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Urban space's morphology and microclimatic analysis: A study for a typical urban district in the Mediterranean city of Thessaloniki, Greece

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ABSTRACT

The present study investigates the impact of different intervention scenarios regarding morphological characteristics of an urban district of Thessaloniki on microclimatic parameters such as surface, air and mean radiant temperature distribution during a typical summer day. The proposed intervention scenarios include the total replacement of concrete pavement and asphalt streets with similar cool materials, increase of the amount of trees and a combination of the above strategies. The three-dimensional non-hydrostatic climate model ENVI-met v.4 is used for the microclimate simulation. The analysis reveals a significant reduction of surface temperatures due to the replacement of conventional coatings with cool materials of higher albedo and emissivity, while changes in air temperature are of lower importance. However, the combined use of cool materials and additional tree planting can contribute to lower air temperatures through shading and leaves' evapotranspiration.

1. Introduction

The increased rates of urbanisation of the 21st century are considered responsible for a negative impact on microclimatic conditions, provoking the significant rise of air temperature in urban districts [1]. This can be initially attributed to the progressive modification of their morphological characteristics, i.e. the replacement of natural, permeable surfaces with mineral, rough materials such as concrete and asphalt, resulting in large quantities of solar radiation stored and then re-emitted in urban areas. As a result of the decreased sky view factor, shortwave and long wave radiation can be entrapped inside the canyons preventing the urban cooling [2]. Increased building heights and high roughness structure are also considered as serious problems of modern cities due to the induced low wind velocities and the corresponding reduction of convective heat removal [3]. In addition, air temperature distribution in cities is strongly correlated with the urban radiation energy balance, directly affected by the albedo of vertical and horizontal surfaces. Low albedo materials can considerably increase the solar radiation absorbed by building envelopes and urban structures, causing higher surface temperatures and severe intensity of long wave radiation emission. Finally, due to the progressive loss of vegetation and green areas, latent heat through evapotranspiration and the corresponding cooling of air around vegetated areas is strongly reduced [4]. Given that the rise of air temperature provokes a serious increase of the energy consumption used mainly for air-conditioning and also strongly affects the thermal comfort of pedestrians [5], the objective of this study is to investigate the impact of three different strategies on the amelioration of the local thermal environment in terms of surface, air and mean radiant temperatures, in a typical urban district in the Mediterranean city of Thessaloniki. The study focuses on the implementation of cool coatings for the horizontal ground surfaces, additional trees as well as a combination of the above techniques. To date, the quantification of the impact of different strategies towards the microclimate's improvement, in cities of the Mediterranean area, has already gained great scientific attention [6–12]. Regarding the city of Thessaloniki, the existing studies mainly deal with urban rehabilitation projects in urban open spaces such as squares [13,14] or large scale application of green roofs [1]. In this context, the present study aims to provide further information on urban climate's amelioration at a district scale, focusing on a central residential area of the city. Furthermore, given that the climatic conditions of Thessaloniki are similar to those of other cities of the Mediterranean such as Marseille, France, Madrid, Spain or Bologna, Italy, etc. [15], the results of this study are expected to provide valuable knowledge for future urban renovation projects at districts with similar geometric and climatic characteristics.

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2. Description of the study area and climatic conditions

The study area, described in Section 3.1, is located at 3 km east from the center of Thessaloniki (40.65°N 22.9°E). The city is situated in the northern part of Greece, along the North-East coast of Thermaikos gulf. The municipality of Thessaloniki, had a population of around 386,000 in 2007, while the larger metropolitan area had around 1,104,400 inhabitants [16]. The climate of the city is characterized by temperate Mediterranean conditions, with generally hot, dry summers, and mild and wet winters; yet, significant seasonal variations can arise. During winter, time records indicate daily temperatures that reach 6.5 °C on average, falling to 2.1 °C overnight; however, during the coldest winters temperatures can even drop below −10 °C. During summer, average high and low temperatures are around 30.5 °C and 17.5 °C respectively, while the recorded maximum air temperatures of the last decades rarely exceeded 40 °C [17]. Previous scientific studies have investigated the magnitude of air temperature differences between central and suburban areas of Thessaloniki during summer, through the use of experimental data. The obtained results revealed an average temperature difference of around 1.7 °C, while peak differences up to 2.0 °C were observed in the very early morning and also during nighttime, due to the re-emission of the heat that has been trapped in daytime in the urban fabric [18].

The densely built-up site, which is part of the municipality of Thessaloniki, extends to 400 m^2 and contains 6 blocks of residential buildings, mainly constructed between 1970–1980 while the area reached its saturation during 90 s. Open spaces are only limited to street canyons and courtyards of irregular shape between building volumes. The aspect ratio (H/W) (i.e. ratio of canyon height to width) of the main canyons (Pittakou, Kalliga and Voga) varies from 1.0 to 1.6 while there are two narrower canyons with H/W ratio close to 2. The majority of the buildings are 7–8 storeys high and building roofs are mostly covered by cement tiles. Ground surface is shielded by asphalt and concrete paving materials and only a small part is covered by loamy soil and other permeable materials. Vegetation consists of low trees and bushes on the sidewalks along the main streets of the study area while there is only a limited number of a tall mature tree.

3. Methodology and tools

The methodology that was used for this study includes the following steps (Fig. 1): (i) in situ measurements of air temperature during August, in order to identify the existing microclimate conditions, prior to any intervention scenario, (ii) computational domain size evaluation, (iii) evaluation of the accuracy of the ENVI-met tool using the observed values of air temperature and (iv) simulation of the proposed intervention methods in order to assess their impact on the amelioration of the local microclimate.

3.1. *In situ measurements*

In order to investigate the current microclimatic conditions of the study area, a monitoring project of air temperature and relative humidity was carried out during 28 days in August 2015, using high accuracy, weatherproof Onset Hobo data loggers with built-in temperature and relative humidity sensors, suitable for outdoor environments. During the measurement period there were not any extreme heat wave conditions and the mean monthly air temperature was 1.27% higher that the corresponding long-term average monthly value of the period 2012–2016 (based on measurements of the National Observatory records at the Nautic Club). The logger was recording air temperature and relative humidity data at an interval of 1 h.During the monitoring period, sky conditions were generally clear and sunny except of five cloudy and rainy days. The technical characteristics of the loggers that were used are the following:

- Model name: HOBO U23001.
- Operation range: −40 °C to 70 °C for the temperature sensor and 0–100% for the relative humidity sensor.
- Logger resolution: 0.02 °C for the temperature sensor and 0.03% for the relative humidity sensor.

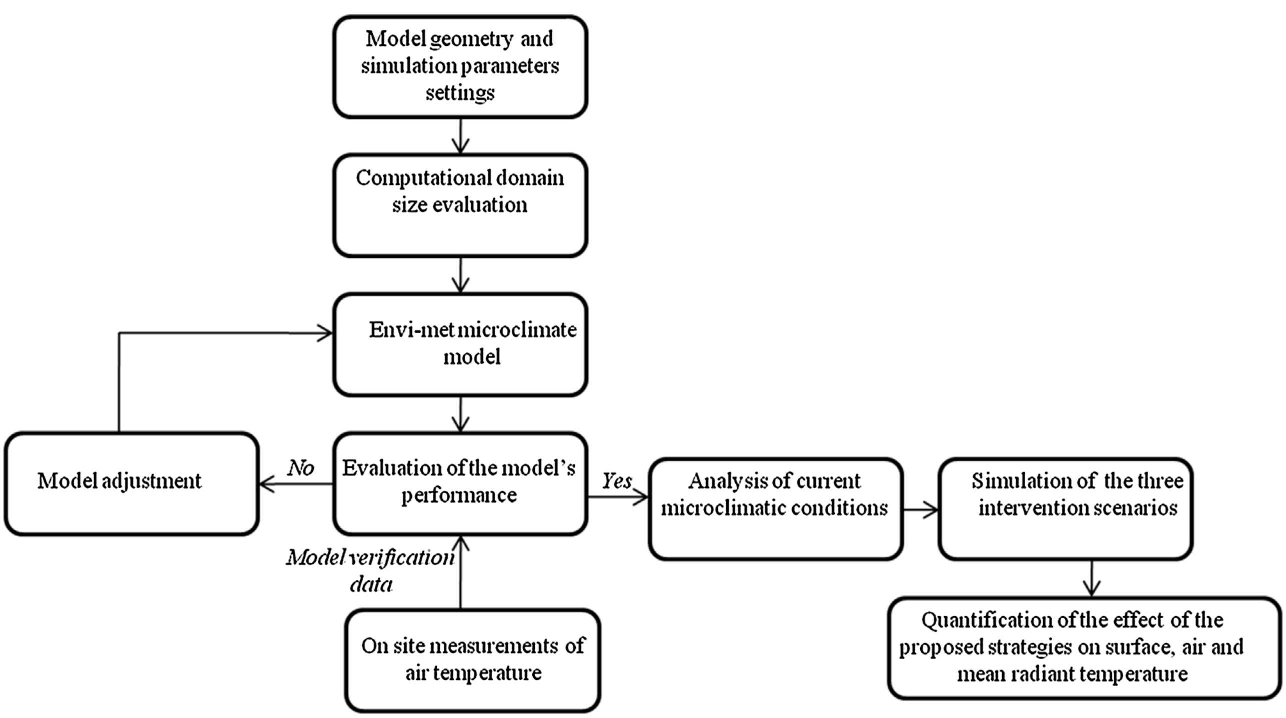

Fig. 1. Flow diagram of the implemented methodology.

