Ground surface materials and microclimates in urban open spaces

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ABSTRACT: Microclimatic conditions in open spaces are affected, among other parameters, by the morphology of the urban tissue and by the properties of surfaces. This paper presents measured data of air and surface temperatures, wind speed and relative humidity, taken in June and August 05, in five open spaces, in the city of Thessaloniki, Greece, to examine the effects of different ground surface cover on the microclimates that develop in each area. The monitored spaces contain materials such as marble, stone, concrete, ceramic tiles and asphalt, as well as grass and water surfaces. Differences found within three areas and between two areas monitored simultaneously, reveal the effects of material and surface properties. Measurements of incident and reflected solar radiation were also taken for an estimation of the surfaces' albedo. The monitored data is also used for the calibration of two software tools, ENVI-met v3.0 and RadTherm v8.0, to evaluate the possibility of a further examination, through simulations, of a wider range of open spaces, as well as of seasonal variations.

Keywords: open spaces, microclimates, materials, simulations

1. INTRODUCTION

Open spaces in cities are encountered in a large variety of forms and ground surface characteristics. The microclimatic conditions that develop in open spaces are affected, among other parameters, by the morphology of the urban tissue and by the properties of the surfaces [1]. Studies have evaluated several surface materials as cool or warm according to their physical properties [2] and others in relation to albedo and building energy consumption [3], however their actual effect on urban microclimates and comfort conditions in open spaces still requires further investigation.

A variety of ground surface materials located in large open spaces in the city of Thessaloniki, Greece, were examined to evaluate the influence of the surfaces on the microclimates that develop in each area. In a previous study [4], the effect of different ground surface cover has been tested through simulation results. This paper reports on monitored data of air and surface temperatures, wind speed and relative humidity, taken in June and August 05, in five open spaces which contain surface materials such as marble, stone, concrete, ceramic tiles, and asphalt, as well as grass and water surfaces. Differences found within three areas and between two areas monitored simultaneously, reveal the effects of the material and surface properties. Measurements of the incident and reflected solar radiation were also taken for the calculation of the surface albedo.

Simulation results by two software tools, ENVI-met v3.0 [5] and RadTherm v8.0 [6], are presented in comparison to the monitored data, for an assessment of the calculations accuracy.

2. URBAN SITES

The selected sites are five open spaces, located in a relatively large distance from surrounding buildings to eliminate, as much as possible, the overshadowing and wind sheltering effect of the surroundings.

Site A is a large square in the city centre, approximately 38000m^2, with a variety of ground surface materials and vegetation. Site B is part of a linear park along a coastal avenue; it is 32m wide, in 10m distance from a row of 7-storey buildings on the east and 200m from the coast on the west. Site C is an area of 4500m^2, in front of an athletic centre in the outskirts of the city, and includes a vegetated tilted surface facing WSW and a 250m^2 large fountain. Site D is an area of 13500m^2 at the entrance of a large exhibition site, with a single material on the ground surface, and site E is a small square approximately 1000m^2, with a single material on the ground as well, interrupted only by a small water surface in the centre. Models of the sites are shown in Fig. 1.

Site E is the only site surrounded by buildings in a close distance of approximately 55m, but the monitored space was not shaded by the buildings at any time during the measurements. In site B the row of buildings shaded the area early in the morning before the start time of the measurements.

Figure 1: Models of the monitored sites

The first three sites were monitored separately as they include various ground surface materials and comparison of differences within the sites would be applicable. The last two sites, containing almost a single material, were monitored simultaneously and compared to each other. However the different configuration of the two sites is likely to have an effect on results and should be taken under consideration.

Ten different ground surfaces were examined, apart from grass and water. Area A contains three different surfaces of marble (white marble with black parts, black marble with white stripes and totally white marble), grey cobble stone, beige porous stone and grass. In area B concrete pavement tiles and grass were measured under solar exposure and under shade. In area C, dark grey marble, asphalt and grass were monitored, as well as air temperature above the water surface. Area D contains almost exclusively a light grey surface of concrete with gravel and area E is covered mostly by dark red ceramic tiles.

3. MONITORING

3.1 Climate data

Measurements were taken during six days in June and five days in August 05 from the morning until the afternoon (8h each day). In June air temperature recorded in the meteorological station [7] during the measuring period fluctuated between 17^{o}C and 32^{o}C, Relative Humidity (RH) between 24 and 78%, wind speed between 0 and 8.75m/s, while the maximum value of total incident solar radiation reached 954W/m^2 [8]. In August, during the measuring period air temperature fluctuated between 19^{o}C and 32^{o}C, RH between 27 and 83%, wind speed between 0 and 5.67m/s and total solar radiation reached 873W/m^2.

