

Article

A Model Integrating Theory and Simulation to Establish the Link Between Outdoor Microclimate and Building Heating Load in High-Altitude Cold Regions

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Abstract

The heating load of residential buildings is closely related to the local microclimate. However, there is a lack of quantitative indicators for assessing the impact of the outdoor microclimate on building heating loads in Lhasa residential buildings. This study established an analytical relationship between surface temperature and building heating load through theoretical derivation. Simulations of the outdoor microclimate and building surface temperatures were conducted using Phoenics2019 and Ladybug1.8.0 tools. Statistical models were developed to correlate outdoor microclimate parameters with the surface temperatures of both transparent and opaque building envelopes. Ultimately, these individual models were integrated to form a comprehensive framework for directly calculating heating loads from microclimate data. The model validation results indicate that the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) is 12.87%, which meets the ASHRAE Guideline 14 international standard requirement of $\leq 30\%$ for hourly data. The Normalized Mean Bias Error (NMBE) is -9.76% , also satisfying the ASHRAE Guideline 14 criterion of $\pm 10\%$ for hourly data. These results suggest that the model exhibits a minor underestimation, which is acceptable from an engineering perspective. The proposed model can provide a quantitative reference to a certain extent for the comprehensive evaluation of outdoor microclimate environmental performance in residential buildings in Lhasa.

Keywords: near-wall microclimate; surface temperature; heating load; residential buildings



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1. Introduction

The ongoing urbanization and improved living standards in Lhasa have led to a growing demand for heating and energy consumption. According to data from the China Statistical Yearbook 2020, both natural gas and electricity consumption in the Tibet region have shown a consistent upward trend over the past decade [1]. As reported in the 2022 Global Status Report for Buildings and Construction, the building sector accounted for approximately 37% of global carbon emissions in 2021, reaching a historical peak [2]. In the context of China's national strategy for energy conservation and emission reduction, there is an urgent need to reduce building energy consumption.

Traditional energy-saving approaches primarily concentrate on building design (including form, window-to-wall ratio, and envelope) and the optimization of equipment

systems. This is reflected in standards such as the “Tibet Autonomous Region Civil Building Energy Efficiency Design Standard (DBJ540001-2016)” [3] and the “Tibet Autonomous Region Green Building Evaluation Standard (DBJ540002-2018)” [4]. However, building energy consumption is not determined solely by the building itself; it is also directly influenced by the surrounding outdoor microclimate. Optimizing the microclimate offers a passive and cost-effective means of reducing heating demand. Therefore, establishing the relationship between the microclimate and building heating load constitutes the central research question of this study.

Microclimate has been demonstrated to significantly influence building energy consumption [5–9]. Wong et al. [10] developed the STEVE tool prediction model, which demonstrated that temperature variations could reduce building energy consumption by 5%. In Rome, an increase in outdoor air temperature by 3.2 °C resulted in an 11% decrease in heating load and a 30% increase in cooling load [11]. Variations in air temperature and humidity affect building energy demand through pathways such as heat transfer via the building envelope and infiltration [12]. In the Amman region, infiltration-related heat loss accounts for approximately 10% of total heat loss [13]. In Mediterranean climates, the annual impact of air infiltration on heating and cooling energy consumption ranged from 2.43 to 16.44 kWh/m² and from 0.54 to 3.06 kWh/m², respectively [14]. Using a coupled CFD-thermal radiation simulation tool in France, Julien Bouyer et al. [15] identified solar radiation as the most influential parameter on building energy consumption. For cities in different climate zones, the variation in building energy consumption due to solar shading fluctuated between 10% and 20% [16].

However, most of these studies focus on the impact of individual microclimate factors on building energy consumption and lack a theoretically clear model capable of quantitatively predicting loads based on multiple microclimate parameters. Lhasa, as a high-altitude cold-region city, currently lacks an analytical model that adequately accounts for local climatic conditions and elucidates the intrinsic relationship between microclimate and heating load.

To address this research gap, the present study proposes a composite model. “Outdoor wall surface temperature” is identified as a critical intermediate variable linking the outdoor microclimate to building heating load. Microclimate parameters—such as solar radiation, air temperature, and wind speed—first influence the temperature of the building’s external surfaces. This surface temperature then affects indoor conditions through heat transfer across the building envelope, ultimately influencing the heating load. By establishing quantitative relationships from “outdoor microclimate” to “wall surface temperature” and then to “heating load,” a complete theoretical model can be constructed to demonstrate how outdoor microclimate parameters influence building heating load.

To establish the relationship between the outdoor microclimate and wall surface temperature, computational fluid dynamics (CFD) simulation can be employed to generate outdoor microclimate data. Common CFD tools include Phoenix 2019, ENVI-metV4.4.5, OpenFOAM 12, and Fluent 2024. ENVI-met is widely used in landscape design; however, it imposes limitations on mesh resolution [17,18]. OpenFOAM and Fluent do not include built-in models and require high user proficiency [19,20]. In contrast, Phoenix2019 offers grid system, a more user-friendly interface, and supports import/export compatibility with SketchUp, 3D Max, and AutoCAD2025 [20]. Moreover, Phoenix2019 has been extensively applied in studies of building-scale microclimates [21–23], and its feasibility and accuracy in simulating outdoor thermal environments have been validated through comparisons between simulated and measured data [24,25]. Given these advantages, Phoenix 2019 was selected as the CFD (Computational Fluid Dynamics) software for modeling microclimatic conditions in residential areas in this study. However, Phoenix2019 cannot simulate solar

radiation. Ladybug1.8.0, as a software capable of solar radiation simulation, can directly interface with the Chinese Standard Meteorological Database [26,27], offering ease of use and intuitive visualization of results [28]. Moreover, the precision and reliability of Ladybug's simulation results have been well documented in previous studies [29,30]. Consequently, Ladybug1.8.0 was selected as the primary simulation software for this research.

Typical Meteorological Year (TMY) data serve as essential inputs for building energy performance simulations [31]. The TMY method was originally developed by Sandia National Laboratories in the United States [32]. It constructs a "typical" year by selecting twelve representative Typical Meteorological Months (TMMs) from long-term historical weather observations, reflecting the statistical characteristics of the local climate. The "typicality" of a TMY is inherently and strongly geographically dependent, as solar radiation, temperature, and humidity patterns differ across global climate zones. Research on TMY data development has been conducted in various countries, including Athens [33], Nicosia [34], China [35], and Argentina [36]. This study focuses on China. As a vast country with a land area of approximately 9.6 million square kilometers, China spans from subtropical regions in the south to temperate zones (including warm and cool temperate) in the north [37], resulting in significant regional variations in meteorological characteristics. In recent years, specific research on TMY selection for different regions of China has also emerged [31,38,39]. To ensure that the simulated meteorological boundary conditions reliably reflect the region's climatic patterns, this study utilizes Typical Meteorological Year (TMY) data obtained from the Lhasa Meteorological Station.

To establish the relationship between wall surface temperature and building heating load, this study introduces several assumptions to simplify the building heat transfer analysis, thereby facilitating the development of a clear theoretical model (see Section 2.1 for details). A key assumption is that material heat storage is negligible during the heat transfer process. This simplification is justified for two reasons. First, the simulation and validation are conducted using an aEPS (expanded polystyrene) insulated wall—a material characterized by low thermal mass and widely adopted in Lhasa's building practices [40]. Second, neglecting thermal mass allows for a more explicit and analytically tractable theoretical formulation. Similar studies have employed analogous assumptions; for example, in research on the influence of Chinese Kang on indoor thermal environments, all components are treated as homogeneous materials with constant physical properties that do not vary with temperature fluctuations [41].

Based on the above ideas, this paper will be carried out in accordance with the following four research objectives:

1. To establish a mathematical theoretical model linking the exterior surface temperature of building envelopes to the building heating load.
2. To simulate the near-facade microclimate and surface temperatures under different scenarios using Phoenix2019 and Ladybug1.8.0 software.
3. To develop a regression model correlating the outdoor microclimate with the exterior surface temperature of buildings.
4. To formulate and validate a composite model that connects the microclimate to the heating load via the intermediate variable of exterior surface temperature.

2. Theoretical Foundation: A Theoretical Model Linking Exterior Surface Temperature and Heating Load

2.1. Heat Transfer Processes and Assumptions

In high-altitude cold regions, the operation of indoor heating systems maintains a higher indoor air temperature compared to the outdoor ambient temperature. The heat gain and loss processes through the building envelope, driven by the interplay of indoor

and outdoor microclimates, can be classified into two primary components. First, heat is lost through the envelope due to the temperature differential between the interior and exterior surfaces ($t_i > t_j$). This encompasses conductive heat transfer, which refers to heat flow to the outdoors due to the temperature differential, as well as the heat accumulation in the materials themselves. Second, solar radiation transmitted through transparent envelope components contributes to heating the indoor thermal environment. Under the assumption of negligible internal heat gains, heat transfer through a transparent building envelope results from conductive heat flow driven by the temperature difference and solar radiation transmitted through the glass. Heat transfer through an opaque envelope primarily results from convective heat exchange between the outdoor air and the exterior surface, as well as conductive heat transfer through the wall driven by absorbed solar radiation [42]. Figures 1 and 2 illustrate the heat transfer processes for transparent and opaque building envelopes, respectively.

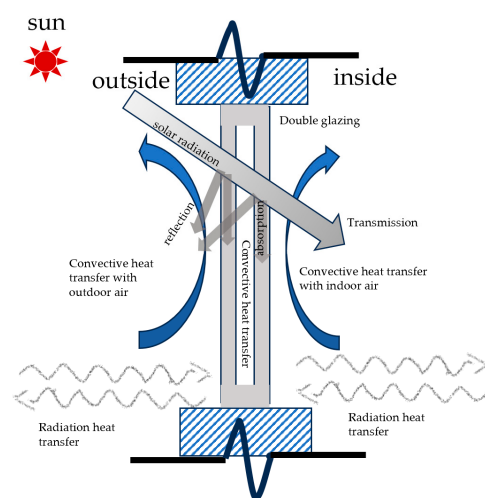


Figure 1. Heat transfer process of transparent building envelope.

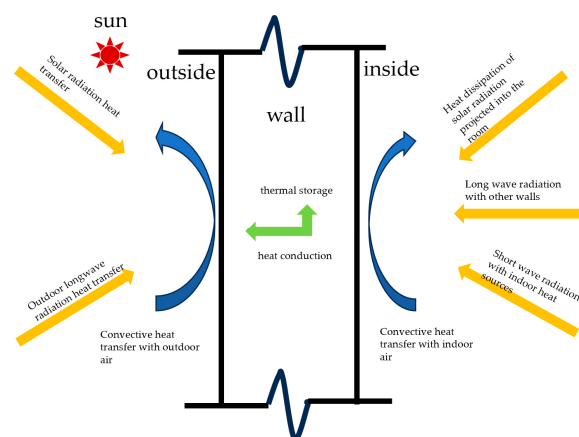


Figure 2. Heat transfer process of opaque building envelope.

Building heat transfer constitutes a highly complex process. This study specifically focuses on the influence of near-facade microclimatic parameters acting upon the building's external surfaces on the heating load. The effects of internal building components on the indoor heating load, as well as air exchange and infiltration between the interior and exterior environments, are not considered. To simplify the modeling process while maintaining calculation accuracy, the following assumptions are adopted, based on theoretical principles from building physics [43], building environmental science [42], and heat transfer [44]:

1. All materials in the model are assumed to be isotropic, with a uniform initial temperature distribution;
2. The impact of thermal bridges on the building envelope's heat transfer is neglected. The heat transfer process is considered one-dimensional through the thickness of the wall. There are no internal heat sources, all materials are non-porous, and contact resistance between material layers is ignored;
3. The heat storage capacity of the materials is assumed to be negligible and thus does not influence the heat transfer process;
4. Radiant heat exchange between the interior surfaces of the building envelope is neglected;
5. Regarding solar radiation entering through windows: direct transmitted solar heat gain is absorbed solely by the indoor floor surface, while the diffuse component is uniformly absorbed by all internal surfaces;
6. Solar radiation transmitted through windows into the interior is entirely absorbed by the indoor surfaces, with no portion being reflected or scattered back to the outdoors;
7. The solar radiation absorbed by the window glazing itself is negligible and its effect on heat transfer is ignored;
8. The building envelope is assumed to be airtight, with no heat transfer due to air infiltration through gaps or pores;
9. The ground slab is modeled as adiabatic. This is based on the assumption that one side extends to infinity, insulating the other side from external thermal influences, resulting in an infinite thermal resistance

2.2. Model Formulation

1. Heat Loss through Opaque and Transparent Envelope Assemblies via Conduction

According to the 2006 ASHRAE Fundamentals Handbook and the third edition of Building Physics [43,45], and assuming negligible heat storage and air infiltration, the heat loss per unit area across a building envelope due to the temperature difference can be expressed as:

$$q = \left(\frac{\lambda}{d}\right)(t_i - t_j)A_1 \quad (1)$$

where:

q = Heat loss per unit area of the building envelope due to the indoor-outdoor temperature difference (W).

d = Thickness of the envelope (m).

λ = Thermal conductivity of the material (W/(m·K)).

t_i = Temperature of the interior surface (°C).

t_j = Temperature of the exterior surface (°C).

A_1 = Per Unit Area (m²).