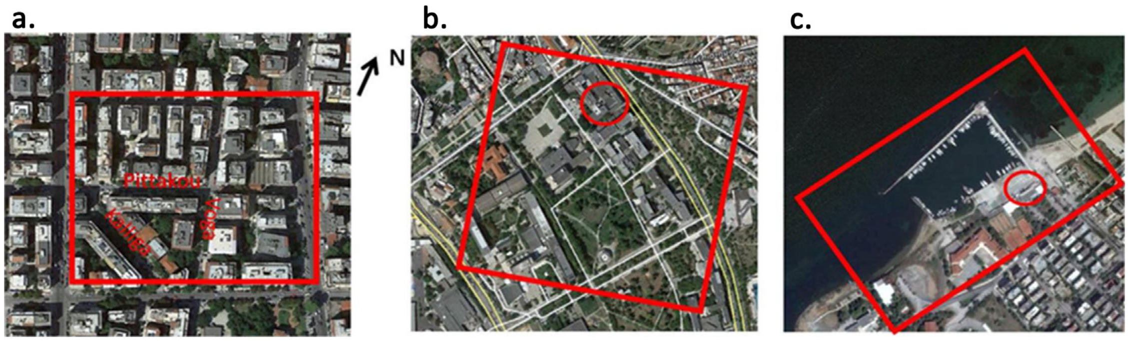

Fig. 2. Aerial photos indicating (a) the study area in the city center, (b) the University campus and position of the Municipality logger. (c) the Nautic Club and position of the National Observatory logger.

The logger was shielded inside a light-colored wooden box (20 cm height), the two vertical sides of which were open to increase ventilation and avoid overheating; it was then mounted on a tripod of 1.0 m height and placed in the middle of a first floor balcony in Pittakou Street, which is one of the main streets of the study area, at a height of nearly 4.5 m from the ground (Fig. 2a). Given that the air temperature sensor was situated on a balcony, special attention was given so as to eliminate potential boundary effects formed along the vertical wall façades that could affect the quality of measurements. In this vein, based on the recommendations of Niachou et al. 2008 [19], the tripod was placed at a distance of 60 cm from the exterior building wall.

In order to perform a comparative assessment, the obtained readings of air temperature were compared with temperature measurements for the same period, acquired by (i) loggers of the Municipality of Thessaloniki, placed at the University campus at the heart of the city, at a height of 40 m (Fig. 2b) (ii) the meteorological station of the National Observatory, placed at the Nautic Club of Thessaloniki, near the sea, at a height of 5 m and in a distance of around 6 km from the University campus (Fig. 2c). As depicted in Fig. 3, during the period of measurements, the mean daily air temperature inside the study area was between 25.0 °C and 31.3 °C, while an average difference of 2.0 °C and 1.4 °C was noted between the above temperature data and those recorded in the University campus and in the Nautic club respectively. Regarding the differences between values of the study area and the campus, the logger of the latter one is placed in a park area with increased vegetation consisting of tall and densely foliated trees, lower solar gains, lower building density and thus better microclimatic conditions.

The logger is also mounted at an important height of around 30 m above ground where the wind effect and thus the air cooling is more prominent than in lower heights. In the case of the Nautic club logger, the sea breeze plays a major role in the recorded air temperature data. In the city of Thessaloniki, the mean frequency of the sea breeze occurrence is around 17 days per month, during the warm period of the year [20]. As previous studies have also indicated, places close to the sea are much cooler than districts inside the densely populated city centres; increased heights of buildings together with high surface densities act as wind barriers, inhibiting thus the sea breeze penetration at street level [21].

3.2. ENVI-met simulation set-up

ENVI-met is a three dimensional microclimate model, based on the fundamental laws of fluid dynamics and thermodynamics, designed to simulate complex surface-vegetation-air interactions in the urban environment. Two main input files are required: (i) the area input file, where the building layout, vegetation, soil type, receptors and project location parameters are defined and (ii) the configuration file, containing simulation settings regarding initialization values for meteorological parameters, definition of output folder names and timings. ENVI-met model has been applied in a great number of scientific studies dealing with urban heat island and human heat stress mitigation strategies [22–25]. The latest version, released in 2014, overcomes important limits of the previous one, as it takes into account different U-values for the buildings' envelope components but also thermal mass and heat inertia of the building elements. Another important improvement concerns the possibility of forcing air temperature and relative humidity input parameters by creating a user specified weather profile with hourly

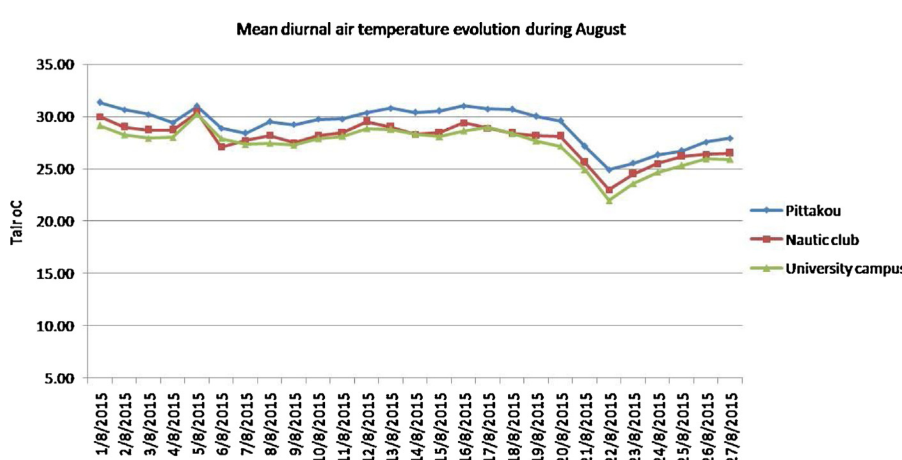

Fig. 3. The evolution of mean air temperature during the period of measurements at all sites.

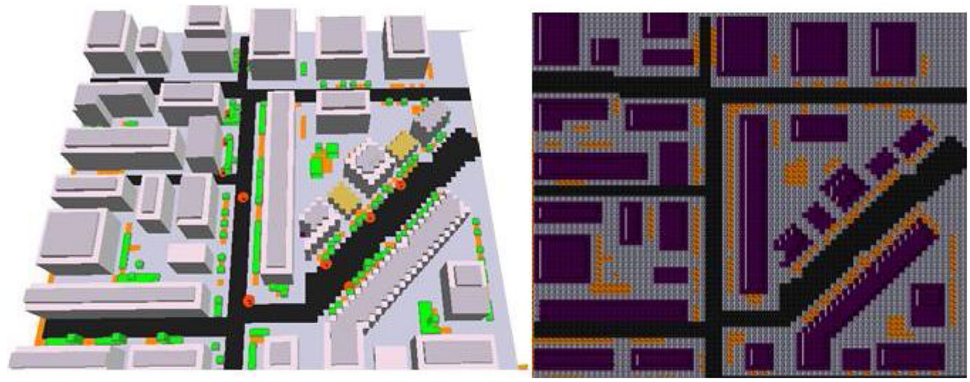

Fig. 4. 3D area model and plan of the study area.

