Thermal Comfort in Pedestrian Spaces of Mountain Cities in Humid and Cold Environments

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Abstract. This study aimed to explore the microclimate and outdoor thermal comfort characteristics of pedestrian spaces in mountain cities under humid and cold conditions. It focused on rainy and cloudy winter days in a typical mountain city (Chongqing), employing a combination of onsite thermal environment measurements and survey questionnaires. The research analyzed the Thermal Sensation Votes (TSV), thermal comfort evaluation indices (Universal Thermal Climate Index—UTCI, Physiological Equivalent Temperature—PET), and thermal environment parameters at representative sites. The findings revealed that firstly, outdoor thermal comfort and perception on cloudy winter days was minimally influenced by the microclimate. In contrast, on rainy winter days, it was significantly impacted by black globe temperature and wind speed. Secondly, the correlation between PET and Mean Thermal Sensation Vote (MTSV) was found to be higher than that between UTCI and MTSV, indicating that PET might be more aligned with the local climate and pedestrian activities. Lastly, the study determined the neutral PET range for different weather conditions in the area and compared it with existing research to identify discrepancies. This paper offers a reference for the neutral thermal comfort range in pedestrian spaces in regions with hot summers and cold winters under humid and cold winter climates, providing theoretical support for urban planning and design, with an emphasis on the results being presented in the past tense to reflect completed experiments.

Keywords: Microclimate · Outdoor thermal comfort · Mountain city · Walking space

1 Introduction

Against the backdrop of global warming, various extreme weather and climate events around the world have become more frequent, with their intensity, duration, and impact range all significantly increasing [1, 2]. However, people's willingness to engage in outdoor activities continues to rise. Outdoor activities are beneficial for increasing physical

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activity, promoting interpersonal interactions, enhancing life satisfaction, and improving physical health [3]. Urban pedestrian spaces, due to their necessity, have always been a focus as the most commonly used spaces for outdoor activities [4, 5]. Yet, the increased frequency of extreme weather events due to climate warming can negatively impact people's outdoor activities by dampening their willingness to be active. Both extreme heat and extreme cold can lead to cardiovascular diseases and, in severe cases, threaten the health or even the lives of organisms, particularly humans. Therefore, thermal comfort plays an unparalleled role in assessing the quality of outdoor environments [6].

The attention of scholars to the microclimate of urban streets and their thermal comfort is gradually increasing, especially in terms of creating livable urban environments and improving local microclimates, which are receiving significant focus. Through interdisciplinary integration, mastering the correct principles of technical means and operational skills provides a reference for guiding climate-adaptive planning and design, conducive to forming design strategies and guidelines. However, thermal comfort indices based on human energy balance cannot fully reflect the complex ways people perceive their environment, change behavior, or gradually adjust their expectations to adapt to it. It requires integrating local comfort perceptions and adjusting the index ranges corresponding to thermal comfort. Yet, the current outdoor thermal comfort indices face great limitations due to regional climate and seasonal adaptability, leading to inconsistent neutral ranges for outdoor thermal comfort.

There are over 165 outdoor thermal comfort evaluation indices, with the most commonly used ones in outdoor thermal comfort research being UTCI and PET [7, 8]. However, due to individuals' adaptation to regional climates and seasons, there is significant variation in the evaluation results between these two indices [9, 10]. There is no definitive conclusion on which index provides a more accurate evaluation. Even when the same index is used for evaluation in the same region, inconsistencies in outdoor thermal comfort ranges may arise due to seasonal variations [11]. These limitations significantly constrain outdoor thermal comfort evaluation. Moreover, research on outdoor thermal comfort in hot summers and cold winters regions typically focuses on clear or cloudy conditions during summer or winter seasons [12, 13], neglecting the importance of the winter thermal environment in these regions, characterized by cold and humid conditions. Furthermore, most studies target pedestrians with light activity levels (1.1–1.9 Met) [7]. However, for outdoor environments in mountainous cities, where people typically engage in uphill walking as part of their daily activities due to the unique topographical features, the metabolic rate is higher, typically around 3.1 Met [14]. This discrepancy in metabolic rates may result in deviations in the outdoor thermal comfort evaluation indices for pedestrian spaces in mountainous cities. If standard range values are still applied, it may lead to misunderstandings in outdoor thermal comfort assessment in these regions and potentially misguide urban planning and design strategies for thermal environment optimization.