The study discretizes the continuous building envelope interface into n micro-elements. The total heat loss Q for a building space of volume V , resulting from the indoor-outdoor temperature difference, is given by the following equation:

$$Q = \left(\frac{\lambda_1}{d}\right)(t_i - t_j)_1 A_1 + \left(\frac{\lambda_2}{d}\right)(t_i - t_j)_2 A_1 \dots \dots + \left(\frac{\lambda_n}{d}\right)(t_i - t_j)_n A_1 \quad (2)$$

Assuming a uniform temperature distribution within the building envelope's interior space, the rate of energy consumption per unit building volume can be expressed as:

$$\frac{Q}{V} = \frac{\left(\frac{\lambda_1}{d}\right)(t_i - t_j)_1 A_1 + \left(\frac{\lambda_2}{d}\right)(t_i - t_j)_2 A_1 \dots \dots + \left(\frac{\lambda_n}{d}\right)(t_i - t_j)_n A_1}{\frac{V}{n}} \quad (3)$$

$$\frac{Q}{v} = \frac{1}{n} \frac{(\frac{\lambda_1}{d}(t_i - t_j)_1)A_1 + (\frac{\lambda_2}{d}(t_i - t_j)_2)A_1 \dots \dots + (\frac{\lambda_n}{d}(t_i - t_j)_n)A_1}{\frac{v}{n}} \quad (4)$$

The term v/n represents the building's total heated volume V partitioned into n enclosed subspaces of equal volume, each corresponding to a specific envelope surface micro-element A_1 .

$$\frac{Q}{v} = \frac{1}{n} \frac{(\frac{\lambda_1}{d}(t_i - t_j)_1)nA_1 + (\frac{\lambda_2}{d}(t_i - t_j)_2)nA_1 \dots \dots + (\frac{\lambda_n}{d}(t_i - t_j)_n)nA_1}{v} \quad (5)$$

$$\frac{Q}{V} = \frac{1}{n} \left[\left(\frac{\lambda_1}{d}(t_i - t_j)_1 \right) s + \frac{\lambda_2}{d}(t_i - t_j)_2 s + \dots \dots + \frac{\lambda_n}{d}(t_i - t_j)_n s \right] \quad (6)$$

$$\frac{Q}{V} = \frac{s}{n} \left(\sum_{i=1}^n \frac{\lambda}{d}(t_i - t_j) \right) \quad (7)$$

2. Heat Gain from Solar Radiation Transmitted through Transparent Envelope

To simplify the computational model, this study does not differentiate between direct and diffuse solar radiation entering the interior. All solar radiation transmitted through the transparent envelope is treated as directionless, diffuse radiation. This diffuse radiation is assumed to be entirely absorbed within the interior, with negligible portions being scattered back to the outdoors. Consequently, the solar heat gain per unit area of the transparent envelope can be expressed as:

$$q' = \tau I A' \quad (8)$$

where:

q' = Solar heat gain per unit area through the transparent envelope (W/m^2).

τ = Solar transmittance of the transparent envelope component.

I = Solar irradiance incident on the window surface (W/m^2).

A' = er Unit Area (m^2).

The window surface is discretized into e finite micro-elements. Therefore, the total thermal energy resulting from solar radiation transmitted into the interior through the building's transparent envelope is given by:

$$Q' = \tau_1 I_1 A' + \tau_2 I_2 A' + \dots \dots + \tau_e I_e A' \quad (9)$$

where:

Q' = Total thermal energy resulting from solar radiation transmitted through the transparent building envelope into the interior (W).

τ = Solar transmittance of the transparent envelope component.

I = Solar irradiance incident on the window surface (W/m^2).

A' = Unit window area (m^2).

Assuming the transparent envelope is located on a wall with a gross area A and a Window-to-Wall Ratio (WWR) of H , then:

$$A' = AH \quad (10)$$

$$A' = \frac{A'}{e} = \frac{AH}{e} \quad (11)$$

The transparent envelope surfaces are discretized into e micro-elements. The total solar heat gain is then given by:

$$Q' = \tau_1 I_1 \frac{AH}{e} + \tau_2 I_2 \frac{AH}{e} + \dots \dots + \tau_e I_e \frac{AH}{e} \quad (12)$$

The solar radiation flux per unit volume entering through the windows is:

$$\frac{Q'}{v} = \frac{\tau_1 I_1 \frac{AH}{e} + \tau_2 I_2 \frac{AH}{e} + \dots + \tau_e I_e \frac{AH}{e}}{V} \quad (13)$$

$$\frac{Q'}{v} = \frac{1}{e} \frac{\tau_1 I_1 AH + \tau_2 I_2 AH + \dots + \tau_e I_e AH}{V} \quad (14)$$

$$\frac{Q'}{v} = \frac{1}{e} \int_1^e \frac{\tau IAH}{V} \quad (15)$$

2.3. Coupling Relationship Between Exterior Surface Temperature and Building Heating Load

The building heating design load index refers to the heat supply required per unit floor area per unit time from the boiler room or other heating facilities to maintain the designated indoor temperature under specified outdoor heating design conditions (W/m^2). When air exchange and infiltration are neglected, the building heating energy consumption is considered to be primarily the energy required to maintain a constant indoor air temperature. The energy consumption per unit volume imposed on the indoor environment by the building envelope due to the outdoor microclimate is given by:

$$Q_{(V)} = \frac{Q}{V} - \frac{Q'}{V} = \frac{s}{n} \left(\sum_{i=1}^n \frac{\lambda}{d} (t_i - t_j) \right) - \frac{1}{e} \int_1^e \frac{\tau IAH}{V} \quad (16)$$

$$Q_{(V)} = \frac{s}{n} \left(\sum_{i=1}^n \frac{\lambda}{d} (t_i - t_j) \right) - \frac{1}{e} \int_1^e \frac{\tau IAH}{V} \quad (17)$$

3. Methods

3.1. Study Area

Lhasa (Figure 3), the capital of China's Tibet Autonomous Region, is located at approximately $91^\circ 06'$ E longitude and $29^\circ 41'$ N latitude. At an elevation of about 3658 m, it ranks among the highest cities in the world. As defined by the Code for Thermal Design of Civil Buildings (GB 50176) [46], Lhasa falls within the severe cold climate zone. Compared to Beijing and Xi'an, which are also in the cold climate regions (Figure 4), the annual air temperature and humidity of Lhasa are relatively low, and the annual humidity difference is relatively small. Beijing and Xi'an sometimes experience hot and wet conditions, while Lhasa almost never experiences these conditions.

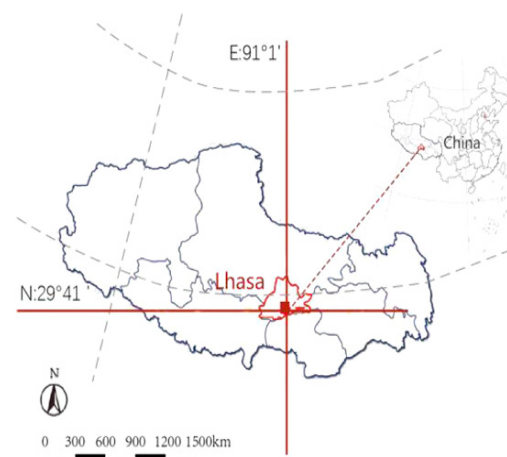


Figure 3. Location of Lhasa.

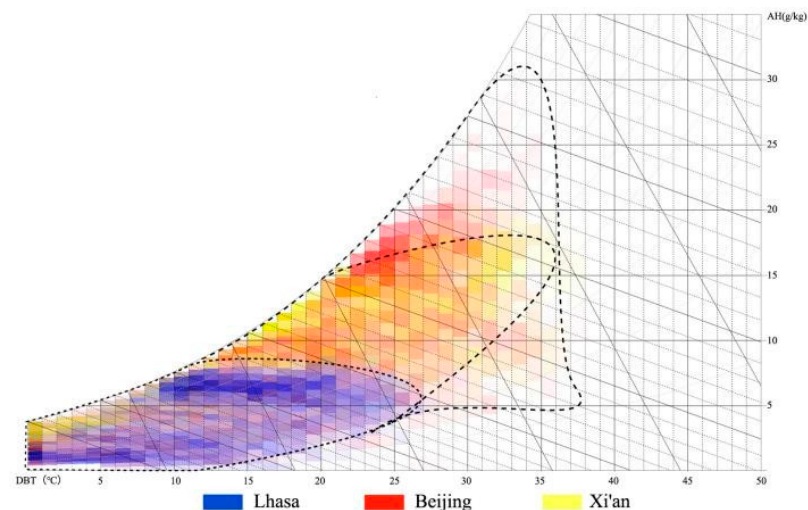


Figure 4. Contrast of psychrometric charts of Lhasa, Xi'an and Beijing.

3.2. Microclimate Simulation

3.2.1. Simulation Tools

Firstly, the exterior microclimate of the building and the exterior surface temperatures were simulated using Phoenix2019 and Ladybug1.8.0; Subsequently, data for microclimate parameters and surface temperatures at various points were extracted using the probe tool in Tecplot 2021. Tecplot [47] is a visualization tool used to efficiently and intuitively display large volumes of scientific data.

3.2.2. Simulation Objects and Scenarios

For geometric modeling, low-rise buildings were derived from the existing single-family courtyard layout of the Duilongdeqing District Resettlement Project, while mid-rise, high-rise, and super high-rise buildings were referenced from the residential layout of the completed Hufeng Urban Plaza (Figures 5 and 6). Most buildings in the Lhasa region adopt a north–south orientation, typically facing due south or with a deviation of 10–30° to the west [48]. A statistical survey by Zhou Tiecheng et al. [40] of exterior windows in 81 existing residential buildings in Lhasa revealed that window openings are predominantly concentrated on the north and south façades, with minimal fenestration on the east and west orientations. Field investigations further indicated that large windows are generally installed on the southern façade, while the window area on the northern side is comparatively smaller (Figures 7 and 8). Consequently, for the modeling in this study, all buildings are oriented due south, with window openings exclusively positioned on the north and south façades.

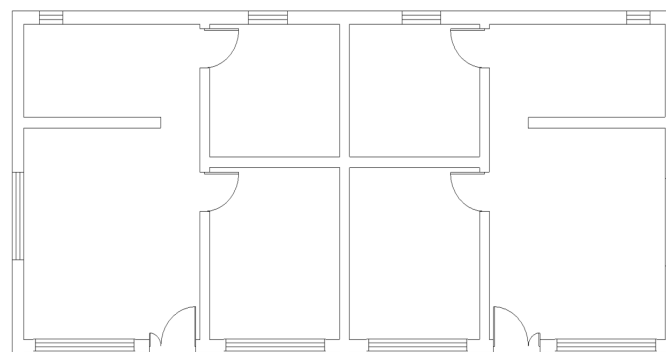


Figure 5. Duilong Deqing District relocation and resettlement project.

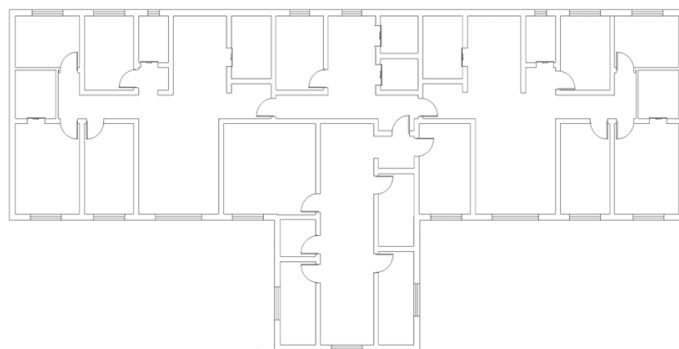


Figure 6. Hufeng city square project.



Figure 7. South orientation.

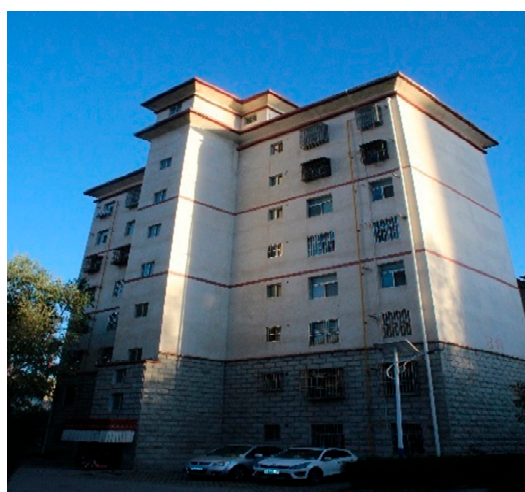


Figure 8. North orientation.

Based on field surveys and the Tibet Autonomous Region Civil Building Energy Efficiency Design Standard (DBJ540001-2016) [3], outdoor microclimate and exterior wall surface temperature simulations were conducted for building models with varying shape coefficients and window-to-wall ratios. Regarding the shape coefficient, one control group and one variable group were established for different building heights, with specific parameters provided in Table 1. For the window-to-wall ratio, one control group and one variable group were configured, featuring larger window areas on the south facade compared to the north facade, and no windows on the east and west facades, as detailed in

Table 1. To maintain controlled variables and facilitate effective comparison, the window-to-wall ratio of the control group was applied to both the control and variable groups of the shape coefficient analysis. Similarly, the shape coefficient of the control group was used in both the control and variable groups of the window-to-wall ratio analysis.

The exterior wall materials of existing residential buildings in Lhasa primarily include concrete hollow blocks, concrete solid blocks, and aerated concrete blocks, with thicknesses typically ranging from 0.2 to 0.3 m [49]. Prior to 2005, buildings in Lhasa were generally constructed without any thermal insulation measures. Even after 2005, only about 3% of residential buildings in Lhasa have incorporated thermal insulation [40]. The primary exterior wall insulation methods employed are self-insulation using aerated concrete blocks, external thermal insulation systems with XPS/EPS polystyrene boards with thin-layer rendering, and external thermal insulation with inorganic insulation mortar.

Table 1. Shape coefficient and window-to-wall ratio variable condition.

Building Storey	Variable Information	Control Group	Variable Group	Window-to-Wall Ratio			
				Control group		Variable group	
				South	North	South	North
2	Floor height	3 m	3.5 m				
	Shape coefficient	0.52	0.5				
5	Floor height	3 m	2.8 m				
	Shape coefficient	0.3	0.33				
8	Floor height	3 m	3.3 m	0.3	0.15	0.35	0.15
	Shape coefficient	0.3	0.28				
11	Floor height	3 m	3.3 m				
	Shape coefficient	0.29	0.28				

In accordance with the limits on the heat transfer coefficient of building exterior walls specified in the Tibet Regional Standard DB54/0016-2007 “Energy Efficiency Design Standard for Residential Buildings” [50], and considering the heat transfer coefficient values of envelope structures with different configurations in Lhasa, the structural layers and heat transfer coefficients of the building envelope in the model developed in this study are established as shown in Table 2. The exterior wall is designed as a thermally insulated wall system using AEP_s insulation material, with a heat transfer coefficient of 0.46 W/(m²·K). The windows are specified as heat-reflective double-glazed units, featuring a heat transfer coefficient of 2.4 W/(m²·K) and a solar heat gain coefficient (SHGC) of 0.42 [46].

Table 2. Parameters of Building Envelopes [3].

