

Article

Evaluation of Downtown Urban Spaces Under Cold Climate Conditions Using Thermal Indices for Climate-Responsive Design: A Case Study of Sapporo, Japan

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Abstract

Urban thermal comfort in winter is an important but insufficiently quantified component of sustainable, climate-adapted urban design in cold-weather cities facing energy-intensive winter environmental challenges. This study uses high-resolution simulations to evaluate discomfort across a downtown district in Sapporo, Japan, based on the standard effective temperature (SET*) index and universal thermal climate index (UTCI). A total of 2438 sampling points were assessed under 69 hourly winter scenarios. Discomfort hotspots were found in east–west streets and wind-exposed corners, driven by limited solar access or intensified wind. SET* is a more sensitive indicator under cold conditions, particularly in shaded areas. Wind speed and mean radiant temperature distributions revealed the environmental drivers of discomfort. The influence of building height was confirmed via quantitative correlation analysis, which revealed significant negative relationships between adjacent building heights and SET* across all streets analyzed, especially in east–west street canyons, where correlation coefficients ranged from -0.80 to -0.52 in the representative street. These findings contribute to urban sustainability by providing a quantitative tool for identifying winter thermal vulnerability and supporting passive, climate-adapted public-space design. The proposed framework can help improve winter walkability, outdoor activity, and the environmental quality of downtown spaces in cold-region cities.

Keywords: urban morphology; sustainable urban design; winter thermal comfort; environment simulation; standard effective temperature; climate-sensitive design



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1. Introduction

Urban outdoor thermal environments in winter cities have become a critical dimension of sustainable urban design, especially as cold-season discomfort continues to constrain livability and public space vitality [1,2]. The Winter Cities movement, which first emerged in the 1980s, highlighted the need for climate-sensitive design strategies to reduce the negative effects of winter and enhance its positive potential [3,4]. Early scholars emphasized that winter conditions, such as low temperatures, limited sunlight, and persistent wind, significantly hinder the use of outdoor spaces, resulting in social withdrawal and reduced economic activity [3,5]. Pressman [6] argued that urban morphology must adapt to climatic realities and criticized modernist approaches for ignoring local environmental

conditions and worsening pedestrian discomfort in winter. These challenges are particularly acute in high-latitude urban areas, where the quality of public life during winter is significantly shaped by built form and microclimate interactions [7]. Stout et al. [1] noted that advancing outdoor livability in cold climates is not only a design concern but also a matter of equity and urban vitality. Moreover, winter outdoor thermal comfort has been shown to vary across cold-region cities, as reflected in differences in neutral UTCI and no-thermal-stress ranges [8]. This highlights the need for city-specific evaluations of winter thermal environments in high-latitude cities such as Sapporo.

Urban morphology, such as street orientation, building height, and canyon geometry, directly shapes winter microclimates by influencing solar access, wind exposure, and radiant heat exchange [7]. Climate-sensitive design principles advocate for forms that block cold winds and capture low-angle sunlight, thereby enhancing pedestrian comfort in winter [9]. Identifying microclimatic variations in these effects is essential for promoting walkability and seasonal livability.

Previous studies have demonstrated that urban form and surface characteristics can significantly modify outdoor microclimates and pedestrian thermal comfort. For example, Chatzidimitriou and Yannas [10] analyzed the effects of courtyard configurations and materials on summer thermal comfort, and Yang et al. [11] identified critical height-to-width thresholds affecting ventilation in Shanghai's high-density blocks. Other studies have examined the roles of street canyon geometry, courtyard type, vegetation distribution, and sky view factor in modifying outdoor thermal conditions [12–15]. However, many simulation-based studies have relied on static or idealized climatic inputs, such as a representative day or a limited number of weather scenarios, which may not fully capture seasonal variations in winter thermal discomfort [16]. These studies provide important evidence that building configuration and urban morphology are closely related to pedestrian-level thermal environments. However, many earlier studies were conducted under summer, warm-climate, or urban heat island mitigation contexts, and some simulation-based studies relied on static or idealized climatic inputs, such as a representative day or a limited number of weather scenarios.

Recent studies have increasingly examined outdoor thermal comfort in cold and severe-cold regions from the perspective of urban morphology. For example, Sun et al. [17] investigated the effect of street geometry on pedestrian thermal comfort in Harbin and showed that canyon aspect ratio, street orientation, sky view factor, mean radiant temperature, and wind conditions jointly affect outdoor thermal comfort in severe cold climates. Liu et al. [18] further analyzed seasonal outdoor thermal comfort in 156 residential blocks in Harbin and reported that block morphology has a stronger influence on UTCI in winter than in summer, with wind speed playing a major role in winter comfort conditions. Studies in other winter or cold-climate cities have also emphasized the influence of street/block orientation and settlement pattern on microclimate and human thermal comfort [19,20]. These recent findings indicate that winter thermal comfort should not be evaluated only by air temperature, but also through the interaction between solar radiation, wind environment, street geometry, and building configuration.

Several thermal comfort indices have been developed to evaluate the combined effects of meteorological conditions and human thermal responses in outdoor environments. PMV and PET have been widely used in urban climate studies [21,22], while UTCI and SET* are increasingly applied to assess outdoor thermal stress under complex microclimatic conditions. UTCI, developed as a physiologically based assessment model of the thermal environment, incorporates air temperature, wind speed, humidity, and radiation, and has been widely adopted in outdoor thermal comfort studies [23,24]. SET*, based on the human heat balance model, reflects physiological responses and is sensitive to changes in radiation,

wind conditions, clothing insulation, and skin wettedness [25,26]. Recent comparative studies have also indicated that the sensitivity and applicability of PET, SET*, and UTCI may vary depending on season, climate, and outdoor microclimatic conditions [27,28]. Recognizing the strengths and limitations of both indicators, this study integrates SET* and UTCI to provide a dual-index evaluation of pedestrian thermal discomfort in a high-density downtown area of Sapporo.

Although recent studies have made important advances in understanding winter outdoor thermal comfort and urban morphology, several aspects remain insufficiently explored. First, many studies have focused on typical residential districts, parks, campuses, or idealized street canyons, whereas fewer studies have examined high-density downtown districts in cold Japanese cities. Second, previous research has often evaluated selected thermal conditions or average comfort levels, while less attention has been given to the spatial frequency of winter thermal discomfort under multiple realistic meteorological scenarios. Third, the relationship between building height along real street canyons and pedestrian-level thermal comfort remains insufficiently quantified at a fine spatial resolution. To address these gaps, this study incorporates 69 hourly winter daytime weather conditions and 2438 pedestrian-level sampling points to evaluate morphology-induced thermal discomfort in a high-density downtown district of Sapporo. The study further develops a spatially explicit, block-scale evaluation framework using SET* and UTCI and quantitatively examines the relationship between building height, street orientation, open-space conditions, and winter thermal comfort. From a sustainability perspective, this framework links thermal comfort indicators with real urban morphology and supports climate-adapted planning for winter walkability, public-space usability, and reduced reliance on energy-intensive environmental control.

2. Materials and Methods

This study uses a high-resolution simulation-based framework that integrates SET* and UTCI as dual evaluation metrics. This dual-index approach captures physiological thermal regulation and meteorological exposure, providing a holistic perspective on pedestrian thermal comfort. A total of 2438 sampling points were assessed across 69 hourly winter daytime weather conditions, selected to represent the diversity of daytime winter climates in the target city. The selected scenarios were also checked according to their intra-seasonal distribution to confirm that they covered different phases of winter, rather than representing only a single design day or a narrow climatic condition. This approach allows for spatially and temporally explicit evaluations that reflect the fluctuating and cumulative nature of cold stress. The central hypothesis is that urban form variations generate significant spatial heterogeneity in winter thermal discomfort, with vulnerable zones consistently emerging in areas characterized by poor solar access, heightened wind exposure, or suboptimal street geometry. By combining thermal comfort simulation, environmental variable mapping, and morphological correlation analysis, this study identifies systematic links between form-based design parameters and outdoor discomfort patterns. By translating microclimatic outputs into spatial discomfort frequencies, the framework also functions as a sustainability assessment tool for monitoring thermal vulnerability and supporting evidence-based urban design decisions. Figure 1 illustrates the stages of the research methodology used in this study.

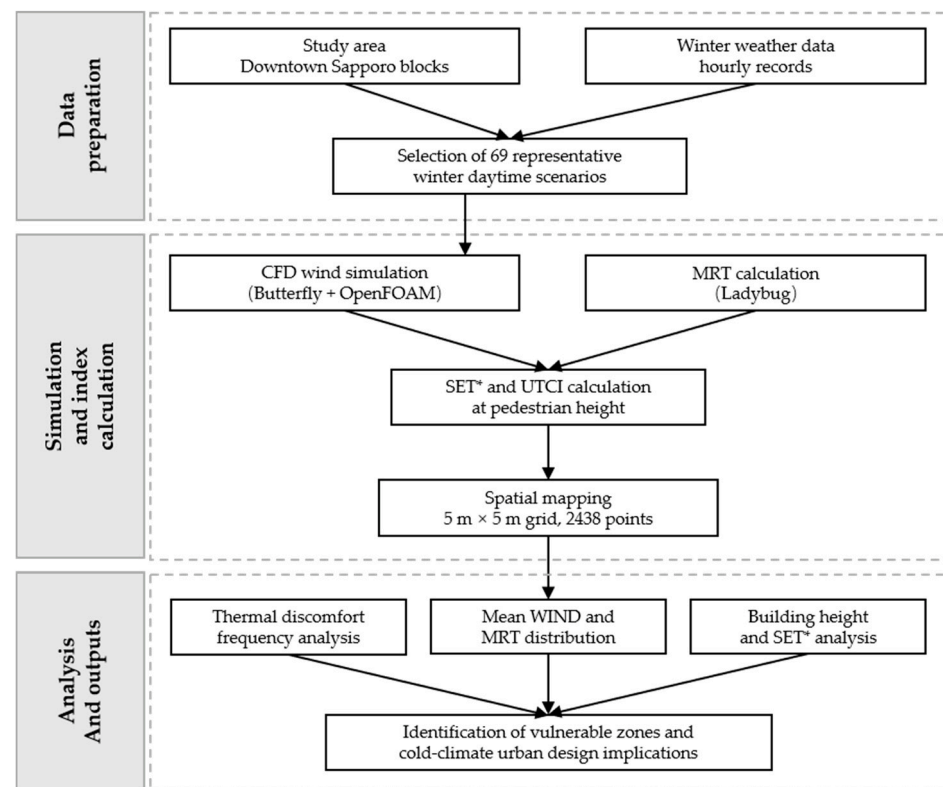


Figure 1. Research methodology flowchart.

