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Article

The Contribution of Urban Morphology to the Formation of the Microclimate in Compact Urban Cores: A Study in the City Center of Thessaloniki

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Abstract: The purpose of this paper is to investigate the contribution of urban morphology to the formation of microclimatic conditions prevailing within urban outdoor spaces. We studied the compact form of a city and examined, at a detailed, street plan level, elements related to air temperature, urban ventilation, and the individual's thermal comfort. All elements examined are directly affected by both the urban form and the availability of open and green spaces. The field study took place in a typical compact urban fabric of an old city center, the city center of Thessaloniki, where we investigated the relationship between urban morphology and microclimate. Urban morphology was gauged by examining the detailed street plan, along with the local building patterns. We used a simulation method based on the ENVI-met© software. The findings of the field study highlight the fact that the street layout, the urban canyon, and the open and green spaces in a compact urban form contribute decisively both to the creation of the microclimatic conditions and to the influence of the bioclimatic parameters.

Keywords: compact urban form; open and green spaces; urban canyons; urban ventilation; thermal comfort

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1. Introduction

Intense urbanization contributes to dramatic changes in built-up areas: changes in urban densities, land use, and land cover. As a result of these changes, very high temperatures are recorded in the urban environment. These high temperatures are related to controlled factors (such as urban design) and uncontrolled factors (such as meteorological parameters and environmental conditions) [1–3]. It has long been acknowledged that cities face multiple problems related to the variety of microclimates that prevail within the various urban open spaces. In general, the parameters of the urban climate are the result of human interventions, with the most influential of these being how cities have been designed, developed, and built and the activities they host [4–7].

The environmental, or bioclimatic, approach to urban design is based on an understanding of the characteristics of the urban microclimate [8–11]. The microclimate refers to the climatic conditions prevailing in the cities, mainly as a result of the form of the urban fabric. Specific forms of urban fabric are determined by land-use planning and urban design and, of course, by the activities of people within this physical form of urban development [4]. Therefore, the microclimate is impacted by human interventions in the built environment, which often leads to unintended climatic conditions, localized within small enclaves of the urban fabric [5,6,12].

The urban microclimate describes the climatic conditions prevailing within any urban locality, such as a neighborhood, a square, etc. The climatic conditions prevailing within this locality usually differ significantly from the climatic conditions of the wider region. Both morphology and the activities within cities can cause changes in the atmospheric and surface properties of the affected areas, disturbances in the thermal equilibrium, the airflows, the inflow of solar radiation, etc. [7]. It is also worth noting that significant differences in air temperature, wind speed, solar radiation, etc., are often observed between the different localities within the urban fabric, even when there is a very short distance between them. This is due to the different spatial configurations of urban morphology including orientation, height to width ratio, and other factors such as the presence of vegetation [1,13].

Urban morphology largely determines airflow (ventilation), the inflow of solar radiation, shading, etc. Therefore, it is responsible for the variation in climatic conditions across different localities within the city [7,14–16]. Characterized as either a “lose” or a “compact” urban form, a locality’s either “scattered” or “cohesive” building complex affects the spatial distribution of the built-up areas, which in turn, causes the commensurate variation in airflow, solar radiation, etc. [17,18]. The ratio “envelope surface-to-volume” (S/V) and the ratio “building height-to-width outdoor space” (H/W) are two basic indicators of the spatial distribution of the built-up area, both of which directly affect the microclimate. The S/V factor expresses the degree of coherence of the building volume. In contrast, H/W expresses the degree of “openness”, i.e., the relationship of the building size to the surrounding outdoor spaces, which can be described by the sky view factor (SVF). SVF is a measure of the solid angle of view of the sky as seen from an urban space [16]. It is directly related to the phenomenon of urban heat island (UHI) [7,16,19] and temperature variations across different urban environments. If the value of this factor is equal to 1, it means that there is a complete view of the sky. Consequently, temperatures tend to be in line with predicted meteorological values, while if the value is 0, the sky view is blocked, and the temperatures are affected by the urban environment [16,19].

The compact urban form is characterized by a small S/V ratio, a large H/W ratio, reduced sky openings (SVF), and large amounts of land occupied by built-up areas. It is structured in cohesive building blocks that ”protect” roads and open spaces. As a result, compact urban forms are presenting difficulties in exploiting the winter sun due to increased shadows and the different orientations of each side of the building blocks. In addition, high urban densities help to shade the surfaces of urban canyons and reduce solar radiation absorption, trapping long-wave radiation emitted from the ground and building surfaces at night, thus preventing cooling. In contrast, loose urban forms are characterized by a large S/V and small H/W ratio, less ground covered by buildings, wider outdoor spaces, and a lower density of a building volume [1,18–21].

The H/W ratio directly affects the urban microclimate as it affects the inflow of solar radiation into the urban canyon, wind flows, and the trapping of radiation emitted by materials. Additionally, the building volumes, the shading, and the form of the openings of the buildings affect the configuration of the microclimate [15]. Different H/W ratios have different effects on individual environmental parameters. For example, a high H/W ratio may mean low to moderate winter solar gains, moderate or high exposure to the summer sun, high trapping of sunlight with reflections, high obstruction of air movement, and the low to moderate available area for tree planting [18]. On the other hand, a low ratio means large solar gains, low exposure to the summer sun, low to moderate trapping of sunlight with reflections, low to moderate obstruction of air movement, and large available area for tree planting [18]. Therefore, it is not easy to achieve an optimal H/W rate that corresponds to all the case-by-case parameters.

The phenomenon of UHI is directly related to the climate prevailing within urban areas as it significantly affects the formation of the urban microclimate [22]. This phenomenon is reflected in the microclimatic changes caused by anthropogenic interventions in the urban environment [23]. These changes can be attributed to multiple factors such as urban morphology, discarded heat, properties of building materials, and insufficient presence of free spaces, green spaces, and water surfaces [4,7,23–26]. Regarding the relationship between urban geometry and the phenomenon of UHI, according to Emmanuel and

Johansson [27] and Oke [19,28], the intensity of the UHI phenomenon increases as the H/W ratio increases.

In addition to the above, more than a quarter of compact urban areas are generally covered by a network of roads, the design of which has a significant effect on the urban climate. Urban roads differ geometrically, as they are defined not only by the height/width (H/W) and length/width (L/W) ratios but also by the orientation of their axes. These parameters directly affect the absorption and emission of solar radiation, as well as the ventilation of the urban environment, resulting in significant temperature variations [29,30]. Different climatic conditions are observed on the roads with different orientations (East-West or North-South). The E-W roads are the least thermally comfortable roads, as they shade in winter and "sunbathe" in summer. Conversely, the N-S roads are considered to be thermally comfortable as they are exposed to the sun's rays in winter, while in summer, they are sufficiently shaded in the morning and evening hours. Finally, roads with a northeast/southwest (NE–SW) and a northwest/southeast (NW- SE) orientation lie somewhere in between these two poles of thermal comfort, being partially sunny in summer and partially shaded in winter [31–33].

Apart from the urban form, which mainly concerns the built environment, green and tree-planted areas that affect the urban climate usually have a positive impact on thermal comfort. More specifically, urban greenery affects the microclimate by absorbing a high percentage of solar radiation, reducing air temperature through transpiration, reducing air speed near the ground, etc. [34,35]. Tree planting, in particular, has a significant impact on the reduction of urban temperatures, and it is an effective strategy for reducing the effect of the UHI phenomenon, improving the air quality, and creating conditions that cause a reduction in temperature [36–38]. Bowler et al. [39] pointed out that data from different studies suggested that, on average, an urban park would be around 1 °C cooler than a non-green site. However, this phenomenon, often referred to as "urban oasis", is also affected by other parameters such as local climatic conditions, the degree of tree cover, and tree types. [39–41].

Finally, special mention should be made of wind and urban air ventilation issues as they are important factors in improving the microclimate and achieving thermal comfort in outdoor urban areas [16]. Givoni [4] stated that the flow of wind in the urban environment changes more than any other climatic element. The wind speed in cities changes significantly over relatively short distances and within relatively short time intervals, creating gusts of wind, which are perceived as sharp increases in speed [7,42]. Modern compact urban environments, whose form consists of accumulated buildings of different heights, experience a phenomenon in which the tallest buildings break the flow of strong winds and often divert them to the axis of the roads, resulting in their ventilation [43].

The present paper examines the microclimatic conditions within a typical urban compact form, focusing on an area within the historical and commercial center of the city of Thessaloniki. Further, it evaluates the contribution of urban morphology to and the effect of open spaces and greenery on such compact forms, examining how the specific parameters of urban morphology contribute to the formation of specific microclimatic conditions.

2. Materials and Methods

2.1. Field Study Methodology, Characteristics of the Study Area, and Typology of the Building Blocks

The overall methodological framework of the present paper follows the diagram in Figure 1, which summarizes all the controlled factors related to urban morphology impacting the formation of the microclimate.

