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Winter Usability and Thermal Risks of Urban Parks in Severe-Cold Cities: An Integrated Assessment of Thermal Comfort, Cold-Stress Risk and Adaptive Behavior

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Abstract

Winter underuse of urban parks in severe-cold cities limits year-round outdoor activity, especially for cold-sensitive users. This study developed a comfort–risk–adaptation framework integrating thermal perception, model-estimated cold-stress risk, and behavioral responses. Field microclimate measurements and synchronous questionnaires were conducted in Nanhu Park, Changchun, China, under clear winter conditions, yielding 386 paired human–environment samples. The Universal Thermal Climate Index (UTCI), Required Clothing Insulation (IREQ), wind chill temperature (WCT), and contact cooling indicators were used to quantify thermal exposure and cold-stress risk. Results showed significant spatial differences in wind speed, solar radiation, mean radiant temperature, and UTCI, while air temperature and humidity varied little. The neutral UTCI was 3.14 °C (unweighted) and 3.70 °C (weighted), and the 80% thermal acceptability threshold was −15.24 °C (95% CI: −16.14 to −14.22 °C). Despite acceptable thermal perception, physiological cold-stress risks remained under certain conditions. The findings highlight the need to integrate solar access, wind mitigation, low-conductivity materials, and moderate activity routes to improve winter usability in severe-cold urban parks. Results are condition-specific and reflect observed users under clear to partly cloudy winter daytime conditions rather than universal thresholds.

Keywords: winter usability; severe-cold cities; urban parks; outdoor thermal comfort; cold-stress risk; thermal risk; climate-adaptive design; adaptive behaviour

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1. Introduction

Urban parks in severe-cold cities are expected to support outdoor recreation, physical activity and social interaction throughout the year. In winter, however, low temperature, wind exposure and limited solar access often reduce park use, shorten staying time and restrict the participation of elderly users, low-intensity users and other groups sensitive to cold exposure. This seasonal underuse weakens the contribution of urban parks to public-space equity, active lifestyles and year-round urban sustainability [1,2]. Parks, squares and other open spaces are therefore not only ecological or recreational resources, but also public infrastructures whose sustainable performance depends on whether they can remain

usable and safe under adverse climatic conditions [3–5]. In cold and severe-cold regions of China, winter conditions may persist for more than three months, making winter usability a critical issue for urban public-space planning and management [6–9]. Understanding how thermal perception, physiological cold-stress risk and adaptive behavior interact is therefore essential for improving the inclusive and sustainable use of urban parks in severe-cold cities.

The sustainable winter use of urban parks is strongly constrained by microclimatic exposure. Air temperature, solar radiation, wind speed, relative humidity and mean radiant temperature jointly affect human heat balance and influence outdoor staying time, activity intensity and spatial choices [10–12]. In park environments, spatial openness, vegetation structure, sky view factor, surface materials and proximity to water can modify local wind and radiation conditions, producing substantial differences in thermal experience among spaces [13]. Previous studies have shown that thermal environment, accessibility and landscape design together shape park-use behavior [14], and that park attendance is closely associated with solar radiation, sky view factor and thermal acceptability range [15,16]. Winter outdoor thermal sensation is also particularly sensitive to air temperature and solar radiation [17]. Beyond physical exposure, thermal history, cultural background, clothing adjustment and activity level further affect subjective responses to the same outdoor conditions [18–20]. These findings suggest that winter park usability is not determined by a single meteorological factor, but by the combined effects of microclimate, spatial form, individual characteristics and behavioral adaptation.

Various indices have been applied to assess outdoor thermal environments, including Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET), Standard Effective Temperature (SET*), Wet-Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI) [21]. Among them, UTCI has been widely used in urban climate and outdoor thermal-comfort studies because it integrates air temperature, wind speed, humidity and radiation into a comprehensive measure of human thermal stress. For severe-cold urban parks, however, identifying thermal neutrality or a thermal acceptability range alone is insufficient [22]. Users may perceive an outdoor space as acceptable for short-term use while still facing physiological risks caused by whole-body cooling, wind-induced local cooling or contact with cold surfaces. The Required Clothing Insulation (IREQ) index can evaluate whether actual clothing insulation is sufficient to maintain heat balance, while wind-chill temperature reflects the combined cooling effect of low temperature and wind. Cold-contact risk is also directly related to the safe use of benches, railings, fitness equipment and other outdoor facilities in winter parks [23–26]. Therefore, sustainable winter park assessment should move beyond comfort-oriented evaluation and incorporate both perceived usability and physiological risk.

Despite these advances, three limitations remain in existing research on winter outdoor thermal environments in cold and severe-cold regions [27]. First, many studies have focused on thermal comfort thresholds, neutral temperatures or acceptability ranges, while giving less attention to whether winter parks can be used safely, continuously and equitably by different user groups. Second, thermal acceptability is often treated as a practical criterion for outdoor use, although it does not necessarily represent the boundary of physiological cold-stress risk. This distinction is particularly important in severe-cold environments, where low-intensity users may remain vulnerable even when subjective discomfort is moderate. Third, design recommendations for winter parks have often emphasized increasing solar access or reducing wind speed, but have less frequently integrated activity intensity, staying behavior and material-contact risk into climate-adaptive renewal strategies. These gaps indicate the need for an integrated framework that connects thermal comfort,

cold-stress risk and behavioral adaptation with the broader goal of sustainable winter park use [28].

To address these gaps, this study examines Nanhu Park in Changchun, China, as a representative urban park in a severe-cold city. Based on field microclimate monitoring and synchronous questionnaire surveys, it develops a comfort–risk–adaptation framework for sustainable winter park use. The specific objectives are as follows: (1) to quantify spatial differences in winter microclimatic exposure, particularly wind speed, solar radiation, mean radiant temperature and UTCI; (2) to distinguish thermal neutrality, directly reported thermal acceptability, and model-estimated cold-stress risk, and to clarify their different implications for winter usability and thermal-safety assessment; (3) to identify vulnerable use conditions by analyzing activity intensity, spatial type, IREQ, wind-chill temperature and cold-contact risk; and (4) to propose climate-adaptive design strategies for improving sustainable winter use in severe-cold urban parks. Figure 1 presents the overall workflow of this study, including field monitoring, synchronous questionnaire survey, biometeorological index calculation, cold-stress assessment and statistical analysis. By linking environmental exposure, subjective thermal response, physiological risk and adaptive behavior, this study provides evidence for improving winter usability, thermal risk and climate-adaptive design in urban parks of severe-cold cities.

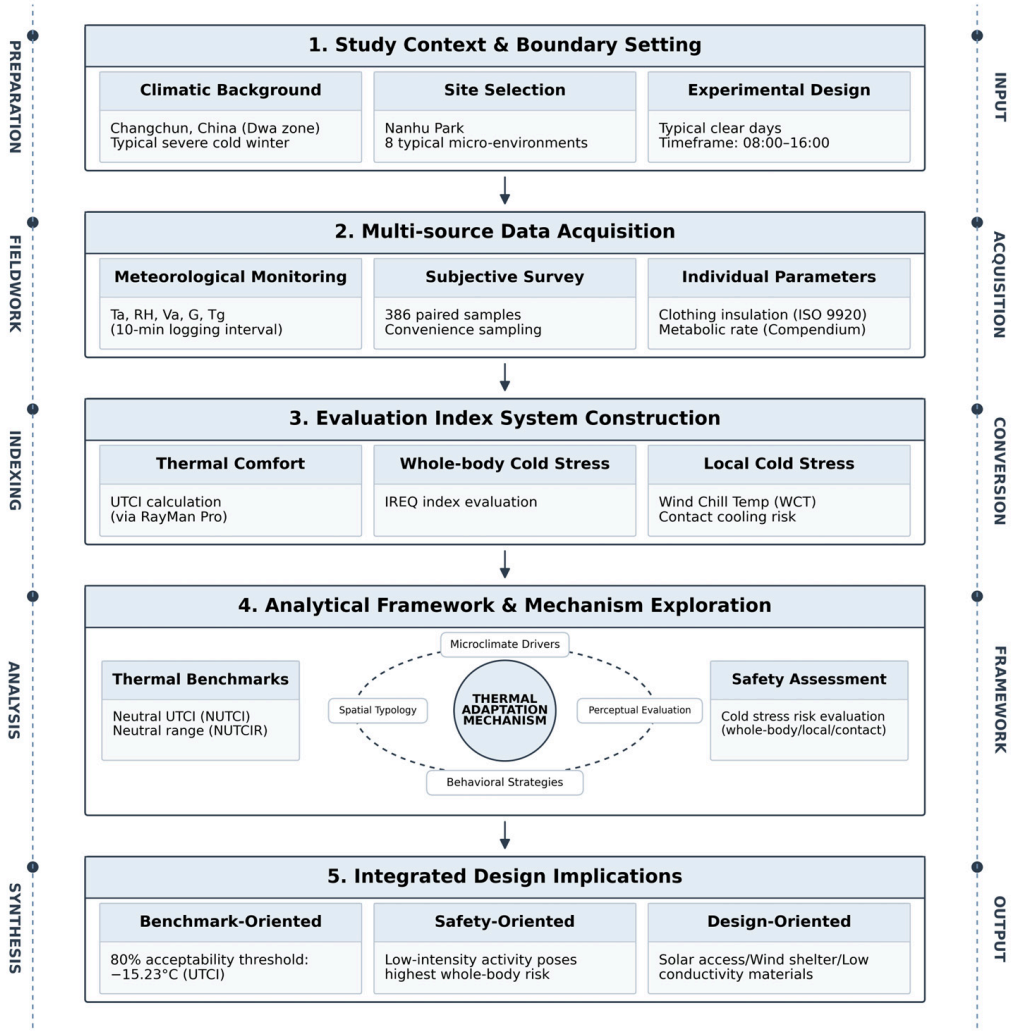


Figure 1. The integrated "comfort–risk–adaptation" research workflow [29].

2. Materials and Methods

2.1. Study Area

This study was conducted in Nanhu Park, Changchun, China (43°51′0″ N, 125°17′58″ E). Changchun is located in a cold climatic region and has a temperate monsoon climate, characterized by dry and windy springs, short and warm summers, clear autumns with large diurnal temperature variation, and long, severe winters (Figure 2). According to the Köppen–Geiger climate classification, Changchun is generally classified as Dwa.

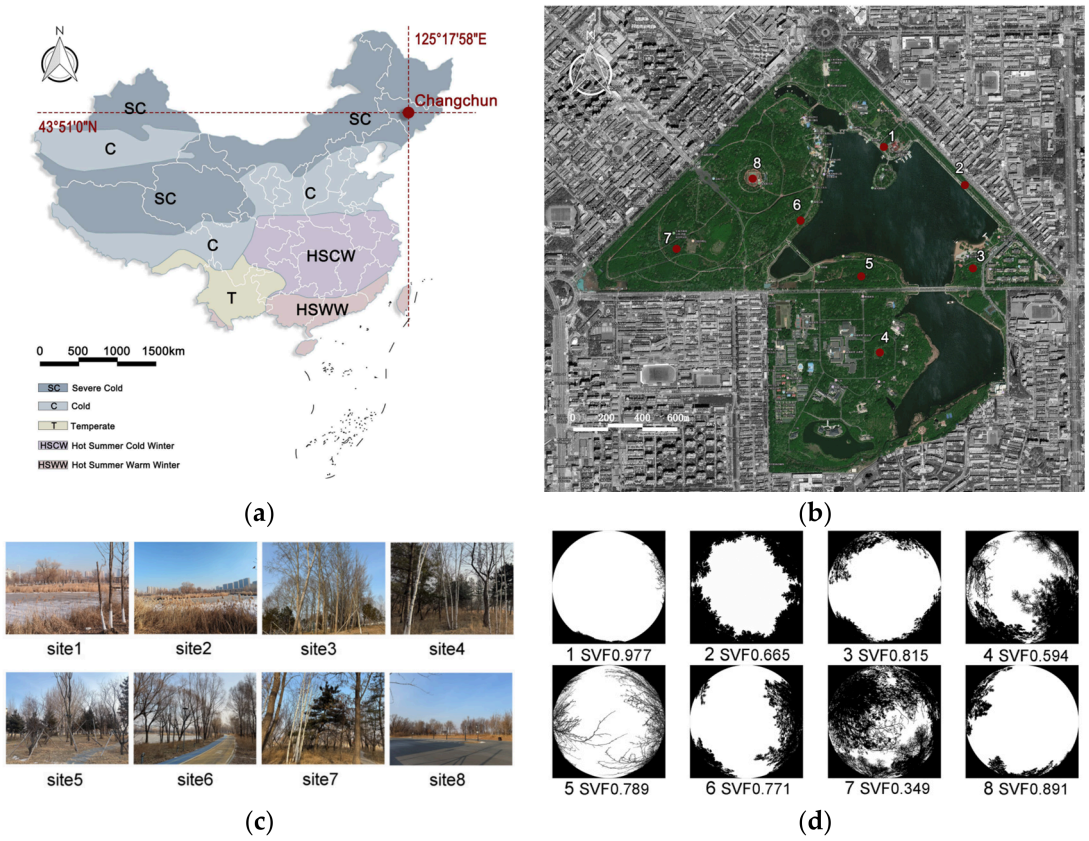


Figure 2. Study area and measurement sites: (**a**) site, (**b**) site location, (**c**) photographs of open spaces, and (**d**) fisheye photographs used to derive sky view factor (SVF).