Therefore, the purpose of this study is to develop outdoor thermal comfort evaluation indices more suitable for winter conditions in mountainous cities and to determine the local thermal comfort neutral range. It focuses on the typical pedestrian spaces in the Yuzhong District of Chongqing, analyzing the spatial and temporal differences between microclimate and thermal comfort under the outdoor microclimate measured and questionnaire surveyed during the cold and humid winter weather. It clarifies the correlation between thermal perception, microclimate and thermal comfort. Through linear regression analysis of the correlation coefficients between UTCI and PET and MTSV, suitable outdoor thermal comfort evaluation indices for the local context are identified, and the neutral range of outdoor thermal comfort in pedestrian spaces in mountainous cities during cold and humid conditions is calculated. This study aims to provide theoretical basis for improving outdoor thermal comfort indices in mountainous cities and to offer technical support for strategies aimed at enhancing outdoor thermal environments in mountainous city.

2 Method

2.1 Study Sites

Chongqing, located in the southwestern part of China, features a subtropical monsoon humid climate, classifying it within the hot summers and cold winters region. The city’s average annual temperature ranges between 17.5 to 20.0 °C, with the coldest month averaging temperatures of 4.0 to 8.0 °C. The average humidity often exceeds 70.0%, and over the past decade, the number of days with precipitation has reached more than 200 days a year, making it one of China’s high-humidity areas. Even during the cold winter months (November to January of the following year), the number of days with precipitation can reach up to 19 days. In December 2020, the highest humidity reached 95.0%. Therefore, as one of the typical regions with hot summers and cold winters, the impact of Chongqing’s cold and humid winter climate conditions on the urban outdoor thermal environment and human thermal comfort cannot be overlooked.

This study selected two pedestrian spaces with mountainous characteristics in Chongqing for its experimental sites: the First Mountain City Trail (Jianxing Ramp—JXR) and the Third Mountain City Trail (Shancheng Lane—SCL) (see Fig. 1). These trails integrate green corridors and urban balconies, serving as crucial pedestrian stairways connecting the upper and lower parts of Chongqing’s main city, aiding in alleviating the inconvenience of vehicular traffic between these areas. Moreover, the buildings along these two streets are mostly traditional Bayu residences, showcasing typical mountain city spaces and traditional Bayu architectural styles, representing a microcosm of Chongqing’s historical and cultural heritage. The primary users of these spaces are residents, with a small number of tourists also visiting.

2.2 Field Measurements

The field measurements were conducted on a rainy winter day and a cloudy day, specifically on January 10, 2021 (rainy day), and December 29, 2021 (cloudy day), from 8:00 to 17:00. The microclimate parameters measured included air temperature (Ta), relative humidity (RH), air velocity (va), and black globe temperature (Tg). These parameters are commonly used to analyze outdoor thermal environments and outdoor thermal comfort. The measurements were taken at 5-min intervals, with the average value for

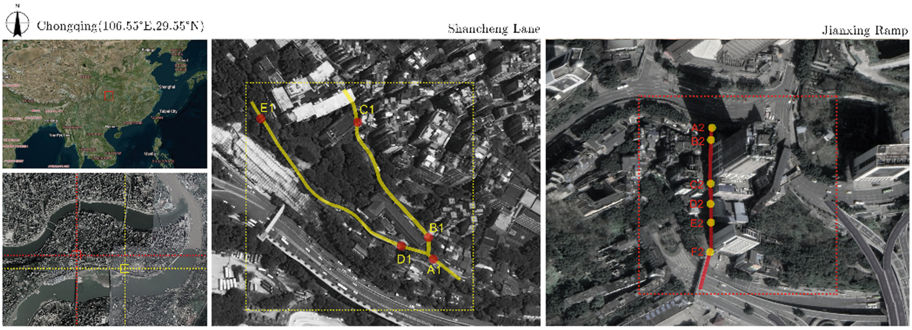


Fig. 1. Study sites and measurement points in the sites

each hour being used for analysis. The sensors for measuring these parameters were positioned approximately 1.1 m above the ground, corresponding to the location of the human body's core temperature. Additionally, these devices were calibrated before the measurements to comply with the ISO 7726 standard [15].

