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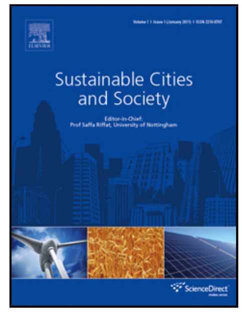

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Modeling the performance of cool pavements and the effect of their aging on outdoor surface and air temperatures

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Highlights

- The high albedo materials' effect is evaluated for the design and aged albedo values.
- Increasing ground surfaces' albedo by 0.28-0.40 led to major Tsurf drop of 9.0□C.
- Peak Tair drop up to 0.85oC was achieved for the 'design' high albedo values.
- The materials' cooling potential was highly reduced for the aged albedo values.
- The achieved Tair drop due to cool materials decreases by 8% for every 3m height.

Abstract

Aiming at the improvement of a dense urban area's microclimatic conditions, this study examines by simulation means, the application of highly reflective materials as a mitigation strategy. Yet, as significant albedo changes may occur due to weathering and aging, the study investigates the surface (Tsurf) and air (Tair) temperature cooling potential of cool paving materials, both for design and aged values of solar reflectance; the aged albedo values are issued from previously reported experimental campaigns. Since the majority of the existing studies evaluate the cool materials impact at the pedestrian's height, the current work aims to provide insight on the vertical profile of the achieved Tair reduction due to cool pavements, at different heights of the study area canyons. The analysis revealed that the Tsurf and Tair decrease due to cool pavements is reduced by 50%, when the aged albedo values are considered while the obtained Tair reduction is negatively related to the distance from the ground. The accurate assessment of the high albedo materials' effect on the urban microclimate imposes thus the consideration of the albedo degradation due to weathering and aging while extra effort should be given on the development of cold materials standing the test of time.

Keywords: microclimate; Envi-met; cool materials; albedo; aging

1. Introduction

The term 'urban microclimate' is generally used to express the divergence of atmospheric conditions occurring in an urban area, compared to those of the surrounding rural areas. This differentiation, well-known as the 'Urban Heat Island' effect, is characterized by higher ambient air temperatures (Tair) a reported in the urban districts when compared to the rural ones ([1], [2], [3]) and it is attributed to various uncontrollable and controllable parameters [4]. The uncontrollable factors refer to environmental and nature related parameters whereas the controllable ones involve urban planning and design parameters. Based on the existing literature, the main humanly controlled factors, identified as a source of higher ambient Tair in urban areas involve:

- The decrease of latent heat flux through evapotranspiration as a consequence of vegetation loss ([5], [1]),
- The large quantities of solar radiation stored and then re-emitted as long-wave radiation inside the urban districts, as a result of the urban materials' thermophysical properties [6],
- The high surface temperatures (Tsurf), and the severe intensity of long wave radiation emission due to the low albedo value of the construction materials [7],
- The high urban densities, contributing to the entrapment of shortwave and long wave radiation inside the canyons inhibiting thus, the urban cooling ([8], [9]).

The occurrence of high ambient Tair in the urban areas along with its negative environmental, social and energy impact consists a very well documented phenomenon worldwide ([10], [11], [12], [13], [14], [15], [16], [17], [18], [19]); in the future, even higher urban air temperatures are to be expected due to the climate change, contributing to the already existing worrying microclimatic issues [17]. Especially for the cooling dominated climates (i.e. climates in which the buildings' cooling energy demand is higher than the respective heating needs), such as the one of the Mediterranean countries [20], the rise of ambient air temperature is expected (a) to provoke a serious degradation of the outdoor thermal comfort of pedestrians [21], (b) to strongly affect the buildings' thermal performance; higher ambient air temperatures are expected to lead to higher buildings' cooling loads that will significantly outweigh the moderate reduction of heating energy needs [22].

In light of the above, a great scientific attention has been paid, during the last decades, on the establishment of methods that would improve the urban thermal environment and attenuate its multiple negative consequences ([1], [7], [23], [24], [25]). Towards this direction, one of the most widely investigated mitigation strategies constitutes the application of the so called 'cool materials' on urban ground and building surfaces ([6], [26]). The involved technologies lead to lower heat storage and lower surface temperatures and as a result, sensible heat transfer to the surrounding environment through convection phenomena can be significantly attenuated, compared to conventional products [27]. A further description of cool materials' properties is provided in section 2.

