Research Article

Field Assessment of Neighboring Building and Tree Shading Effects on the 3D Radiant Environment and Human Thermal Comfort in Summer within Urban Settlements in Northeast China

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Received 21 May 2020; Revised 31 July 2020; Accepted 31 August 2020; Published 23 September 2020

Academic Editor: Alastair Williams

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Shading is one of the most effective strategies to mitigate urban local-scale heat stress during summer. Therefore, this study investigates the effects of shading caused by buildings and trees via exhaustive field measurement research on urban outdoor 3D radiant environment and human thermal comfort. We analyzed the characteristics of micrometeorology and human thermal comfort at shaded areas, and compared the difference between building and tree shading effects as well as that between shaded and sunlit sites. The results demonstrate that mean radiant temperature T_{mrt} (mean reduction values of 28.1°C for tree shading and 28.8°C for building shading) decreased considerably more than air temperature T_a (mean reduction values of 1.9°C for tree shading and 1.2°C for building shading) owing to shading; furthermore, the reduction effect of shading on UTCI synthesized the variation in the above two parameters. Within the shaded areas, short-wave radiant components (mean standardized values of 0.104 for tree shading and 0.087 for building shading) decreased considerably more than long-wave radiant components (mean standardized values of 0.848 for tree shading and 0.851 for building shading) owing to shading; the proportion of long-wave radiant flux densities absorbed by the reference standing person was high, leading to a relatively high long-wave mean radiant temperature, and R^2 between long-wave mean radiant temperature and air temperature exceeded 0.8. Moreover, the directional sky view factor (SVF) was utilized in this study, and it showed significant positive correlation with short-wave radiant flux densities, but no statistically evident correlation with long-wave radiant flux densities. Meanwhile, T_{mrt} was most relevant with SVF_{sky} , with R^2 of 0.9756. Furthermore, UTCI rose two categories at the sunlit areas compared with that at the shaded areas. In contrast, T_a and T_{mrt} played the first positive role in UTCI at shaded and sunlit areas, respectively.

1. Introduction

Urbanization is accelerating worldwide and is affecting urban living and transforming human society in various manners [1]. Among them, increasing urban severe heat in summer is a problem for many countries, which has strongly aggravated human thermal stress within urban spaces [2]. The outdoor thermal environment is significantly affected by the design of the built and vegetation environment [3], and it affects the thermal comfort experienced by people; furthermore, people's perception for the thermal environment

as a result influences their usage of outdoor spaces [4, 5]. As outdoor leisure activities can improve people's health and vitality [6, 7], thermally comfortable and environmentally healthy outdoor spaces in densely urban areas are of significance for citizens.

For the reasons outlined above, urban planning requires quantified information to improve outdoor space utilization for a better thermal environment and thermal comfort. Several studies indicated that shading can considerably contribute to a higher quality urban living in summer, particularly on a small scale [8, 9]. So far, related studies have

been conducted in a few countries and regions with various climates, such as Hong Kong, China [10–12]; Guangzhou, China [13]; Tempe, USA [14]; Freiburg, Germany [15]; Russi, Italy [16]; and Malaysia [17]. Local shading to block the solar radiation within urban areas can be accomplished by (1) optimized design of buildings, streets, and open spaces [18–20], (2) natural shading, such as trees [12, 13, 21–24], or (3) man-made devices and structures, such as awnings or sunshades and tunnels [14, 25]. Some studies have analyzed the shading effects of these methods on the outdoor local thermal environment. For instance, height-to-width ratio (H/W) is often used as an index to assess the shading level of simple building objects or street canyon geometry [20, 26, 27]. As for the tree shading method, researchers have applied leaf area index (LAI) to describe the occlusion of tree canopies to solar radiation [28]. Sky view factor is another important factor to weigh the shading degree of complex urban structures [11, 29, 30]. Shading is utilized to obstruct the incident solar radiation directly into urban spaces and further influences the surface temperature of the surrounding surfaces such as building exterior surface, underlying surface, and tree surface [11, 23, 28, 31]. Additionally, near-surface air temperature and flow are affected because of convective heat transfer [15]. As a result, the radiant environment, air temperature, and human-biometeorology vary with shading circumstances, with outdoor local-scale energy reduction and with space cooling [28]. Studies have demonstrated that, under normal circumstances, a higher H/W , lower SVF, or higher LAI can create a more obstructed shaded area [11] and thus decrease the heat stress. Urban outdoor shading can also effectively reduce the severe heat that people receive, thus considerably influencing people's thermal sensation and comfort. To evaluate people's perception of the surrounding thermal environment based on the energy balance between human body and outdoor environment, several thermophysiological indices are employed, such as physiological equivalent temperature (PET) [32], outdoor standard effective temperature (OUT_SET^*) [33], and Universal Thermal Climate Index (UTCI) [34]. According to a study by Lee et al. [15], building and tree shade decreases PET by 13.1°C and 15.7°C, respectively, compared with the sunlit areas nearby. In summary, shading can be an effective method to ameliorate outdoor heat stress and improve thermal comfort during summer.

There are a few limitations in the existing studies: (1) they focused on the shading effects on traditional outdoor micrometeorological parameters such as air temperature and seldom concentrated on the urban outdoor radiant environment; (2) few have analyzed the shading effects considering radiant flux densities in detail, for example, directional radiant components; and (3) most existing studies have focused on a specific shading structure in a particular region and season. As a result, the comparisons between the effects of diverse shading forms, for example, shading by neighboring buildings and trees, on the radiant environment and human comfort were generally neglected. The above subjects have not been widely investigated.

In this study, exhaustive measurements and an investigation that targeted different practical effects of building and tree shading forms on the outdoor thermal and 3D radiant environment and human thermal comfort during summer were conducted in a severely cold region. The research involved the subdivision and proportion of the composition of radiant flux densities that related to short- and long-wave radiation; the reduction influence of the two shading methods on detailed directional short- and long-wave radiant flux densities from 3D environment and thus the roles of short- and long-wave radiant flux densities in T_{mrt} ; the radiant environment features and different wavelength radiant flux densities functions at the shaded areas; and finally, the different shading effects on human thermal comfort. The research also used novel applications of the long-wave mean radiant temperature (LT_{mrt}) and directional SVF [11] to emphasize the importance of long-wave radiant flux densities under shaded conditions and 3D directional radiant characteristics, respectively. Moreover, the research subject of this study is in a severely cold region. Unlike studies that were conducted in warm or hot areas, the local-scale ambient temperature in severely cold regions is not as high as in other climates, but the heat stress is still high during summer because of the high radiant flux densities outdoors. This indicates that the outdoor radiant environment may affect human thermal comfort differently in severely cold regions than in other regions. Therefore, research subjects with the regional features of this study provide a necessary supplement to expand the research locations and results for related fields of study.