Table 1
Input parameters for ENVI-met simulation.

Input parameters	9th of August 2015- Initial simulation	9th of August 2015 After model adjustment
Mean wind speed at 10 m above ground (data from the meteo station of the National Observatory)	0.80 m/s	0.40 m/s
Prevailing wind direction (data from the meteo station of the National Observatory)	SW (225°)	SW (225°)
Roughness length	0.1[a]	0.1[a]
Air temperature forcing	Hourly data from meteo station	Hourly data from meteo station increased by 2 °C
Relative humidity forcing	Hourly data from meteo station	Hourly data from meteo station
Cloud coverage	No clouds	No clouds
Specific humidity at 2500m	7 g/kg[a]	7 g/kg[a]
Solar adjustment factor	1	1
Soil upper layer (0–20 cm) initial temperature (data from meteo station of Aristotle University of Thessaloniki)	305 K	305 K
Soil upper layer(20–50 cm) initial temperature (data from meteo station of Aristotle University of Thessaloniki)	304 K	304 K
Soil deeper layer (below 50 cm) initial temperature	293 K[a]	293 K[a]
Soil upper layer(0–20 cm) moisture content[a]	50%[a]	50%[a]
Soil upper layer(20–50 cm) moisture content[a]	60%[a]	60%[a]
Soil upper layer(below 50 cm) initial moisture content[a]	60%[a]	60%[a]

[a] ENVIi-met default values.

T_{air} and RH data derived from nearby meteorological stations. The full forcing function is a major improvement, as it provides higher simulation accuracy and more realistic results [26,27]. For this study, numerical simulations using ENVI-met v.4 were performed for the 9 August 2015, which was considered as a typical summer day under clear sky conditions. The simulation domain, subdivided in a 3-D grid is depicted in Fig. 4 and its size was defined after a sensitivity check, as described in the following paragraph. The simulations were carried out for 24 h with a time step of 1 h. The set of meteorological parameters that were defined for ENVI-met preliminary simulation are the following: (i) Wind speed at 10 m was set to 0.8 m/s, according to National Observatory recordings (mean wind speed value for the simulation day), (ii) air temperature and relative humidity hourly values were obtained from the nearby meteo station of Thessaloniki Municipality, (iii) ENVI-met default values were used for roughness length and specific humidity at model top. Building walls and roofs albedo values were set to 0.4 and 0.3 respectively. All model initialization parameters are given in Table 1.

3.2.1. Envi-met computational domain size sensitivity check

In order to define the suitable spatial resolution, a domain size sensitivity analysis was performed. The study area was modelled using 2 different domain sizes: 136*136 grids and 86*86 grids corresponding to a horizontal grid size of 1.5*1.5 m and 2.5*2.5 m respectively. In the vertical axis, 20 grids of 3 m were used in both models. The simulations were performed under the same meteorological conditions. With the aim of assuring numerical stability and minimize boundary effects which may affect the output data [27], 10 nesting grids were set around the main model area, for both domains. For this comparison, air temperature results at a receptor point in Pittakou Street were compared. Fig. 5 presents the comparison of the air temperature for the two domain sizes in a scatter plot. The root mean square deviation of the two situations is 0.11 °C, indicating that further simulations with a 2.5*2.5 grid size and a 86*86 number of grids in the domain introduce a very small and acceptable deviation in air temperature results, while the simulation duration is significantly reduced.

3.2.2. ENVI-met evaluation

The precision of the microclimate simulation results strongly depends on the initial boundary conditions and the input data; therefore, special attention should be given when defining the initial simulation parameters [28]. Checking on the adequacy of the model is thus crucial since the early phases of the study. In our case, the accuracy of the ENVI-met model was assessed by comparing the series of air temperature measurements, carried out during the selected day of the 9th of August 2015, with the corresponding simulated values. Based on the recommendations of Willmot [29], the statistical evaluation of the model was performed using

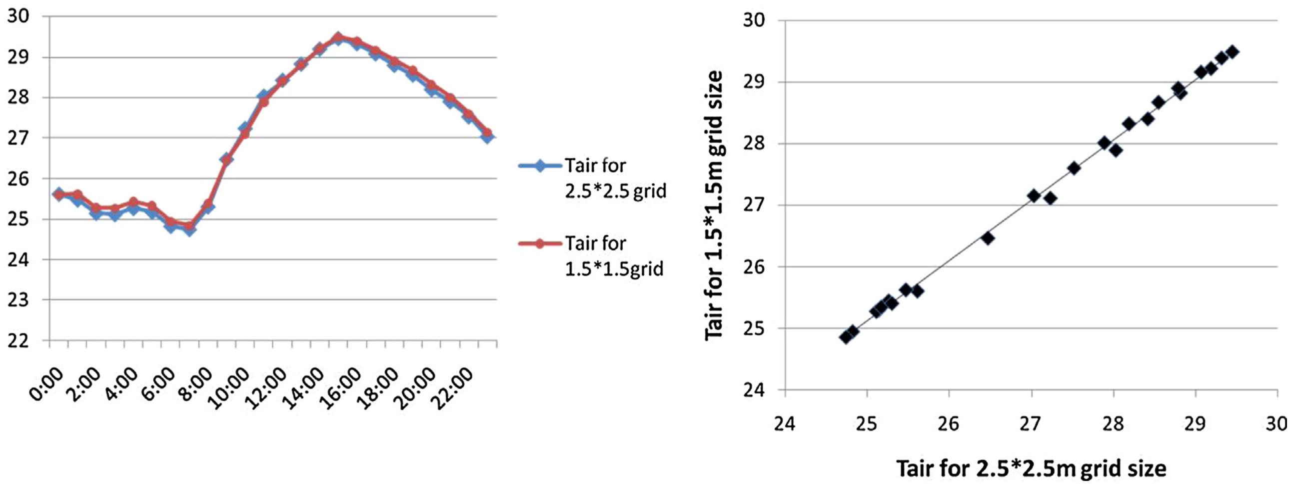

Fig. 5. Comparison of the air temperature results using a scatterplot, for two different domain sizes. Air temperatures in the two models present slight differences and thus, the trendline is almost perfectly 45°.

a set of indices that describe the magnitude of difference between observation and prediction. The recommended measures include: (i) the root mean square error (RMSE) (ii) the mean absolute error [30] and (iii) the index of agreement (d). The RMSE and the MAE provide information on the average error and are generally considered suitable measures for the model's performance. Regarding the index of agreement, it indicates how possible is for the model to predict a variable without errors with values ranging from 0 to 1.

In the preliminary simulations, the diurnal amplitude of air temperature was underestimated and high values of the statistical indices were obtained, indicating the need of model calibration by adjusting some of the initial input data. Previous studies have suggested that air temperature evolution is significantly sensible to wind speed [31]. In our case, the provided value of the average daily wind speed, derived from a meteorological station situated near the sea, was progressively decreased in order to take into account the wind velocity attenuation inside the urban district. After a number of tests, the average mean wind speed was set to 0.40 m/s and the hourly values of air temperature forcing were increased by 2 °C, resulting in a generally good agreement of the simulated values with the onsite measurements and in acceptable magnitudes of statistical indices (Fig. 6). The comparison between observed and simulated air temperature values revealed that the model generally underestimated the diurnal air temperature evolution with maximum deviations being reported between 12:00 and 15:00. The tendency of the model to underestimate diurnal air temperature variations has been also previously mentioned by [32] and [33] while other studies have found that the model underestimates (overestimates) daytime (nighttime) air temperature [23,34,35].

Differences between modelled and measured air temperature values and the magnitude of the corresponding errors can be explained by the following causes: (i) the anthropogenic heat flux resulting from the use of air conditioners, transportation and other human activities is not taken into account during the microclimate simulation. As previously mentioned, the study area is situated in the densely populated city center, characterized by increased traffic during daytime and also a major number of split units for air conditioning, which are extremely common in Greek market, when it comes to cooling purposes; indicatively, the corresponding sales have dramatically increased from 76,000 units in 1990 to more than 200,000 units in 2000 [36]. Given that the A/C units are mainly hanging on the buildings' facades, the amount of rejected heat is significantly important at the street level, enhancing thus the ambient air temperature and also the electricity demand [37]. In this context, a previous study in Tokyo has indicated that the heat flux released from air conditioners can provoke considerable increase urban air temperatures of around 1 °C–2 °C on summer weekdays [38] while similar results were reported on a study carried out in several American cities, where the increase of air temperature due to anthropogenic heat was estimated around 1.7 °C [39], (ii) The effect of multiple reflections and the entrapment of longwave radiation due to reduced sky view factor are not taken into account in the basic version of Envi-met v.4. High H/W ratios and the induced low opening to the sky involve inferior infrared losses and reduced ability of the urban surfaces to cool down increasing thus the ambient air temperature through convention [40], (iii) air temperature on the boundaries of the model correspond to records of the campus meteo station and not from a sensor at the domain entry. As a result, higher ambient air temperatures on the boundaries of the urban district were not handled by the model.

