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Research Article

Contribution of Greening and High-Albedo Coatings to Improvements in the Thermal Environment in Complex Urban Areas

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The aim was to identify microclimate characteristics in relation to ground cover in green areas and the reflectivity of building coating materials. Furthermore, microclimate modeling of temperatures was conducted using ENVI-met, to analyze the effects of improved thermal environments based on increased green areas and increased reflectivity of exterior coatings. The accuracy of ENVI-met was validated through comparisons with field temperature measurements. The RMSE deviation of the predicted and actual field temperature values was 3–6°C; however, the explanatory power was as high as 60%. ENVI-met was performed for commercial and single residential areas that have high densities of artificial cover materials, before and after changes related to development of green areas and to increase in the reflectivity of coating materials. The results indicated that both areas exhibited distinct temperature reductions due to the creation of green spaces. When the reflectivity of the coating material was increased, a temperature increase was observed in all land-use types. Therefore, in order to improve the thermal environment of complex urban areas, it is necessary to improve green-area development and to use high-reflectivity ground and building cover materials, while taking into account the spatial characteristics of land-use types and their surrounding areas.

1. Introduction

Urban areas consist of a variety of land covers and geometrical structures of various heights, characteristics that result in a unique climate. The albedo (reflectance) of land cover is mostly determined by its color. This characteristic has a significant impact on the radiation accumulated within the ground surface and thus on the surface temperature as well [1, 2]. Moreover, urban green areas have the function of lowering the surface temperature of surrounding areas and are thus effective in improving the urban thermal environment [3, 4]. However, because artificial ground covers like asphalt and concrete, which have low reflectivity, are increasing in urban areas while green areas and water surfaces are decreasing, a great deal of heat is constantly accumulating in our cities [5]. For this reason, issues related to urban thermal environments and urban heat-island effect (urban temperatures clearly higher than outskirts) [6, 7] are of growing concern. Recently, climate change has caused record-breaking heat waves that have become a serious environmental issue in urban areas all over the world. This in turn has increased interest in space-environment engineering for improving the thermal outdoor comfort of city dwellers and for minimizing the accumulation of heat in artificial structures [8–11].

Many recent studies have revealed that the thermal environment of urban areas can be improved through methods such as developing green areas and greening the roofs of buildings [3, 12–21]. Other studies have focused on ways to reduce surface and air temperature by increasing the albedo of roof and land covers and at the same time reducing the energy consumption of buildings [22–34]. Studies have also been conducted on how to adjust the dimensions, configurations, and placement of buildings (urban form and design) to improve the thermal environment. This is

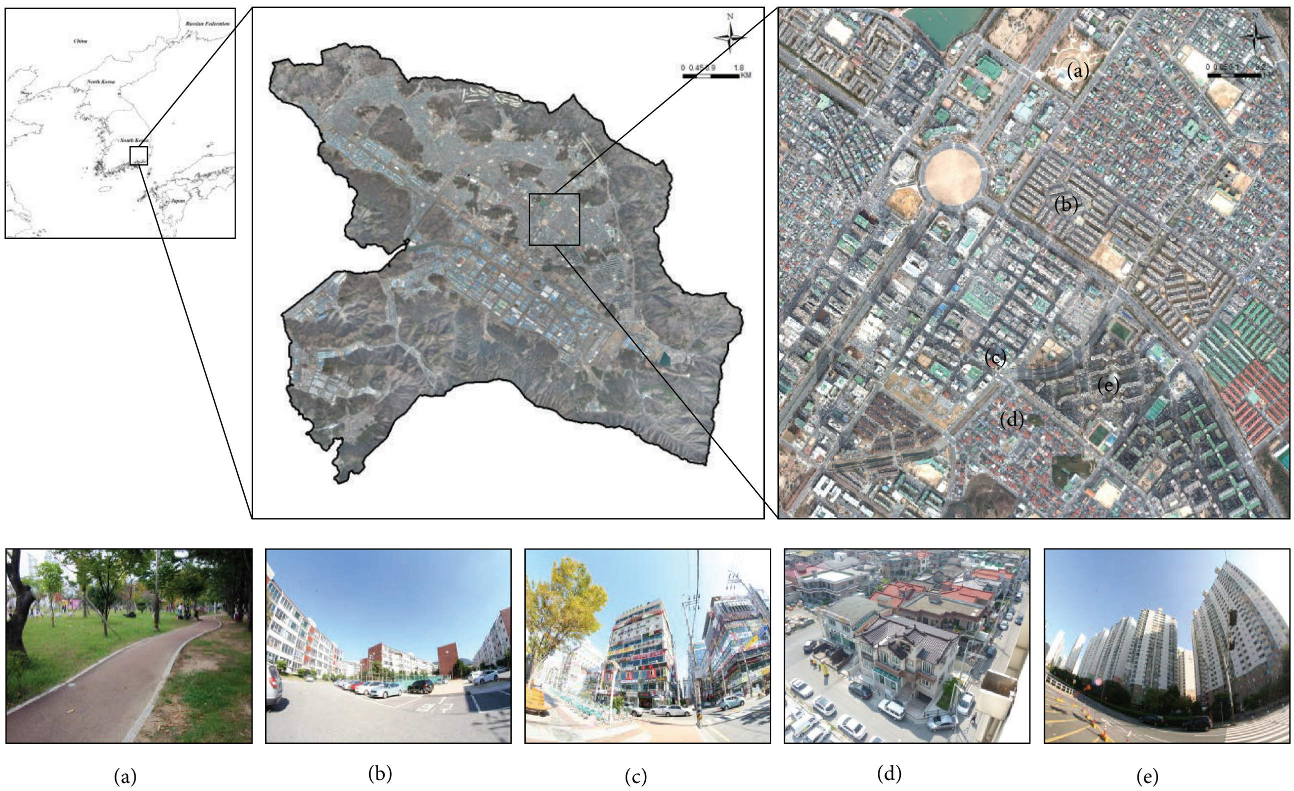


Figure 1: Five analysis areas encompassing different urban landscapes and land-use types in Changwon City, namely, (a) an urban park, (b) a low-rise apartment area, (c) a commercial area, (d) a single residential area, and (e) a high-rise apartment area.

accomplished by making systematic provisions for shade [26, 35–38].