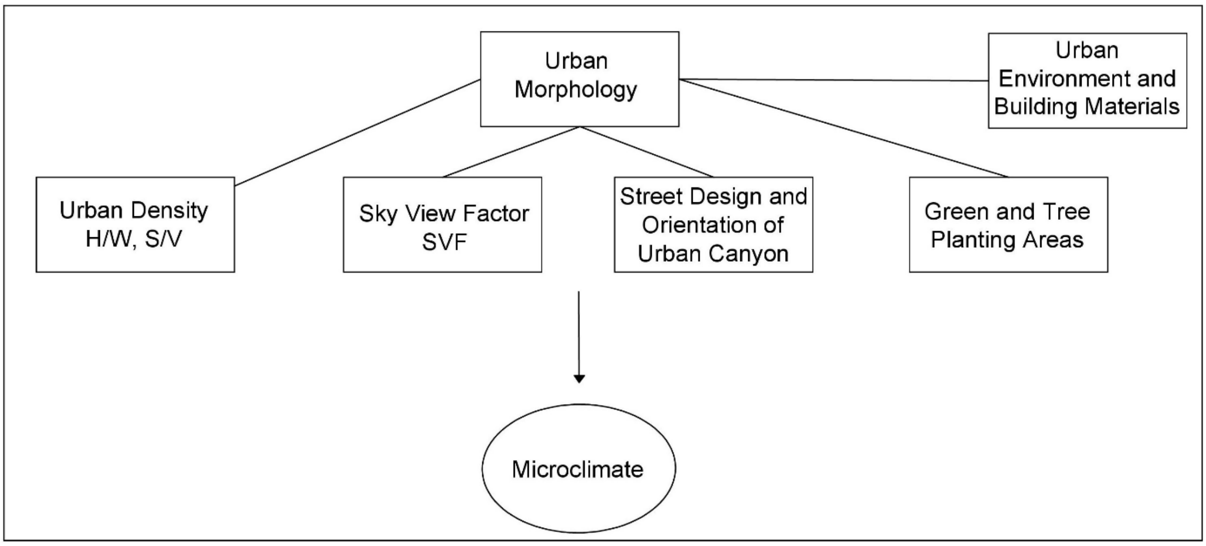


Figure 1. Controlled factors related to urban morphology and influencing the formation of the microclimate.

The field research focused on an area within the city center. To facilitate comparison, the area that was selected included two sections with certain crucial differences regarding the availability of open and green spaces. Section A represents a typical morphological structure within the city, characterized by a complete lack of open and green spaces. Section B differs from the first in that, apart from the compact built-up structure, it also contains urban "openings" such as open spaces and green parklets.

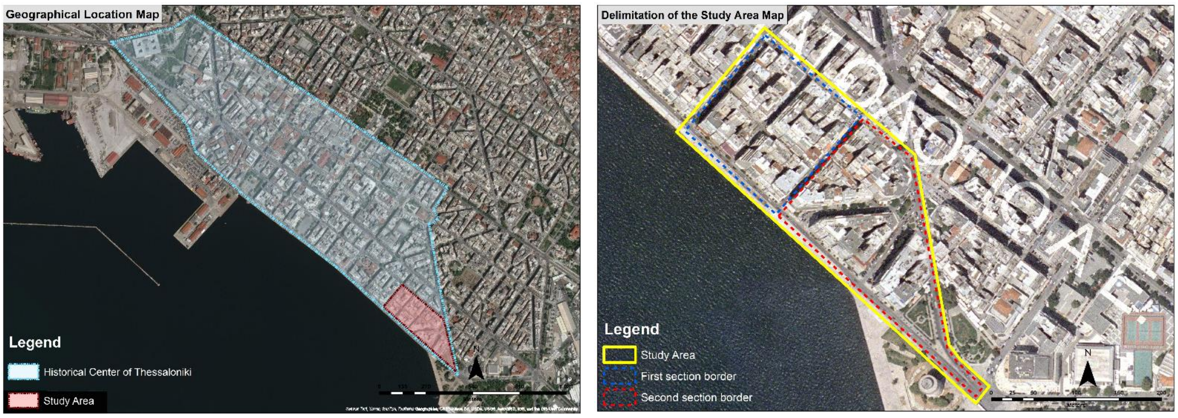
Field study methodology adhered to the following procedure. First, a detailed analysis of the urban characteristics of the study area was carried out, paying close attention to the spatial differences between the two sections of the study area. More specifically, this analysis included data concerning the height of the buildings and the width of the urban canyon, which was then used to calculate the H/W ratio of different/formations within the two areas. In addition, an urban assessment was carried out regarding land uses, the relationship between the built and unbuilt/open space, the orientation of the urban canyons, and the amount of green cultivation—a crucial parameter.

The second step was recording a typology of the built areas within each of the sections and the calculation of their main geometric characteristics, such as the height of buildings and the width of the urban canyon. These findings were then used to classify urban canyons, categorizing them according to airflow regime.

The final step was using ENVI-met© software (version 4.4.3) to simulate the microclimatic conditions prevailing in both sections of the study area. Using this simulation, we estimated the air temperature, the wind speed, and the average expected thermal index predicted mean vote (PMV) in order to gain a detailed understanding of the variations in the microclimatic phenomena and their links to the urban morphology.

2.2. *Analysis of the Urban Characteristics*

The study area consisted of 8 building blocks and covered a total area of 50,753 sq.m. This area is located on the south-eastern edge of the main historical and commercial center of Thessaloniki in immediate proximity to the seafront (Figure 2).



(**a**) (**b**)

Figure 2. (**a**) The study area and the historic and commercial center of Thessaloniki; (**b**) Delimitation of the study area and the individual sections, ArcGIS software (basemap: orthophoto Cadastral SA).

The study area is a typical mixed-use area, within the center of an old Mediterranean city [44]. This area has high residential densities and is characterized by apartment buildings of 7 to 8 stories. These have a variety of uses, with retail, cafes, restaurants, and other businesses on the ground floors and offices on the upper floors of the apartment buildings. The field record showed that retail is the dominant use of the ground floors with recreation (cafés, bars, etc.) being the next most frequent use (Figure 3a).

Limited public, open, and green spaces are the norm. It is worth mentioning here that, in general, in the compact part of the city of Thessaloniki, an important feature in terms of the formation of the urban microclimate is the low percentage of green spaces—among the lowest in European cities. This lack of open and green spaces in a very compactly built-up city with high population densities intensifies the phenomenon of UHI [45]. The uncovered spaces within the building blocks are also limited, and therefore, the built-up space prevails over the unstructured space within the building blocks (Figure 3b). The 8 building blocks within the study area contain 86 buildings, with heights ranging from 17 to 38 m. With an average height of about 31.5 m. (Figure 4a,b).

Regarding urban canyons, their width varies from 8.6 m (i.e., narrow urban canyons) to 24 m (i.e., wider urban canyons), depending on the road in question (Figure 5a,b). The orientation of urban canyons is mainly NE-SW or NW-SE (Figure 3c), where the roads with this orientation are partially shaded in winter and partially sunny in summer [18]. Following the street layout that pertains to the wider area of the city center, the study area has several roads perpendicular to the sea, facilitating the ventilation of the urban space. However, there are also some parts where the location of the buildings and the orientation of the roads create obstacles to airflow, resulting in insufficient ventilation and higher temperatures.

Furthermore, although the area is characterized by the insufficient presence of open and green spaces, it has a sufficient number of large trees planted along its streets, especially in the narrowest urban canyons. However, insufficient tree planting is recorded along the coastal road Avenue Nikis where there are only a few small trees with sparse foliage. In combination with seafront "glare", this absence of tree shading creates a feeling of intense thermal stress (Figure 3d).

Table 1 summarizes the urban characteristics of the study area.