Building Envelope Type	Material and Thickness (mm)	Thermal Transmittance (W·m ⁻² ·K ⁻¹)
External wall	20 Cement mortar +300 Concrete hollow block + 60 AEP _s + 20 Cement mortar	0.46
Internal wall	20 Cement mortar + 200 Concrete hollow block + 20 Cement mortar	1.55
Roof	20 Cement mortar + 120 steel concrete+ 80 Expanded perlite + 20 Cement mortar	2.14 [40]
Window	Double-layer hollow casement window 6 + 12 + 6	2.4 [46]
Door	Wooden door	2.8

Data for specific values (2.4, 2.14) are from [40,46], respectively; other data were calculated based on our investigation and references [3,46,50].

3.2.3. Simulation Model Establishment

Based on the aforementioned simulation conditions, building models with varying shape coefficients and window-to-wall ratios were created in SketchUp. The control and variable groups for the shape coefficient are designated as Group 1 and Group 2, while those for the window-to-wall ratio are designated as Group 1 and Group 3, as illustrated in Figure 9.

In the building shape coefficient group, the control group (E1) maintained a fixed story height ($H = 3$ m) and window-to-wall ratio (0.30; 0.15), with shape coefficients set as 0.52 for two-story buildings, 0.3 for five-story buildings, 0.3 for eight-story buildings, and 0.29 for eleven-story buildings. The variable group retained the same window-to-wall ratios as the control group, with parameters set as follows: two-story building ($H = 3.5$ m, $S = 0.5$), five-story building ($H = 2.8$ m, $S = 0.33$), eight-story building ($H = 3.3$ m, $S = 0.28$), and eleven-story building ($H = 3.3$ m, $S = 0.28$). In the window-to-wall ratio group, the control group reused the parameters from the shape coefficient control group (fixed S and H , $WWR = 0.30; 0.15$). The variable group maintained the same S and H values but adjusted the window-to-wall ratio to 0.35; 0.15.

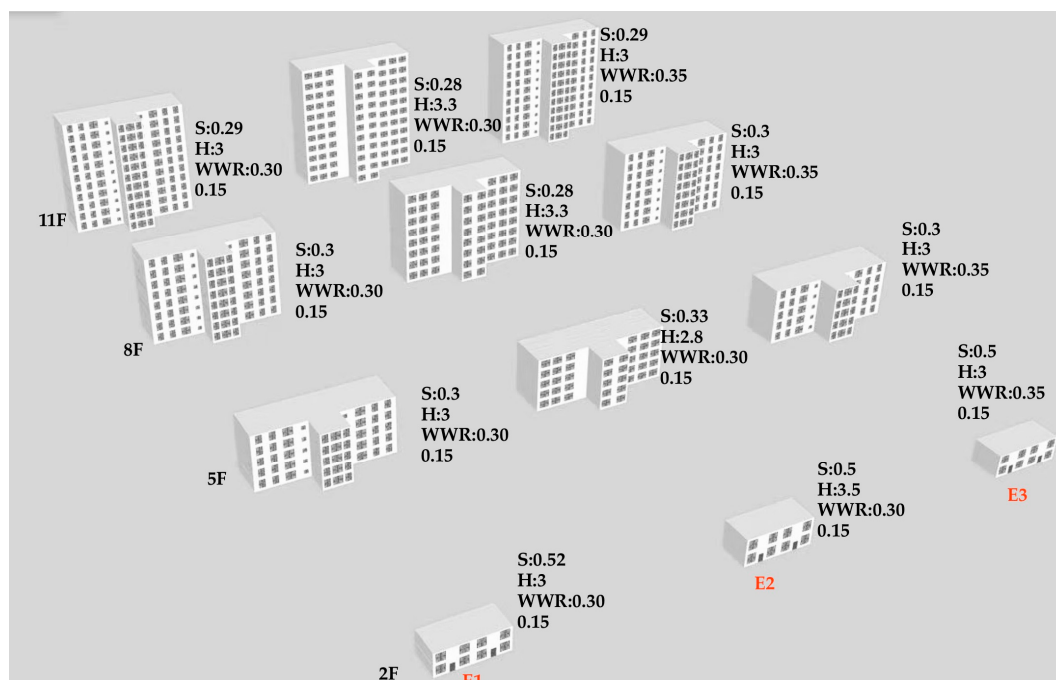


Figure 9. Models under different design parameters. S = Shape coefficient; H = Floor height; WWR = Window-to-wall ratio, and the numbers represent the South-facing WWR and North-facing WWR , respectively.

3.2.4. Simulation Boundary Conditions

Based on the data of the coldest month (January) in the Typical Meteorological Year (TMY) for Lhasa and in accordance with the definition and calculation method of a Typical Meteorological Day (TMD) [51], 21 January was extracted from the coldest month (January) as a representative day that characterizes the most typical winter heating conditions in the region. Utilizing 24-hour meteorological data from the Lhasa Meteorological Station (Station ID: 55591), steady-state simulations were performed based on an hourly time step corresponding to the meteorological conditions of each specific hour. Air temperature, relative humidity, wind speed, and solar radiation parameters were directly obtained from the recorded meteorological data of the simulation day, while wind direction was set as the predominant direction observed during different time periods in Lhasa's typical meteorological-

logical records. Specific simulation boundary conditions were defined with reference to the Tibet Energy Efficiency Design Standard for Residential Buildings [50] and the Research on Structural Systems for Low-Energy Consumption Residential Buildings in the Tibetan Plateau [52] (Table 3).

3.2.5. Simulation Condition Settings

1. Phoenix Computational Domain Selection and Mesh Generation

The computational domain dimensions were set to five times the length and width of the physical model, with a boundary height three times that of the model. The total computational domain was configured with actual dimensions of 150 m × 150 m × 80 m (L × W × H), including an internal region of 33 m × 18 m × 36 m (L × W × H). A non-uniform mesh was adopted, with a grid size of 0.5 m × 0.5 m in the vicinity of the building. To enhance computational efficiency, the grid size was gradually increased to 5 m × 5 m in areas farther from the building, with a mesh gradation rate of 2 along both the X and Y axes. The model contained approximately 1,152,000 grid cells in total.

Table 3. Initial boundary conditions of simulation.

Simulation Parameters	Input Value	Simulation Parameters	Input Value
Solar radiation intensity	Meteorological parameters of Lhasa meteorological station	Atmospheric pressure	64,160 Pa
Solar radiation latitude	29.39' N	Building surface roughness	0.01
Solar time	8:00~18:00	Ground solar radiation absorptivity	0.2
Relative humidity at 10 m	Meteorological parameters of Lhasa meteorological station	Ground solar radiation reflectivity	0.04
Wind velocity at 10 m	Annual average wind speed/dynamic wind speed	Reflectivity of exterior wall	0.6
Wind direction	Meteorological parameters of Lhasa meteorological station	Roof reflectivity	0.3

Optimizing grid size and quantity is essential for achieving an optimal balance between simulation accuracy and computational efficiency [53]. In this study, three grid schemes of varying scales (0.75 million, 1.15 million, and 2.04 million, respectively) were implemented for grid independence verification. Taking E1 as an example, the wind speed distribution at a height of 6 m near the building (0.5 m away) is shown in Figure 10. When the grid count increased from 0.75 million to 1.15 million, the wind speed curve exhibited significant variation, indicating that the simulation results were sensitive to grid density. However, further increasing the grid count to 2.04 million resulted in only minimal changes in wind speed. Therefore, to utilize computational resources rationally, the 1.15-million-cell grid scheme was selected for subsequent simulations.

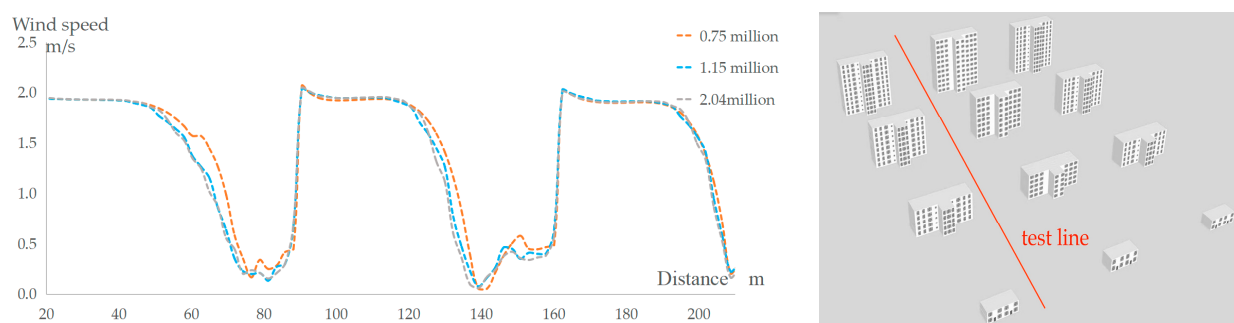


Figure 10. Results of Grid Independence Analysis.

2. Development of Solar Radiation Simulation Module Based on Ladybug

The module was developed primarily using the solar radiation simulation operation battery. Configuration included meteorological parameters, simulation duration, grid size, and simulation data display. Meteorological parameters were imported in EPW format for a typical meteorological day during Lhasa's heating season. Based on the geometric parameters described in Section 3.2.2 and the Phoenix model parameters, a corresponding building model was constructed on the Rhino platform. The grid size was set to 0.5 m × 0.5 m at a distance of 0.5 m from the building surfaces. Hourly simulations were performed to quantify the solar radiation received at different points on the exterior surfaces of various building models, and the data were converted into solar radiation intensity values.

3.3. Data Analysis

Regarding the analytical methodology, this study employed Pearson correlation analysis to examine the relationships between outdoor surface temperatures and various microclimatic factors under different building design conditions. Multivariate statistical analysis was conducted using multiple regression to develop a regression model linking outdoor surface temperature to microclimate factors. The performance of the model was further validated by comparing its calculated heating load values against simulated results using standard statistical metrics, including the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and the Normalized Mean Bias Error (NMBE), implemented via Python 3.14.0. In addition, a Sobol sensitivity analysis was applied to quantitatively assess the influence of microclimate parameters on the heating load model, thereby identifying the key variables driving thermal load variations.

4. Results

4.1. Simulation Results and Correlation Analysis Under Different Building Design Conditions

The following presents the near-wall microclimate contour maps and statistical analysis charts for the building at a height of 6 m, comparing conditions without solar radiation at 02:00 and with solar radiation at 14:00.

4.1.1. Microclimate Simulation Results

1. Outside Near-Wall Wind Speed

For 2- and 5-story buildings with a low window-to-wall ratio (E1), the area of high wind speed near the wall surface (yellow and red areas) is relatively small (Figure 11). In contrast, for 8- and 11-story buildings with a low window-to-wall ratio (E1), the area of high wind speed near the wall surface is larger.

At 14:00, a larger shape coefficient corresponds to a more extensive high-wind-speed zone around the 2-story building, while for the 5- and 8-story buildings, the high-wind-speed zones under a larger shape coefficient are relatively smaller. The opposite pattern is observed at 02:00: a larger shape coefficient is associated with a reduced high-wind-speed zone around the 2-story building, whereas the zones around the 5- and 8-story buildings become larger. For the 11-story building, the shape coefficient has a negligible impact on near-wall wind speed. These findings suggest that the influence of the shape coefficient on near-wall wind speed varies with both time of day and building height.

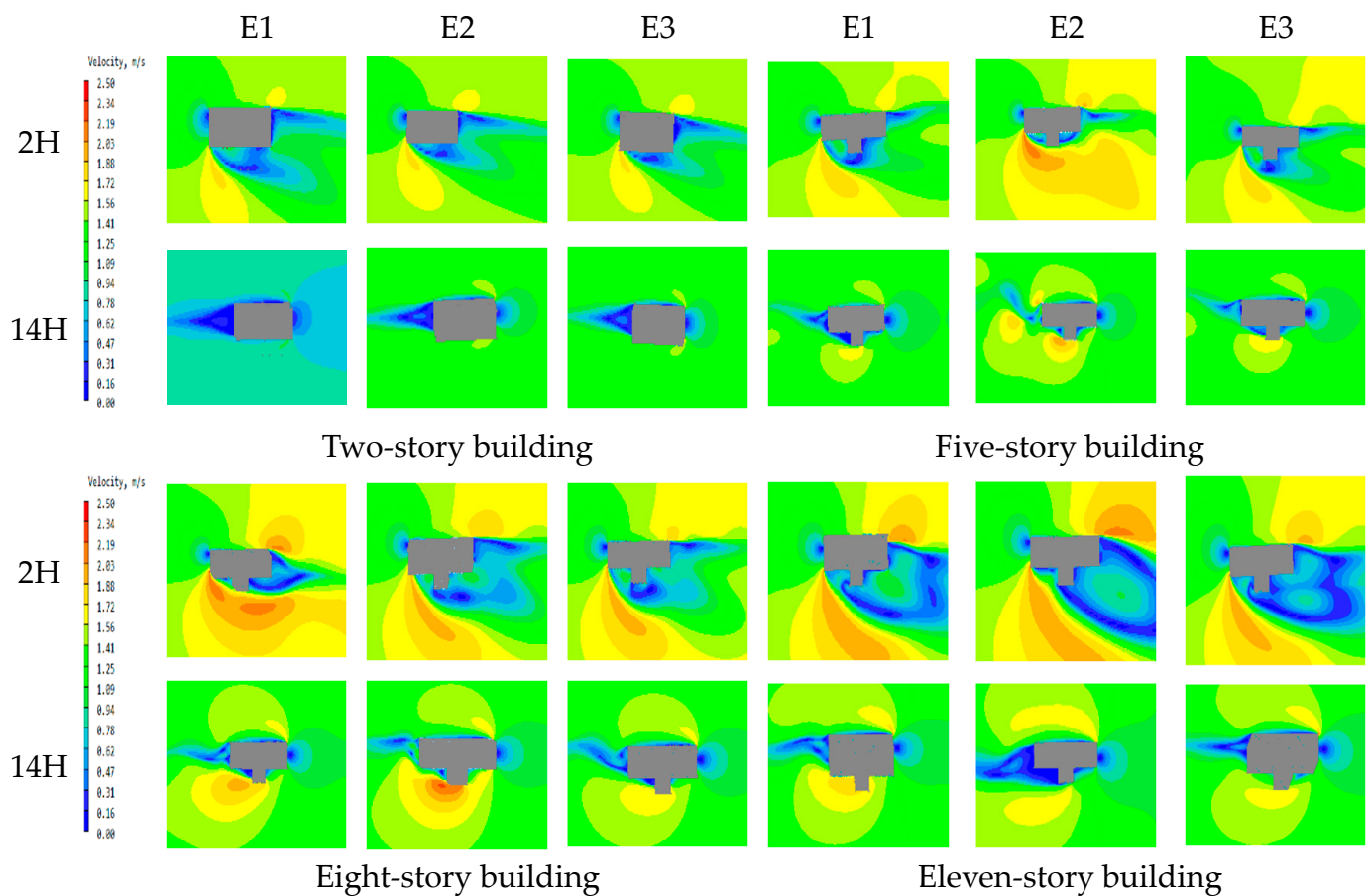


Figure 11. Outside Near-Wall Wind Environment Simulation.