Eight measurement sites were selected in Nanhu Park and grouped into four spatial types according to their dominant winter microclimatic and morphological characteristics, including openness, shading condition, lakeside exposure, pedestrian-use function, and solar–wind exposure. As shown in Table 1, each spatial type includes two representative measurement points, thereby ensuring a balanced distribution of samples under different conditions and providing a standardized basis for subsequent comparative analysis.

Table 1. Spatial mapping of measurement sites and thermal environment types in Nanhu Park.

Spatial Type	Thermal–Morphological Definition	Measurement Sites	Key Characteristics
Type I: Open wind-exposed lakeside space	High openness, strong wind exposure, proximity to lake surface	Site 1, Site 6	High wind speed, strong convective cooling, high exposure variability
Type II: Open sun-exposed activity space	Open space with high solar access and recreational function	Site 3, Site 8	High solar radiation, relatively favorable MRT, active use intensity
Type III: Transitional circulation space	Edge or movement corridor linking functional areas	Site 2, Site 5	Moderate SVF, mixed wind–solar conditions, short-duration stay
Type IV: Enclosed shaded cold space	Semi-enclosed or shaded interior park zones	Site 4, Site 7	Low SVF, low radiation, persistent cold accumulation

Type I, open wind-exposed lakeside spaces, includes Site 1 (lakeside area) and Site 6 (lakeside path). These spaces are characterized by proximity to the lake, high openness, and relatively strong wind exposure. Type II, open sun-exposed activity spaces, includes Site 3 (open activity area) and Site 8 (open activity space), representing open environments with relatively favorable solar access and active recreational use. Type III, transitional activity spaces, includes Site 2 (park edge) and Site 5 (pedestrian path), representing edge and circulation zones used for walking, short stays, and spatial transition. Type IV, enclosed shaded cold spaces, includes Site 4 (shaded area) and Site 7 (park interior), characterized by limited solar radiation, lower sky view factor, and relatively colder perceived conditions. Sky view factor (SVF), derived from fisheye photographs, was used as the main quantitative descriptor of spatial openness.

According to long-term climatic records, Changchun has a pronounced seasonal temperature range, with cold and dry winters and relatively warm summers. The climatic background indicates that winter outdoor activity is strongly constrained by low temperature and wind exposure, making Changchun a representative setting for examining winter thermal comfort and cold-stress risk in severe cold urban parks.

2.2. Data Collection

2.2.1. Field Microclimate Measurements

Field microclimate measurements were conducted in Nanhu Park, Changchun, from 1 to 3 January 2026. The survey was designed to capture the climatic conditions of the coldest month in the study area. January was selected because it is typically the coldest month in Changchun, often accompanied by snowfall, and also coincides with the city's winter tourism season, during which daily park use tends to increase. Considering Changchun's high latitude and limited winter daylight hours, the field survey was conducted from 08:00 to 16:00 Beijing time.

The survey days were selected as clear to partly cloudy winter days without snowfall, with stable sky conditions and continuous variation in solar radiation. Portable weather stations were used to record meteorological parameters, including air temperature (Ta), relative humidity (RH), wind speed (Va), solar radiation (G), and globe temperature (Tg). The measurement ranges and accuracies of the instruments are listed in Table 2. Before the fieldwork, all instruments were carefully calibrated in the laboratory and programmed to record data at 10 min intervals. Synchronous monitoring was conducted at the eight measurement sites to ensure that the observed microclimatic differences among spatial settings mainly reflected variations in spatial morphology rather than temporal fluctuations.

Table 2. Technical specifications of the meteorological instruments.

Instrumentation	Manufacturer	Microclimatic Parameters	Accuracy	Range	City and Country
Kestrel NK5500	Nielsen-Kellerman Co.	Air temperature (T_a) Relative humidity (RH) Wind speed (Va)	±0.5 °C ±3% 0.1 m/s	−30–70 °C 10–90% 0–40 m/s	Boothwyn, PA, USA
Delta HD 32.2	Delta OHM S.r.l.	Globe temperature (T_g)	±0.1 °C	−30–120 °C	Caselle di Selvazzano, Padua, Italy
Apogee Instruments MP-200	Apogee Instruments, Inc.	Solar radiation (G)	≤±5%	0–2000 W/m^2	Logan, UT, USA

The field campaign was designed to capture clear to partly cloudy winter-use conditions, rather than to characterize the full spectrum of winter weather scenarios. Accordingly, the findings should be regarded as case-specific evidence under relatively stable winter conditions, rather than as a comprehensive seasonal assessment encompassing snowy, overcast, or extreme-wind conditions.

2.2.2. Questionnaire Survey

A subjective questionnaire survey was conducted with park users who were present near the portable weather stations during the field-monitoring periods. To avoid implying probability-based random sampling, the term "randomly selected" was revised. In this study, participants were approached opportunistically within a site-based stratified quota sampling framework. At each measurement site and during each survey period, eligible park users who were exposed to the corresponding outdoor environment were invited to complete the questionnaire. This approach has been widely applied in previous outdoor thermal comfort studies [30]. The questionnaire consisted of two parts. The first part collected respondents' personal information, including age, gender, clothing, activity type, and the location and time of the survey. Based on ASHRAE 55 and ISO 7730 [31,32], respondents' clothing and activity types were converted into clothing insulation values and metabolic rates. The second part focused on thermal comfort-related responses. A five-point thermal comfort vote (TCV) scale adapted from subjective thermal-environment assessment protocols was used. This scale was designed to capture the degree of perceived thermal discomfort under outdoor conditions [33]. This scale has also been used in previous studies [34,35]. The TCV scale in this study differs from the standard ASHRAE seven-point thermal sensation scale. It was specifically used to evaluate perceived thermal discomfort intensity rather than thermal sensation or thermal acceptability. A direct thermal acceptability vote (TAV) was also included in the questionnaire to assess whether participants considered the current outdoor thermal environment acceptable for their ongoing activity or stay.

The questionnaire survey was carried out synchronously near each microclimate measurement site. Park users who were active or staying around the measurement sites were approached opportunistically according to the site-based quota structure. Their current location, survey time, clothing ensemble, activity type, and subjective thermal perception were recorded. All questionnaires were completed in the outdoor environments to which the respondents were actually exposed, thereby avoiding potential bias in subjective thermal evaluation caused by artificial relocation between measurement sites. Participants were eligible if they were present in the survey area during monitoring, had sufficient exposure to the local outdoor environment to report current thermal perception, and agreed to participate voluntarily. Incomplete, repeated, or site- or time-mismatched questionnaires, or those missing key variables, were excluded. Each respondent participated only once, after being informed that the survey was anonymous, voluntary, and used solely for academic research.

2.2.3. Study Design and Sample Distribution

To improve comparability across park spaces and activity states, a site-based stratified quota sampling strategy was adopted. The primary quota was defined by measurement site, with 48–49 valid paired subject–microclimate samples collected at each of the eight sites. Within each site, park users were approached opportunistically during the survey periods. Gender, age group, and activity intensity were recorded and monitored during data collection to avoid substantial imbalance. Based on the four spatial types described above, two representative measurement sites were selected for each type. A total of 400 questionnaires were collected, of which 386 were valid after excluding incomplete or unmatched responses, resulting in a valid-questionnaire rate of 96.5%. Each sample corresponded to a specific measurement site, survey period, microclimatic parameters, individual attributes, activity level, and subjective thermal perception record. These paired data were used for subsequent analyses of UTCI-based thermal comfort, IREQ-based whole-body cooling risk, wind-chill exposure, and behavioral adaptation.

The sample included 219 men (56.7%) and 167 women (43.3%), and age groups were distributed as 91 youth (23.6%), 221 middle-aged (57.3%), and 74 elderly (19.2%). Activity intensity was classified as low (113 samples), moderate (210 samples), and vigorous (63 samples). This distribution ensured a relatively balanced representation of spatial locations, sex, age, and activity levels for subsequent analyses.

This sample structure supports comparative analyses of thermal comfort and cold-stress differences across spatial types, gender, age groups, and activity intensities. It also provides a data basis for explaining the relationships among microclimatic exposure, human metabolic regulation, and thermal adaptive behavior in winter urban parks.

2.2.4. Survey and Coding of Thermal Adaptive Behavior

To identify behavioral responses to cold exposure among winter park users, the questionnaire recorded the dominant thermal adaptive behavior adopted by each respondent under the current thermal environment. The behavioral options included moving to sunny areas, increasing or maintaining physical activity, adding clothing, drinking hot water, and shortening the stay or making only a brief stay. These behaviors correspond to increased solar radiation exposure, enhanced metabolic heat production, increased clothing insulation, short-term subjective warming compensation, and control of cold-exposure duration, respectively.

In the statistical analysis, only one dominant behavior was retained for each respondent. To further interpret the thermal-regulation mechanisms underlying different behaviors, the five behavioral options were grouped into three adaptive types. Moving to sunny areas was classified as environmental exposure adjustment, representing an increase in solar radiation exposure through spatial relocation. Increasing or maintaining physical activity was classified as metabolic heat enhancement, representing increased human heat production through a higher activity level. Adding clothing, drinking hot water, and shortening the stay were classified as passive insulation or exposure reduction, representing the alleviation of cold discomfort through increased insulation, short-term thermal compensation, or reduced exposure duration (Table 3).

Table 3. Coding scheme for thermal adaptive behaviors.

Recorded Behavior	Adaptation Type	Behavioral Mechanism	Code
Moving to a sunny area	Environmental exposure adjustment	Increasing solar radiation exposure by changing location	1
Increasing physical activity/regular exercise	Metabolic heat enhancement	Increasing internal heat production through activity	2
Putting on extra clothes	Passive insulation/exposure reduction	Increasing clothing insulation	3
Drinking hot water	Passive insulation/exposure reduction	Short-term perceived warming and heat compensation	4
Short stopover/brief stay	Passive insulation/exposure reduction	Reducing cold exposure duration	5

This coding scheme was used to compare differences in thermal adaptive behavior across gender, activity intensity, and spatial type. It also provides a basis for explaining behavioral pathways such as sun-seeking, continuous activity, and exposure shortening in winter urban parks.

2.3. Clothing Insulation and Metabolic Rate

Respondents' clothing was assessed using the clothing ensemble method specified in ISO 9920 [29]. Table 4 presents the winter clothing items worn by the respondents during the survey and their corresponding clothing insulation values.

Table 4. Clothing insulation values used in the survey.

Category	Item	Variant/Description	Evaluation Value
Sundries	Gloves	/	0.05
	Cap	/	0.01
Upper body	Underwear T-shirt	/	0.08
	Underwear-shirt	long sleeves, thermal	0.20
		long sleeves	0.25
	Short sleeves	/	0.15
	Vest	/	0.20
	Shirt	/	0.25
	Jacket	thin	0.25
		thick	0.35
		fiber-pelt	0.40
	Down vest	/	0.30
	Down jacket	/	0.55
	Coat	/	0.60
Lower body	Underwear-pants	long-legged, thermal	0.15
		long-legged	0.22
	Sweatpants	/	0.28
	Flannel	/	0.28
	Trousers	thin	0.15
		thick	0.24
		fiber-pelt	0.40
	Winter dress	long sleeves	0.40
Feet	Shoes	thin-soled	0.02
		thick-soled	0.04
	Boots	/	0.10
	Socks	thin	0.02
		thick & ankle	0.05
		thick & long	0.10

Activity intensity was classified according to the metabolic equivalents of different activities provided in the Compendium of Physical Activities [36]. Considering common behavioral patterns in winter parks, the recorded activities were grouped into three categories: light activity (<3.0 METs), moderate activity (3.0–5.9 METs), and vigorous activity ($\geq$6.0 METs). Representative activities for each winter park scenario were selected as coding items (Table 5) [37,38]. This classification supports the analysis of how activity intensity influences outdoor thermal sensation, cold-stress responses, and clothing-insulation adjustment behavior [39].