The main objectives of this study are as follows: (1) to explore the shading effects on micrometeorological parameters, particularly on the detailed directional 3D radiant components, and on human thermal comfort; (2) to investigate the radiant characteristics under shaded conditions; (3) to propose and apply directional SVF and evaluate its relationship with 3D radiant flux densities; and (4) to probe human thermal comfort differences and the impact of micrometeorological parameters on thermal comfort under shaded and sunlit conditions. This study offers a practical research method and quantified data targeting summer conditions for developing general and specific strategies of rational urban planning.

2. Methodology

2.1. Case Study Area and Field Measurement Scheme

2.1.1. Study Area. We took Harbin (45.75°N, 126.77°E) as the research location, which is a central city in northeast China [35]. Summertime here is ephemeral, from early July to late August; however, the solar radiation is relatively high, and air temperature may exceed 30°C [36]. In this study, shaded areas obstructed by buildings (SHA_Buil) and trees (SHA_Tree) and a sunlit background meteorological station (SUN_0), in a university campus in the city center, were selected. Figure 1 shows the location of Harbin and the distribution of each research site in the university campus. In detail, SHA_Buil was occluded by 45 m height nine-story

FIGURE 1: Location of Harbin and the distribution of the research sites in the university campus.

(on the east, south, and west side of the research spot) and 20 m height four-story (on the north side of the research spot) buildings, with light gray elastic coating exterior surfaces. SHA_Tree was under tall elm trees with a mean height of 10 m. Underlying surface material under both shaded sites was seepage brick, with light gray and red colored at SHA_Buil and light red colored at SHA_Tree. In addition, the playground where SUN_0 was on was covered by imitation turf and plastic track. SHA_Buil and SHA_Tree were selected strictly according to the height and degree of the enclosure that blocked most of the direct solar radiation from all directions. Quantitatively, the sky view factor with a lens facing upward was closed to or less than 0.3, and the lateral sky view factors were close to or less than 0.15. Moreover, they also met the requirements for denizens' outdoor activities. SUN_0 was on a playground that was sufficiently broad to represent an open space that received high radiation.

Measurements at all the research sites were conducted from 7:30 to 18:00 within a week, from July 28 to August 3 in 2018, simultaneously. The meteorological conditions of short-term sample days should meet the characteristics of typical seasonal weather conditions [14, 27, 37, 38]. For this study, the days for measurement were selected under clear-sky conditions with relatively intense solar radiation in July and August, which are the hottest months of the year. Moreover, according to the official historical summer weather database over the years for Harbin (refer to the data for July and August from 2002 to 2018), the daytime ranges

of air temperature and global radiant flux densities were 19.0–36.0°C and 14.0–1031.0 W/m², respectively [39]. In this study, during the same period with the official weather data, the ranges of the measured air temperature and global radiant flux densities were 26.7–35.5°C and 20–1025 W/m², respectively. This indicates that the meteorological conditions during the sample measurement period in this study were representative of the norm.

2.1.2. Field Measurement Scheme. At SHA_Buil, SHA_Tree, and SUN_0, air temperature (T_a), relative humidity (RH), wind speed (v), and the directional 3D short- and long-wave radiant flux densities reaching the reference standing person (K_i and L_i , respectively) were recorded every 1 min at 1.1 m above ground level using three sets of tailor-made human-biometeorological measurement units. Among these, 3D K_i and L_i were from the vertical (downward: ↓ and upward: ↑) and horizontal directions (easterly: E→, westerly: W→, southerly: S→, and northerly: N→). Surface temperature T_s was recorded every 1 min using button-type temperature recorders that were fixed to the measurement positions using industrial adhesive. In detail, the specific locations of the T_s recorders were as follows: five were used at SHA_Buil, among which one was pasted on the ground under the measurement unit, and four were fixed to the four surrounding building walls at 1.1 m above ground level right facing the measurement unit; another five recorders were used at SHA_Tree, and one was also pasted on the ground

under the measurement unit; the other four were fixed to the four tree trunks facing the measurement unit with a distance of 1.1 m to the ground; for SUN_0, the surrounding environment was much more open, so only one recorder was fixed to the ground under the measurement unit. Generally, 4410 data points were obtained for each parameter measured above. Moreover, directional sky view factor SVF_i values were obtained through fisheye photos taken adjacent to each radiometer and calculated by RayMan software [40, 41]. In detail, SVF was subdivided into five directions to represent the urban structures: lens facing upward for $SVF_{\uparrow}$ and facing lateral directions for $SVF_{E\rightarrow}$, $SVF_{W\rightarrow}$, $SVF_{S\rightarrow}$, and $SVF_{N\rightarrow}$. Table 1 lists the main technical parameters of the sensors used in this study.

Because RH depends on T_a to a certain degree, it makes more sense under a human-biometeorological perspective to use the water vapor pressure (VP) [30]. Therefore, in the following content, we converted RH to VP by multiplying RH and saturated water vapor pressure corresponding to various T_a . To describe and compare the data under different shaded or sunlit conditions, the seven-day mean data and standard deviation (SD) were used as statistical indices to display the overall distribution, centralization tendency, and dispersion degree of the local-scale micrometeorological variables. Figure 2 shows the mean and SD distributions of T_a , VP , global radiant flux densities G (equal to $K_{\downarrow}$ in this study), and v from all the research sites during the measurement period. The figure illustrates that there was a relatively large difference in micrometeorological conditions among the shaded and sunlit areas, as well as between different shading forms. The values and discrete degrees of the four types of micrometeorological parameters at the shaded sites were significantly lower than those at the sunlit background meteorological station, particularly for G , which indicated that both building and tree shading can effectively reduce outdoor radiation.

Figure 3 shows the overall distribution, centralization tendency, and dispersion degree of the surface temperature T_s of the exterior walls, tree trunks, and underlying grounds. As can be seen, T_s at the shaded areas was evidently lower than that at the sunlit area. Mean ground surface temperature at SHA_Buil and SHA_Tree was 10.9°C and 11.4°C lower than that at SUN_0, respectively. Comparing the two shaded areas, T_s of surfaces facing the same direction at near SHA_Buil was higher than that at near SHA_Tree, with 1.1°C mean facade temperature difference and 0.5°C ground surface temperature difference; furthermore, it fluctuated more strongly at SHA_Buil than at SHA_Tree comparatively.

2.2. Mean Radiant Temperature. According to the radiation budget between the radiant environment and the reference standing person, the “six-directional method” was utilized to calculate T_{mrt} in this study [43], as shown in the following equation:

$$T_{mrt} = \sqrt[4]{\frac{K_{abs} + L_{abs}}{\alpha_l \cdot \sigma}} - 273.15, \quad (1)$$

where K_{abs} and L_{abs} are the total of short- and long-wave radiant flux densities absorbed by the standing human-biometeorological reference person [44], respectively (both in W/m^2). Parameter α_l is the long-wave absorption coefficient, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/(m^2 \cdot K^4)$), and the unit of T_{mrt} is °C.