2.1. Study Area

The study area is located in the central district of Sapporo (Figure 2), Hokkaido, Japan, and includes four contiguous urban blocks (Figure 3): Block A (Kita 3-jo 4-chome), Block B (Kita 2-jo 4-chome), Block C (Kita 3-jo 3-chome), and Block D (Kita 2-jo 3-chome). These blocks are bounded and traversed by a network of six major streets forming the primary street framework: Nishi-3 Dori, Nishi-4 Dori, and Nishi-5 Dori (running north–south), and Kita-2 Jo Dori, Kita-3 Jo Dori, and Kita-4 Jo Dori (running east–west). Although several narrower internal streets are also present within the blocks, they are not considered in this study due to their irregular geometry and limited continuity.

Japan’s northernmost island, Hokkaido, is characterized by a cold, snowy winter climate, and Sapporo, its largest city, experiences long, harsh winters with heavy snowfall and persistent seasonal winds. This area typifies Sapporo’s downtown urban morphology, featuring a regular grid layout, dense mid- to high-rise buildings, and compact block configuration. These climatic and morphological characteristics make Sapporo an ideal representative case for examining the spatial variation of outdoor thermal comfort and the effect of urban form on winter microclimates. This context provides valuable insights into the development of climate-sensitive urban design strategies for cold-climate cities.

The weather data of Sapporo were obtained from the Japan Meteorological Agency. The full winter daytime dataset included 990 hourly records from December 2019 to February 2020, covering the period from 7:00 to 17:00. To represent general daytime winter conditions, 69 point-in-time scenarios were selected based on the distribution trend of the full dataset in the MRT–wind speed space. In addition to the MRT–wind-based sampling, the selected scenarios were checked according to their intra-seasonal distribution. The selected cases included 23 cases in December, representing early winter conditions; 22 cases in January, representing peak winter conditions; and 24 cases in February, representing the late-winter transition period. This grouping was introduced to clarify that the selected scenarios covered different phases of the winter season. Figure 4 shows the distribution

of winter daytime climatic conditions (7:00–17:00) based on wind speed and MRT in the target urban block in Sapporo. The gray dots represent all hourly data points recorded throughout the winter season ($n = 990$). The colored dots indicate the 69 representative conditions selected via uniform spatial sampling in the MRT–wind speed distribution. These selected conditions were further classified according to their intra-seasonal phases: early winter in December ($n = 23$), peak winter in January ($n = 22$), and late-winter transition in February ($n = 24$). This classification confirms that the selected scenarios covered different phases of the winter season, rather than representing only a single design day or a narrow climatic condition.

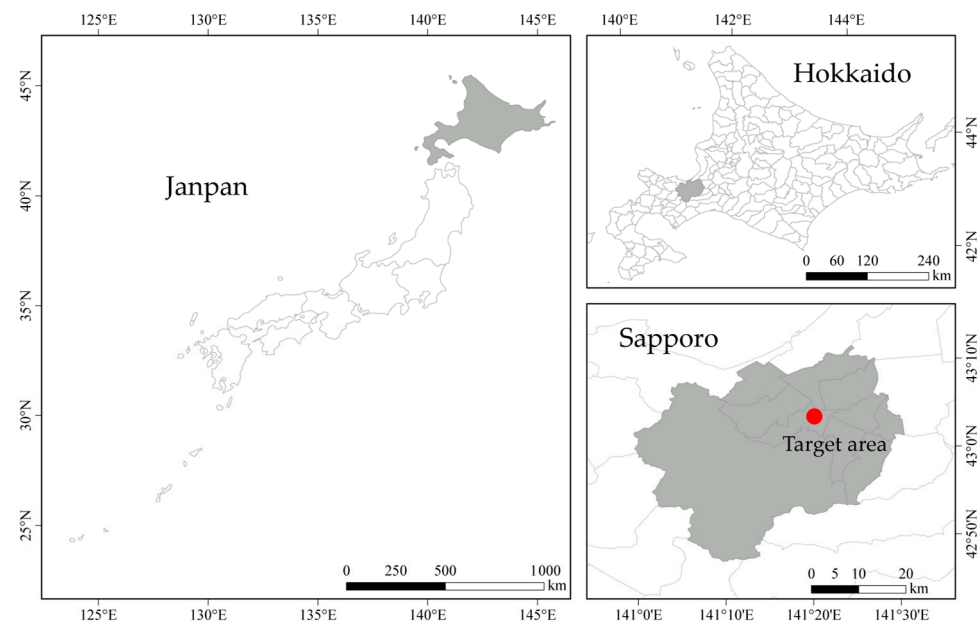


Figure 2. Location of the study area.

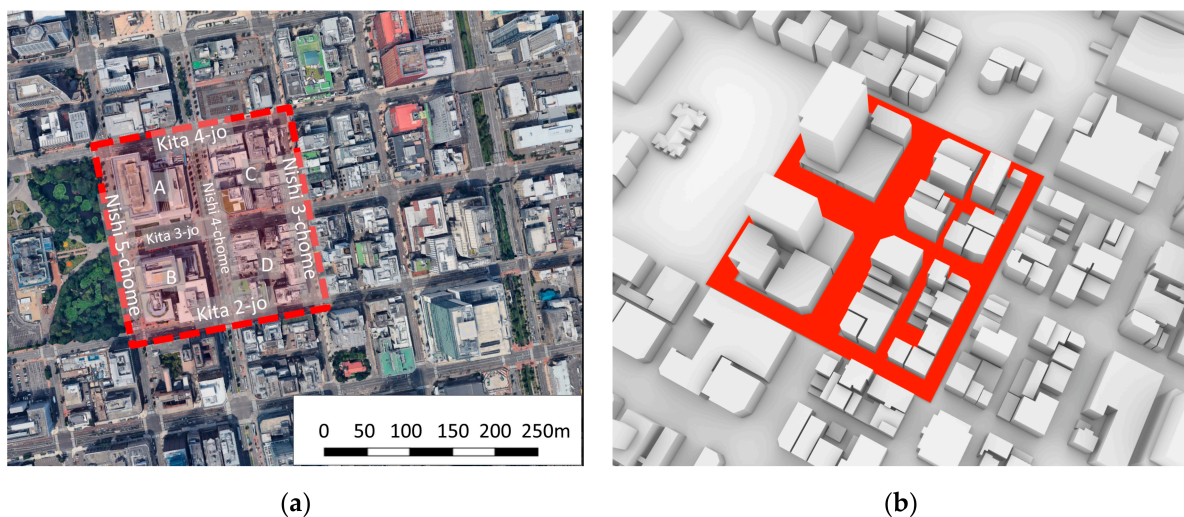


Figure 3. Target downtown area: (a) two-dimensional (2D) map; (b) three-dimensional (3D) model map.

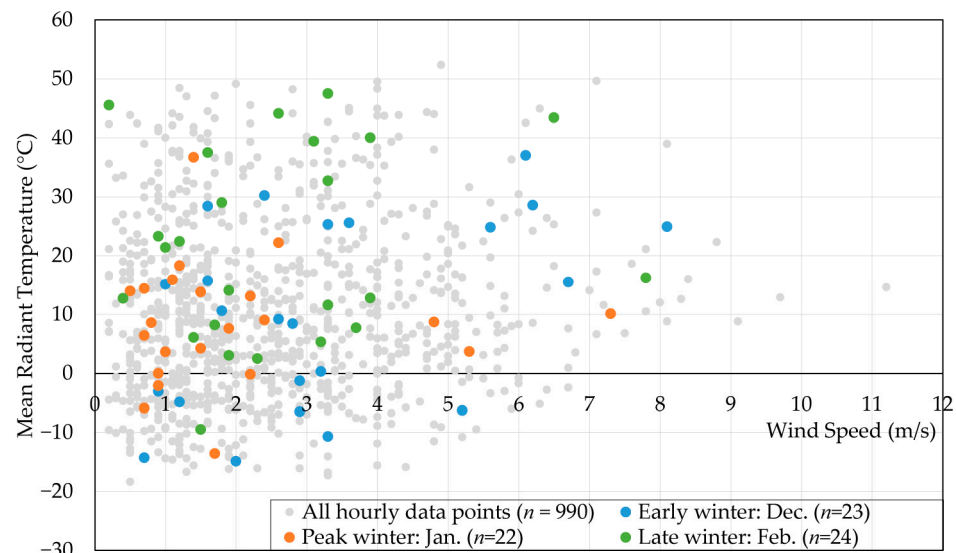


Figure 4. Distribution of winter daytime climate conditions in the MRT–wind speed space.

The selected scenarios were used in environmental simulations to reflect the diversity of wintertime thermal situations experienced within the study area and support climate-responsive block design analysis.

2.2. Thermal Comfort Index

As discussed in the Introduction, this study adopts SET* and UTCI as dual evaluation indices to capture physiological strain and environmental exposure. The following section details their definitions, stress categories, and computational methods.

2.2.1. SET*

SET* is a rational thermal comfort index derived from the two-node model of human thermoregulation developed by Gagge et al. [25,26]. It represents the equivalent air temperature of an isothermal environment at 50% relative humidity in which a person, wearing standardized clothing and performing a defined activity, experiences the same core and skin temperatures and skin wettedness as in the actual environment. The limiting physiological variables in SET* are skin temperature (T_{sk}) and skin wettedness (w).

SET* has been extensively used in outdoor thermal assessments, and Nazarian et al. [29] demonstrated that computational fluid dynamics (CFD)-based simulations coupled with detailed MRT calculations can significantly improve the accuracy of SET evaluations in complex urban environments. SET* accounts for convective and radiative heat exchange and is particularly sensitive to wind and solar radiation, making it suitable for evaluating thermal discomfort in cold regions. In this study, SET* was calculated using hourly values of wind speed (from CFD simulation), MRT (from Ladybug), and meteorological parameters, including air temperature and humidity, extracted from the EnergyPlus Weather File (EPW) format file.