During winter, the maximum wind speeds generally occur around 16:00 and 22:00, while the minimum wind speeds are concentrated around 02:00 and 08:00 (Figure 12). Additionally, the average wind speed at a height of 6 m is consistently higher than that at 2 m (Table 4). This phenomenon is mainly attributed to the decrease in surface friction with increasing height and the corresponding increase in background wind speed with height, which has also been observed in relevant studies [21,25].

Table 4. Descriptive statistics of near wall wind velocity.

Wind Velocity (m/s)		Two-Story Building		Five-Story Building		Eight-Story Building		Eleven-Story Building	
		2 m	6 m	2 m	6 m	2 m	6 m	2 m	6 m
E1	Avg	1.2702	1.8584	1.3161	1.5957	1.3390	1.7449	0.9071	1.0044
	Max	2.8425	4.3702	3.3626	3.6649	3.1419	3.623	1.5642	1.8932
	Min	0.4406	0.6521	0.2204	0.2636	0.3036	0.3973	0.2427	0.1813
	SD	0.7478	1.1072	0.9136	1.0969	0.8337	1.0243	0.4720	0.5600
E2	Avg	1.0166	1.6135	1.3101	1.6802	1.0267	1.6708	0.6882	0.8012
	Max	2.8181	3.1576	3.4639	3.6139	2.2461	3.8101	1.2456	1.9812
	Min	0.284	0.1775	0.0969	0.2611	0.0779	0.2563	0.1326	0.1818
	SD	0.7214	1.0071	0.9137	1.1073	0.6638	1.1520	0.3736	0.4929
E3	Avg	1.1672	1.8723	1.1331	1.6229	1.4250	1.5910	1.3640	1.7218
	Max	2.7806	4.002	3.0217	3.6365	3.6728	4.3504	3.6344	4.0659
	Min	0.2869	0.3696	0.1763	0.2377	0.2075	0.1186	0.116	0.1656
	SD	0.7882	1.0633	0.8188	1.0522	1.1302	1.3200	1.0341	1.2975

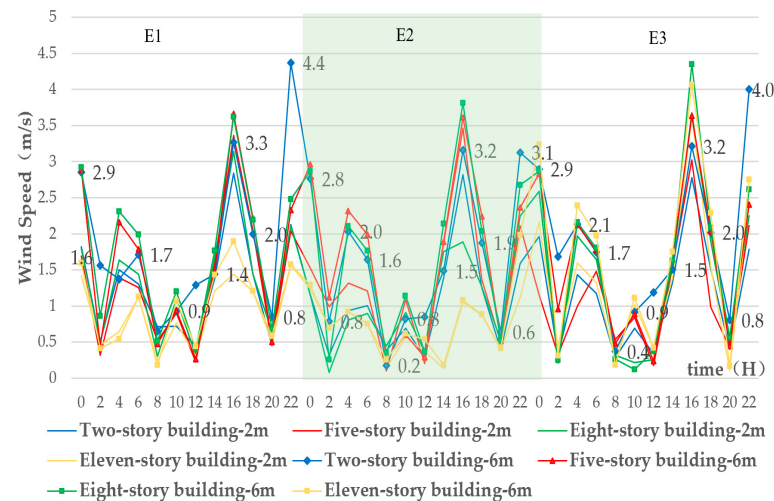


Figure 12. Near-Wall wind speed.

2. Outside Near-wall Air Temperature

During winter in Lhasa, outdoor near-wall air temperatures remain relatively low at approximately -5°C around 8:00, reaching their peak of about 5°C around 16:00 (Figure 13). The average outdoor near-wall temperature is maintained around 0.8°C (Table 5).

Table 5. Descriptive statistics of near wall air temperature.

Air Temperature ($^{\circ}\text{C}$)		Two-Story Building		Five-Story Building		Eight-Story Building		Eleven-Story Building	
		2 m	6 m	2 m	6 m	2 m	6 m	2 m	6 m
E1	Avg	0.9093	0.9185	0.7699	0.7310	0.8325	0.7916	0.7718	0.7754
	Max	4.8699	4.8296	4.8865	4.8215	4.9591	4.83	4.9674	4.9288
	Min	-4.9945	-3.7822	-5.3373	-5.2563	-5.2988	-5.2221	-5.3206	-5.3041
	SD	3.1799	3.0000	3.2055	3.2021	3.1989	3.1833	3.2256	3.2326
E2	Avg	0.8754	0.8574	0.8286	0.8368	0.7670	0.7777	0.8248	0.7986
	Max	4.9321	4.8657	5.3857	4.9139	6.1437	5.0803	4.9248	4.8952
	Min	-5.1256	-4.6656	-5.3696	-5.3642	-5.3389	-5.1989	-5.2797	-5.2553
	SD	3.2101	3.1401	3.2554	3.1386	3.2343	3.1971	3.2738	3.2631
E3	Avg	0.7341	0.7507	0.7524	0.7265	0.7777	0.7647	0.7431	0.7215
	Max	4.8024	4.8	5.0016	4.8197	4.9274	4.8288	4.8776	4.8337
	Min	-5.2277	-4.8842	-5.3445	-5.2371	-5.3077	-5.2736	-5.3243	-5.3103
	SD	3.2004	3.1484	3.2665	3.2012	3.1971	3.1778	3.2166	3.2134

For the five-storey building, the configuration characterized by a higher shape coefficient demonstrates an overall elevated outdoor near-wall air temperature (Figure 14), with a greater propensity for localized high-temperature regions (indicated by green and red areas). At the 2 m measurement height, for instance, the mean temperature for configuration E2 is 0.8286°C , surpassing the 0.7699°C recorded for E1—a trend similarly reflected at the 6 m height. Conversely, in the eight-storey building, the configuration with a lower shape coefficient exhibits a generally higher near-wall air temperature and is more susceptible to localized thermal accumulation (green and red zones) (Figure 14). At the 2 m height, the average temperature for E1 reaches 0.8325°C , exceeding the 0.7670°C observed for E2, with consistent results at the 6 m height.

In the two-storey building, the configuration featuring a larger window-to-wall ratio yields lower temperatures: at the 2 m height, E3 registers a mean of 0.7341°C , lower than the 0.9093°C for E1, and a comparable outcome is noted at the 6 m height. For buildings of five, eight, and eleven storeys, the influence of window-to-wall ratio appears negligible.

This indicates that the window-to-wall ratio has a more significant impact on the near-wall air temperature of low-rise buildings.

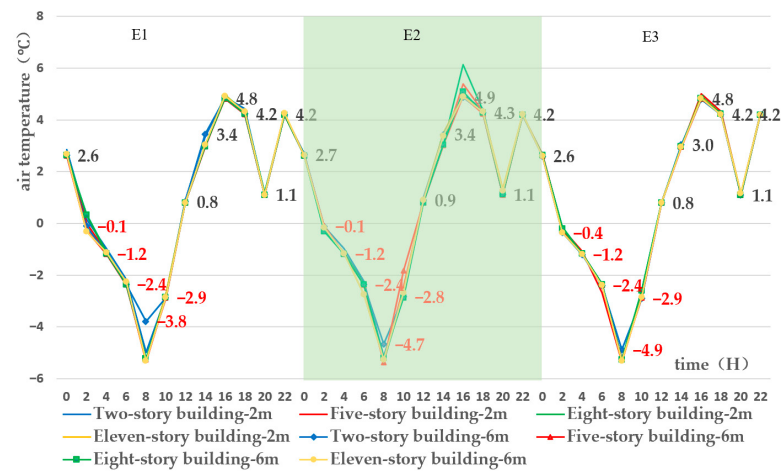


Figure 13. Near-Wall air temperature.

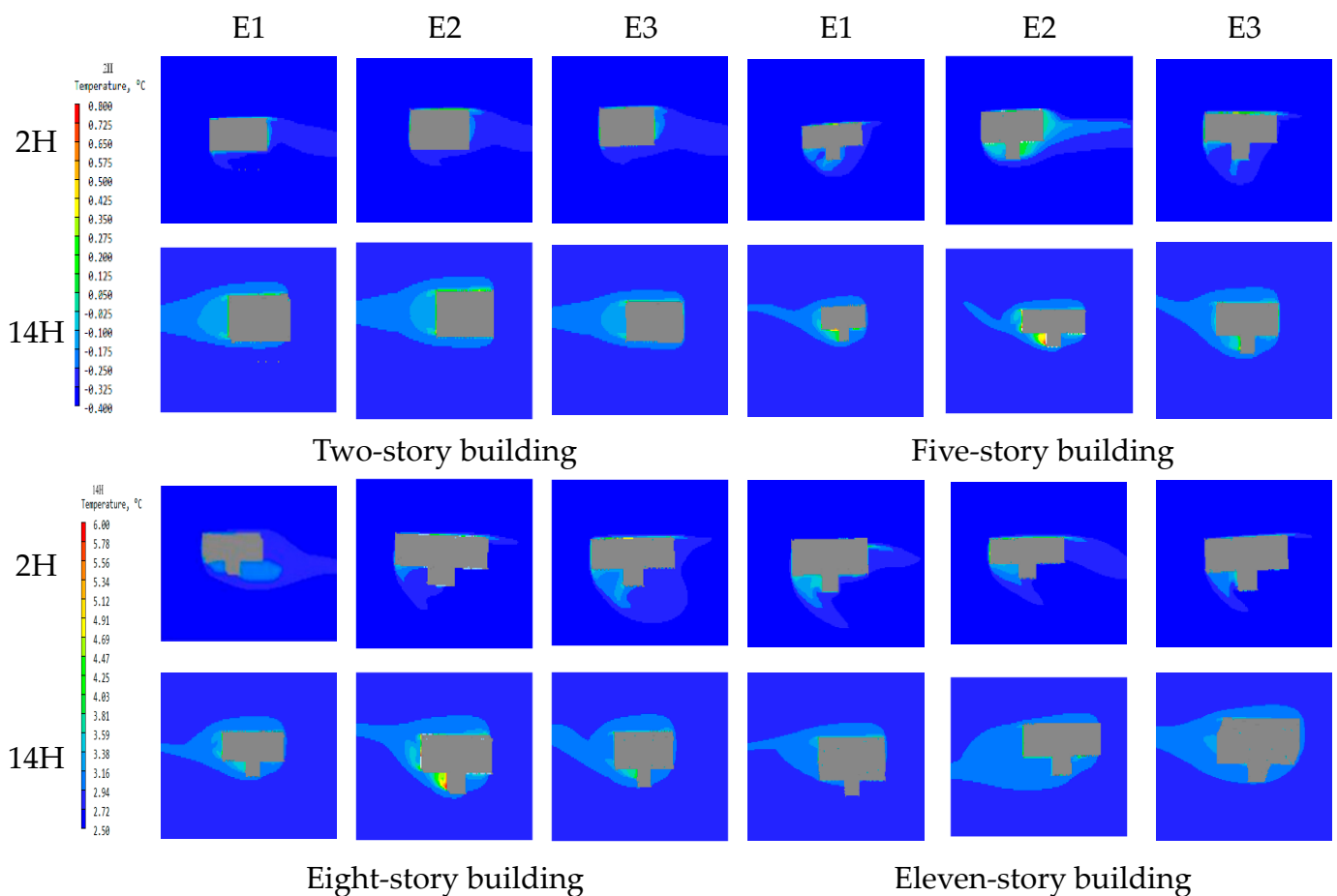


Figure 14. Outside Near-Wall Air temperature Simulation.

3. Outside Near-Surface Relative Humidity

During winter nights, the outdoor near-wall relative humidity gradually increases, reaching a peak at around 8:00. As solar radiation increases, the outdoor near-wall relative humidity decreases, hitting a minimum at 22:00 (Figure 15). The minimum values of relative humidity are all around 6%, the maximum values around 23%, and the average values around 13% (Table 6).

At 2:00 AM (Figure 16), buildings with a high shape coefficient exhibit lower overall outdoor near-wall relative humidity levels and are more prone to localized low-humidity zones (green areas). This phenomenon occurs because buildings with a larger shape coefficient possess a relatively greater external surface area, which enhances heat dissipation. During the night, their exterior surface temperatures are more likely to fall below the dew point of the ambient air. Condensation forms as a result, thereby reducing the relative humidity near the wall surface.



Figure 15. Near-Wall relative humidity.

