

Article

MDPI

Determining Favourable and Unfavourable Thermal Areas in Seoul Using In-Situ Measurements: A Preliminary Step towards Developing a Smart City

You Jin Kwon ¹, Dong Kun Lee ²,* and Kiseung Lee ³

- ¹ Interdisciplinary Program in Landscape Architecture, Seoul National University, Seoul 08826, Korea; eugene.kwon@snu.ac.kr or eugeneugene.kwon@gmail.com
- ² Department of Landscape Architecture and Rural System Engineering, Seoul National University, Seoul 08826, Korea
- ³ Graduate School of Public Health, Seoul National University, Seoul 08826, Korea; sslks93@snu.ac.kr
- * Correspondence: dklee7@snu.ac.kr; Tel.: +82-2-880-4885

Received: 15 May 2019; Accepted: 13 June 2019; Published: 17 June 2019



Abstract: Urban heat island effects (UHIE) are becoming increasingly widespread, thus, there is an urgent need to address thermal comfort, which significantly influences the daily lives of people. In this study, a means of improving the thermal environment by spatial analysis of heat was implemented to ensure basic thermal comfort in future smart cities. Using Seoul as the study site, the relationship between sensible heat and land cover type was used to identify heat islands in this city. Thereafter, k-means clustering was employed to extract unfavourable and favourable thermal areas. High sensible heat indicates locations where environmental heat needs to be mitigated. Sensible heat distribution data were used for spatial typification to formulate an effective land cover factor to mitigate the UHIE. In-situ net radiation data measured at six sites were utilised to confirm the spatial typification of the thermal environment. It was found that expanding the green space by 1% reduces the sensible heat in compact residential areas. The study results can be used to establish spatial planning standards to improve the thermal environments of sustainable cities.

Keywords: energy budget; land cover ratio; sensible heat flux; heat mitigation; thermal environment improvement; sustainability; in-situ validation; spatial typification by heat flux

1. Introduction

1.1. Urban Heat and Spatial Typification for Sustainability

The urban heat island effect (UHIE) depends on the land cover, roughness of the urban surface, presence of buildings, and albedo. The land cover type significantly affects the thermal environment, which determines the local climate zone (LCZ) [1,2] and is affected by thermal radiation in urban canyons. The UHIE is considered a function of time, weather conditions, and structural characteristics in practical applications such as road engineering, climatology, phenology, energy conservation, and weather forecasting [3,4]. Oke et al. [5] noted that although studies on the UHIE have explained this phenomenon, they are still lacking with respect to its causes, suggesting that the situation is well described but not well understood. Because the UHIE is influenced by various spatial factors, its assessment via a spatial multi-scale approach is required.

Thus far, the causes of heat generation with respect to space have been studied macroscopically to understand the UHIE [6]. From this perspective, the UHIE is caused by the temperature difference between urban and suburban areas and is usually studied on a regional scale. However, thermal

comfort at the micro-scale (that is, at the building scale) is of immediate concern to the residents of urban areas. Therefore, research on heat generation and its mitigation is increasing in importance. Micro-scale studies [7] need to be approached from the meso-scale [8,9] and multi-scale [10], and the irradiation of land must be accounted for [11].

Moreover, increases in population and population density cause the thermal environment to deteriorate [12,13]. As rapid urbanization and the corresponding increase in global warming are becoming worldwide concerns [14], every country is aiming to develop sustainable cities to promote heat island reduction. Energy sustainability is being emphasized to achieve this objective [15]. Amongst anthropogenic factors, the use of air conditioners, especially during summers [16], has led to further deterioration of the urban thermal environment [17]. This deterioration is characteristic of especially large cities [18]. Moreover, smart solutions are applied mainly in medium and large cities. Smart cities are being increasingly developed and are among the means of attaining energy sustainability and improving the thermal environments of urban areas [19]. Therefore, a practical means of implementing methods of enhancing sustainability is necessary. However, the development of smart cities also involves ideological issues that favour business-led technological solutions [20] without practical means. The development and evolution of the smart city concept are more complex than they are described. For instance, a report was published on an integrated conceptual model for Vienna, which states that the framework of a smart city must compensate for insufficient environmental sustainability [21]. The implementation of the smart city framework should also take natural resources into consideration [22]. Yigitcanlar emphasises that the effects of smart cities, such as CO₂ reduction, are insufficient for attaining sustainability [23]. To improve quality of life, the comfort provided by the thermal environment is important [24,25]. Detailed spatial analysis of the thermal environment to ensure this comfort merits further investigation, as a preliminary step for thermal environment improvement with the objective of developing smart cities in the future.

1.2. Heat Energy and Spatial Typification

Concrete spatial analysis of the thermal environment is a current priority. As stated by Howell, 'Energy radiates from one object to another one under all conditions and at all times' [26]. Since heat energy is intangible in tangible space [27], one spatial solution for improving the thermal environment is the typification of the latter. In meteorology, sensible heat flux, or sensible heat, is defined as the conductive heat flux from the land surface to the atmosphere and is evident in the transportation of energy being an important factor in the energy budget of the surface of the earth [28]. Sensible heat flux is a less popular quantity for defining the thermal environment than temperature, but it is effective for presenting the physical characteristics in space or performing quantitative estimations, such as heat transfer prediction [29,30].

In this research, we analysed the UHIE in terms of sensible heat flux instead of temperature over a wide area, considering factors such as the presence, size, and density of buildings as well as the presence of greenery in the relevant area. However, the relationships between the causes of thermal radiation generation and the effects of the spatial factors that are the fundamental causes of the UHIE are difficult to comprehend. Moreover, the thermal approach is challenging to apply to planning or designing in a practical geographical range. However, the urban surface temperature and ambient temperature are the results of heat exchange. By accurately diagnosing the urban land cover elements and analysing the heat distributed in an urban space, it is possible to understand the characteristics of the space to improve the urban thermal environment. In particular, to reduce or adapt the UHIE, it is necessary to understand this phenomenon itself and to examine the relationships between the physical elements of the urban space and the UHIE as well as the factors affecting the sensible heat flux.

1.3. Studies Using the Existing Spatial Approaches

The increase in summer temperatures affects individuals vulnerable to heat [31,32]. In this context, many studies have been conducted with the objective of mitigating the UHIE. These include studies

on the effects of green spaces on temperature reduction [33–36] (shadows of trees [37–39], grass in parking spaces [40,41], and rooftop greenery [42–44]), changes in the surface temperature according to the materials of buildings [45,46], temperature reduction due to the optimal spatial arrangement of buildings (ventilation path, road width, and pith of building) [47,48], land use, land cover change, and urban ecological service function [49,50].

Further, researchers have attempted to identify heat-vulnerable areas by investigating the distributions of social indicators and heat [51]. Efforts have also been made to identify the causes of high temperatures in urban areas in summer and the consequent formation of urban heat islands [52,53]. However, because of the characteristics of temperature, it is difficult to identify physical, spatial features. For example, the surface of a coating or building is composed of various materials but the amount of radiant heat incident on the surface and reflected off it varies with time according to its composition ratio [54]. The physical method of measuring radiant heat is a quantitative approach [26]. Radiant heat has been measured using the physical approach on both a global scale [55] and an urban scale (meso-scale) from an atmospheric or meteorological perspective.

There have also been micro-scale studies on indoor temperature reduction in summer from a green architectural perspective [56]. Further, global-scale studies have been conducted using physical models of heat generation or transfer [57,58]. A study on climate change involving satellite remote sensing captured the long-term trends of many meteorological variables [59] between heat and space that digitise the characteristics of the latter, and remote sensing studies have been conducted to explore the relationship between surface temperature and land cover factors [60,61]. This approach is not applicable on a small scale, that is, considering the microclimate; thus there is little difference in identifying linkages with the spatial elements that form cities on land. In addition, several computational fluid dynamics studies have been conducted, such as those involving ENVI-met or RayMan [62–64]. However, there are limits on the edges of the domains used to simulate urban spaces including all relevant urban characteristics.

1.4. Typification Method

Several researchers have attempted to classify the energy budgets of areas based on their spatial characteristics; for instance, Köppen established a climate classification system [65]. Regional zones can be spatially characterised depending on their temperatures (high or low). Based on the climate classification system developed by Köppen, intangible climatic elements have been used in other systems to identify climate zones [65], ecosystem maps [66], agricultural land [67], and hydrological areas [68]. In this study, thermal spatial typification was employed to determine climate zones and map the heat, based on which another method was derived. Several means of classifying thermal environment into climate zones exist; in this study, a statistical approach called k-means clustering analysis [69] was chosen. This approach is a representative non-hierarchical clustering method and can quickly group large amounts of data, such as weather data. Further, in the case of choosing the initial configuration for the relative distinction of the characteristics of isothermal heat, k-means clustering is advantageous compared to hierarchical analysis [70]. ased on the k-means clustering results, we define an 'unfavourable thermal area' (UTA) as a region in which heat is concentrated; these regions should be prioritised for heat reduction. Conversely, a region with a relatively low heat concentration is defined as a 'favourable thermal area' (FTA).