Table 1 lists the SET* stress categories, which are frequently used in outdoor comfort studies in urban and climate-responsive design contexts [30].

Table 1. Stress classification of outdoor thermal environment according to SET* ranges.

Range of SET* (°C)	Thermal Sensation Classification
>37.5	Very hot, very uncomfortable
34.5–37.5	Hot, very unacceptable
30–34.5	Warm, uncomfortable, unacceptable

Table 1. *Cont.*

Range of SET* (°C)	Thermal Sensation Classification
25.6–30	Slightly warm, slightly unacceptable
22.2–25.6	Comfortable and acceptable
17.5–22.2	Slightly cool, slightly unacceptable
14.5–17.5	Cool and unacceptable
10–14.5	Cold, very unacceptable
<10	Extremely cold, severely unacceptable

2.2.2. UTCI

UTCI is an advanced outdoor thermal comfort index calculated as an equivalent ambient temperature. It is based on a multinode thermophysiological model (UTCI-Fiala) that simulates the dynamic responses of the human body to changing meteorological conditions, including air temperature, wind speed, MRT, and humidity [23,31].

UTCI was developed within the framework of COST Action 730 and has been validated across various climates, spanning from the Arctic to subtropical, and urban microclimates [23]. The model incorporates adaptive clothing insulation and walking speed effects, which enhance its ability to represent human heat exchange under real outdoor conditions. Unlike simpler indices, UTCI integrates the physiological impact of solar radiation and wind-induced cooling with greater fidelity.

Table 2 shows the UTCI thermal stress classification system, which provides a comprehensive framework for interpreting human thermal strain across diverse climatic settings.

Table 2. Stress classification of outdoor thermal environment according to UTCI ranges.

Range of UTCI (°C)	Stress Classification
>+46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
+9 to 0	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
<−40	Extreme cold stress

2.3. Simulation Setups

Based on the selected thermal comfort indices, high-resolution simulations were performed to generate spatially explicit SET* and UTCI distributions under diverse winter conditions. The simulation procedure was organized into CFD-based wind field calculation, MRT estimation, and thermal comfort index calculation.

2.3.1. Simulation Workflow

This study employed a parametric simulation framework based on Rhinoceros 6 and its built-in Grasshopper environment, integrated with the Butterfly 0.0.05 plugin for Grasshopper, which calls OpenFOAM 7 as the CFD solver. This workflow allows three-dimensional urban geometry and environmental simulation settings to be managed within the same design environment and has been applied in previous studies on architect-friendly wind environment simulation [30,32]. The CFD simulation was used to calculate pedestrian-level wind speed, while Ladybug Tools 1.8.0 was used to calculate mean radiant

temperature (MRT). The resulting wind speed, MRT, air temperature, and relative humidity were then combined to calculate SET* and UTCI.

2.3.2. Computational Domain

The computational domain was defined as an 815 m × 898 m × 500 m rectangular volume, encompassing the target area, following the guidelines of the Architectural Institute of Japan (AIJ) [33]. Additional best-practice recommendations for urban CFD simulations were also considered to reduce artificial boundary effects and ensure sufficient space around the target geometry [34,35]. The maximum building height in the study area was approximately 173 m, and the vertical domain height was set to 500 m to provide sufficient clearance above the urban canopy layer.

2.3.3. Grid Settings

The base mesh was generated using blockMesh with a grid resolution of 98 × 90 × 26. Local mesh refinement was performed using snappyHexMesh to improve the representation of building surfaces and pedestrian-level spaces. The refinement level was set to 5, and the maximum global cell count was limited to 10 million. Inflation layers were applied near the ground and building surfaces to improve near-wall resolution. The layer settings included an expansion ratio of 1.3, a final layer thickness of 1, and a minimum layer thickness of 0.1. The mesh settings were selected to balance spatial resolution and computational cost across the 69 winter scenarios. Following common recommendations for pedestrian-level CFD analysis, local refinement was applied around buildings and near the ground surface, and all CFD results were extracted at a height of 1.5 m above ground level [33–35].

2.3.4. Boundary Conditions

The inlet boundary was assigned a velocity inlet condition, while the outlet boundary was assigned a pressure outlet condition. The top and lateral boundaries were treated as symmetry boundaries. No-slip wall conditions were applied to the ground and building surfaces. Surface roughness was corrected using the modified roughness height method to improve the consistency of the atmospheric boundary layer near the ground [36].

2.3.5. Turbulence Model and Inlet Wind Profile

Steady-state Reynolds-averaged Navier–Stokes (RANS) equations were solved using the realizable k – ϵ turbulence model. This model was selected because it provides a practical balance between computational efficiency and prediction accuracy for urban-scale pedestrian wind simulations, especially when multiple scenarios are analyzed [35,37]. The realizable k – ϵ model has also been widely used in pedestrian-level wind environment simulations and benchmark studies around buildings [38,39].

The governing equations for incompressible steady flow can be expressed as Equations (1) and (2):

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial U_i}{\partial x_j} \right) - \frac{\partial}{\partial x_j} (\overline{u'_i u'_j}) \quad (2)$$

where U_i and U_j are the mean velocity components, x_i and x_j are coordinate directions, P is pressure, ρ is air density, ν is kinematic viscosity, and $-\overline{u'_i u'_j}$ is the Reynolds stress term.

The inlet wind profile was defined using a power-law atmospheric boundary layer profile based on the reference wind speed and terrain roughness setting in Butterfly [40], as shown in Equation (3):

$$U(z) = U_{\text{ref}} \left(\frac{z}{z_{\text{ref}}} \right)^{\alpha} \quad (3)$$

where $U(z)$ is the wind speed at height z , U_{ref} is the reference wind speed, z_{ref} is the reference height, and α is the terrain-dependent roughness exponent. The turbulent kinetic energy k and dissipation rate ε were initialized following standard computational wind engineering formulations [40].

2.3.6. Convergence Criteria and Simulation Settings

The simulations were solved under steady-state conditions. Convergence was checked based on residual reduction and the stabilization of representative monitoring values. The main simulation settings are summarized in Table 3.

Table 3. Baseline simulation settings.

Item	Setting
Simulation platform	Rhino/Grasshopper + Butterfly
CFD solver	OpenFOAM
Study area	Downtown Sapporo, Japan
Computational domain	815 m × 898 m × 500 m
Maximum building height	Approximately 173 m
Base mesh	blockMesh, 98 × 90 × 26
Local refinement	snappyHexMesh, refinement level 5
Maximum global cell count	10,000,000
Inflation layer settings	Expansion ratio = 1.3; final layer thickness = 1; minimum thickness = 0.1
Turbulence model	Steady RANS, realizable k- ε model
Inlet boundary	Velocity inlet
Outlet boundary	Pressure outlet
Top and side boundaries	Symmetry
Ground and building surfaces	No-slip wall
Inlet wind profile	Power-law atmospheric boundary layer
Output height	1.5 m above ground level
Thermal comfort indices	SET* and UTCI
Spatial mapping grid	5 m × 5 m
Number of analysis points	2438
Number of winter scenarios	69
Convergence check	Residual reduction and stabilized monitoring values

2.3.7. MRT and Thermal Comfort Post-Processing

In parallel with the CFD-based wind field simulation, MRT was calculated using the Ladybug Tools 1.8.0 within Grasshopper environment of Rhinoceros 6. The “Outdoor Solar Temperature Adjustor” component was used to process the local EPW weather file, which was customized using meteorological data from the Japan Meteorological Agency for the study period. Hourly MRT was calculated based on geographic location, solar

geometry, radiation data, ground albedo, and the three-dimensional building geometry of the target area.

The human-related input parameters were configured as follows: standing posture, orientation facing the prevailing wind, ground albedo of 0.23, and winter clothing insulation of 0.99 clo. The calculated MRT values were combined with pedestrian-height CFD wind speed, hourly air temperature, and relative humidity to calculate SET* and UTCI.

To facilitate spatial analysis and visualization, both SET* and UTCI results were mapped onto a uniform 5 m × 5 m grid across the study area. This produced 2438 analysis points for discomfort frequency analysis and subsequent correlation analysis with urban morphological parameters.

Although direct field measurement-based validation was not conducted in the present study and site-specific validation data were not available for the study area, the simulation setup followed established CFD guidelines for pedestrian-level urban wind environments and adopted commonly used boundary conditions, turbulence modeling, and pedestrian-height output settings. In addition, previous studies have evaluated Grasshopper-based Butterfly/OpenFOAM simulations using benchmark wind tunnel datasets; for example, Hu et al. [32] compared Butterfly simulations with AIJ Case D wind tunnel data at pedestrian level, and Liu et al. [30] validated Butterfly simulations using an AIJ standard pedestrian wind environment model and wind tunnel measurements. These studies provide methodological support for the use of Butterfly/OpenFOAM in comparative pedestrian-level wind environment analysis. However, because such benchmark validation cannot fully replace site-specific field validation, the results of the present study are interpreted primarily as comparative, scenario-based evidence for identifying spatial tendencies of winter thermal discomfort rather than as direct predictions of absolute field-measured thermal conditions.

2.4. Statistical Analysis

To quantify the relationship between urban morphology and pedestrian-level thermal comfort, two statistical approaches were applied in this study. First, Pearson correlation analysis was conducted to examine the linear relationship between average SET* and adjacent building height along representative street canyons. The Pearson correlation coefficient (r) was calculated for each selected street, and the statistical significance was evaluated using a two-tailed test.

Second, a multiple linear regression analysis was conducted to further examine the combined effects of morphological factors on pedestrian-level SET*. Multiple regression was adopted because pedestrian-level thermal comfort is influenced by several morphological factors simultaneously, and regression-based approaches have been widely used in previous outdoor thermal comfort studies to quantify the relative effects of urban form and microclimatic variables [17,41,42]. In this model, average SET* was used as the dependent variable, while average building height, height difference between the two sides of the street, street orientation, and open-space condition were used as explanatory variables. Categorical variables, including street orientation and open-space condition, were converted into dummy variables before analysis. Regression results were reported using unstandardized coefficients, standard errors, t -values, p -values, and 95% confidence intervals.

For all statistical tests, a confidence level of 95% was adopted, and $p < 0.05$ was considered statistically significant. The standard error was used to indicate the uncertainty of regression coefficient estimates. The thermal discomfort frequency maps and mean spatial distributions were calculated descriptively from the 69 winter scenarios and were used to support the spatial interpretation of the statistical results.