2.4. Thermal Comfort Assessment Index

The Universal Thermal Climate Index (UTCI) was used to assess thermal comfort in this study. UTCI is a widely applied comprehensive biometeorological index in outdoor thermal-environment research. It represents human thermal stress under the combined effects of air temperature, wind speed, humidity, and radiation as an equivalent temperature, making it suitable for the integrated assessment of cold stress and thermal comfort in complex outdoor environments [40,41].

Table 5. Activity categories and corresponding metabolic rates.

Physical Activity Levels	Activity	Activity Coding	Met Units	Metabolic Rate(W/m^2)
Low intensity < 3 METs	sitting quietly	07021	1.3	75.66
	standing, talking in person/on the phone/text messaging	09050	1.8	104.76
	walking, less than 2.0 mph	17151	2.0	116.40
Moderate intensity 3-5.9 METs	walking, 2.5 mph	17170	3.0	174.60
	walking, 2.8 to 3.2 mph	17190	3.5	203.70
	walking for pleasure	17160	3.5	203.70
	walking, 3.5 mph, brisk, walking for exercise	17200	4.3	250.26
	table tennis	15660	4.0	232.80
	badminton	15030	5.5	320.10
	bicycling, 9.4 mph	01019	5.8	337.56
	skating, ice, 9 mph or less	19020	5.5	320.10
Vigorous intensity ≥ 6 METs	running, 4 mph (13 min/mile)	12029	6.0	349.20
	jogging	12020	7.0	407.40
	tennis	15675	7.3	424.86
	general dancing	03031	7.8	453.96

In this study, air temperature (T_a), relative humidity (RH), wind speed (Va), and mean radiant temperature (T_{mrt}) were used as input parameters for UTCI calculation. Because the field measurement height of wind speed differed from the standard input height required for UTCI calculation, the measured wind speed was height-corrected before analysis. UTCI values were then calculated using RayMan Pro 2.1 based on meteorological inputs (T_a, RH, Va, and T_{mrt}), following the RayMan model methodology for human thermal environment assessment [42]. Mean radiant temperature (T_{mrt}) was derived from globe temperature (T_g), air temperature (T_a), wind speed (Va), globe diameter (D), and globe emissivity (ε). T_{mrt} was calculated using Equation (1).

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.10 \times 10^8 V^{0.6}}{\varepsilon D^{0.4}} (T_g - T_a) \right]^{\frac{1}{4}} - 273 \quad (1)$$

In Equation (1), D corresponds to the diameter of the black globe (D = 0.05 m), ε indicates the emissivity of the black globe (ε = 0.95).

2.5. Cold-Stress Assessment Indices

2.5.1. Required Clothing Insulation (IREQ)

Required Clothing Insulation (IREQ) is a measure of thermal stress determined by the combined effects of internal heat production and heat exchange with the surrounding environment [43]. In this study, the IREQ index was used to assess the risk of whole-body cooling during outdoor exposure in severe winter conditions. IREQ estimates the clothing insulation required to maintain human heat balance or prevent unacceptable cold stress under specific conditions of air temperature, wind speed, humidity, mean radiant temperature, and metabolic rate. Unlike UTCI, which mainly represents integrated thermal exposure, IREQ further identifies whether actual clothing insulation is sufficient to protect the body against whole-body cooling in low-temperature environments.

Based on ISO 11079, two key thresholds were calculated using IREQ: minimum required clothing insulation (ICLmin) and neutral required clothing insulation (ICLneutral) [43–45]. ICLmin represents the minimum insulation level required to prevent excessive body cooling under acceptable physiological strain, whereas ICLneutral represents the

clothing insulation required to maintain a thermally neutral state. By comparing actual clothing insulation (Icl) with these thresholds, the whole-body cooling risk of each respondent under the corresponding microclimatic exposure can be determined.

The clothing insulation reported from the questionnaire was first calculated as basic clothing insulation from the clothing ensemble values listed in ISO 9920. For the IREQ calculation, this value was converted to resultant clothing insulation after accounting for the effects of wind exposure and body movement, following the correction logic of ISO 11079 and ISO 9920. In line with ISO 11079 cold-exposure assessment practice, DLE values were capped at 8 h, corresponding to the maximum evaluation period of a standard full-shift exposure. Therefore, DLE values reported as 8.00 h indicate that the relevant thermal strain criterion was not reached within the 8 h evaluation window; they should not be interpreted as exact physiological failure times. The full computational framework, equations, parameter definitions, correction procedure, and DLE truncation rule are provided in Appendix A.

When Icl < ICLmin, the existing clothing insulation is insufficient, indicating a high risk of whole-body cooling. When ICLmin $\leq$ Icl $\leq$ ICLneutral, the existing clothing can maintain a relatively acceptable cold-exposure state, although thermal neutrality has not yet been achieved. When Icl $\geq$ ICLneutral, the direct risk of whole-body cooling is relatively low; however, for respondents engaged in vigorous activity, sweating and secondary heat loss after activity cessation should still be considered (Table 6).

Table 6. Classification criteria for whole-body cooling risk based on IREQ.

Condition	Thermal Interpretation	Risk Level	Suggested Response
Icl $\geq$ IREQneutral	Clothing insulation meets or exceeds neutral requirement	Low whole-body cooling risk; possible overheating during vigorous activity	Maintain or adjust clothing according to activity intensity
IREQmin $\leq$ Icl < IREQneutral	Clothing insulation meets minimum requirement but does not reach neutral level	Moderate whole-body cooling risk	Maintain clothing and activity; avoid prolonged sedentary exposure
Icl < IREQmin	Clothing insulation is insufficient for cold exposure	High whole-body cooling risk	Increase clothing insulation, reduce exposure duration, or increase activity level

2.5.2. Wind-Chill Temperature (WCT)

In severe winter outdoor environments, wind speed enhances convective heat loss from the human body surface, making the perceived coldness stronger than that indicated by air temperature alone. In this study, wind-chill temperature (WCT) was used to assess the local cooling risk caused by the combined effects of low temperature and wind speed [46]. A lower WCT indicates stronger cold stimulation of exposed skin and a higher risk of local cold discomfort and frostbite.

Because the standard wind-chill formula generally uses wind speed at a height of 10 m as the input, whereas the wind speed in this study was measured at the pedestrian activity height, a height correction was first applied. The measured wind speed was converted to the equivalent wind speed at 10 m using the power-law equation:

$$V_{10} = V_z \left(\frac{10}{z} \right)^{\alpha} \quad (2)$$

where V_{10} is the wind speed at a height of 10 m, in m/s; V_z is the measured wind speed at height z, in m/s; z is the installation height of the anemometer; and α is the surface roughness exponent. Considering that the study area is an urban park environment,

α = 0.20 was adopted as an approximate correction coefficient. The corrected wind speed V_{10} was then converted from m/s to km/h for WCT calculation:

$$V_{10,\mathrm{km/h}} = 3.6V_{10} \quad (3)$$

Wind-chill temperature was calculated as follows:

$$WCT = 13.12 + 0.6215T_a - 11.37V_{10}^{0.16} + 0.3965T_aV_{10}^{0.16} \quad (4)$$

where WCT is the wind-chill temperature, in °C; T_a is air temperature, in °C; and V_{10} is the wind speed at a height of 10 m, in km/h. This equation was used to evaluate wind-chill exposure under low-temperature and windy conditions. When wind speed is very low, the wind-chill effect is weak, and WCT remains close to air temperature.

A sensitivity analysis was conducted using surface roughness exponent values between 0.15 and 0.25, which showed negligible variation in WCT-based risk classification. Based on the calculated WCT values, local cooling risk was classified into four levels. When WCT was above −10 °C, the local cooling risk for exposed skin was relatively low. When WCT ranged from −27 to −10 °C, marked cold discomfort and local cooling risk could occur. When WCT ranged from −39 to −27 °C, the risk of frostbite increased. When WCT was below −39 °C, exposed skin faced a high frostbite risk (Table 7). This classification was used to compare wind-chill exposure across different spatial types and to identify local cold-risk issues in open, wind-exposed, and low-activity staying spaces during winter.

Table 7. Classification criteria for local cooling risk based on wind-chill temperature.

WCT Range (°C)	Risk Level	Thermal Interpretation	Implication for Winter Park Use
WCT > −10	Low local cooling risk	Weak wind-induced cooling stress	Short-term outdoor exposure is generally tolerable
−27 < WCT ≤ −10	Cold discomfort/local cooling risk	Exposed skin may experience marked cold discomfort	Wind protection and short-stay nodes are recommended
−39 < WCT ≤ −27	Increased frostbite risk	Frostbite risk increases with exposure duration	Prolonged stay should be avoided in wind-exposed spaces
WCT ≤ −39	High frostbite risk	Continuous exposure may be unsafe for exposed skin	Outdoor stay should be restricted; protective design is necessary

2.5.3. Contact Cooling Risk

In addition to whole-body cooling and wind-induced local cooling, direct contact with cold outdoor surfaces may cause localized discomfort or injury in winter parks. Benches, railings, handrails, steps, and fitness facilities are frequently touched by users during outdoor activities; therefore, material-related contact cooling was included as a supplementary local safety indicator in this study.

Contact cooling risk was assessed following ISO 13732-3, Ergonomics of the thermal environment—Methods for the assessment of human responses to contact with surfaces—Part 3: Cold surfaces [47]. The assessment focused on four representative materials commonly used in urban park facilities: wood, nylon, stone, and steel. For each material, surface temperature was measured under two exposure conditions: sunlit and shaded. Measurements were conducted at the eight measurement sites and matched with the corresponding microclimate observation period. For each material–exposure combination, surface temperature was averaged over a 10 min interval to maintain consistency with the microclimate records.

Two contact scenarios were defined according to typical winter park use: 10 s finger contact and 100 s hand grasp. The 10 s finger-contact scenario represents short-term

incidental touch, such as touching a railing, bench surface, or fitness equipment. The 100 s hand-grasp scenario represents sustained contact, such as holding a handrail or gripping outdoor equipment. These two scenarios involve different contact areas, contact pressure, exposure duration, and heat-transfer characteristics; therefore, they were analyzed separately rather than treated as two time points of the same exposure process.

For each material, exposure condition, and contact scenario, measured surface temperature was compared with the ISO 13732-3 threshold values for pain, numbness, and frostbite responses. The risk level was determined using a threshold-screening logic. When the measured surface temperature was lower than or equal to the corresponding threshold temperature, the relevant contact cooling response was identified:

$$Risk_i = \begin{cases} 1, & T_s \leq T_{i,threshold} \\ 0, & T_s > T_{i,threshold} \end{cases} \quad (5)$$

where $Risk_i$ indicates whether the i-th type of contact cooling risk occurs; T_s is the measured material surface temperature; $T_{i,threshold}$ is the risk threshold corresponding to the specific material and contact scenario; and i denotes pain, numbness, or frostbite risk.

The final contact cooling output was organized as a three-dimensional matrix:

$$\text{Material} \times \text{Exposure condition} \times \text{Contact mode}$$

For each matrix cell, the dominant risk class, the number of affected sites, and the mean surface temperature were reported. This matrix-based approach improves reproducibility by ensuring that each risk outcome can be traced to a specific combination of material type, solar exposure, and contact scenario.

Because the assessment was based on bare-skin contact thresholds, the results should be interpreted as conservative screening indicators of material-related local cooling potential rather than direct predictions of actual injury probability. In real winter park use, gloves, skin moisture, individual sensitivity, contact pressure, contact area, surface roughness, and exposure duration may modify the actual contact response. Therefore, contact cooling risk was used in this study as a relative material safety indicator for winter park facilities. The risk categories were assigned according to the ISO 13732-3 threshold tables for cold surface contact. This matrix-based formulation ensures the full traceability of each risk outcome to a specific combination of material, exposure condition, and contact mode.

Surface temperatures of park facility materials were measured using a contact-type thermocouple thermometer (Table 8). All surface temperature measurements were conducted using direct contact measurement mode. The thermocouple probe was placed in direct physical contact with the surface materials to ensure stable thermal equilibrium between the sensor and the measured surface. Each measurement point was recorded continuously for 10 min, and the final value was obtained by averaging the stabilized readings over the measurement period to match the 10 min microclimate observation interval. The measured materials represent actual in situ park facilities and surfaces located within the study area, rather than standardized or laboratory-prepared material samples. All measurements were conducted under both sun-exposed and shaded conditions at the same field monitoring sites used for microclimate observations.

2.6. Statistical Analysis

A multi-level statistical framework was employed to ensure the robustness of the results, including aggregate-level bin analysis, individual-level clustered modelling, and uncertainty quantification.

Table 8. Technical specifications of the contact-type thermocouple thermometer.

