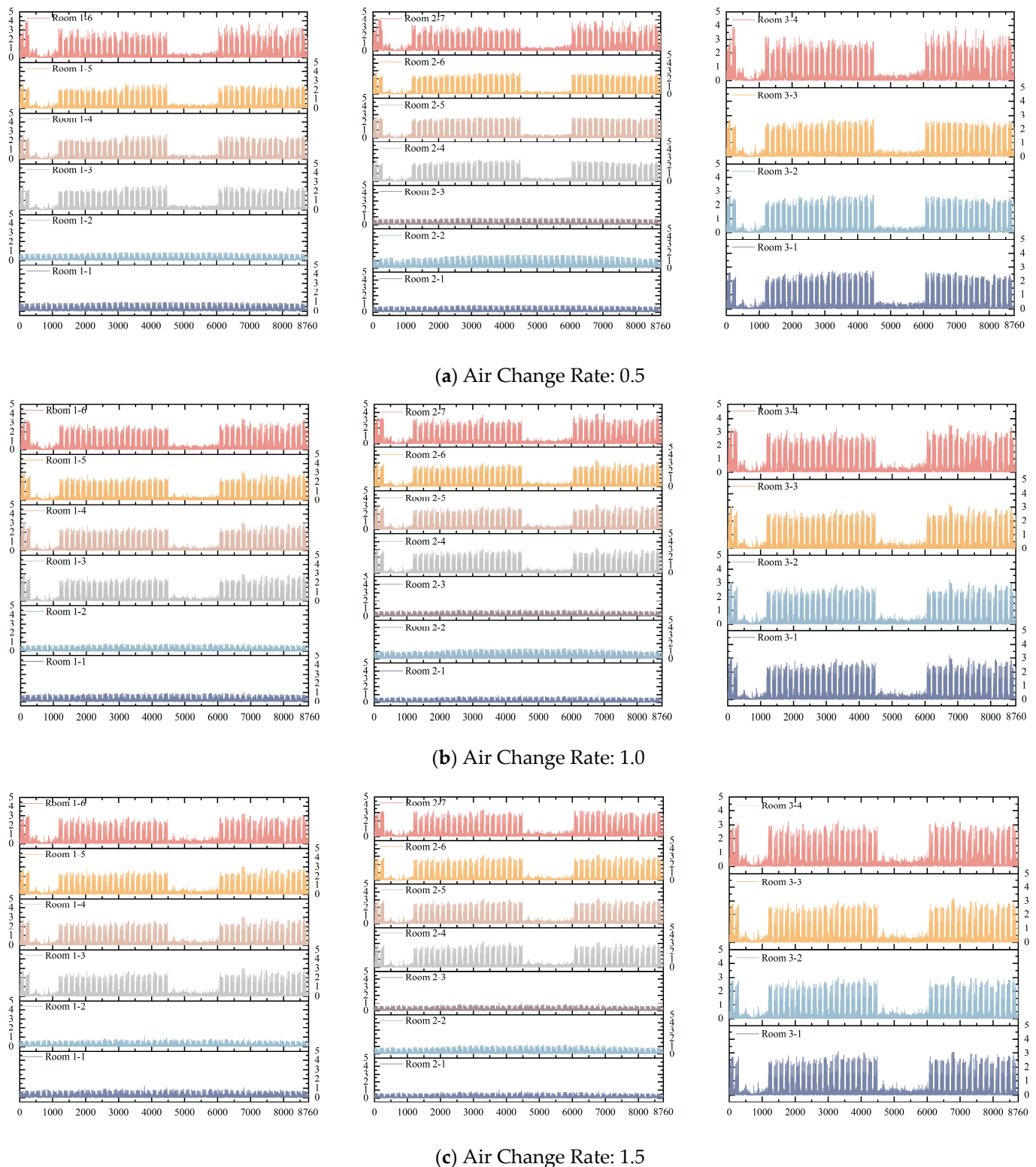


Figure 5. Hourly Temperature Fluctuation Rates in Each Room at Different Air Change Rates in Hot Summer and Warm Winter Areas.

3.2. Hot Summer and Cold Winter Area

Analysis of Figure 6 reveals that in hot summer and cold winter areas, the comfort ratio of each room decreases as the air change rate increases. At an air change rate of 0.5, the room's comfort ratio reaches its peak. However, the effect of air change rate on room

comfort ratios is not significant, with all rooms maintaining comfort ratios at a moderate level. The most noticeable change amounts to only about 4%. Among different floors with identical air change rates, the first floor exhibits the highest thermal comfort ratio, followed by the third floor, with the second floor ranking last. However, the differences in thermal comfort ratios between each floor remain relatively minor.

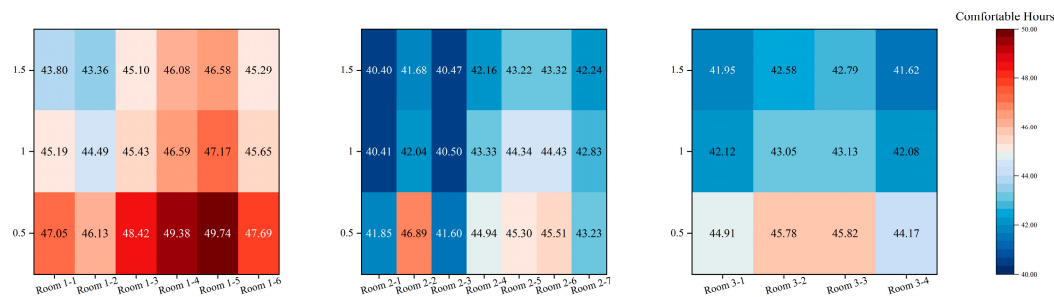


Figure 6. Percentage of Comfort Hours in Key Functional Rooms at Different Air Change Rates in Hot Summer and Cold Winter Areas.

Analysis of Figure 7 reveals that in hot summer and cold winter areas, all types of thermal comfort conditions occur, but the proportion of hours spent in the comfortable zone consistently remains the highest. The proportion of hours perceived as muggy remained largely unchanged with variations in air change rate. While the number of hours perceived as hot decreased when air change rates increased, the proportion of hours perceived as chilly or cold showed a significant reduction as air change rates decreased. A significant reason for the opposite trend observed in hot summer and cold winter areas compared to hot summer and warm winter areas may be that increased air change rates during winter enhance air exchange within rooms. This heightened airflow causes occupants to perceive cold or chilliness, thereby reducing the proportion of comfortable hours. Consequently, lower air change rates paradoxically result in a higher percentage of comfortable hours.