Various studies focused on urban form and design (building dimensions) are being conducted to improve the thermal environment. However, there are too few studies involving complex high-density urban areas. These typically consist of various types of buildings and cover materials, feature extensive land development, and involve complicated land-use types. In recent years, urban areas in South Korea have exhibited increases in power usage and frequent power-supply interruptions, due to a growing number of heat-wave days in summer. These urban areas also face other problems in connection with heat waves, such as increases in disease and death rates [38]. Hence, it is necessary to provide plans for improvement of the outdoor thermal environment that take into account the diverse and complex land-use types, as well as the spatial arrangement, of urban areas in South Korea.

It was the goal of this study to identify microclimate characteristics, in relation to green-area development and the reflectivity of exterior coating materials, using field measurements of temperature in the urban area of Changwon City, South Korea. Furthermore, the effects from improving the thermal environment were identified for various land-use types, and their characteristics were determined. This was accomplished by analyzing the effects from additional green-area development and from the application of high-reflectivity cover materials to existing space. For this analysis, the climate model ENVI-met was used. Based on this investigation, a plan for optimal space design to improve the thermal environment was provided at the level of urban environment planning.

2. Materials and Methods

2.1. Target Study Area. The urban area of Changwon City (35°14′01.02″N, 128°41′19.95″E) in South Korea is a basin-form city surrounded by mountains, with a population of approximately 50 million [39, 40]. Because it is the first planned city in South Korea, the land-use types there are distinct. These include densely distributed residential, commercial, and public facilities, but large-scale national industrial complexes are also located in the vicinity. The average annual temperature is approximately 15°C. Warmer weather is experienced in summer, which lasts from June to September (average temperature of ~24°C) [41].

Five different urban land-use types in Changwon City were selected as targets for analysis. These include urban park, low-rise apartment, commercial, single-detached residential, and high-rise apartment areas (Figure 1). The urban park area consists mostly of trees and grass, as well as landscape arrangements such as marble stones and sculpture. The area surrounding the urban park consists of roads, public offices, and single residential areas. The low-rise apartment area consists of relatively low-rise buildings (up to five floors), and the buildings are densely distributed. The land surface in this area is mostly covered with asphalt. Trees are present in

Table 1: Characteristics of land cover at the measure points.

Site	Land cover
Urban park (9 points)	(1) Granite
	(2) Brick
	(3) Brick
	(4) Lawn
	(5) Urethane
	(6) Wooden board
	(7) Brick
	(8) Granite
	(9) Lawn
Low-rise APT (6 points)	(10) Asphalt
	(11) Sand
	(12) Asphalt
	(13) Asphalt
	(14) Concrete
	(15) Asphalt
Commercial area (3 points)	(16) Asphalt
	(17) Brick
	(18) Gravel
Single residential (4 points)	(19) Asphalt
	(20) Asphalt
	(21) Gravel
	(22) Asphalt
High-rise APT (5 points)	(23) Sand
	(24) Brick
	(25) Brick
	(26) Tile
	(27) Brick

the spaces between the edges of the apartment complex and the buildings. The commercial area consists of very densely distributed high-rise buildings (height > 30 m) that are all 10 m wide. The ground is covered with asphalt. Moreover, the commercial area includes resting places for citizens in the form of a fountain square and a small green park. The single residential area consists of buildings with two floors. The buildings are densely distributed and form a block of approximately 10 houses. The interval between the blocks is approximately 5 m, and the land surface is covered with asphalt. Retail shops (20 m in width) and parking lots covered by asphalt are situated in the area. The high-rise apartment area comprises vast areas of greenery with a spacious square covered in tiles; the building density in this area is not high.

2.2. Field Measurements. Field measurements were conducted in summer between June and August, under clear weather conditions (almost no clouds, less than 10% coverage). Daytime measurements were conducted on 29 June 2013 and 09 August 2013, whereas nighttime measurements were conducted over three days starting from 14 August 2013. Daytime measurements were conducted from 1:00 p.m. to 3:30 p.m. (UTC+9), whereas nighttime measurements were conducted from midnight to 2:30 a.m. (UTC+9), and each round of measurements took approximately 2.5 h. These measurement intervals should have captured the maximum and minimum daily temperatures. As shown in Figure 2 and Table 1, 27 points (urban park: 9, low-rise apartment area: 6, commercial area: 3, single residential area: 4, and high-rise apartment area: 5) were selected as the measurement points based on the three-dimensional (3D) spatial characteristics of the buildings and the reflectivity of the ground and building cover materials. The temperatures of bricks, lawn, and granite were measured in the urban park. Most of the temperatures measured in the low-rise apartment, commercial, and single residential areas were for asphalt and concrete. The temperatures measured in the high-rise apartment area were mostly for bricks. The distance from the urban park to the high-rise apartment area is approximately 5 km.

At each study site, three researchers used a mobile meteorological measuring device (Davis Vantage Pro2, accuracy of ±0.5°C) set at a height of 1.2 m (see Figure 3). The measurements were then taken by fixing the device in a horizontal position, relative to the ground surface, for 2 min. Measurement start and end times, as well as the surface temperatures at each measurement point, were recorded in a field book. Each cycle of measurements occurred in the following order: urban park area → low-rise apartment area → high-rise commercial area → single residential area → high-rise apartment area. In the urban park area, the granite material located in the northern section was selected as the measurement point. Since temperature changes as time passes, corrections must be made based on specific time. This study corrected the time to 2 p.m. for daytime measurement and 1 a.m. for nighttime measurement and set the final point of measurement to be equal to the starting point, correcting it through

$$\alpha = \frac{\left\{\left(X_f - X_s\right)/X_f\right\}}{\left(T_f - T_s\right)},$$
$$Y = X - X \times \left(T - T_s\right) \times \alpha. \tag{1}$$

For (1), X_f is the measurement value of the end point, X_s is the measurement value of the start point, T_f is the measurement time of the end point, T_s is the measurement time of the start point, α is the correction factor, X is the measured value, T is the measured time, and Y is the corrected value.