Item	Description
Instrument	TASI TA610A (Single-channel K-type thermocouple thermometer)
Sensor type	K-type thermocouple probe
Measurement range	−200 °C to 1372 °C (−328 °F to 2501 °F)
Accuracy	±(0.2% + 0.7 °C)
Resolution	0.1 °C (−99.9 to 999.9 °C); 1 °C outside this range
Sampling rate	1 measurement per second

At the aggregate level, 1 °C UTCI bin-based regressions were used to estimate the relationship between mean thermal sensation vote (MTSV) and UTCI. Both unweighted and sample-size-weighted regressions were conducted. The weighted regression was used as a sensitivity estimator to assess the influence of unequal bin sample sizes on the stability of the neutral UTCI estimate. In the weighted approach, each bin was weighted according to its sample size to reduce bias caused by uneven data distribution.

At the individual level, generalized estimating equation (GEE) models were applied to account for the clustered structure of the dataset. Site–time blocks, defined by combining measurement site, survey date, and 10 min microclimate interval, were used as clustering units. Cluster-robust (sandwich) standard errors were applied to the generalized estimating equation (GEE) models to correct for within-cluster correlation at the site–time block level. This adjustment ensures that statistical inference is not biassed by repeated observations within identical environmental exposure conditions. Both binary and ordinal link functions were tested depending on variable type.

To quantify uncertainty in thermal benchmarks, cluster-aware bootstrap resampling (1000 iterations) was applied at the site–time block level. Bootstrap procedures were used to generate bias-corrected 95% confidence intervals for both neutral UTCI and thermal acceptability thresholds, ensuring that uncertainty estimates accounted for within-cluster correlation.

Sensitivity analyses were performed by varying UTCI bin widths (0.5 °C, 1 °C, and 2 °C) and minimum bin size thresholds ($n \geq 3$, $n \geq 5$, $n \geq 10$). Alternative model specifications with and without interaction terms (UTCI × metabolic rate; UTCI × clothing insulation) were compared to test the stability of estimates.

This combined analytical framework ensures that the results are not dependent on a single modelling assumption and improves the reliability and generalizability of thermal benchmark estimation in severe-cold urban park environments.

3. Results

3.1. Descriptive Analysis

3.1.1. Meteorological Parameters

The descriptive statistics and between-group significance tests for microclimatic conditions at the eight measurement sites are presented in Figure 3. Overall, air temperature and relative humidity showed only limited variation among the sites. The mean air temperature (Ta) ranged from −16.03 to −14.24 °C, while relative humidity (RH) ranged from 54.46% to 56.53%. The Kruskal–Wallis test showed that the spatial differences in Ta and RH were not statistically significant (Ta: $H = 8.94$, $p = 0.257$; RH: $H = 8.34$, $p = 0.303$), indicating that all measurement sites were exposed to a similar winter weather background during the survey period.

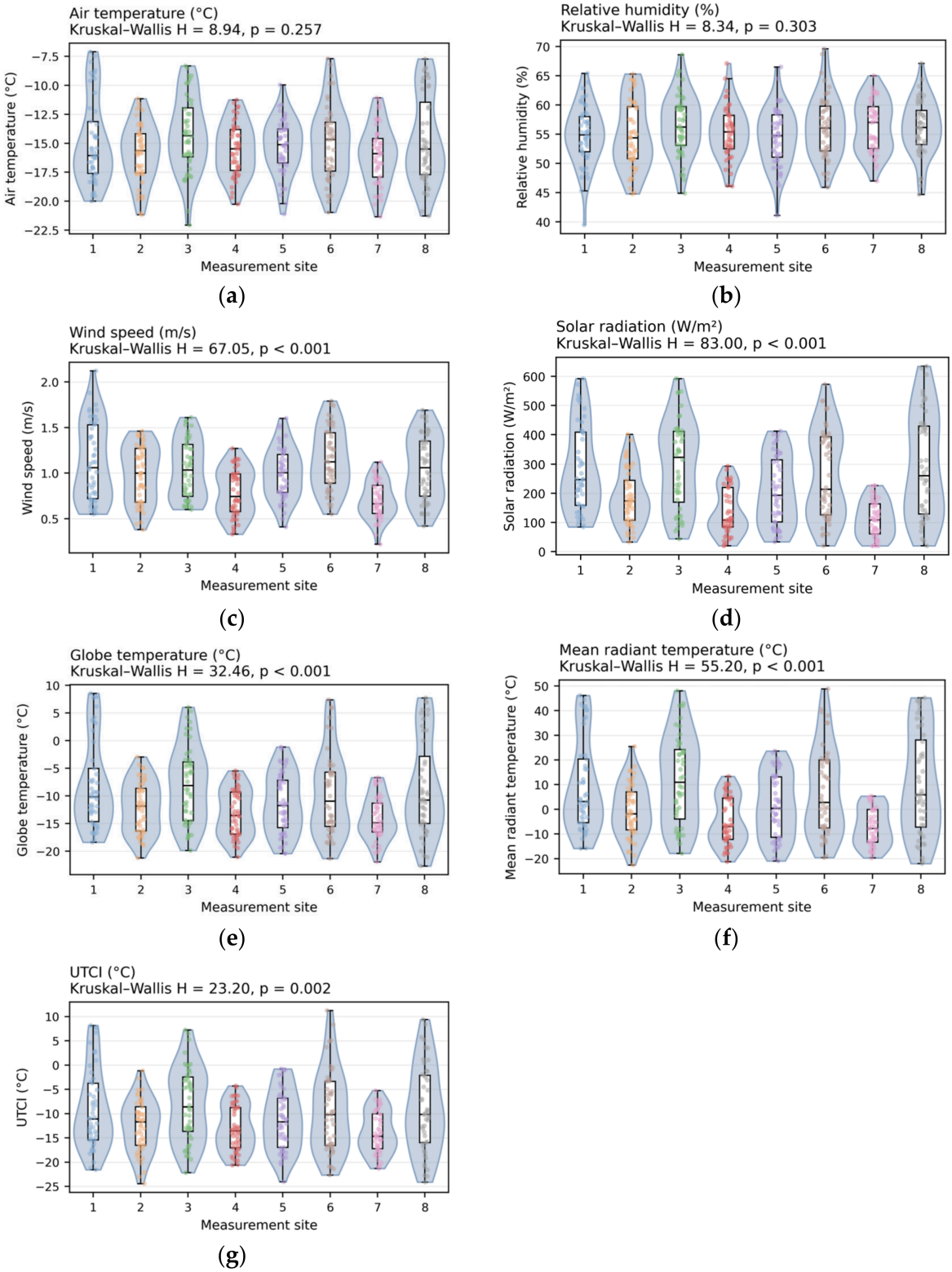


Figure 3. Spatial variation in microclimatic parameters across the eight measurement sites. (**a**) Air temperature; (**b**) relative humidity; (**c**) wind speed; (**d**) solar radiation; (**e**) globe temperature; (**f**) mean radiant temperature; (**g**) UTCI.

By contrast, wind speed, solar radiation, and radiation-related variables exhibited significant spatial differences. Va, G, T_g, T_{mrt}, and UTCI differed significantly among the eight measurement sites ($p < 0.05$). Among these variables, solar radiation (G) showed the largest effect size ($\varepsilon^2 = 0.201$), followed by wind speed (Va; $\varepsilon^2 = 0.159$) and mean radiant

temperature (T_{mrt}; ε^2 = 0.128). Further Dunn–Bonferroni post hoc comparisons indicated that the most pronounced differences occurred between open sun-exposed or lakeside sites and shaded or park-interior sites, particularly for G, T_{mrt}, and UTCI. Type I open wind-exposed lakeside spaces generally showed higher wind speed and stronger wind-chill potential, whereas Type IV enclosed shaded cold spaces were characterized by lower solar radiation and lower T_{mrt}. Type II open sun-exposed activity spaces provided relatively favorable radiant conditions, while Type III transitional activity spaces showed intermediate microclimatic characteristics. Specifically, Site 3, Site 8, and Site 1 had relatively high solar radiation levels; Site 6, Site 1, and Site 8 had relatively high wind speeds; and Site 7 showed the lowest values of G, Va, and T_{mrt} (Figure 3). The SVF values and field-observed spatial descriptors provided a morphological explanation for these microclimatic differences. More open sites generally had higher SVF values and stronger potential solar exposure, whereas shaded or semi-enclosed sites had lower SVF values and weaker radiative gains. However, SVF was not interpreted as the sole determinant of winter thermal exposure, because lakeside wind exposure and activity-space function also influenced measured wind speed, T_{mrt}, and UTCI.

These results indicate that winter microclimatic variation within Nanhu Park was mainly shaped by wind and radiation rather than by background air temperature. For sustainable winter use, this distinction is important. Air temperature and relative humidity are largely controlled by regional weather conditions and are difficult to modify through park design, whereas wind exposure, solar access, surface-contact conditions and the distribution of staying nodes can be adjusted through spatial planning and material selection. Therefore, winter optimization in severe-cold urban parks should focus not only on whether spaces are open or enclosed, but also on how wind and solar radiation are coordinated to support safe outdoor staying, walking and activity.

3.1.2. Preference Votes

To identify users' demands for microclimate regulation in winter parks, this study analyzed preference votes for air temperature, relative humidity, wind speed, and solar radiation. Overall, the strongest preferences were concentrated on increasing air temperature, increasing solar radiation, and reducing wind speed. Specifically, 53.9% of respondents preferred a higher air temperature, and 45.1% preferred stronger solar radiation. Preferences for relative humidity were weak, with 75.6% of respondents preferring the current humidity level to remain unchanged. Regarding wind speed, 29.5% of respondents preferred lower wind speed, 50.0% preferred no change, and only 20.5% preferred higher wind speed (Figure 4). These results indicate that, in severe winter park environments, users' dominant needs are not related to humidity adjustment, but to increasing heat gain and reducing wind-induced cooling exposure.

Correlation analysis showed that air temperature preference was significantly negatively correlated with UTCI. Solar radiation preference was also significantly negatively correlated with UTCI, indicating that the colder the thermal exposure, the stronger the users' preference for higher air temperature and increased sunshine. Wind speed preference was significantly negatively correlated with measured wind speed, suggesting that higher wind exposure intensified the demand for wind reduction. By contrast, relative humidity preference showed no stable association with the main thermal environmental variables.

Differences in preference votes among spatial types were mainly observed for air temperature and solar radiation. The chi-square test showed that air temperature preference differed significantly across spatial types. The proportions of respondents preferring higher air temperature were relatively high in Type IV enclosed shaded cold spaces and Type III transitional activity spaces, reaching 63.5% and 60.8%, respectively. In contrast, the

corresponding proportions were lower in Type II open sun-exposed activity spaces and Type I open wind-exposed lakeside spaces, at 46.9% and 44.3%, respectively. Solar radiation preference also showed significant spatial variation. The highest proportion of respondents preferring stronger solar radiation was observed in Type IV enclosed shaded cold spaces, at 54.2%, whereas the lowest proportion was observed in open sun-exposed spaces, at 25.0%. By contrast, wind speed and relative humidity preferences did not differ significantly among spatial types.

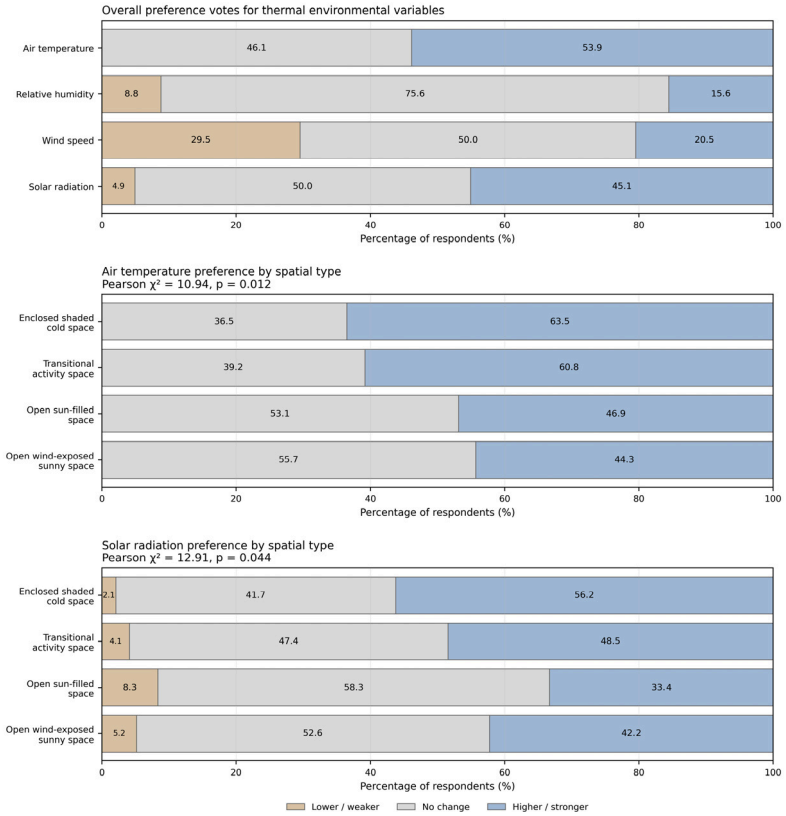


Figure 4. Thermal preference votes across microclimatic variables and space types.