To date, the performance of cool materials applications has been investigated either by observational approaches ([28], [29]) or by simulation means ([30], [31], [32]), with the latter enabling the comparative assessment of microclimatic parameters before and after the morphological intervention, under similar boundary conditions. In the current study, the effect of cool materials towards the improvement of the thermal environment of a dense urban area is examined by simulation means, using the ENVI-met microclimate model ([33], [34]). Moreover, the performance of ground surface cool materials applications is assessed under hot summer conditions, both for the initial values of optical properties and after considering the impact of weather and aging process. A further analysis on the research objectives and the investigated scenarios is given in section 3 and 4.3 respectively.

2. Background

2.1. Definitions

According to Qin [35], the materials characterized as 'cool' ones, should absorb and store lower amounts of solar radiation, compared to conventional materials, to maintain reduced surface temperatures (Tsurf. To this aim, the first and most popular technique entails the increase of solar reflectance (also referred as 'albedo') and infrared emittance ([36], [37]) so as to reduce the surface temperatures due to lower solar radiation absorption and at a second step, to decrease the ambient Tair, because of reduced heat convection intensity [38]. Cool pavements of this category were initially designed to be light colored, and highly-reflective in the visible wavelength; yet recent scientific research has led to the development of cool non-white materials with embedded cool pigments, highly reflective in the near-infrared radiation spectrum [39]. Other techniques involve porous and water-retaining pavements in which the lower surface temperatures are achieved through the evaporation of the rain or irrigation water, draining into the pavement holes ([40], [41]) or changes on the heat storage of pavements, using Phase Change Materials (PCM) ([42], [43], [44]); in the latter case, the absorbed heat during daytime will be used for the material's phase change (i.e. melting process) instead its temperature rise while at night, when the ambient temperature is relatively low, the PCM solidifies and the stored heat is released. In the present study, the analysis concerns the use of cool materials of the first cluster (i.e. increased solar reflectance and increased thermal emissivity).

2.2. Investigating cool materials applications with the ENVI-met model

So far, the ENVI-met microclimate model has been widely applied to evaluate the impact of cool materials' applications on the improvement of the outdoor thermal environment. The investigated cool materials' scenarios comprise of the following three subcategories: (a) cool roofs applications ([45], [46], [47]), (b) cool asphalts and pavements applications ([45], [32], [48], [31], [49]) and (c) combined cool envelope facades and cool ground surfaces ([50], [51], [52], [53]). It has to be mentioned that, in the majority of the existing works conducted with the ENVI-met model, the cooling potential of cool pavements having modified solar reflectance and absorptivity is examined, whereas fewer studies also investigate changes on materials' thermal properties (i.e. volumetric heat capacity and thermal conductivity) ([54], [55], [56]). In other words, for most of the studies, the acquired changes on the thermal environment are due to the increase of the surfaces' solar reflectance and a consequent reduction of absorption coefficient.

The existing ENVI-met simulation results indicate that the unique application of high albedo materials on building roofs may lower Tair above the roof surfaces but no significant reductions are achieved at the pedestrian's level (i.e. close to 1.5m height from the ground). Furthermore, the maximum cooling intensity at human level was found negatively related to building heights, with cool roofs' effect being more prominent in detached house areas than in high-rise urban districts ([56], [55]). Regarding high albedo materials' applications on ground surfaces, the simulation results of a study in Los Angeles [45], suggested that the increase of asphalt and concrete pavements' albedo by 0.30 may lead to an important Tair reduction at human level, reaching 2.0^{o}C, during hot summer conditions; similar magnitudes of max Tair cooling were also reported by Battista et al. [54] for a case study in Rome, where the ground surface albedo was increased by 0.20. In the same context, a recent study conducted in a densely built-up area of Thessaloniki, reported a peak summer ground Tsurf reduction ranging from 8.5 °C to 10.5 °C and a peak midday Tair drop of 0.70 °C, after increasing the asphalt's and concrete pavements albedo by 0.28 and 0.40 respectively [32]. The effect of replacing all asphalt roads with concrete paving materials, having higher albedo by 0.20 and lower volumetric heat capacity by around 7% was examined for different urban areas in Toronto [55]. The acquired results showed an important peak summer Tsurf reduction at noon, ranging from 7.9 °C in the detached area to 7.6 °C in the middle-rise area, while the respective maximum Tair changes at human level were lower than 0.40 °C in all areas. At this point it is important to stress that, different magnitudes of Tair cooling as a consequence of cool pavements applications, should be also attributed to the varying spatial configuration of the investigated study areas (apart from general climatic conditions such as solar radiation intensity etc.); urban morphology features involving, 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 and as a result, on the reduced heat convection from the ground surfaces to the ambient air.