Based on the previous remarks and on statistical indices values, already accepted in previous ENVI-met evaluation studies [23,41–43], the model can be considered as a reliable tool for microclimate simulation, especially when taking into account that the aim of this study is to establish relative quantities such as air and surface temperature reductions rather than absolute values.

3.3. Simulation scenarios

In order to quantify the impact of different strategies on the amelioration of local microclimatic parameters, four different scenarios were simulated (Fig. 7):

- Case A: current situation.
- Case B: total replacement of concrete pavements and asphalt streets with the corresponding cool materials with high albedo and emissivity.
- Case C: increase of the number of tall and dense trees inside the main canyons. Crown width is also increased.
- Case D: combination of the above strategies.

4. Results

4.1. The effect of cool materials on surface and air temperatures

Cool materials are characterized by increased solar reflectivity and high infrared emittance and are considered as a solution towards the urban heat island mitigation. Due to their thermophysical properties, they absorb smaller amounts of solar radiation,

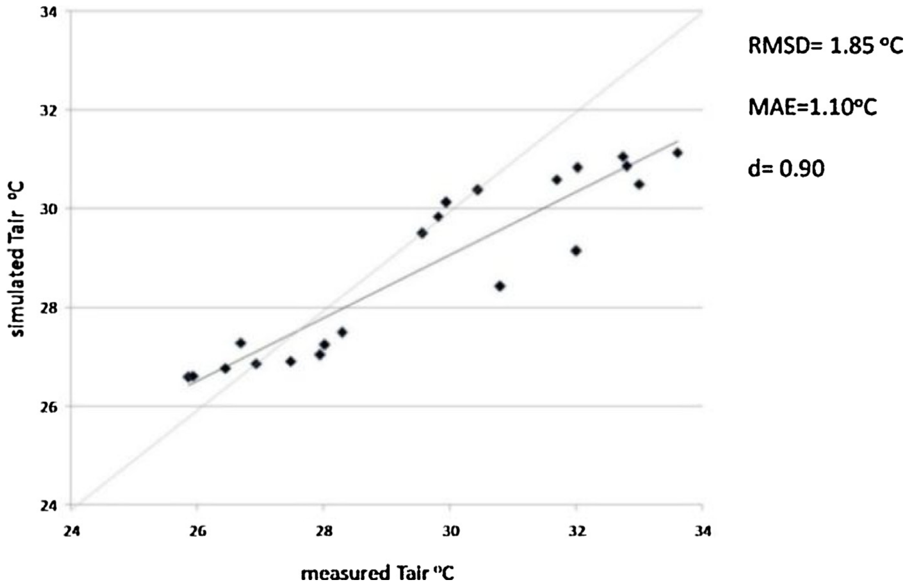

Fig. 6. Evaluation of observed vs. simulated air temperature time series.

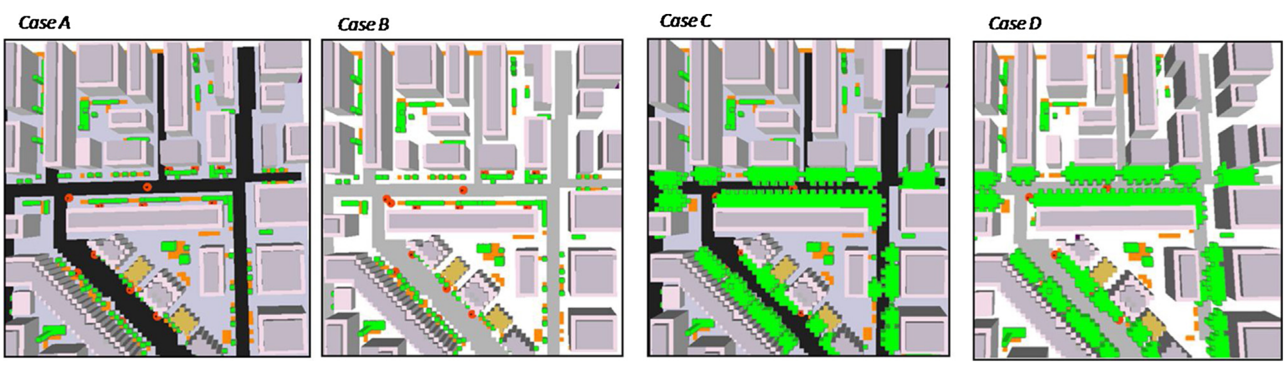

Fig. 7. Area input files' 3D view of the current situation and the different intervention scenarios: Case A: current conditions; Case B:cool materials application; Case C: Additional vegetation; Case D: combined application of cool materials and additional trees.

resulting in lower heat storage and smaller surface temperatures. Kinouchi et al. [44] have performed surface temperature measurements during summer on a new type of pavement with high albedo, the creation of which is based on the application of an innovative paint coating on conventional asphalt pavement. Experimental testing has shown a maximum surface temperature difference up to 15 °C between the conventional asphalt pavement and the new one. In the same context, Synnefa et al. [45] have evaluated the thermal performance of 5 thin layer asphalt samples with high solar reflectance, applied on existing and new asphalt pavements and they reported major measured surface temperature differences due to the difference in albedo, up to 12 °C. As a result of lower surface temperatures, longwave radiation emittance and increase of ambient air temperature through convention can be significantly attenuated [46]. However, in the urban context, the spatial configuration of the study area will play a significant role towards the extent of microclimate parameters' alteration [47]. Urban morphology characteristics such as orientation and H/W ratio will strongly influence the exposure of the canyon surfaces on direct solar radiation, altering thus the magnitude of the cool materials effect on ground surface temperature reduction. More precisely, the ground surfaces of North-South (N-S) canyons will be fully exposed at midday but mostly shaded in the very early morning and late afternoon; in East-West (E-W) canyons, ground surfaces will be fully exposed in the early morning and late afternoon but also at midday due to increased solar heights reported for the city of Thessaloniki. Yet, for both orientations, the sky view factor consists a crucial parameter regarding the amount of solar radiation arriving in horizontal surfaces.

For this study, the following surface properties of ground surface materials have been taken into account [24,48]:

- Conventional dark asphalt: emissivity = 0.90 and albedo = 0.12
- Conventional concrete pavement: emissivity = 0.90 and albedo = 0.30
- Cool grey asphalt: emissivity = 0.90 and albedo = 0.40
- Cool grey pavement: emissivity = 0.92 and albedo = 0.70

Fig. 8i.a and i.b illustrate the absolute values of surface temperature distribution for cases A and B (i.e. the existing case and the use of cool materials) during noon. Fig. 9i.b depicts the corresponding surface temperature differences inside the study area after the cool materials' application (Case A-Case B). In Pittakou E-W canyon, almost 50% of the ground is kept in shadow, presenting rather small surface temperature alterations due to cool materials, varying from 0.30 °C–2.0 °C. However, an important surface temperature reduction around 6 °C–8.5 °C and 8 °C–10.5 °C was reported for the exposed asphalt and concrete pavements respectively. Regarding Voga N-S canyon, part of ground surfaces was kept in shadow till 11:00 but during noon, all ground surfaces are fully exposed to solar