2.3. ENVI-Met Model. In this study, thermal-improvement effects were compared by considering outdoor space design using the ENVI-met model version 3.1. This is a microclimate analysis program that simulates meteorological factors (e.g., distribution of air currents, flow fields of fluids, temperature, humidity, and radiation energy) in 3D, based on input information that includes land surface, structures, and vegetation of urban spaces in grid form [21, 42]. This program has a spatial resolution of 0.5–10 m, temporal resolution of 10 s, and can simulate time frames of 24–48 h [18, 43].

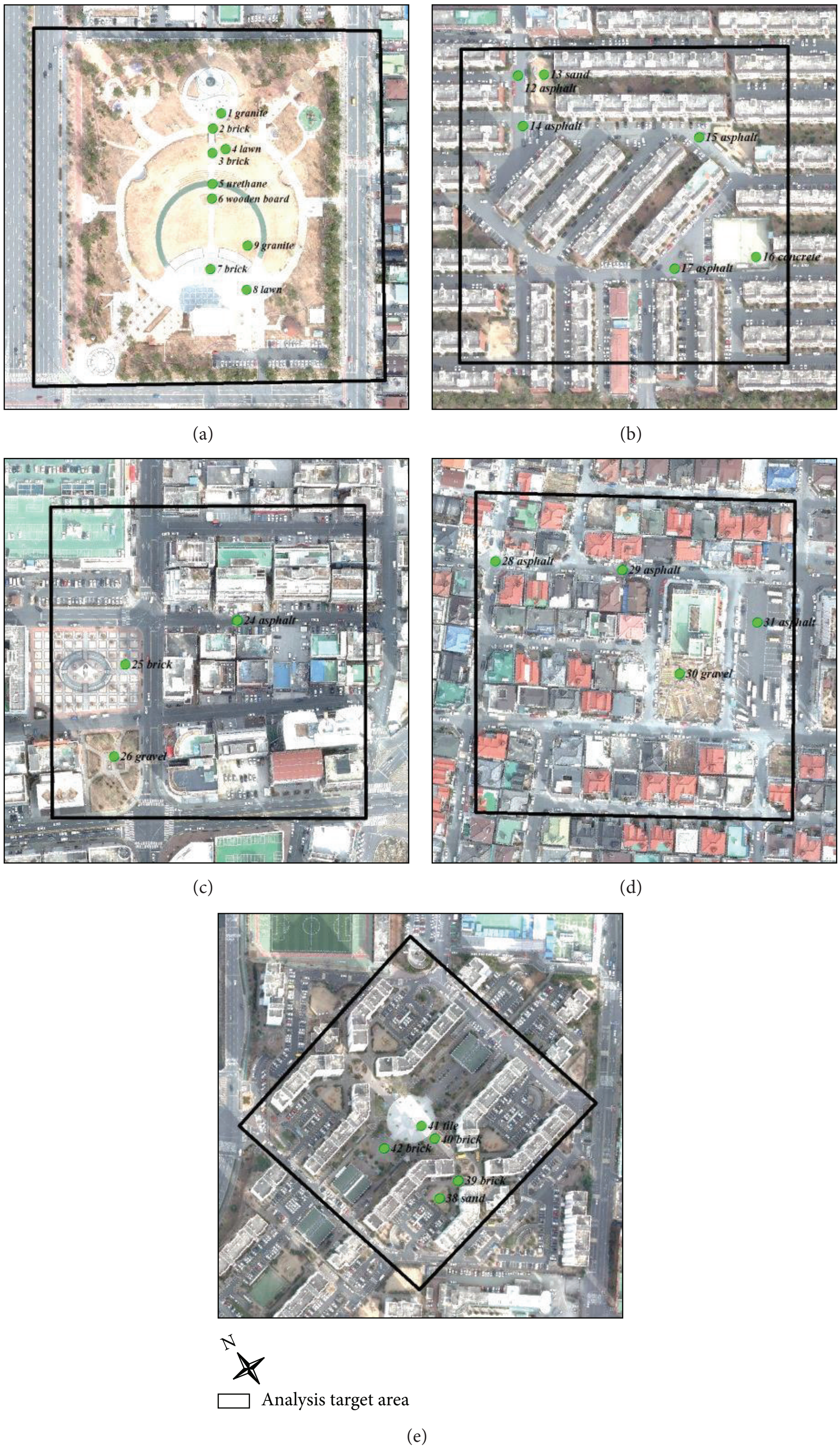


Figure 2: Field measurement points in the analysis target sites: (a) urban park area (9 points), (b) low-rise apartment area (6 points), (c) high-rise commercial area (3 points), (d) single residential area (4 points), and (e) high-rise apartment area (5 points).

Figure 3: Portable measurement equipment: (a) meteorological measuring device, (b) data logger box.

For this work, the input data consisted of an area input file (∗.in) and a configuration file (∗.cf). The former included representations of the geographic location, building arrangement and height, type of ground cover, or type of vegetation of the target area, whereas, the latter includes the initial simulation of weather conditions. The information for each area input file was compiled based on surface fabric classification, geographic information systems (GIS) data, emissivity and reflectivity of coating materials, and a field survey based on the study by Song [44]. The horizontal grid resolution was set at 4 m after considering the area of each site, and the vertical grid resolution was set at 1 m. The number of grids was 60 × 60 × 30 grids for the urban park area, 52 × 52 × 30 grids for the low-rise apartment area, 50 × 50 × 30 grids for the high-rise commercial area, 34 × 34 × 30 grids for the single residential area, and 52 × 52 × 30 grids for the high-rise apartment area. Moreover, buildings were rotated vertically or horizontally to accurately express the building shape. The rotation degree was set at 35° for the urban park area, low-rise apartment area, high-rise commercial area, and single residential area but set at 78° for high-rise apartment area. A receptor was positioned at the same location as the field measurement point.