Spatial heterogeneity can significantly impact the outdoor thermal environment [16]. Therefore, considering the high degree of heterogeneity displayed by different interfaces (buildings, mountains, water bodies, etc.), building heights, and vegetation coverage on either side of the pedestrian spaces, this study arranged 5 and 6 measurement points in characteristic locations along SCL and JXR, respectively, with the locations of these points shown in Fig. 1. These two streets differ in building heights, street orientation, and vegetation. The pedestrian space of SCL is very narrow, ranging from 2 to 5 m in width, while JXR is about 10 m wide [15]. The street direction of JXR runs from north to south, while that of SCL is northwest. Moreover, SCL is close to the Yangtze River, with one side of the street adjacent to the river and the other side against a mountain or buildings. The pedestrian spaces on either side of JXR are primarily composed of traditional commerce and residences.

2.3 Questionnaire Survey

During the measurements of the outdoor thermal environment in pedestrian spaces, a questionnaire survey was conducted simultaneously. Randomly selected respondents were asked to complete the questionnaire after staying at each measurement point for 3 to 5 min. The questionnaire consisted of two parts: respondent basic information and their thermal perception votes. The basic information section included gender, type of respondent (permanent residents, visitors from other places, etc.), age group, weight range, clothing condition, outdoor stay duration, and activity state before the survey. The thermal perception voting section involved an overall evaluation of the outdoor thermal environment and an assessment of individual thermal environment factors (air temperature, humidity, wind speed, and sunlight). The overall thermal sensation evaluation in the questionnaire was based on the 7-point thermal sensation vote (TSV) according to the ASHRAE 55–2013 standard, with the overall thermal comfort evaluation set according to a 5-point thermal comfort vote (TCV) [17]. The acceptability levels of microclimate factors (sunlight, temperature, humidity, and wind speed) were assessed using a 4-point voting index [9].

2.4 Outdoor Thermal Comfort Indices

This study employs PET and UTCI as indices for evaluating thermal comfort. It combines actual measurement data and questionnaire surveys to analyze which index is more suitable for evaluating the cold and humid winter conditions of mountain cities. During outdoor testing, the mean radiant temperature (MRT) can be approximately calculated from the black globe temperature (Tg) and air velocity (va) using a formula (see formula 1) [18]. PET and UTCI are calculated using the Rhino & Grasshopper platform, where the input microclimate parameters are obtained from actual measurements. In terms of individual human factors, except for the activity level, which is set based on the climbing slope (5°) value (3.1 Met), all other parameters are set according to the software's built-in winter settings. Additionally, the wind speed required for UTCI calculations is at the height of 10 m/s. This study approximates the calculation based on the formula provided by Bröde, P. et al. [19].

$$\mathrm{MRT} = \left[\left(\mathrm{T_g} + 273.15\right)^4 + \frac{1.1{*}10^8{*}\mathrm{v_a^{0.6}}}{\varepsilon{*}D^{0.4}}\left(\mathrm{T_g} - \mathrm{T_a}\right)\right]^{0.25} - 273.15 \tag{1}$$

ε: Emissivity of black bulb thermometer; D: Diameter of black bulb thermometer, mm; Diameter of black bulb in this study is 150 mm.

3 Results and Discussion

3.1 The Results of the Questionnaire Survey

The survey was conducted over two days, with 430 respondents interviewed. Almost all respondents were residents of Chongqing, accustomed to the local climate, and thus capable of accurately and objectively evaluating the thermal environment during the field measurements. The gender distribution among respondents was nearly equal, with a male to female ratio close to 1:1. The majority of respondents were aged between 18 and 40 years, with weights mostly ranging from 40 to 70 kg.

Based on the statistics related to different weather conditions, the outdoor activities of the respondents were analyzed (including outdoor stay duration, types of activities, and whether they had been in an air-conditioned room within 15 min prior to completing the questionnaire). The results revealed that respondents generally spent a long time outdoors. On cloudy winter days, over 45% of respondents stayed outdoors for 3–4 h, and even on rainy winter days, around 35% stayed outdoors for the same duration. Regarding the type of activities, walking was the most frequently mentioned activity. There was a higher proportion of people standing during the rainy days compared to cloudy days.

Nonetheless, over 50% of respondents reported walking as their activity on rainy winter days. In terms of thermal experience, the vast majority of respondents had not been in an air-conditioned room in the 15 min before completing the questionnaire.

However, the proportion of respondents who had been in such a room was higher on a cloudy day than on a rainy day.

The study analyzed the thermal sensation and thermal comfort voting results of respondents under different weather conditions, yielding the following findings. On rainy winter days, respondents tended to feel cold, with 47% feeling cold and 16.5% feeling cool. Only 14% of respondents felt neutral. On cloudy winter days, however, 38.7% of respondents felt neutral, and 9.5% felt moderately warm or warmer. Additionally, over 60% of respondents voted the thermal environment on rainy winter days as uncomfortable or slightly uncomfortable. In contrast, on cloudy winter days, more than 70% of respondents indicated they felt neutral, comfortable, or slightly comfortable.