3. Results

3.1. Thermal Discomfort Frequency Analysis

To identify thermally vulnerable zones within an urban district, we first analyzed the frequency of thermal discomfort using two indices: SET* and UTCI. For each of the 2438 target points in the study area, the frequency of thermal discomfort occurrence was calculated across 69 selected simulation cases. For winter conditions, a point was considered “uncomfortable” when the SET* was below 14.5 °C or the UTCI was below −13 °C, which are thresholds suggested by existing studies for cold stress in outdoor environments. The discomfort frequency at each point represents the percentage of the 69 simulated winter conditions under which the point was classified as thermally uncomfortable.

As shown in Figure 5, the spatial distribution of SET*-based discomfort frequency reveals that higher discomfort frequencies tend to occur within the east–west-oriented streets (Zone A) and the eastern segments of the north–south-oriented streets (Zone B). These areas are likely to be more thermally stressful because of limited solar exposure, particularly during winter when the solar angle is low. Conversely, lower SET*-based discomfort frequencies are observed within north–south streets (Zone C) and areas located on the leeward sides of large building masses (Zone D) relative to the prevailing northwesterly winter wind. These zones benefit from both wind protection and potentially greater sunlight exposure during the midday hours, contributing to more favorable microclimatic conditions.

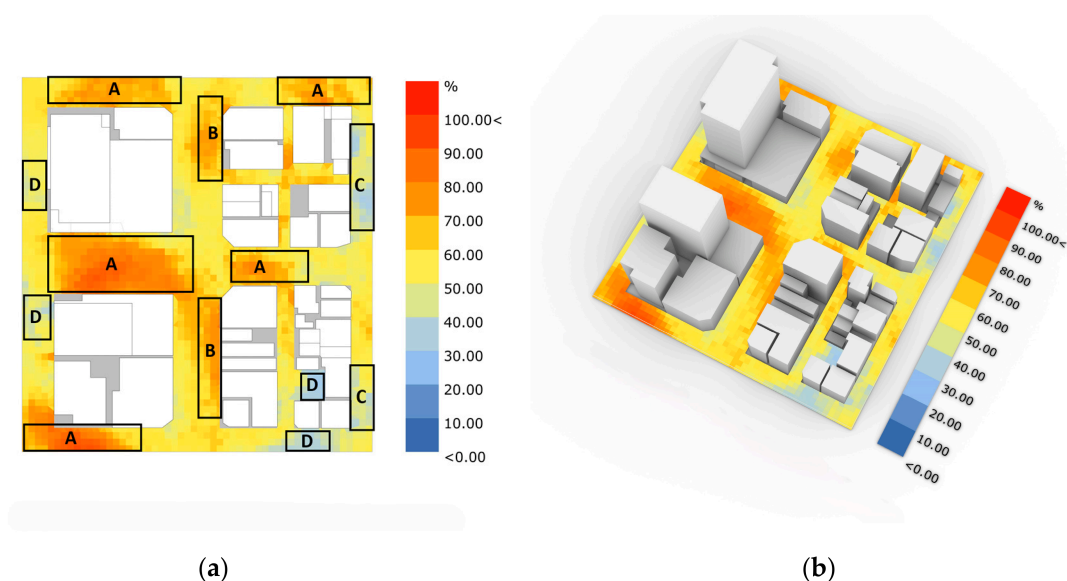


Figure 5. SET* discomfort frequency heatmap: (a) 2D and (b) 3D heatmaps.

Although the UTCI-based discomfort frequency is generally lower than that based on SET* (Figure 6), it exhibits meaningful spatial variations. Except for the same zones as in the SET*, high discomfort frequencies are primarily found near the windward-facing corners of large building blocks, particularly where one façade is exposed to wind and the adjacent façade is sheltered (Figure 6a, Zone E). These microlocations are subject to increased wind exposure and turbulent airflows, which increase convective heat loss and intensify cold stress. This wind amplification at corner zones, which is typically accompanied by eddies or vortex formation, results in more frequent thermal discomfort even when other thermal indices (e.g., MRT) are moderate.

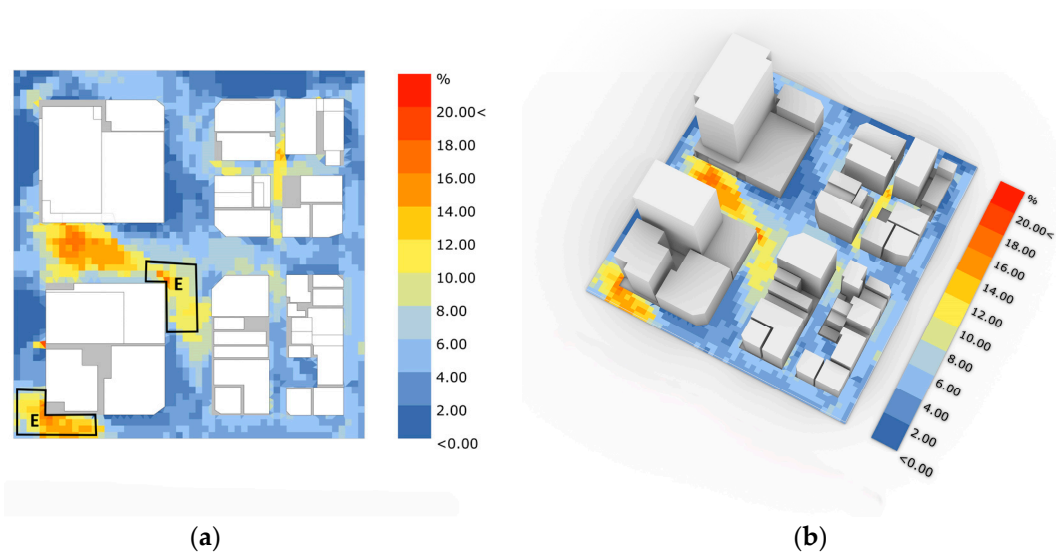


Figure 6. UTCI discomfort frequency heatmap: (a) 2D and (b) 3D heatmaps.

These results suggest that SET* is a more sensitive indicator under cold conditions, particularly in urban contexts where wind speed and MRT vary rapidly across the built environment. The higher discomfort frequency detected by SET* indicates that this index responds more clearly to small-scale variations in radiation and wind conditions at pedestrian level. In contrast, UTCI mainly highlighted locations with stronger wind exposure, such as building corners. Therefore, the two indices should be interpreted as complementary tools: SET* is useful for identifying radiation-deficient cold areas, while UTCI helps capture wind-induced cold stress.

The thermally vulnerable zones identified using both indices share the following urban and environmental characteristics (Figure 7):

- East–west-oriented streets with limited solar access, resulting in a persistently low radiant temperature.
- Corner areas of large building blocks, especially at windward positions exposed to prevailing northwesterly winds.
- Leeward zones and north–south corridors exhibit improved comfort due to wind shielding and potential solar gains.

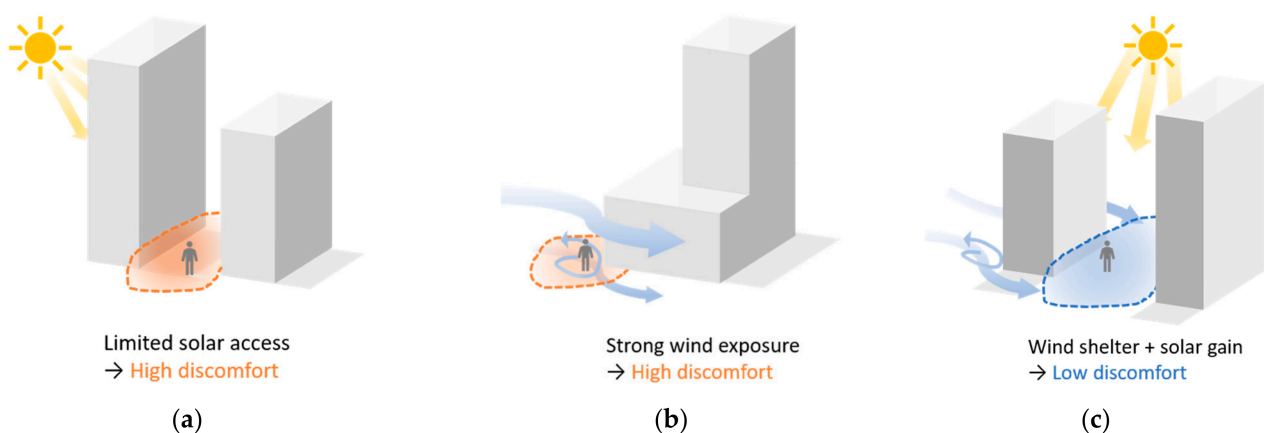


Figure 7. Conceptual diagrams of typical urban morphological conditions associated with winter thermal discomfort: (a) east–west-oriented streets with limited solar access; (b) wind-exposed building corners under prevailing northwesterly winds; (c) leeward zones and north–south streets benefiting from wind sheltering and solar gain.

These insights suggest that solar access, prevailing wind direction, and geometries are key morphological factors affecting thermal discomfort in winter and should be addressed in climate-sensitive urban design. In particular, shaded east–west streets and wind-exposed corners represent different mechanisms of cold discomfort: the former is mainly related to reduced radiant heat gain, while the latter is mainly associated with increased convective heat loss. This distinction provides the basis for the following analysis of wind speed and MRT distributions, which further explains the environmental causes of the discomfort patterns identified in this section.

3.2. Key Components of Winter Thermal Environment: Wind and MRT Distributions

To reinforce the spatial discomfort patterns identified in Section 3.1, the average distributions of wind speed and MRT across 69 representative winter daytime cases were examined. These maps help elucidate the environmental factors that underlie discomfort-prone areas.

The average wind speed map in Figure 8a indicates that high wind speeds are concentrated near the northeastern and southwestern corners of the urban blocks, particularly in areas where building heights are significant. These areas are aligned with the prevailing northwesterly winds in winter. In contrast, lower wind speeds are found within sheltered zones and narrower street spaces, which tend to experience less thermal discomfort, because excessive wind exposure in cold seasons can aggravate heat loss and discomfort. This pattern supports the conclusion in Section 3.1 that wind-exposed corners of tall blocks typically correspond to high UTCI-based discomfort frequencies.