1.5. Objectives and Application

In the aforementioned micro-scale studies, the UHIE has been explored in terms of temperature changes with respect to the presence of buildings, as well as their size and density, and the presence of surrounding green spaces. The urban surface temperature and atmospheric temperature are the results of accumulating heat. As mentioned by Ma [71], differences in albedo due to land use and land cover type cause spatial changes in surface heat flux [71]. By accurately determining urban land cover elements and analysing the heat distributed in an urban space, it is possible to improve the thermal

environment of that space. In this study, based on an existing empirical model, we classified the estimated sensible heat distribution. Thereafter, using the classification results, in-situ measurements of the net radiation and sensible heat were performed to confirm the classification accuracy (as explained in Section 2).

The purpose of this study was to identify the distribution of sensible heat, which affects thermal comfort, through spatial typification with the objective of improving the thermal environment. The heat typification is based on five elements: the buildings, green spaces, water spaces, roads, and impervious surfaces in areas inhabited by urban residents. Further, the study results provide useful tools for sustainable urban development, including (1) the quantitative validation of two types of thermal areas through measurement at the micro-scale for proper spatial typification, (2) the suggestion of urban land cover ratio criteria for urban planning and design, and (3) an evaluation of the contribution of green spaces to improving thermal comfort [72].

1.6. Research Process

Our study was focused on the validation of spatial typification for thermal environment improvement through in-situ measurement. Firstly, we reviewed the current research related to the questions addressed in and purposes of our study (Figure 1).



Figure 1. Research flow (see Figure A1 in Appendix B for details).

Secondly, we analysed the thermal environment of Seoul with reference to the method employed in our previous work [73]. In this step, we rasterised the sensible heat flux based on existing data, considering the energy balance, net radiation, latent heat, sensible heat, storage heat, and artificial heat. Then, the heat flux was clustered through the k-means approach and the results were categorised. Next, in the 'thermal area extraction' stage, the UTA and FTA were extracted through the mapping. In addition, the land cover ratios of the thermal areas were derived from the daytime shift of the sensible heat flux and local land cover scale data. To select the study sites for the in-situ measurements, correlation analysis of the land cover ratio and sensible heat flux was conducted. The building cover ratio (BCR) and green spaces were found to be two significant factors affecting the changes in and distribution of the sensible heat flux (Appendix C).

Thirdly, we performed validation using field measurements. The two factors derived from the previous step become the criteria for selecting six study sites for in-situ measurement. We measured the sensible heat flux of the spatially typified thermal areas, i.e., the UTAs and FTAs, at the study sites. From the in-situ measurements, we collected net radiation and air temperature data. We also analysed the land cover ratios at each site. In the validation stage, we analysed the calculated values of the sensible heat flux based on the net radiation measured at the six sites corresponding to the two types of thermal areas. Furthermore, we validated the typification method by matching the sites with high sensible heat fluxes according to the in-situ measurements to the areas identified as having high sensible heat fluxes (UTAs) according to the spatial typification. If they matched, the results were analysed, and if not, the study site was re-searched.

We further considered how to create an implemental tool, a spatial typification system, and planning standards for thermal environment improvement. We also suggest that this approach has an indirect effect on sustainable energy use.

2. Extraction of Favourable and Unfavourable Areas

Intangible heat is dynamic in nature. However, in an environment experiencing continuous heat inflow, the heat stagnates and accumulates, causing a considerable increase in temperature [74] and making the region/space heat-intensive. Mitigating this excessive heat improves the thermal comfort of the residents [75]. Therefore, to reduce heat enhancement, we attempted to elucidate the causes of spatial concentration of heat by identifying the common spatial characteristics of areas with high heat. Thus, in this section, we describe the characteristics of spaces where heat is concentrated.

2.1. Spatiotemporal Scope

The city of Seoul is an interesting space because its thermal comfort related problems can be solved in a sustainable manner using the various surface characteristics of its compact urban area [76]. For validation, we conducted measurements at Gwanak, Mapo, and Seocho, which are residential areas in Seoul with high sensible heat concentrations. Temporal data for the summer of 2015, based on the automatic weather station (AWS) data format, time, and spatial resolution, were provided by the Seoul Metropolitan Government Meteorological Agency and SKTech X, a private company. The measurements for validation of the typification were conducted in 2018.

2.2. Input Data

The hourly heat flux was calculated using the air temperature, atmospheric pressure, and relative humidity collected from 287 stations in total, including 38 meteorological stations in Seoul and 249 SKTech X meteorological stations. We typified the heat flux and land cover data (Figure 2) on a day with clear weather, low cloud cover, and peak air temperature in August (Table 1). We also created a 100 m \times 100 m grid to map the thermal environment and thermal distribution data.



Figure 2. Input data: (a) impervious surfaces, (b) green spaces, (c) buildings, (d) water and wetlands, (e) roads, and (f) administrative map.

Classification	Input Data	Source
Meteorological data for heat flux distribution	-Air temperature, relative humidity, cloud cover, saturated water vapour pressure	-Korea Meteorological Administration (38 stations) -SKTech X (249 stations)
Extraction of FTAs and UTAs	-Latent heat model, sensible model, storage heat model	Holtslag, 1983 Loridan, Grimmond 2011
Spatial attributes	-Subdivided land cover map (green spaces, wetlands, impervious surfaces) shp file of Seoul administrative district-building .shp file shp file depicting the widths of roads shp file depicting the width of roads	-Ministry of Environment, -Statistical Geographic Information Service (SGIS), -Seoul Information Communication Plaza

Fab	le 1.	N	letro	logy	and	spatial	attri	butes	(land	cover	factors): c	lata	and	sources.
------------	-------	---	-------	------	-----	---------	-------	-------	-------	-------	---------	------	------	-----	----------

2.3. Methodology

In k-means clustering, centroid data are used as prototypes and are divided into clusters composed of the data closest to the prototype. This process is based on the theory established by Tobler stating that ' ... near things are more related than distant things ... ' [77]. K-means clustering is characterised by rapid grouping of vast amounts of data and selection of initial configurations; further, it is suitable for thermal analysis, which is an isometric rather than hierarchical approach [78]. Therefore, thermal distribution typification through k-means clustering allows the group to be expressed as a heat value while classifying heat-concentrated spaces based on the land cover ratio, which is a spatial factor [73].

To reflect only the land cover characteristics for the urbanised parts of the city, we initiated the cluster analysis based on the heat values, excluding the main mountains and large hydrological systems around the major ecological axis that considerably influence the latent heat flux (Q_e) and sensible heat flux (Q_h).

The k-means clustering was performed on sensible heat flux data distributed every $100 \text{ m} \times 100 \text{ m}$ in Seoul to derive the UTAs. The number of divided groups was derived from the natural break function of the sensible heat flux. The mean values of the sensible heat clusters were compared with those obtained from research on spatial typification based on heat flux [73] to distinguish the values as unfavourable and favourable.

2.4. Results of K-Means Clustering

The thermal areas that were grouped through k-means clustering are referred to as 'heat-concentrated regions'. Among these, the UTAs were identified as areas with sensible heat fluxes higher than the mean value in Seoul; similarly, the values of low sensible heat-concentrated regions, called FTAs, are lower than the mean value of the sensible heat flux in Seoul. In Figure 3, the reddish areas correspond to UTAs and the blue areas represent FTAs.



Figure 3. UTAs and FTAs.

We analysed the building composition and BCR in the UTAs and FTAs corresponding to residential areas. The UTAs are characterised by high building density with no green cover, while the FTAs are characterised by low building density and low population density of greenery or water (Figure 4). The verification of these areas is discussed in detail in Section 3.



wt : water, gr: green, bd: building, rd: road, im: impervious

Figure 4. Concepts of UTAs and FTAs.