K_{abs} and L_{abs} are calculated using the following equations, respectively:

$$K_{abs} = \alpha_k \cdot \sum_{i=1}^6 W_i \cdot K_i, \quad (2)$$

$$L_{abs} = \alpha_l \cdot \sum_{i=1}^6 W_i \cdot L_i, \quad (3)$$

where α_k is the absorption coefficient of human body for short-wave radiant flux densities K_i (W/m^2) and α_l is the absorption coefficient of human body for long-wave radiant flux densities L_i (W/m^2). The standard value of the two physical quantities above is as follows: $\alpha_k = 0.70$ and $\alpha_l = 0.97$. W_i are the angular factors of the reference standing person for K_i and L_i and are set to 0.06 for the two vertical directions as well as 0.22 for the four horizontal directions [43].

The total short- or long-wave radiant flux densities absorbed by the reference standing person can be classified into the vertical and horizontal ones ($K_{ver,abs}$, $K_{hor,abs}$, $L_{ver,abs}$, and $L_{hor,abs}$) by adding the corresponding components.

The main purposes of using T_{mrt} in this study are summarized as follows: (1) to comprehensively quantify the short- and long-wave radiation from the 3D environment and to evaluate the specific shading effects on the radiant environment; (2) to determine the thermal comfort index UTCI and to assess its role in human thermal comfort under different shaded and sunlit conditions.

In this study, long-wave mean radiant temperature (LT_{mrt}) was inducted to represent the impact of long-wave radiant flux densities at the shaded areas by substituting L_{abs} for $K_{abs} + L_{abs}$, as shown in the following equation [11]:

$$LT_{mrt} = \sqrt[4]{\frac{L_{abs}}{\alpha_l \cdot \sigma}} - 273.15. \quad (4)$$

2.3. Standardization Processing. In this study, the data were presented by means of difference related to the micrometeorological parameters and thermal comfort index such as T_a , T_{mrt} , and UTCI, and of ratio for the radiant flux densities (short- and long-wave radiant flux densities), instead of absolute values. The impact of different shading forms on the micrometeorological parameters, thermal comfort index, and radiant flux densities was then compared.

Difference of T_a , T_{mrt} , or UTCI was calculated as follows:

$$\begin{aligned} \Delta T &= T_{SHA_Buil} - T_{SUN_0}, \\ \Delta T &= T_{SHA_Tree} - T_{SUN_0}, \end{aligned} \quad (5)$$

where ΔT represents the T_a , T_{mrt} , or UTCI difference between the building or tree shading and the sunlit background

TABLE 1: Main technical parameters of the instruments.

Location	Parameter	Instrument	Quantity/site	Range	Accuracy	Resolution
SHA_Buil/SHA_Tree/ SUN_0	T_a	HoBo	1	$-40\sim70^\circ\text{C}$	$\pm0.21^\circ\text{C}$	0.02°C
	RH	U23-002		$0\sim100\%$	$\pm2.5\%$	0.03%
	v	WFWZY-1	1	$0.05\sim30\text{ m/s}$	$\pm0.05\text{ m/s}$	0.01 m/s
	K_i	TBQ-2	6	$0\sim2000\text{ W/m}^2$	$<5\%$	1 W/m^2
	L_i	TBL-1	6	$0\sim2000\text{ W/m}^2$	$\pm2\%$	1 W/m^2
	T_s	DS1922L	5 at SHA_Buil and SHA_Tree and 1 at SUN_0	$-40\sim85^\circ\text{C}$	$\pm0.5^\circ\text{C}$	0.5°C

All the instruments complied with the ISO 7726 standard [42].

FIGURE 2: Statistical distribution of micrometeorological parameters at the research sites: (a) T_a and VP ; (b) G and v .

FIGURE 3: Surface temperature of the solid surfaces at different positions around the research sites.

areas (ΔT_a , ΔT_{mrt} or ΔUTCI); $T_{\text{SHA_Buil}}$ and $T_{\text{SHA_Tree}}$ are T_a , T_{mrt} or UTCI at the building and tree shading areas, respectively; and T_{SUN_0} is T_a , T_{mrt} , or UTCI at the sunlit background meteorological station.

With regard to the radiant flux densities, ratios were utilized, as shown below:

$$rK = \frac{K_{\text{SHA_Buil}}}{K_{\downarrow \text{SUN}_0}}, \quad (6)$$

$$rK = \frac{K_{\text{SHA_Tree}}}{K_{\downarrow \text{SUN}_0}},$$

$$rL = \frac{L_{\text{SHA_Buil}}}{L_{\uparrow \text{SUN}_0}}, \quad (7)$$

$$rL = \frac{L_{\text{SHA_Tree}}}{L_{\uparrow \text{SUN}_0}},$$

where rK and rL are the standardized short- and long-wave radiant ratios of the shaded to the sunlit background areas, respectively; $K_{\text{SHA_Buil}}$ and $K_{\text{SHA_Tree}}$ are the short-wave radiant flux densities at the building and tree shading areas, respectively; $L_{\text{SHA_Buil}}$ and $L_{\text{SHA_Tree}}$ are the long-wave radiant flux densities at the building and tree shading areas, respectively; and $K_{\downarrow \text{SUN}_0}$ and $L_{\uparrow \text{SUN}_0}$ are the reference short- and long-wave radiant flux densities at the sunlit background meteorological station, respectively (downward $\downarrow$ short-wave radiant flux densities and upward $\uparrow$ long-wave radiant flux densities).

3. Results and Discussion

3.1. Overall Shading Effects by Neighboring Buildings and Trees. Based on the abovementioned calculation processing, the shading effects of neighboring buildings and trees on the micrometeorological parameters including T_a , the short- and long-wave radiant components, and thus T_{mrt} , and the human thermal comfort evaluation index UTCI are analyzed in this section.

3.1.1. Shading Effects on T_a . 29 July 2018 was selected as the typical weather day. Figure 4(a) shows the temporal variation in T_a at the shaded and sunlit sites. Different T_a patterns and magnitudes appeared among the three areas that peak T_a was observed at noon at SUN_0 and SHA_Build, but T_a at SHA_Tree peaked in the morning, then fluctuated at noon and early afternoon, and dropped in the late afternoon and dusk. By applying equation (5), the effect of shading by neighboring buildings and trees on T_a can be analyzed, as presented in Figure 4(b). Tree shading brought about a stronger decrease in T_a especially in the afternoon, with a mean reduction value of 1.9°C and a peak value of -2.8°C at about 12:10; while building shading caused T_a to decrease relatively smoothly with a mean reduction value of 1.2°C and a peak value of -2.0°C at 12:10. The main reason of shading's decreasing effect on T_a is that shading can occlude a considerable part of incident solar radiation. This weakened the radiant exchange and decreased the surface temperature of the surrounding solid surfaces (see Figure 3), thus lowering the convective heat transfer between the exterior surfaces and local air. Moreover, the evapotranspiration cooling effect of the vegetation [21–23, 45], as well as the more enclosed environment (involving more occlusion to incident solar radiation), around SHA_Tree reduced T_a more than SHA_Build.