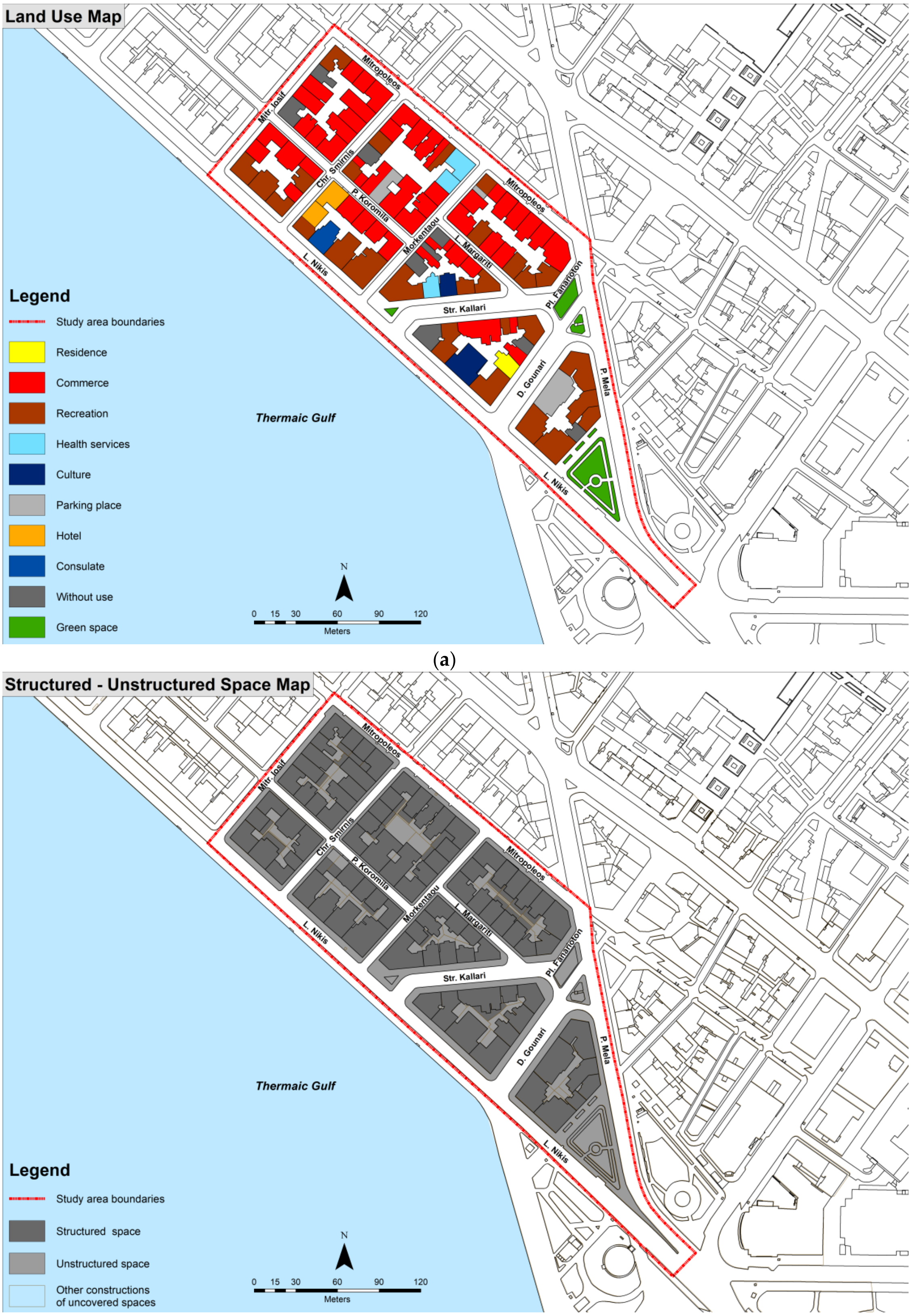
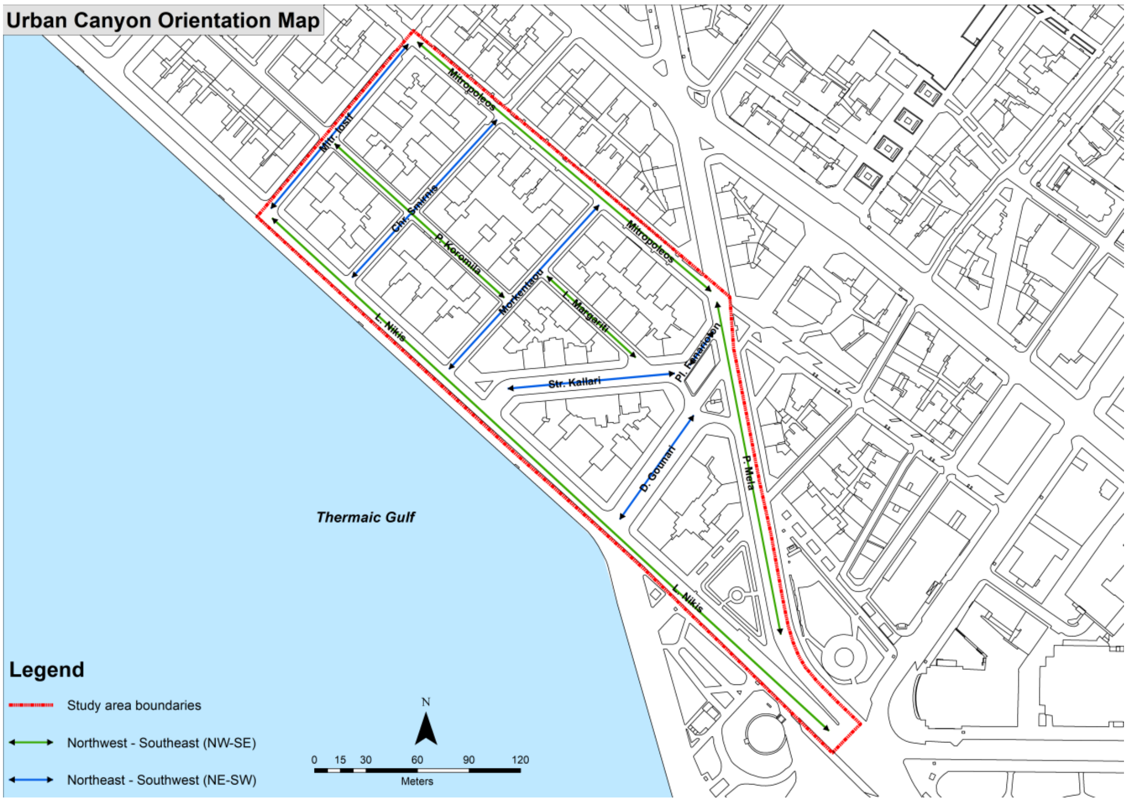


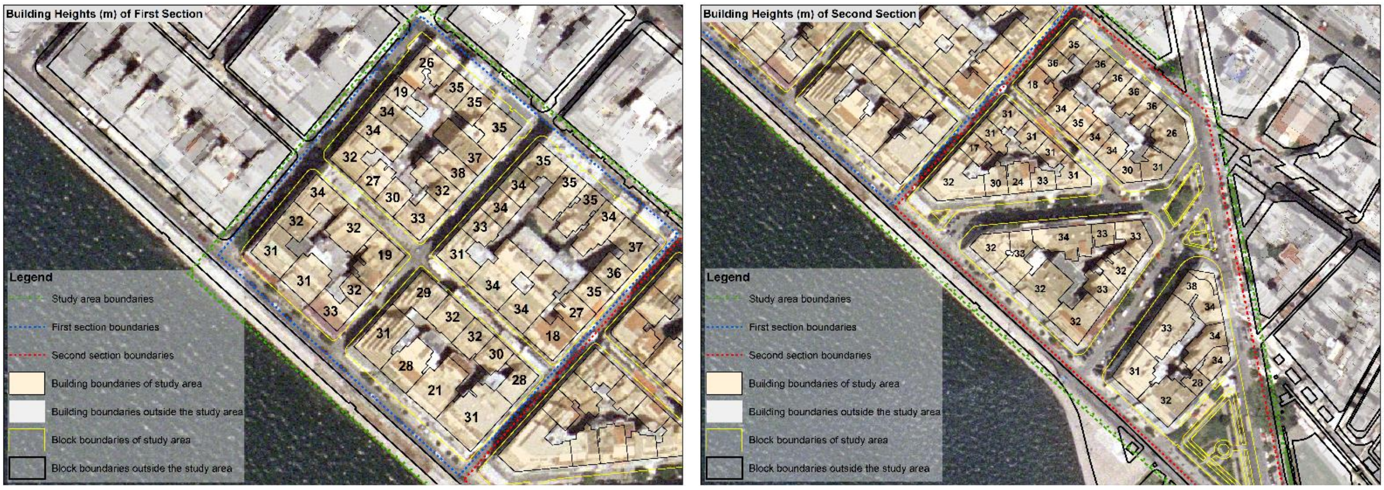
Figure 3. *Cont.*



(c)

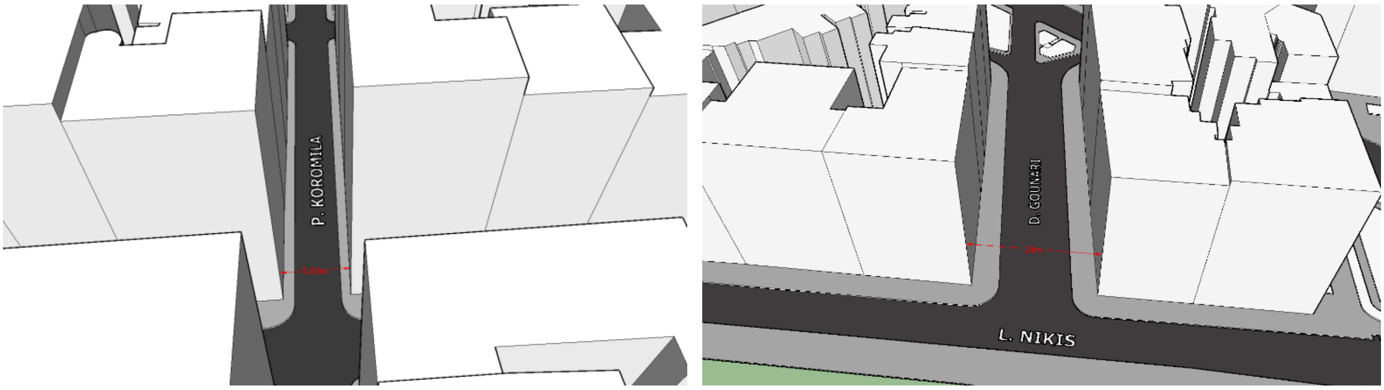
(d)

Figure 3. (**a**) Land-use map; (**b**) Structured—unstructured space (within each building block) map; (**c**) Urban canyon orientation map; (**d**) Green space and tree planting map, ArcGIS software.



(**a**) (**b**)

Figure 4. (**a**) Building heights (in meters) of the first section; (**b**) Building heights (in meters) of the second section (the numbers from the heights have been rounded), ArcGIS software (basemap: orthophoto Cadastral SA).



(**a**) (**b**)

Figure 5. (**a**) Urban canyon with large width (Dim. Gounari street: 24 m.) which represents a wide urban gorge; (**b**) Urban canyon with very small width (P. Koromila street: 8.6 m.) which represents a narrow urban gorge, SketchUp software.