The data for factors such as temperature, wind speed, wind direction, and humidity were obtained from an automatic weather-measuring device, which managed the information on weather conditions from the configuration file. This device was installed at the Changwon Disaster Prevention and Countermeasures Headquarters, located near the target area. Ng et al. [18] stated that the best time to start a simulation is at sunrise and that the total running time should be longer than 6 h, in order to overcome the influence of the initialization. The simulation start time in this study was 06:00 on 29 June, 09 August, and 13 August 2013. The simulation duration was set to 24 h, and the data was stored at 10 min intervals. Moreover, the albedo of walls was set to 0.2, and the albedo of roofs was set to 0.3 (Table 2).

For ENVI-met, analysis data was assumed to be measured from a height of 2 m and at 2 p.m. (daytime) or 1 a.m. (nighttime), which is equivalent to the actual site measurements. The distribution of the ENVI-met results was analyzed using the ArcGIS 9.3 program.

Table 2: ENVI-met model configuration-file settings.

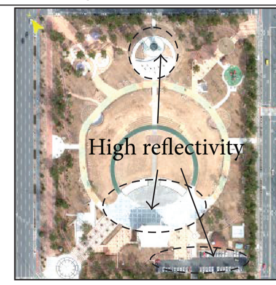
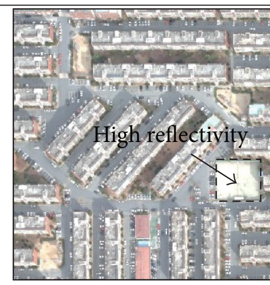
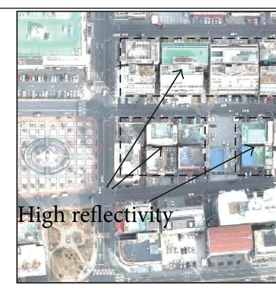
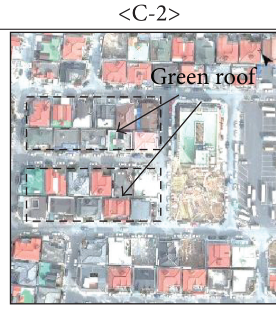
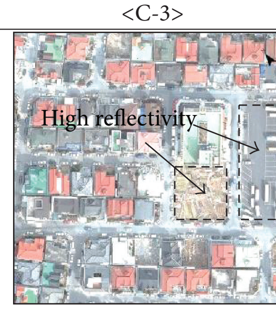
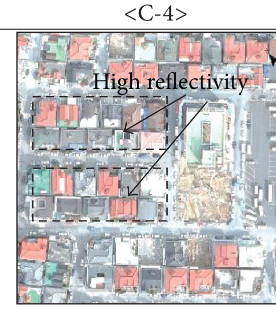
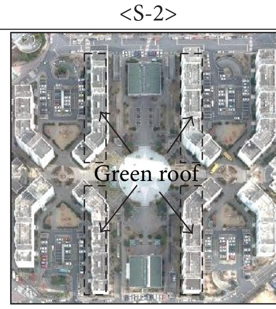
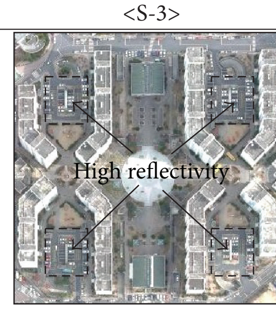
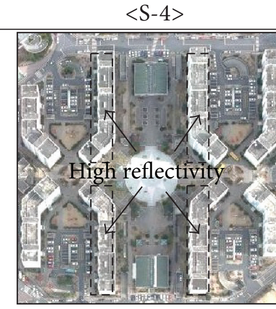
Category	Test dates		
	29/06/2013	09/08/2013	14/08/2013
Simulation setting			
Start simulation day (dd.mm.yyyy)	29.06.2013	09.08.2013	13.08.2013
Start simulation time (hh.mm.ss)	06:00:00	06:00:00	06:00:00
Total simulation time in hours (h)	24	24	24
Save model state (min)	10	10	10
Meteorological inputs			
Wind speed in 10 m above ground (m/s)	1.0	0	0.9
Wind direction (°)	135	112.5	225
Initial temperature atmosphere (K)	293.4	301.2	300.1
Specific humidity in 2500 m (g/kg)	3.48	3.52	3.52
Relative humidity in 2 m (%)	81.3	88.5	74.7
Albedo of walls		0.2	
Albedo of roofs		0.3	

Since information on soil ingredients and vegetation used as input data for ENVI-met analysis (infrared and visible range and calculations of radiation) was all measured using the values or formulas provided by the program, there are considerable gaps between the target areas. The accuracy of the models utilized must be validated using actual field data. There have been a number of recent tests [18, 36, 37, 45–47] of the accuracy of the ENVI-met model. For this study, the results of the ENVI-met model were validated by comparison with field data generated at a receptor installed at the measurement points.

2.4. Space Design. Space design was established by considering green-area development and increases in the reflectivity of each target area (Table 3). The green areas were developed by growing broad-leaf trees to a height of 2 m or by growing grass 10 cm high in parking lots and squares distributed within the target areas. On rooftops, green areas were expanded using 1.5 m high trees. Design changes intended to increase albedo have been studied actively in previous research using ENVI-met [48]. Based on these previous results, an albedo increase of 0.2 was added to the ground cover data provided by the ENVI-met program, mostly by applying them to parking facilities or building roofs.

Following analysis of the target areas, the urban park area was found to consist of scattered sections covered by marble and granite. Green ground cover was set up in these areas (U-1, Table 3) by growing grass, which increased their reflectivity

Table 3: Space design plan for each target area.