Sky conditions were generally clear and sunny except for two cloudy days, 20/06 and 25/08, as well as a few hours with cloudy sky in 19/06 (10:00-14:00), 29/06 (9:00-13:00) and 27/08 (14:00).

3.2 Method

Readings of air temperature, relative humidity and surface temperature were taken every 30 minutes above the different surfaces, with Onset HOBO data-loggers. Wind speed was also measured every 30 min, with a hand-held anemometer.

Air temperature sensors were placed inside a white plastic cup hanging upside down, approximately 1m above the ground surface. The sensor was protected from solar radiation from the top and the open side of the cup facing downwards allowed air circulation. However, the opening also allowed reflected radiation from the ground to reach the sensor, and although this would not be significant in the case of absorptive surfaces, it may have affected the results above highly reflective surfaces such as white marble and light coloured concrete.

Surface temperature measurements were taken with sensors mounted on the ground and covered with insulating tape and reflective aluminium tape for protection from solar radiation.

3.3 Albedo measurements

Measurements of incident and reflected solar radiation, above each surface, were taken later, in October 05, to give a rough estimate of the albedo of the ground surfaces. The measurements were taken on two days with clear sky, with a pyranometer placed at 0.5m above the ground surface, first facing upwards to record incident solar radiation and then downwards to record reflected solar radiation. The rotation of the pyranometer took place within 1min to ensure identical sky conditions between the two measurements. The albedo was estimated directly by the ratio of reflected to incident solar radiation considering that the area of the examined surfaces is large enough to avoid any correction regarding the view factor [9]. The results for each surface are given in Table 1, as well as reported albedo values [10, 11] for similar surfaces.

Table 1: Incident and reflected solar radiation measured above different ground surfaces (October 05) and estimated albedo of each surface.

surface	$R_{sw}\downarrow$ W/m^2	$R_{sw}\uparrow$ W/m^2	albedo measured	albedo reported
marble white(+black)	382	146	0.38	-
marble black(+white)	361	75	0.21	-
marble white	327	173	0.53	0.60-0.64[10]
cobble stone grey	371	100	0.27	-
porous stone beige	370	146	0.40	0.35[10]
concrete tiles	276	93	0.34	0.30-0.40[11,10]
marble dark grey	266	43	0.16	-
asphalt	353	53	0.15	0.05-0.20[11]
concrete & gravel	327	123	0.38	-
red ceramic tiles	359	75	0.21	0.35[10]
grass	284	86	0.30	0.30[11]
grass	381	111	0.29	0.30[11]

4. RESULTS

According to the monitored data, generally higher surface temperatures are observed in June when the solar radiation values are higher, while high air temperatures are observed in August when the large amount of stored heat caused higher emission of longwave radiation from the surfaces. Surface temperatures up to 56°C were observed on asphalt, in June, while the coolest surface was grass with temperature up to 34.8°C. Air temperature up to 41.1°C was recorded above asphalt in August while the lowest maximum air temperature was 29.9°C above grass in June. High air temperatures were also observed above light colored surfaces possibly due to the effect of reflected radiation on the sensors.

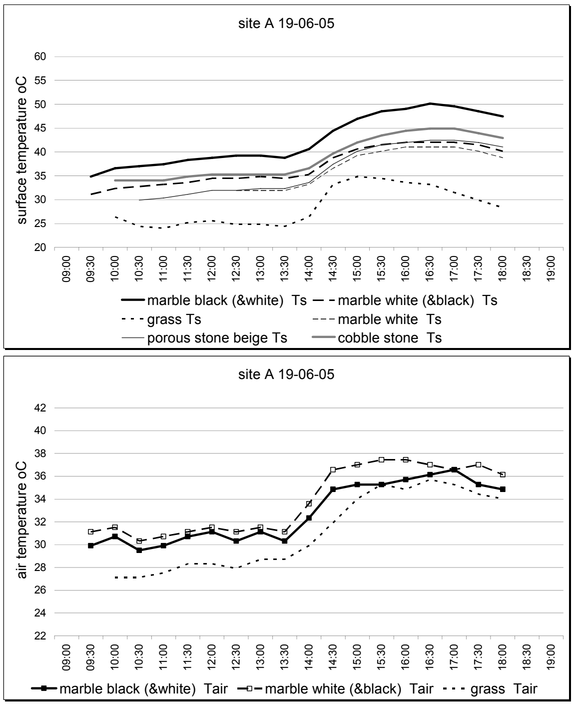

Figure 2: Surface and air temperatures at site A.