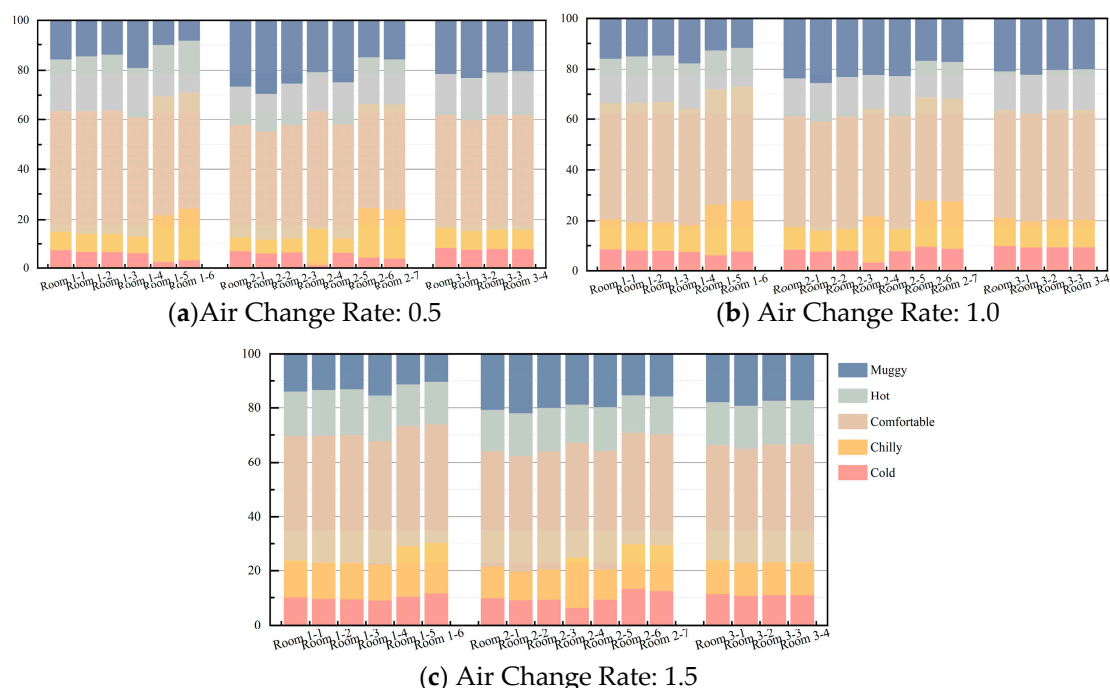


Figure 7. Percentage of Comfortable Conditions in Each Room at Different Air Change Rates in Hot Summer and Cold Winter Areas.

Analysis of Figure 8 reveals that, similar to hot summer and warm winter areas, different room types exhibit identical trends across varying air change rates, and trends remain consistent across different floors. Temperature fluctuations in the children's activity units are more pronounced than in the teachers' offices, with changes concentrated during the middle of the semester. When the air change rate increased from 0.5 to 1.0, the peak temperature fluctuations in the children's activity unit rose significantly, from approximately 2 °C to around 3 °C. However, the peak values in the teachers' office showed a decreasing trend. When the air change rate increased from 1.0 to 1.5, the temperature fluctuation remained virtually unchanged.

3.3. Temperate Area

Analysis of Figure 9 reveals that in temperate areas, some rooms achieve optimal comfort hours at an air change rate of 1.0, while others reach it at 1.5. However, the difference is negligible. Therefore, selecting either 1.0 or 1.5 air changes per hour will yield optimal comfort hours. Overall, the proportion of comfortable hours across rooms remains consistently high at different air change rates. For some rooms on the second and third floors, adjusting air change rates significantly increases their comfortable hour ratio. However, for rooms on the first floor, the optimization effect of air change rates is relatively less pronounced. When air change rates are identical across different floors, the first floor performs best, the third floor second best, and the second floor worst, mirroring the patterns observed in the other two climate areas. The gap between the first and third floors is not very pronounced, but the gap between the second floor and the other two floors is more noticeable.

Analysis of Figure 10 reveals that at an air change rate of 0.5, cold discomfort is rarely experienced, but significant hot discomfort is likely to occur. As the air change rate increases, the proportion of cold discomfort states gradually rises, reaching a point where cold sensations are even observed at 1.5. Meanwhile, the proportion of hot discomfort states gradually decreases, with some rooms showing no hot discomfort states at 1.5. Therefore, in summary, for temperate areas, selecting an air change rate of 1.0 while considering the THI index and temperature fluctuations yields optimal results. This ensures a high proportion of comfortable hours across all rooms, with low percentages of both cold and hot discomfort. All rooms experience only a sensation of chilliness, never reaching cold levels, while some rooms avoid experiencing muggy heat entirely.