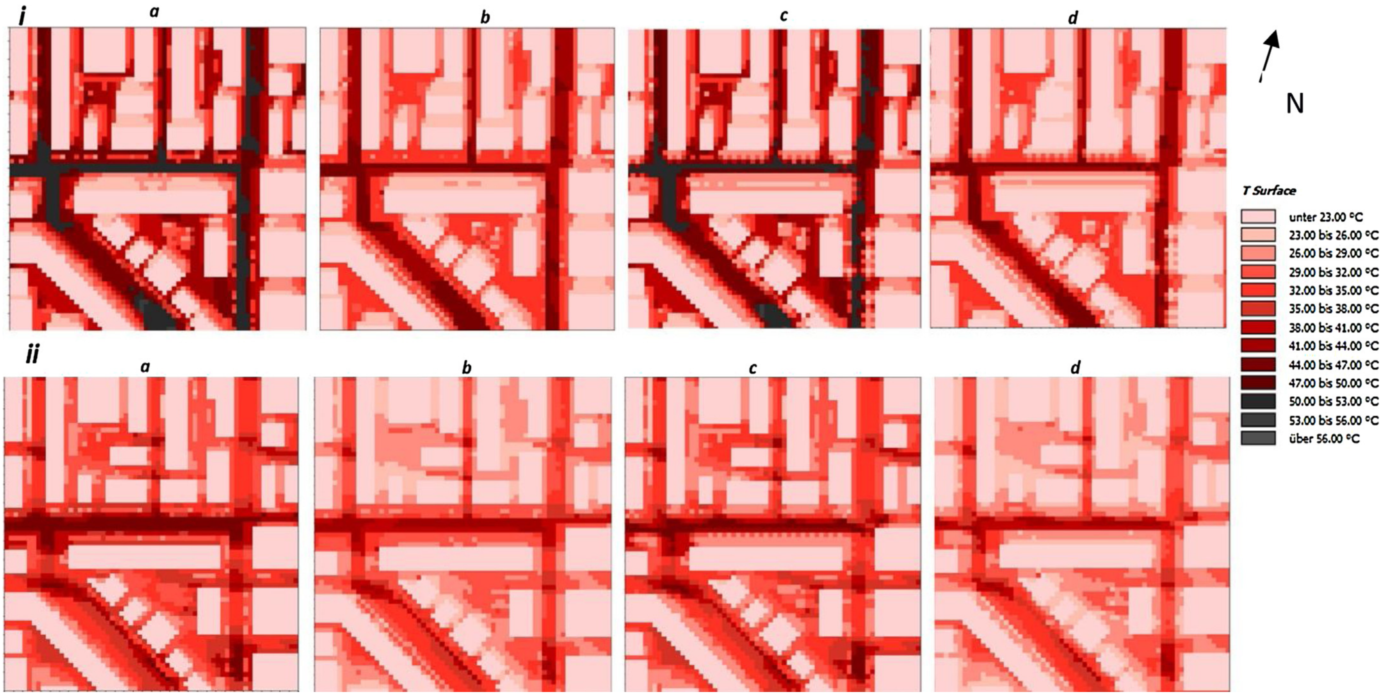

Fig. 8. Absolute values of surface temperature distribution at (i) 12:00 and (ii) at 16:00 for the four case studies: (a) current condition; (b) use of cool materials; (c) additional vegetation; (d) combination of cool materials and additional vegetation.

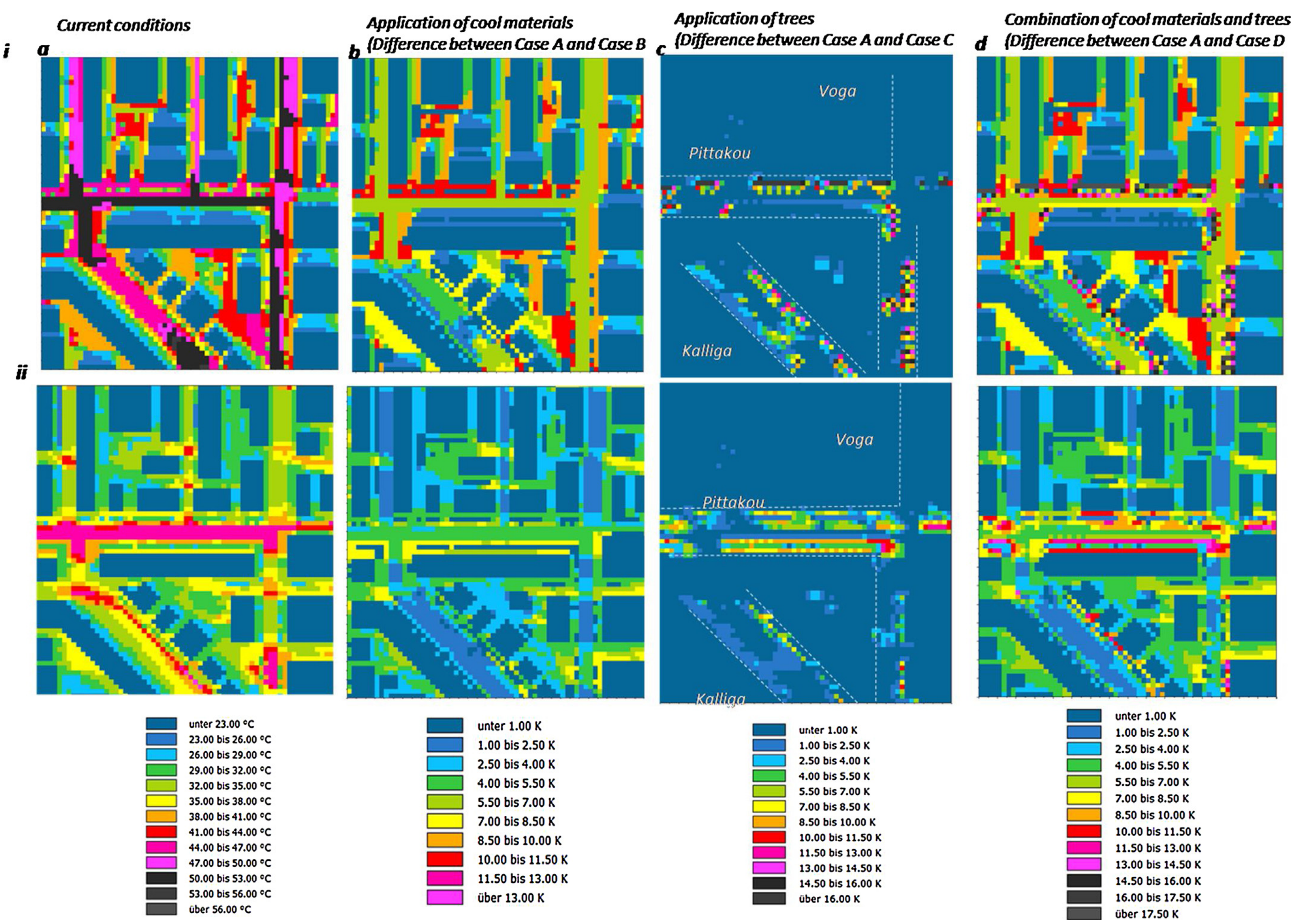

Fig. 9. Ground surface cooling potential of the different proposed strategies at (i) 12:00 and (ii) 16:00: Comparison of (a) current conditions with (b) cool materials application, (c) extra trees and (d) combined application of reflective coatings with additional vegetation.

radiation. Once again, the use of cool materials resulted in very important decrease of surface temperature, reaching maximum values of 9 °C and 10 °C for the exposed asphalt and pavements respectively; the surface temperature change for areas being previously shaded was reported around 8.5 °C. In this line, it is important to note that the thermal properties of cooler asphalt and pavements (i.e. volumetric heat capacity and thermal conductivity) have not been modified when compared to the base case scenario. Thus, the lower surface temperatures are only attributed to the significantly higher amounts of solar radiation that are reflected and not absorbed by the ground surfaces. Regarding the narrowest canyons of the study area, smaller asphalt surface temperature reductions, around 3 °C–6 °C were observed due to solar obstruction. In the afternoon, when Pittakou E-W street is fully exposed to solar radiation, a reduction of 4.5 °C–7.0 °C and 5.0 °C–7.5 °C was observed for the asphalt street and pavements respectively, with a maximum temperature difference of 8.5 °C for cross road areas being exposed to solar radiation since early the morning. Little temperature modification, up to 2 °C–4 °C was reported for ground surfaces in Kalliga NW-SE canyon and Voga N-S canyon, an important part of which has been shaded by building volumes since 14:00 (Fig. 8ii.a, ii.b and Fig. 9ii.b). Similar magnitudes of surface temperature reduction under hot summer conditions werealso reported in previous studies [49,50].