3. Sensible Heat Flux Calculations

Since there is no dedicated equipment for measuring sensible heat flux, we estimated the heat flux using the existing models for calculating the energy budget by defining the relationships among the net radiation and the four heat fluxes. The energy budget is composed of four elements, namely, the anthropogenic heat flux (Q_F), sensible heat flux (Q_h), latent heat flux (Q_e), and storage heat flux (Q_s). The horizontal heat flux due to wind-borne transportation (ΔQ_A) was included in the energy budget at

a value of 0, because of the warm and mild wind conditions on the measurement day. The sensible heat flux was extracted from these four heat fluxes. The model for calculating the sensible heat flux using the net radiation (Q_n) is as follows [79–82]:

$$Q_n + Q_F = Q_h + Q_e + Q_s + \Delta Q_A. \tag{1}$$

The net radiation was derived from the urban energy balance in (1), which was derived by Offerle [79]. All of the heat fluxes have units of W/m^2 :

$$\Delta Q_S = \sum_{i=1}^{l} f_i \times (a_{1i}Q_n + a_{2i}\Delta Q_n + a_{3i})$$
⁽²⁾

f_i: land cover ratio (unit: ratio)

i: green cover, water cover, impervious land, building cover, and road cover $\frac{\gamma}{s} = -0.00003178 \times temp^3 + 0.03 \times temp^2 - 0.092 \times temp + 1.463$

The storage heat flux in (2) was derived from an equation considering the land cover ratio and empirical coefficients. γ is a psychrometric constant, and s is the slope of the curve of saturation vapour pressure versus temperature:

$$Q_h = \left[\frac{\left\{(1-\alpha) + \left(\frac{\gamma}{s}\right)\right\}}{\left\{1+\left(\frac{\gamma}{s}\right)\right\}}\right] \times (Q_n - \Delta Q_s) + 20$$
(3)

$$Q_e = \left[\frac{\alpha}{\left\{1 + \left(\frac{\gamma}{s}\right)\right\}}\right] \times (Q_n - \Delta Q_S) + 20$$
(4)

 α : an empircal parameter related to the moisture status of the surface

Both the sensible heat flux (3) and latent heat flux (4) were estimated using the model developed by Holtsalg [79]. In these equations, 20 (W/m²) is an empirical constant. Both α and 20 (W/m²) were determined based on the Penman Monteith approach [82]:

$$Q_F = 6.8 (T_C - T_d) + 12 (\text{for } T_d \le T_C)$$
(5)

where T_C : Daily maximum temperature (unit: K) and T_d : Daily mean temperature (unit: K)

The anthropogenic heat flux (5) was estimated using a model considering temperature. The advection (ΔQ_A) was negligible at the six investigated sites on the day of measurement because we chose a day with a wind speed of approximately 0 m/s.

The land cover ratio (f_i) was calculated using the relative area occupied by each type of land cover within a 100 m × 100 m grid (Tables 2 and 3).

Table 2. Empirical land cover coefficients.

Land Cover Coefficient	a_1 (Ratio)	<i>a</i> ₂ (h)	$a_3 (W/m^2)$
Green	0.34	0.31	-31
Building	0.07	0.06	-5
Impervious	0.83	0.4	-54.2
Water	0.5	0.21	-39.1
Road	0.61	0.41	-27.7

Source: Grimmond and Oke [83], Roberts and Oke [84].

Neighbourhood	LCZ	Anthropogenic Heat Flux (W/m ²)	Site
Large dense, city centre	1,2	100–1600 *	4
Medium dense, city centre	3	30-100 *	6
Low dense, open, low-rise	6	5-50 *	2
Open high-rise	4	26-80 **	1
Green (Low-planted), Water	D,G	-	3,5

Table 3. Anthropogenic heat flux at the neighbourhood scale.

Source: * Oke, Mills, Christen and Voogt [85]; ** Pigeon, G., et al. [81].

4. In-Situ Validation

In this section, we present the results of our examination of whether the UTA and FTA identification method can be applied to actual sites, considering the land cover rate (in particular, the BCR). The degree of sensible heat flux loss derived using the urban canyon structure can also be determined. Therefore, an empirical study was conducted to verify the accuracy of the classification method by dividing the study area based on sensible heat, which was done to develop methods that can help improve the thermal environment.

In the previous section, we presented the characterization of the disadvantageous thermal zones using low-rise buildings in residential areas with high BCR. We considered such residential areas and focused on heat transfer to estimate the UTAs and FTAs. Because no instrument has been developed to measure sensible heat, we estimated the sensible heat using a physical model based on the net radiant heat data measured by a sensor. Therefore, to validate the results of the in-situ measurements aimed at controlling the outdoor conditions during measurement, the following in-situ measurements were conducted:

- a BCR and net radiation time shift data
- b Time shifts with variations in BCR
- c Mixed-deployment observation of the overall effects of land coverage
- d Various urban climate data for calculating the sensible heat flux

Observations were made to obtain net radiation data to calculate the sensible heat flux under different land cover compositions, especially BCRs. In addition, we collected air temperature, wind speed, humidity, albedo, and sky view factor (SVF) data for sensible heat flux estimation (Equation (1), Section 4).

4.1. In-Situ Measurement Process (Appendix B)

4.1.1. Considerations for Measurement Design

According to the BCR values and measurement techniques reported previously [86], we designed a net radiation measurement technique. The observation sites were required to be in residential areas with mild wind speed, as the wind speed is often used as an independent variable when measuring heat flux. Wind speed causes surface turbulence; in addition, heat flux transfer can be determined by airflow. Furthermore, the heat flux incident on a space could be controlled by varying the relative humidity. When both the wind speed and humidity were controlled, the effects of other parameters on the energy budget could be determined. Because these two variables cannot be controlled easily, the measurement data were obtained by varying the BCR in areas under similar microclimate conditions.

4.1.2. Observation Site Selection

This study was focused on validating FTAs based on the influence of the BCR on the net radiation and sensible heat flux of a micro-scale urban area, by performing in-situ measurements in Seoul. Thus, we identified the study areas that were extracted as FTAs and UTAs and had continuous, similar densities and shapes of buildings in the neighbourhood. Moreover, we sought locations with high sensible heat flux (Q_h), UFA, and the place with low Q_h , which represented FTA. Therefore, areas with different land coverage included in the UTAs and FTAs in Seoul were selected as sites to measure the net radiation. Most residential and commercial complexes in Seoul have high BCRs. Among the residential complexes in Seoul, the six sites we chose have plane topography; further, permission was obtained from the resident committees prior to performing the measurements.

4.1.3. Measurements and Data Collection

The observations were conducted from May to June 2018. This date range was selected considering the availability of the location for measurement and the presence of favourable weather conditions, because cloudy weather is often observed from 9:00 to 19:00 in Seoul. The types of equipment used to obtain the measurements were as follows. The net radiation was collected using a CNR4 (Campbell Scientific, Inc., Logan, UT, USA; Figure 5, Table A1 in Appendix A) with two-directional sensors, where the upper sensor was used to collect the net radiation and the data were collected in a logger (CR1000, Campbell Scientific, Inc.). A thermometer, an anemometer, and loggers were used to measure and collect the air temperature and wind data (Figure 5). A camera with a fish-eye lens was used to determine the SVF. The measurements were performed when the mean wind speed was 0 m/s and temperature was 18–28 °C. The humidity was 55% (measured 7–10 m from the 12-story building). The data were collected from 9:00 to 18:00 in 1 min intervals. The times of sunrise and sunset in Seoul from May to June are 7:00 and 18:30, respectively. All instruments were deployed within 1 m from each building, and each instrument was elevated 1.2 m above the ground.



Figure 5. Observation instruments: (**a**) mobile net radiometer instrument kit, (**b**) anemometer, (**c**) thermometer (revised from Park, [87]), and (**d**) bi-directional radiation sensors (Kwon and Lee, [86]).

4.1.4. Context of the Study Sites

For the six sites mentioned earlier, net radiation measurements were performed to calculate the energy budget and air temperature, albedo, wind speed, and relative humidity data were collected on warm, sunny days.

According to the objective of obtaining in-situ measurements, residential areas in Seoul were divided into two categories: low density and high density (Figure 6). Most apartments are exposed concrete slab or brick structures and face south. The distances between the buildings and the instrument deployment locations were 3–36 m. The SVF of the complex for in-situ observation is 0.46–0.90, and the building heights are in the range of 7–40 m. Two open spaces exist: one offers a plain view with green land coverage and the other is a riparian area (Sites 3 and 5, Figure 7).



Seoul is located in South Korea, in the Asian continent, DMS latitude longitude coordinates for Seoul are 37°33'57.6"N, 126°58'42.24"E

Google Earth images

Figure 6. Sites: Sangdo (1), Daehak (2), Montmartre Park (3, Banpo), Yeoyido (4), Riverside Park (5), Shilim (6).



Figure 7. Street views of the study sites.

4.2. Limitations of the in-situ Measurement

The measurements are intended to show the influence of the BCR on the net radiation and sensible heat flux in the spaces around different densities of buildings [88]. However, because the study sites were residential areas, the residents did not readily allow us to obtain measurements because they think that vulnerability to heat directly impacts land and housing prices. Thus, the study was limited by the restricted number of observation locations and hours. Moreover, it was difficult to obtain reliable data owing to the frequent movement of the floating population in the study areas. Finally, the CNR4 (a net radiometer) is expensive and limited in number; thus, it was impossible to examine the multiple sites simultaneously.