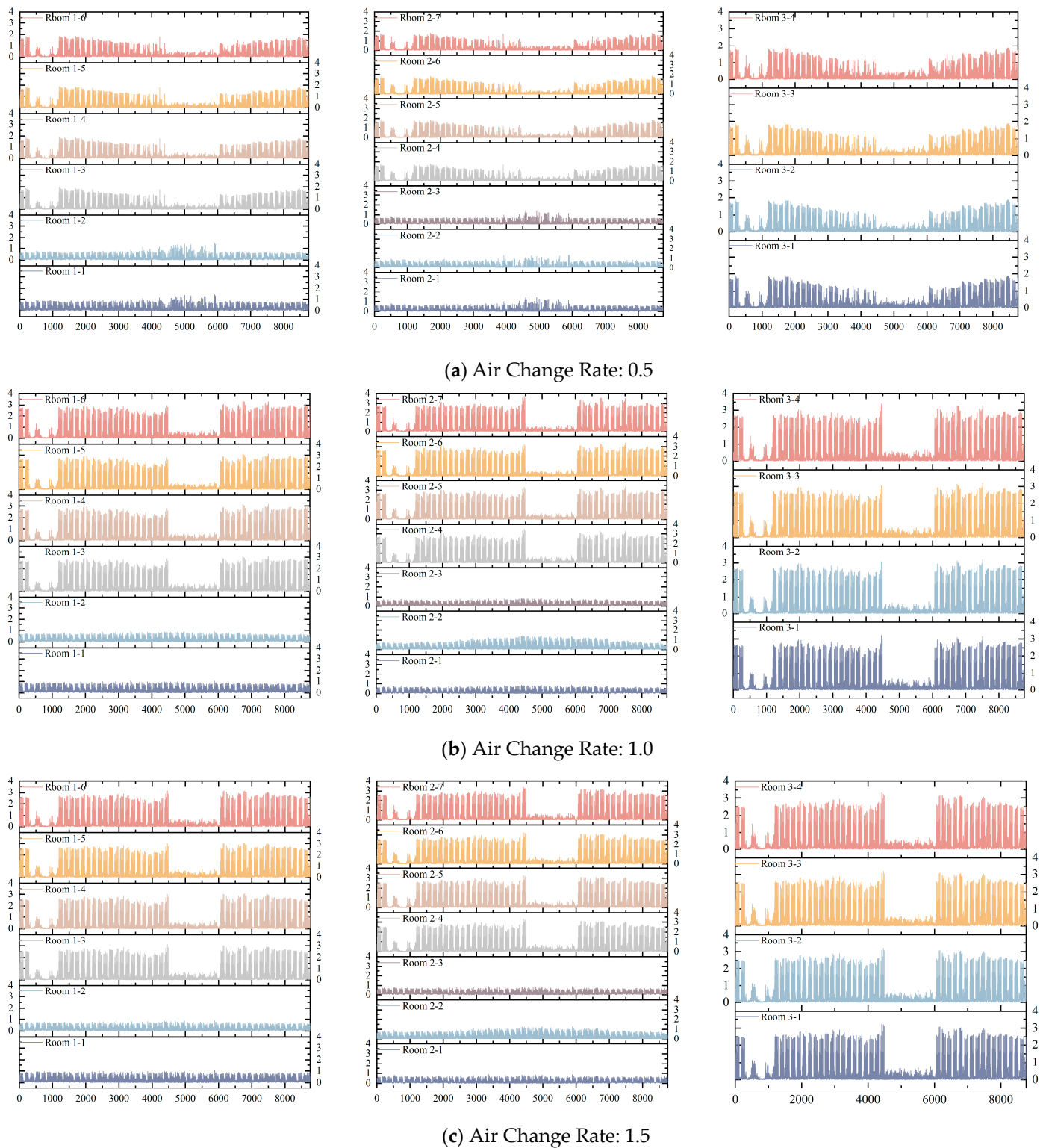


Figure 8. Hourly Temperature Fluctuation Rates in Each Room at Different Air Change Rates in Hot Summer and Cold Winter Areas.

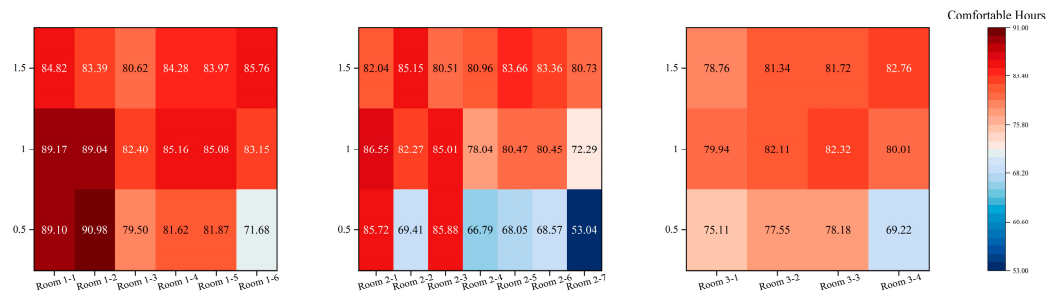


Figure 9. Percentage of Comfort Hours in Key Functional Rooms at Different Air Change Rates in a Temperate Area.

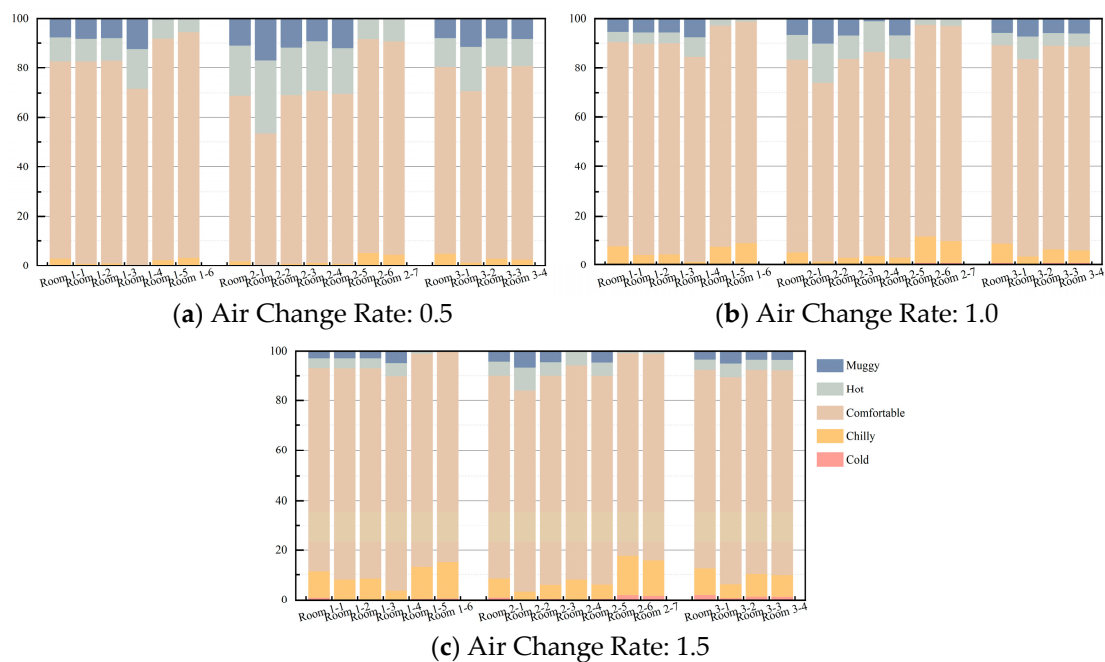


Figure 10. Percentage of Comfortable Conditions in Each Room at Different Air Change Rates in a Temperate Area.