It is also worth mentioning the results of a recent study, suggesting that the use of cool materials on the vertical building envelope surfaces may sometimes lead to an increase of ambient Tair and to higher building cooling loads, as a result of increased solar reflections, being trapped inside the urban canyons [50]. Moreover, the latter finding is also more evident in high density areas, compared to low density districts as the vertical exposition of the building facades is larger [30].

Even if it is not is the scope of the study, it has to be emphasized that, according to findings of prior scientific studies, the increase of the albedo of ground pavements will considerably affect the radiative balance of the ground surfaces and thus, the radiative exchange of the pedestrians with the surrounding environment [57]. In other words, the achieved peak

Tair reduction as a consequence of lower sensible heat transfer to the air is often compromised by the increased reflection of solar radiation, affecting the Tmrt values and thus, the human thermal balance. The latter effect has been widely discussed in many previous studies ([32], [58], [45]) reflecting a potential compromise of the human's thermal stress, when applying high albedo materials on ground surfaces.

2.3. Albedo vs. time

Given that the albedo value is determined by the optical properties of the outer surface layer of the materials, significant changes may occur over time [59]; concerning the albedo of a new paved asphalt, it has been measured around 0.05 ([60], [61]) and presented an increase during the first months of exposure to 0.10-0.15 [35], due to the oxidization of the binder and the corresponding exposure of the aggregates. The latter finding was also confirmed by a recent study, reporting that the measured albedo of asphalt pavements increased in the first month after the construction due to weathering; minor changes were reported for the following 5 months of measurements [61]. In terms of the concrete tiles, a new cast pavement has an albedo value that ranges between 0.35 - 0.40 [60]; while carbonation procedure may increase the concrete pavement's solar reflectance during the first month of exposure, the albedo finally decreases over time by 0.06 - 0.19 due to weathering and abrasion ([62], [35]). Based on the previous remarks, it could be claimed that the assumption of a constant albedo during the whole lifecycle of the materials may be misleading when it comes to the evaluation of their effect on the outdoor thermal environment. In other words, the assessment of the long-term performance of urban coatings requires the consideration of potential changes in solar reflectance and emittance over time [39].

As far as the ageing effect of cool materials and the corresponding loss of albedo is concerned, it is a topic that has been widely discussed for both building envelope and urban ground surfaces applications; hence, experimental measurements of albedo changes due to aging and weathering are more often available either for cool roof materials ([63], [64], [65], [66], [67], [68]) or samples of cool paving materials placed in specially modulated areas or platforms ([39], [69], [70], [61], [44], [71],) rather than for real applications of cool concrete pavements and asphalts ([29], [49]) mainly due to the difficulty of circulation and traffic in the latter case. Apart from the degradation that occurs due to environmental conditions, such as rain, wind, sunlight, experimental data from former scientific studies suggest that the solar reflectance of roofs may also decrease due to dust, increased bacterial loads or biomass growth ([68], [72]). For the cool asphalts, the decrease of reflectivity occurs not only by the dust and the pollutants, but also from the deposition of rubber from the tires of vehicles [29]. It is also interesting to mention that, according to previous observations, most of the albedo loss occurs during the first few months of exposure and then it almost stabilizes ([49], [73]).