To answer the research question posed at the beginning of the study, we performed validation by obtaining the sensible heat flux and comparing the results with those reported previously [73]. The sensible heat was estimated based on the in-situ measurements of the net radiation. The equations related to the estimation are addressed in Section 3. The residential areas of Sites 2, 4, and 6 have high densities (Table 4), and Sites 2 and 6 are low-rise residential areas. However, Site 4 is also a high-density building area but with high-rise quasi-residential units (Table 2). The building areas of Sites 1, 3, and 5 are low-density areas, and Site 1 is high-rise residential area including green land coverage. Site 3 is a neighbourhood park, and Site 5 is a riverside park located in a residential district. To collect net radiation and land cover data from the various locations, we deployed a mobile net radiometer instrument kit at six measuring stations (Sites 1–6; Figure 7, Table 2).

Table 4. Two types of sites (O: pertinent; X: NA).

Туре	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
High density	Х	0	Х	0	Х	0
Low density	Ο	Х	Ο	Х	Ο	Х

The four land cover ratios of Site 1 are evenly distributed, without water (Figure 8). Because Seoul has a high density of buildings, the building ratio is the highest among the five land cover ratios at Site 6 (0.73), Site 2 (0.60), Site 4 (0.52), and Site 1 (0.35), in sequence. As a neighbourhood park, Site 3 has the highest green cover ratio. Lastly, the water ratio is the h ighest at Site 5, the riverside.



Figure 8. Land cover ratios at six sites.

5. Validation Results: Comparison of Sensible Heat Fluxes from the Six Sites

The sensible heat fluxes at the six sites were compared, indicating that FTAs and UTAs are more likely to be validated in an urban landscape under the same microclimatic conditions. Therefore, we examined the changes in Q_h by classifying the measurement sites into high and low density areas using the spatial characteristics of the FTAs and UTAs in Seoul, Korea.

Site 1 is a low-density residential area with a neighbourhood garden: the Butterfly Garden. The maximum heat flux there is 357.97 W/m^2 , and the minimum is 52.19 W/m^2 . The average sensible heat flux at Site 1 is 269.13 W/m^2 (Figure 9a, Table 5). Site 2 is a high-density residential area composed of low-height buildings. The maximum heat flux there is 524.60 W/m^2 , and the minimum is 65.02 W/m^2 . The average sensible heat flux at Site 2 is 389.05 W/m^2 (Figure 9b, Table 5).

Site 3 is a neighbourhood park near a residential area. The maximum heat flux there is 123.12 W/m², and the minimum is -7.69 W/m². The average sensible heat flux at Site 3 is 83.39 W/m² (Figure 9c, Table 5). Site 4 is a high-density, quasi-residential area composed of high-rise buildings. The maximum heat flux there is 616.72 W/m², and the minimum is 165.50 W/m². The average sensible heat flux at Site 4 is 379.01 W/m² (Figure 9d, Table 5). Site 5 is a riverside park along the Han River, which is the main waterway in Seoul. The maximum heat flux there is 432.61 W/m², and the minimum is 32.61 W/m². The average sensible heat flux at Site 5 is 311.19 W/m² (Figure 9e, Table 5). Site 6 is a high-density residential area without green space. The maximum heat flux there is 595.07 W/m², and the minimum is 170.67 W/m². The average sensible heat flux at Site 6 is 444.06 W/m² (Figure 9f, Table 5).



Figure 9. Sensible heat flux versus time plots of the six sites. (**a**) Site 2: Daehak; (**b**) Site 6: Shilim; (**c**) Site 4: Yeoyi quasi-residential; (**d**) Site 1: Sangdo; (**e**) Site 3: Montmartre Park; (**f**) Site 5: Hangang riverside.

Site	Site 1		Site Site 1		Sit	te 2	Sit	e 3	Sit	e 4	Sit	te 5	Sit	te 6
Time	Qn	Q_h	Qn	Q_h	Qn	Q_h	Qn	Q_h	Qn	Q_h	Qn	Q_h		
Peak ± 0.5 (h) *	540	278	586	398	351	85	548	376	456	315	672	466		
After sunset **	168	89	184	124	52	6	256	174	96	85	323	222		

Table 5. Mean values of net radiation and sensible heat flux (W/m^2) .

* average values over an hour extending 30 min before and after the peak time; ** average values over an hour after sunset.

Besides the high-density residential areas, Site 6 (Shilim) exhibits the highest values of both Q_n (672 W/m²) and Q_h (466 W/m²) (please see Table 5). Site 6, which is a high-density residential area with low-rise buildings and minimal green cover, is the most suitable place to apply thermal environment improvement strategies in Seoul. The greatest temporal change in Q_n (456 W/m²) is evident at Site 5, a riverside area, but the most rapid temporal transition in Q_h is at Site 2, a dense residential area (398 – 124 = 274 W/m²). At Site 3, a green space, on the other hand, the heat flux changes moderately from the peak until sunset (85 – 6 = 79 W/m²).

The sensible heat values of the six sites exhibit parabolic trends (red dotted line: parabolic fit) similar to those of the net radiation, but with time shifts (Figure 9). Each measured site exhibits the highest Q_h value between 12:00 and 13:00 but has a different slope. The sites corresponding to high-density residential areas (Sites 2, 4, and 6) display higher slopes, and the heat values decrease rapidly between 100 W/m² and 200 W/m² after the peak points. However, at 16:00, the sensible heat

slope for Site 3 (a neighbourhood park) decreases more gradually than those of the other sites. The Q_h range of the high-density residential areas (50–600 W/m²) is higher than those of the non-high-density residential areas, including the low-density residential areas, green spaces, and waterfronts (–20 to 400 W/m²) (Figure 9). It is assumed that the wider space of the urban canyon receives active natural convection that transfers heat flux [89] from the buildings, ground, or surrounding environment into the air [90].

6. Discussion

Because of the rapid densification of cities and climate change, which are contrary to sustainability developments, summer heatwaves occur, and many means of reducing these heatwaves have been explored. Most previous research has been focused on blocking solar radiation to improve thermal comfort. However, in this study, we investigated whether the FTAs and UTAs determined spatially as presented in Section 2 correspond to those at the actual sites chosen. Therefore, our research was mainly focused on finding the appropriate thermal environmental conditions for residents by validating the spatial typification after determining the FTAs in summer.

We investigated the net radiation values of the sites representing FTAs and UTAs, with additional emphasis on the temporal shifts in the sensible heat flux; further, the heat fluxes of these different thermal environments were compared from the perspective of FTAs and UTAs, considering the BCR.

6.1. Spatiotemporal Shift in Sensible Heat Flux

We determined the effects of spatial and environmental factors on Q_h in Seoul by measuring the net radiation and calculating Q_h in residential areas located in urban canyons and green spaces. The temporal shifts in Q_h in the urban canyons were determined for two types of areas: high-density residential areas (Sites 2, 4, and 6) and low-density areas (Sites 1, 3, and 5).

The study areas were enlarged to examine the correlation between the sensible heat fluxes measured in-situ and those based on two types of areas broadly classified as FTAs and UTAs. The high-density residential areas (Sites 2, 4, and 6; UTAs) have higher sensible heat flux ranges, while the low-density residential areas (Sites 1, 3, and 5; FTAs) have lower ranges, because natural convection enables sensible heat flux transfer [89]. Further, green spaces increase the latent heat, thereby decreasing the sensible heat. By designing wider spaces between buildings and providing green spaces within a residential complex, the sensible heat flux can be decreased; therefore, green spaces should be considered in the layouts of residential areas.

The measurement equipment used in this study was located in the urban canyons 1.2 m above the ground; thus, the sensor readings may not adequately reflect the land cover conditions beyond the nearest buildings. Because this research was conducted in a limited number of areas, the net radiation trends in more places should be investigated to obtain more accurate results.

Firstly, the extent of the effects of the five land cover types on the sensible heat was observed to follow the sequence green area > road > building > impervious surface > water surface (Appendix D). Secondly, we found that green areas impact the sensible heat the most. However, Site 6 has the highest sensible heat flux (444 W/m²) with the lowest green surface ratio (0.02), and Site 3, with the highest green surface ratio (0.96), has the lowest sensible heat flux (82 W/m²) (Table 6). Thirdly, the gradients of the sensible heat flux trends for each site were examined, which reflect the shift rate ($\Delta y/\Delta x$) of Q_h . The change rates were found to follow the order Site 2 > Site 6 > Site 4 > Site 5 > Site 1 > Site 3. This order corresponds to that of daytime Q_h , except for the order of Sites 6 and 2. The reason that Site 6 has the greatest slope is that the higher buildings there cause slower cooling than at the other sites (nighttime Q_h) [91]. Fourthly, the sensible heat trend line was examined, and it was found that the greatest negative slope corresponds to a rapid decrease in heat flux. According to the relative effects of the land cover types, the order of green surface ratio effects on sensible heat the most. Moreover, the green coverage ratio follows the order Site 3 > Site 1 > Site 5 > Site 4 > Site 2 > Site 6. Based on comparison with the results in, the green areas promote low sensible heat flux, except at Sites 2 and 6.