2.3. *Typology of the Building Blocks and Initial Findings for the Microclimate Conditions*

An analytical, quantitative typology of the study area building blocks was carried out to record their main characteristics. These last included calculating the geometric characteristics (ratio H/W) of the streets' urban canyons and their categorization into three different categories of airflow regime. Thus, we were able to investigate ventilation and other elements that shape the microclimate (Figures 6 and 7). In addition, we examined whether the actual development strictly followed the official building regulations or whether it contravened these regulations. According to the official urban plan of the area, the coverage ratio should not exceed 60% of a plot's area, and the highest building ratio (i.e., the figure which, when multiplied by the m^2 of a plot, gives the total m^2 that are allowed to be built in the plot) is defined as 4.8 [46]. The latter is a recurrent issue in the city development patterns. Here, it should be borne in mind that creating the urban space is a complex process, one which does not always precisely follow the specific geometric rules that result from the application of the official land-use planning legislation.

Table 1. Analysis of urban characteristics of the study area.

Analysis of Urban Characteristics of the Study Area	Location	Southeastern end of the historic center of Thessaloniki
	Area of study area and individual sections	Total: 50,753 sq.m. Section A: 20,297 sq.m. Section B: 30,456 sq.m.
	Morphological characteristics	Compact city with strong residential development
	Average percentage of green areas for the municipality of Thessaloniki	2.7 sq.m. per inhabitant
	Free spaces—green spaces	Lack of free space—green spaces, adequate tree planting
	Construction rules	Building ratio: 4.8; coverage ratio: 60%
	Building construction system	Continuous
	Land use	Urban center
	Relationship of structured—unstructured space	Problematic predominance of the structured
	Building height	Ranging from 17 to 38 m. Average height: 31.5 m.
	Road width	8.6–24 m.
	Orientation of urban canyon	NE-SW or SW-SE

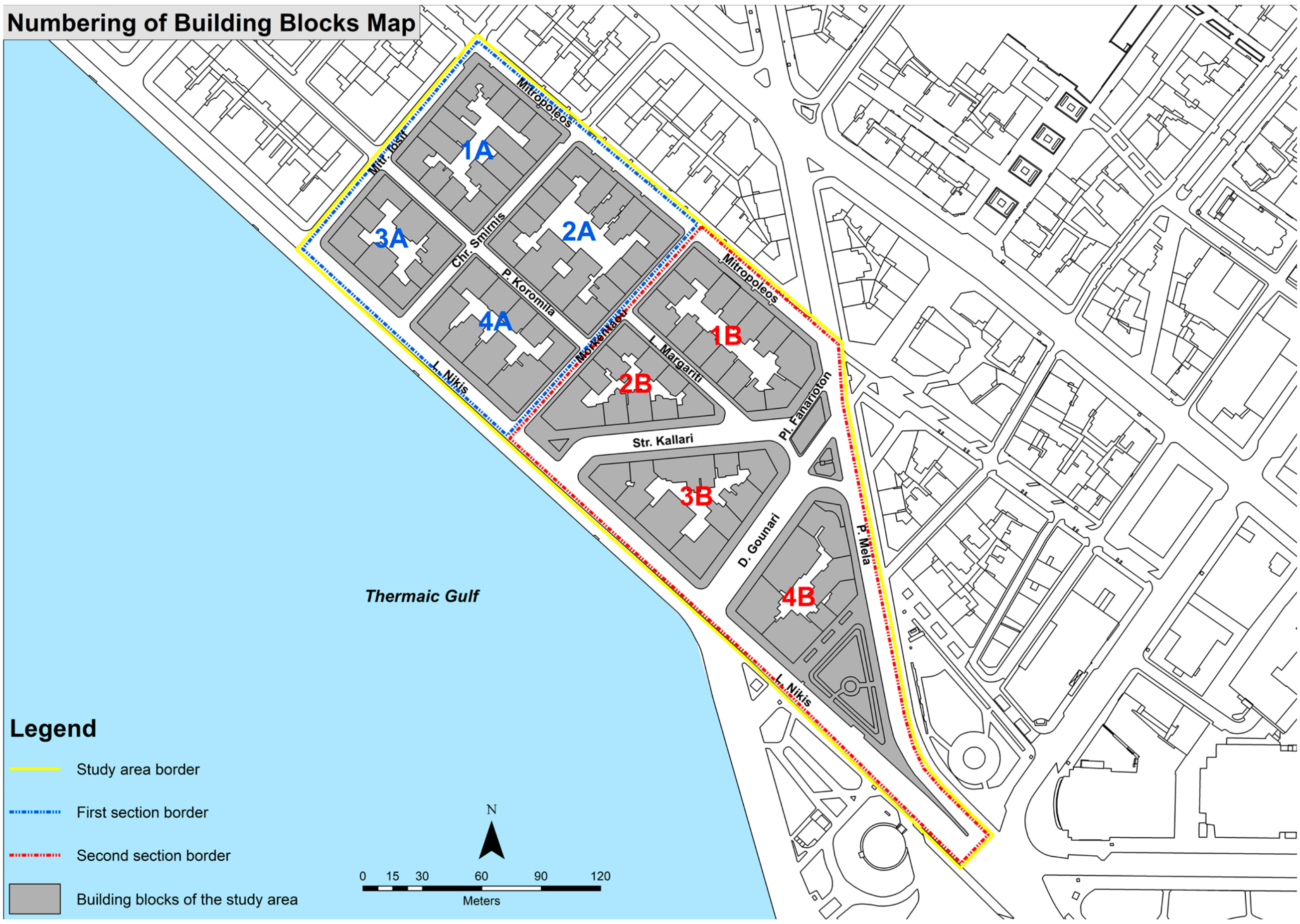


Figure 6. Numbering of building blocks of the study area, ArcGIS software.

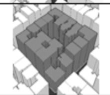
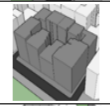
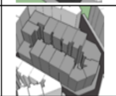
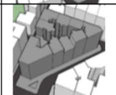
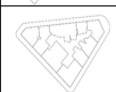
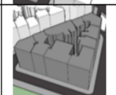
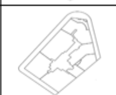
BUILDING BLOCK	BUILDING BLOCK AREA (m²)	2D FORM OF BUILDING BLOCK	3D FORM OF BUILDING BLOCK	GROUND COVER (m²)	BUILT-UP AREA (m²)	AVERAGE ROAD WIDTH (m)	AVERAGE HEIGHT (m)	AVERAGE NUMBER OF FLOORS	COVERAGE RATIO	BUILDING RATIO	H/W OF URBAN CANYON	AIR FLOW REGIME
1A	4242			2839	20,833	13	32	7	0.67	4.91	Str. Chr. Smirnis between B.B. 1A and 2A= 3.5	skimming flow
2A	5246			3515	26,962	13	33	8	0.67	5.13	Str. P. Koromila between B.B. 2A and 4A= 3.4	skimming flow
3A	2879			1812	14,268	13	31	8	0.62	4.95	Str. Chr. Smirnis between B.B. 3A and 4A= 2.9	skimming flow
4A	3647			2402	16,666	13	29	7	0.65	4.56	Str. Morkentaou between B.B. 2A,4A and 1B,2B= 3	skimming flow
1B	4610			3058	20,890	17	33	7	0.66	4.53	Str. L. Margariti between B.B. 1B and 2B= 3.5	skimming flow
2B	3402			2046	13,307	17	29	6	0.60	3.91	Str. Stratigou Kallari between B.B. 2B and 3B= 1.6	skimming flow
3B	4643			2759	22,072	17	32	8	0.59	4.75	Str. D. Gounari between B.B. 3B and 4B= 1.4	skimming flow
4B	3575			2316	18,075	17	33	7	0.64	5.05	-	-

Figure 7. Typology of building blocks of the study area.

In section A of the study area, which includes several deep urban canyons, the average width of a road is 13 m. In section B, we recorded a wider average of 17 m. This is due to the inclusion of wider roads in this section. With regard to actual development, the building blocks in the study area are densely built, having a high average "ground cover" ratio (i.e., percentage of a plot covered by built-up area), frequently exceeding the official building regulations. This means that the built-up areas are disproportionately large in relation to the uncovered spaces, which have extremely limited coverage. While a 60% "ground cover" ratio is the upper limit permitted by building regulations, in the great majority of building blocks within the study area, ratios of up to or in excess of this limit were recorded. Similarly, within certain building blocks, many of the building coefficients (i.e., total built-up area per plot area) we recorded exceeded the official limits, sometimes including buildings with more floors than the number officially permitted. The building blocks also lacked transparent openings in the uncovered areas, and in these cases, ventilation was very limited as the renewal of the air was inhibited [18].

Significant findings were also drawn from the geometrical analysis of the urban canyon within the study area. The largest H/W ratio of 3.5 was recorded in two of the roads in section A, and the lowest H/W ratios of 1.6 and 1.4 were taken from two roads within section B (Figure 6). Therefore, according to these results, all the urban canyons examined fall into the category of "skimming flow" (where the H/W ratio has a value greater than 0.7) [19], where the air cannot easily flow along a road. As a result, in such cases, when the wind direction is at right angles to the direction of the road, the road is not ventilated, or its ventilation is very limited. Such a condition (skimming flow) is found in most urban canyons as the H/W ratio is usually high [34]. However, it is worth noting that no definite conclusion regarding ventilation in the study area can be safely drawn, as other factors may play an important part in the ventilation of the urban canyon, such as its orientation, proximity to the sea, etc.