Thereafter, the potential of cool materials towards the reduction of ambient air temperature is examined. The absolute values of air temperature distribution at (i) 12:00 and at (ii) 16:00 for the (a) current condition and (b) use of cool materials are depicted in Fig. 10i.a and i.b. A review of previous studies investigating the thermal impact of cool materials, reported maximum ambient air temperature decrease ranging from 0.2 °C to 3 °C, depending on the albedo increase and the spatial configuration of the study area [48]. In this study, all simulation results refer to a height of 1.5m, which corresponds to the human – biometeorological height [26]. The analysis revealed that increasing the asphalt and pavements reflectance by 0.28 and 0.4 respectively, caused an air temperature reduction around 0.3 °C–0.5 °C and 0.4 °C–0.6 °C in Pittakou and Kalliga Street respectively, with maximum values close to 0.65 °C, mainly at places that were receiving direct solar radiation for a long period (Fig. 11i.b). In the afternoon, the average air temperature reduction in Pittakou canyon ranged from 0.30 °C to 0.40 °C whereas lowest alteration around 0.25 °C–0.35 °C was noted in the shaded parts of the study area (Fig. 11ii.b).The obtained results comply with previous studies, indicating that the implementation of cool materials in urban street canyons, results in a notable reduction of surface temperatures, while their contribution towards the decrease of air temperature is less important [47,49,51].

4.2. The effect of additional vegetation on surface and air temperatures

The following scenario involves (i) the addition of trees in order to create a continuous shading canopy in both sides of Pittakou Street and (ii) the replacement of the existing trees with taller and denser ones in Kalliga and Voga street. To date, urban greenery, involving additional trees and park areas, has been widely investigated as a solution to fight increased urban air temperature and pedestrians' thermal discomfort [26,52–54]. Green spaces create additional solar protection to surfaces, resulting in lower temperatures and thus lower sensible heat transfer to the air. In parallel, increased latent heat through the evapotranspiration process can contribute to the urban cooling. A very common scientific indicator for trees and plants is Leaf Area Index, representing the ratio of the one-sided area of leaf to the total ground surface area. ENVI-met model uses the Leaf Area Density (LAD) for the characterisation of plants, derived from Leaf Area Index at 10 intervals along the height of the plant [25]. Plant characteristics regarding trees height, crown width and LAD values that were taken into account for the simulations are presented in Table 2.

Fig. 8i.c illustrates the absolute values of surface temperature distribution for case C at 12:00 (i.e. extra vegetation) while Fig. 9i.c presentsthe surface temperature cooling potential of the corresponding strategy (Case A–Case C). At this point it has to be mentioned that zero surface temperature alteration was reported in places that there was no change of vegetation. Thus, for the sake of the clarity, the traces of the main street canyons are displayed in the cross comparison diagrams (Fig. 9i.c and ii.c)

The analysis revealed that, during noon, tree shading contributed to major surface temperature reduction of 7 °C–15 °C on solar protected pavements of the study area, while already shaded parts of the ground surfaces presented lower temperature by 4 °C–8 °C. Maximum values of asphalt temperature alteration were reported in lower parts of Voga Street, where tree shading covered the 75% of street width, contributing to a temperature decrease up to 16 °C. Moreover, replacing concrete pavement with loamy soil led to a major surface temperature drop by 16 °C–19 °C mainly attributed to the evaporation process of the water and moisture passing through the soil pores. In the afternoon, a reduction of 2.7 °C–8.5 °C was observed for paved surfaces whereas asphalt temperature was lower by 4 °C–10 °C because of the solar protection (Fig. 9ii.c). Similar high magnitudes of surface temperature alteration, in areas underneath the trees foliage, were also reported in previous studies [55–57]. Finally, in ground surfaces that are still not protected by trees foliage (i.e. in the middle of Pittakou street canyon) no surface temperature alteration was reported.

As previously mentioned for cool materials, achieving the surface temperature reduction of urban horizontal surfacesis of major importance, when trying to mitigate the urban heat island effect, as it contributes to a further reduction of the longwave radiation intensity and thus to lower sensible heat flux to the ambient air through convection phenomena. Previous literature reviews have reported considerable diurnal air temperature reductions inside the urban parks, compared to the neighbouring urban areas, with maximum reported differences reaching 5 °C, due to increased evapotranspiration, lack of anthropogenic heat release, and increased solar protection [58]. Yet, existing studies have indicated that the cooling influence of additional greenery inside street canyons can be rather minor during daytime, in urban zones where surface densities and anthropogenic heat release from transportation are very high [52,59]. The same conclusion was drawn in the present study where, during noon, a minor change between 0.15 °C and0.25 °C was observed inside Pittakou and Voga Street (Fig. 10i.c); at 16:00, additional trees resulted again in a rather small decrease of air temperature of around 0.35 °C–0.40 °C inside Pittakou canyon with a maximum value of 0.43 °C, observed below the trees' foliage (Fig. 10ii.c). The above mentioned minor air temperature differences can be attributed to the fact that important parts of the street canyons are still exposed to solar radiation and also to the heavy traffic and the corresponding heat release reported to the main adjacent avenues of the study area. The acquired results comply with previous studies, indicating the major impact of trees on the surface temperature modification but a lower impact on the decrease of air temperature inside the street canyons [25,60].

4.3. The effect of combined methods on surface and air temperatures

Combining cool materials with additional vegetation resulted in the most significant modifications in terms of surface and air temperature. As depicted in the cross comparison diagrams of Fig. 9i.d and ii.d, surface temperatures for asphalt and concrete pavements

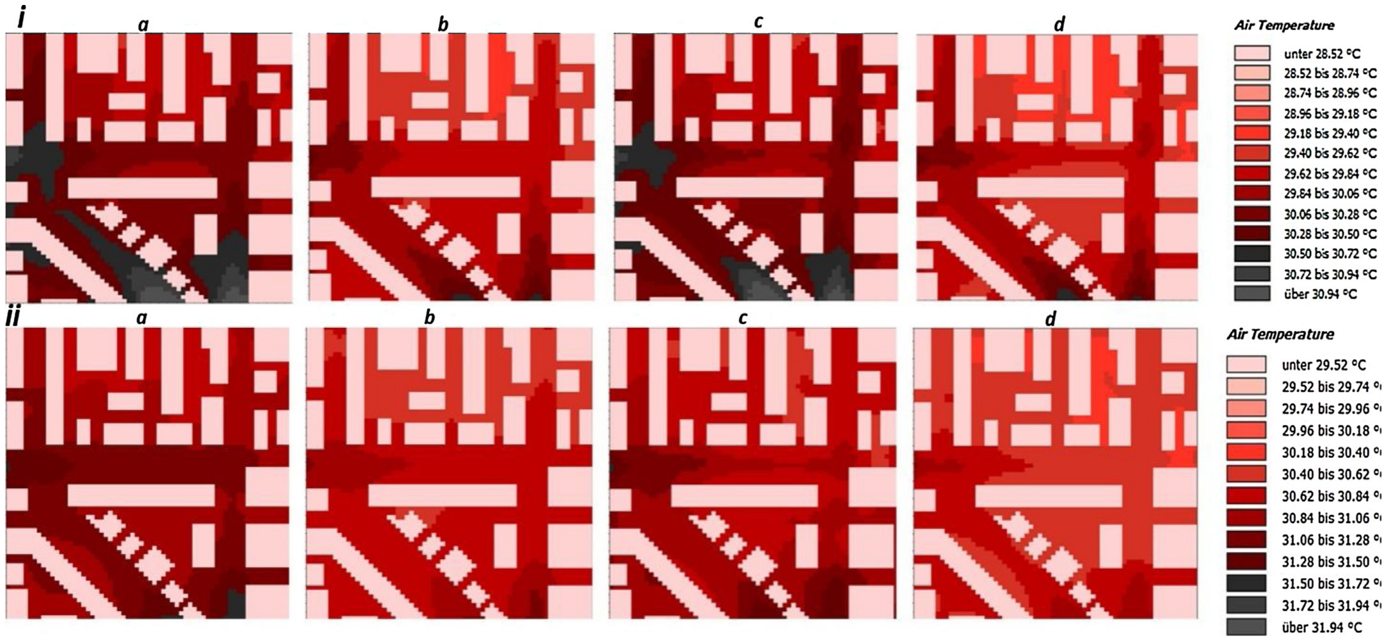

Fig. 10. Absolute values of air temperature distribution at (i) 12:00 and at (ii)16:00 for the four case studies: (a) current condition; (b) use of cool materials; (c) additional vegetation; (d) combination of cool materials and additional vegetation.