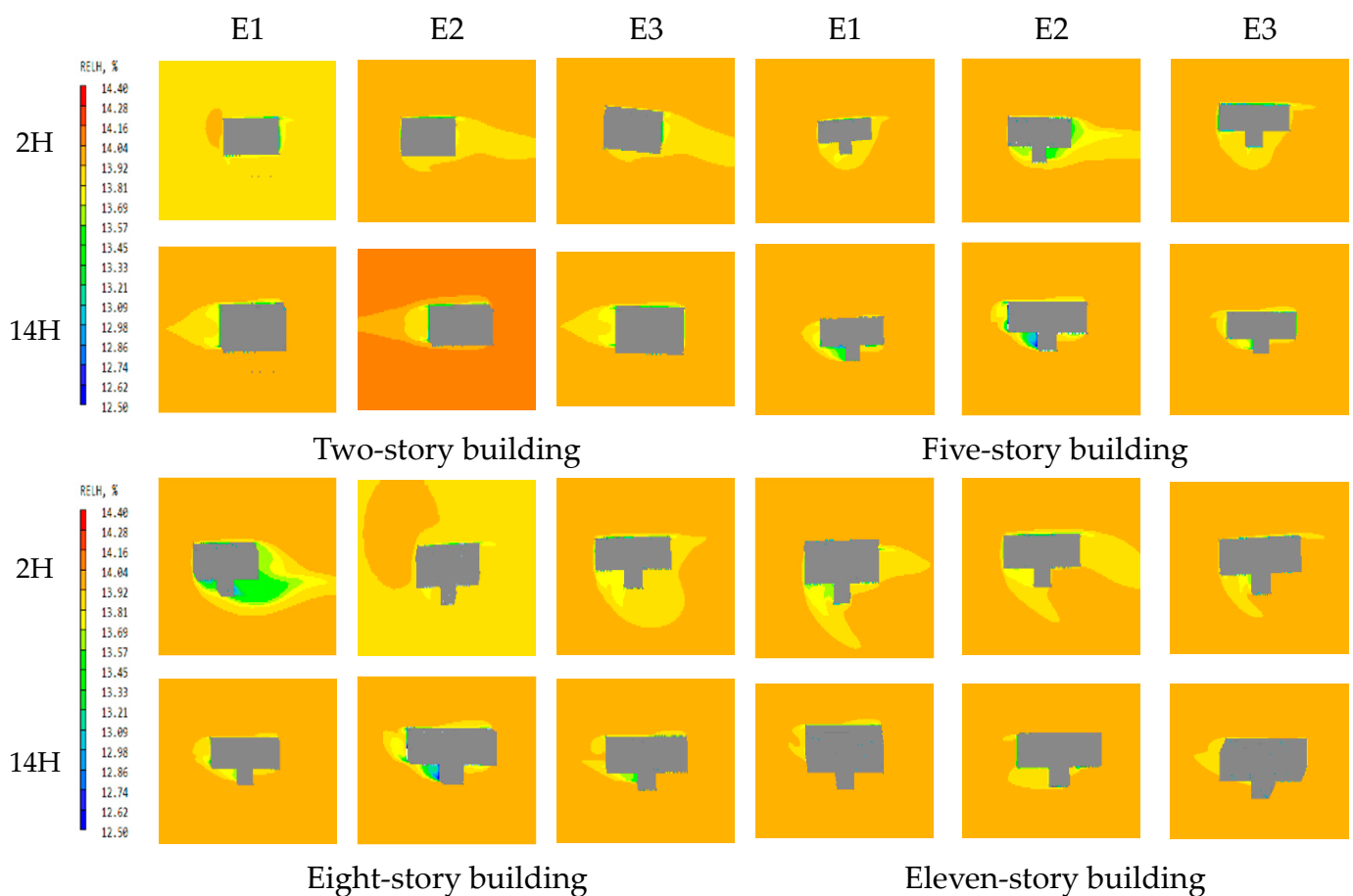


Figure 16. Outside Near-Wall Relative humidity Simulation.

At 2:00 AM (Figure 16), buildings with a low window-to-wall ratio (E1) demonstrate lower overall outdoor near-wall relative humidity and an increased tendency for localized low-humidity areas (green areas). This is attributable to the significantly inferior thermal insulation properties of glass compared to walls. A large window area lowers the average interior surface temperature of the entire facade, making the air in the indoor area near the window more susceptible to reaching the dew point temperature.

Table 6. Descriptive statistics of near wall relative humidity.

Relative Humidity (%)		Two-Story Building		Five-Story Building		Eight-Story Building		Eleven-Story Building	
		2 m	6 m	2 m	6 m	2 m	6 m	2 m	6 m
E1	Avg	12.8624	12.7539	13.0017	13.0375	12.9385	12.9619	13.0033	13.0051
	Max	23.2742	21.2452	23.8861	23.7398	23.8168	23.6791	23.8559	23.8261
	Min	5.999	5.9995	5.9977	6	5.9879	6.0006	5.971	5.9773
	SD	5.5128	5.1977	5.6055	5.6000	5.5828	5.5768	5.5983	5.6123
E2	Avg	12.8853	12.8885	12.9494	12.8809	12.9187	13.0081	12.9272	12.9490
	Max	23.506	22.7033	23.9446	23.9348	23.5847	23.637	23.782	23.7381
	Min	5.9988	6	5.9987	5.9866	5.9999	6	5.9911	5.9945
	SD	5.5451	5.4343	5.5774	5.4563	5.6069	5.5961	5.5773	5.5749
E3	Avg	13.0325	12.9942	12.9994	13.0364	13.4869	12.9163	13.0279	13.0496
	Max	23.6887	23.0811	23.8992	23.7054	23.8327	23.7712	23.8627	23.8372
	Min	6	6	5.9964	6	6.9849	6	6.0004	6.001
	SD	5.5924	5.4950	5.6183	5.5916	5.1379	5.6277	5.6057	5.6143

4. Outside Wall Surface Temperature

During winter nights, the outdoor wall surface temperature decreases, reaching a minimum at around 8:00. As solar radiation increases, the outdoor wall surface temperature rises, peaking at 14:00 in the afternoon (Figure 17).

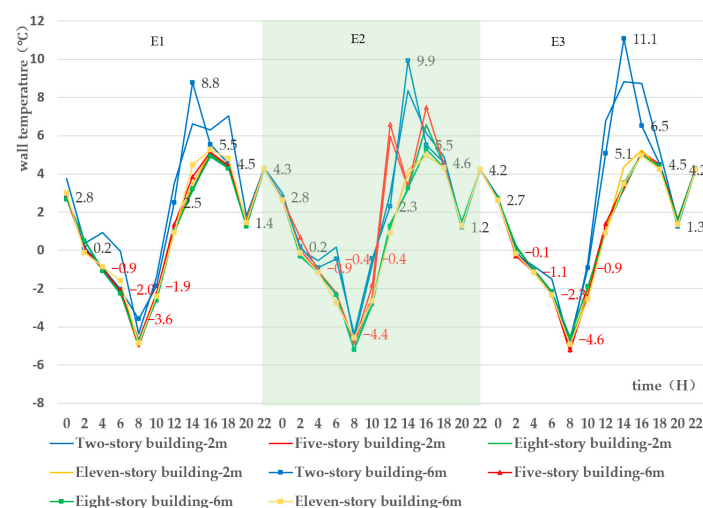


Figure 17. Wall temperature.

On the front and rear facades during the daytime (14:00), the outdoor wall surface temperature of building model E3 is significantly higher (yellow and red areas) (Figure 18). This demonstrates that a higher window-to-wall ratio leads to an increase in the exterior wall surface temperature. Based on the statistical results in Table 7, under the same building height and measurement level, E3 with a higher window-to-wall ratio ($WWR = 0.35$) generally exhibits higher average external wall temperatures compared to E1 with a lower WWR (0.30). For instance, at the 2 m measurement height of the two-storey building, the mean temperature for E3 is 2.4904 °C, exceeding the 2.4056 °C recorded for E1. A more

marked divergence is observed at the 6 m height of the same building, where E3 averages 2.1869 °C compared with 1.7975 °C for E1. For buildings ranging from 5 to 11 stories, the average temperature of E3 is also mostly higher than that of E1, though at certain heights—such as the 6 m level of the five-storey building, and the 2 m and 6 m levels of the eleven-storey building—the values are comparable. These observations suggest that an increase in the window-to-wall ratio generally leads to an overall elevation of external wall surface temperature, particularly in low-rise buildings.

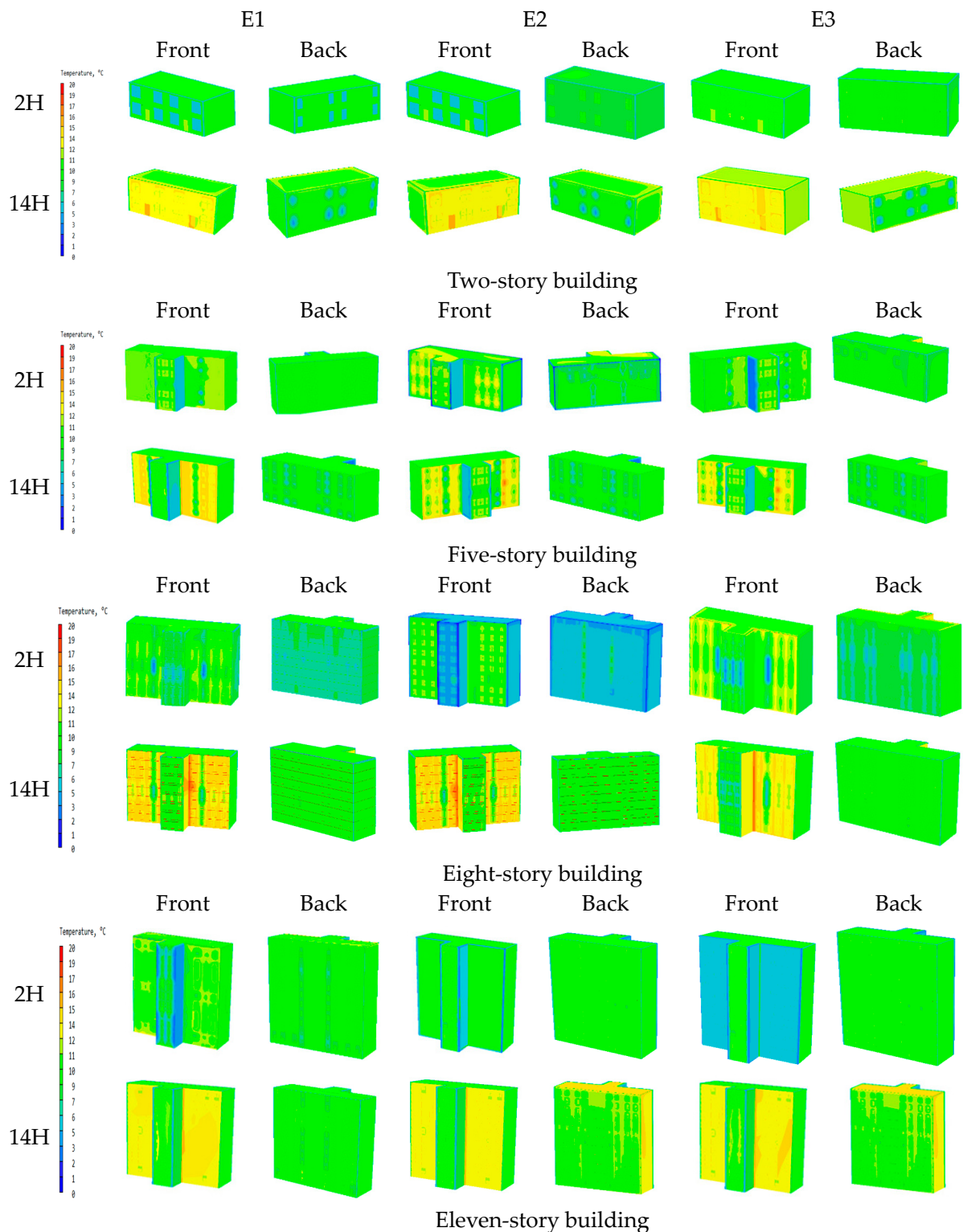


Figure 18. Outside Wall temperature Simulation.

During the nighttime (02:00), for the 2 and 5-story buildings, a smaller shape coefficient corresponds to a higher wall surface temperature, whereas for the 8 and 11-story buildings, a larger shape coefficient results in a higher temperature (Figure 18). This contrast reveals that in low and mid-rise buildings, although a larger shape coefficient promotes faster heat dissipation, the structures' relatively low thermal mass prevents them from retaining this heat effectively. Conversely, for the 8 and 11-story buildings, despite similar heat loss rates from a large shape coefficient, their substantial thermal mass allows them to retain heat more effectively.

Furthermore, the 2-story buildings consistently registered higher outdoor wall surface temperatures than the 5, 8, and 11-story buildings (Figure 17 and Table 7).

Table 7. Descriptive statistics of Outside Wall temperature.

Outside Wall Temperature (°C)		Two-Story Building		Five-Story Building		Eight-Story Building		Eleven-Story Building	
		2 m	6 m	2 m	6 m	2 m	6 m	2 m	6 m
E1	Avg	2.4056	1.7975	1.0082	1.1110	0.9746	0.9471	1.0583	1.1952
	Max	7.0323	8.7745	5.0449	5.1408	5.0067	4.9176	5.1324	5.2691
	Min	−4.3648	−3.5922	−5.0388	−4.6788	−4.9515	−4.6999	−4.8700	−4.8682
	SD	3.4937	3.6304	3.1483	3.1378	3.1334	3.0944	3.1433	3.2519
E2	Avg	2.1077	2.0489	1.4985	1.7429	1.0262	0.8910	0.9640	0.9233
	Max	8.3713	9.9309	6.5722	7.4929	6.5792	5.2888	4.9834	4.9562
	Min	−4.6517	−4.3643	−4.8979	−4.8060	−5.1696	−5.1989	−4.5752	−4.5755
	SD	3.5508	3.7209	3.6410	3.7517	3.4245	3.2789	3.2279	3.2080
E3	Avg	2.4904	2.1869	1.0096	0.9346	1.0061	1.0746	1.0137	0.8881
	Max	8.8314	11.0820	5.1587	5.0272	5.0476	5.0031	5.2420	4.9669
	Min	−4.9690	−4.6459	−5.3344	−5.2097	−4.8498	−4.5416	−5.0750	−4.9322
	SD	4.3533	4.3610	3.2155	3.2316	3.1165	3.0385	3.2692	3.1678

5. Outside Solar Radiation Intensity

In winter, the outdoor near-wall solar radiation begins to increase at around 8:00, reaches a maximum at approximately 14:00, and then decreases, dropping to zero at around 20:00 (Figure 19).

At 10:00 (Figure 20), the building's eastern facade receives a higher intensity of solar radiation. By 12:00 (Figure 21), the overall solar radiation reaches its peak, with the highest intensities observed on the rooftop and southern facade. At 14:00 (Figure 22), the western facade begins to receive increased solar radiation. A gradual decline in radiation intensity is noted by 16:00 (Figure 23), followed by a significant reduction by 18:00 (Figure 24).

The variation of solar radiation follows identical trends at both the 2 m and 6 m heights for all building models (Figure 24). Statistical analysis, particularly the standard deviation data presented in Table 8, indicates a pronounced spatial heterogeneity in solar radiation distribution.