3.1.2. Shading Effects on 3D Radiant Environment. The diurnal temporal variations of short- and long-wave radiant components reaching the reference standing person are plotted in Figures 5(a) and 5(b). It can be seen that the short-wave radiant component's variation ranges remained steady at a lower level between 27 and 107 W/m² at SHA_Build regardless of the solar position. In contrast, at SHA_Tree, short-wave radiation fluctuated during the pre- and post-periods of high solar altitude angles from the incident directions (↓, S, and E in the morning and W in the afternoon), respectively, because of solar radiation transmission through the leaves. The highest values occurred at SUN_0, especially for $K_{\downarrow}$ and $K_{S\rightarrow}$, with the peak value reaching 1025 W/m² when the solar altitude angle was the highest during the day. Besides, $K_{E\rightarrow}$ and $K_{W\rightarrow}$ were symmetrically reversed at approximately the highest solar altitude angle, and they reached their peak values in the morning and afternoon, respectively. Figure 5(b) presents the changing profiles of the long-wave radiant components. It can be seen that the patterns of the long-wave radiant components and the relative magnitudes among the research sites were similar to those of the local-scale T_a , indicating that the temporal

variation in T_a could affect the long-wave radiant components. There might exist a certain correlation between long-wave radiation and T_a (it will be further analyzed in Section 3.2.2). In addition, directional differences among the components at the two shaded areas were smaller than those at SUN_0. Comparing the two shaded areas, the long-wave radiant flux densities were lower at SHA_Tree than at SHA_Build. As mentioned in Section 3.1.1, T_a could be lowered near greenery. Therefore, it is well-founded that the long-wave radiation could also be lower, as T_a was, because of the effect of the evapotranspiration of the trees around SHA_Tree.

We also used equations (6) and (7) to compare the different summer shading effects on outdoor 3D short- and long-wave radiant flux densities reaching the reference standing person on July 29, as shown in Figures 5(c) and 5(d). For rK_i in Figure 5(c), before 17:00, the reduction effect of building shading on short-wave radiation had much weaker fluctuations than that of tree shading. In particular, rK at SHA_Build remained below 0.15 until late afternoon; tree shading led to a higher standardized short-wave radiation in the short-wave incident directions from ↓, S, and E in the morning and from W in the early afternoon, which was mainly caused by the transmission of solar radiation under the tree shading condition. After 17:00, shading effects on reducing the short-wave radiation began to decrease at both shaded areas.

As delivered in Figure 5(d), the directional standardized long-wave radiation under both shaded conditions presented different patterns compared with standardized short-wave radiation that they reduced from the beginning of the measurement, reached their lowest values close to 0.75 at noon, and increased till the measurement ended. By contrast, the standardized long-wave radiation variations from different directions were larger at SHA_Build than at SHA_Tree. A special circumstance appeared from 9:30 to 10:50 when the downward standardized long-wave radiation had a mutation, which corresponded to the time at which rK showed an abrupt change at SHA_Tree because of the radiant transmission effects.

3.1.3. Shading Effects on T_{mrt} . As shown in Figure 6(a), the temporal trends of T_{mrt} were primarily similar to those of the short-wave radiant flux densities from the main incident directions (downward and southerly), which was caused by the significant correlation between T_{mrt} and $K_{\downarrow}$ and $K_{S\rightarrow}$. It has been proved by some studies [30, 35]. Moreover, when taking T_a in the foregoing content into account, T_{mrt} was much higher than T_a with a mean difference ($T_{mrt}-T_a$) of 13.5°C at SHA_Build, 15.5°C at SHA_Tree, and 40.7°C at SUN_0 during the daytime. Figure 6(b) shows the shading effects by neighboring buildings and trees on T_{mrt} on July 29 using equation (5). As can be seen in the figure, building shade reduced T_{mrt} more significantly than tree shade did before 11:00; however, after this time, the two shading forms showed similar reduction effects on T_{mrt} . Meanwhile, shading could significantly reduce T_{mrt} with mean values of 28.8°C for building shading and 28.1°C for tree shading

(a)

(b)

FIGURE 4: Diurnal patterns of T_a and ΔT_a on July 29, 2018: (a) temporal variation in T_a at the shaded and sunlit areas; (b) ΔT_a between the two shaded and the sunlit background meteorological areas.

(a)

(b)

FIGURE 5: Continued.

FIGURE 5: Diurnal patterns of K_p , L_p , rK_p , and rL_i on July 29, 2018: (a) temporal variation in short-wave radiant flux densities reaching the reference standing person at the measurement sites; (b) temporal variation in long-wave radiant flux densities reaching the reference standing person at the measurement sites; (c) standardized short-wave radiant components from six directions; (d) standardized long-wave radiant components from six directions.

compared with the sunlit background meteorological station. According to the results discussed in Section 3.1.2, summer shading had a stronger impact on short-wave radiant components than on long-wave radiant components. Therefore, T_{mrt} reduction by shading was mainly caused by the decrease in short-wave radiant flux densities. Furthermore, T_{mrt} reduction by shading was stronger than the T_a

reduction (Figure 4), revealing that shading can lead to a more significant effect on outdoor radiant environment than on air temperature.

3.1.4. Shading Effects on UTCI. The Universal Thermal Climate Index (UTCI) is an important thermophysiological index to quantify outdoor heat and cold stress based on the

FIGURE 6: Diurnal patterns of T_{mrt} and ΔT_{mrt} on July 29, 2018: (a) temporal variation in T_{mrt} at the shaded and sunlit areas; (b) ΔT_{mrt} between the two shaded and the sunlit background meteorological areas.