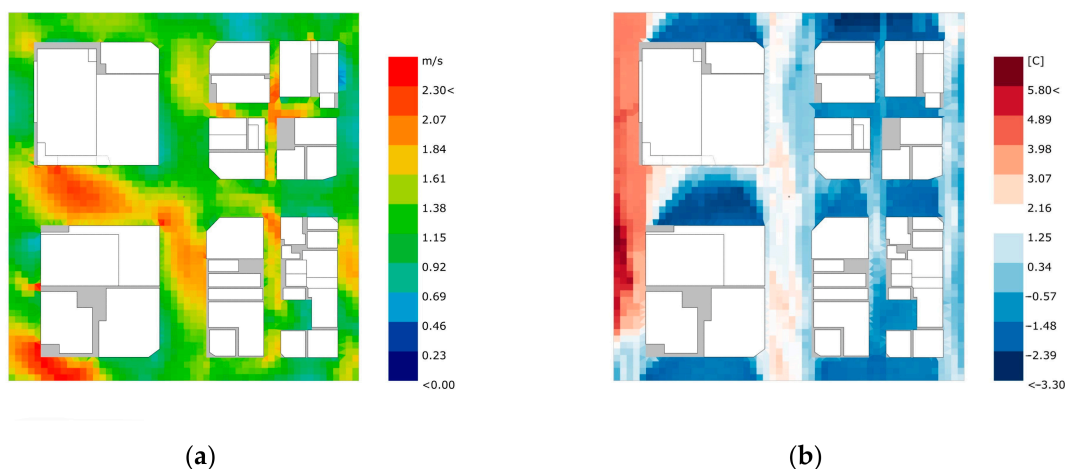


Figure 8. Average distribution map: (a) wind speed and (b) MRT.

The MRT distribution map in Figure 8b shows that lower MRT values are primarily distributed along east–west-oriented streets and on the eastern portions of north–south streets, particularly where the adjacent buildings cast long shadows. These areas receive limited solar radiation due to the low sun angle in winter and the orientation of the street canyon, resulting in a reduced MRT. This MRT pattern agrees with the SET-based discomfort distribution*, where discomfort was more frequent in shaded, sun-deprived spaces.

Collectively, the wind and MRT distributions validate the discomfort trends shown in the previous section: high discomfort frequency tends to occur in either wind-exposed or radiation-deficient zones, depending on the index used. Based on these observations, the next section focuses on the influence of urban morphological features, particularly building height along street canyons, on spatial thermal comfort patterns.

3.3. Relationship Between Building Height Along Street Canyons and Thermal Comfort

Building upon the spatial observations in Sections 3.1 and 3.2, where higher thermal discomfort was frequently found in areas with high wind speed or limited solar access, this section quantitatively investigates the effects of urban morphological features, particularly building height along street canyons, on localized thermal comfort conditions. In particular, the relationship between average SET* and adjacent building height is explored via visual comparison and statistical correlation, with a focus on typical north–south- and east–west-oriented canyons.

3.3.1. Spatial Trends of Thermal Comfort and Building Height

Figure 9 shows the spatial distribution of the average SET* values across all 69 simulated winter cases. Higher values are primarily found along north–south-oriented streets and at intersections with east–west corridors, where solar exposure is less obstructed. In contrast, lower SET* values appear near tall buildings, particularly in shaded sections of east–west streets. These thermal patterns form the basis for the following street canyon analysis.

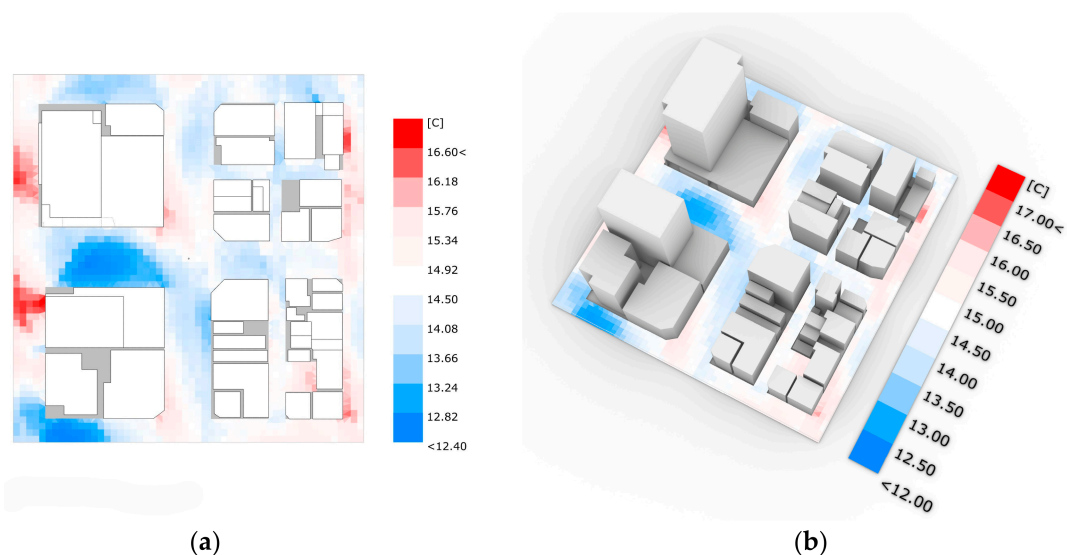


Figure 9. Average SET* heatmap: (a) 2D and (b) 3D heatmaps.

Two representative street canyons were selected for examination: one oriented in the north–south direction and the other in the east–west direction. Each canyon was subdivided into several vertical sampling lines aligned with the canyon orientation. For each line, the average SET* values of the measurement points were calculated to characterize thermal comfort along the cross-section of the canyon.

Figure 10a shows the distribution of average SET* values across the east–west-oriented Kita 3-jo Street and adjacent building elevations. The colored grid represents SET* values at each sampling location, and the upper and lower gray blocks represent the north- and south-side street-facing building elevations, flanking the east–west street, respectively. The view is rendered in a “flattened projection,” aligning measurement lines (Lines 1–9) from south to north for visual clarity. Figure 10b shows the relationship between the average SET* values and the heights of the adjacent buildings on both sides of the east–west street. The SET* trends are shown along nine transects (Lines 1–9), and the building height bars indicate the immediate flanking structure heights to the north and south at each sampling point. Higher SET* values are generally observed at both ends of the street and in the central section with no flanking buildings, corresponding to zones with a building height

of zero. The lowest SET* values are found in segments with the tallest adjacent buildings on both sides of the street. This trend corresponds well with the surrounding building height profile.

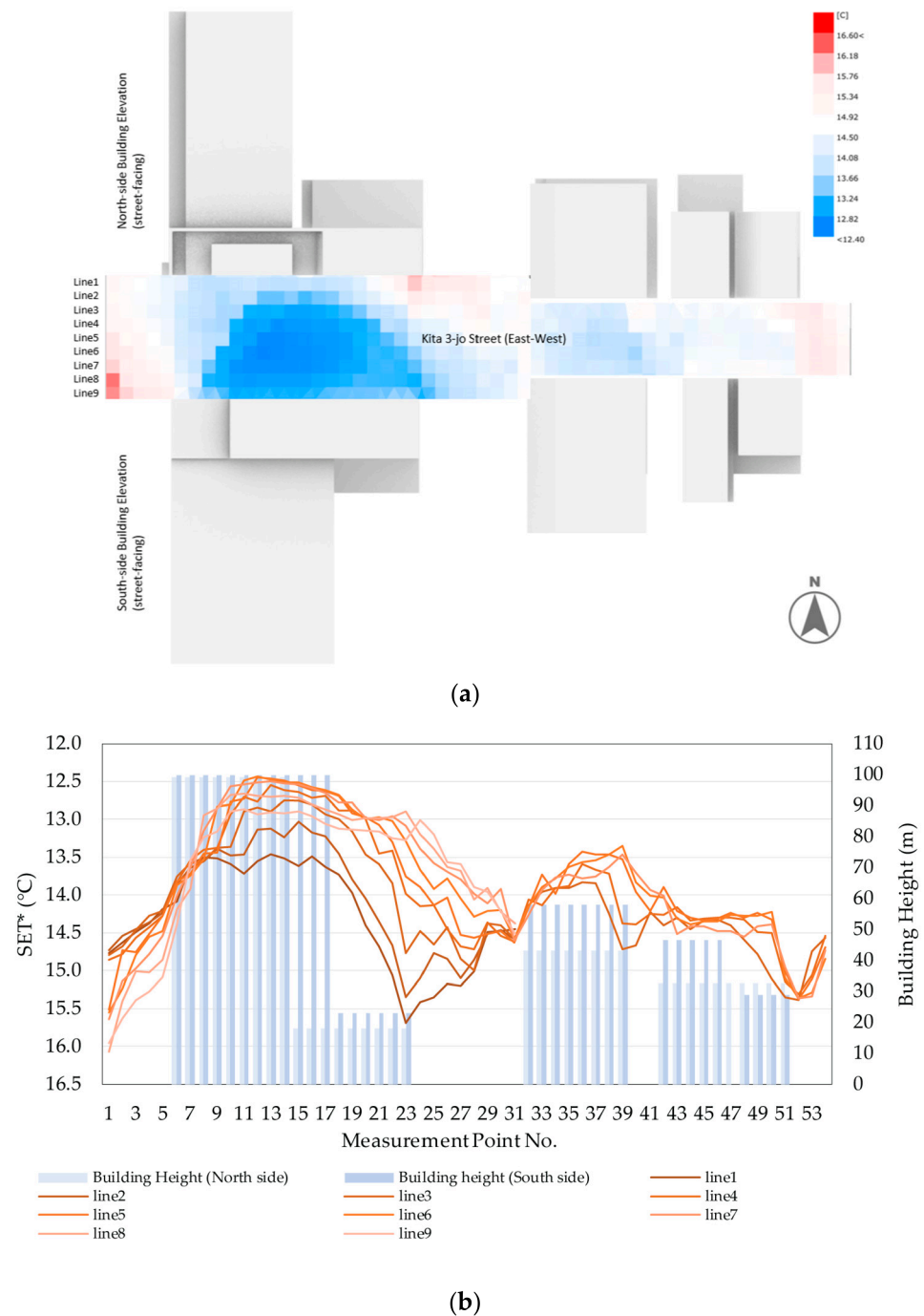


Figure 10. (a) Average SET* distribution across the east–west-oriented Kita 3-jo Street canyon and adjacent building frontages; (b) longitudinal profiles of average SET* values and building height along the east–west primary street canyon (Lines 1–9).