Site	Space design: Green space formation		Space design: Covering material replacement	
Urban park	 <U-1>		 <U-2>	
Low-rise apartment	 <L-1>	 <L-2>	 <L-3>	 <L-4>
Commercial area	 <C-1>	 <C-2>	 <C-3>	 <C-4>
Single residential	 <S-1>	 <S-2>	 <S-3>	 <S-4>
High-rise apartment	 <H-1>	 <H-2>	 <H-3>	 <H-4>

(U-2, Table 3). In the low-rise apartment area, the parking lot was equipped (L-1, Table 3) with trees and the roof cover was replaced (L-3, Table 3) with high-reflectivity material. Furthermore, for each of the four buildings located at the center of the analysis area, a green roof (1.5 m high) was built (L-2, Table 3) and the reflectivity of the roof was increased by applying (L-4, Table 3) high-reflectivity roof-cover materials. In the commercial area, a green area was formed (C-1, Table 3). In the fountain square, green roofs (C-2, Table 3) were built on the high-rise buildings, and their reflectivity was increased (C-4, Table 3). The reflectivity of the coating materials in the parking lot was also increased (C-3, Table 3) by 0.2. In the single residential area, plants were grown (S-1, Table 3) in the parking facilities, and its reflectivity was increased (S-3, Table 3). Green plants were placed on the roofs of approximately 20 households (S-2, Table 3), and their reflectivity was increased (S-4, Table 3). In the high-rise apartment area, greenery was added (H-1, Table 3) to tile-covered squares; for the four buildings located at the center, rooftop greening (H-2, Table 3) and reflectivity (H-4, Table 3) were increased. Furthermore, the asphalt material of the parking lot located between the buildings was replaced (H-3, Table 3) with a high-reflectivity material.

Simulations were conducted for each target area using the ENVI-met model, considering the plan adopted for the space design. Improvements in the thermal environment were equated by comparing the spatial changes in climate according to the space designs, using ArcGIS 9.3. The ENVI-met model time was set as 09 August 2013, which corresponded to the highest recorded field measured temperature. The comparisons were done using the simulated 14 h results.

3. Results and Discussion

3.1. Field Measurement Results. Table 4 shows the field temperature values by measurement point. The average temperature (29.5°C) occurred on 29 June 2013, reaching the highest average (35.4°C) on 09 August 2013. On 14 August 2013, the average nighttime temperature was 29.5°C. Among the different measurement areas, the high-rise commercial and single residential areas had high average temperatures (29 June: 30.0°C, 09 August: 35.8°C, and 14 August: 29.2°C). These two areas also had a high density of artificial structures composed of asphalt and concrete. The high-rise apartment area had relatively more greenery and shade due to the presence of taller buildings. This area had lower average temperatures than the others (29 June: 29.4°C, 09 August: 34.7°C, and 14 August: 28.4°C). The measurement points (points 1–4, Table 4) in the northern part of the urban park area were strongly affected by the surrounding area. During the field analysis, moderate winds (1-2 ms^{-1}) were experienced, resulting in considerably lower temperatures than at other measurement points.

3.2. Accuracy of the ENVI-Met Model. Figure 4 shows the results of modeled temperature and measured temperature in each measurement area. Measured temperatures turned out to be higher than modeled temperatures. A scatter plot was examined to determine the accuracy of the modeled temperature, and the result is shown in Figure 5. The temperatures of points 1–4 (Table 4), corresponding to the urban park area, were excluded because they were severely affected by the surrounding area. The coefficient of determination was very high on 09 August 2013 (0.627) and on 14 August 2013 (0.613). Ng et al. [18] and Yang et al. [49] found the coefficient of determination to be 0.6–0.7 and 0.94. The former was a bit higher and the latter much higher, than the values determined in the present study (Figure 5). In previous studies, the daily variations at each measurement point of the model and field data were compared. In the present study, the data at the same time were compared for the various points.

Table 4: Field temperature measurement (°C).

ID	Surface cover	06/29/2013	08/09/2013	08/14/2013
	Urban park			
1	Granite	28.3	37.0	28.4
2	Brick	28.7	37.3	29.1
3	Brick	28.9	36.9	29.0
4	Lawn	29.0	35.9	28.9
5	Urethane	29.1	35.4	28.8
6	Wooden board	29.2	35.3	28.7
7	Brick	29.1	34.8	28.6
8	Granite	29.1	34.7	28.5
9	Lawn	29.2	34.6	28.4
	Mean	**29.0**	**35.7**	**28.7**
	Low-rise APT			
10	Asphalt	29.8	35.0	28.4
11	Sand	29.9	35.1	28.5
12	Asphalt	29.9	35.2	28.5
13	Asphalt	30.0	35.4	28.5
14	Concrete	30.3	35.4	28.6
15	Asphalt	30.4	35.4	28.6
	Mean	**30.1**	**35.3**	**28.5**
	Commercial area			
16	Asphalt	29.9	35.6	29.1
17	Brick	30.1	35.8	29.2
18	Gravel	30.0	35.9	29.2
	Mean	**30.0**	**35.8**	**29.2**
	Single residential			
19	Asphalt	29.8	35.6	29.1
20	Asphalt	29.9	35.8	28.9
21	Gravel	30.0	35.8	28.8
22	Asphalt	29.9	35.9	28.7
	Mean	**29.9**	**35.8**	**28.9**
	High-rise APT			
23	Sand	29.5	34.7	28.4
24	Brick	29.5	34.7	28.4
25	Brick	29.3	34.7	28.4
26	Tile	29.3	34.6	28.4
27	Brick	29.3	34.6	28.4
	Mean	**29.4**	**34.7**	**28.4**

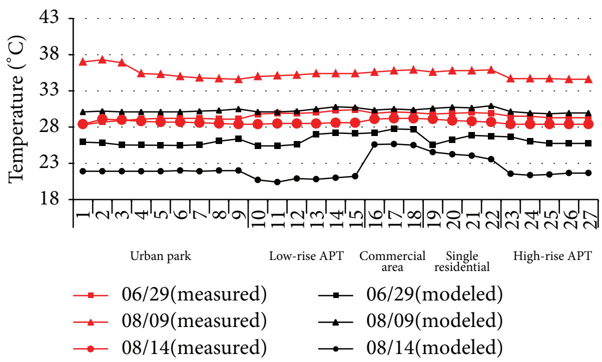


FIGURE 4: Comparison of modeled and measured temperatures at each measurement point.

Therefore, direct comparison of these results with those of earlier studies is not possible. Nevertheless, the temperature data from the model and field measurements showed high correlation, and it was determined that the ENVI-met results were suitable. The root-mean-square error (RMSE) showed a difference of 3.4°C on 29 June 2013, 4.6°C on 09 August 2013, and 6.5°C on 14 August 2013. The field measurement data were consistently higher. The mean difference between the ENVI-met model and field measurements reported by Middel et al. [37], Yang et al. [49], and Chow et al. [45] were 1.4–2.0, 1.01, and 1.53°C, respectively. In sharp contrast, a study by Park [50] showed a mean difference of 7.0–11.0°C. However, the remaining literature, showed a temperature difference of approximately 3°C between the model and field measurements over the course of 14 h. This is in agreement with the findings of this study. Therefore, it was found that the difference between the model and field measurements in this study was not significant, compared to previous studies, and that the correlation was very high. Thus, it was concluded that the accuracy of the model was sufficient.