For the 11-story building, the mean solar radiation intensity near the E3 model's walls (186.08 W/m^2) is lower than that of the E1 model (187.07 W/m^2). This suggests that a higher window-to-wall ratio can lead to a reduction in the solar radiation received by the exterior wall surfaces. Variations in the shape coefficient (E1 vs. E2) exhibit a negligible impact on the statistical outcomes of solar radiation.

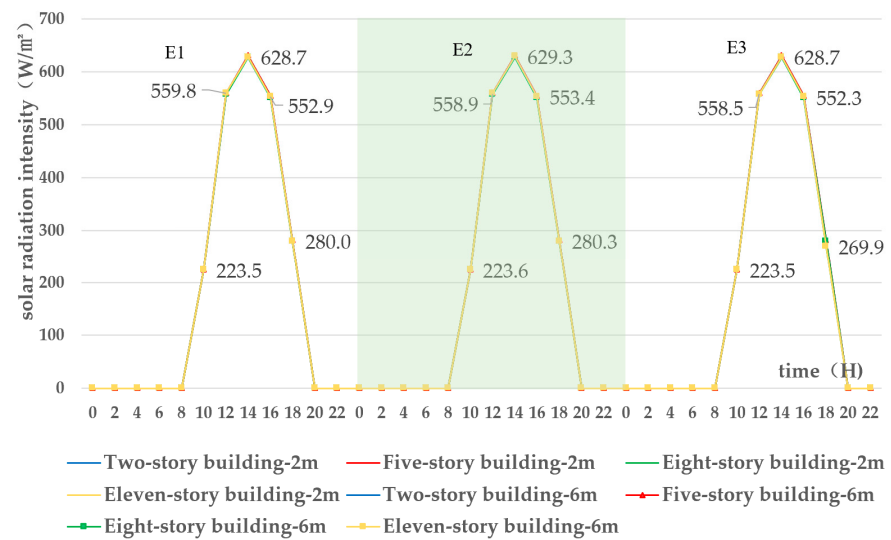


Figure 19. Outside solar radiation.

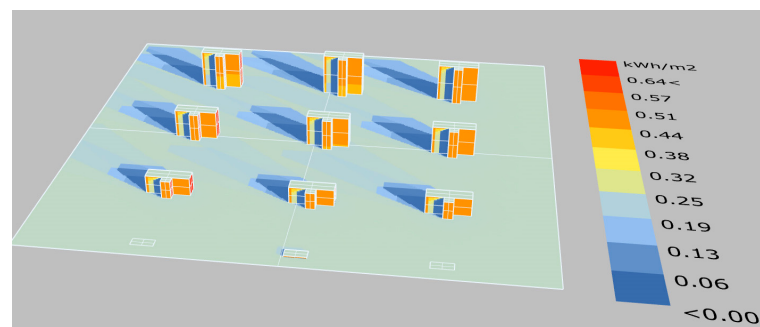


Figure 20. Outside solar radiation Simulation-10H.

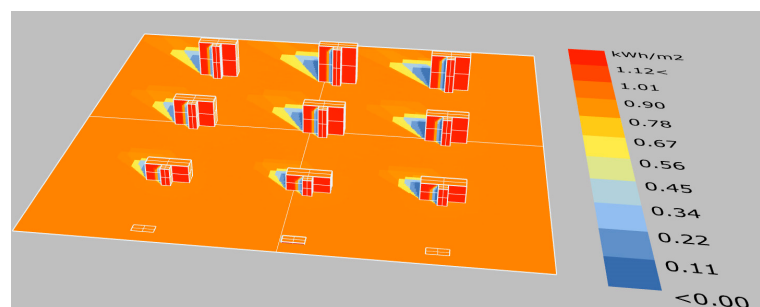


Figure 21. Outside solar radiation Simulation-12H.

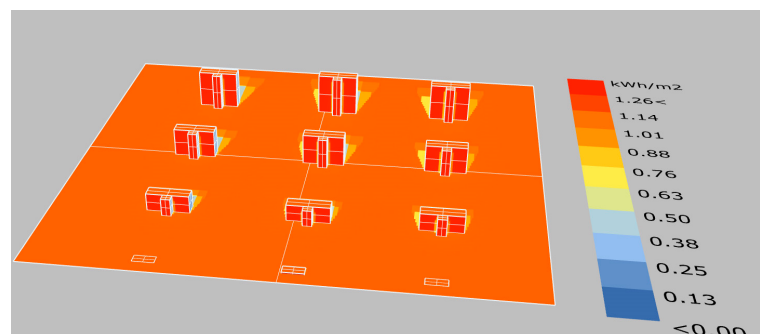


Figure 22. Outside solar radiation Simulation-14H.

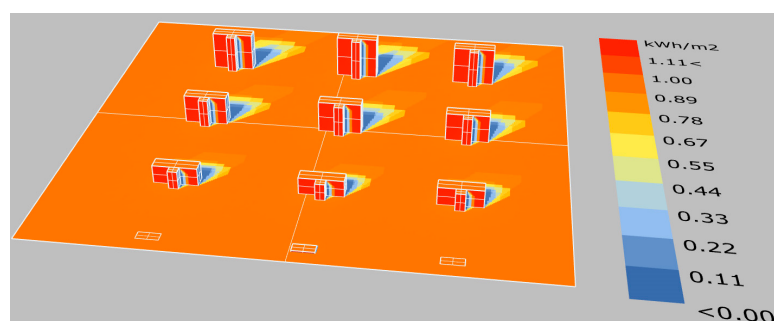


Figure 23. Outside solar radiation Simulation-16H.

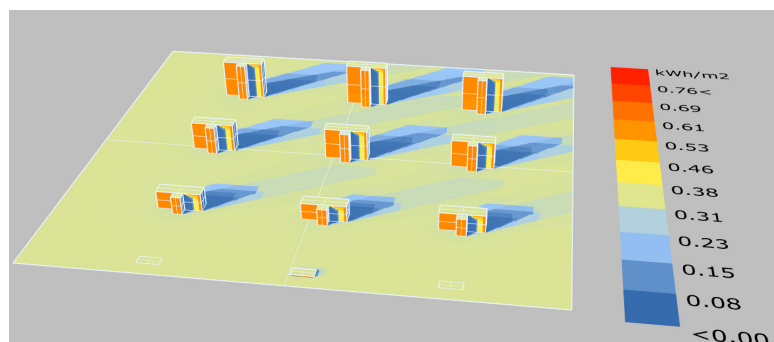


Figure 24. Outside solar radiation Simulation-18H.

Table 8. Descriptive statistics of solar radiation.

Solar Radiation (W/m ²)		Two-Story Building		Five-Story Building		Eight-Story Building		Eleven-Story Building	
		2 m	6 m	2 m	6 m	2 m	6 m	2 m	6 m
E1	Avg	187.4198	187.4198	187.4198	187.4198	186.5547	186.7797	187.0718	187.0718
	Max	630.8620	630.8620	630.8620	630.8620	627.2375	627.9315	628.6505	628.6505
	Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	SD	256.80	256.80	256.80	256.80	255.55	255.85	256.32	256.32
E2	Avg	187.4198	187.4198	187.4198	187.4198	186.5547	186.7797	187.1280	187.1280
	Max	630.8620	630.8620	630.8620	630.8620	627.2375	627.9315	629.3445	629.3445
	Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	SD	256.80	256.80	256.80	256.80	255.55	255.857	256.38	256.38
E3	Avg	187.4198	187.4198	187.4198	187.4198	185.7146	186.7797	186.0801	186.0801
	Max	630.8620	630.8620	630.8620	630.8620	627.2620	627.9315	628.6755	628.6755
	Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	SD	256.80	256.80	256.80	256.80	255.23	255.85	255.76	255.76

4.1.2. Correlation Analysis Between Exterior Wall Surface Temperature and Microclimate Parameters

Exterior wall surface temperature serves as a critical intermediate variable linking microclimatic parameters near the building envelope to the building heating load. Based on the simulation data presented in Section 4.1.1, this study examined the relationship between exterior wall surface temperature and microclimatic parameters.

E1 was selected as the study subject, and correlation analyses were conducted, respectively, between the outdoor wall surface temperature and near-wall wind speed, relative humidity, air temperature, and solar radiation at the same height of 6 m during the 0 to 24 h period (Table 9). The analysis reveals that the wall surface temperature exhibits a moderate positive correlation with both the near-wall wind speed and solar radiation intensity. A strong negative correlation was identified with near-wall relative humidity. A strong positive correlation was observed with the near-wall air temperature (Table 9).

Table 9. Correlation analysis of outside wall Surface temperature with microclimate parameters.

	P	R	
Outside Wall Surface temperature	0	0.632	Wind velocity
	0	−0.953	Relative humidity
	0.023	0.462	Solar radiation
	0	0.999	Air temperature

4.2. Statistical Modeling of the Exterior Near-Wall Microclimate and Wall Surface Temperature

4.2.1. Statistical Modeling of the Exterior Near-Wall Microclimate and Wall Surface Temperature

New building models with fully transparent and fully opaque envelopes were created, each with identical dimensions of 18 m (L) × 8 m (W) × 6 m (H). The heat transfer coefficient (U-value) was set at 2.4 W/m²·K for the fully transparent envelope and 0.46 W/m²·K for the fully opaque envelope, with their thicknesses following the specifications for exterior walls and windows in Table 2. Under a uniform indoor air temperature setting of 18 °C, simulations of the near-wall microclimate were conducted for both models.

Analysis of the statistical data (Table 10) and simulation contours (Figure 25) reveals that, while the solar radiation intensity in the near-wall region shows no significant difference between the transparent and opaque envelopes at any given time, distinct variations are evident in wind speed, air temperature, relative humidity, and wall surface temperature. This clear divergence necessitates the development of separate statistical models for each envelope type.

Table 10. Statistical Results of the Outside Near-Wall Microclimate for Different Envelope Types.

	Transparent Envelope		Opaque Envelope		Transparent Envelope		Opaque Envelope	
	Solar radiation				Air temperature			
	2 m	4 m	2 m	4 m	2 m	4 m	2 m	4 m
Avg	187.4198	187.9198	187.4198	187.9198	0.7347	0.7412	0.8108	0.8169
Max	630.862	630.862	631.862	631.862	4.8004	4.8001	4.801	4.8
Min	0.0000	0.0000	0.0000	0.0000	−5.2354	−5.2391	−5.0328	−4.7671
SD	256.8068	257.3046	256.8068	257.3046	3.2058	3.2195	3.1740	3.1175
	Wind velocity				Relative humidity			
Avg	0.6868	1.2259	0.8641	1.3205	13.0338	13.0314	12.9478	12.9211
Max	2.864	3.1249	2.9012	3.1312	23.7023	23.7089	23.3405	22.8759
Min	0.0895	0.1055	0.327	0.1654	6.0006	6.0006	6.0004	6.0006
SD	0.8686	0.9733	0.8354	0.9855	5.5974	5.6075	5.5286	5.4415
	Outside Wall temperature							
Avg	0.8346	0.8062	1.2561	1.2680				
Max	4.838	4.8282	5.1443	5.8714				
Min	−5.093	−5.0321	−4.844	−4.6216				
SD	3.1727	3.1866	3.1993	3.3135				

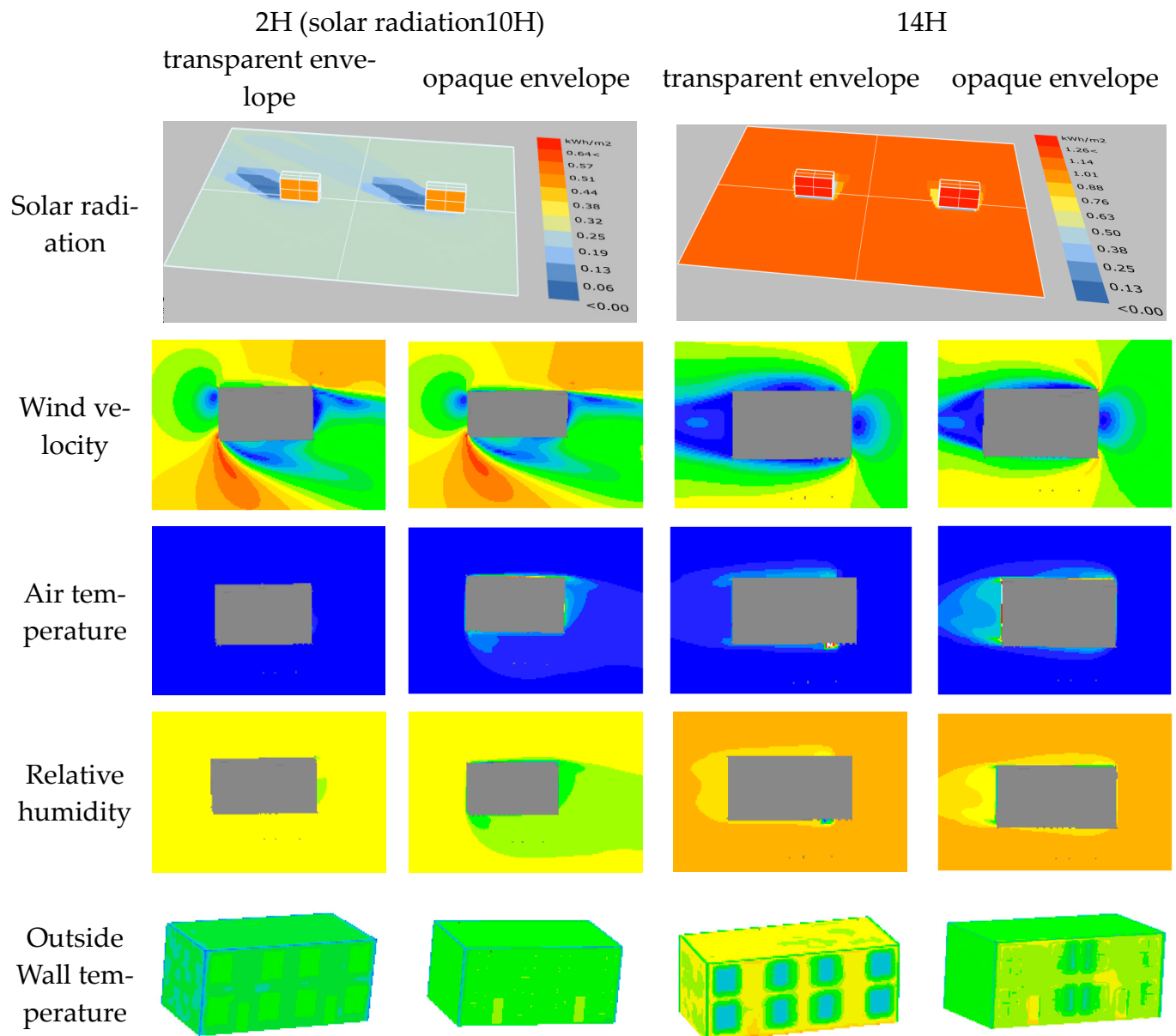


Figure 25. Simulation Contours of the Outside Near-Wall Microclimate for Different Envelope Types.