In other words, green surfaces have the greatest effects on restricting heat flux among the various land cover types. Lastly, regression analysis between the building, green area, and impervious coverage ratios indicated that the sensible heat flux decreases by 4.9 W/m² when the green coverage increases by 1%. Because of the low correlation (Appendix D), the riverside site, Site 5, was excluded from the regression analysis.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
$Q_h \text{ day (W/m^2)}$	278	398	82	379	311	444
Q_h night (W/m ²)	89	124	6	174	85	222
$Q_n \operatorname{day}(W/m^2)$	540	586	351	548	456	673
Q_n night (W/m ²)	168	184	52	256	96	323
Trend line a	-10	-15,	-4,	-13	-12	-14
formula: y (Q _h) b	252	358	100	308	293	353
$=ax^2+bx+c$ c	-1213	-1692	-490	-1382	-1368	-1696
Green	0.23	0.06	0.96	0.08	0.17	0.02
Building	0.35	0.6	0.02	0.52	0	0.73
Impervious	0.22	0.14	0.01	0.15	0.06	0.1
Road	0.2	0.2	0.01	0.25	0.05	0.15
Water	0	0	0	0	0.72	0
Location	Sangdo	Daehak	Montmartre	Yeoyi	Riverside	Shilim
Aspect (land use)	Resid. * high-rise	Resid. * low-rise	Park	Quasi_Resi. **	Waterfront	Quasi_Resid. **

Table 6. Comprehensive results.

* Resid.: Residential district, ** Quasi Resid.: Quasi-residential district.

We found that the sites with high densities, low-rise residential buildings, and high percentages of impervious paved areas, Sites 2 and 6, have higher sensible heat fluxes than the site with high-rise residential buildings and green surfaces, Site 1. In these cases, the in-situ measurement results do correspond to the concept of UTA and FTA in residential areas (Figure 4, Table 6).

In this study, we found that focused sensible heat flux directly affects the urban thermal environment relative to the surface type and spatial conditions in an urban canyon [92]. The in-situ data agreed well with the thermal spatial typification results overall. Thus, net radiation measurement allows the proposal of new methods to locate areas in which the UHIE can be mitigated preferentially. Moreover, our study elucidates techniques for increasing energy efficiency by manipulating the spatial aspects and land cover types of overpopulated residential areas with high densities of buildings. Research on the temporal changes and energy budgets of low-density areas with green spaces will help urban planners develop microclimate-change adaptation methods.

We expect that these findings regarding the interactions among the green cover ratio, BCR, and sensible heat flux can contribute to rationalising landscape and architectural standards for the redevelopment of residential apartment complexes in megacities. However, to solve the heat problems in such apartment complexes, the role of green coverage, which reduces the sensible heat flux, is important. The development of high-density residential areas will require the establishment of guidelines for construction, considering the temporal changes in sensible heat in the canyon widths between buildings in residential areas. In addition, land use characteristics such as those of the terrestrial and surrounding environments affect the sensible heat flux variations and resulting trends.

6.2. Development of Thermally Sustainable Smart Cities

Criteria for ensuring energy sustainability [93] and micro-scale residential space comfort should be considered in detail for thermally sustainable smart city development projects. This approach will help promote the participation of residents [94] in developing smart, environmentally sustainable cities [21]. In particular, it is necessary to establish criteria to describe the thermal environment and spatial scale of the design of a city [95]. For this purpose, sustainable development perspectives are required and it is necessary to study these criteria to understand the limitations related to the use of space with awareness of the thermal vulnerability of the plan. In addition, the increase in the green

16 of 24

coverage rate is due to the reduction in UHIs in the case of smart urban planning, and this increase in green space also contributes to the enhancement of thermal comfort and resident welfare. Sustainable urban development also requires small-scale investigation of the function of green space in rendering ecosystem benefits to society [96], as a substantial part of it.

For energy sustainability, it is necessary to remove energy imbalances to promote the equality [97] and comfort of residents as a precondition for the development of smart cities. Based on the finding of this study, green designs and technologies for smart cities should be examined and a green digital charter for energy conservation and typification should be implemented. In particular, an integrated conceptual model that incorporates considerations other than environmental sustainability should be established, because environmental sustainability alone is insufficient for the construction of a suitable smart city framework.

7. Conclusions

The objective of this research is to examine the effectiveness of a spatial typification method in improving environmental conditions for the sustainable development of smart cities. Spatial types were identified for thermal environmental improvement considering heat flux and land cover, which influence the sensible heat flux, using empirical formulas instead of approaches using temperature [1]. The UTAs identified using this method are prioritised for heat reduction. Then, the spatial typification was verified through in-situ measurement of the net radiation in UTAs and FTAs at six research sites in which such areas were derived by thermal spatial typification. The k-means clustering method was applied to classify the values of three kinds of heat flux: latent, sensible, and storage heat, and a type of unfavourable urban thermal environment was defined to identify measures that would increase thermal comfort. The characteristics of each thermal environmental type are based on the land cover type. The ratios of impervious surfaces, roads, and buildings in UTAs are higher than those of FTAs (relatively comfortable thermal environments). For thermal environment improvement, the following measures are proposed to urban planners and designers based on the results of this study: (a) green surfaces promote sensible heat flux mitigation, (b) typification of thermal environment in terms of UTAs and FTAs by K-means clustering is effective, as verified by the in-situ measurements, and (c) expansion of the green space by 1% reduces the sensible heat flux by 4.9 W/m². Thus, heat can be mitigated and spatial thermal comfort can be improved in urban areas by performing thermal spatial typification.

Among the six study areas, the highest values of both Q_n and Q_h were observed at Site 6, which has a high density and low-rise buildings with less green cover. Therefore, areas with spatial properties similar to those of Site 6 are considered to be the most suitable places to implement thermal mitigation in Seoul. Site 5, which is a riverside park, had the best cooling effect owing to the fact that the maximum heat decrease was noted between the peak hour and 18:00. Site 2, which is a high density area with low-rise buildings, exhibited an abrupt temporal change in Q_h . Unlike Site 2, Site 3, which is a neighbourhood park, showed moderate changes from the peak hour to sunset. Therefore, green areas and waterside surfaces are significant for decreasing the sensible heat flux and net radiation.

The proposed approach will eventually lead to appropriate energy consumption, and sustainable energy policies will indirectly contribute to energy usage reduction in sustainable smart cities. By enabling sustainability to be maintained via improvement of the thermal spatial environment, this method will provide a valuable tool for the implementation of smart cities. This research is expected to facilitate the establishment of a minimum land cover rate criterion to improve urban thermal environments; in addition, a standard index for implementing thermal environmental improvement can be derived. The study results offer new insights that can be utilised to develop rational methods of thermal environment improvement. In future research related to sustainable techniques for mitigating daytime radiation during heat waves, appropriate areas with adequate green coverage could be investigated in depth to control the net radiation and sensible heat flux in residential areas. More advanced studies regarding naturally emitted surplus radiation could also be performed to enable the positive reuse of energy and to achieve community energy budget goals. In the future,

we expect to conduct radiation measurement research at additional sites to determine the influences of land cover factors on the net radiation over time.

In the future, the characteristics of FTAs that result in improved thermal environments should be reflected in residential areas considering the intrinsic culture. In environmental psychology, familiarity is related to place identity, which suggests that familiarity has a positive effect on the emotional stability of the citizens because it includes a unique culture and historical context [98,99]. An ideal smart city would improve the comfort of the citizens by maintaining the unique cultural identity of the place in their living environment. Thus, it is necessary to develop smart cities considering their inherent cultural identities, rather than developing such cities simply to improve quality of life [100].

To promote the development of sustainable smart cities, it is necessary to implement urban thermal environmental improvement plans and energy management policies to cope with climate change. Ultimately, smart cities, in which energy sustainability is emphasised, should be built based on a system of continuous spatial analysis and development accounting for the thermal environments and identities of the cities.

Author Contributions: Data curation, Y.J.K., K.L.; Conceptualization, Y.J.K.; Formal analysis, Y.J.K.; Funding acquisition, D.K.L.; Investigation, Y.J.K., K.L.; Methodology, Y.J.K., D.K.L.; Visualization, Y.J.K.; Supervision, D.K.L.; Writing—original draft, Y.J.K.; Writing—review & editing, D.K.L.

Funding: This research was funded by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant of the Ministry of Land, Infrastructure, and Transport (Grant 19AUDP-B102406-05).