3.3. Thermal Environment Improvement Effect. Table 5 and Figure 6 show the results of the analysis of temperature changes according to space design, using the ENVI-met model. Table 6 shows the changes in surface temperature at the measurement points.

3.3.1. Urban Park. The temperature provided by the ENVI-met model for 09 August 2013, at 14:00, on the road east of the park was >31°C, whereas that for the inner park was lower (<30.4°C). When the artificial material covering the ground inside the park was replaced with grass (U-1), the average temperature increased by 0.05°C. Considering the uncertainty level of the model, this change was considered insignificant. Moreover, the temperature increased by 0.15°C when the reflectivity was increased (U-2). However, unlike in the unaltered park space, a road located in the eastern part of the park exhibited lower temperatures. This was because of changes in the microclimate after the material covering of the ground was replaced (Figure 5). Therefore, in the urban park area, establishing grass as the ground cover in place of artificial coverings, or increasing the reflectivity of the ground

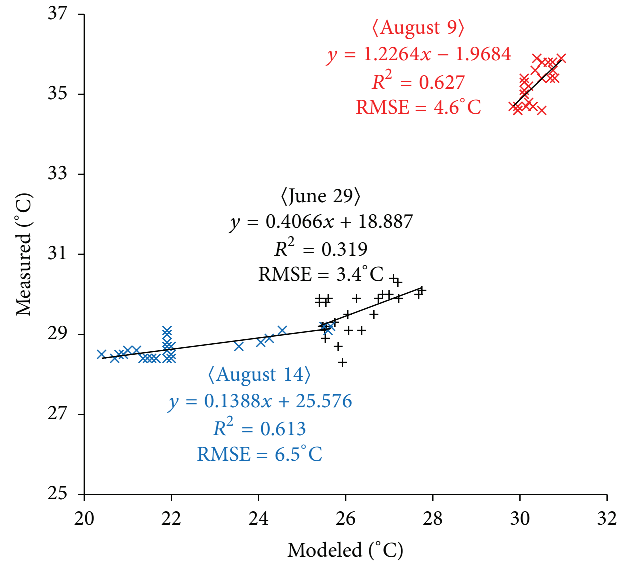


FIGURE 5: Comparison of the 2013 ENVI-met modeled and field measured temperatures for the following: 29 June: lower left set (x), 09 August: central set (+), and 14 August: upper right set ($*$).

TABLE 5: Changes in temperature by space design.

Site	Temperature changes (°C)			
Urban park	U-1	U-2		
	+0.05	+0.15		
Low-rise apartment	L-1	L-2	L-3	L-4
	+0.15	−0.05	+0.15	+0.18
Commercial area	C-1	C-2	C-3	C-4
	−0.21	−0.07	+0.15	+0.17
Single residential	S-1	S-2	S-3	S-4
	−0.28	−0.01	+0.18	+0.11
High-rise apartment	H-1	H-2	H-3	H-4
	+0.08	+0.46	+0.06	+0.06

cover, resulted in an increase in the average temperatures. However, these alterations decreased the temperatures of the surrounding areas.

3.3.2. Low-Rise Apartment Area. The results of the temperature distribution analysis, given the space design of the low-rise apartment area, showed that the initial temperature in the parking lot was 30.8–31.0°C, whereas, in the south the temperature was comparatively high, measuring 31.0–31.2°C. Conversely, the analysis showed that the temperature was less than 30.6°C in most areas. When the concrete material of the parking lot was replaced (L-1) with grass, the surface temperature decreased significantly (8.6°C); however, the average temperature increased by 0.15°C and the temperature of the parking lot increased to 31.0–31.2°C. As roof-top greening was applied to the buildings (L-2), the average temperature decreased by 0.05°C, and the surface temperature of the surrounding area decreased by 1.7–5.0°C. Once the reflectivity of the cover materials (L-3) of the parking lot