Analysis of Figure 11 reveals that, consistent with the previous two climate zones, temperature fluctuation patterns across different room types in temperate areas remain identical under varying air change rates and floor conditions. Temperature variations in the children's activity units are significantly more pronounced than those in the teachers' offices. When the air change rate increased from 0.5 to 1.0, the peak temperature fluctuation in the children's activity unit rose significantly, from approximately 3 °C to around 4.5 °C. However, when the air change rate was further increased to 1.5, the peak temperature fluctuation decreased slightly, dropping from approximately 4.5 °C to around 4 °C. Meanwhile, temperature fluctuations in the teachers' office were significantly reduced as the air change rate increased.

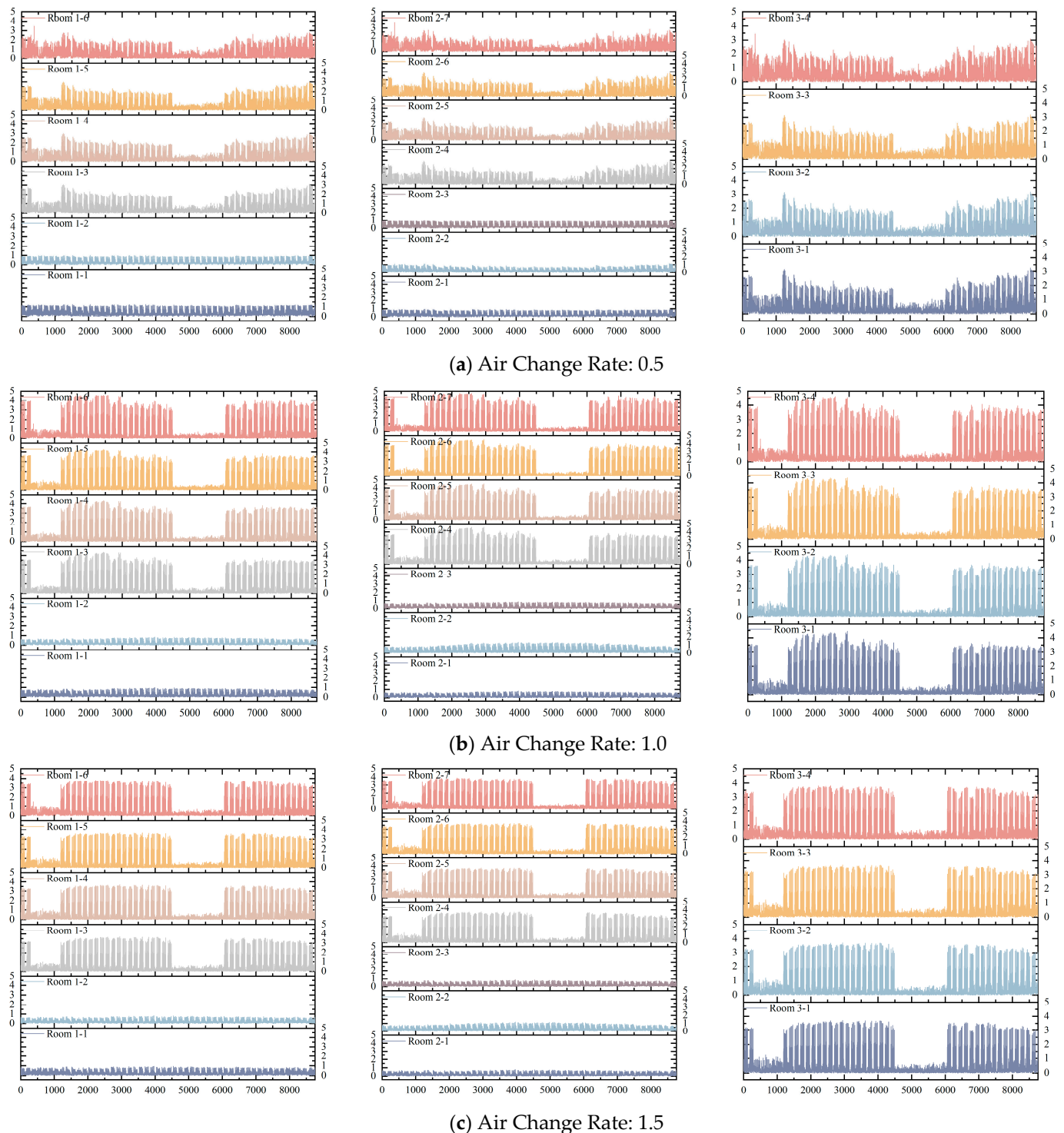


Figure 11. Hourly Temperature Fluctuation Rates in Each Room at Different Air Change Rates in a Temperate Area.

4. Discussion

4.1. Comparative Analysis

As revealed by the preceding analysis, the impact of air changes per hour on comfort levels varies across different climate zones. In summer, the proportions of muggy sensations are the most pronounced in the hot summer and warm winter area. Although increasing the air change rate can slightly alleviate this issue, the proportion of hot

discomfort remains higher than in the other climate zones. In hot summer and cold winter areas, the proportion of muggy is moderate. Increasing air change rates reduces the perceived proportion of hot discomfort, indicating that air change can effectively lower temperatures in this climate zone. In temperate areas, the proportion of hot discomfort during summer is relatively low due to the inherently cooler climate and moderate humidity. As air change rates increase, the incidence of hot discomfort decreases significantly, indicating that air change can markedly improve hot comfort levels. In winter, the hot summer and warm winter area experiences relatively warm temperatures during the colder months, making discomfort from the cold virtually nonexistent. In hot summer and cold winter areas, cold discomfort is significantly more prevalent, particularly at high air change rates. This may be because increased air change rate causes greater heat loss indoors, making winter cold discomfort more pronounced. The temperate area also experiences some cold discomfort, although at a relatively low level, with almost no occurrences of cold sensations. Increasing the air change rate still leads to a rise in cold discomfort in this area.

The impact of temperature fluctuations also varies across different climate zones. In hot summers and warm winters area, the peak temperature fluctuations gradually decrease as the air change rate increases. However, when the air change rate reaches 1.0, the peak temperature fluctuations cease to decrease further. In hot summer and cold winter areas, as the air change rate increases, the peak temperature fluctuations gradually grow larger. However, when the air change rate reaches 1.0, the peak temperature fluctuations cease to increase further. In temperate areas, as the air change rate increases, the peak temperature fluctuations initially rise significantly. When the air change rate reaches 1.0, the peak temperature fluctuations begin to decrease slightly. The highest temperature fluctuation peak occurs at 1.0 air changes per hour in temperate areas, while the lowest temperature fluctuation peak occurs at 0.5 air changes per hour in hot summer and cold winter areas.