Table 2
Plant characteristics regarding height, crown width and L.A.D. All types correspond to deciduous trees.

Case studies	Type	Height	Crown width	LAD
A and B	1	3m	2.5m	0.00;0.00;2.10,2.10;2.10;2.10;2.10;2.10;1.70;0.00
	2	2m	2.5m	0.00;0.00;0.00;0.075;0.250;1.150;1.060;1.050;0.920;0.00
C and D	3	7m	5m	0.00;0.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;0.00

were considerably lower compared to the base case scenario, due to lower heat storage provoked by the high albedo materials and additional shading; maximum reductions of 17 °C and 12 °C were reported for the pavements, at 12:00 and 16:00 respectively. In addition, during noon, the lower surface temperatures and the reduced heat convection to the air, as well as the increased evapotranspiration and conversion of the direct solar radiation to latent heat, caused a reduction close to 0.50 °C and 0.60 °C in Pittakou and Kalliga Street while the maximum change of 0.8 °C was observed in lower parts of Voga Street (Fig. 11i.d). In the afternoon, the air temperature alteration in Pittakou Street was around 0.50 °C–0.70 °C, whereas in most of the other parts of the study area, a lower difference close to 0.4 °C–0.5 °C was reported due to their shading by building volumes (Fig. 11ii.d).

4.4. The impact of the different cooling strategies on mean radiant temperature

Mean radiant temperature (Tmrt) is a parameter that sums up all short and long wave radiation fluxes issued from solar irradiation and from surroundings with different surface temperatures on a specific point [61]; it is considered to have the strongest influence on the calculation of many thermo-physiological indices used for the description of human thermal comfort including Physiologically Equivalent Temperature (PET) [62], Standard Effective Temperature [63] and the more recent Universal Thermal Comfort Index [64]. To date, several procedures for determining Tmrt have been reported in the existing literature, depending on whether this variable is modelled or measured [65–68]. In this respect, the ENVI-met model provides a reasonable approximation of Tmrt at the pedestrian's level [53,69] described by the following equation [70]:

$$\mathrm{Tmrt} = \left[\frac{1}{\sigma}(Et(z) + \frac{ak}{\varepsilon\rho}(Dt(z) + It(z))\right]^{0.25}$$

Where:

σ αk and εp are the Stefan Boltzmann constant, a body's total absorption coefficient for shortwave radiation and emissivity;

Et (z), Dt (z) and It(z) are longwave, total diffuse shortwave and direct shortwave radiation flux absorbed by a body at height *z*, respectively.

The ability of the model to accurately reproduce Tmrt values has been already investigated in previous scientific studies; the obtained results indicated that Envi-met tends to overestimate daytime and underestimate night-time Tmrt values [69,26,71] whereas the magnitude of the daytime maximum values can be accurately reproduced [72,73]. As the authors claimed, potential discrepancies between simulated and experimental values of Tmrt may be attributed to the fact that static sky-condition and steady state wind profile are assumed during the simulation runs [71,73] while daytime solar radiation is also slightly overestimated [74,69]. Hence, fairly acceptable magnitudes of statistical errors, indicating differences between modelled and experimental Tmrt, were obtained suggesting that the Envi-met model could be further applied for microclimate analysis [75].

Based on the above mentioned remarks and in order to identify the way the three proposed mitigation strategies can affect outdoor thermal comfort, values of the mean radiant temperature were defined for four specific points in Pittakou street canyon (Fig. 12) at midday, during the peak solar radiation intensity. At this point, it has to be mentioned that experimental values of Tmrt were not

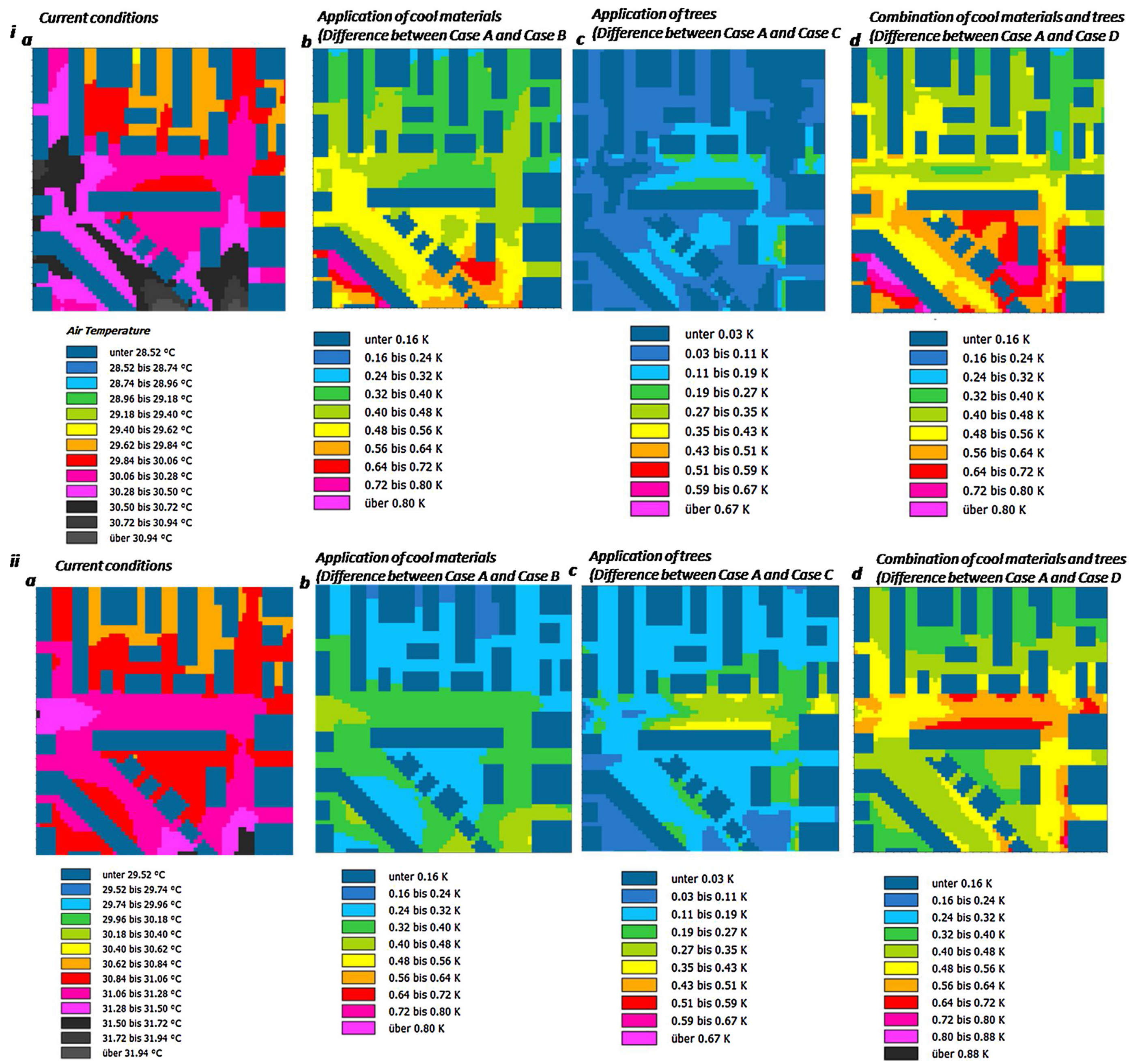

Fig. 11. Ambient air cooling potential of the different proposed strategies at (i) 12:00 and (ii) 16:00: Comparison of (a) current conditions with (b) cool materials application, (c) extra trees and (d) compined application of reflective coatings with additional vegetation.

available due to limitation of resources and as a result, the analysis was mainly focused on the comparison of the change of the climatic parameter with respect to the base case scenario.All results refer to a height of 1.5 m. The examined points are the following:

- P1: exposed pavement during current conditions (protected after intervention scenario of case 3)
- P2: protected pavement below tree's foliage
- P3: exposed asphalt street-middle of the canyon
- P4: exposed asphalt street, at the border of the sidewalk (protected after intervention scenario of case 3)

Table 3 summarizes the simulation results of mean radiant temperature and air temperature for the 4 points during noon, for the four simulation scenarios. Concerning current conditions, it can be noticed that Tmrt was significantly higher in places exposed to solar radiation (i.e. P1, P3 and P4) compared to those protected by tree's foliage (i.e. P2), with reported differences reaching 17.0 °C (P4-P2). This can be attributed to the fact that trees' foliage acts as a radiation shield, preventing solar radiation from reaching the ground and being reflected; similar magnitudes of Tmrt differences between solar exposed and protected points have been reported in previous scientific studies [51,76].