Figure 11a shows the distribution of average SET* values across the north–south-oriented Nishi 4-chome Street and adjacent building frontages. The colored grid represents SET* values at each sampling location, and the gray blocks represent the adjacent building frontage forms flanking the north–south street. Figure 11b shows the relationship between the average SET* values and the heights of the adjacent buildings on both sides of Nishi

4-chome Street. The SET* trends are shown along seven transects (Lines 1–7), and the building height bars indicate the immediate flanking structure heights to the north and south at each sampling point. Similarly, in the north–south-oriented canyon, the SET* values tend to be higher near the unshaded entrances of the street (building height = 0). An additional local maximum of SET* is identified slightly north of the central intersection, suggesting the influence of solar exposure or wind patterns. Areas with relatively lower SET* values are typically located adjacent to taller building masses.

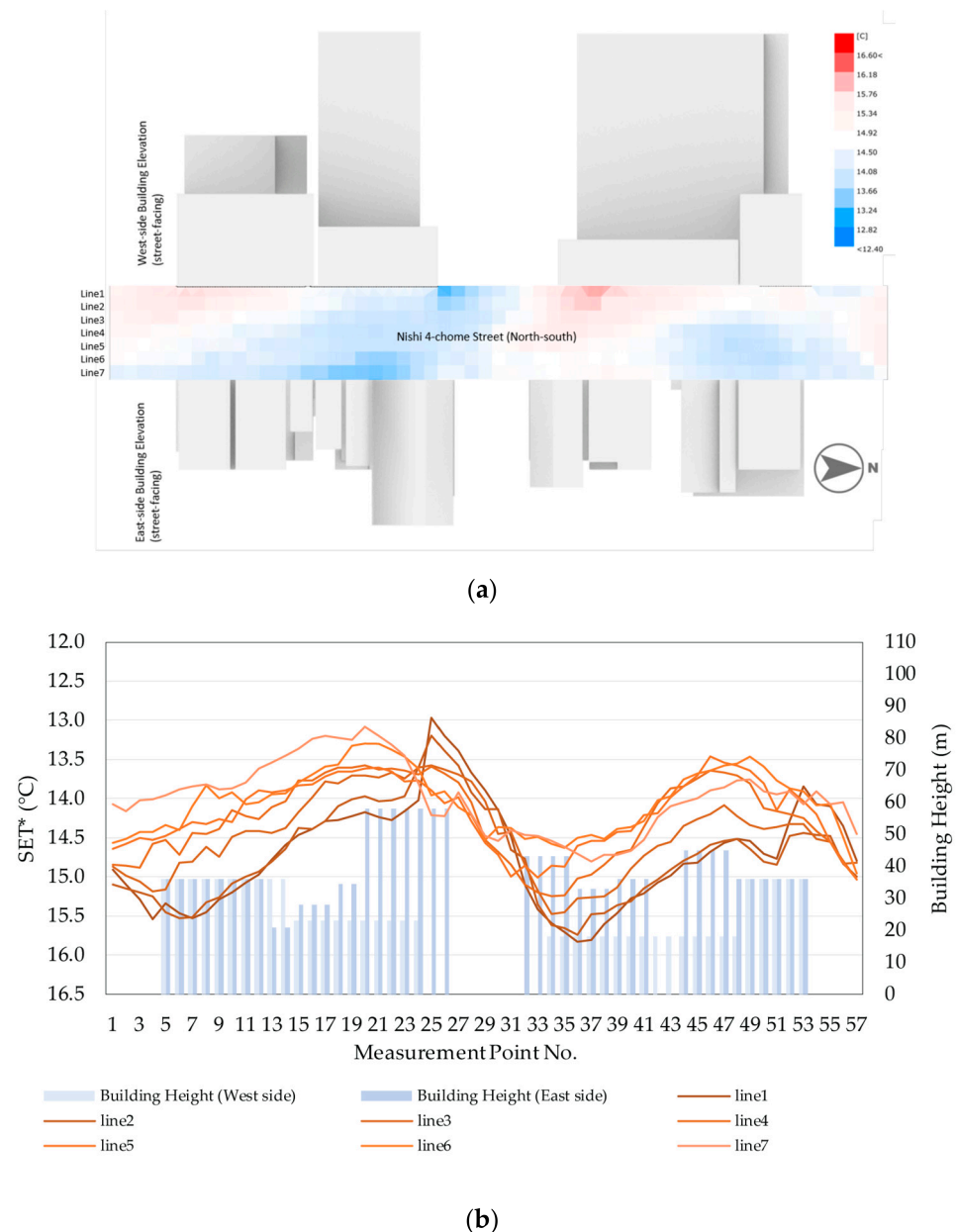


Figure 11. (a) Average SET* distribution across the north–south-oriented Nishi 4-chome Street canyon and adjacent building frontages; (b) longitudinal profiles of average SET* values and building height along the north–south primary street canyon (Lines 1–7).

Overall, the longitudinal variation in SET* generally follows the trend of adjacent building heights. Such insights highlight the potential influence of urban skyline morphology on spatial thermal comfort distribution, which is further examined in the next section via quantitative correlation analyses.

3.3.2. Line-Based Profile Analysis of Street Canyons

To further examine the effect of street canyon morphology on pedestrian-level thermal comfort in winter, this section presents a Pearson correlation analysis between the average SET* values and building height along both sides of selected streets. Building upon the spatial observations and longitudinal transects introduced in Section 3.3.1, this quantitative approach statistically validates the strength and direction of their relationship.

Two sets of representative streets were analyzed: three east–west-oriented canyons (Kita 3-jo, Kita 2-jo, and Kita 4-jo) and three north–south-oriented canyons (Nishi 4-chome, Nishi 3-chome, and Nishi 5-chome). Each street was divided into transverse measurement lines aligned perpendicularly to the street axis (i.e., line1 to lineN), arranged from north to south in east–west streets and from west to east in north–south streets. For each line, the average SET* was correlated with three variables: the average building height (R_AVE), the building height on the north or west side (R_N or R_W), and the building height on the south or east side (R_S or R_E).

As summarized in Table 4, all three east–west-oriented streets demonstrated statistically significant negative correlations between the average building height and pedestrian thermal comfort. In Kita 3-jo, the primary street, the R_AVE values ranged from -0.80 to -0.52 across the nine lines (line1 to line9), with p -values consistently below 0.01, indicating a robust inverse relationship. The correlations with south-side building heights (R_S) were stronger and more statistically significant than those with north-side heights (R_N) in nearly all segments. For example, line2 exhibited a correlation of -0.86 for R_S ($p < 0.001$) compared with -0.68 for R_N. This pattern reflects the significant role of south-side buildings in obstructing low-angle solar radiation during winter, thereby reducing the MRT and SET* values.

Table 4. Pearson correlation coefficients (r) and significance (p) between average SET* and building height (R_S: south side; R_N: north side; R_AVE: average) along lines in east–west-oriented streets *.

	Line No.	r (R_N)	r (R_S)	r (R_AVE)	p (R_N)	p (R_S)	p (R_AVE)
Kita 3-jo Street	line1	-0.68275	-0.80489	-0.77459	$2.32 \times 10^{-5} *$	$4.80 \times 10^{-8} *$	$3.15 \times 10^{-7} *$
	line2	-0.67689	-0.85904	-0.80092	$2.86 \times 10^{-7} *$	$6.23 \times 10^{-10} *$	$6.26 \times 10^{-8} *$
	line3	-0.56785	-0.73495	-0.68098	$7.52 \times 10^{-8} *$	$2.49 \times 10^{-10} *$	$1.46 \times 10^{-8} *$
	line4	-0.57625	-0.73529	-0.68526	$5.12 \times 10^{-8} *$	$2.42 \times 10^{-10} *$	$1.09 \times 10^{-8} *$
	line5	-0.55619	-0.71405	-0.66380	$1.26 \times 10^{-5} *$	$1.35 \times 10^{-9} *$	$4.47 \times 10^{-8} *$
	line6	-0.52206	-0.66605	-0.62077	$5.15 \times 10^{-5} *$	$3.88 \times 10^{-8} *$	$5.51 \times 10^{-7} *$
	line7	-0.48724	-0.62061	-0.57881	$1.90 \times 10^{-4} *$	$5.56 \times 10^{-7} *$	$4.55 \times 10^{-8} *$
	line8	-0.47146	-0.59310	-0.55503	$7.42 \times 10^{-3} *$	$4.40 \times 10^{-4} *$	$1.19 \times 10^{-3} *$
	line9	-0.43766	-0.55374	-0.51694	$1.38 \times 10^{-2} *$	$1.23 \times 10^{-3} *$	$2.90 \times 10^{-3} *$
Kita 2-jo Street	line1	-0.34558	-0.32544	-0.15712	$0.016336 *$	0.256513	$0.010483 *$
	line2	-0.31464	-0.39587	-0.16257	$0.003046 *$	0.240176	$0.020491 *$
	line3	-0.37099	-0.4544	-0.2072	$0.000557 *$	0.132744	$0.00575 *$
	line4	-0.4076	-0.49639	-0.23123	$0.000135 *$	0.092507	$0.00222 *$
Kita 4-jo Street	line1	-0.43093	-0.46722	-0.35238	$0.000368 *$	$0.008967 *$	$0.001142 *$
	line2	-0.34083	0.072738	-0.47558	0.601183	$0.000279 *$	$0.011669 *$
	line3	-0.28828	0.13173	-0.43351	0.342363	$0.001058 *$	$0.034521 *$
	line4	-0.5912	-0.6256	-0.4903	$4.24 \times 10^{-7} *$	$0.000168 *$	$2.51 \times 10^{-8} *$

* Statistically significant values ($p < 0.05$) are shown.

Figure 12 shows these spatial variations through a line-by-line plot of correlation coefficients for each street and building-side category. In Kita 3-jo, a clear spatial trend was observed: the magnitude of the negative correlation decreased from line1 (north end) to line9 (south end), indicating that the influence of building height on thermal comfort gradually weakens toward the southern sections of the canyon. This spatial gradient aligns with previous findings on solar access variability and the shading effects of higher buildings in northern segments.