Fiala multinode model [34]. It is appropriate for thermal assessments on any scale as well as in all climates and seasons [34, 46]. In this study, we calculated UTCI by inputting T_a , T_{mrt} , $T_{a'}$ and VP at 1.1 m above ground level and v at 10 m above ground level (extrapolated from 1.1 m to 10 m above ground level by equation (8) [47]) for the shaded and sunlit areas ([46], <http://www.utci.org>) based on the adaptive clothing model [48] and reference human activity level of walking at a speed of 4 km/h [46]. To quantify the shading impact on UTCI, the differences between the building or tree shading and the sunlit background meteorological station on July 29 were calculated using equation (5), as shown in Figure 7. Overall, tree shading brought about a stronger decrease in UTCI than building shading did and that shading decreased UTCI with mean values of 9.2°C for tree shading condition and 7.8°C for building shading condition. Moreover, both shading conditions reduced UTCI most strongly at noon. An opposite pattern appeared from 9:30 to 10:50 where $\Delta UTCI$ was higher at SHA_Tree than at SHA_Build, the period of which was corresponding to the radiant flux densities' sudden increase at SHA_Tree (see Section 3.1.2). The shading reduction effect on UTCI depended on its comprehensive impact on the micrometeorological parameters, especially on T_a and T_{mrt} . As a result, $\Delta UTCI$ integrated the characteristics of ΔT_a along with ΔT_{mrt} :

$$v_{10} = v_{1.1} \cdot \left(\frac{z}{z'} \right)^\alpha, \quad (8)$$

where v_{10} is the wind speed at a height of 10 m above ground level (m/s), $v_{1.1}$ is the wind speed measured by the sensors at 1.1 m above ground level in this study (m/s), z is the distance from the ground (10 m in this case), α is the mean speed exponent set to 0.33 in city-center areas, and z' is the height of the sensors installed above ground level (1.1 m in this study).

To sum up, both building and tree shading had considerable reduction effects on the radiant components and thus on T_{mrt} , which was greater than that on T_a . Their

FIGURE 7: $\Delta UTCI$ between the two shaded and the sunlit background meteorological areas on July 29, 2018.

influence on UTCI consequently integrated the characteristics of ΔT_a along with ΔT_{mrt} . Meanwhile, the differences between the two types of shading forms were nonnegligible.

3.2. Radiant Characteristics under Shaded Conditions. As the radiant environment is an important factor in the summer shading function, detailed analyses considering directional short- and long-wave radiant components are conducted in this section. In particular, the different influences and contributions of short- and long-wave radiation are compared.

3.2.1. Definition and Application of Long-Wave Mean Radiant Temperature. Figure 8 reveals the short- and long-wave radiant components absorbed by the reference standing person under building and tree shading conditions

FIGURE 8: Short- and long-wave radiant flux densities absorbed by the reference standing person: (a) $K_{i,abs}$; (b) $L_{i,abs}$.

based on the seven-day measurement data. From Figure 8(a), we can see that the variation ranges of $K_{i,abs}$ under the tree canopies were higher than those under the neighboring building obstacles because of the greater short-wave radiant flux densities transmission through the leaves under the tree shading condition. However, values of $L_{i,abs}$ were higher at SHA_Build than those at SHA_Tree, as presented in Figure 8(b). This was mainly because there existed massed solid surfaces at the building shading area that received more long-wave radiant flux densities. Moreover, directional differences among the two vertical directions and the four horizontal directions were distinct in both $L_{i,abs}$ and $K_{i,abs}$ components; the average values of short- or long-wave radiant flux densities absorbed by the reference standing person from a single horizontal direction were three to four times those of a single vertical direction. This also resulted in the mean $K_{hor,abs}$ or $L_{hor,abs}$ being six to eight times greater than that of $K_{ver,abs}$ or $L_{ver,abs}$. These results mainly attributed to the larger emission intensity from the horizontal directions and the higher absorption for the horizontal short- or long-wave radiant flux densities by the reference standing person of 0.22 versus for the vertical ones of 0.06.

In urban outdoor settlements, shaded conditions do not mean the complete absence of short-wave radiation during the daytime. There still exist diffuse and a small amount of direct short-wave radiation. Some studies have proved that the proportion of long-wave radiant flux densities absorbed by the human body was relatively high in the outdoor environments [14, 30, 35]. This study further calculated and compared the proportion of K_{abs} and L_{abs} in $K_{abs} + L_{abs}$ under different shaded and sunlit conditions. Figure 9 presents $K_{abs}/(K_{abs} + L_{abs})$ and $L_{abs}/(K_{abs} + L_{abs})$ at the shaded areas in this study. $K_{abs}/(K_{abs} + L_{abs})$ did not exceed 10% under the shaded condition by neighboring buildings, which implied that $L_{abs}/(K_{abs} + L_{abs})$ reached more than 90%. The proportion range of K_{abs} in $K_{abs} + L_{abs}$ under the

FIGURE 9: Proportion of K_{abs} and L_{abs} in $K_{abs} + L_{abs}$ at the shaded and sunlit areas.

tree shading condition was larger with a peak value of 23%, indicating a minimum $L_{abs}/(K_{abs} + L_{abs})$ value of 77%. By comparison, $L_{abs}/(K_{abs} + L_{abs})$ at the sunlit area was much lower, with a minimum value even below 65% and a maximum value below 88%. Therefore, shading not only reduced the air temperature, 3D radiant flux densities, and T_{mrt} , but also caused a higher portion of L_{abs} in $K_{abs} + L_{abs}$ under shaded conditions at the same time. Similar studies were carried out in summer by Middel and Krayenhoff [14] and Lee et al. [30]. The former distinguished the decomposed contributions of directional short- and long-wave radiation on T_{mrt} at a series of sites during one day. They concluded that there was a higher proportion of lateral and hence total long-wave radiation at shaded areas than at sunlit areas. The latter considered clear-sky summer days from 2007 to 2010 and did not differentiate between shaded and sunlit conditions but also pointed out that the

proportion of K_{abs} did not exceed 40% with L_{abs} proportion not falling below 60%.

Because summer shading can greatly increase $L_{abs}/(K_{abs} + L_{abs})$, we applied LT_{mrt} by substituting L_{abs} for $K_{abs} + L_{abs}$ under shaded conditions (see equation (4)). LT_{mrt} was the degenerated T_{mrt} considering only long-wave radiant flux densities absorbed by the reference standing person [11]. It also reacted to the mean surface temperature of surrounding objects within shaded areas where the long-wave radiant flux densities played a more essential role. Figure 10 shows the distributions of LT_{mrt} at the two shaded research sites. As can be seen, LT_{mrt} at SHA_Buil fluctuated more strongly (with a peak of 41.8°C and a mean value of 39.6°C) than that at SHA_Tree (with a peak of 40.4°C and a mean value of 38.8°C). This again confirmed the results shown in Figure 8(b) that the $L_{i,abs}$ values and variation range were higher at SHA_Buil than those at SHA_Tree.