The results regarding the acceptance of microclimatic elements by respondents in different winter weather conditions show clear differences in the acceptability of sunlight, temperature, humidity, and wind speed under different weather conditions. On a rainy day compared to a cloudy day, the acceptance of microclimatic elements was significantly lower. The largest gap was in the acceptance of sunlight, with only 37.5% of respondents on rainy days indicating they slightly accept or accept it. In comparison, more than 59.5% of respondents on cloudy days found it acceptable. The acceptance of temperature also showed that the rainy day had a lower acceptability compared to the cloudy day. On cloudy days, 59.1% of respondents indicated that they found the temperature acceptable, whereas on rainy days, only 39.5% of respondents reported finding it somewhat acceptable.

In summary, there are clear differences in outdoor activity preferences, thermal sensations, and thermal comfort evaluations among respondents under different weather conditions. These differences provide an important reference for environmental regulation and urban planning.

3.2 Heterogeneity of Microclimate and Thermal Comfort

This study conducted measurements and analysis of microclimatic elements (Ta, RH, va and Tg) in pedestrian spaces of a mountain city during the winter rainy and cloudy days, revealing the heterogeneity of its microclimatic elements and thermal comfort. The results showed that there were certain differences in microclimatic elements and thermal comfort on rainy and cloudy winter days, with RH showing the largest variance, followed by PET. Other elements and UTCI also demonstrated some degree of diversity. On the one hand, these differences are reflected in the spatial morphology, vegetation cover, and other distinctive features of the measurement points [14]. On the other hand, the variations are also evident across different times and weather conditions.

Table 1 presents the statistical results of microclimatic elements and thermal comfort evaluations, showing significant differences in the results of each microclimatic element and thermal comfort evaluation under different weather conditions. For example, on a rainy day, the average Ta was only 4.8 °C, with a standard deviation (SD) of 0.4; while on a cloudy day, the average Ta was 9.1 °C, with an SD reaching 1.1. Similarly, the Tg showed similar results. However, for va, the wind was stronger on a rainy day than on a cloudy day, with a larger SD. The maximum va on the rainy day could reach 2.0 m/s, while on the cloudy day, it was 1.3m/s. On a rainy day, the RH ranged from 69.4% to 99.9%, with an average RH of 87.3%; on a cloudy day, the RH ranged from 55.8% to

78.5%, with an average of 66.1%, more than 20% lower than on the rainy day. However, the SD of RH on both rainy and cloudy days, although relatively large, was close, at 7.6 and 6.8, respectively.

Regarding the comparison of thermal comfort indices under different weather conditions, it was found that the averages of PET and UTCI were significantly different. On the rainy day, the weather was coldest, with an average PET of only 2.6 °C and a minimum value of −1.9 °C. On a cloudy day, the average PET was 7.4 °C, nearly three times higher than on a rainy day. Similarly, the average UTCI on a cloudy day (10.6 °C) was more than twice that on a rainy day (5.2 °C), indicating significant variability in thermal comfort indices across different weather conditions.

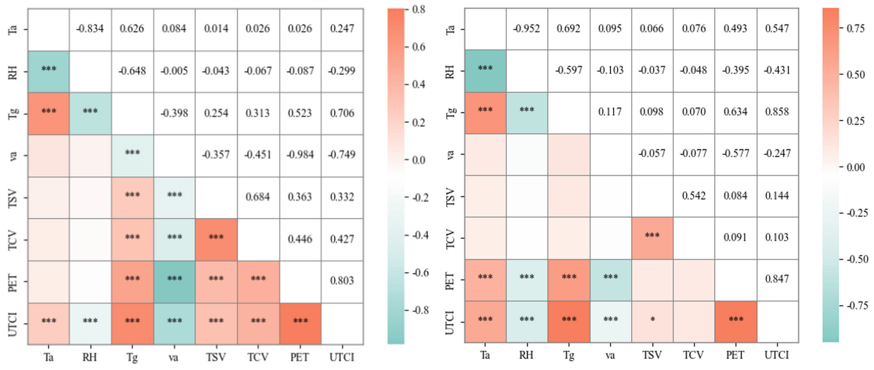
Table 1. The statistics of microclimate parameters and thermal comfort indices