4.2.2. Statistical Modeling of the Exterior Near-Wall Microclimate and Wall Surface Temperature

Based on the analyses presented in Sections 4.1.2 and 4.2.1, this study focuses on further investigating the influence of outdoor near-wall wind speed, air humidity, air temperature, and solar radiation on the exterior surface temperature of two distinct envelope types, with the aim of developing corresponding regression models. A multiple linear regression analysis was conducted using SPSS v29.0 software. The independent variables were the microclimatic parameters from the near-wall region—namely, wind speed, air humidity, air temperature, and solar radiation intensity, while the dependent variable was the exterior wall surface temperature.

To ensure the robustness of the multiple linear regression model and the interpretability of its coefficients, this study systematically diagnosed multicollinearity among the variables. The Variance Inflation Factor (VIF) was calculated for all initial independent variables—including near-wall air temperature, solar radiation intensity, wind speed, and relative humidity—to quantify their degree of collinearity. Collinearity diagnostics, as indicated by the values outside parentheses in Tables 11 and 12, revealed collinearity between

near-wall relative humidity, air temperature, and the wall surface temperature. Relative humidity was found to exhibit severe multicollinearity, whereas the collinearity associated with outdoor air temperature was not significant. Consequently, the factor of outdoor near-wall relative humidity was excluded from the regression model.

After excluding relative humidity, collinearity diagnostics were re-conducted. The results within parentheses in Tables 11 and 12 indicate that the independent variables—near-wall wind speed, solar radiation intensity, and temperature—are mutually independent. This demonstrates that these key microclimatic drivers satisfy the statistical independence assumption in the final model, rendering it suitable for multiple regression analysis.

Table 11. Model collinearity test of Opaque Envelope.

	V_w	I	T_a	RH
Eigenvalue (>0)	0.4469 (0.446)	0.128 (0.123)	1.426 (0.979)	0.003
Condition Index (<10)	2.5929 (2.346)	4.842 (4.469)	1.54 (1.583)	32.902
Variance Proportion (<0.9)	0.37 (0.84)	0.42 (0.09)	0.92 (0.57)	1
Variance Inflation Factor VIF (<10)	2.84 (1.729)	2.21 (1.249)	37.692 (1.975)	25.982

1. Development of the Opaque Envelope Model

A multiple regression equation for the opaque building envelope was established using SPSS. The coefficient of determination ($R^2 = 0.994$) for the linear equation signifies an excellent model fit, demonstrating that the wall surface temperature is effectively explained by wind speed, air temperature, and solar radiation intensity. A Durbin-Watson test was performed on the final model to verify whether its residuals satisfied the assumption of independence. The test yielded a statistic of 1.706, which exceeds the upper critical value ($dU = 1.656$). This result indicates that the residuals are independent with no autocorrelation.

The regression equation for the opaque envelope is:

$$Y_1 = 0.274 - 0.093 \times V_w + 0.001 \times I + 0.990 \times T_a \quad (18)$$

where:

$Y_1 = t_j$ = Wall surface temperature for the opaque envelope ($^{\circ}\text{C}$)

V_w = Outdoor near-wall wind speed (m/s)

I = Outdoor near-wall solar radiation intensity (W/m^2)

T_a = Outdoor near-wall air temperature ($^{\circ}\text{C}$)

2. Development of the Transparent Envelope Model

A multiple regression equation for the transparent building envelope was established using SPSS. The linear equation achieves a coefficient of determination ($R^2 = 0.999$), indicating a near-perfect fit for the model relating the wall surface temperature to wind speed, air temperature, and solar radiation intensity. A Durbin-Watson test was performed on the final model to verify whether its residuals satisfied the assumption of independence. The Durbin-Watson statistic of 1.994, which is greater than the upper critical value ($dU = 1.656$), confirms that the residuals are independent with no autocorrelation.

The regression equation for the transparent envelope is:

$$Y_2 = 0.073 + 0.004 \times V_w + 0.988 \times T_a \quad (19)$$

where:

$Y_2 = t_j$ = Wall surface temperature for the transparent envelope ($^{\circ}\text{C}$)

V_w = Outdoor near-wall wind speed (m/s)

T_a = Outdoor near-wall air temperature (°C)

Table 12. Model collinearity test of Transparent Envelope.

	V_w	I	T_a	RH
Eigenvalue (>0)	0.428 (0.425)	0.236 (0.212)	1.242 (0.806)	0.002
Condition Index (<10)	2.688 (2.453)	3.621 (3.470)	1.577 (1.782)	36.364
Variance Proportion (<0.9)	0.02 (0.59)	0.43 (0.27)	0.91 (0.31)	1
Variance Inflation Factor VIF (<10)	1.223 (1.182)	2.240 (1.257)	34.304 (1.416)	28.970

The sensitivity analysis was initiated with baseline values of 2 m/s for wind speed, 500 W/m² for solar radiation, and 2 °C for air temperature. Subsequently, each parameter was varied by $\pm 20\%$ to assess its individual impact. The results are presented in Table 13.

When other conditions remained constant, variations in wind speed and air temperature resulted in greater changes to the exterior surface temperature derived from the opaque building envelope model. Among the three variables, the near-wall air temperature demonstrated the highest sensitivity to changes in the surface temperature, followed by solar radiation. Wind speed exhibited the lowest sensitivity (Figure 26).

Table 13. Model variable sensitivity.

Initial Value		2 m/s		500 w/m ²		2 °C		
Degree of change (%)	wind velocity	Outside Wall temperature		Solar radiation intensity	Outside Wall temperature	Air temperature	Outside Wall temperature	
		transparent envelope	opaque envelope		opaque envelope		transparent envelope	opaque envelope
−20	1.6	2.0754	2.61	400	2.468	1.6	1.6618	2.172
−15	1.7	2.0758	2.601	425	2.493	1.7	1.7606	2.271
−10	1.8	2.0762	2.592	450	2.518	1.8	1.8594	2.37
−5	1.9	2.0766	2.583	475	2.543	1.9	1.9582	2.469
0	2	2.077	2.574	500	2.568	2	2.057	2.568
5	2.1	2.0774	2.565	525	2.593	2.1	2.1558	2.667
10	2.2	2.0778	2.556	550	2.618	2.2	2.2546	2.766
15	2.3	2.0782	2.547	575	2.643	2.3	2.3534	2.865
20	2.4	2.0786	2.538	600	2.668	2.4	2.4522	2.964
Overall amplitude	--	0.16	3.6	--	10	--	39.52	39.6

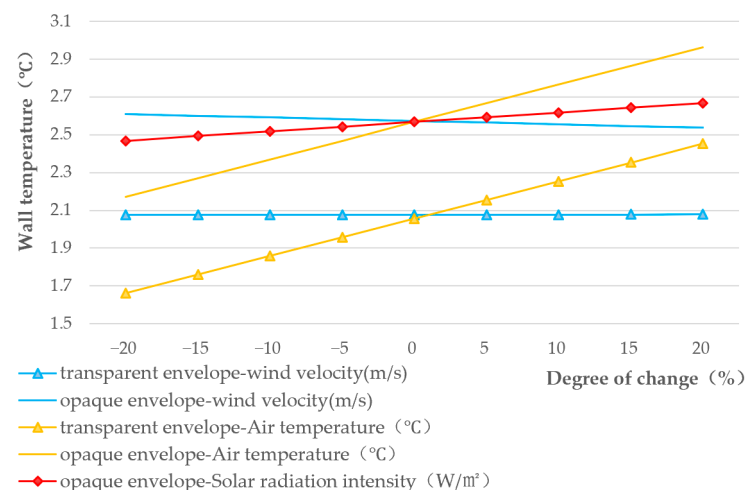


Figure 26. Model variable sensitivity.

4.3. Development and Validation of the Outdoor Near-Wall Microclimate and Building Heating Load Model

4.3.1. Coupled Model of Outdoor Near-Wall Microclimate and Building Heating Load

Using the exterior near-wall temperature t_j as an intermediate variable, the coupling relationship between the indoor and outdoor surface temperatures and the building heating load (Equation (17)) was integrated with the statistical model linking the exterior near-wall microclimate and surface temperatures of different envelope types. This integration produced a composite expression relating the outdoor near-wall microclimate to the building heating load:

$$Q_{(V)} = \frac{s}{n} \left(\sum_{i=1}^n \frac{\lambda}{d} (t_i - (\omega + \alpha \times V_w + \beta \times I + \varphi \times T_a)) \right) - \frac{1}{e} \int_1^e \frac{\tau I A H}{V} \quad (20)$$

ω = Model constant, taken as 0.073 for transparent envelopes and 0.274 for opaque envelopes.

α = Model constant, taken as 0.004 for transparent envelopes and -0.093 for opaque envelopes.

β = Model constant, taken as 0 for transparent envelopes and 0.001 for opaque envelopes.

φ = Model constant, taken as 0.988 for transparent envelopes and 0.99 for opaque envelope.

4.3.2. Validation by Comparing Calculated and Simulated Heating Load Values

Based on field surveys and previous studies on residential building orientation by Sun Wenjing [48] and Tian Yuefeng [54], building models with different orientations were established, including due south, 30° east of south, and 30° west of south (Figure 27). Additionally, models with building obstructions but identical orientation were developed, focusing on Building #2 and Building #3 (Figure 28).

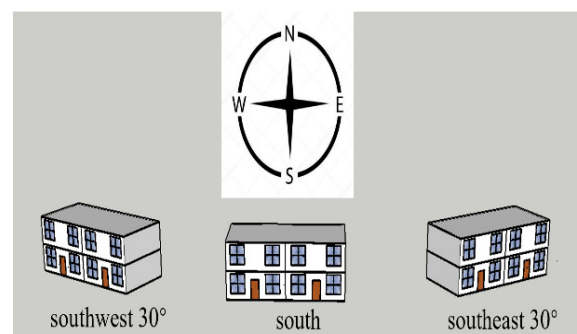


Figure 27. Different orientation simulation model.

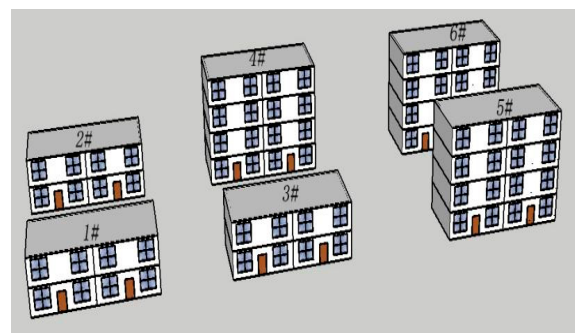


Figure 28. Simulation model with building shading.

The simulation settings followed the configuration described in Section 3.2. The external surfaces of the models were discretized into finite zones of 1 m^2 each, with the near-wall microclimate assumed to be uniform within each zone, resulting in a total of 436 surface zones. The microclimate data at the centroid of each surface zone in the

simulation model were taken as representative values for that zone. These values were then substituted into the mathematical model (Equation (20)) to calculate the building heating load. The calculated heating load values under different orientation and shading conditions during the period of 13:00–14:00 are presented in Table 14.

Chang Ming, Michael J., Zhu Dandan et al. [55–57] compared EnergyPlus simulation results with those from other building energy modeling programs and demonstrated its accuracy and reliability for building energy simulation in high-altitude regions. Although EnergyPlus offers notable advantages, its user interface is less intuitive [58]. DesignBuilder features an operator-friendly interface, a comprehensive database, and robust energy simulation capabilities [59]. Therefore, this study employs DesignBuilder, which retains the strengths of EnergyPlus while addressing its usability limitations.

Using the simulated microclimate data as input, building energy consumption was simulated in DesignBuilder under consistent climatic parameters. The simulated values for different orientations and shading conditions during the period of 13:00–14:00 are summarized in Table 14.

Table 14. Simulated and Calculated results.

Energy Consumption (kw)	Southeast 30°	South	Southwest 30°	2#	3#
Simulated results	1.0406	1.227	1.190105	1.3226	1.2097
Calculated results	1.1028	1.0836	0.9424	1.1827	1.0937

A comparison between the computed and simulated heating load values, as presented in Table 14, indicates that the simulated results are generally higher than the calculated values across all orientations except for the south-east 30° case. Nevertheless, the overall variation trends remain consistent between the two sets of results (Figure 29). Validation metrics were calculated by comparing the simulated values with the calculated values, as presented in Table 15. It is important to note that the CV(RMSE) value of 12.87% meets the ASHRAE Guideline 14 [60] requirement of $CV(RMSE) < 30\%$ for hourly model calibration. The NMBE value of -9.76% falls within the recommended $\pm 10\%$ hourly data acceptance range specified by ASHRAE Guideline 14 [60], indicating a systematic underestimation by the model, which remains within acceptable engineering accuracy. This deviation clearly suggests that certain heat loss terms—such as long-wave radiative cooling and air infiltration, which were simplified in the model—may have been underestimated.

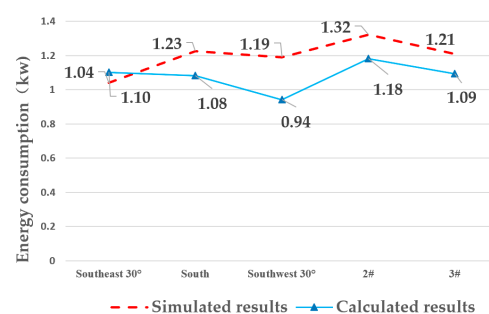


Figure 29. Simulated and Calculated results.

Table 15. Validation analysis and uncertainty quantification results of simulated and calculated values.