In summary, the hot summer and warm winter area experiences moderate temperature fluctuations. During summer, the humidity-induced heat load is extremely high, and ventilation struggles to significantly alleviate the muggy heat. This makes such climates the most severe in terms of hot discomfort. Even with increased air change rates, hot discomfort remains the predominant concern, while cold discomfort is virtually nonexistent in winter. Therefore, there is no need to worry about temperature drops caused by ventilation during the colder months. In hot summer and warm winter areas, to further enhance comfort levels, more effective cooling and dehumidification measures, such as mechanical ventilation, should be considered. In hot summer and cold winter areas, temperature fluctuations exhibit a more stable overall trend compared to the other two climate zones, yet they display pronounced seasonal characteristics. The combination of humid, oppressive summers and bitterly cold winters results in more pronounced discomfort at both extremes than in temperate zones. The role of air change rates shows opposite trends during winter and summer, making this climate zone the most reliant on ventilation strategies to balance seasonal demands. The temperate climate zone exhibits the least temperature fluctuation compared to the other two climate zones, yet its climate remains relatively stable throughout the year. Buildings in this zone maintain comfort more easily year-round, making it the climate zone with the highest overall thermal comfort level.

4.2. Building Load Analysis

Analysis of Figure 12 and Table 5 shows that in the hot summer and warm winter area, the outdoor temperature remains relatively high throughout the year; therefore, the annual air-conditioning load is dominated by cooling load, with cooling loads far exceeding heating loads. Heating loads appear primarily around the 800th hour of the year,

corresponding to late January. Under all three air change rate conditions, the annual variation trends of the HVAC load are similar. Around the 1800th hour (mid-March), the cooling load increases sharply and remains at a high level until approximately the 4500th hour (mid-June). It then drops rapidly and rises again around the 6000th hour (August), before declining after the 7500th hour (mid-October). As the air change rate increases, the cooling load also increases. When the air change rate is 0.5 h^{-1} , the peak cooling load is approximately 450 kW, total cooling load is $-398,402.48 \text{ kW}$; when the air change rate increases to 1.0 h^{-1} , the peak cooling load rises to about 475 kW, and the total cooling load is $-406,903.87 \text{ kW}$; and at 1.5 h^{-1} , the peak cooling load further increases to roughly 500 kW, and the total cooling load is $-415,812.87 \text{ kW}$. As the air change rate increases, not only does the building's cooling load rise, but the heating load also increases; however, its total value is almost negligible compared to the cooling load.

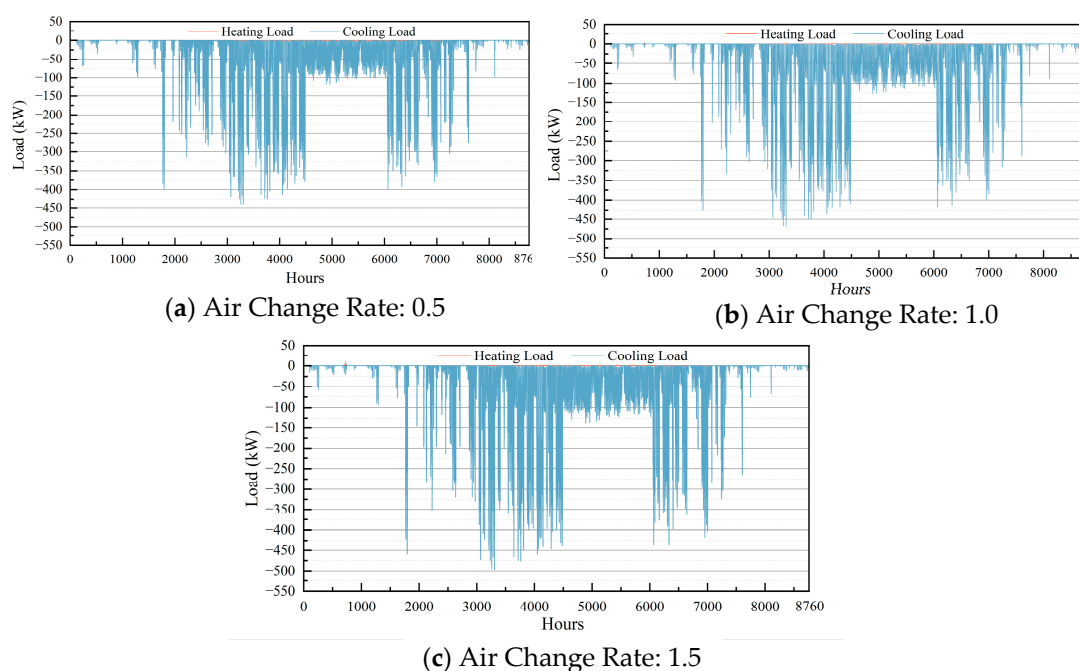


Figure 12. Hourly cooling and heating loads for each room at different air change rates in a hot summer and warm winter area.

Table 5. Total cooling and heating loads for each room at different air change rates in a hot summer and warm winter area.

Air Change Rates	Total Heating Load	Total Cooling Load
0.5	1.74 kW	$-398,402.48 \text{ kW}$
1.0	10.12 kW	$-406,903.87 \text{ kW}$
1.5	32.60 kW	$-415,812.87 \text{ kW}$

Analysis of Figure 13 and Table 6 reveals that in hot summer and cold winter areas, both cooling and heating loads coexist. However, the cooling load exhibits a larger peak and longer duration, resulting in a dual peak demand pattern dominated by cooling, yet requiring significant heating during winter. The trend of heating and cooling loads remains consistent across different air change rates. Cooling loads are concentrated between approximately the 3500th and 6500th hours (May to September), while other months exhibit smaller cooling loads. The heat load primarily occurs from the 7000th hour to the 2500th hour of the following year, spanning October to April. At an air change rate of 0.5, the peak heating load is approximately 250 kW, the total heating load is $94,351.42 \text{ kW}$,

while the peak cooling load is around 450 kW, and the total cooling load is −152,823.85 kW. At an air change rate of 1.0, the peak heating load is near 300 kW, the total heating load is 122,302.68 kW, and the peak cooling load is close to 500 kW; the total cooling load is −162,025.80 kW. At an air change rate of 1.5, the peak heating load is around 350 kW, the total heating load is 149,411.56 kW, and the peak cooling load is around 550 kW; the total cooling load is −172,969.54 kW. As the air change rate increases, both heating and cooling loads show a significant rise. This is likely because increased ventilation introduces more outdoor air, both warmer and cooler, into the space, thereby amplifying both heating and cooling demands.