Among the surfaces at site A (Fig. 2), on June 19th -20th and August 28th, black marble was the warmest, with mean surface temperature up to 44.9°C, while cobble stone, white marble and grass were up to 13.9%, 14.5% and 32.9% cooler respectively. Surface temperatures of totally white marble and porous stone, were 21.4% and 22.3% cooler than black marble respectively. The results among hard surfaces reveal lower temperatures on surfaces with higher albedo. Low temperature was also observed on the porous stone surface, similar to the temperature of totally white marble which has a higher albedo.

The mean air temperature above black marble reached up to 36.3°C, while values above cobble stone (results only in August) and grass were up to 4.97% and 11% lower, respectively. Air temperatures seem to have a correlation with surface temperatures, except for the case of white marble where the highest mean air temperature was recorded (up to 6.6% higher than that above black marble) despite its cooler surface. This may be attributed to the high reflectivity of the white surface and the large amount of reflected solar radiation which probably affected the sensor's readings, as mentioned earlier.

Wind speed measured at site A, varied between 0.3m/s and 3m/s and average values were 1.9m/s on 19-06, 1.1m/s on 20-06 and 0.7m/s on 28-08. In June average relative humidity was recorded between 23% and 35% above hard surfaces and between 25% and 30% above grass. In August, average RH values were higher, between 33% and 37% above all surfaces except white marble (average 26%).

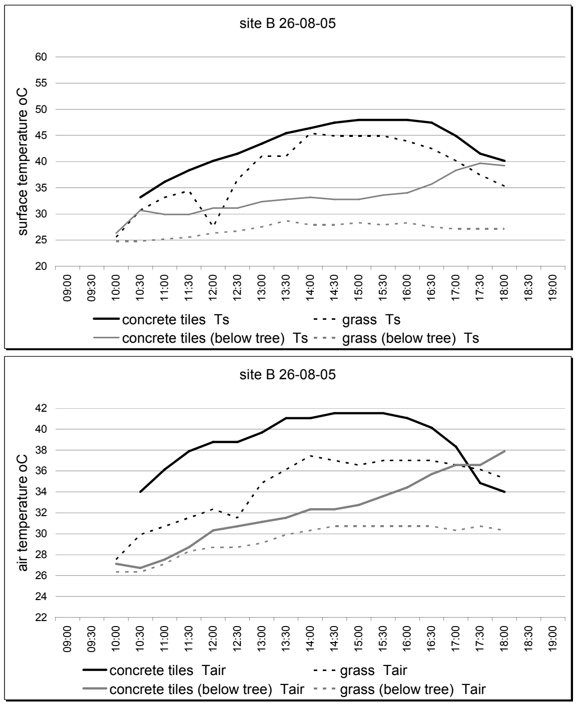

Figure 3: Surface and air temperatures at site B.

At site B grass and concrete tiles were examined under solar exposure and under the shade of trees on June 22nd-23rd and August 26th. Mean surface temperature of the exposed concrete tiles was up to 46.2°C and exposed grass up to 9.6% cooler, while mean temperature of shaded tiles reached 33.1°C and shaded grass was up to 18.6% cooler. In Fig. 3, a steep drop of surface temperature of grass at 12:00 is due to temporary shading, while the warming of the concrete surface below tree is due to exposure to solar radiation late in the afternoon. In the case of exposed surfaces, mean air temperature above concrete reached 38.1°C while above grass was up to 9.7% lower. In the case of shaded surfaces, mean air temperature above concrete was recorded up to 32.1°C and above grass up to 8.5% lower. It should be noted that the temperature of the shaded surfaces was at most times lower than that of the air above them even up to 4K. The shaded grass surface was up to 40.7% cooler than the exposed one, and the shaded concrete pavement was up to 41.6% cooler than the exposed one.

The concrete tiles were also examined, on June 22nd-23rd and August 27th (Fig. 4), under two more shading covers; a timber gallery and a white fabric tent, however the mean surface temperature difference among the shaded concrete pavements (below tree, gallery and tent) was lower than 1K and considered negligible. The mean air temperature above the shaded concrete pavements was similar among them, and up to 21% lower than that above the exposed concrete pavement. A steep drop of air temperature above exposed concrete at 14:30 in Fig. 4 is due to temporary cloud cover in combination with a slight increase of wind speed (up to 1.4m/s).