		Ta (°**C)**	RH(%)	Tg (°C)	va (m/s)	PET (°C)	UTCI (°C)
Rainy	Mean	4.8	87.3	4.8	0.5	2.6	5.2
	Max	6.3	99.9	6.0	2.0	6.3	7.2
	Min	4.0	69.4	4.1	0.0	−1.9	−1.2
	Mean ± SD	0.4	7.6	0.5	0.5	2.5	1.8
Cloudy	Mean	9.1	66.1	10.4	0.6	7.4	10.6
	Max	10.6	78.5	14.8	1.3	11.5	14.5
	Min	7.0	55.8	7.1	0.1	2.5	5.9
	Mean ± SD	1.1	6.8	1.8	0.3	2.0	1.8

3.3 Correlation Between Thermal Perception and Microclimate and Thermal Comfort

A single-sample Kolmogorov-Smirnov (K-S) test was performed on all variables to check for the normality of the samples. The results showed that the asymptotic significance (two-tailed) $p < 0.05$ for all variables, indicating that the samples of all variables are not normally distributed. Therefore, Spearman's correlation was used to analyze the mechanisms of how thermal perception is influenced by microclimate and thermal comfort. The results are presented in Fig. 2, where '*' indicates $p < 0.1$, '**' indicates $p < 0.05$, and '***' indicates $p < 0.01$.

Overall, the correlation between thermal perception and microclimate and thermal comfort on a rainy day is stronger. The specific findings are as follows: (1) On a rainy day, the effects of Tg and va on TSV and TCV are significant, with Tg having a positive impact on both TSV and TCV, and va having a negative impact. On a cloudy day, however, all microclimate parameters have no significant impact on TSV and TCV. This suggests that wind protection in urban design needs to be emphasized for rainy winter days. (2) On rainy days, both PET and UTCI show a positive correlation with TSV and TCV, indicating that these indices can accurately assess thermal perception to some extent during such weather. On a cloudy day, the impact of PET and UTCI on TSV and TCV is almost negligible, with only UTCI showing a positive correlation with TSV at $p < 0.1$. The result reveals that the applicability of PET and UTCI varies under different weather conditions, and even within the same weather conditions, their applicability can differ.



(a) Rainy day (b) Cloudy day

Fig. 2. Correlation of thermal perception with microclimate and thermal comfort in different winter weather

3.4 Neutral PET Range

To further understand the applicability of different evaluation indices to human thermal sensation, this study used the temperature frequency method (Bin method) [20] to group PET and UTCI values from questionnaires under different weather conditions by intervals of 1 °C. It then calculated the average values of PET, UTCI, and thermal sensation votes (MTSV) for each interval, as well as the number of cases per interval. Using Python software, the study conducted statistical analysis on PET and UTCI against TSV, resulting in regression graphs of PET, UTCI, and MTSV under different weather conditions (see Fig. 3).

The analysis revealed the distinct applicability of thermal comfort indices under different weather conditions. On rainy winter days, the relationship between PET and MTSV was more pronounced, with a determination coefficient of 0.682. On cloudy winter days, the relationship between UTCI and MTSV was closer, with a determination coefficient of 0.547. Furthermore, on a rainy day, the slope of the regression equation between PET and MTSV was 0.162, which was higher than the slope on a cloudy day (0.085). This indicates that PET more influences MTSV on a rainy day than on a cloudy day. Combining the results from rainy and cloudy days, PET demonstrated stronger applicability than UTCI.

These findings suggest that for the cold and humid winter climate of the Chongqing area, using PET as an outdoor thermal comfort evaluation index is more in line with the local climate and pedestrian activities.

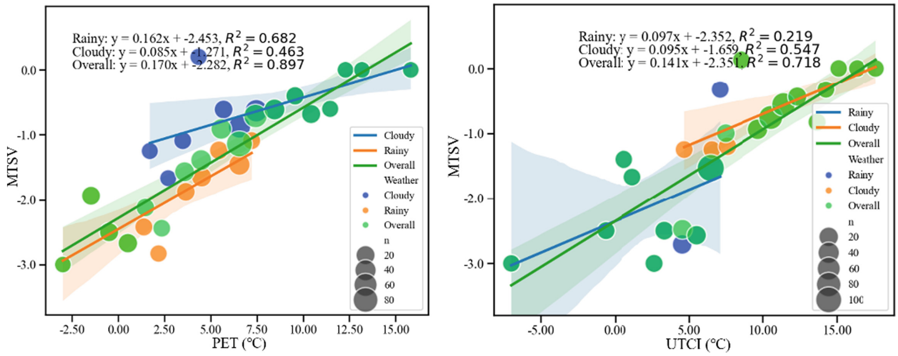


Fig. 3. The outdoor thermal perception benchmarks during the winter (left) based on the relationship between MTSV and PET, (right) based on the relationship between MTSV and UTCI