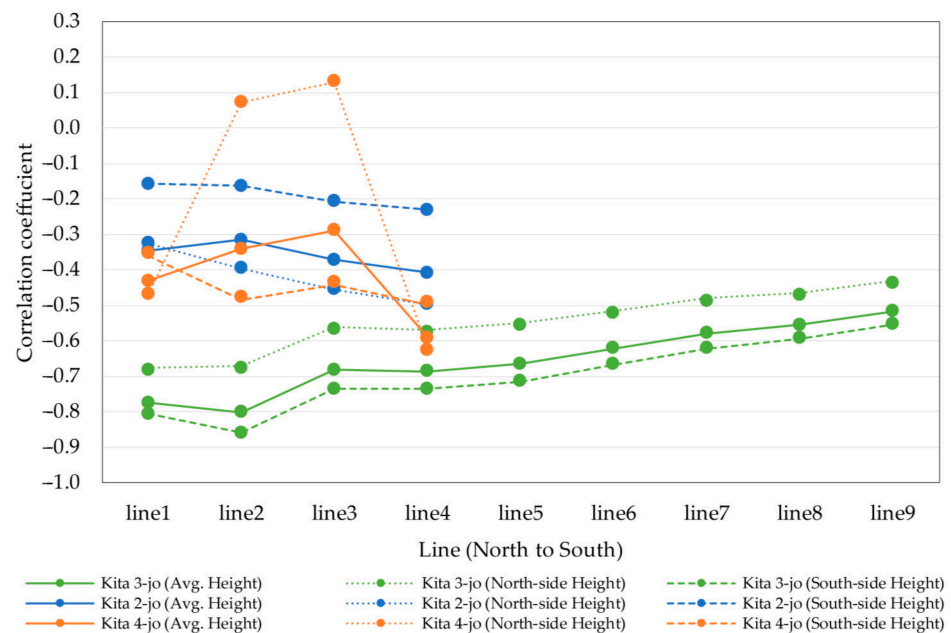


Figure 12. Pearson correlation coefficients (r) between SET* and building height across three east–west-oriented street canyons (Kita 3-jo, Kita 2-jo, and Kita 4-jo).

In contrast, Kita 4-jo exhibited an opposite asymmetry, where the north-side buildings (R_N) exhibited stronger correlations with SET*, whereas the south-side values were not statistically significant. This inversion is likely due to the presence of a continuous, uniformly high façade along the south side, which limits height variations and thus diminishes its influence on thermal comfort variations. Conversely, Kita 2-jo, similar to the primary street, followed a more typical pattern where the south-side morphology had greater influence. However, the overall correlation strength was slightly weaker, probably because of the extended open areas and lack of buildings along significant portions of the north side, which reduced the effect of morphological variations on the thermal environment.

The results for the north–south-oriented canyons (Table 5) revealed greater heterogeneity. In Nishi 4-chome (the primary street), a strong and spatially consistent negative correlation was found between building height and SET*, particularly in the eastern segments (line4 to line6). The R_{AVE} values dropped from 0.12 in line1 to -0.57 in line6, with significant p -values throughout. Both R_W and R_E contributed to this effect even though the west-side buildings generally had stronger statistical significance. Figure 13 confirms this spatial trend with a steady decline in the correlation coefficients along the west-to-east axis.

Table 5. Pearson correlation coefficients (r) and significance (p) between average SET* and building height (R_W : west side; R_E : east side; R_{AVE} : average) along lines in north–south primary street *.

	Line No.	r (R_W)	r (R_E)	r (R_{AVE})	p (R_W)	p (R_E)	p (R_{AVE})
Nishi 4-chome Street	Line 1	0.26601	−0.00522	0.12329	$4.55 \times 10^{-2} *$	9.69×10^{-1}	3.61×10^{-1}
	Line 2	0.22245	−0.14755	0.00621	9.63×10^{-2}	2.73×10^{-1}	9.63×10^{-1}
	Line 3	−0.05952	−0.26718	−0.20917	6.60×10^{-1}	$4.45 \times 10^{-2} *$	1.18×10^{-1}
	Line 4	−0.30247	−0.37162	−0.39566	$2.22 \times 10^{-2} *$	$4.40 \times 10^{-3} *$	$2.30 \times 10^{-3} *$
	Line 5	−0.47413	−0.46408	−0.54007	$2.00 \times 10^{-4} *$	$3.00 \times 10^{-4} *$	$1.00 \times 10^{-5} *$
	Line 6	−0.47201	−0.51097	−0.57078	$2.00 \times 10^{-4} *$	$5.00 \times 10^{-5} *$	$4.00 \times 10^{-8} *$
	Line 7	−0.43386	−0.24143	−0.37021	$7.00 \times 10^{-4} *$	7.04×10^{-2}	$4.60 \times 10^{-3} *$

Table 5. Cont.

	Line No.	r (R_W)	r (R_E)	r (R_AVE)	p (R_W)	p (R_E)	p (R_AVE)
Nishi 5-chome Street	line1	0.290984	NaN	0.430171	NaN	$8.38 \times 10^{-4} *$	$2.81 \times 10^{-2} *$
	line2	0.481078	NaN	0.481078	NaN	$1.52 \times 10^{-4} *$	$1.52 \times 10^{-4} *$
	line3	0.542971	NaN	0.542971	NaN	$1.28 \times 10^{-5} *$	$1.28 \times 10^{-5} *$
	line4	0.557438	NaN	0.557438	NaN	$6.66 \times 10^{-8} *$	$6.66 \times 10^{-8} *$
Nishi 3-chome Street	line1	−0.1401	0.018788	−0.23242	0.889676	0.081896	0.298613
	line2	−0.21301	−0.12638	−0.24376	0.348894	0.067665	0.111643
	line3	0.000742	0.066635	−0.04599	0.622375	0.734106	0.995631
	line4	−0.24136	−0.16469	−0.26099	0.220873	0.049888 *	0.070503

* Statistically significant values ($p < 0.05$) are shown.

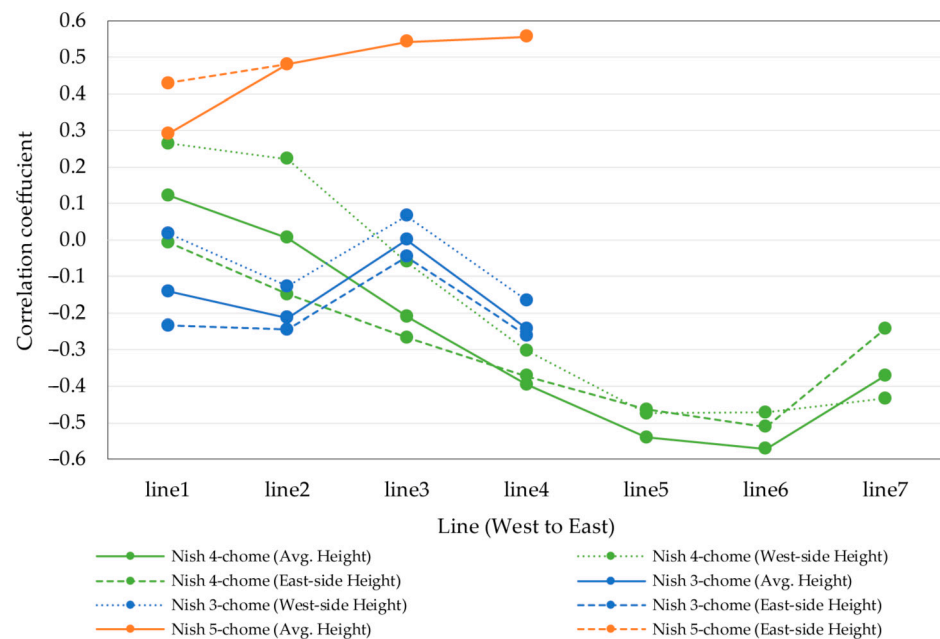


Figure 13. Pearson correlation coefficients (r) between SET* and building height across three north-south-oriented canyons (Nishi 4-chome, Nishi 5-chome Street, and Nishi 3-chome Street).

Nishi 3-chome exhibited weaker and less consistent correlations. The R_AVE values remained moderately negative, but only one segment (line4) exhibited statistical significance. The east-side buildings (R_E) exhibited slightly stronger correlations than the west-side buildings; however, the differences were marginal. This result suggests that building height plays a more subdued role in this canyon, probably because of more symmetric or lower building profiles.

Nishi 5-chome presented a unique case. Because the west side of the street borders an open park, no correlation could be computed for the west-side building height. However, the east-side buildings (R_E) exhibited statistically significant positive correlations with SET* across all segments ($r = 0.43$ – 0.56 , $p < 0.01$). This reversal suggests that, in the absence of shading from the west, taller east-side buildings improve thermal comfort by mitigating wind exposure. The presence of a highly asymmetric urban boundary inverts the expected relationship, highlighting the importance of context.

This line-based Pearson correlation analysis reinforces the identified spatial trends and asymmetries in Section 3.3.1. Although all six street canyons exhibit a degree of statistical relationship between building height and winter thermal comfort, the direction and strength of influence vary depending on orientation and morphological contexts. East-west streets typically exhibit stronger negative correlations, particularly on the south side, because of solar obstruction effects. North-south streets reveal more diverse patterns, including asymmetric conditions (e.g., adjacent parks) that produce positive correlations.

These findings highlight the importance of integrating street orientation and morphological contexts into cold-region urban design. The observed correlations confirm that building height plays a significant but context-dependent role in shaping the thermal comfort of pedestrians.

To supplement the line-based Pearson correlation analysis and further address the multi-causal nature of winter thermal comfort, a multiple regression analysis was conducted using mean SET* as the dependent variable. Four morphological variables were used as explanatory variables: average adjacent building height (H_avg), height difference between the two street sides (H_diff), street orientation, and open-space condition. H_avg represents the average building height on both sides of the street, while H_diff represents the absolute height difference between the two sides. Street orientation was coded as 0 for east–west-oriented streets and 1 for north–south-oriented streets. Open-space condition was coded as 0 for streets without an open-space side and 1 for streets adjacent to an open space or park on one side. The analysis was based on 1821 sampling points extracted from the six analyzed street canyons. MRT and wind speed were not included as explanatory variables in this model because they were direct input variables in the calculation of SET*, and their inclusion could lead to circular interpretation.