In addition to the ventilation of the urban space, according to Bartholomeos [18], the high H/W ratio found in the study area's urban canyons may mean small winter solar gains, large exposure to the sun, great obstruction of air movement, a small allocation of land for tree planting, large trapping of gaseous pollutants, etc. Moreover, according to Emmanuel and Johansson [27] and Oke [19,28], a high value of this ratio intensifies the phenomenon of UHI. In addition, the deeper urban canyons, for example, in the Chr. Smirnis and L. Margariti streets, are likely to be colder during the day and have a more favorable temperature in summer when compared to the shallowest. This fact was also validated by the field research in the area. However, the opposite effect will occur in winter, as the deeper canyons have less exposure to the sun, while the shallower ones, for example, Str. Kallari and Dim. Gounari, are probably more favorable to solar access. It is worth mentioning here that deeper canyons may also easily trap waste heat emitted from transport and reflective radiation (radiative trapping) and lead to a higher temperature at night.

3. Simulations of the Microclimate in the Compact Center of Thessaloniki and Main Results

3.1. Modeling the Study Area Using ENVI-met©

Figure 8 shows, diagrammatically, the process followed to create the model of the study area in the ENVI-met© simulation software. It should be noted here that modeling in the ENVI-met© software requires a background image in bmp format which allows the user to successfully identify the various elements one wishes to design and display. These elements are buildings, uncovered areas of the building blocks, roads, sidewalks, green spaces, and tree positions in the present study. For the design of the study area by the ENVI-met software, various input data were required. Table 2 presents this input data, while Table 3 shows the necessary data input for temperature, wind, and thermal comfort simulations. The Albedo, or "solar reflectivity", indicator, which refers to the materials used in the model, comes from the database provided by ENVI-met (Database Manager) and is presented in Table 4. The Albedo values from the ENVI-met database were compared to those provided by Androutsopoulos et al. [47] that include the official national specifications of parameters for calculating the energy efficiency of buildings. The differences between these two sets of values were found to be very small and insignificant.

Figure 9 shows the final models of the study areas in both two-dimensional and three-dimensional forms, as they were designed in ENVI-met©. In addition, as the airflow within an area is naturally affected by the surrounding building, the outside walls of the buildings that "skirted" the study area were also designed to rule out errors in wind simulation. However, due to the design of the tiles in the software used, it was difficult to capture complex urban geometries, such as angle, circular shapes of buildings, sidewalks, etc. For this reason, the model of the study area designed by ENVI-met© represents a geometrically simplified one.

Table 2. Input data of the study area in ENVI-met© software. (The meteorological factors come from https://www.meteo.gr/ (accessed on 9 December 2020) [48], and the human parameters were randomly selected.)

Study Area Input Data	
Location on earth	Thessaloniki
Geographic location (latitude, longitude)	40.64, 22.93
Reference longitude	30
Model dimensions (number of grids) xyz-grids	$50 \times 50 \times 40$
Size of grid cell (meters) dx,y,z	$2 \times 2 \times 2$
Model rotation out of grid north	42°

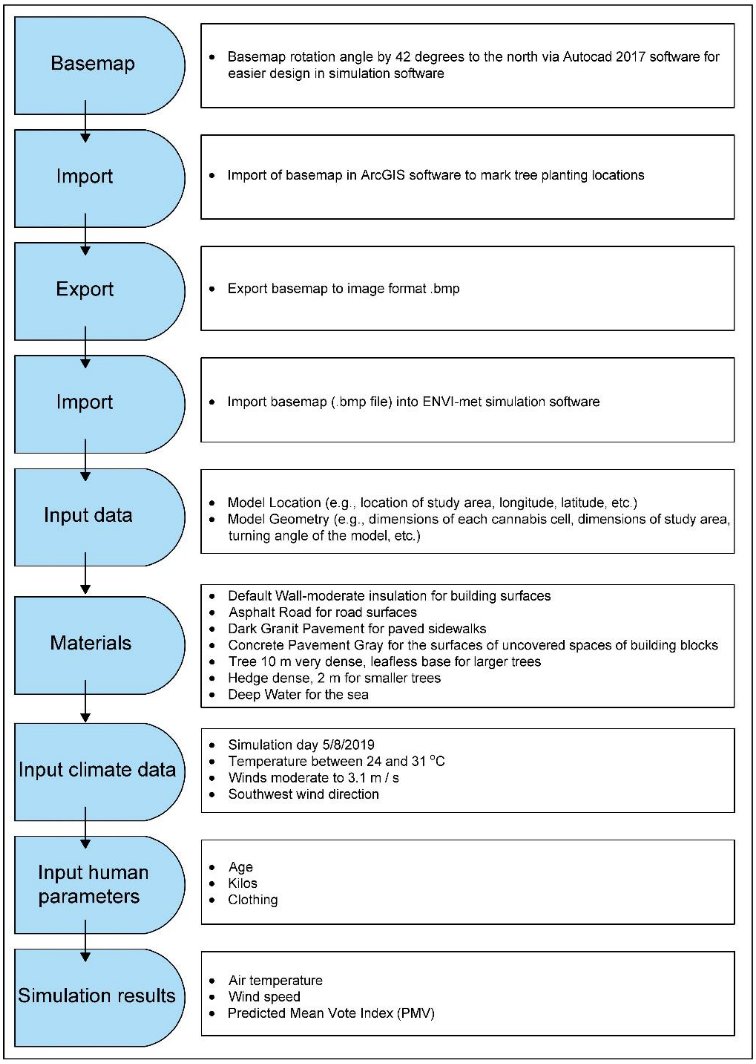


Figure 8. Procedure for creating the model of the study area.

Table 3. Input simulation data in ENVI-met© software.

Simulation Input Data	
Simulation date	5/8/2019
Start and duration of simulation	05:00, 24 h
Wind speed	3.1 m/s
Wind direction	SW, 225°
Temperature of atmosphere	Hot
Min temperature	24 °C
Max temperature	31 °C
Age of person (y)	35
Gender	Male
Weight (kg)	75
Height (m)	1.75
Static clothing insulation (clo)	0.90
Total metabolic rate (W)	164.49

Table 4. Element types used in ENVI-met© software and Albedo.

Element Type	Albedo
Default wall—moderate insulation	0.2
Asphalt road	0.2
Dark granit pavement	0.3
Concrete pavement gray	0.5
Tree 10 m very dense, leafless base	0.2
Hedge dense, 2 m	0.2
Deep water	0.0

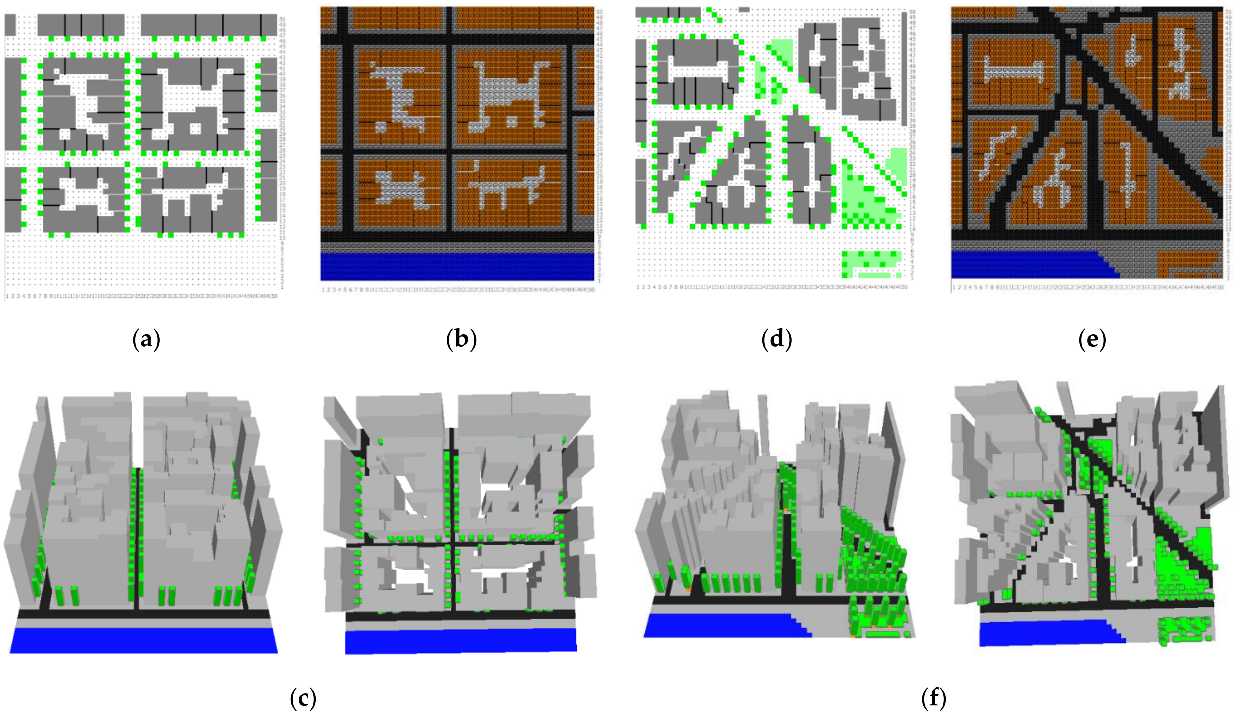


Figure 9. (**a**) Two-dimensional display of the first section where the buildings are shown in gray and the positions of the tree planting in green; (**b**) Two-dimensional display of the first section which shows the surfaces of the model where brown is the clay soil, dark gray is the surface sidewalk, light gray is the uncovered spaces, black is the asphalt, and blue is the sea; (**c**) Three-dimensional display of the first section; (**d**) Two-dimensional display of the second section where the buildings are shown in gray and the positions of the tree planting in green; (**e**) Two-dimensional display of the second section which shows the surfaces of the model where brown is the clay soil, dark gray is the surface sidewalk, light gray is the uncovered spaces, black is the asphalt, and blue is the sea; (**f**) Three-dimensional display of the second section.