In a recent study of Alchapar et al. [71] the optical properties of various concrete pavements of different colors were analyzed so as to detect potential changes after a year of exposure on the pedestrians' circulation (vehicular pavements have not been evaluated)The results indicated that the albedo of lightly colored pavements was severely affected by the aging process, with reported albedo decrease even up to 25% at the end of the first year of exposure. In the same context, Li et al. [61] have measured the albedo change due to time, for different colored interlocking concrete pavers and have reported an albedo decrease of around 10%, at the end of 6 months. In both later cases, the test samples were exposed to external conditions but not to vehicles and circulation. Furthermore, Kyriakodis et al. [29] have evaluated the aging and the induced albedo decrease of a yellow reflective asphalt with infrared reflective pigments and aggregates in Athens; they have found that after 6 months of continuous use, the cool asphalt had lost almost 50% of its initial albedo value as a consequence of atmospheric pollutants and particles issued by vehicles emissions but also due to dirt and rubber from the vehicles tires; yet, albedo changes on cool concrete pavements were of lower importance. In the same vein, Lontorfos et al.[49] have carried out measurements of solar reflectivity for cool concrete and bitumen pavements, implemented in the context of an urban rehabilitation project in Athens. The acquired observations indicated that, after a year from the construction, an important loss of solar reflectivity, up to 40% and 15% occurred for asphalt and concrete pavements respectively again as a consequence of dust and rubber deposition. Considering that the positive contribution of cool materials on the outdoor thermal environment was attenuated due to the aging and weathering process, the two latter scientific studies have also suggested that the scrubbing of the surfaces with wet solvents would enable the full recovery of the initial value of solar reflectivity.

3. Research objectives

Considering the above-mentioned findings concerning the aging of high albedo materials but also the increased scientific interest towards the respective applications as a strategy to improve local thermal environment, this study has the following objectives:

i. At a first step, to investigate the magnitude of the potential differences between air temperature and relative humidity, measured in the densely built-up urban zone and the green, low density area of the meteo station. These differences are expected to occur as a consequence of the urban heat island effect.

ii. At a second step, to evaluate the cooling effect of high albedo materials, applied on the ground surfaces (a)having the design values of solar reflectance and (b) after weathering and aging period, resulting in a degradation of reflectivity. The analysis concerns the microclimatic parameters of surface and air temperature. To this end, microclimate simulations with the ENVI-met microclimate model will be performed for an urban district in Thessaloniki, presented in section 4. The analysis is carried out under hot summer conditions, during which the maximum cooling potentials due to high albedo materials is expected. The simulation scenarios along with the corresponding values of the cool materials' optical properties are provided in section 4.4.

To date, the majority of the existing studies evaluate the cool materials' impact at the pedestrian's height ([58], [29], [74], [55], [45], [32], [75]) and only a few at diverse vertical levels [30]. Furthermore, the focus in the existing papers is mainly given on the outdoor thermal comfort of pedestrians and how it is affected by the application of high albedo pavements. Yet, microclimatic changes and the respective reduction of the ambient Tair due to cool pavements' applications, will not only influence the pedestrians' thermal balance but will also strongly affect the buildings energy performance ([76], [77]). In this context, the present paper aims to fill the gap in the existing literature and provide further insight on the effect of cool pavements on lowering the ambient Tair not only at the pedestrian's level but also at different heights (i.e. from the first floor till the rooftop) both for the design and the aged albedo values. Moreover, to the authors' knowledge, the aging of high albedo materials and the achieved Tair cooling as a function of height has not been investigated up to date.

4. Methods and tools

The implemented methodology includes the following steps: At a first step, on site measurements of air temperature (Tair) and relative humidity (RH) during summer conditions, were performed to identify current microclimatic conditions of the study area, prior to any intervention scenario. At a second step, the ENVI-met model performance was evaluated through the comparison of simulated and measured Tair and RH. The next step involves the establishment of the simulated cool materials scenarios; finally, the acquired simulation results are analyzed and discussed.

4.1. Description of the study area

The study area is located in a high-density residential neighborhood of the city of Thessaloniki (40.65 °N, 22.9 °E), which is situated in the northern part of Greece and placed along the North-East coast of Thermaikos gulf.