The findings suggest that using PET to predict thermal sensation is more accurate for this study. The study calculated the PET values corresponding to an MTSV between −0.5 and 0.5, which is defined as the Neutral PET Range (NPETR), to determine the neutral range of human thermal perception using PET. The NPETR varied significantly under different weather conditions (see Table 2). On the cloudy day, the neutral range was broader, from 9 to 21 °C, whereas on the rainy day, the NPETR was from 12 to 18 °C. Combining the results from rainy and cloudy days, the overall NPETR was determined to be from 10 to 16 °C.

Comparing this with the NPETR of other regions yields several insights (see Table 2). First, there is a considerable gap between the NPETR of different climatic zones and the initial NPETR. For instance, Chen, Hong et al.'s study on outdoor thermal comfort in Xi'an identified an NPETR of 7 to 16 °C [21], significantly lower than 18 to 23 °C. Secondly, even within the same climate zone, the NPETR can differ between cities. The results of this study are closer to He, Gao et al.'s findings on NPETR in Zhejiang [10] but diverge significantly from those for Shanghai [22], which also falls within the Cfa climate zone.

Overall, the neutral range for thermal comfort in outdoor studies varies. This variation can be attributed to differences in climatic zones, as well as the sample size, seasons, and weather conditions of the studies, which all influence the outcomes. Therefore, future research will need to include larger sample sizes to substantiate these findings further.

Table 2. Neutral PET range in different outdoor thermal comfort studies

Source	Climate zone	Season/ Weather	Site	NPETR(°C)	R^2
This study	Cfa	Winter/rainy	Chongqing, China	12–18	0.682
		Winter/cloudy		9–21	0.463
		Winter/overall		10–16	0.897
Matzarakis and Mayer(Initial) [23]	Cfb	Summer	Middle/western Europe	18–23	-
Yahia and Johansson [24]	BSk	Winter	Damascus, Syria	20–29	0.604
Chen, Wen et al. [22]	Cfa	Winter	Shanghai, China	15–29	0.74
Zhang, Wei et al. [25]	Cwa	Winter	Chengdu, China	11–21	0.356
Chen, Hong et al. [21]	Cwa to BSk	Winter	Xi'an, China	7–16	0.919
He, Gao et al. [10]	Cfa	Winter	Zhejiang, China	11–18	0.944

4 Conclusion

With the rapid changes in global climate due to significant greenhouse gas emissions, urban climate issues are becoming increasingly severe. Addressing how to improve urban climates and create comfortable pedestrian environments to meet people's aspirations for a healthy and livable living environment is an urgent issue. For regions with hot summers and cold winters, while the outdoor thermal environment in summer is important, thermal comfort outdoors during the cold, humid winter is equally critical. This study measured the microclimatic parameters of pedestrian spaces in a typical mountain city (Chongqing) during rainy and cloudy days in winter. At the same time, respondents were surveyed on their thermal perception, and the PET and UTCI thermal comfort indices were used to evaluate the outdoor thermal environment of the mountain city, leading to the following conclusions:

- The outdoor microclimate in winter is influenced by spatial heterogeneity, showing variations, especially in terms of humidity differences.
- On rainy winter days, thermal comfort is highly sensitive to black globe temperature and wind speed, which are the main environmental parameters affecting thermal comfort. In the future design of pedestrian spaces in mountainous urban areas, measures should be taken to prevent wind and minimize cold radiation. Additionally, it is advisable to increase the radiation heat sources appropriately, such as outdoor

vertical heaters, to improve outdoor thermal comfort during the winter's humid and cold seasons.

- Under the cold and humid conditions of Chongqing's winter, using PET as an outdoor thermal comfort index may be more aligned with the local climate and human activities. When assessing the neutral temperature for outdoor thermal comfort during winter, the NPETR is between 10 and 16 °C.

This study provides a foundation for research on outdoor thermal comfort during the cold and humid winter in regions with hot summers and cold winters. It also offers experience and reference for comfortable design in the construction of future urban environments that are livable and healthy.

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