Wind speed at site B fluctuated between 0.2m/s and 1.7m/s, with average values 0.8m/s on 22-06, 0.6m/s on 23-06, 1m/s on 26-08 and 0.9m/s on 27-06. In June, average RH above exposed concrete tiles was 23-24%, and above shaded surfaces was higher, 27%-58%, without large differences between grass and concrete (the higher values correspond to 23-06 when grass was watered). In August average RH was 35%-40% above exposed concrete, 34% above exposed grass and between 42% and 50% above shaded surfaces probably due to reduced airflow.

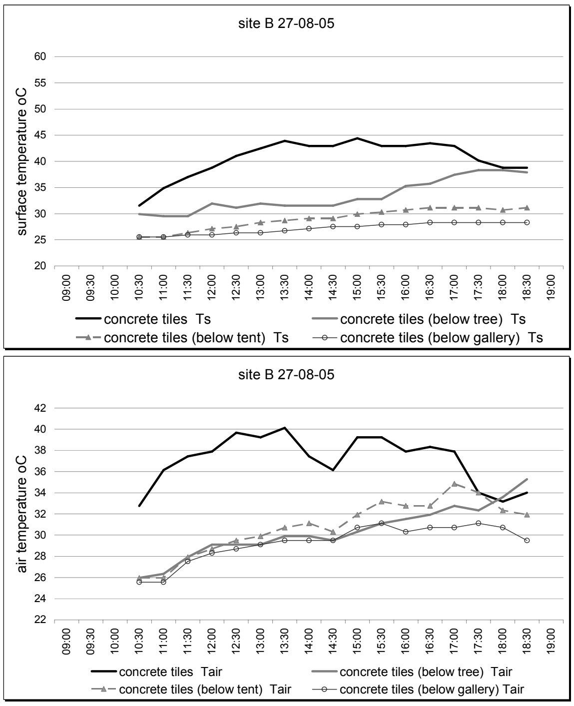

Figure 4: Surface and air temperatures at site B.

At site C, on June 28th (Fig. 5) and August 25th, asphalt was the warmest among the examined surfaces with mean surface temperature up to 49^{o}C. Grey marble and grass were cooler than asphalt up to 12.5% and 21.1% respectively. Grey marble and asphalt seem to have similar colour and albedo but the rough asphalt surface is warmer. Mean air temperature above asphalt was also the highest, reaching 37.3^{o}C. Air above grey marble was up to 6.45% cooler, above grass up to 8.6% cooler and above water up to 14.1% cooler. It should be noted that the sensors above marble and asphalt were located at 1m and 9m distance from the water, respectively, and that at 16:00 in August the air temperature difference between water and marble reached 3.4K and between water and asphalt 8.3K. The respective differences in June were 2K and 4.5K. Air temperature above water and above marble reached the same values when the flow of water stopped for half an hour in the afternoon of 28-06, and the water level in the pool dropped.

Wind speed at site C in August fluctuated between 0.7m/s and 1.8m/s, with an average value of 1.3m/s. Average RH values above the surfaces were up to 25% in June, and up to 29% in August.

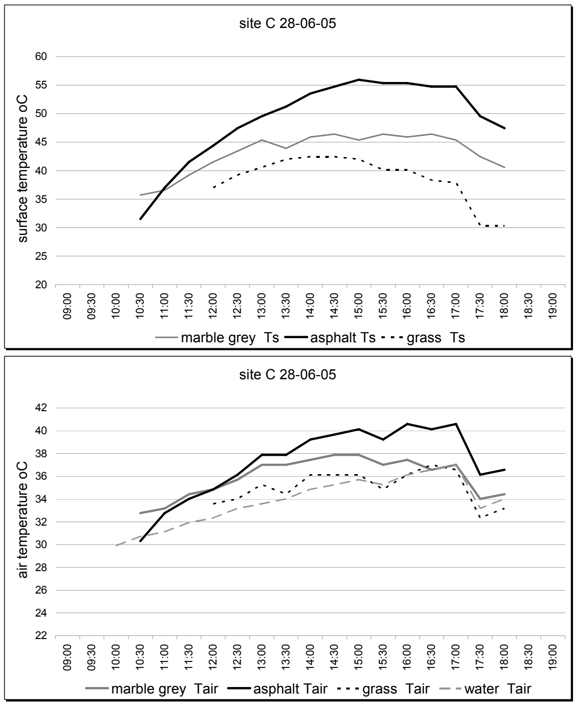

Figure 5: Surface and air temperatures at site C.