Overall, the preference results suggest that winter park users were not simply unwilling to use outdoor spaces under cold conditions. Rather, they required more perceptible thermal benefits, including access to sunshine, reduced wind exposure and opportunities for short, protected stays. The strong preference for higher air temperature and stronger solar radiation, together with the demand for lower wind speed in exposed areas, indicates that winter park usability depends on whether users can find microclimatic choices that help them regulate cold exposure. For sustainable winter use, shaded and low-radiation spaces should be compensated by nearby sun-exposed nodes, while wind-exposed spaces should be supported by sheltered interfaces and short-stay thermal buffer areas.

3.1.3. Thermal Sensation Vote (TSV)

Air temperature (T_a), relative humidity (RH), wind speed (Va), and globe temperature (T_g) are key factors influencing outdoor thermal comfort in urban open spaces [48]. Overall, respondents' thermal sensation votes were skewed toward the cold side, with a mean TSV of -0.88 ± 0.73, mainly distributed between -2 and 0. The highest proportion was observed at TSV = -1, indicating that winter park users generally experienced slightly cool conditions, followed by neutral thermal sensations. Extreme cold sensation and warm-side responses accounted for relatively small proportions. These results suggest that winter

park spaces remained usable to some extent, although cold exposure was still the dominant thermal experience.

Correlation analysis showed that TSV was closely associated with the integrated thermal environment. Spearman's rank correlation analysis indicated a significant positive correlation between UTCI and TSV ($\rho = 0.591$, $p < 0.001$), suggesting that improved integrated thermal exposure can substantially reduce perceived coldness (Figure 5). Metabolic rate was also significantly positively correlated with TSV ($\rho = 0.296$, $p < 0.001$), indicating that activity-related heat production is an important compensatory factor for subjective thermal sensation in winter. After a multiple linear regression model was further established, UTCI and metabolic rate remained significant predictors of TSV. After controlling for gender, age, clothing insulation, and spatial type, each 1 °C increase in UTCI was associated with an average increase of 0.059 units in TSV, while each 1 W/m^2 increase in metabolic rate was associated with an average increase of 0.002 units in TSV. The adjusted R^2 of the model was 0.431, indicating that integrated microclimatic exposure and activity-related heat production together explained a substantial proportion of the variation in winter thermal sensation.

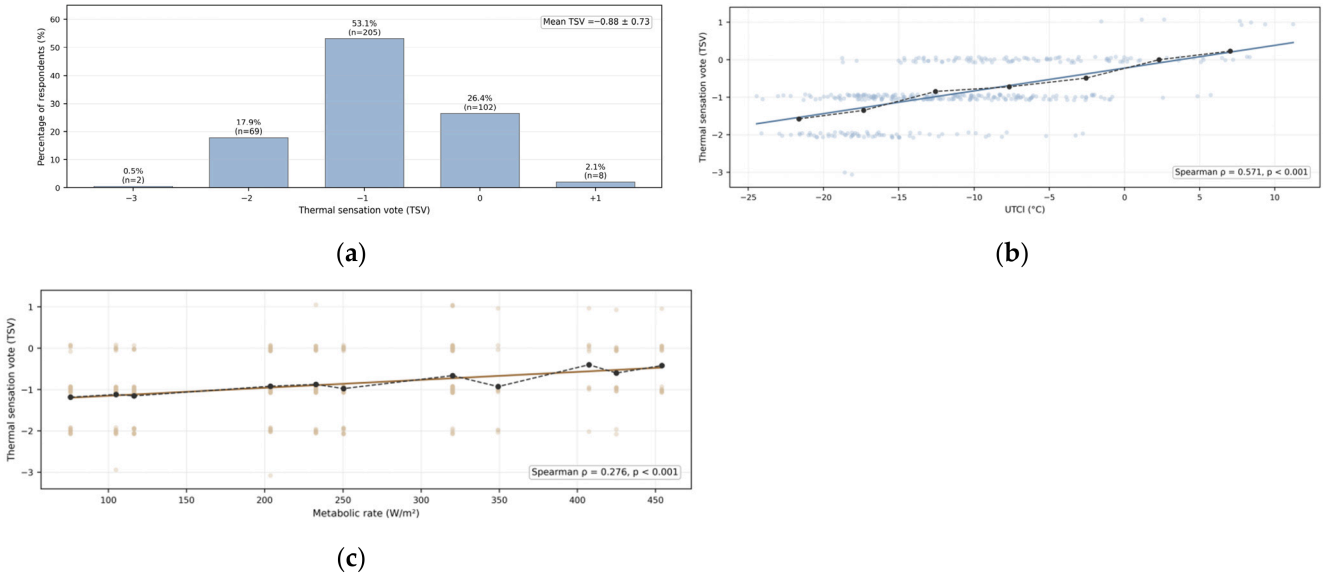


Figure 5. Distribution of thermal sensation votes and their main determinants under winter park exposure. (**a**) TSV distribution. (**b**) Association between UTCI and TSV. (**c**) Association between metabolic rate and TSV.

These results indicate that winter thermal sensation was influenced not only by integrated microclimatic exposure, but also by users' activity-related heat production. Higher UTCI improved perceived thermal conditions, while higher metabolic rate helped reduce cold sensation under the same winter background. From the perspective of winter park usability, this means that active use should be treated as part of the thermal adaptation mechanism. Continuous walking routes, light-to-moderate activity spaces and distributed activity nodes can help users maintain metabolic heat production and improve perceived thermal conditions without relying solely on static resting spaces.

3.1.4. Thermal Comfort Vote (TCV)

In addition to meteorological factors, individual parameters and psychological adaptation also influence outdoor thermal comfort [49]. The thermal comfort vote (TCV) results showed that winter park users were generally in a slightly uncomfortable state. The mean TCV for the full sample was 0.85 ± 0.71. The highest proportion was observed at TCV = 1,

accounting for 49.7%, followed by TCV = 0 (32.9%) and TCV = 2 (16.6%), while TCV = 3 accounted for only 0.8%. These results indicate that although most respondents did not report strong discomfort, winter cold exposure still shifted the overall thermal comfort evaluation away from a fully comfortable state.

Spearman's rank correlation analysis showed that TCV was significantly associated with integrated thermal exposure. TCV was significantly negatively correlated with UTCI ($\rho = -0.494$, $p < 0.001$), and also with air temperature (T_a), globe temperature (T_g), and mean radiant temperature (T_{mrt}). This indicates that improved thermal environmental conditions can effectively reduce the degree of discomfort. Among individual factors, metabolic rate was significantly negatively correlated with TCV ($\rho = -0.478$, $p < 0.001$), suggesting that activity-related heat production helps alleviate winter cold discomfort. By contrast, clothing insulation was positively correlated with TCV ($\rho = 0.269$, $p < 0.001$), reflecting that higher clothing insulation levels were generally observed under colder and more uncomfortable exposure conditions.

Group comparisons further indicated that activity intensity was a major factor influencing TCV. Because TCV is an ordinal variable, the Kruskal–Wallis H test was used to compare differences among activity-intensity groups. The results showed significant differences among the low-intensity, moderate-intensity, and vigorous-activity groups ($H = 80.46$, $p < 0.001$). Further Dunn–Bonferroni post hoc comparisons indicated that TCV in the low-intensity activity group was significantly higher than that in the moderate-intensity and vigorous-activity groups, suggesting that users in low metabolic states were more likely to experience cold discomfort. TCV also differed significantly among the four spatial types ($H = 9.30$, $p = 0.026$). Type IV enclosed shaded cold spaces showed higher TCV values, indicating stronger cold discomfort, whereas Type II open sun-exposed activity spaces and Type I open wind-exposed lakeside spaces showed lower TCV values under the observed clear-winter conditions. This suggests that solar radiation partly compensated for cold exposure, although wind exposure in lakeside spaces still requires separate consideration through WCT-based local cooling assessment.

Overall, winter thermal comfort in Nanhu Park was mainly influenced by integrated thermal exposure and activity intensity. Higher UTCI and higher metabolic rate reduced cold discomfort, whereas shaded, low-radiation and low-activity conditions intensified discomfort. This result identifies low-intensity users as a vulnerable group in the sustainable winter use of severe-cold urban parks. These users may include elderly visitors, slow walkers, landscape viewers, caregivers and short-stay users, who cannot always compensate for cold exposure through increased activity. Therefore, winter park renewal should provide sun-exposed, wind-sheltered and easily accessible buffer nodes for low-activity users, while also supporting continuous moderate-intensity movement for users with greater activity capacity.

3.2. Thermal Benchmarks

3.2.1. Neutral UTCI (NUTCI) and Neutral UTCI Range (NUTCIR)

Neutral temperature refers to the thermal condition under which people feel neither hot nor cold. In this study, the mean thermal sensation vote (MTSV) was calculated within 1 °C UTCI bins, and a linear regression was then established between MTSV and UTCI to determine the neutral UTCI and its neutral range [50]. To reduce the influence of unstable estimates caused by small sample sizes, only UTCI bins with $n \geq 3$ were retained for regression analysis.

The retained UTCI bins were mainly distributed between −21 °C and −4 °C, reflecting the typical clear winter exposure conditions during the field survey. MTSV generally increased with increasing UTCI. In the low-UTCI range, respondents mainly reported cold

sensations, whereas *MTSV* gradually approached thermal neutrality as UTCI increased. The bin-based regression showed a strong linear relationship between *MTSV* and UTCI:

$$MTSV = 0.0607UTCI - 0.1906 \quad (6)$$

The bin-based regression showed an apparent positive association between UTCI and *MTSV* under the observed clear to partly cloudy winter conditions. Based on the unweighted 1 °C bin regression, the neutral UTCI was 3.14 °C, and the neutral UTCI range corresponding to $-0.5 \leq MTSV \leq 0.5$ was −5.09 to 11.37 °C. However, because the analysis was based on aggregated bin means, the R^2 value should be interpreted as a descriptive fit at the bin level rather than as individual-level explanatory performance (Figure 6).

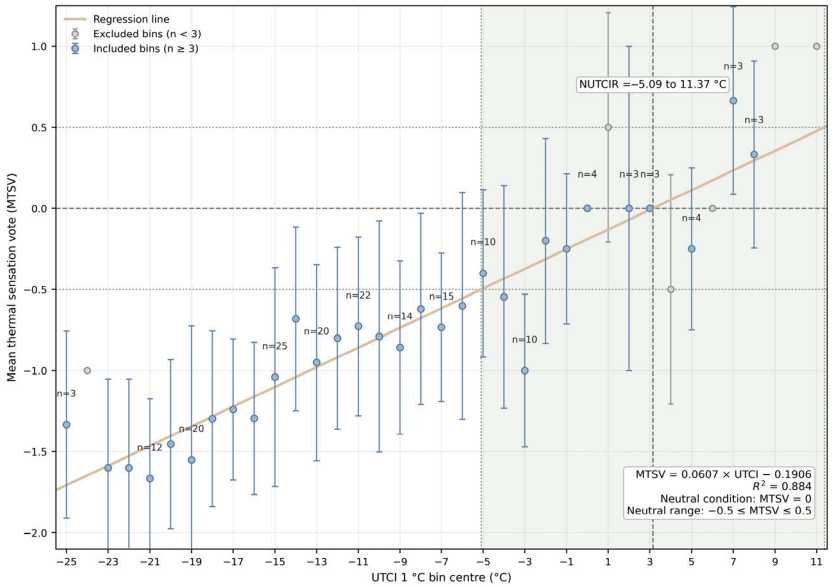


Figure 6. Relationship between UTCI and mean thermal sensation vote based on 1 °C UTCI bins.

To examine the robustness of this estimate, a sample-size-weighted bin regression was further conducted. The weighted model produced a neutral *UTCI* of 3.70 °C. Bootstrap resampling with 1000 iterations yielded a 95% confidence interval of 1.68 to 7.09 °C. Sensitivity analyses using alternative UTCI bin widths and minimum bin-size thresholds produced neutral UTCI estimates ranging from 1.41 to 5.56 °C. These results indicate that the estimated neutral UTCI remained on the slightly positive side of the UTCI scale, but its exact value was sensitive to binning and sampling structure.