As shown in Table 6, the model was statistically significant ($F = 134.59$, $p < 0.001$) and explained 22.9% of the spatial variation in mean SET* ($R^2 = 0.229$, adjusted $R^2 = 0.227$). H_avg showed a significant negative association with mean SET* (coefficient = -0.0091 , $p < 0.001$), indicating that taller adjacent buildings tended to reduce pedestrian-level winter thermal comfort. In contrast, H_diff showed a significant positive association with mean SET* (coefficient = 0.0048 , $p < 0.001$), suggesting that asymmetric street-edge conditions may reduce continuous enclosure and allow greater solar access in some segments. Street orientation was also significant (coefficient = 0.4714 , $p < 0.001$), indicating that north–south-oriented streets generally had higher SET* values than east–west-oriented streets after controlling for the other morphological variables. Open-space condition showed a positive but statistically non-significant tendency (coefficient = 0.0881 , $p = 0.069$). These results suggest that building height should not be interpreted as an isolated factor, but rather as one component of a broader morphological system involving street orientation, canyon asymmetry, and local openness.

Table 6. Supplementary multiple regression results for average SET* *.

Variable	Coefficient	Standard Error	t-Value	p-Value	95% CI
Intercept	14.1857	0.0503	282.03	<0.001	14.0870 to 14.2843
H_avg	−0.0091	0.0011	−8.39	<0.001	−0.0112 to −0.0070
H_diff	0.0048	0.0007	6.43	<0.001	0.0033 to 0.0063
Orientation	0.4714	0.0337	14.00	<0.001	0.4054 to 0.5375
Open-space condition	0.0881	0.0484	1.82	0.069	−0.0068 to 0.1830

* Note: $n = 1821$; $R^2 = 0.229$; adjusted $R^2 = 0.227$. Coefficients are unstandardized regression coefficients.

4. Discussion

4.1. Implications

The spatial distributions of thermal discomfort identified through SET* and UTCI analyses highlight the pivotal role of urban form in shaping outdoor microclimates during winter. Discomfort hotspots were primarily located in the east–west-oriented streets and the eastern parts of the north–south streets, where solar access is constrained by street orientation and adjacent building shadows. Conversely, lower discomfort levels occurred in the north–south corridors and leeward areas protected from prevailing northwesterly winds, benefiting from greater solar gains and reduced convective cooling. Previous studies have reported similar patterns linking street orientation and canyon geometry to variations

in solar radiation and radiant temperature in cold climates [43]. Recent studies in severe-cold cities have also shown that street geometry, sky view factor, wind exposure, and block morphology jointly influence winter outdoor thermal comfort [17,18]. However, while previous studies have mainly focused on residential blocks, simplified canyon models, field surveys, or the calibration of thermal comfort indices, the present study provides a high-resolution spatial diagnosis of thermal discomfort in the downtown area of Sapporo based on 69 representative winter scenarios and 2438 pedestrian-level sampling points.

A further contribution of this study is the combined use of SET* and UTCI to identify different types of winter thermal discomfort. SET* exhibited greater spatial sensitivity to cold-stress conditions than UTCI, particularly in shaded or low-radiation environments. Although UTCI captured peak discomfort in highly wind-exposed zones, SET* more effectively highlighted discomfort in radiation-deficient or sheltered areas. This divergence reflects the differing sensitivity of the indices to environmental drivers, as noted in earlier comparative studies on thermal comfort metrics [23]. Recent comparative studies also suggest that PET, SET*, and UTCI may differ in applicability under different seasonal and microclimatic conditions [27], and that UTCI alone may be limited under very cold and windy winter conditions [28]. The results of this study support this view. The complementary nature of SET* and UTCI indicates the importance of multi-indicator frameworks in cold-climate assessments in urban areas. The environmental patterns of wind speed and MRT further support the observed discomfort trends. Wind intensification was consistently observed near the windward corners of tall urban blocks, whereas MRT depression was common in the shaded east–west canyons. Wind amplification and radiation deprivation have been extensively recognized as key drivers of pedestrian thermal discomfort in dense urban settings [10,11]. Their manifestation in this study confirms that local morphological characteristics, such as building height and street orientation, mediate both convective and radiative processes.

The correlation and multivariate analyses further quantified how local building-height configurations influence pedestrian-level thermal comfort. While previous studies have often examined urban morphology through general indicators such as H/W ratio, sky view factor, street orientation, urban density, and block morphology [17,18], this study directly related SET* variations to the heights of buildings adjacent to street canyons in a real downtown district. Significant negative correlations were found between average SET* and adjacent building heights, especially in segments flanked by tall buildings. The multivariate analysis further showed that average building height, height difference, and street orientation jointly affected pedestrian-level SET*, whereas the influence of open-space condition was weaker. These effects were more pronounced on the southern sides of east–west canyons and the eastern sides of north–south canyons, consistent with solar access patterns. Similar trends in the secondary streets further support the robustness of these findings. Overall, the results indicate that taller buildings and asymmetric canyon forms tend to reduce winter thermal comfort by limiting solar access and modifying wind conditions, which is consistent with previous findings [44,45].

4.2. Limitations

Several limitations should be acknowledged. First, this study is based on numerical simulations using selected winter daytime meteorological conditions. Although the selected 69 scenarios represent a broad range of winter weather conditions in Sapporo, the results may not fully capture nighttime conditions, transitional seasons, or interannual climatic variability. Second, the CFD-based wind environment and thermal comfort calculations depend on model assumptions, boundary conditions, and grid settings. Additional

comparison with field measurements or wind-tunnel data would further strengthen the quantitative reliability of the simulation results.

Third, this study evaluates thermal discomfort mainly through physical environmental variables and thermal comfort indices. Actual human responses, such as thermal sensation vote (TSV), thermal comfort vote (TCV), thermal preference vote (TPV), clothing insulation, metabolic rate, and local adaptation to cold, were not directly collected through questionnaire surveys or field observations. Therefore, the results should be interpreted as an objective microclimatic assessment rather than a complete representation of perceived human comfort. Future studies should combine simulation results with human-subject surveys to improve the biometeorological validity of winter thermal comfort evaluation.

Fourth, although the newly added multivariate analysis helps clarify the combined effects of average building height, height difference, street orientation, and open-space condition, the statistical results should be interpreted as associations within the selected study area rather than universal causal relationships. The morphological analysis still focuses mainly on building-height-related indicators and does not explicitly include other three-dimensional urban form parameters, such as sky view factor, height-to-width ratio, frontal area index, canyon openness, urban roughness, or compactness. These parameters should be incorporated in future studies to better explain radiation and wind dynamics in winter.

Finally, the study area is limited to four urban blocks in downtown Sapporo. Therefore, the findings provide context-specific evidence for a high-density cold-climate urban district, but they cannot yet be directly translated into general planning thresholds, such as optimal H/W ratios, maximum building heights, or universally applicable road-alignment criteria. Future research should examine more diverse urban morphologies and conduct comparative studies across different cold-climate cities to develop transferable quantitative design guidelines. Vegetation, snow cover, surface material properties, and dynamic pedestrian behavior should also be incorporated to further develop the proposed framework for winter urban design.

Overall, this study demonstrates that urban morphology has a measurable and context-dependent influence on winter thermal comfort. Urban design strategies, such as staggered rooflines, solar-oriented street grids, porous block layouts, and carefully arranged open spaces, may mitigate discomfort by improving solar access and reducing wind exposure at the pedestrian level. Although vegetation was not the main variable examined here, previous studies have shown that vegetation and green-space configuration can influence outdoor thermal comfort through shading, radiation exchange, humidity, and wind conditions [45,46]. Future studies should build on this framework by integrating field validation, human thermal perception surveys, additional morphological indicators, and comparative analyses across different cold-climate cities.

5. Conclusions

1. Observed hourly winter weather data in Sapporo were used to select 69 representative daytime scenarios for wind and solar simulations in the downtown open space. SET* and UTCI were then calculated to assess pedestrian-level thermal discomfort. By using multiple scenarios derived from actual winter weather data rather than a single assumed condition, this study provides a seasonally representative assessment of winter outdoor thermal comfort for sustainable, climate-adapted urban design. Thermal discomfort was most pronounced in the east–west-oriented streets and at wind-exposed corners of large buildings, where limited solar access and intensified wind flows contributed to greater cold stress.
2. SET* consistently exhibited greater sensitivity than UTCI under typical winter conditions in Sapporo. Its responsiveness to low wind speed and reduced solar radiation

makes it a more suitable indicator for diagnosing thermal discomfort in cold climates, thereby supporting its use in urban design optimization.

3. Building height exhibited a statistically significant negative correlation with SET*, indicating that taller adjacent buildings tend to reduce pedestrian thermal comfort, primarily because of shading effects and altered wind dynamics. This pattern was particularly evident on the southern sides of the east–west canyons and the eastern sides of the north–south canyons.
4. The multivariate analysis further showed that pedestrian-level SET* is affected not by building height alone, but by the height difference, street orientation, and local open-space conditions. These results emphasize the importance of considering multiple morphological factors when evaluating winter thermal comfort in high-density urban districts.
5. The findings suggest that winter urban design should balance solar access and wind protection. Strategies such as stepped or staggered building forms, careful placement of taller buildings, solar-oriented street layouts, and appropriately arranged open spaces may help reduce cold discomfort at the pedestrian level.

These design strategies should be interpreted as context-specific tendencies rather than transferable quantitative planning thresholds, such as optimal H/W ratios, maximum building heights, or universally applicable road-alignment criteria. Future research should strengthen the proposed framework through field measurement validation, seasonal comparisons, and the incorporation of vegetation and dynamic pedestrian behavior. These extensions would support a more comprehensive understanding of winter thermal comfort and provide more practical guidance for sustainable cold-climate urban design.

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Abbreviations

The following abbreviations are used in this manuscript:

SET*	Standard effective temperature
UTCI	Universal thermal climate index
MRT	Mean radiant temperature
CFD	Computational fluid dynamics
AIJ	Architectural Institute of Japan
PET	Physiological equivalent temperature
2D	two-dimensional
3D	three-dimensional
SVF	sky view factor
H/W	height-to-width
FAI	frontal area index

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