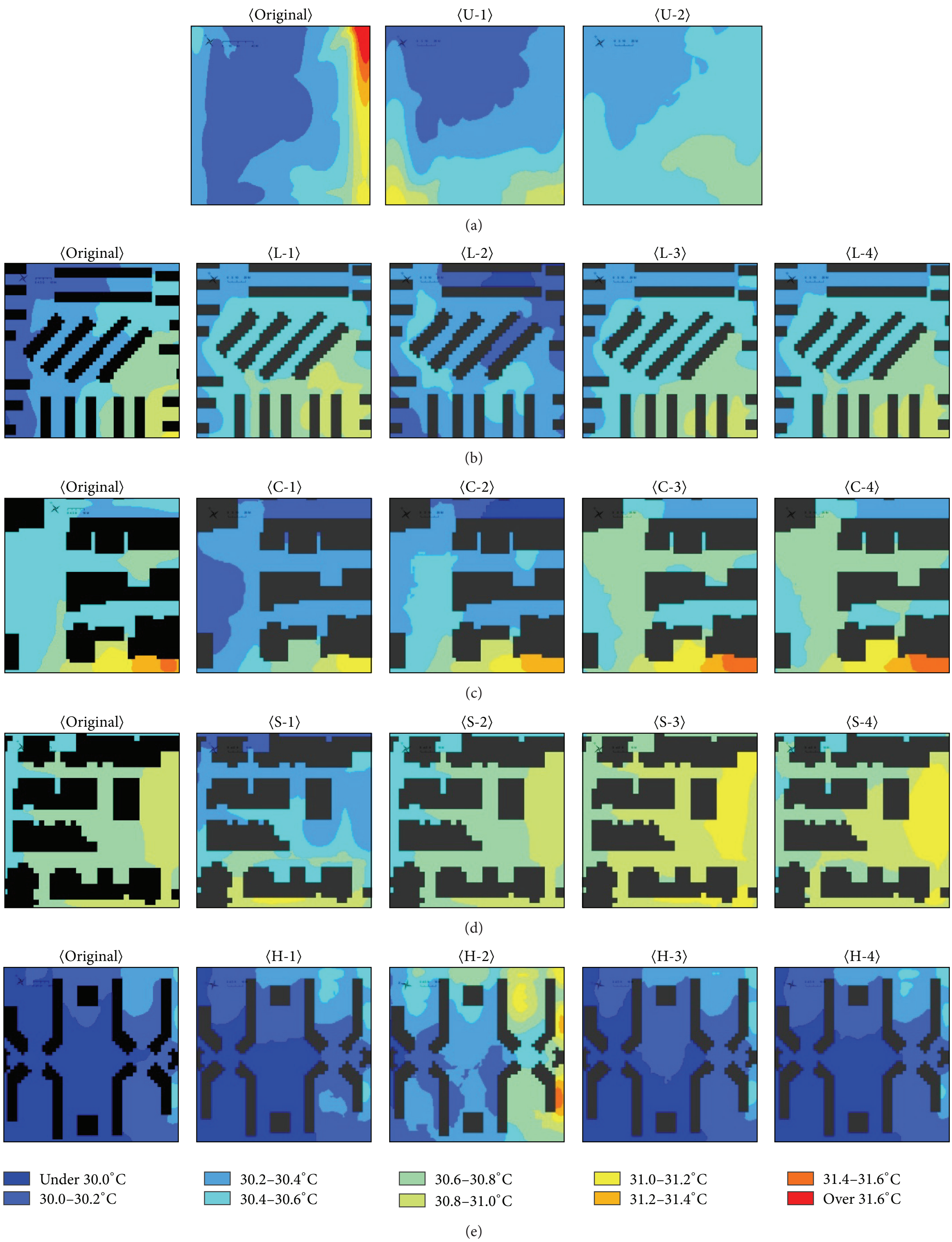


Figure 6: Changes in temperature distribution according to the scenario settings: (a) urban park area, (b) low-rise apartment area, (c) high-rise commercial area, (d) single residential area, (e) high-rise apartment area.

Table 6: Differences in surface temperature of existing spaces and space design.

Point	Scenario																	
	Urban park		Low-rise apartment				Commercial area				Single residential				High-rise apartment			
	U-1	U-2	L-1	L-2	L-3	L-4	C-1	C-2	C-3	C-4	S-1	S-2	S-3	S-4	H-1	H-2	H-3	H-4
Urban park																		
1	+6.6	+12.1																
2	−2.4	−1.7																
3	+2.9	−1.7																
4	+1.3	+1.9																
5	+12.5	+8.3																
6	+2.9	−0.7																
7	+2.3	−2.3																
8	−4.7	−0.8																
9	+0.4	+1.3																
Low-rise apartment																		
10			−4.4	−1.7	−3.1	−4.0												
11			+0.1	+1.1	+0.7	+0.8												
12			−5.0	−5.0	−5.1	−5.0												
13			+1.6	+1.4	+1.6	+1.6												
14			−8.6	+2.7	+0.7	+3.0												
15			−4.2	−5.1	−4.8	−4.8												
Commercial area																		
16							−1.2	−0.6	−0.3	−0.2								
17							−11.0	+2.8	+2.5	+2.6								
18							+0.0	+8.8	+13.5	+13.7								
Single residential																		
19											−0.4	+0.1	+2.5	+2.4				
20											−0.5	−0.1	+1.8	+1.5				
21											−7.1	−0.1	+10.2	+12.0				
22											−20.6	−3.4	−2.5	−3.8				
High-rise apartment																		
23															+0.2	+0.6	+0.2	+0.2
24															+0.1	+0.9	+0.0	+0.0
25															+0.6	+1.6	+0.7	+0.7
26															−3.9	+3.2	+10.8	+0.4
27															+1.6	+1.8	+1.6	+1.4

and the building rooftop (L-4) was increased, the average temperature increased by 0.15 and 0.18°C, respectively. It was also observed that the temperature around the parking lot and building increased from 30.4 to 30.8°C and that the temperature of the existing space rose by the same amount (from 30.2 to 30.6°C, for an increase of 0.4°C in both cases).

3.3.3. Commercial Area. In the commercial area, the temperature in the southern section was generally higher than 31.0°C. For C-1 (Figure 5), which was designed with a green park, the average temperature decreased by 0.21°C, compared with the existing space, and the temperature was found to be less than 30.4°C in most areas. The surface temperature of the measure points with green areas decreased by about 11°C. When the green spaces of the commercial area were developed, a distinct temperature reduction effect was confirmed. Following rooftop greening (C-2), the surface temperature of the surrounding area increased slightly; however, the average temperature decreased by 0.07°C. Most areas showed a lower temperature distribution (30.2–30.6°C) than that of the existing space (30.4–30.6°C). As the reflectivity of the cover material (C-3) of the parking lot and building rooftop (C-4) was increased, the average temperature increased by 0.15 and 0.17°C, respectively, compared with the existing space; many of the areas were observed to be within the temperature range of 30.6 to 30.8°C.

3.3.4. Single Residential Area. The existing single residential area mostly showed a temperature distribution ranging between 30.6 and 31.0°C. When green covering was added to the parking lot (S-1), the average temperature decreased by 0.28°C, and the surface temperature range was between

7.1 and 20.6°C, showing a significant decrease. After the rooftop greening was applied (S-2), the average temperature decreased by 0.01°C, which is insignificant considering the existing space. Moreover, the surface temperatures around the buildings decreased slightly. When the reflectivity of the materials in the parking lot (S-3) and the building rooftop (S-4) were increased, the average temperature increased by 0.18 and 0.11°C, respectively. As the reflectivity of the parking lot was increased, the surface temperature at the measurement point adjacent to the building increased by 10.2°C, whereas the surface temperature decreased by 2.5°C at a measurement point far away from the building. Similarly, when the reflectivity of the rooftop was increased, the surface temperature at the measurement point adjacent to the building increased by 12.0°C, but the surface temperature decreased by 3.8°C at the measurement point far away from the building.