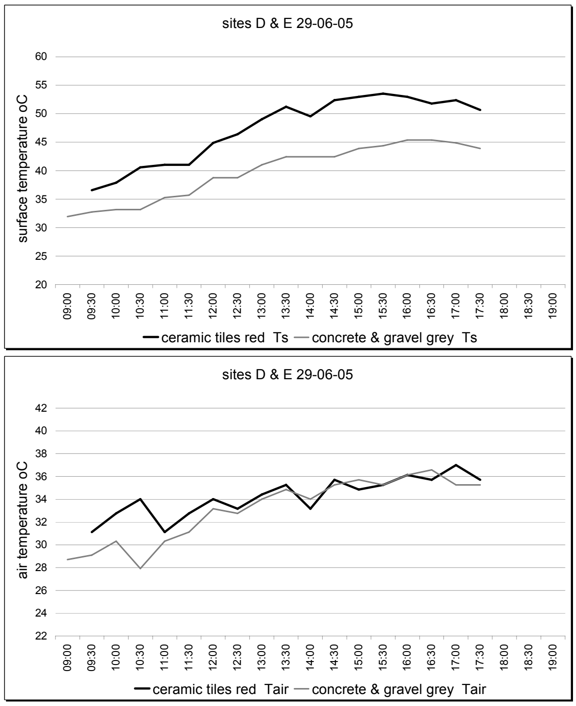

Figure 6: Surface and air temperatures at sites D&E.

The comparison between sites D and E (Fig. 6) revealed once more the effect of reflected solar radiation on the air temperature sensor. Although the light coloured concrete and gravel surface in site D was 16% cooler on 29th of June and 11.8% cooler on the 29th of August than the dark red ceramic tiles (mean surface temperature 47.3°C and 41.5°C) at site E, the air temperature above the light coloured surface was only 2.35% cooler in June and 7.7% warmer in August. Taking into consideration the different configuration of the two sites, the air would have been expected to be cooler in site D, which is surrounded by lower buildings in larger distance, is more exposed to the wind, located in closer proximity to the coast and neighbouring to a large vegetated area. Therefore, the high albedo of the concrete and gravel surface probably affected the sensor, which was exposed to reflected solar radiation.

Wind speed in site D, in August fluctuated between 0.7 and 2.1m/s with an average value of 1.4m/s. Relative humidity recorded above concrete and gravel was higher than that above red ceramic tiles. Average RH at site D was 44% in June and 43% in August, while at site E average RH was 29% and 36% in June and August respectively.

5. SIMULATIONS

5.1 ENV-met v3.0

Simulations of the five areas were performed with Envi-met software [5] and the results of mean air and surface temperatures were compared with the monitored data. The comparison revealed differences lower than 15% in 29 of 36 series of monitored surface temperatures and in 25 of 33 series of monitored air temperatures (Fig. 7).

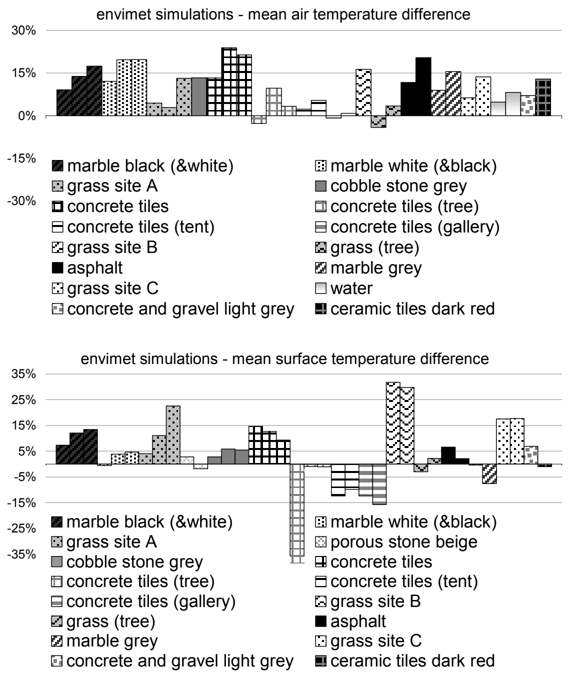

Figure 7: Differences between measurements and simulation results by ENVI-met v.3, for (a) air and (b) surface temperatures.