An ordinal GEE model was also fitted at the individual-response level to account for the clustered site–time structure of the dataset. After controlling for metabolic rate, clothing insulation, age group, gender and spatial type, UTCI remained positively associated with warmer thermal sensation. This confirms that the relationship between UTCI and TSV was not solely an artefact of binning. Nevertheless, the neutral UTCI should be interpreted as a case-specific descriptive benchmark for surveyed winter park users under clear to partly cloudy winter conditions, rather than as a universal winter comfort threshold for severe-cold cities. These procedures ensured that the estimate was not sensitive to data discretization or sampling imbalance.

3.2.2. Thermal Acceptability Range (TAR)

Thermal acceptability was analyzed using the directly reported thermal acceptability vote (TAV), rather than being derived from the thermal comfort vote (TCV). In the questionnaire, respondents were asked whether the current outdoor thermal environment was

acceptable for their ongoing activity or stay, with responses recorded as "acceptable" or "unacceptable". Among the 386 valid paired human–environment samples, 66 respondents reported the current outdoor thermal environment as unacceptable, corresponding to an unacceptability rate of 17.1%. For statistical modelling, TAV was coded as a binary variable, with 0 representing acceptable and 1 representing unacceptable. In this study, TAV is defined as a binary behavioral usability judgement rather than a thermal sensation-derived construct. It directly reflects whether respondents consider the current thermal environment suitable for continuing their ongoing outdoor activity or stay. Therefore, TAV is conceptually independent from thermal sensation (TSV) and thermal discomfort (TCV), and represents a higher-level decision variable related to outdoor usability under real behavioral conditions.

To account for the clustered structure of the dataset, a binary generalized estimating equation (GEE) logistic model was fitted using a site–time block as the clustering unit. The site–time block was created by combining measurement site, survey date, and the matched 10 min microclimate interval, because multiple respondents could share the same local environmental record. UTCI was used as the main explanatory variable, while metabolic rate, clothing insulation, age group, gender, and spatial type were included as covariates. Interaction terms between UTCI and metabolic rate, and between UTCI and clothing insulation, were further tested to examine whether activity intensity and clothing adjustment modified the relationship between UTCI and thermal unacceptability.

The GEE logistic model showed that UTCI was negatively associated with the probability of thermal unacceptability, indicating that higher UTCI reduced the likelihood that respondents judged the current outdoor environment as unacceptable. To ensure model robustness, cluster-robust standard errors were applied using site–time blocks as clustering units. In addition, bootstrap resampling (1000 iterations) was conducted to estimate the uncertainty of the thermal acceptability threshold. Sensitivity tests using alternative model specifications confirmed the stability of the estimated threshold. Based on the fitted GEE logistic model, the UTCI corresponding to a 20% probability of thermal unacceptability was −15.24 °C. Cluster bootstrap resampling with 1000 iterations produced a 95% confidence interval of −16.14 to −14.22 °C. The relatively low temperature associated with 80% thermal acceptability does not indicate thermal comfort or physiological neutrality, but reflects behavioral tolerance under adaptive winter use conditions. Users may still continue outdoor activities under strong cold stress when compensatory mechanisms such as increased metabolic activity, solar seeking, and shortened exposure duration are available, leading to a divergence between perceived acceptability and physiological strain. This result was close to the original logistic estimate, suggesting that the cold-side acceptability threshold remained relatively stable after accounting for the clustered site–time structure. Detailed clustered-model and robustness results are provided in Table A1. Full GEE model outputs are provided in Table A2.

The resulting threshold should be interpreted cautiously. It represents a direct TAV-based subjective acceptability boundary for surveyed winter park users under clear to partly cloudy winter conditions. It does not indicate thermal neutrality, nor does it represent a physiological safety boundary. Users may still face model-estimated whole-body cooling, wind-chill exposure, or contact-cooling potential even when they report that the outdoor thermal environment is acceptable for their current activity or stay. Therefore, the TAV-based acceptability threshold was interpreted together with IREQ, WCT, and contact-cooling indicators in the assessment of winter usability and estimated cold-stress risk.

3.3. Outdoor Cold Stress

3.3.1. Whole-Body Cooling Assessment

Cold stress is assessed in terms of both whole-body and local cooling. In this study, the Required Clothing Insulation (IREQ) index was used to evaluate the risk of whole-body cooling under winter park exposure conditions. The results showed that the respondents' actual clothing insulation was 1.63 ± 0.19 clo, which was lower than the mean values of both ICLmin (2.24 ± 1.31 clo) and ICLneutral (2.55 ± 1.35 clo). In total, 68.7% of the samples had actual clothing insulation lower than ICLmin, and 82.4% were lower than ICLneutral, indicating that conventional winter clothing may not fully meet whole-body insulation requirements under some severe cold exposure conditions.

The results for allowable exposure duration were consistent with the above interpretation. In the low-intensity activity group, DLEmin and DLEneutral were only 0.70 ± 0.10 h and 0.61 ± 0.11 h, respectively. In the moderate-intensity activity group, they increased to 5.68 ± 0.62 h and 3.26 ± 0.65 h, respectively. In the vigorous-activity group, both reached 8.00 h (Table 9). By contrast, differences in IREQ-related indicators among spatial types were not statistically significant (all $p > 0.05$), suggesting that whole-body cooling risk was mainly determined by the combined effects of activity-related metabolism and clothing insulation.

Table 9. IREQ-based whole-body cooling assessment by activity intensity.

Activity Intensity	n	Clothing Insulation (clo)	ICLmin (clo)	ICLneutral (clo)	DLEmin (h)	DLEneutral (h)	Main Risk Interpretation
Low	113	1.76 ± 0.18	4.15 ± 0.16	4.54 ± 0.17	0.70 ± 0.10	0.61 ± 0.11	Insufficient insulation
Moderate	210	1.60 ± 0.15	1.72 ± 0.13	2.00 ± 0.14	5.68 ± 0.62	3.26 ± 0.65	Mainly insufficient insulation
Vigorous	63	1.49 ± 0.18	0.55 ± 0.10	0.83 ± 0.10	≥8.00	≥8.00	No cooling risk/monitor sweating

Overall, vigorous activity may be constrained by age, physical capacity, and health conditions, and may increase the risk of secondary heat loss after sweating or activity cessation. By contrast, moderate-intensity activity provides a better balance among reducing cold-exposure risk, maintaining an acceptable physical load, and supporting longer outdoor activity duration. Under the observed conditions, moderate-intensity activity was associated more with lower estimated whole-body cooling risk than low-intensity activity, while avoiding some potential limitations of vigorous activity.

3.3.2. Local Cooling Assessment

Local cooling was reflected in both wind-chill exposure and cold-surface contact risk. The WCT results showed that the mean wind-chill temperature for the full sample was −19.33 ± 3.69 °C, ranging from −27.80 to −9.52 °C. Most samples were classified as cold discomfort or local cooling risk, accounting for 94.8% of the total. A small proportion reached the level of increased frostbite risk (4.7%), while only 0.5% were classified as low local cooling risk. Differences in WCT among the four spatial types were not statistically significant (Kruskal–Wallis H = 2.59, $p = 0.459$), indicating that wind-induced local cooling was a widespread exposure condition across the park rather than being limited to a single spatial type.

Contact cooling risk exhibited significant variability across material type and exposure condition. The mean surface temperature of all tested materials was −18.47 ± 3.42 °C. Surface temperature differed significantly among materials (H = 61.90, $p < 0.001$) and between sunlit and shaded conditions (H = 40.11, $p < 0.001$). Sunlit surfaces were warmer than shaded surfaces, with mean temperatures of −16.47 ± 3.67 °C and −20.47 ± 1.40 °C, respectively. Stone surfaces had the lowest temperature (−21.74 ± 1.10 °C), followed by steel, whereas wood surfaces were relatively warmer and generally associated with lower-severity contact responses.

The matrix-based contact cooling results further showed that risk patterns varied with material, solar exposure and contact mode (Figure 7). Under 10 s finger contact, stone and steel were more likely to reach frostbite-level screening outcomes, particularly under shaded conditions. Under 100 s hand grasp, the dominant risk shifted toward pain or numbness rather than frostbite. Wood and nylon generally showed lower-severity responses than stone and steel, although shaded conditions still increased their local cooling potential. These results indicate that 10 s finger contact and 100 s hand grasp should not be interpreted as simple extensions of the same exposure process, because they correspond to different contact modes and threshold systems.

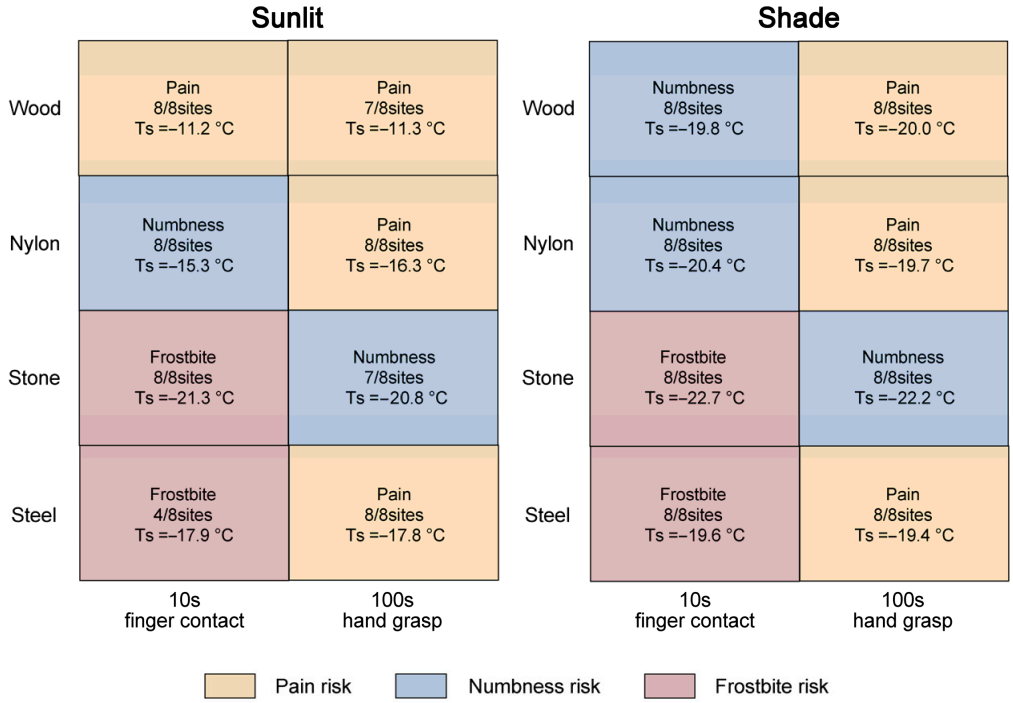


Figure 7. Matrix-based contact cooling risk under different material, exposure and contact-mode conditions.

Overall, local cooling risk in Nanhu Park was not determined by air temperature alone. Wind exposure created widespread convective cooling stress, while high-conductivity and shaded contact surfaces produced localized material-related risks. Therefore, winter park safety should consider both environmental exposure and touchable surface design. For severe-cold urban parks, wind mitigation, sun-exposed resting nodes, and low-conductivity or protected contact materials are necessary to reduce hidden local cooling risks.

3.4. Thermal Adaptive Behavior

Winter park users showed clear behavioral adaptation to cold exposure. Overall, moving to sunny areas accounted for the highest proportion, at 29.5%, followed by increasing or maintaining physical activity at 27.7%. Shortening the stay, adding clothing, and drinking hot water accounted for 17.4%, 16.8%, and 8.5%, respectively. After grouping these behaviors by adaptive mechanism, passive insulation or exposure reduction accounted for 42.7%, environmental exposure adjustment for 29.5%, and metabolic heat enhancement for 27.7% (Figure 8). These results indicate that winter park users were not merely passively exposed to cold conditions, but dynamically adjusted their thermal state by obtaining solar radiation, increasing activity level, and reducing exposure duration.