3.2.2. Relationship between LT_{mrt} and T_a . The outdoor radiant environment is the decisive factor for urban micro-meteorological and human-biometeorological conditions. First, as shown in the foregoing section, shading can reduce T_a slightly. As the atmosphere is almost transparent to solar radiation (short-wave), it is very weak for the atmosphere to increase air temperature by receiving solar radiation directly. In general, convective heat transfer between the local atmosphere and the solid surfaces (including underlying surfaces, neighboring building exterior walls, and vegetation surfaces) is the principal factor causing T_a to change, in which the surface temperature of the solid surfaces plays a direct role. The surface temperature varies with the incident solar radiation, which affects the radiation exchange. By taking the surface temperature at the same position (the underlying ground surface) of the three research sites for instance (Figure 3), the mean T_s at the shaded research sites was approximately 11.1°C lower than that at the sunlit sites, thus reducing T_a to a certain extent. As a result, shading not only decreased radiation intuitively but also decreased T_a indirectly.

LT_{mrt} reflects the long-wave radiant flux densities emitted from the surrounding solid surfaces. Therefore, the surface temperature has a higher explanatory power for the outdoor long-wave radiant flux densities emissions under shaded conditions [11]. As proved in the previous paragraph, T_a was significantly influenced by the surface temperature. Thus, we analyzed the relationship between these two affected factors influenced by surface temperature of the shaded areas.

First of all, the time during the measurement was divided into four periods: morning (7:30–10:00), noon (10:00–13:00), afternoon (13:00–16:00), and dusk (16:00–18:00) according to the solar altitude angle. As shown in Figure 11, the solar altitude angle range was 6–60° during the research period. 30° and 50° were selected as the degree nodes to classify, and their nearest sharp-time points were set as the division bases. Then, the analysis of variance was conducted at SHA_Buil and SHA_Tree taking LT_{mrt} , T_a , and time into account. Finally, the

FIGURE 10: Long-wave mean radiant temperature at the two shaded areas.

FIGURE 11: Time division of the measurement period.

estimated marginal mean results at the two shaded areas are obtained, as shown in Figure 12.

It can be seen that LT_{mrt} varied with T_a and elapsed time. On the one hand, the time segments for LT_{mrt} and T_a to reach their highest values were different at the two shaded sites. In detail, the highest LT_{mrt} with the corresponding T_a appeared in the afternoon and at dusk at SHA_Buil; however, LT_{mrt} and T_a were higher at noon and in the afternoon than at other periods at SHA_Tree. It can be interpreted that, as time lapsed, the heat accumulation increased till afternoon and dusk at SHA_Buil, where there were numerous structures with strong heat storage capacity. However, because of the transmission at SHA_Tree, radiation from various directions from the external environment was allowed to enter the research space to heat solid surfaces such as trunks. As is known, radiation is strongest around midday, which directly causes LT_{mrt} and the corresponding T_a during noon and afternoon being higher than those in the morning and at dusk.

On the other hand, from the trend in the scatter plots between the estimated marginal mean LT_{mrt} and T_a , linear

FIGURE 12: Estimated marginal mean LT_{mrt} under temporal variation in T_a at the building and tree shaded areas: (a) SHA_Build; (b) SHA_Tree.

increase in the estimated marginal mean LT_{mrt} with T_a was found at both SHA_Build and SHA_Tree. Therefore, Table 2 summarizes their relationship that is quantified by the coefficient of determination R^2 (LT_{mrt} and T_a at the two shaded areas satisfied the normal distribution), based on the data throughout the measurement period. Evidently, the correlation coefficients were intensely significant at the significance level $\text{sig} = 0.000$ regardless of SHA_Build, SHA_Tree, and the total values. Therefore, LT_{mrt} had a significant positive correlation with T_a in which the correlation was stronger at SHA_Build. Meanwhile, the difference in the analyses of variance and regression results between the building and tree shading was attributed to the urban microclimatic factors owing to the neighborhood: the organization, disposition, and material of the surrounding environment. To conclude, T_a can offer a basic statistical comprehension to a local-scale LT_{mrt} at shaded areas.

From the results in this section, we discover that summer shading also led to variations in the short- and long-wave proportions. LT_{mrt} varied with T_a and elapsed time under different shaded conditions. Yet how the neighboring building and tree obstacles, that are ascribed to urban morphology, block radiation and quantitatively influence the radiant components should be investigated further, as presented in the following section.

3.3. Quantified Directional Urban Morphology and Radiant Environment. The shading effects on urban local-scale microclimate are mainly caused by the blocking of direct short-wave radiation. As mentioned in Section 3.1.2, shading primarily influenced short-wave radiant flux densities from the incident directions of the direct radiation to the greatest extent. Furthermore, shading of the direction-dependent short-wave radiant flux densities had consequences for other

TABLE 2: Linear fitting analysis between estimated marginal mean LT_{mrt} and T_a at the building and tree shading areas and the total.

Research site	SHA_Build	SHA_Tree	Total
R^2	0.976	0.814	0.835
Significance	0.000	0.000	0.000

radiant flux densities. Ultimately, different shading modes mainly affect the short- and long-wave radiant flux densities in the spatial distribution and range. Their temporal variations primarily change with the solar altitude and orientation. Moreover, the urban morphology reflected by SVF of the research site plays an essential role in the microclimate. Thus, directional SVF was proposed to examine the dependence of microclimate on the urban structure in terms of different shading methods in this study [11].

Table 3 summarizes the SVF_i from five directions at the research sites. From the SVF images at SHA_Tree, we can infer that it offered a higher probability of short-wave radiant flux densities entering the space from more tilt angles. To conclude, although the directional SVF_i values at SHA_Tree were lower than those at SHA_Build in the corresponding direction, the short-wave radiant flux densities reaching the tree shading site still maintained a higher level and a stronger fluctuation (see Figure 8(a)).

To analyze the detailed relationship between the radiant components and SVF_i , five directional short-wave (long-wave) averaged radiant data at each research site were calculated over the seven measurement days and were associated with the five corresponding directional SVF_i values [11, 14]. Therefore, fifteen data points in total were linearly fitted for the directional short- or long-wave and the corresponding SVF_i with the same direction, as presented in

TABLE 3: Summary of SVF_i from five directions.

Direction	SHA_Build	SHA_Tree	SUN_0
Downward ↓	0.256	0.069	0.804
Easterly E→	0.107	0.026	0.367
Westerly W→	0.128	0.053	0.388
Southerly S→	0.067	0.074	0.402
Northerly N→	0.156	0.038	0.335

Figure 13. Evidently, directional SVF_i caused the short-wave radiant flux densities to linearly increase and the long-wave radiant components to decrease. However, no clear dependence of long-wave radiant flux densities on SVF_i was found because of the exceedingly low R^2 . Therefore, SVF had a higher explanatory power for the short-wave radiant flux densities, but this was not evident for the long-wave radiant flux densities.