3.2. Simulation Results

In the following paragraphs, we present the microclimate simulation results for each of the two sections of the study area. The simulations concern the air temperature, the wind speed, and the average expected PVM thermal index for a summer day (5/8/2019). More specifically, investigation of a typically hot day revealed the time at which the temperature reached its maximum. This was then recorded using the actual meteorological values. The readings were taken at 16:00, which was a time when the maximum temperature for this day, of 31 °C, was recorded. It is worth noting that on the day of the simulation, as well as during previous days, we made empirical observations within the area, which confirmed the following results. According to https://www.meteo.gr/ (accessed on 9 December

2020) [48] for the day of the simulation, the maximum temperature was recorded at 16:00 h, a fact which was confirmed by empirical observation of the authors. The observation height was set at 180 cm above ground level.

3.2.1. Air Temperature

Temperatures in the study area were high and reached 31.6 °C and 31.8 °C in sections A and B, respectively. The highest temperatures were observed mainly in the southern section B, probably due to the direction of the wind, which, as mentioned above, is southwesterly. This wind, known in Greek as "livas" or "garbis" (SW—225°) [49,50], appears mainly during summer months and is characterized by the intense thermal loads that it carries, while it is also responsible for the sharp increases in temperature.

Despite the fact that section A is totally lacking in open and green spaces, we recorded lower temperatures there than in section B, which does have open and green spaces. This may be due to the fact that warm wind flows unhindered in urban canyons with a NE-SW orientation, thus raising the temperature, in this case to over 31%. In such conditions, greenery cannot have a positively cooling effect on the air. However, it was observed that the greenery that exists on the sidewalks, that is, tree planting, managed to reduce the wind speed, as a result of which, the air temperature gradually decreased as we moved further north on the roads. It was also observed that in cases where there was a decrease in wind speed, such as in urban canyons with NW-SE orientation, temperatures of about 2 °C lower were recorded. This was because the rapid decrease in the wind's speed, before it entered these canyons, rendered it incapable of transmitting the same amount of heat it was previously carrying.

The reduced speed of the wind in the urban canyons of NW-SE orientation, in combination with tree planting, had the effect of reducing the air temperature. There was an even more noticeable drop in temperature on roads with more moderate wind speeds and where trees were planted densely on both sides of the road. In contrast, the temperature drop was less noticeable on roads with the same orientation, where the trees were more sparsely planted. In addition, the high ratio of H/W with deep canyons played an important role in reducing the temperature in section A, resulting in less exposure of outdoor areas to the summer sun, through the provision of adequate shading. In other words, this is a case where the higher H/W ratios have a positive effect on the microclimate during the summer period.

Conversely, in section B, higher temperatures were recorded due to the almost unobstructed flow of hot air along the wider streets with a NW-SE orientation and subsequent transfer to the northern parts of the area. In addition, in this section, the adversely affected and comparatively lower H/W ratio allows more sunlight exposure. It is also noteworthy that very high temperatures were recorded in the park area in section B. Despite being planted with grassy areas and trees, this park is exposed both to the sun, due to the lack of buildings on its south and east side, and to the hot winds. Therefore, the absence of buildings to protect the park from the sun and the hot wind, which flows unhindered, results in very high temperatures. It also seems that, although there were large trees with dense foliage, they failed to cool the surrounding space due to the fact that they were neither densely planted nor adequate in number.

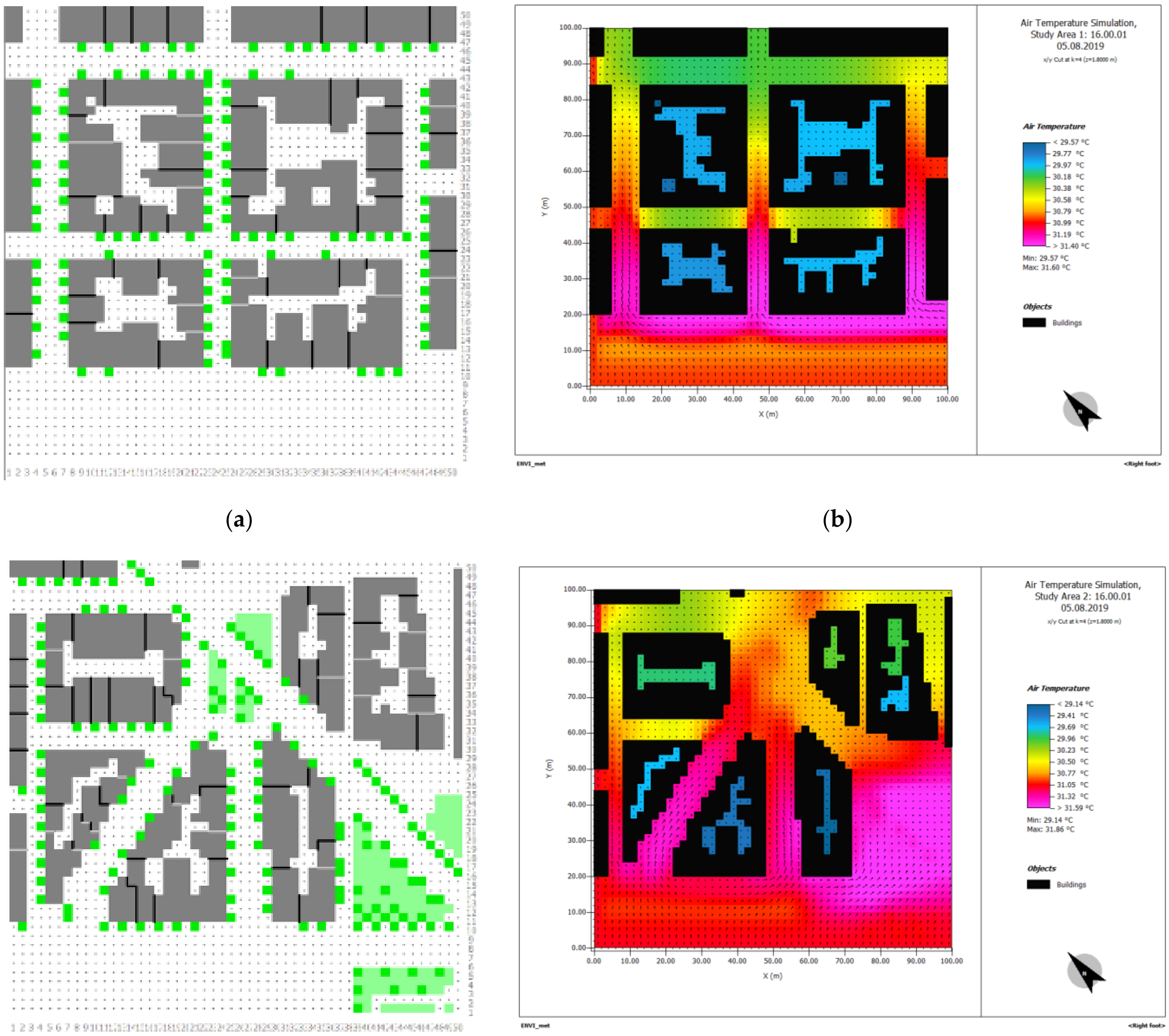
The air temperature simulation and comparison between the two sections are shown in Figure 10.

3.2.2. Wind Speed

In the present simulation, the wind had a southwesterly direction, and in the northern areas, it sharply decreased in speed, mainly due to the obstacles that it encountered from the compact and large building blocks, the narrow gorges, and tree planting. However, despite this fact, high acceleration of wind speed was observed in the "pressure zones" located in the corners of buildings. This "corner phenomenon" [7,18,34,42] was responsible for wind speed acceleration, sometimes reaching 4.5 m/s in section B, and 6 m/s in section

A, also due to the narrow streets. Furthermore, the tall buildings found in the corners of the building blocks create strong vortices, further disrupting the speed of the air at ground level where pedestrians move, apparently causing discomfort. In section A, the very deep and relatively narrow urban canyons contributed to what seemed to be a sharper decrease in wind speed than in section B. This was the result of these narrowly constricted passages slowing down the flow of air. On the other hand, section B is characterized by a high H/W ratio; however, the wider roads allow an easier airflow.

By examining the wind speed, important conclusions can be drawn about the ventilation of the urban space. It seems that streets with NW-SE orientation are well ventilated, with the air flowing unhindered and accelerating in the urban canyons. The direction of the wind, which is almost parallel to the road axis, obviously contributes to this phenomenon, described in the literature as a "channel phenomenon" [16,18]. On the other hand, there was a significant reduction in air movement in the urban canyons of NW-SE direction, with the result that their ventilation was insufficient.



(**a**) (**b**)

(**c**) (**d**)

Figure 10. (**a**) Two-dimensional display of the first section where the buildings are shown in gray and the positions of the tree planting in green; (**b**) Air temperature simulation for the first section of the study area; (**c**) Two-dimensional display of the second section where the buildings are shown in gray and the positions of the tree planting in green; (**d**) Air temperature simulation for the second section of the study area, ENVI-met© software.

The vegetation seems to be a significant obstacle to the flow of air. On the roads with sufficient tree planting in rows, there was a decrease in the air speed near the ground and along the sidewalk. The same, rather sharp decrease in wind speed, was observed in the park of Section B, where there are sufficient trees. At the same time, very limited ventilation of the uncovered areas of the building blocks was observed. This was due to the absence of bright openings between the buildings allowing the entry of air.