According to the Köppen Climate Classification the climate type of the city is "Csa" corresponding to hot-summer Mediterranean climate with generally hot, dry summers, mild, wet winters and evenly distributed rainfall throughout the year [78] ; 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 −10.0 °C. During summer, average high temperatures are around 30.0 °C, while the recorded maximum air temperatures of the last decades rarely exceeded 40.0 °C [79]. In a previous study of Giannaros et al. [80], the average and peak daily temperature difference between central and suburban areas of Thessaloniki during summer have been found close to 1.7 °C and 2.0 °C; the maximum differences have been 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. The study area is considered representative for the broader city center of Thessaloniki, regarding the characteristics of the urban space (i.e. geometry of the street canyons, surface cover properties, materials and building height.)

Concerning morphological characteristics of the study area, the densely built-up site extends to 40 000 m^2 and contains 6 blocks of residential buildings, covering 35% of the ground surface of the study area. The buildings are 7-8 storeys high (i.e. 22 - 25m) while there is a very limited number of detached houses, of 7-9m height. Moreover, the sky view factor of the study area fluctuates between 0.20 and 0.50 and the pervious surface fraction is lower than 15%. Based on the above mentioned morphological characteristics and according to the ‘Local Climate Zone’ classification proposed by Stewart et al. [81], the study area can be classified in the compact midrise class. Building envelope construction materials mainly comprise of cement and concrete elements, while the ground surfaces are dominated by impervious materials such as asphalt and concrete pavements and only a small part is covered by loamy soil and other permeable materials.

In terms of open spaces, they are only limited to street canyons and courtyards of irregular shape between building volumes. The main streets traversing the study area are (a) Papandreou and Voga canyons, having an N-S orientation and running along the western and eastern edge of the model domain respectively, (b) Pittakou canyon, the axis of which is East-West orientated and (c) Kalliga street canyon, having a NW-SE orientation (Fig.1 and Fig.2). Two narrower secondary N-S street canyons (i.e. Height/Width ratio close to 2) are also connected to Pittakou street and are orientated N-S. Finally, vegetation consists of low deciduous trees and bushes placed on both sides along the main streets of the study area while there is only a limited number of tall mature trees. The detailed plant characteristics regarding trees’ height, crown width and LAD values that were taken into account for the simulations are given in [32].

4.2. Onsite microclimate measurements

Onsite microclimatic measurements of air temperature and relative humidity, performed for 15 consecutive days during July 2016, would serve:

- To identify potential differences between atmospheric conditions occurring in the densely built-up urban zone and the green low-density area of the meteo station.

- To acquire the necessary data for the ENVI-met microclimate model evaluation.

To this aim, a high accuracy weatherproof Hobo-data logger, suitable for outdoor environment, was applied. According to the logger manufacturer, the accuracy of the air temperature sensor is ±0.21°C for records varying from 0.0 °C to 50.0 °C while for the relative humidity sensor, the accuracy is ± 2.5% for the corresponding measurements ranging between 10% and 90% The logger, placed inside a suitable radiation shield, was mounted on a tripod and then positioned in a 1st floor balcony in a building of Pittakou Street, at 4.5 m from the ground level. The height of the sensor above the balcony was 1.10 m. Given that the sensor was located in a balcony, special attention was given so as to eliminate potential boundary effects formed along the building walls; following the recommendations of Niachou et al. [82], the tripod was placed at a distance of 60cm from the exterior building wall. The sensor was recording air temperature and relative humidity at an interval of 1 hour. Measurements during all days were performed under clear-sky and low wind speed conditions while there were not any extreme heat-wave events.

The obtained records were compared with the corresponding observations of the meteorological station of the Department of Meteorology and Climatology of the Aristotle University. The latter logger was situated inside the University Campus, in a straight distance of around 4.0 km from the study area. **Error! Reference source not found.**.i and **Error! Reference source not found.**.ii depict the evolution of the hourly and mean daily air temperature in Pittakou street and the meteo station respectively, for the period 15th - 31st of July 2016; Fig.4.i and 4.ii show the corresponding box plots with the respective air temperature data of both datasets. It can be seen that the air temperature is always higher inside the urban area, compared to the meteo station with the peak reported mean daily Tair reaching 30.27 °C in Pittakou canyon and 29.33 °C in the meteo station.