We further investigated the impact of the directional SVF_i on T_{mrt} . The nondirectional T_{mrt} of the three research sites was averaged over the seven measurement days [14, 15, 20, 30, 49] and was linearly fitted with the five

directional SVF_i and the mean SVF, with three data points around one fitting line, as shown in Figure 14. Table 4 summarizes R^2 values, indicating that T_{mrt} was strongly correlated with the mean SVF, in which T_{mrt} was most relevant to $SVF_{s_}$. Figure 14 simultaneously shows that the slope values were all positive, which once again proved that T_{mrt} was mainly governed by short-wave radiant flux densities, that shading in terms of a lower SVF brought out a lower $K_{abs} + L_{abs}$ even if the long-wave radiant flux densities were increasing.

Similarly, Middel and Krayenhoff also demonstrated that the lateral short-wave radiation correlated more strongly

FIGURE 13: Linear fitting between seven-day mean short- or long-wave radiant flux densities and directional SVF_i .

FIGURE 14: Linear fitting between seven-day mean T_{mrt} and the directional SVF_i as well as the mean SVF.

TABLE 4: Summary of R^2 in linear fitting between seven-day mean T_{mrt} and the directional SVF_i as well as the mean SVF.

Direction	↓	E→	W→	S→	N→	Mean SVF
R^2	0.7174	0.8913	0.4540	0.9756	0.1209	0.7341
Significance	0.000	0.000	0.000	0.000	0.000	0.000

with $SVF_{\downarrow}$ (with R^2 of 0.78 at noon and 0.70 in the afternoon) than the lateral long-wave radiation did (with R^2 of 0.02 at noon and 0.08 in the afternoon). Besides, T_{mrt} was found to have R^2 values of 0.66 at noon and 0.64 in the afternoon related to $SVF_{\downarrow}$ during the daytime [14].

In brief, it has turned out that directional SVF_i values were meaningful for the study of the effects of shading on

outdoor directional radiant components and the comprehensive radiant parameter T_{mrt} .

3.4. Human Thermal Comfort (Distributions and Influencing Micrometeorological Parameters). The effects of shading on micrometeorological parameters such as radiant components and air temperature have been discussed in the previous sections. The outdoor shaded or sunlit conditions would affect the denizens' thermal experience and thermal comfort. Therefore, further analyses of the impact of different shading forms on human thermal comfort will be explored in this section.

3.4.1. UTCI Distribution. Jin et al. conducted the outdoor meteorological measurements and thermal sensation and comfort questionnaire survey also in Harbin and determined the ranges of UTCI that represent people's feeling of comfort based on the field research [50]. In this study, we utilized the UTCI values categorized in terms of thermal stress reclassified by them (Table 5). Seven-day UTCI values were separated into different thermal stress categories, as shown in Figure 15. At the shaded areas, UTCI was primarily distributed over "strong heat stress" and "moderate heat stress," in which the proportion of "moderate heat stress" at SHA_Tree was 22% higher than that at SHA_Buil. By contrast, UTCI at the sunlit areas was raised by two categories under similar background weather conditions that the thermal stress was categorized as "extreme heat stress," "very strong heat stress," and "strong heat stress." It indicates that the outdoor heat stress during summer daytime was at a high level, which also reflected the necessity of summer shading to improve human thermal comfort outdoors.

3.4.2. Impact of Micrometeorological Parameters on Human Thermal Comfort. Urban design is interested in human-biometeorological results, whose application contributes to the citizens' thermal comfort, health, outdoor activities, work efficiency, and well-being [51]. Based on all the seven-day field measurement data at shaded and sunlit areas, the partial correlation analysis results in Table 6 demonstrated that UTCI was positively determined by T_a , T_{mrt} , and VP but negatively depended on v on summer days. It can be seen that both T_a and T_{mrt} were highly correlated with UTCI, with the partial correlation coefficient r values exceeding 0.96. Nevertheless, subtle differences appeared when distinguishing shaded and sunlit sites, that UTCI firstly depended on T_a at the shaded areas, followed by T_{mrt} ; but conversely, T_{mrt} played the most important role in UTCI at the sunlit areas where the radiant flux densities were significantly high and denizens experienced strong heat stress. The reason can be explained as follows. The radiation exchange, quantified by T_{mrt} is the key meteorological variable in summer. At shaded areas in the daytime, there is usually a strong correlation between T_{mrt} and T_a [52]. Meanwhile, there is less incident short-wave radiation entering these enclosed spaces. This is the reason why we found that T_a was the first positive variable for the human thermophysiological

TABLE 5: Thermal classification of UTCI equivalent temperatures for Harbin [50].

UTCI range (°C)	Thermal stress category
>49.4	Extreme heat stress
40.9 to 49.4	Very strong heat stress
29.1 to 40.9	Strong heat stress
23.0 to 29.1	Moderate heat stress
-3.8 to 23.0	No thermal stress
-7.2 to -3.8	Slight cold stress
-18.3 to -7.2	Moderate cold stress
-25.6 to -18.3	Strong cold stress
-30.2 to -25.6	Very strong cold stress
<-30.2	Extreme cold stress

FIGURE 15: Histograms of seven-day UTCI distributions.

TABLE 6: Partial correlation analysis results of UTCI depending on the microclimatic parameters at the shaded and sunlit research sites.

Research sites	Index	T_a	T_{mrt}	VP	ν at 10 m
SHA_Buil and SHA_Tree	r	0.991	0.968	0.920	-0.919
	Sig	0.000	0.000	0.000	0.000
SUN_0	r	0.990	0.996	0.807	-0.970
	Sig	0.000	0.000	0.000	0.000

r : partial correlation coefficient; Sig: significance.

perception to the outdoor environment. In other words, T_a had the role of a proxy variable for the radiation exchange under shaded condition. While at the sunlit area, T_{mrt} was still the dominant factor for UTCI.

The above outcomes were also illustrated by Lee et al., who indicated that the correlation between human thermal comfort and T_{mrt} was slightly stronger than with T_a on clear-sky summer days [15, 30]. In comparison, Middel and Krayenhoff conducted day-night measurements in 22 sunlit or shaded sites on the hottest day in Tempe and found that UTCI was most sensitive to T_a , whereas it was about half as sensitive to T_{mrt} as T_a [14]. The differences of the results between their research and this study are mainly because (1) their study considered not only the daytime but also the

evening and night after sunset when solar radiation passed off and T_a was dominant and (2) they focused on all the sunlit areas together with the shaded sites, so the relationship between UTCI and each individual micrometeorological variable under shaded and sunlit conditions was not identified.

The relatively low partial correlation coefficient values between UTCI and VP as well as ν indicated that these two microclimatic parameters at the shaded and sunlit areas played a more subsidiary part in the perception of outdoor heat by denizens, which was also proved by Middel and Krayenhoff using sensitivity analysis [14].