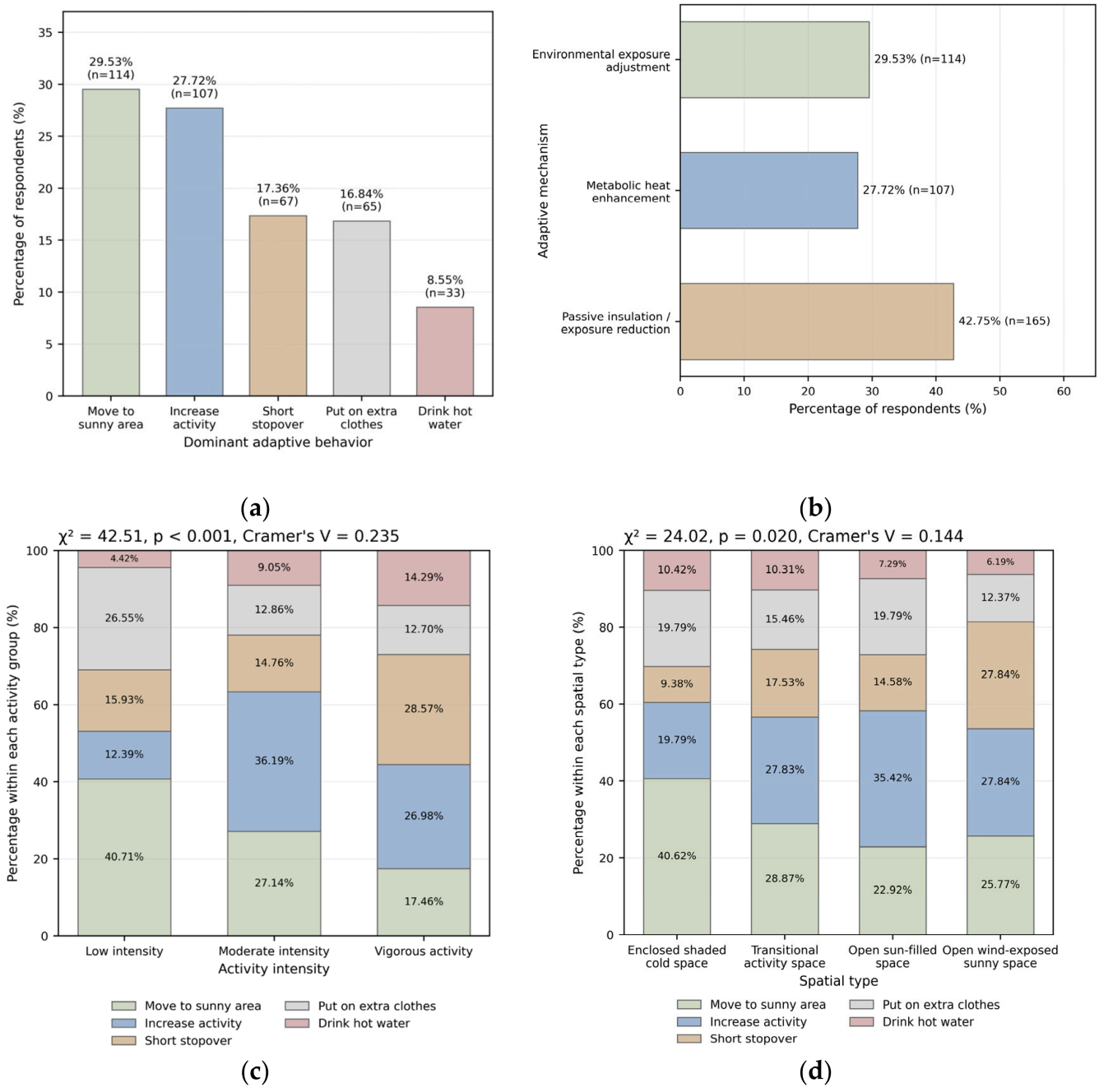


Figure 8. Thermal adaptive behavior across activity intensity and space type. (**a**) Overall distribution of dominant thermal adaptive behaviors. (**b**) Overall distribution of adaptive behavior mechanisms. (**c**) Dominant adaptive behavior by activity intensity. (**d**) Dominant adaptive behavior by spatial type.

Chi-square tests indicated that thermal adaptive behaviors differed significantly across activity intensity ($\chi^2 = 28.01$, df = 4, $p < 0.001$, Cramer's V = 0.19). No significant associations were found between behavior and sex ($\chi^2 = 2.99$, df = 2, $p = 0.224$, Cramer's V = 0.088) or age group ($\chi^2 = 0.62$, df = 4, $p = 0.960$, Cramer's V = 0.028), while differences across space types were weak ($\chi^2 = 10.69$, df = 6, $p = 0.098$, Cramer's V = 0.118). These results confirm that adaptive behavior showed significant variation across activity-intensity groups. Corresponding behavioral distributions are illustrated in Figure 8. By contrast, gender and age group showed no significant association with thermal adaptive behavior, suggesting that behavioral differences in this study were mainly driven by activity state and spatial microclimatic conditions [51,52].

Overall, winter thermal adaptive behavior in Nanhu Park showed a combined pattern of spatial exposure and activity regulation. Moving to sunny areas reflected users' active acquisition of solar radiation, increasing activity reflected metabolic heat compensation, and shortening the stay or adding clothing reflected the control of exposure duration. These behaviors indicate that users adapt to winter parks by choosing where to stay, how long to remain and how actively to move. Therefore, sustainable winter park design should provide selectable microclimatic conditions rather than a uniform spatial environment. Accessible sun-exposed spaces, wind-sheltered staying nodes and continuous moderate-intensity activity routes can support different forms of behavioral adaptation and improve winter usability for users with different activity capacities.

4. Discussion

4.1. Suitability for Winter Use in Clear Weather Conditions

This study investigated winter thermal conditions and usability in a severe-cold urban park based on field observations conducted under clear winter weather conditions. Accordingly, the results primarily reflect typical daytime winter exposure under stable radiative and wind conditions, rather than the full spectrum of seasonal or extreme winter meteorological variability.

Under such conditions, spatial differences in microclimate were mainly driven by variations in wind exposure and shortwave radiation, while background air temperature and humidity remained relatively uniform across measurement sites. This confirms that winter usability in urban parks is predominantly controlled by site-level exposure conditions rather than regional-scale air temperature differences.

Therefore, the findings should be applied to evidence regarding people's use of Winter Park under favorable outdoor conditions during clear weather, when users are more likely to engage in outdoor activities. The derived thermal thresholds and behavioral response patterns help reveal how spatial design influences usability during typical winter daytime use.

4.2. Differentiating Perception, Discomfort Tolerance and Estimated Cold-Stress Risk

The results highlight clear distinctions among thermal perception, discomfort tolerance, and physiological cold-stress risk. Thermal sensation (TSV/TCV) reflects the subjective perception of thermal conditions, while thermal acceptability (TAV-based in this study) represents a behavioral judgement regarding whether outdoor conditions remain usable. In contrast, indices such as UTCI, IREQ, WCT, and contact cooling risk describe physiological or exposure-related stress mechanisms rather than subjective evaluation.

A key finding is that thermal acceptability can persist under conditions substantially below thermal neutrality. This indicates that outdoor winter use in severe-cold cities is not constrained by neutral thermal conditions, but instead by user tolerance and behavioral adaptation. However, such acceptability does not imply physiological safety. The results demonstrate that whole-body cooling, wind-induced heat loss, and local contact cooling may still occur even when users report acceptable thermal conditions [53–55].

This divergence highlights that thermal acceptability should not be interpreted as a safety boundary. Instead, thermal perception, behavioral tolerance, and physiological stress represent independent but interacting dimensions of winter outdoor environmental evaluation. Reliance on a single indicator may therefore misrepresent actual exposure risk in severe-cold urban environments [56–59].

These three dimensions—thermal perception (TSV/TCV), behavioral acceptability (TAV), and physiological exposure (UTCI, IREQ, WCT)—form a hierarchical but non-equivalent evaluation system for winter outdoor environments. Acceptability reflects

behavioral decision-making under adaptive conditions, rather than a direct translation of thermal sensation or physiological stress.

4.3. Activity Intensity, Clothing Behavior and Heterogeneous Cold Exposure

Activity intensity and clothing insulation jointly regulate winter thermal balance and contribute to substantial heterogeneity in cold exposure risk among users. Low-intensity users are more vulnerable to cold stress due to limited metabolic heat production, making them more dependent on environmental conditions such as solar radiation and wind shelter.

In contrast, higher activity intensity can temporarily enhance thermal balance through increased metabolic heat production, extending tolerable exposure duration. However, this effect is context-dependent and cannot be considered a universal adaptation strategy, as it is constrained by user health status, functional purpose, and behavioral feasibility in public spaces.

Clothing behavior further introduces variability in exposure outcomes. In many cases, observed clothing insulation levels were insufficient under specific environmental conditions, indicating a mismatch between adaptive requirements and actual user behavior. This mismatch suggests that winter thermal exposure in urban parks is jointly shaped by environmental conditions, behavioral choices, and physiological capacity.

In addition, localized risks such as wind chill and contact cooling further amplify heterogeneity in exposure conditions. These risks vary significantly across spatial types and are particularly pronounced in open or shaded environments with high-conductivity surfaces [60,61].

4.4. Potential Strategic Implications at the Design Level

Based on the observed relationships between microclimate, perception, and cold stress indicators, several climate-responsive design implications can be proposed.

First, maintaining solar access is essential for improving winter usability, as shortwave radiation significantly contributes to perceived thermal improvement in cold environments [62]. Second, wind mitigation at the pedestrian level is critical in reducing convective heat loss, particularly in open and lakeside areas where exposure is intensified [63].

Third, material selection for urban furniture and contact surfaces plays an important role in mitigating localized cold exposure. High-conductivity materials such as stone and steel may increase the risk of pain, numbness, or frost-related discomfort during direct contact under low-temperature conditions. Therefore, the use of low-conductivity materials or protective surface treatments may improve user safety and comfort in winter conditions [64].

Finally, rather than pursuing uniform thermal optimization, winter park design should support spatial diversity in microclimatic conditions. Providing a combination of sun-exposed nodes, wind-sheltered pathways, and moderate activity areas can better accommodate heterogeneous user needs and adaptive behaviors.

4.5. Limitations and Future Research

This study has several limitations. First, the field investigation was conducted under clear winter weather conditions in a severe-cold urban park. Therefore, the results primarily represent typical winter daytime exposure and should not be generalized to extreme weather conditions or other climatic contexts.

Second, although a site-based stratified quota sampling strategy was applied, the survey did not follow a probability-based sampling design. Therefore, the results should be interpreted as representative of observed park users rather than the general urban population.

Third, spatial morphology was primarily characterized using SVF and field-based categorical descriptors. More detailed quantitative GIS- and 3D-based morphological analyses are needed to further refine the relationship between spatial structure and thermal exposure.

Fourth, the field investigation was conducted using an opportunistic quota sampling strategy rather than a probability-based random sampling design. Therefore, the sample represents observed park users during the survey period rather than a statistically representative population of all residents in severe-cold cities.

Finally, contact cooling risk highlights the importance of material selection in mitigating localized cold exposure in winter urban parks. Future experimental studies are needed to improve the physiological realism of contact-based cold exposure assessments.

5. Conclusions

This study examined winter usability and thermal risk in Nanhu Park, Changchun, by integrating field microclimate monitoring, questionnaire surveys, UTCI, IREQ, wind-chill temperature and contact cooling risk. Rather than treating winter thermal comfort as a single perceptual issue, the study framed severe-cold urban parks as public spaces whose sustainable performance depends on whether they can support safe, active and inclusive use throughout the year. The main conclusions are as follows.

1. Winter microclimatic differences within Nanhu Park were shaped mainly by wind and radiation conditions rather than by background air temperature. The four spatial types captured different winter exposure patterns: Type I open wind-exposed lakeside spaces were more affected by wind exposure; Type II open sun-exposed activity spaces provided relatively favorable radiation conditions; Type III transitional activity spaces showed intermediate conditions; and Type IV enclosed shaded cold spaces were more constrained by insufficient solar access. Air temperature and relative humidity showed limited spatial variation, while wind speed, solar radiation, mean radiant temperature and UTCI differed significantly among park spaces. This indicates that the key to winter park renewal is not simply increasing openness or enclosure, but coordinating solar access with near-ground wind mitigation.
2. Thermal neutrality, thermal acceptability and cold-stress risk represent different boundaries and should not be used interchangeably. Users may still accept outdoor conditions far below the thermally neutral state, but perceived acceptability does not necessarily indicate physiological risk. Whole-body cooling, wind-chill exposure and contact cooling may remain present under conditions that users consider acceptable. Winter park assessment should therefore combine subjective comfort, behavioral tolerance and physiological risk.
3. Risk-informed winter park renewal should adopt differentiated strategies for the four spatial types: wind mitigation for open lakeside spaces, solar-access preservation for open activity spaces, sheltered connectivity for transitional spaces, and radiation compensation with low-conductivity facilities for enclosed shaded spaces. Sun-exposed staying nodes can improve perceived thermal conditions, wind-sheltered spaces can reduce local cooling, low-conductivity surfaces can lower contact risk, and continuous walking or light-to-moderate activity routes can support metabolic heat production. These coordinated strategies can improve winter usability, thermal risk and age-friendly access in severe-cold urban parks.