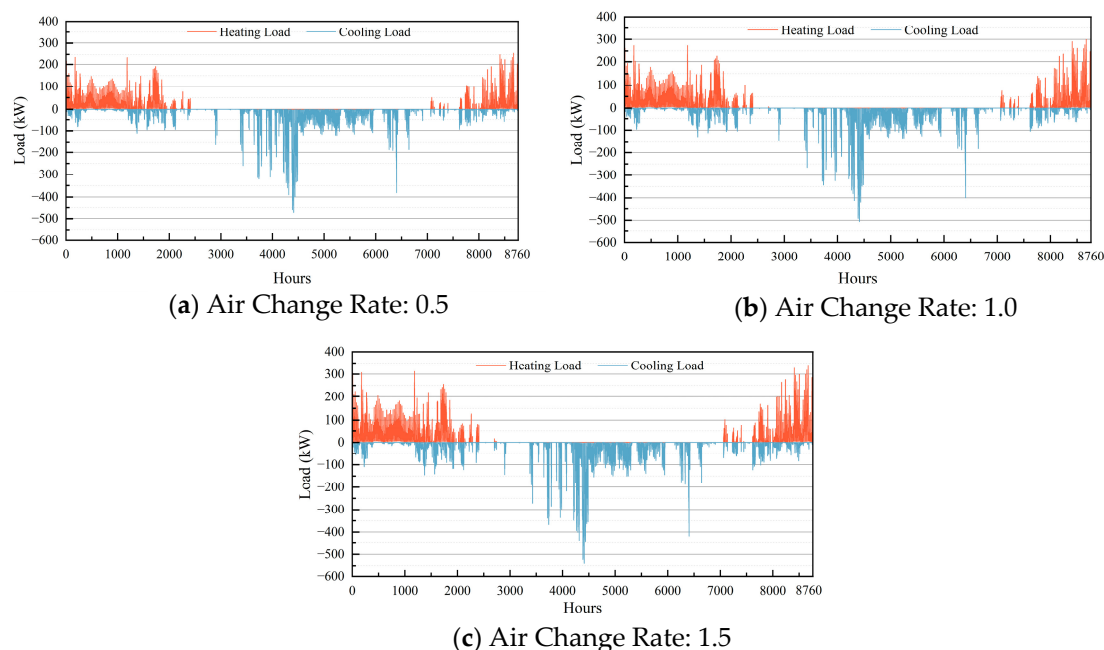


Figure 13. Hourly cooling and heating loads for each room at different air change rates in a hot summer and cold winter area.

Table 6. Total cooling and heating loads for each room at different air change rates in a hot summer and cold winter area.

Air Change Rates	Total Heating Load	Total Cooling Load
0.5	94,351.42 kW	−152,823.85 kW
1.0	122,302.68 kW	−162,025.80 kW
1.5	149,411.56 kW	−172,969.54 kW

Analysis of Figure 14 and Table 7 reveals that in temperate areas, heating loads dominate while cooling loads are minimal but persist over extended periods. The trends in heating and cooling loads are similar across different air change rates. Heating loads primarily occur between the 7500th hour and the 1500th hour of the following year (October to February), while cooling loads are present throughout the year. At an air change rate of 0.5, the peak heating load is approximately 225 kW, the total heating load is 28,031.15 kW, and the peak cooling load is around 75 kW; the total cooling load is −11,487.52 kW. At an air change rate of 1.0, the peak heating load is around 275 kW, the total heating load is 41,500.03 kW, and the peak cooling load is also around 75 kW, though slightly higher than at an air change rate of 0.5; the total cooling load is −13,403.40 kW. At an air change rate of 1.5, the peak heating load occurs around 300 kW, the total heating load is 54,209.04 kW, and the peak cooling load occurs around 100 kW, the total cooling load is −15,897.21

kW. As the air change rate increases, both heating and cooling loads show an upward trend.

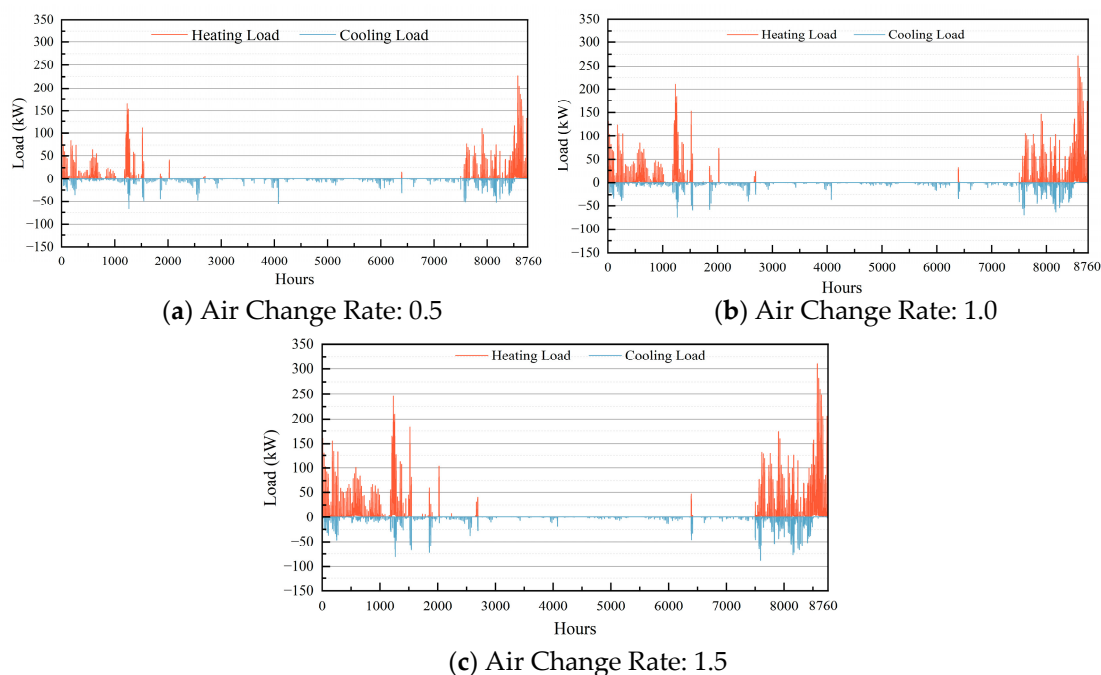


Figure 14. Hourly cooling and heating loads for each room at different air change rates in a temperate area.