The wind speed simulation and comparison between the two sections are shown in Figure 11.

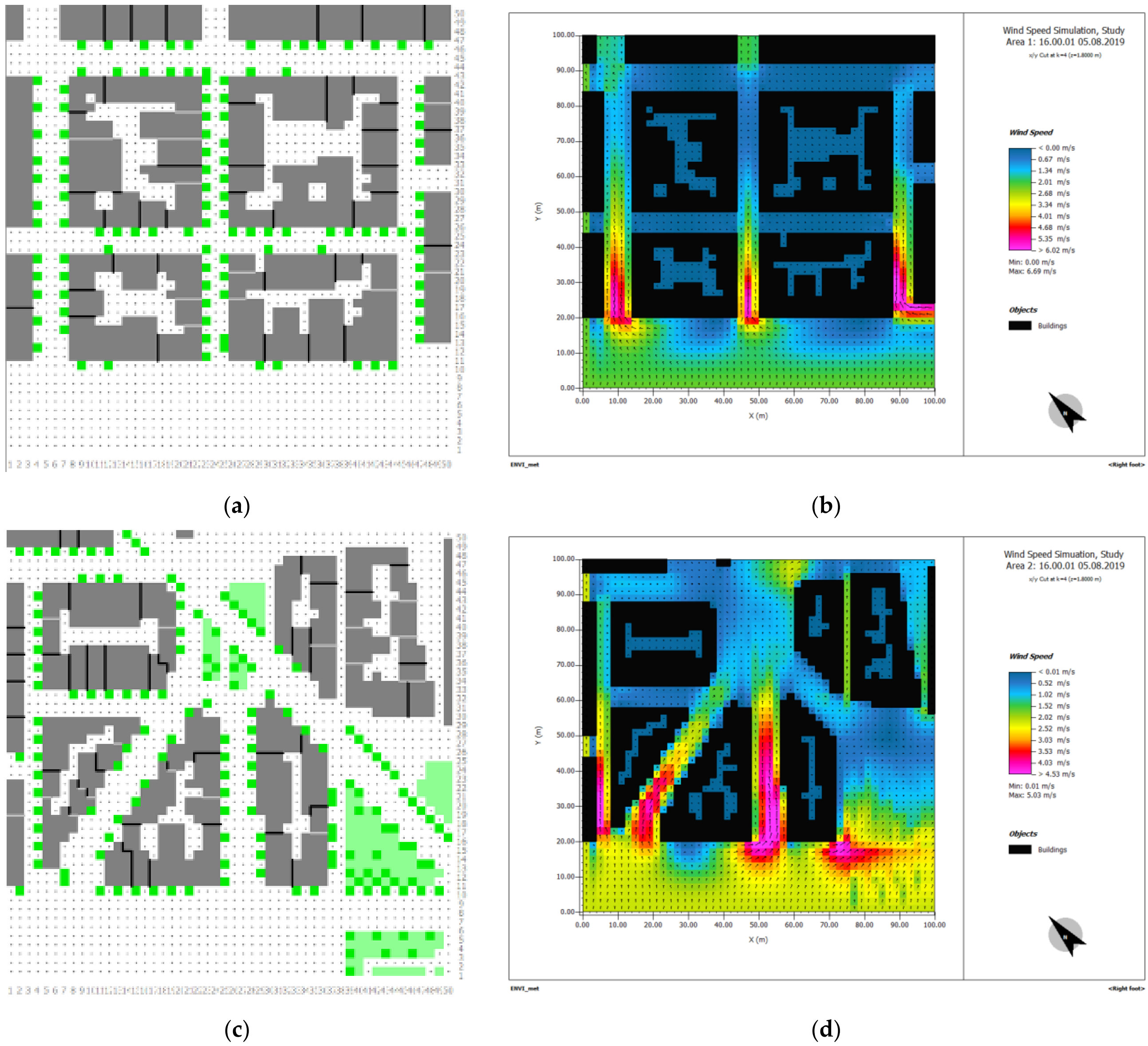


Figure 11. (**a**) Two-dimensional display of the first section where the buildings are shown in gray and the positions of the tree planting in green; (**b**) Wind speed simulation for the first section of the study area; (**c**) Two-dimensional display of the second section where the buildings are shown in gray and the positions of the tree planting in green; (**d**) Wind speed simulation for the second section of the study area, ENVI-met© software.

3.2.3. Predicted Mean Vote (PMV) Index

Tree planting and grass cultivation seemed to significantly affect air temperature, especially in areas where there had been a reduction in the flow of warm air. Moreover, it seems to be a more perceptible, positive, human thermal comfort factor [51]. There is also a decrease in the average expected thermal index in places where there is a sufficiency of tree cover, with denser foliage trees naturally having a greater positive effect. In addition, the impact on thermal comfort can be felt for up to the vegetation. This effect is most noticeable in the section B park, where there are sufficient trees and grassy areas. The PMV index ranges from 1.95 to 3, corresponding to both moderate and high thermal loads. The PMV index values of these parts correspond to a fairly high thermal load, but they are still less than those for parts without tree cover. Another important parameter for thermal comfort in the urban canyons is the high H/W ratio in the area. As a result of this high ratio, there is little exposure to the sun and significant shading of streets from the buildings.

The PMV index is expressed as PMV = [0.303 exp(−0.036M) + 0.028] × L, where PMV = predicted mean vote index, M = metabolic rate, and L = thermal load—defined as the difference between the internal heat production and the heat loss to the actual environment—for a person at comfort skin temperature and evaporative heat loss by sweating at the actual activity level. Within the PMV index, +3 translates as very hot, while −3 translates as very cold [52–55], as indicated in Table 5.

The PMV simulation and comparison between the two sections are shown in Figure 12.

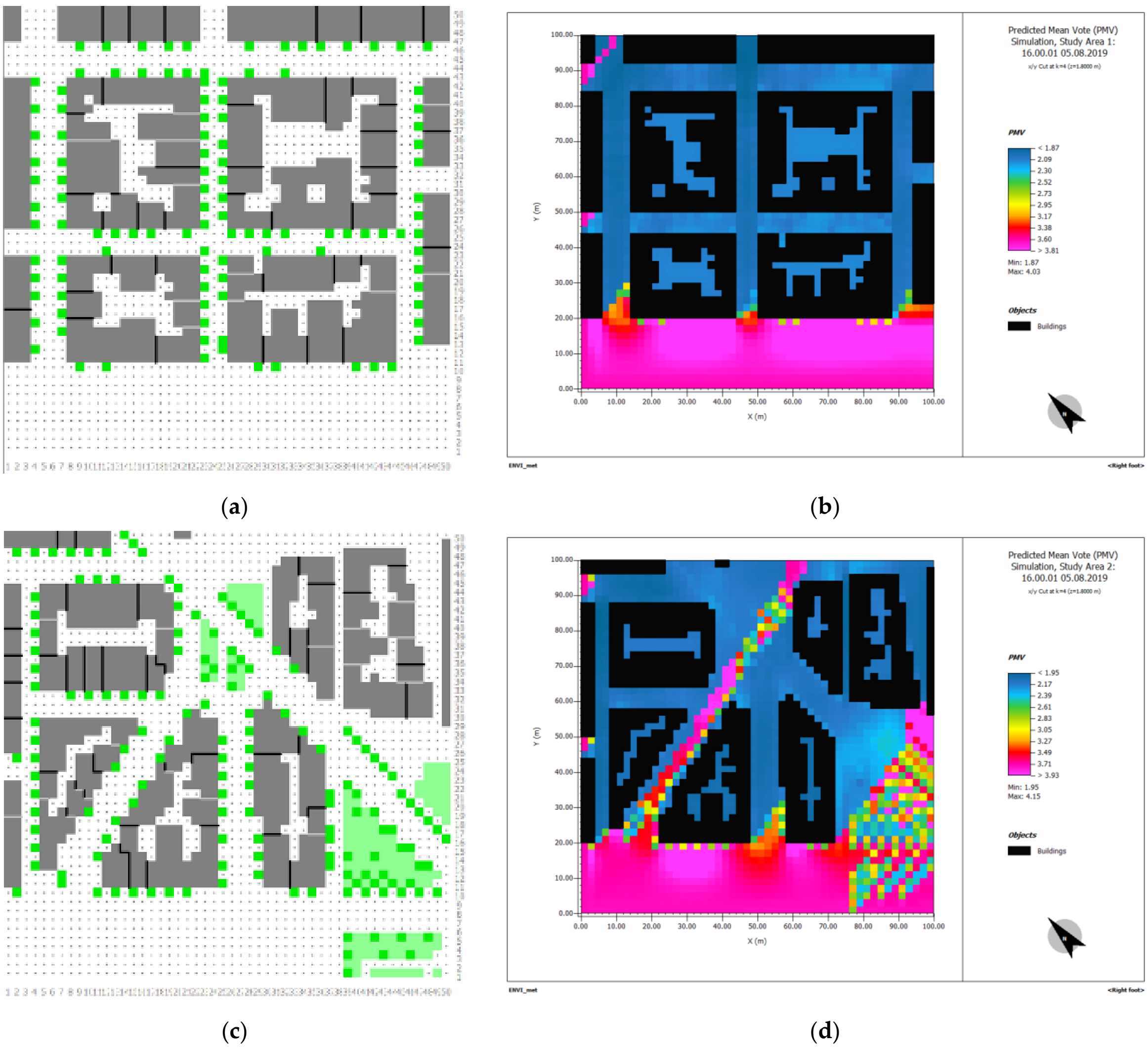


Figure 12. (**a**) Two-dimensional display of the first section where the buildings are shown in gray and the positions of the tree planting in green; (**b**) PMV simulation for the first section; (**c**) Two-dimensional display of the second section where the buildings are shown in gray and the positions of the tree planting in green; (**d**) PMV simulation for the second section, ENVI-met© software.