Acknowledgments: This work was supported by the BK 21 Plus Project in 2018 (Seoul National University Interdisciplinary Program on Landscape Architecture, Global Leadership Program toward Innovative Green Infrastructure). We truly appreciate for helping designing a colorful plot who is one of the lab colleagues at SNU, Sangjin Park. Also, we appreciate the anonymous reviewers for their constructive suggestions and elaborate comments to improve the quality of this paper and also to the editors, Tan Yigitcanlar, Md. (Liton) Kamruzzaman, Hoon Han and Elaine Chen.

Conflicts of Interest: The authors declare no conflicts of interest. The funding bodies had no role in the design of the study; in the collection, analyses, and interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. CNR4 specifications of the pyranometer (details of CNR4, a net radiometer).

Pyranometer Specification	Value (unit)	Definition		
Sensing sensitivity	5–20 (µV/W/m ²)	Calibration factor		
Irradiance range	0–2000 (W/m ²)	Measurement range		
Net irradiance range	$-250 \text{ to } +250 \text{ (W/m}^2\text{)}$			
Shortwave radiation spectral range	300–2800 (nm)			
Longwave radiation spectral range	4500–430,000 (nm)			
Field of view	Upper detector: 180°, lower detector: 150°	Sensor opening angle		
Nonlinearity	Less than 1 (%)	0–1000 W/m ² irradiance—Max. deviation fro the responsivity at 500 W/m ² owing to chan in irradiance within the indicated range.		
Uncertainty in daily total	Less than 5 (95% confidence level)	Achievable uncertainty		
Temperature dependence of sensitivity	−10 to +40 (°C)			
Operating temperature	-40 to +80 (°C)			
Environmental	0–100% RH	Relative humidity		
Response time	less than 18 s	95% response		
Directional error	less than 20 (W/m ²)	Angles up to 80° with 1000 W/m ² Beam radiation–combined zenith and azimuth errors of 0–80° with a 1000 W/m ² beam		

Source: KIPP & ZONEN CNR4 Net Radiometer Instruction Manual.

Appendix **B**

The following flow chart shows our overall research process.



Figure A1. Overall research flow chart.

Appendix C



Figure A2. Automatic weather station locations.

We used weather data from 287 AWSs.

Appendix D

		C	orrelation	S			
		Q_h	gr	bd	im	water	rd
	Q_h	1.000	-0.727	0.593	0.209	-0.003	0.637
	gr	-0.727	1.000	-0.799	-0.443	0.048	-0.908
Degreen correlation	bd	0.593	-0.799	1.000	0.542	-0.610	0.898
rearson correlation	im	0.209	-0.443	0.542	1.000	-0.554	0.493
	water	-0.003	0.048	-0.610	-0.554	1.000	-0.357
	rd	0.637	-0.908	0.898	0.493	-0.357	1.000
	Q_h	-	0.000	0.000	0.000	0.439	0.000
	gr	0.000	-	0.000	0.000	0.003	0.000
Sig (1 tailed)	bd	0.000	0.000	-	0.000	0.000	0.000
Jig. (1-tailed)	im	0.000	0.000	0.000	-	0.000	0.000
	water	0.439	0.003	0.000	0.000	-	0.000
	rd	0.000	0.000	0.000	0.000	0.000	-
	Q_h	3240	3240	3240	3240	3240	3240
	gr	3240	3240	3240	3240	3240	3240
NT	bd	3240	3240	3240	3240	3240	3240
IN	im	3240	3240	3240	3240	3240	3240
	water	3240	3240	3240	3240	3240	3240
	rd	3240	3240	3240	3240	3240	3240

Table A2. Correlations of Sensible heat flux and five land covers.

The sensible heat (Q_h) has the highest correlation (-0.727) with green surfaces, among the five land cover factors, but green surfaces negatively affect Q_h . We found that the BCR and road cover are related to Q_h but that impervious surfaces and water cover are not, because the absolute ratios of impervious surfaces and water cover are equivalent to small portions of the overall land surface of Seoul.

References

- Stewart, I.D.; Oke, T.R. Local climate zones for urban temperature studies. *Bull. Am. Meteorol. Soc.* 2012, 93, 1879–1900. [CrossRef]
- 2. Oke, T.R. The temperature profile near the ground on calm clear nights. *Q. J. R. Meteorol. Soc.* **1970**, *96*, 14–23. [CrossRef]
- 3. Jochner, S.; Menzel, A. Urban phenological studies—Past, present, future. *Environ. Pollut.* **2015**, 203, 250–261. [CrossRef] [PubMed]
- 4. Arnfield, A.J. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.* **2003**, *23*, 1–26. [CrossRef]
- 5. Oke, T.R. The energetic basis of the urban heat island. Q. J. R. Meteorol. Soc. 1982, 108, 1–24. [CrossRef]
- 6. Res, C.; Pape, R.; Wundram, D.; Löffler, J. Modelling near-surface temperature conditions in high mountain environments: An appraisal. *Clim. Res.* **2009**, *39*, 99–109. [CrossRef]
- 7. Johansson, E.; Thorsson, S.; Emmanuel, R.; Krüger, E. Instruments and methods in outdoor thermal comfort studies—The need for standardization. *Urban Clim.* **2014**, *10*, 346–366. [CrossRef]
- 8. Gluch, R.; Quattrochi, D.A.; Luvall, J.C. A multi-scale approach to urban thermal analysis. *Remote Sens. Environ.* **2006**, *104*, 123–132. [CrossRef]
- Li, Y.Y.; Zhang, H.; Kainz, W. Monitoring patterns of urban heat islands of the fast-growing Shanghai metropolis, China: Using time-series of Landsat TM/ETM+ data. *Int. J. Appl. Earth Obs. Geoinf.* 2012, 19, 127–138. [CrossRef]
- 10. Mauree, D.; Blond, N.; Clappier, A. Multi-scale modeling of the urban meteorology: Integration of a new canopy model in the WRF model. *Urban Clim.* **2018**, *26*, 60–75. [CrossRef]
- 11. Liao, W.; Liu, X.; Wang, D.; Sheng, Y. The impact of energy consumption on the surface urban heat island in China's 32 major cities. *Remote Sens.* **2017**, *9*, 250. [CrossRef]
- 12. Ahmed Memon, R.; Leung, D.Y.; Chunho, L. A review on the generation, determination and mitigation of Urban Heat Island. *J. Environ. Sci.* **2008**, *20*, 120–128. [CrossRef]
- 13. Grimmond, S.U.E. Urbanization and global environmental change: Local effects of urban warming. *R. Geogr. Soc.* **2007**, *173*, 83–88. [CrossRef]
- 14. Cohen, J.E. Human Population: The Next Half Century. Science 2003, 302, 1172–1175. [CrossRef] [PubMed]
- 15. Dell, R. Energy storage—A key technology for global energy sustainability. J. Power Sources 2001, 100, 2–17. [CrossRef]
- Kondo, H.; Kikegawa, Y. Temperature Variation in the Urban Canopy with Anthropogenic Energy Use. In *Air Quality*; Rao, G.V., Raman, S., Singh, M.P., Eds.; Springer Basel AG: Basel, Switzerland, 2003; pp. 317–324. ISBN 9783764370053.
- 17. Narumi, D.; Kondo, A.; Shimoda, Y. Effects of anthropogenic heat release upon the urban climate in a Japanese megacity. *Environ. Res.* 2009, *109*, 421–431. [CrossRef] [PubMed]
- Huang, H.; Ooka, R.; Kato, S. Urban thermal environment measurements and numerical simulation for an actual complex urban area covering a large district heating and cooling system in summer. *Atmos. Environ.* 2005, *39*, 6362–6375. [CrossRef]
- 19. Angelidou, M. Smart city policies: A spatial approach. Cities 2014, 41, S3–S11. [CrossRef]
- 20. Grossi, G.; Pianezzi, D. Smart cities: Utopia or neoliberal ideology? Cities 2017, 69, 79-85. [CrossRef]
- 21. Fernandez-Anez, V.; Fernández-Güell, J.M.; Giffinger, R. Smart City implementation and discourses: An integrated conceptual model. The case of Vienna. *Cities* **2018**, *78*, 4–16. [CrossRef]
- 22. Baum, S.; Yigitcanlar, T.; Horton, S.; Velibeyoglu, K.; Gleeson, B. Knowledge Work(ers) in Urban Context. In *The Role of Community and Lifestyle in the Making of a Knowledge City*; Urban Research Program Griffith University: Brisbane, Australia, 2007; pp. 18–24, ISBN 9781921291012.
- 23. Yigitcanlar, T.; Kamruzzaman, M. Does smart city policy lead to sustainability of cities? *Land Use Policy* **2018**, 73, 49–58. [CrossRef]
- 24. Rodríguez-Pose, A.; Ketterer, T.D. Do local amenities affect the appeal of regions in europe for migrants? *J. Reg. Sci.* **2012**, *52*, 535–561. [CrossRef]
- 25. Deller, S.C.; Tsai, T.; Marcouiller, D.W.; English, D.B.K. The Role of Amenities and Quality of Life in Rural Economic Growth. *Am. J. Agric. Econ.* **2013**, *83*, 352–365. [CrossRef]