Validation Metrics	RMSE	NMBE	CV(RMSE)	Residual Range	Residual Standard Deviation
Results	0.1542	−9.76%	12.87%	[−0.062200, 0.247705]	0.1123

RMSE: Root mean square error; NMBE: Normalised mean bias error; CV(RMSE): Coefficient of variation of the root mean squared error.

4.3.3. Sensitivity Analysis of Microclimatic Parameters on the Heating Load Model

To investigate the sensitivity of microclimate parameters to building heating load, this study employed the Sobol method to quantify the contribution of wind speed (V_{wind}), radiation intensity (I), and air temperature (q_{air}) to variations in heating load. The near-wall air temperature, solar radiation, and wind speed varied within the ranges of 1.6–2.4 °C, 400–600 W/m², and 1.6–2.4 m/s, respectively. As illustrated by the convergence curves of the first-order sensitivity index (S) and total-effect sensitivity index (ST) with respect to sample size (n_{Pop}), when the sample size reached 10,000, the sensitivity indices of all parameters stabilized, indicating that the calculation results are highly reliable (Figures 30 and 31).

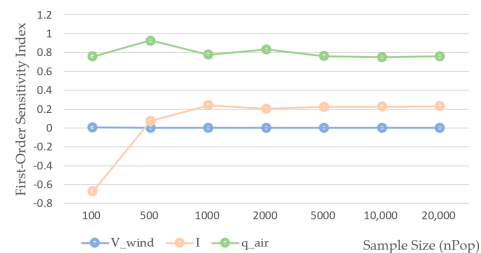


Figure 30. Convergence process of the first-order sensitivity index with sample size.

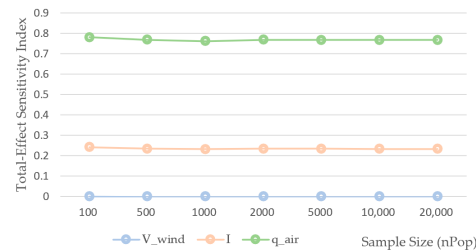


Figure 31. Convergence process of the total-effect sensitivity index with sample size.

The final results of the Sobol index analysis (Figure 32) revealed significant differences in the impacts of various parameters on heating load: Air temperature (q_{air}) was the absolute dominant factor, with its first-order effect ($S = 0.7509$) and total effect ($ST = 0.7662$) accounting for approximately 76% of the total contribution; radiation intensity (I) served as a secondary influencing factor, contributing about 22% through its first-order effect ($S = 0.2242$) and total effect ($ST = 0.2337$); and both the first-order effect and total effect of wind speed (V_{wind}) were close to 0, suggesting that within the parameter range and building scenario adopted in this study, wind speed had no significant impact on heating load. These findings demonstrate that the influences of microclimate parameters on building heating load are highly uneven, and air temperature and radiation intensity are the core factors driving changes in heating load. Based on the correction of heat loss items (such as air infiltration and long-wave radiation) in Section 4.3.2, the relationship between these items and “air temperature” or “solar radiation” should be considered first.

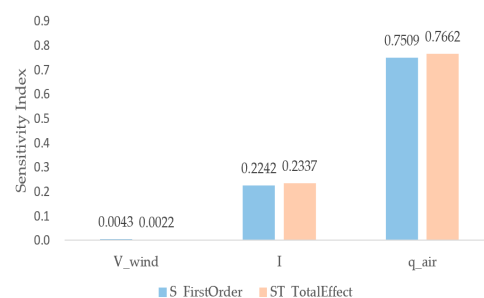


Figure 32. Final results of sensitivity indices ($n_{\text{Pop}} = 10,000$).

5. Discussion

5.1. Discussion on the Regression Model of Outdoor Near-Wall Microclimate and Wall Surface Temperature

1. Selection of Model Variables

At the preliminary stage of model construction, we systematically evaluated a wide range of potential variables including building morphological parameters (e.g., shape coefficient, window-to-wall ratio). The analysis indicated that the impacts of these morphological parameters on microclimate are highly dependent on specific time periods and building heights. As elaborated in Section 4.1.1 (1), for 2-story and 5-story buildings, those with a smaller window-to-wall ratio exhibit a narrower range of high wind speed zones in the near-wall outdoor environment. In contrast, for 8-story and 11-story buildings, a smaller window-to-wall ratio corresponds to a wider range of near-wall high wind speed zones. During the daytime, for 2-story buildings, a larger shape coefficient is associated with an expanded high wind speed zone, whereas for 5-story and 8-story buildings, a larger shape coefficient results in a narrower high wind speed zone. The opposite trend is observed during the nighttime. Changes in morphological parameters can also affect wall surface temperature, as shown in Section 4.1.1 (4). Given that this part aims to identify the relationship between outdoor near-wall microclimate and wall surface temperature, the independent variables of this regression model are focused on outdoor microclimate parameters, with building morphological parameters excluded to avoid the complex interference caused by other factors. The shape factor and window-to-wall ratio are incorporated in deriving the theoretical model that relates wall surface temperature to heating load. Therefore, the current regression model is suitable for predicting how a building's surfaces respond to changes in environmental factors under a given building morphology. It is not intended for comparing wall temperature variations resulting from different morphological parameters.

The results of correlation analysis revealed a negative correlation between relative humidity and wall surface temperature. However, relative humidity was ultimately excluded from the regression model due to its multicollinearity with solar radiation and air temperature. In Lhasa, the air consistently maintains low moisture content, and the impact of humidity variations is significantly smaller compared to regions with high temperature and humidity (Figure 4). Under such conditions, it can be argued that sensible heat exchange dominates the heating load. Nevertheless, excluding humidity does not imply a complete neglect of its physical effect. In high-altitude, high-radiation regions like Lhasa, variations in relative humidity are primarily driven by radiation-induced temperature changes: during clear nights, intense long-wave radiation cooling leads to sharp drops in wall and air temperatures, causing relative humidity to rise; during daytime under strong solar radiation, increases in wall and air temperatures result in a decrease in relative humidity. Thus, the additional information conveyed by relative humidity largely overlaps with that captured by the two core driving variables—"solar radiation" and "air temperature."

2. Model Parameter Setting and Model Boundaries

The regression model was developed based on a typical day of winter heating conditions (21 January) derived from the Typical Meteorological Year (TMY) dataset of Lhasa. This constitutes a clear premise and boundary of the present model. The model coefficients are not universally applicable to other climate zones. Therefore, when applying this model to other climatic regions, systematic parameter localization is necessary, which entails using the TMY data of the target climate zone. Simultaneously, different indoor design heating temperatures should be set according to local heating requirements.

The coefficients of the regression model are derived from the response under the configuration of south-facing double-glazed low-emissivity (SHGC = 0.42) windows. The properties of the glazing, such as emissivity, have a decisive influence on the microclimate and energy consumption. For instance, research in South Australia [61] indicates that higher emissivity in winter slightly improves the ambient environment, while lower emissivity in summer enhances outdoor thermal comfort. Different façade orientations yield distinct Mean Radiant Temperature (MRT) values. The study by Zhai et al. [62] points out that building energy consumption is highly orientation-dependent, and the optimal Window-to-Wall Ratio (WWR) differs between south and north orientations. An et al. [63] found that ultra-thin double-glazed windows can reduce energy consumption by approximately 6.5% compared to conventional double-glazed windows. Consequently, directly applying the regression coefficients to configurations with different optical properties or orientations would limit the model's prediction accuracy. To address this limitation, it is necessary to further analyze the mechanisms by which key parameters (such as SHGC, emissivity, and building orientation) influence the regression coefficients, and accordingly develop a more generalized predictive model.

It should be noted that the present model serves as a foundational reference for characterizing the microclimate-wall temperature relationship in low- and medium-rise buildings. For high-rise buildings, there exist significant vertical gradients in boundary layer wind shear, wind pressure distribution, and radiation exposure. When applying this model to the refined analysis of high-rise or super-high-rise buildings, the impact of vertical variability should be carefully considered. In future research, dividing the building facade into low, middle, and high zones and performing coupled simulations for each zone separately can improve the accuracy of the model.

3. Systematic Deviations

Given the limitations of the Phoenix 2019 software in simulating radiative heat transfer and the advantages of Ladybug1.8.0 in simulating solar radiation, we used Ladybug1.8.0 to independently simulate solar radiation under the same boundary conditions. However, this simulation workflow may introduce errors associated with the interaction between radiation and convection fields. Compared with standalone CFD simulations, coupled simulations (EnergyPlus and Fluent) have been proven to yield an error of approximately 0.94% [64], enabling more accurate prediction of thermal environments. Nevertheless, the magnitude of errors arising from decoupled simulations (Phoenix-Ladybug) has not yet been investigated.

5.2. Discussion on the Composite Model of Outdoor Microclimate and Building Heating Load

1. Core Mechanism and Positioning of the Coupled Model

This study aims to establish a simplified model for the relationship between outdoor near-wall microclimate and building heating energy consumption. Therefore, in the derivation of the coupled model, only the fundamental theoretical relationship between outdoor near-wall microclimate and thermal load was focused on, while internal heat gains from indoor occupants, equipment, and lighting were not considered, nor were occupant behaviors, control strategies, and psychological/behavioral thermal responses. This simplification follows the methodology in building physics research of separating outdoor driving factors from indoor disturbance factors to clarify the dominant mechanisms [65]. This assumption implies that the numerical results generated by the model may be biased toward the safe side (i.e., overestimated). In future research, emotion-sensitive control coefficients [66] (e.g., MSCF) could be adopted to enhance the applicability of the model.

2. Impact of Key Simplifying Assumptions and Model Boundaries

Given that the building envelope is modeled using a lightweight aEPS (expanded polystyrene) insulated wall, which is common in the Lhasa region, the influence of thermal mass has been neglected. Consequently, this model is most suitable for evaluating insulated envelopes. Its application to uninsulated heavy-mass walls (such as concrete walls) in regions with large diurnal temperature variations may introduce significant errors, and therefore requires particular caution.

In fundamental research on building thermal performance and load calculation, neglecting air infiltration is a common simplification. As in similar studies [41], the assumption of “closed doors and windows, neglecting natural convection terms” has been adopted by scholars. This is also supported by literature [67], which states that “when the air-conditioned zone maintains positive pressure, infiltration cooling load need not be calculated.” Situated in a cold climatic region, Lhasa’s building practices prioritize window airtightness for thermal conservation, leading to minimal air infiltration during the heating season under steady-state conditions. Nevertheless, it is essential to recognize that this simplification may introduce a modest underestimation in the model’s load predictions.

To establish a fundamental theoretical model of “microclimate-load” with a clear mechanism, the impact of thermal bridges was neglected in this study. The extent of thermal bridge effects is highly dependent on detailed design, materials, and construction quality. Neglecting thermal bridges will theoretically lead to a systematic underestimation of heat loss and heating load in the model. Quantitative evaluation of thermal bridge impacts can be achieved by combining measured energy consumption and thermal performance data from actual buildings.

Additionally, longwave radiant exchange between building surfaces is excluded from the model. During the daytime, solar radiation serves as the dominant heat gain term, and its intensity is far greater than the heat loss term caused by long-wave radiation; therefore, neglecting the latter has a limited impact on the analysis of the daytime-dominated thermal process trends. In winter nights, however, solar radiation is absent, and longwave radiative cooling becomes the primary heat loss mechanism. Neglecting this term therefore results in a systematic underestimation of the nighttime load and even the total daily load. However, a complete calculation of long-wave radiation involves highly coupled and complex variables such as sky temperature, view factor, and multi-surface temperatures, for which empirical values are often adopted. As indicated by Li Nianping [65], when the difference in long-wave radiation heat transfer between vertical surfaces is considered negligible, an empirical value of 0 is usually assigned to the vertical surfaces of buildings. To focus on the relationship between microclimate and thermal load, this simplification was implemented.

6. Conclusions and Future Research Directions

Under the background of Lhasa’s urbanization and increasing heating demand, the task of building energy conservation and emission reduction is urgent. While traditional energy-saving approaches often focus on the building envelope itself, this study focuses on quantifying the impact of microclimate on heating load. The main conclusions are as follows:

1. To realize the modeling pathway of “outdoor microclimate → wall surface temperature → heating load”, a mathematical model relating indoor and outdoor surface temperatures to building heating load was established (Equation (17)). This model was then integrated with the statistical model linking outdoor microclimate to outdoor surface temperature, resulting in a composite model that quantifies the relationship between near-wall microclimate and building heating load (Equation (20)).

2. To validate the reliability of the proposed composite model, this study compares the simulated values from energy consumption simulation software with the calculated values from the composite model under identical climatic parameters. The results indicate that the overall trends of the simulated and calculated values are generally consistent. The Coefficient of Variation of Root Mean Square Error (CV(RMSE)) between the simulated values and calculated values is 12.87%, which meets the hourly data requirement ($\leq 30\%$) specified in ASHRAE Guideline 14; the Normalized Mean Bias Error (NMBE) is -9.76% , which complies with the hourly data criterion ($\pm 10\%$) recommended by ASHRAE Guideline 14. The validation results indicate that the proposed model linking the near-wall outdoor microclimate and building heating load can be used, under specific conditions, to calculate the heating load of residential buildings affected by the near-wall outdoor microclimate, and can also provide a quantitative reference for the microclimate evaluation of residential buildings.
3. The core contribution of this study lies in the establishment of a coupled model of microclimate and building heating, and the proposal of the modeling path of “outdoor microclimate $\rightarrow$ wall surface temperature $\rightarrow$ heating load”. In the future, the top-priority research direction is to obtain heating energy consumption and microclimate data from real buildings to confirm and quantify the deviations of the current model. Secondly, comparative experiments can be designed to investigate the systematic differences between the “Phoenix-Ladybug decoupled simulation” and the CFD simulation method that can directly simulate all microclimatic conditions. Based on the resulting empirical and diagnostic insights, model refinement could focus first on integrating long-wave radiative cooling effects and air-infiltration correction factors to mitigate the existing underestimation bias. In addition, exploration can be conducted to adopt comprehensive thermal-humidity indicators (such as air enthalpy, wet-bulb temperature, etc.) to more accurately characterize the thermal impact of microclimate, thereby avoiding the collinearity problem caused by a relative humidity indicator.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

S	Shape coefficient
H	Floor height
WWR	Window-to-wall ratio
RMSE	Root mean square error
NMBE	Normalised mean bias error
Cv(RMSE)	Coefficient of variation of the root mean squared error

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