Table 5. Predicted mean vote (PMV) index values and the corresponding thermal comfort values.

−3 cold	−2 cool	−1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot

3.3. Validation of ENVI-Met Software

The reliability, validity, and sensitivity of the ENVI-met results were verified by several numerical/quantitative studies, which entail comparisons between simulation results and measurements [38,56,57]. In this paper, the model's reliability and validity were verified by making hourly comparisons of the meteorological measurements and simulation results. We added the information about per hour temperature to the ENVI-met software. This information was taken from the official, national meteorological site [48] and its nearest meteorological station, which is located 700 m away from the study area. ENVI-met software allows the user to enter temperatures for each hour manually, via the "Simple Forcing" command. The model ran for 24 h and calculated the "normal" distribution of temperatures per hour. We checked the simulation results for every hour for a period of 24 h, and the distribution was found to be correct. The maximum temperature of 31 °C, recorded at 16:00, was selected for examination. The model indicated fluctuations in the temperatures in various parts of the examined sections, along with the fluctuations which accorded to the various meteorological values that were inputted (e.g., in some spots, the temperature reached 31.8 °C). These higher temperatures were mainly due to the impact of urban morphology and the density of tree planting in the area, these being two main parameters addressed in this paper. However, there were other influential factors, such as the materials used to build the urban environment.

Regarding wind speed and urban ventilation, the model's validity can be verified by the findings in Section 2.3. As shown in Figure 7, the urban canyons with a high H/W ratio are not adequately ventilated, a fact that is also evidenced by the theoretical framework. For example, Figure 7 shows that P. Koromila street has a ratio of H/W = 3.4 and is not adequately ventilated. This lack of ventilation is due to the fact that the air does not enter easily because the street is perpendicular to the wind, and the adjacent buildings are disproportionately high in relation to the width of the road. This condition is fully confirmed by the simulation model, where a complete absence of ventilation and air movement is observed. Therefore, it seems that the theory itself can confirm the validity of the results of the ENVI-met software.

4. Discussion

The findings of the present study indicate a strong relationship between urban morphology and the microclimate, as defined by the local climatic conditions prevailing within the urban environment, even at a very local scale. Geometrical characteristics of the urban form, such as building height, street width, etc., directly and variously affect the ventilation and insolation of the urban fabric, thereby significantly impacting the formation of microclimatic conditions. In particular, within the compact urban forms, it is easy to detect differences in climatic conditions between areas that lie very short distances from each other. These variations are due to small differences in urban morphology, for example, the availability of open and green spaces or the properties of building materials, etc. In the present research, the emphasis was placed on very compact forms within the city center, characterized by the high coherence of building blocks and the great soil sealing. The findings of the simulation developed in the field study show that this particular urban form can, in some cases, have a positive effect on the microclimate in the summer period due to outdoor protection areas and road shading, whereas, during the winter, this form presents obstacles exploiting the winter sun and increased shading.

Comparisons were drawn between the two, adjacent sections of the study area. These differed in terms of the urban canyon's width, the availability of open spaces, green spaces, and tree planting, and there were indications that these disparities lead to disparate effects on the microclimate. This was evidenced by the significant variations in values for variables recorded in areas that lay a very short distance from each other, within the same urban space. For example, the simulations have shown that while the type of urban fabric is equally compact in both sections, a small change in the H/W ratio of the urban canyon can cause an unimpeded flow of hot air (if the ratio is small), thereby increasing the temperature inside the urban space, or it can act as a barrier (in case of a bigger ratio) to the access of hot air to the interior of the urban fabric, thereby creating a cooling effect.

Another significant finding of the paper concerns how the design of roads and urban canyons, the geometry and orientation of which greatly affect the ventilation of urban space, solar radiation, shading, etc., affects the overall indoor and outdoor environment. According to the season, the effect of the orientation of the canyons on the microclimate can differ, therefore choosing a suitable design to achieve optimum microclimate conditions in all seasons is a difficult task. For example, wind and temperature simulations showed that urban canyons perpendicular to the wind flow showed a significantly improved atmospheric temperature, compared to canyons whose orientation was parallel to the wind flow. It should be emphasized here that the simulations generated from the present study concern the summer season. As mentioned in the introduction, the morphology of the urban space can have different results in different seasons.

Urban morphology affects the ventilation of urban space significantly. This is a complex process and one of the most important factors in shaping the microclimate. In general, the compactly built-up space is responsible for the reduction of the wind speed. However, high H/W ratios obstruct its movement, creating local gusts. Given that the ventilation factor is the most changeable climatic factor within the urban space, it was examined in detail in this work. The findings show that the H/W ratio, along with the orientation of the urban ravine and the through openings in the building blocks, is the factor mainly responsible for the urban space's ventilation. Within the study area, in cases where airflows were perpendicular to the urban canyon, the high H/W ratio and the lack of through openings were responsible for the urban environment's lack of ventilation. At the same time, the tall buildings at the corners of the building blocks appeared to create strong local gusts of wind.

It is well known and widely acknowledged that urban greenery and tree planting within the urban areas affect the urban climate, mainly having a positive impact on thermal comfort. In addition to lowering air temperature, urban greenery can also reduce other factors which harm the microclimate, such as pollution, and is also an effective strategy for dealing with the UHI [45]. However, the results of the simulation show that planting's positive effects on air temperature can only be seen in cases of dense tree cover, as sparse and spot planting cannot have significant effects. The simulations of the present case study indicated that positive effects are recorded only in cases where there is adequate tree planting on both sides of the streets. At the same time, on roads with sparse and spot planting the air temperature remains high. In addition, the simulations for section B showed that, due to the lack of dense tree cover and shading in existing parks, the latter does not necessarily function as an obstacle to the flow of hot wind, with the result that there is an invasion of intense thermal loads, especially within the built-up area.

This study has, of course, certain limitations, which, however, affect neither its main findings nor the issues raised in the discussion above. To begin with, a simulation model to be fully validated should be tested and compared to field measurements of air temperature, humidity, wind speed, etc. Sensitivity analysis and a spin-up period of more than 24 h would also provide much safer results. Significant limitations of such a study relate also to the limited availability of similar studies with field measurements in the city of Thessaloniki. Moreover, there is a lack of data reporting measurements of both air pollution and the heat released from vehicle traffic. If such studies were available, even for other compact urban cores within Greek cities with similar characteristics, they could be used to investigate other factors affecting the formation of the microclimate and to provide further validation of the reliability of our results. Our main purpose was to focus on issues of urban morphology and open and green spaces. In other words, to focus on issues, determined, to a large extent, by urban planning and design. Therefore, a further assessment of all the factors that may influence the formation of the microclimate in compact urban fabrics is critical.

Another limitation of the study is that the simulations were carried out for the summer period and an average hot day, for which we examined a typical afternoon hour. Hence, the results extracted concern this specific period. During the winter period, simulations will, of course, deviate significantly from the findings reported in the present study. Therefore, a comparative assessment of the microclimate for different time periods/seasons is also necessary. Among the critical challenges ahead is the use of such models to implement appropriate regeneration proposals for improving the microclimatic conditions in the compact inner cores of the cities. Urban morphology, in the areas which are already built-up, is difficult to change. The use of simulation models enables planners and policymakers to look into various alternative solutions for implementation within different urban forms and within different seasons of the year.

5. Conclusions

This study aimed to analyze how critical elements of urban morphology, such as the street layout, the urban canyon, and the open and green spaces in a compact urban form, contribute decisively both to the creation of the microclimatic conditions and to the influence of the bioclimatic parameters. In the context of a compactly planned and built-up city center with a Mediterranean climate, our findings, based on simulations, are generally in line with findings from previous studies regarding the impact of urban morphology on microclimate. Within this field of literature, we paid particular attention to the detailed, street plan level, where we examined the microclimatic variations in elements such as air temperature, urban ventilation, and the individual's thermal comfort.

Overall, our study highlighted that, in highly compact areas, it is important to conduct a detailed investigation of the typological relationship between the building blocks within the urban fabric and the microclimate. This would enable the evaluation of microclimatic conditions and provide insights into the necessary and appropriate urban planning and design interventions to improve these conditions. Compact areas, especially densely built-up ones, with open and green spaces comprising a low percentage of the total area, are the norm in older cities with old housing stocks. In such areas, improving the microclimate conditions due to urban morphology is a very difficult and multi-dimensional task, made even more complex when the related effects of UHI and general adaptation to climate change are considered. In these cases, it is equally important that the simulation models used are supported by field measurements of specific parameters such as air temperature, humidity, and wind speed so as to acquire more accurate and much safer results which are needed to find adequate solutions for improvements.

The current evidence base shows that to make specific recommendations for best handling of the microclimate problem in these urban forms, we need detailed investigation at the very local scale. There is no doubt that some of the most accessible measures would be nature-based. These may include increasing the various forms of urban greenery, its detailed distribution and design within the street layout, as well as on building facades and roofs, creating bright openings in building blocks for ventilation of the entire urban space, and a change of materials used to build structures, roads, and sidewalks, along with the pedestrianization of roads. Finally, as there are no "one-size-fits-all" solutions, this detailed planning and design should be continuously evaluated in order to substantially contribute to the improvement of diverse urban forms and their microclimates.

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