- 26. Howell, B.R.; Menguc, M.P.; Siegel, R. *Thermal Radiation Heat Transfer*, 6th ed.; CRC Press: Boca Raton, FL, USA, 2015; ISBN 9780429190599.
- 27. Sheth, J.; Sisodia, R. Feeling the heat-Part 1 and Part 2. Mark. Manag. 1995, 4, 8-23, 19-33.
- Stull, R.B. Chap 03: Heat. In *Meteorology for Scientists and Engineers*; Brooks/Cole: Belmont, CA, USA, 2015; pp. 53–86, ISBN 978-0-534-37214-9.
- 29. Zhuang, Q.; Wu, B.; Yan, N.; Zhu, W.; Xing, Q. A method for sensible heat flux model parameterization based on radiometric surface temperature and environmental factors without involving the parameter KB –1. *Int. J. Appl. Earth Obs. Geoinf.* **2016**, *47*, 50–59. [CrossRef]
- 30. Voogt, J.A.; Grimmond, C.S.B. Modeling Surface Sensible Heat Flux Using Surface Radiative Temperatures in a Simple Urban Area. *J. Appl. Meteorol.* **2010**, *39*, 1679–1699. [CrossRef]
- 31. Stern, N.; Taylor, C. Climate Change: Risk, Ethics, and the Stern Review. *Science* 2007, 317, 203–204. [CrossRef] [PubMed]
- 32. Grimm, N.B.; Faeth, S.H.; Golubiewski, N.E.; Redman, C.L.; Wu, J.; Bai, X.; Briggs, J.M. Global Change and the Ecology of Cities SUPPLEMENTARY. *Science* **2008**, *319*, 756–760. [CrossRef]
- 33. Ng, E.; Chen, L.; Wang, Y.; Yuan, C. A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Build. Environ.* **2012**, *47*, 256–271. [CrossRef]
- 34. Oliveira, S.; Andrade, H.; Vaz, T. The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. *Build. Environ.* **2011**, *46*, 2186–2194. [CrossRef]
- 35. Hamada, S.; Ohta, T. Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. *Urban For. Urban Green.* **2010**, *9*, 15–24. [CrossRef]
- 36. Wong, N.H.; Yu, C. Study of green areas and urban heat island in a tropical city. *Habitat Int.* **2005**, *29*, 547–558. [CrossRef]
- 37. Armson, D.; Stringer, P.; Ennos, A.R. The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban For. Urban Green.* **2012**, *11*, 245–255. [CrossRef]
- Monk, C.D.; Gabrielson, F.C. Effects of Shade, Litter and Root Competition on Old-Field Vegetation in South Carolina. *Bull. Torrey Bot. Club* 1985, 112, 383–392. [CrossRef]
- 39. Kobayashi, T.H.Y.; Nomoto, N. Effects of trampling and vegetation removal on species diversity and micro-environment under different shade conditions. *J. Veg. Sci.* **1997**, *8*, 873–880. [CrossRef]
- 40. Takebayashi, H.; Moriyama, M. Study on the urban heat island mitigation effect achieved by converting to grass-covered parking. *Sol. Energy* **2009**, *83*, 1211–1223. [CrossRef]
- 41. Onishi, A.; Cao, X.; Ito, T.; Shi, F.; Imura, H. Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban For. Urban Green.* **2010**, *9*, 323–332. [CrossRef]
- 42. Rowe, D.B.; Getter, K.L.; Durhman, A.K. Effect of green roof media depth on Crassulacean plant succession over seven years. *Landsc. Urban Plan.* **2012**, *104*, 310–319. [CrossRef]
- 43. Jim, C.Y.; Peng, L.L.H. Weather effect on thermal and energy performance of an extensive tropical green roof. *Urban For. Urban Green.* **2012**, *11*, 73–85. [CrossRef]
- 44. Peng, L.L.H.; Jim, C.Y. Green-roof effects on neighborhood microclimate and human thermal sensation. *Energies* **2013**, *6*, 598–618. [CrossRef]
- Maciel, C.D.R.; Kolokotroni, M.; Paulo, S. Cool Materials in the Urban Built Environment to Mitigate Heat Islands: Potential Consequences for Building Ventilation. Available online: http://bura.brunel.ac.uk/handle/ 2438/15309 (accessed on 14 May 2019).
- Santamouris, M.; Synnefa, A.; Karlessi, T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Sol. Energy* 2011, *85*, 3085–3102. [CrossRef]
- Hong, B.; Lin, B. Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement. *Renew. Energy* 2015, 73, 18–27. [CrossRef]
- 48. Gu, Z.L.; Zhang, Y.W.; Cheng, Y.; Lee, S.C. Effect of uneven building layout on air flow and pollutant dispersion in non-uniform street canyons. *Build. Environ.* **2011**, *46*, 2657–2665. [CrossRef]
- Blum, J. Contribution of Ecosystmes Servies to Air Quality and Climate Change Mitigation Policies: The Case of Urban Forests in Barcelona, Spain. In *Urban Forests*; Blum, J., Ed.; Apple Academic Press: New York, NY, USA, 2016; pp. 3–36, ISBN 9781315366081.

- Tran, D.X.; Pla, F.; Latorre-Carmona, P.; Myint, S.W.; Caetano, M.; Kieu, H.V. Characterizing the relationship between land use land cover change and land surface temperature. *ISPRS J. Photogramm. Remote Sens.* 2017, 124, 119–132. [CrossRef]
- Nayak, S.G.; Shrestha, S.; Kinney, P.L.; Ross, Z.; Sheridan, S.C.; Pantea, C.I.; Hsu, W.H.; Muscatiello, N.; Hwang, S.A. Development of a heat vulnerability index for New York State. *Public Health* 2018, 161, 127–137. [CrossRef] [PubMed]
- 52. Shahadat Hossain, M.; Kwei Lin, C. Land Use Zoning for Integrated Coastal Zone Management Remote Sensing, GIS and RRA Approach in Cox's Bazar Coast, Bangladesh. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.471.1264&rep=rep1&type=pdf (accessed on 14 May 2019).
- 53. Kim, S.; Ryu, Y. Describing the spatial patterns of heat vulnerability from urban design perspectives. *Int. J. Sustain. Dev. World Ecol.* **2015**, *22*, 189–200. [CrossRef]
- 54. Lunetta, R.S.; Knight, J.F.; Ediriwickrema, J.; Lyon, J.G.; Worthy, L.D. Land-cover change detection using multi-temporal MODIS NDVI data. *Remote Sens. Environ.* **2006**, *105*, 142–154. [CrossRef]
- 55. Pandey, P.K.; Soupir, M.L. A new method to estimate average hourly global solar radiation on the horizontal surface. *Atmos. Res.* **2012**, *114–115*, 83–90. [CrossRef]
- 56. Malys, L.; Musy, M.; Inard, C. Direct and indirect impacts of vegetation on building comfort: A comparative study of lawns, greenwalls and green roofs. *Energies* **2016**, *9*, 32. [CrossRef]
- 57. Weng, Q. Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *ISPRS J. Photogramm. Remote Sens.* **2009**, *64*, 335–344. [CrossRef]
- Zou, L.; Wang, L.; Li, J.; Lu, Y.; Gong, W.; Niu, Y. Global surface solar radiation and photovoltaic power from Coupled Model Intercomparison Project Phase 5 climate models. *J. Clean. Prod.* 2019, 224, 304–324. [CrossRef]
- 59. Yang, J.; Gong, P.; Fu, R.; Zhang, M.; Chen, J.; Liang, S.; Xu, B.; Shi, J.; Dickinson, R. The role of satellite remote sensing in climate change studies. *Nat. Clim. Chang.* **2013**, *3*, 875–883. [CrossRef]
- 60. Dousset, B.; Gourmelon, F. Satellite multi-sensor data analysis of urban surface temperatures and landcover. *ISPRS J. Photogramm. Remote Sens.* **2003**, *58*, 43–54. [CrossRef]
- Saha, S.K. Retrieval of Agrometeorological parameters using satellite data. In *Satellite Remote Sensing and GIS Applications in Meteorology*; Sivakumar, M.V.K., Roy, P.S., Harmsen, K., Saha, S.K., Eds.; World Meteorological Organisation: Geneva, Switzerland, 2004; pp. 175–194, ISBN 978-0-415-40166-1.
- 62. Crank, P.J.; Sailor, D.J.; Ban-Weiss, G.; Taleghani, M. Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Clim.* **2018**, *26*, 188–197. [CrossRef]
- 63. Simon, H.; Lindén, J.; Hoffmann, D.; Braun, P.; Bruse, M.; Esper, J. Modeling transpiration and leaf temperature of urban trees—A case study evaluating the microclimate model ENVI-met against measurement data. *Landsc. Urban Plan.* **2018**, *174*, 33–40. [CrossRef]
- Tsoka, S.; Tsikaloudaki, A.; Theodosiou, T. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications—A review. *Sustain. Cities Soc.* 2018, 43, 55–76. [CrossRef]
- 65. Sentelhas, P.C.; Alvares, C.A.; Stape, J.L.; Sparovek, G.; de Moraes Gonçalves, J.L. Köppen's climate classification map for Brazil. *Meteorol. Z.* **2014**, *22*, 711–728.
- 66. Guo, X.; Coops, N.C.; Tompalski, P.; Nielsen, S.E.; Bater, C.W.; John Stadt, J. Regional mapping of vegetation structure for biodiversity monitoring using airborne lidar data. *Ecol. Inform.* **2017**, *38*, 50–61. [CrossRef]
- 67. Lechner, A.M.; Baumgartl, T.; Matthew, P.; Glenn, V. The Impact of Underground Longwall Mining on Prime Agricultural Land: A Review and Research Agenda. *Land Degrad. Dev.* **2016**, *27*, 1650–1663. [CrossRef]
- 68. Mcmanamay, R.A.; Bevelhimer, M.S.; Kao, S.C. Updating the US hydrologic classification: An approach to clustering and stratifying ecohydrologic data. *Ecohydrology* **2014**, *7*, 903–926. [CrossRef]
- 69. Jain, A.K. Data clustering: 50 years beyond K-means. Pattern Recognit. Lett. 2010, 31, 651–666. [CrossRef]
- 70. Janssens, F.; Glänzel, W.; De Moor, B. A hybrid mapping of information science. *Scientometrics* **2008**, 75, 607–631. [CrossRef]
- 71. Ma, E.; Deng, X.; Zhang, Q.; Liu, A. Spatial variation of surface energy fluxes due to land use changes across China. *Energies* **2014**, *7*, 2194–2206. [CrossRef]
- Lindberg, F.; Grimmond, C.S.B. The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: Model development and evaluation. *Theor. Appl. Climatol.* 2011, 105, 311–323. [CrossRef]