Table 7. Total cooling and heating loads for each room at different air change rates in a temperate area.

Air Change Rates	Total Heating Load	Total Cooling Load
0.5	28,031.15 kW	−11,487.52 kW
1.0	41,500.03 kW	−13,403.40 kW
1.5	54,209.04 kW	−15,897.21 kW

In summary, regarding annual cooling loads, the hot summer and warm winter area exhibits the highest cooling demand, followed by the hot summer and cold winter area, and then the temperate area. Cooling loads dominate the annual energy consumption in the hot summer and warm winter area. Although the peak cooling load in the hot summer and cold winter area is comparable to that in the hot summer and warm winter area, its duration is shorter; however, the hot summer and cold winter area requires substantial heating during winter, resulting in a relatively high overall mixed cooling and heating load. With respect to annual heating loads, the hot summer and cold winter area shows the highest values, followed by the temperate area, while the hot summer and warm winter area has minimal heating demand. In terms of the impact of air change rates on energy consumption, all three climate zones, hot summer and warm winter, hot summer and cold winter, and temperate areas, show an overall trend in which higher air change rates lead to increased total energy use. However, the specific effects differ across climates: in the hot summer and warm winter area, increased air change rate primarily raises cooling loads; in the hot summer and cold winter area, both cooling and heating loads increase; and in the temperate area, air change rate mainly affects heating loads. These variations are largely attributable to the inherent climatic differences among the three regions.

5. Conclusions

This study primarily investigates the impact of air change rates on indoor thermal comfort and energy consumption in kindergartens under different climate areas. To more accurately assess indoor thermal comfort in kindergartens, the THI index was modified to establish child-oriented THI evaluation criteria under different climatic conditions, and optimal ventilation strategies for kindergarten activity units were identified accordingly. In hot summer and warm winter areas, an air change rate of 1.5 achieves the highest thermal comfort percentage and the smallest peak temperature fluctuations. In hot summer and cold winter areas, an air change rate of 0.5 yields the highest thermal comfort percentage and the smallest peak temperature fluctuations. In temperate regions, both air change rates of 1.0 and 1.5 can be selected when prioritizing thermal comfort percentage. When considering building energy consumption, the hot summer and warm winter area achieves the lowest energy use at an air change rate of 0.5. However, in kindergarten buildings, safeguarding children's health takes precedence over energy conservation. Therefore, in such regions, an air change rate of 1.5 is more appropriate. In the hot summer and cold winter area, the building energy consumption is lowest at an air change rate of 0.5, consistent with considerations for thermal comfort. Therefore, selecting an air change rate of 0.5 is optimal for such climates. In temperate areas, the building energy consumption is lowest, and temperature fluctuation peaks are smallest at an air change rate of 0.5. However, thermal comfort is superior at air change rates of 1.0 and 1.5. This is because thermal comfort accounts for a higher proportion overall in temperate areas, and the 0.5 rate exhibits significantly smaller temperature fluctuations, which is more conducive to children's health. Therefore, an air change rate of 0.5 is optimal for temperate areas. These findings are expected to provide valuable references for the ventilation design of future kindergarten buildings.

However, this study still has several limitations. The simulation did not account for the activities of children and teachers within the kindergartens, resulting in discrepancies from real-world conditions. For instance, teachers' window-opening habits can significantly impact actual ventilation performance. Consequently, the air change rate setting in this study is somewhat idealized. The THI index does not account for other factors affecting thermal comfort, such as air velocity and mean radiant temperature, and therefore cannot fully represent indoor thermal comfort conditions. The thermal comfort model employed in this study could further improve its accuracy in terms of age specificity and climate adaptability. Additionally, this paper only considers the impact of thermal comfort on children's health, but factors such as CO₂ concentration and PM_{2.5} also affect children's health. Furthermore, this study selected only one representative city per climate zone, failing to capture broader variations within the same climate zone. Therefore, to address the limitations of this research, the following prospects are proposed:

(1) Future field research at kindergartens, such as questionnaire surveys, can be conducted to understand factors affecting indoor thermal comfort, including children's daily routines and teachers' window-opening habits, ensuring that research findings better serve the health protection of young children.

(2) Future research may incorporate CO₂ concentration, PM_{2.5}, and other factors influencing thermal comfort to establish a comprehensive evaluation framework encompassing thermal comfort, CO₂ levels, pollutants, and energy consumption. Further exploration should address the age-specificity and climate adaptability of the evaluation model. Employing multi-objective optimization methods to explore trade-offs among different indicators aims to achieve a more scientifically grounded ventilation strategy design for kindergartens.

(3) Future studies may incorporate additional urban samples across various climate zones and include microclimate parameters such as the urban heat island effect, building

density, surrounding greenery, and wind conditions to explore the adaptability and transferability of optimal ventilation strategies under different urban conditions.

Author Contributions: Conceptualization, C.Y. and Y.Z.; methodology, C.Y. and Y.Z.; software, M.Z.; validation, F.G. and Y.L.; formal analysis, C.Y.; investigation, M.Z. and Y.L.; resources, F.G.; data curation, J.W.; writing—original draft preparation, C.Y.; writing—review and editing, M.Z., F.G., J.L., and J.W.; visualization, Y.L.; supervision, J.L. and J.W.; project administration, Y.Z.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Central Universities Graduate Innovation Fund of China (No. ZYN2025230), Key Research Base Program of Sichuan Social Sciences Association of China (No. 25SCZSXW02), Sichuan Science and Technology Program (No. 2024NSFSC0877), and College Students' Innovative Entrepreneurial Training Plan Program, Sichuan University of Science & Engineering (No. cx2025162).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Fei Gao was employed by the Sichuan Provincial Architectural Design and Research Institute. The remaining 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..