In particular, regarding the comparison between measured and simulated mean surface temperatures, differences higher than 15% (and up to 38.5%) were presented only in the cases of grass and concrete pavement tiles and are attributed mostly to temporary shading by surrounding obstacles. Regarding mean air temperatures, differences higher than 15% (and up to 23.9%) were observed in 4 cases of marble, 2 cases of concrete tiles, 1 case of grass and 1 case of asphalt.

5.2 RadTherm v8.0

Simulations performed with RadTherm software [6] presented differences lower than 10% between measured and simulated mean surface temperatures (Fig. 8) in 36 out of 38 series of measurements. Only 2 cases of shaded concrete tiles presented higher differences (18.8% and 11.4%), which are attributed to incorrect shading patterns due to dissimilarity between the modelled and the actual shading covers.

The particular software focuses on calculation of surface conditions and does not directly report on air temperature results above different surfaces.

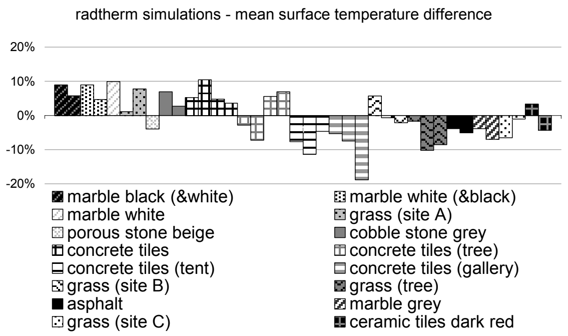

Figure 8: Differences between measured surface temperatures and simulation results by RadTherm v.8

5.3 Measurements - simulations discrepancies

Differences between measurements and simulation results may be a result of several parameters such as cloud cover not included in the weather files, temporary shading by urban equipment not included in the models, watering of grass and discrepancies between the properties of the modelled surfaces and the actual surfaces. Differences may also be attributed to deficiencies of the software calculations. In particular, Envi-met calculates solar radiation according to global position, and wind speed according to an initial input value, without using the actual weather data, while RadTherm does not take into account the effect of vegetation regarding evapotranspiration.

6. CONCLUSION

Monitored data in five urban open spaces, during warm summer conditions, has been used to evaluate the effect of different ground surface materials on the microclimate of each area.

The measurements reveal a link between surface temperatures and surface albedo; i.e. lower temperatures are observed on surfaces with higher albedo, except for the cases of grass, where the influence of evapotranspiration, shade and thermal capacity of soil is higher.

A correlation between air and surface temperatures is also observed except for the cases of two light coloured surfaces (white marble and light grey concrete with gravel). This exception may be attributed to the deficiency of the measurement method which allowed reflected solar radiation to reach the sensor. However, the fact that light coloured surfaces may increase the amount of radiation, reaching an exposed body, raises questions on their suitability for use in open spaces, especially regarding comfort conditions of pedestrians. Studies have reported higher mean radiant temperatures at areas with high albedo surfaces, compared to less reflective surfaces [12].

Surface roughness also seems to have an important role in increasing surface temperatures. A rough asphalt surface seems to be warmer than a smoother surface of marble with similar colour and albedo. Other studies have also reported higher surface temperatures on rough surfaces compared to smooth surfaces of the same colour [2].

The effect of porosity is observed in the comparison of surface temperatures of porous stone and marble. The light coloured porous stone presents similar temperature with white marble which has a higher albedo and a smoother surface. Studies have reported lower temperature of porous pavement materials attributed to higher amount of water exchange between the surface and the deeper soil, which enhances cooling by evaporation [13].

Shaded surfaces (grass and concrete tiles) have lower surface temperatures than the air temperature above them and are over 40% cooler than the same surfaces which are exposed to solar radiation. The temperature difference between different surfaces under shade is small and between the same surfaces under different shading cover is negligible.

The effect of water evaporation may result to differences of air temperature even up to 8.3K in a distance of 9m, as observed by the comparison of air temperature above water and asphalt.

Simulation results, for mean air and surface temperatures, produced by ENVI-met v.3 presented differences from the measured data up to 15% in the majority of examined cases. Simulations in RadTherm v.8 presented mean surface temperature differences lower than 10%. The differences, which are attributed to details in weather data and urban morphology parameters, are considered low enough to ensure accuracy of the simulation results and to allow a further assessment of the effect of surfaces, on a wider range of open spaces with different morphological features as well as seasonal variations.

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