So far, human thermal comfort within urban settlements affected by neighboring building and tree shading has been taken into account by implementing the “human-oriented” concept in urban planning and design objectives.

4. Conclusions

This study investigates the summer shading effects caused by neighboring buildings and trees and analyzes the difference between shaded and sunlit conditions as well as that between different shading forms in a typical city in the severely cold region. Summer shading can significantly reduce outdoor heat stress and offer the diversity in thermal environment and spaces for denizens. Based on the analyses, we obtained the following conclusions:

- (1) Shading led to a stronger reduction on T_{mrt} than on T_a , and its effect on UTCI synthesized the variation in the above two parameters that building shading decreased T_{mrt} , T_a , and UTCI with mean values of 28.8, 1.2, and 7.8°C and tree shading of 28.1, 1.9, and 9.2°C, respectively, compared with the background meteorological site with sunlit condition.
- (2) Within the shaded areas, short-wave radiant components decreased considerably more than long-wave radiant components owing to shading; the proportion of L_{abs} in $K_{abs} + L_{abs}$ was high, and it led to a relatively high LT_{mrt} , which had an R^2 with T_a exceeding 0.8, and reached their highest values in the afternoon and at dusk at SHA_Buil and at noon and in the afternoon at SHA_Tree.
- (3) Directional SVF_i exhibited a significantly positive correlation with short-wave radiant flux densities; however, the relationship between SVF_i and 3D long-wave radiant flux densities was not statistically evident. Meanwhile, T_{mrt} was most relevant with SVF_s , with a R^2 of 0.9756.
- (4) UTCI at the sunlit areas rose two categories compared with that at the shaded areas under the similar background weather conditions; T_a and T_{mrt} played the first positive part in UTCI under shaded and sunlit conditions, respectively.
- (5) Future research will aim to conduct long-term measurements considering urban morphology variations, and to obtain more novel insights.

Nomenclature

G :	Global radiation, W/m^2	$L_{E\rightarrow}$:	Easterly long-wave radiant flux densities, W/m^2
K_i :	Short-wave radiant flux densities from different directions (i : $\downarrow$, $\uparrow$, east, west, south, or north), W/m^2	$L_{E\rightarrow,abs}$:	Easterly long-wave radiant flux densities absorbed by the reference standing person, W/m^2
$K_{i,abs}$:	Short-wave radiant flux densities from different directions absorbed by the reference standing person (i : $\downarrow$, $\uparrow$, east, west, south, or north), W/m^2	$L_{hor,abs}$:	Short-wave radiant flux densities absorbed by the reference standing person from horizontal directions, W/m^2
$K\uparrow$:	Upward short-wave radiant flux densities, W/m^2	$L_{N\rightarrow}$:	Northerly long-wave radiant flux densities, W/m^2
$K\uparrow_{abs}$:	Upward short-wave radiant flux densities absorbed by the reference standing person, W/m^2	$L_{N\rightarrow,abs}$:	Northerly long-wave radiant flux densities absorbed by the reference standing person, W/m^2
$K\downarrow$:	Downward short-wave radiant flux densities, W/m^2	$L_{S\rightarrow}$:	Southerly long-wave radiant flux densities, W/m^2
$K\downarrow_{abs}$:	Downward short-wave radiant flux densities absorbed by the reference standing person, W/m^2	$L_{S\rightarrow,abs}$:	Southerly long-wave radiant flux densities absorbed by the reference standing person, W/m^2
K_{abs} :	Total of short-wave radiant flux densities absorbed by the reference standing person, W/m^2	LT_{mrt} :	Long-wave mean radiant temperature, $^{\circ}C$
$K_{E\rightarrow}$:	Easterly short-wave radiant flux densities, W/m^2	$L_{ver,abs}$:	Short-wave radiant flux densities absorbed by the reference standing person from vertical directions, W/m^2
$K_{E\rightarrow,abs}$:	Easterly short-wave radiant flux densities absorbed by the reference standing person, W/m^2	$L_{W\rightarrow}$:	Westerly long-wave radiant flux densities, W/m^2
$K_{hor,abs}$:	Short-wave radiant flux densities absorbed by the reference standing person from horizontal directions, W/m^2	$L_{W\rightarrow,abs}$:	Westerly long-wave radiant flux densities absorbed by the reference standing person, W/m^2
$K_{N\rightarrow}$:	Northerly short-wave radiant flux densities, W/m^2	RH :	Relative humidity, %
$K_{N\rightarrow,abs}$:	Northerly short-wave radiant flux densities absorbed by the reference standing person, W/m^2	R^2 :	Coefficient of determination
$K_{S\rightarrow}$:	Southerly short-wave radiant flux densities, W/m^2	r :	Partial correlation coefficient
$K_{S\rightarrow,abs}$:	Southerly short-wave radiant flux densities absorbed by the reference standing person, W/m^2	SD :	Standard deviation
$K_{ver,abs}$:	Short-wave radiant flux densities absorbed by the reference standing person from vertical directions, W/m^2	Sig :	Significance
$K_{W\rightarrow}$:	Westerly short-wave radiant flux densities, W/m^2	SVF_i :	Directional sky view factor (i : $\downarrow$, east, west, south, or north)
$K_{W\rightarrow,abs}$:	Westerly short-wave radiant flux densities absorbed by the reference standing person, W/m^2	$SVF\downarrow$:	Downward SVF
L_i :	Long-wave radiant flux densities from different directions (i : $\downarrow$, $\uparrow$, east, west, south, or north), W/m^2	$SVF_{E\rightarrow}$:	Easterly SVF
$L_{i,abs}$:	Long-wave radiant flux densities from different directions absorbed by the reference standing person (i : $\downarrow$, $\uparrow$, east, west, south, or north), W/m^2	$SVF_{N\rightarrow}$:	Northerly SVF
$L\uparrow$:	Upward long-wave radiant flux densities, W/m^2	$SVF_{S\rightarrow}$:	Southerly SVF
$L\uparrow_{abs}$:	Upward long-wave radiant flux densities absorbed by the reference standing person, W/m^2	$SVF_{W\rightarrow}$:	Westerly SVF
$L\downarrow$:	Downward long-wave radiant flux densities, W/m^2	T_a :	Air temperature, $^{\circ}C$
$L\downarrow_{abs}$:	Downward long-wave radiant flux densities absorbed by the reference standing person, W/m^2	T_{mrt} :	Mean radiant temperature, $^{\circ}C$
L_{abs} :	Total of short-wave radiant flux densities absorbed by the reference standing person, W/m^2	T_s :	Surface temperature, $^{\circ}C$
		$UTCI$:	Universal Thermal Climate Index, $^{\circ}C$
		v :	Wind speed, m/s
		VP :	Water vapor pressure, hPa.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (grant no. 51438005). The authors thank the students for helping during the measurement campaign.

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