References

1. Mukherji, A. *Climate Change 2023 Synthesis Report*; IPCC: Geneva, Switzerland, 2023.
2. Ubalde, J.; Bradshaw, C.J.; Le Souëf, P.N.; Judge, M.A. Climate change policies fail to protect child health. *Glob. Health* **2025**, *21*, 47.
3. Almeida, R.M.; Ramos, N.M.; De Freitas, V.P. Thermal comfort models and pupils' perception in free-running school buildings of a mild climate country. *Energy Build.* **2016**, *111*, 64–75.
4. Mendell, M.J.; Heath, G.A. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air* **2005**, *15*, 27–52.
5. Wargocki, P.; Wyon, D.P. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). *HvacR Res.* **2007**, *13*, 193–220.
6. Almeida, R.M.; De Freitas, V.P. Indoor environmental quality of classrooms in Southern European climate. *Energy Build.* **2014**, *81*, 127–140.
7. Heebøll, A.; Wargocki, P.; Toftum, J. Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624. *Sci. Technol. Built Environ.* **2018**, *24*, 626–637.
8. Zomorodian, Z.S.; Tahsildoost, M.; Hafezi, M. Thermal comfort in educational buildings: A review article. *Renew. Sustain. Energy Rev.* **2016**, *59*, 895–906.
9. Trebilcock, M.; Soto-Muñoz, J.; Yañez, M.; Martin, R.F.-S. The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. *Build. Environ.* **2017**, *114*, 455–469.
10. Kim, J.; de Dear, R. Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students. *Build. Environ.* **2018**, *127*, 13–22.
11. Juan, Y.-K.; Gao, P.; Wang, J. A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy Build.* **2010**, *42*, 290–297.
12. Shahnazari, H.; Mhaskar, P.; House, J.M.; Salisbury, T.I. Heating, ventilation and air conditioning systems: Fault detection and isolation and safe parking. *Comput. Chem. Eng.* **2018**, *108*, 139–151.
13. Deng, J.-Y.; Xia, Y.; Lao, H.; Ye, Y.; Wang, Z.; Jiang, H. Natural ventilation potential of teaching building complexes with different block shapes and layout patterns. *J. Build. Eng.* **2024**, *96*, 110420.

14. Zhang, H.; Yang, D.; Tam, V.W.; Tao, Y.; Zhang, G.; Setunge, S.; Shi, L. A critical review of combined natural ventilation techniques in sustainable buildings. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110795.
15. Zhong, H.-Y.; Sun, Y.; Shang, J.; Qian, F.-P.; Zhao, F.-Y.; Kikumoto, H.; Jimenez-Bescos, C.; Liu, X. Single-sided natural ventilation in buildings: A critical literature review. *Build. Environ.* **2022**, *212*, 108797.
16. Liu, S.; Song, R.; Zhang, T.T. Residential building ventilation in situations with outdoor PM_{2.5} pollution. *Build. Environ.* **2021**, *202*, 108040.
17. Jones, B.; Das, P.; Chalabi, Z.; Davies, M.; Hamilton, I.; Lowe, R.; Mavrogianni, A.; Robinson, D.; Taylor, J. Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies. *Build. Environ.* **2015**, *92*, 644–656.
18. Wang, S.; Qian, H.; Sun, Z.; Cao, G.; Ding, P.; Zheng, X. Comparison of airborne bacteria and fungi in different built environments in selected cities in five climate zones of China. *Sci. Total Environ.* **2023**, *860*, 160445.
19. Park, S.; Choi, P.; Song, D.; Koo, J. Impact of door-opening events on air exchange rates in naturally ventilated spaces. *J. Build. Eng.* **2025**, *109*, 113028.
20. Peng, Y.; Wang, D.; Kong, L.; Wang, Y.; Liu, Z.; Shi, S. Air infiltration rate distributions of urban residences in China. *Build. Environ.* **2025**, *278*, 112976.
21. Deshko, V.; Bilous, I.; Sukhodub, I.; Yatsenko, O. Evaluation of energy use for heating in residential building under the influence of air exchange modes. *J. Build. Eng.* **2021**, *42*, 103020.
22. Liu, X.; Wang, H.; Li, Z.; Zhao, J.; Li, C.; Xie, D. Effectiveness of natural ventilation through single-sided window opening in air-conditioning rooms. *Energy Build.* **2024**, *314*, 114260.
23. Alhindawi, I.; McGrath, J.A.; Sood, D.; O'Donnell, J.; Byrne, M.A. A seasonal assessment of indoor air quality and thermal performance in naturally ventilated airtight energy-efficient dwellings. *Build. Environ.* **2025**, *276*, 112862.
24. Chiesa, G.; Cesari, S.; Garcia, M.; Issa, M.; Li, S. Multisensor IoT platform for optimising IAQ levels in buildings through a smart ventilation system. *Sustainability* **2019**, *11*, 5777.
25. Cai, C.; Sun, Z.; Weschler, L.B.; Li, T.; Xu, W.; Zhang, Y. Indoor air quality in schools in Beijing: Field tests, problems and recommendations. *Build. Environ.* **2021**, *205*, 108179.
26. Rizzo, K.; Camilleri, M.; Gatt, D.; Yousif, C. Optimising mechanical ventilation for indoor air quality and thermal comfort in a mediterranean school building. *Sustainability* **2024**, *16*, 766.
27. Lee, D.; Kim, Y.; Hong, K.-J.; Lee, G.; Kim, H.-J.; Shin, D.; Han, B. Strategies for Effective Management of Indoor Air Quality in a Kindergarten: CO₂ and Fine Particulate Matter Concentrations. *Toxics* **2023**, *11*, 931.
28. Munckton, B.; Rajagopalan, P. Interaction between Thermal Conditions and Ventilation in Kindergartens in Melbourne, Australia. *Sustainability* **2024**, *16*, 1186.
29. Yun, H.; Nam, I.; Kim, J.; Yang, J.; Lee, K.; Sohn, J. A field study of thermal comfort for kindergarten children in Korea: An assessment of existing models and preferences of children. *Build. Environ.* **2014**, *75*, 182–189.
30. Nam, I.; Yang, J.; Lee, D.; Park, E.; Sohn, J.-R. A study on the thermal comfort and clothing insulation characteristics of preschool children in Korea. *Build. Environ.* **2015**, *92*, 724–733.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.