3.3.5. High-Rise Apartment Area. The temperatures in the existing space of the high-rise apartment area were typically below 30.0°C. Following the space design, the average temperatures increased, but there were no significant differences (H-1 +0.08°C, H-3 +0.06°C, and H-4 +0.06°C) except after rooftop greening was performed (H-2 +0.46°C). The surface temperature at H-3, where the reflectivity of the cover materials of the parking lot was increased, showed a significant increase in temperature of 10.8°C compared to the surface temperature of the existing space. An increase in surface temperature was observed at all measurement points except for H-1, which was designed with trees.

3.4. Discussion. When a green area was developed near trees in the space design plan, commercial and single residential area land-use types that were mostly covered in artificial materials, such as asphalt and concrete, showed significant decreases in temperature. The urban park, low-rise apartment, and high-rise apartment areas, all of which had comparatively rich green areas, exhibited low surface temperatures; however, after similar changes were applied the temperatures increased. After rooftop greening was performed, the decrease in temperature was not as significant as it was when a green park was formed. The temperatures were slightly lower in the low-rise apartment and commercial areas than in the single residential area. The formation of green areas resulted in different effects depending on the spatial characteristics of the surrounding area. Furthermore, it was revealed that the temperature-reducing effect of green areas became more distinct as the density of artificial structures within the space increased.

When the reflectivity of the cover material was increased, an increase in temperature was observed; the surface temperature increased as the distance between the measurement point and the building decreased. Taha et al. [51] compared surface temperatures with reflectivity for a variety of cover materials. White elastomeric coatings (albedo of 0.72) exhibited surface temperatures that were 45°C lower than black coating (albedo of 0.08). Furthermore, Li et al. [25] examined the temporal changes in reflectivity in relation to the colors of cover materials such as concrete and asphalt. They observed that surface temperature decreased as reflectivity increased. This is because when reflectivity is increased, the amount of net-radiative energy accumulating on the surface decreases. However, the analytical results of the present study showed that surface temperatures increased slightly even when reflectivity increased. It was concluded that the reflected radiation energy was absorbed by the surrounding buildings and was consequently reradiated to the surface from the building. The observed low surface temperatures at the measurement points in the park (without buildings) and at a distance from the buildings confirm this conclusion. Additionally, studies by Lau and Yang [24], Lin et al. [26], and Wang et al. [32] showed that although surface temperature decreased as reflectivity increased, it had a negative effect on the physical and mental health of pedestrians. Yang et al. [33] showed that when the reflectivity of the land surface was increased to 0.4, the physiological equivalent temperature increased by 5–7°C, thereby reducing the level of overall outdoor thermal comfort. A number of studies [27, 29, 34, 52–54] have demonstrated that a reduction in building energy and mitigation of the urban heat-island effect can be achieved by increasing the reflectivity of roof surfaces. However, these studies have not shown that thermal comfort is improved in outdoor spaces with a high density of buildings; therefore, it is necessary to establish the reflectivity of cover materials, which is one aspect of the space design plan, while considering the arrangement of the surrounding buildings.

4. Conclusions

In this study, an effective application plan was established for improving the thermal environment in the urban areas of Changwon City, South Korea. The plan was based on space design, and it included the development of a green area and increasing the reflectivity of ground and building cover materials for various types of land use. The results from analysis of the changes caused by this plan are summarized below.

The results of the field measurements showed that the highest temperature occurred on 09 August 2013, (35.4°C), while on 29 June 2013 the temperature was 29.5°C. The average nighttime temperature (28.7°C) was recorded on 14 August 2013. Based on the accuracy of the ENVI-met model, it was concluded that the temperatures exhibited a high RMSE; however, analysis showed that the coefficient of determination of the linear regression on 09 August 2013 and 14 August 2013 exceeded 0.6, thereby increasing the explanatory power of the ENVI-met model. The analysis of the temperature changes (according to the space design), taking into account increases in reflectivity and development of green areas for different types of land use, showed distinct temperature reduction effects due to creation of green spaces in areas where buildings and artificial cover materials were densely distributed (i.e., commercial and single residential areas). The urban park, low-rise apartment, and high-rise apartment areas, with relatively many green areas, were predicted to exhibit temperature increases. When the reflectivity of the cover materials was increased, those areas exhibited increases in temperature; when the reflectivity in areas with high building density was increased, the surface temperature increased.

The results suggest that the effects of thermal improvement due to green area development and increasing reflectivity differ depending on land use. This is because different land uses have different building arrangements and proportions of cover materials. To achieve the optimal thermal environment improvement effect at an urban and environmental planning level, it is necessary to consider the spatial characteristics of the land-use types and the surrounding areas appropriately. For example, the single residential or apartment areas, which had copious green space, showed an insignificant decrease in temperature even after rooftop greening and creation of a park. Therefore, in order to improve the thermal environment, it is more beneficial to increase the effect of shading by varying the arrangement of buildings, rather than by developing a green area. Furthermore, areas with a high density of artificial cover materials and of buildings displayed increases in air and surface temperatures after increasing the reflectivity of cover materials. Furthermore, this study showed that in spaces where artificial cover materials and buildings are concentrated the increased reflectivity of cover materials rather led to an increase in temperature. To clarify the temperature reduction effect according to cover materials of high reflectivity, it is also necessary to consider urban geometry (e.g., the sky-view factor), as well as the reflectivity or emissivity of building walls. These should be considered in future research.

In order to validate the accuracy of the model, the results of the ENVI-met model were compared with temperatures measured in the field, and a high correlation was found. However, there was a significant difference in the RMSE. This is because the ENVI-met model only takes into consideration the geographical location and initial weather conditions, without accounting for seasonal impacts. To solve this problem, a method must be utilized that can simulate the changes in climate for longer periods. In addition to temperature, other factors (e.g., radiation flux, wind speed, humidity, and surface temperature) also affect the thermal environment; therefore, it is necessary to consider the validity of the model with respect to these various factors. It is believed that an optimal space design plan for the improvement of the thermal environment can be provided, at the urban and environmental planning level, by taking into account a wider range of factors.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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