Discussing the potential of cool materials as a mitigation strategy towards the urban heat island and its negative effects on outdoor thermal environment (Case A-Case B), it could be claimed that their application would lead to a significant reduction of ground surface temperatures and as a result, to lower sensible heat flux to the air. At a second step, the implicit expectations of lowering the ambient air temperature would involve improved thermal

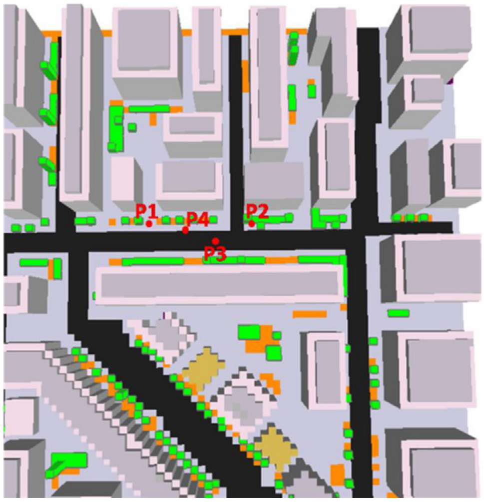

Fig. 12. Site model indication the locations of mean radiant temperture investigation.

Table 3
Summarizing data of mean radiant temperature for the 4 points during noon, for Case A (current conditions), Case B(cool materials application), Case C (additional trees) and Case D (combined strategies), for August 9th 2015.

		P1	P2	P3	P4
Mean radiant temperature (°C)	Case A	60.65	43.55	60.95	61.01
	Case B	65.06	45.75	65.5	65.63
	Case C	40.12	39.82	60.42	44.41
	Case D	44.81	44.14	63.2	48.80
Air temperature (°C)	Case A	30.21	30.01	30.20	30.19
	Case B	29.75	29.70	29.80	29.76
	Case C	30.03	29.93	30.08	30.01
	Case D	29.65	29.59	29.80	29.68

comfort for pedestrians in outdoor urban spaces [47]. However, the achieved reduction of air temperature is counterbalanced by the high rise of mean radiant temperature (Tmrt), which is strongly correlated with the human energy balance [77]. More precisely, increasing pavements' and asphalt's albedo by 0.4 and 0.28 respectively, led to an average rise of Tmrt close to 4.5 °C for P1, P3 and P4; a lower rise of 2.2 °C was found for P2. It has to be emphasized that the small increase of Tmrt below the foliage was attributed to the fact that trees may offer significant protection of direct solar radiation, but only in part function as a complete surface shields and thus as a barrier to reflected solar radiation (this would have been the case of increased trees density, such as parks or low height greenery, such as bushes and hedges, providing solar shielding and a barrier to reflected radiation) [51].

The analysis of the data corresponding to the creation of a dense shading canopy in both sides of Pittakou street canyon (i.e. case C) revealed the prominent effect of shading on mean radiant temperature. In this scenario, only a small part in the middle of the canyon was fully still exposed to solar radiation. Points P1and P4, being henceforward in shade presented a noticeable reduction of 20.5 °C and 16.6 °C respectively, while Tmrt modification in P2 was of lower importance as it has been already protected by solar radiation (Case C-Case A). From one hand, the creation of the dense shading shield by the newly added trees, has led to a high reduction of shortwave radiation reaching the ground (as it is directly absorbed by the foliage) and on the other hand both short-wave reflection and long-wave emission were considerably attenuated. Yet, a marginal Tmrt alteration was found for P3, still not being under tree's shade.

Finally, combining cool materials with additional trees seemed to be the most proper solution so as to control the increased values of reflected solar radiation when high albedo coatings are applied on the ground surface. The reduction of Tmrt for points P1and P4 (Case A-Case D) was found 15.8 °C and 12.2 °C, which is around 23% lower that the corresponding reduction reported for Case C. However, the combination of mitigation strategies has contributed in higher ambient air cooling, compared to case C. As a result, further analysis through the definition of thermal comfort indices would be necessary so as to derive solid conclusions with respect to pedestrian thermal comfort.

5. Conclusions and discussion

During the last decades, important research has been carried out towards the establishment of mitigation strategies that would attenuate the negative impact of the increased urbanisation on the urban microclimate. In this context, the present study investigated the thermal impact of three methods involving (i) the application of cool materials, having high solar reflectance and high emissivity, on ground surfaces, (ii) the addition of green spaces and trees inside the urban districts and (iii) the combination of the above mentioned techniques. To this end, ENVI-met microclimate model was applied and simulations for the current conditions and after the intervention scenarios were performed for a typical summer day. The obtained results indicate that increasing the asphalt's and concrete pavements' solar reflectance by 0.28 and 0.4 respectively, may lead to major corresponding surface temperature reductions reaching 9.0 °C and 10.5 °C, during noon. However, cool materials' impact is significantly lower for the ground surface temperature of narrowest canyons because of significant solar obstruction caused by building volumes and the decreased shortwave radiation reaching the ground surface. In terms of the climatic potential of cool materials to decrease the ambient air temperature inside the densely built-up area, the analysis revealed less significant modifications, compared to the initial conditions with peak differences reaching 0.7 °C and 0.4 °C during noon and afternoon respectively.

At this point it is important to stress that despite the cool materials' potential to provide considerable decrease of surface temperature and less important changes on ambient air temperature, their application will also strongly influence the radiative balance of the ground surface and thus the radiant exchange of the pedestrian with the surrounding environment. In other words, a potential reduction in ground surface temperatures due to high albedo may reduce the long-wave emission and as a consequence, the sensible heat transfer to the air. On the other hand, this effect is counterbalanced by the increased reflection of solar radiation, affecting mean radiant temperature (Tmrt) and as thus, the human thermal balance [47,51]. In this study, simulation results showed that increasing the average albedo of ground surfaces (i.e. asphalt and pavements) by 0.35 may lead to a peak rise of Tmrt close to 5.0 °C at a height of 1.5 m, in the exposed parts of the street canyons of the study area. Given that this parameter is the primary one affecting thermal feeling during summer, its potential increase may considerably deteriorate pedestrian's thermal comfort [77]. This was also highlighted by Erell et al. [47], who reported that the use of cool materials in canyon surfaces located in warm climates, would lower surface and ambient air temperature but would also increase radiative exchange and thermal stress.

It can be concluded that when it comes to urban rehabilitation guidelines, the proposed strategies should be evaluated under a global point of view, where urban heat island mitigation and thermal comfort are both taken into consideration. In this context, the results of this study indicate that combining the use of cool materials with extra densely foliated trees inside the street canyons constitutes a more effective way to ameliorate the urban microclimate without compromising the pedestrians' thermal comfort. For all canyons, it was found that the simultaneous application of high albedo materials and the addition of trees has led to major pavements surface temperature changes and to higher air temperature reductions (compared to the reductions achieved after the single application of cool coatings or additional trees), while Tmrt is controlled by the dense foliage of trees. Indicatively, at noon, in Pittakou street canyon where the percentage of trees was increased by 60%, the mean radiant temperature at 1.5 m above ground was estimated (i) 16.8 °C lower than the corresponding value in case B (i.e. when only cool materials are applied) at areas directly below the trees' foliage, (ii) 2 °C lower than the corresponding value in case B, at areas in the middle of the canyon, still exposed to solar radiation. Similar remarks were also derived in a recent study where the authors claimed that increased urban vegetation together with high albedo pavements are an appropriate solution for improving thermal energy balance in street canyons [78].

Finally, large scale implementation of cool materials in urban areas, as a solution towards the increased urban temperatures and its corresponding negative effects, may also involve their application on building roofs. As already indicated by many previous studies, the use of cool materials on building roofs may lead in lower amounts of heat transferred from the roof into the building and thus, to lower cooling energy needs.

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