- 73. Kwon, Y.J.; Ahn, S.; Lee, D.K.; Yoon, E.J.; Sung, S.; Lee, K. Spatial Typification based on Heat Balance for Improving Thermal Environment in Seoul. *J. Korea Plan. Assoc.* **2018**, *53*, 109–126. [CrossRef]
- 74. Parsons, K. Thermal Models. In *Human Thermal Environments*; Parsons, K., Ed.; CRC Press: Boca Raton, FL, USA, 2002; pp. 161–186. ISBN 978-1-4665-9600-9.
- 75. Mohajerani, A.; Bakaric, J.; Jeffrey-Bailey, T. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *J. Environ. Manag.* **2017**, 197, 522–538. [CrossRef]
- 76. Choi, H.-J.; Lee, H.-W.; Sung, K.-H. Air Quality Modeling of Ozone Concentration According to the Roughness Length on the Complex Terrain. *J. Korean Soc. Atmos. Environ.* **2011**, 23, 430–439. [CrossRef]
- 77. Miller, H.J. Tobler's First Law and Spatial Analysis. Ann. Assoc. Am. Geogr. 2004, 94, 284–289. [CrossRef]
- 78. Janssens, W.; Wijnen, K.; De Pelsmacker, P.; Kenhove, P. Van Cluster analysis. In *Marketing Research with SPSS*; Janssens, W., Ed.; Pearson Education: London, UK, 2008; pp. 319–362, ISBN 9780273703839.
- 79. Offerle, B.; Grimmond, C.S.B.; Fortuniak, K. Heat storage and anthropogenic heat flux in relation to the energy balance of a central European city centre. *Int. J. Climatol.* **2005**, *25*, 1405–1419. [CrossRef]
- 80. Holtslag, A.A.M.; Van Ulden, A.P. A Simple Scheme for Daytime Estimates of the Surface Fluxes from Routine Weather Data. *J. Clim. Appl. Meteorol.* **1983**, 22, 517–529. [CrossRef]
- 81. Pigeon, G.; Legain, D.; Durand, P.; Masson, V. Anthropogenic heat release in an old European agglomeration_Toulouse, France. *R. Meteorol. Soc.* **2007**, *27*, 1969–1981. [CrossRef]
- 82. Ng, Y. A Study of Urban Heat Island using "Local Climate Zones"—The Case of Singapore. *Br. J. Environ. Clim. Chang.* **2015**, *5*, 116–133. [CrossRef] [PubMed]
- Grimmond, C.S.B.; Cleugh, H.A.; Oke, T.R. an Objective Urban Heat Storage Model and Its. *Atmos. Environ.* 1991, 25, 311–326. [CrossRef]
- 84. Roberts, S.M.; Oke, T.R.; Grimmond, C.S.B.; Voogt, J.A. Comparison of four methods to estimate urban heat storage. *J. Appl. Meteorol. Climatol.* **2006**, *45*, 1766–1781. [CrossRef]
- 85. Grimmond, C.S.B.; Roth, M.; Oke, T.R.; Au, Y.C.; Best, M.; Betts, R.; Carmichael, G.; Cleugh, H.; Dabberdt, W.; Emmanuel, R.; et al. Climate and more sustainable cities: Climate information for improved planning and management of cities (Producers/Capabilities Perspective). *Procedia Environ. Sci.* **2010**, *1*, 247–274. [CrossRef]
- Kwon, Y.J.; Lee, D.K. Thermal Comfort and Longwave Radiation over Time in Urban Residential Complexes. Sustainability 2019, 11, 2251. [CrossRef]
- 87. Park, C.Y.; Lee, D.K.; Asawa, T.; Murakami, A.; Kim, H.G.; Lee, M.K.; Lee, H.S. Influence of urban form on the cooling effect of a small urban river. *Landsc. Urban Plan.* **2019**, *183*, 26–35. [CrossRef]
- 88. Hart, M.A.; Sailor, D.J. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theor. Appl. Climatol.* **2009**, *95*, 397–406. [CrossRef]
- Cengel, Y.; Ghajar, A. Introduction and Basic Concepts. In *Heat and Mass Transfer: Fundamentals and Applications Chapter 16: Heating and Cooling of Buildings*; Francis, C.P., Ed.; McGraw Hill: New York, NY, USA, 2015; pp. 1–60, ISBN 978-0-07-339818-1.
- 90. Taleghani, M.; Kleerekoper, L.; Tenpierik, M.; Van Den Dobbelsteen, A. Outdoor thermal comfort within five different urban forms in the Netherlands. *Build. Environ.* **2015**, *83*, 65–78. [CrossRef]
- 91. Nichol, J. Remote sensing of urban heat islands by day and night. *Photogramm. Eng. Remote Sensing* **2005**, 71, 613–621. [CrossRef]
- 92. Vallati, A.; Mauri, L.; Colucci, C.; Ocłoń, P. Effects of radiative exchange in an urban canyon on building surfaces' loads and temperatures. *Energy Build*. **2017**, *149*, 260–271. [CrossRef]
- Kramers, A.; Höjer, M.; Lövehagen, N.; Wangel, J. Smart sustainable cities—Exploring ICT solutions for reduced energy use in cities. *Environ. Model. Softw.* 2014, 56, 52–62. [CrossRef]
- 94. Granier, B.; Kudo, H. How are citizens involved in smart cities? Analysing citizen participation in Japanese "smart Communities". *Inf. Polity* **2016**, *21*, 61–76. [CrossRef]
- 95. Punter, J. Developing urban design as public policy: Best practice principles for design review and development management. *J. Urban Des.* **2007**, *12*, 167–202. [CrossRef]
- Fisher, B.; Turner, R.K.; Morling, P. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* 2009, *68*, 643–653. [CrossRef]
- 97. Bouzarovski, S.; Simcock, N. Spatializing energy justice. Energy Policy 2017, 107, 640–648. [CrossRef]
- 98. Ujang, N. *Place Attachment, Familiarity and Sustainability of Urban Place;* Department of Landscape Architecture, Faculty of Design and Architecture, University Putra Malaysia: Seri Kembangan, Malaysia, 2008; p. 10.

- 99. Ujang, N. Place Attachment and Continuity of Urban Place Identity. *Procedia Soc. Behav. Sci.* **2012**, 156–167. [CrossRef]
- Han, H.; Hawken, S. Introduction: Innovation and identity in next-generation smart cities. *City Cult. Soc.* 2018, 12, 1–4. [CrossRef]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).