It should be noted that all reported thermal thresholds and cold-stress risk estimates are derived from observed winter park users under clear to partly cloudy daytime conditions, and therefore represent context-specific evidence rather than universally generaliz-

able values for all populations in severe-cold cities. Overall, the optimization of severe-cold urban parks should shift from comfort-oriented evaluation to climate-adaptive renewal. By linking microclimatic exposure, physiological risk and behavioral adaptation, this study provides evidence for improving the year-round sustainability of urban public spaces in cold-region cities.

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Institutional Review Board Statement: According to Article 32 of the Measures for Ethical Review of Life Science and Medical Research Involving Humans (2023, National Health Commission of the People's Republic of China and related ministries), research based on anonymized data and non-invasive observational surveys in public spaces that poses no risk to participants may be exempt from formal ethical review.

Informed Consent Statement: Informed consent was obtained from all participants prior to participation. Participants were informed of the study purpose, voluntary participation, data anonymity and confidentiality, and their right to withdraw at any time without penalty. Questionnaire completion in public urban parks was voluntary and was treated as implied informed consent for participation and anonymous use of data for academic research.

Data Availability Statement: The data can be provided upon reasonable request from the corresponding author.

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

Abbreviations

The following abbreviations are used in this manuscript:

UTCI	Universal Thermal Climate Index
IREQ	Required Clothing Insulation
WCT	Wind-Chill Temperature
PMV	Predicted Mean Vote
PET	Physiologically Equivalent Temperature
SET*	Standard Effective Temperature
WBGT	Wet-Bulb Globe Temperature
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
MTSV	Mean Thermal Sensation Vote
NUTCI	Neutral Universal Thermal Climate Index
NUTCIR	Neutral Universal Thermal Climate Index Range
TAR	Thermal Acceptability Range
Ta	Air Temperature
RH	Relative Humidity
Va	Wind Speed
G	Solar Radiation

Tg	Globe Temperature
Tmrt	Mean Radiant Temperature
Icl	Actual Clothing Insulation
ICLmin	Minimum Required Clothing Insulation
ICLneutral	Neutral Required Clothing Insulation
DLEmin	Minimum Allowable Exposure Duration
DLEneutral	Neutral Allowable Exposure Duration
MET	Metabolic Equivalent
AUC	Area Under the Receiver Operating Characteristic Curve
CI	Confidence Interval
GEE	Generalized Estimating Equations
SE	Standard Error
Ts	Surface Temperature
TPV	Thermal Preference Vote

Appendix A

Winter Outdoor Thermal Comfort and Cold Stress Questionnaire for Urban Park Users in Nanhu Park, Changchun

This questionnaire was used for the field survey in Nanhu Park, Changchun, China. The survey was conducted synchronously with microclimate measurements. All responses were collected anonymously and used only for academic research on winter outdoor thermal comfort, cold-stress risk, and adaptive behavior in severe-cold urban parks. Participation was voluntary, and informed consent was obtained before the survey.

Survey information

Questionnaire ID: _____ Date: _____ Time: _____

Measurement site: _____ Location: Nanhu Park, Changchun, China

Weather condition: ☐ Sunny ☐ Partly cloudy ☐ Cloudy ☐ Other: _____

Basic information of respondent

Gender: ☐ Male ☐ Female Age: _____ years Height: _____ cm Weight: _____ kg

How many years have you lived in Changchun? _____ year (s)

1. What are you wearing now? Multiple choices are allowed.

Sundries:

☐ Gloves ☐ Cap ☐ Scarf ☐ Mask ☐ Other: _____

Upper body:

☐ Underwear T-shirt ☐ Underwear shirt, long sleeves, thermal ☐ Underwear shirt, long sleeves ☐ Short-sleeved shirt ☐ Vest

☐ Shirt ☐ Jacket: Thin ☐ Jacket: Thick ☐ Jacket: Fibre-pelt ☐ Sweater: Sleeveless ☐ Sweater: Thin ☐ Sweater: Thick

☐ Down vest ☐ Down jacket ☐ Coat ☐ Other: _____

Lower body:

☐ Underwear pants, long-legged, thermal ☐ Underwear pants, long-legged ☐ Trousers: Thin ☐ Trousers: Thick ☐ Flannel trousers

☐ Sweat pants ☐ Trousers, fibre-pelt ☐ Winter dress, long sleeves ☐ Other: _____

Feet:

☐ Shoes: Thin-soled ☐ Shoes: Thick-soled ☐ Boots ☐ Socks: Thin ☐ Socks: Thick and ankle-length ☐ Socks: Thick and long

☐ Other: _____

2. What is your current activity?

Light-intensity activity:
☐ Sitting ☐ Standing quietly ☐ Standing and talking ☐ Walking slowly, less than 3.2 km/h ☐ Passing through the park
☐ Other: _____
Moderate-intensity activity:
☐ Walking the dog ☐ Walking, 4.5–5.1 km/h ☐ Brisk walking ☐ Playing table tennis ☐ Badminton ☐ Ice skating, less than 4 m/s
☐ Other: _____
Vigorous activity:
☐ Running ☐ Basketball ☐ General skating ☐ Other: _____

3. How do you feel thermally at this moment?

Thermal sensation vote (TSV):
☐ Very cold ☐ Cold ☐ Slightly cold ☐ Cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot ☐ Very hot

4. What are your preferences regarding the current meteorological conditions?

Meteorological parameter Prefer higher/stronger/wetter No change Prefer lower/weaker/drier
Air temperature ☐ Higher ☐ No change ☐ Lower
Solar radiation ☐ Stronger ☐ No change ☐ Weaker
Relative humidity ☐ Wetter ☐ No change ☐ Drier
Wind speed ☐ Stronger ☐ No change ☐ Weaker

5. Please describe your current thermal comfort level.

Thermal comfort vote (TCV):
☐ Comfortable ☐ Slightly uncomfortable ☐ Uncomfortable ☐ Very uncomfortable ☐ Extremely uncomfortable

6. Is the current outdoor thermal environment acceptable to you?

Thermal acceptability vote:
☐ Acceptable ☐ Unacceptable

Table A1. Robustness and clustered-model results for thermal benchmarks.

Model	Outcome	Cluster/Robustness Structure	Main Result	Interpretation
Unweighted 1 °C bin regression	MTSV	n ≥ 3 bins retained	Neutral UTCI = 3.14 °C	Descriptive bin-level estimate
Sample-size-weighted bin regression	MTSV	Weighted by bin sample size	Neutral UTCI = 3.70 °C	Reduced influence of sparse bins
Bootstrap analysis	Neutral UTCI	1000 resamples	95% CI = 1.68 to 7.09 °C	Neutral point has uncertainty
Sensitivity analysis	Neutral UTCI	Alternative bin widths/minimum bin sizes	Range = 1.41 to 5.56 °C	Estimate broadly stable but not exact
Binary GEE logistic model	TAV unacceptability	Site–time cluster	TAR = −15.24 °C	Direct acceptability threshold
Cluster bootstrap	TAV threshold	1000 resamples	95% CI = −16.14 to −14.22 °C	Threshold robust to clustered resampling

Table A2. GEE model outputs for thermal sensation and thermal acceptability.

Model	Term	β	Robust SE	Wald χ^2	*p*-Value	OR/Cumulative OR (95% CI)
Thermal sensation vote (TSV)	Sex: Female vs Male	−0.1523	0.2112	0.5201	0.471	0.859 (0.568–1.299)
	Age group: Middle-aged vs Youth	0.1942	0.2754	0.4973	0.481	1.214 (0.708–2.083)
	Age group: Older adults vs Youth	−0.7676	0.3237	5.6246	0.018	0.464 (0.246–0.875)
	Spatial type: Type II vs Type I	0.0272	0.3086	0.0078	0.930	1.028 (0.561–1.882)
	Spatial type: Type III vs Type I	−0.4356	0.3038	2.0557	0.152	0.647 (0.357–1.173)
	Spatial type: Type IV vs Type I	−0.1854	0.2708	0.4685	0.494	0.831 (0.489–1.413)
	UTCI (°C)	0.2336	0.0206	129.0093	<0.001	1.263 (1.213–1.315)
	Metabolic rate (W/m^2)	0.0080	0.0012	41.5380	<0.001	1.008 (1.006–1.011)
	Clothing insulation (clo)	1.1647	0.6521	3.1902	0.074	3.205 (0.893–11.505)
TAV unacceptability (Main TAV unacceptability mode)	Sex: Female vs Male	−0.6170	0.3211	3.6937	0.055	0.540 (0.288–1.012)
	Age group: Middle-aged vs Youth	−0.5937	0.4261	1.9420	0.163	0.552 (0.240–1.273)
	Age group: Older adults vs Youth	0.3612	0.5098	0.5019	0.479	1.435 (0.528–3.898)
	Spatial type: Type II vs Type I	−0.2434	0.4741	0.2637	0.608	0.784 (0.310–1.985)
	Spatial type: Type III vs Type I	0.4744	0.4858	0.9536	0.329	1.607 (0.620–4.164)
	Spatial type: Type IV vs Type I	0.2706	0.4510	0.3600	0.549	1.311 (0.542–3.172)
	UTCI (°C)	−0.3844	0.0553	48.3107	<0.001	0.681 (0.611–0.759)
	Metabolic rate (W/m^2)	−0.0012	0.0018	0.4425	0.506	0.999 (0.995–1.002)
	Clothing insulation (clo)	0.1704	1.0686	0.0254	0.873	1.186 (0.146–9.630)
TAV unacceptability (Sensitivity model with mean-centered interaction terms)	UTCI × metabolic rate (centered)	−0.0003	0.0005	0.3240	0.569	1.000 (0.999–1.001)
	UTCI × clothing insulation (centered)	−0.2559	0.4210	0.3697	0.543	0.774 (0.339–1.767)

Appendix A.1. IREQ Heat Balance Formulation

The Required Clothing Insulation (IREQ) is calculated according to ISO 11079:2007 based on the human steady-state heat balance equation:

$$M - W = Q_{res} + Q_{sk}$$

where:

M: metabolic rate ($W \cdot m^{-2}$)
W: external mechanical work (assumed 0 in this study)
Q_{res}: respiratory heat loss
Q_{sk}: total dry heat loss from skin

Dry heat loss from the body surface is expressed as:

$$Q_{sk} = \frac{T_{sk} - T_a}{I_{cl} + I_a}$$

where:

T_{sk}: mean skin temperature (ISO standard value, 34 °C)
T_a: air temperature (°C)
I_{cl}: clothing insulation ($m^2 \cdot K \cdot W^{-1}$)
I_a: boundary air layer insulation (function of wind speed)

Appendix A.2. Wind-Dependent Insulation Correction

Boundary layer insulation is calculated as:

$$I_a = \frac{1}{f(v)}$$

where $f(v)$ is the convective heat transfer function dependent on wind speed v, following ISO 11079 empirical formulation.

Measured pedestrian-level wind speed was used after height correction to 10 m equivalent using:

$$v_{10} = v_z \left(\frac{10}{z} \right)^{\alpha}$$

where:

v_z: measured wind speed
z: measurement height
α= 0.20 (urban terrain)

Appendix A.3. Clothing Insulation Definition

Clothing insulation was defined as:

$$I_{cl} = \sum I_{cl,i}$$

based on ISO 9920 clothing ensemble values.

For IREQ evaluation, resultant clothing insulation was considered:

$$I_{cl,eff} = I_{cl} \cdot f_{mv} \cdot f_{wind}$$

where:

f_{mv}: movement correction factor
f_{wind}: wind penetration correction factor

Both factors follow ISO 11079 adjustment tables.

Appendix A.4. Determination of IREQmin and IREQneutral

IREQ is obtained by solving:

$$IREQ = f(M, T_a, T_{mrt}, v, RH)$$

iteratively under two boundary conditions:

IREQmin: corresponds to acceptable physiological strain limit
IREQneutral: corresponds to thermal equilibrium condition

These are solved numerically until:

$$S = 0$$

where S is body heat storage rate.

Appendix A.5. Allowable Exposure Duration (DLE)

Allowable exposure time is computed from heat storage balance:

$$DLE = \frac{C_{body}}{|S|}$$

In this study:

$$DLE = \min(DLE_{calculated}, 8h)$$

Thus:

DLE = 8 h indicates no critical cold strain reached within simulation window

Appendix A.6. Cooling Risk Classification

$$\text{Risklevel} = \begin{cases} \text{High}, & I_{cl,eff} < IREQ_{min} \\ \text{Moderate}, & IREQ_{min} \leq I_{d,eff} < IREQ_{neutral} \\ \text{Low}, & I_{cl,eff} \geq IREQ_{neutral} \end{cases}$$

All calculations strictly follow ISO 11079:2007 without modification of governing equations.

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