In terms of the differences between the daily averages of Tair, reported in both sites, they fluctuated between 0.70 °C and 1.83 °C, (for the 15 days of measurements). The observed differences of Tair can be explained by the following facts: The sensor of the meteo station is located in the green, low-density area of the campus, rather far from the urban texture and the traffic heat releases. The green coverage ratio is also high, with vegetation comprising of densely foliated trees and thus, low solar gains; moreover, the biggest part of ground surfaces is covered by pervious surfaces such as soil, grass etc. enhancing the release of latent heat. All the above-mentioned parameters suggested better microclimatic conditions, resulting in lower Tair values, compared to the urban study area.

Moreover, during the period of measurements, peak hourly differences within the day were mainly reported after midnight with maximum value reaching 2.60 °C, suggesting the presence of the nocturnal urban heat island effect, the energetic basis of which has been widely investigated during the last decades ([83], [8], [84], [85]). In this study, the release of longwave radiation, as a result of heat being stored by the building envelopes' components and ground surfaces of the urban area during daytime, was considered as the major parameter governing the nocturnal urban energy balance; low or scarcely foliated trees and bushes did not provide any significant solar radiation sheltering to the ground or building surfaces. Moreover, the reduced opening to the sky as a result of the increased building heights, would inhibit the radiative cooling and also increase the entrapment of longwave radiation, which is then re-absorbed by the urban surfaces ([86], [15]). On the other hand, the increased greenery inside the University campus and the induced solar shading, would contribute in lower heat storage by the ground and building surfaces during the day and thus to lower emission of longwave radiation after sunset.

Regarding peak hourly Tair differences during the daytime hours (i.e. from 06:00 a.m. to 20:00 p.m.), they reached values up to 2.35°C and were mainly observed in the afternoon period during which the Pittakou canyon (i.e. where the logger is placed) was fully exposed to solar radiation.

Regarding the hourly measurements of relative humidity, the acquired records inside Pittakou canyon are close to the corresponding values of the meteo station, with the median value of the hourly deviations (i.e. for 360 hours in total during the 15 days of measurements) reaching 3.37%. The mean daily values of relative humidity in Pittakou street are also slightly higher than the respective values of the meteo station with the median, maximum and minimum value of the mean daily deviations (for the 15 days of measurements) reaching 2.50%, 6.80% and 0.40% respectively. Considering that the accuracy of the relative humidity logger is ± 2.5%, the acquired deviations can be considered rather minor. What is important to mention is that the air temperature difference between the 2 sites will also contribute to the difference in relative humidity as well, in spite of no change in the absolute humidity. Moreover, the fact that the relative humidity values of the urban area are similar to those of the meteo station could potentially be attributed to the sea breeze effect and the corresponding humid air masses, penetrating in the study area canyons, which is situated in a straight distance of 250 m from the seaside.

4.3. Simulation set-up

As already mentioned, the assessment of ground surface cool materials' performance both for the design values of solar reflectance and after the aging period, is performed by simulation means with the ENVI-met v.4 microclimate model, based on the fundamental laws of fluid dynamics and thermodynamics and designed to simulate complex surface-vegetation-air interactions in the urban environment ([33]). The model's detailed characteristics along with its structure and the mathematical equations governing the various sub-models (i.e. atmospheric, soil and vegetation sub-model) are provided in [34]. The latest version of the tool, released in 2014, overcomes important limits of the previous one, as far as the initialization data are concerned [34], leading to more accurate and realistic results. Yet, it is important to stress that despite its significant advantages, a number of limitations of the model, including the calculation of shortwave radiation, the turbulence model and the grid generation have been discussed in the existing literature ([34], [87], [88], [89]). As a result, the ENVI-met model can be considered a very helpful tool for urban climate analysis, provided the acquisition of proper model initialization data and the deep knowledge of the tools' limits.

As simulations at a micro scale are vastly time consuming, calculations are generally carried out for a single specific day. In this study, the 22nd of July 2016 was selected as a representative day for microclimate calculations. During that day, there were clear sky conditions and the median daily Tair, recorded inside the study area was 27.55 °C. The detailed methodology for selecting the representative day, based on a statistical analysis of long-term records, is provided in a previous scientific work [90].

The main input files required for the microclimate simulations comprise of the area input file, (Fig 1.ii and 1.iii), where the building layout, vegetation, soil type, receptors (i.e. specific grids points) and project location parameters are defined and the configuration file, containing simulation settings in terms of initialization values for meteorological parameters, definition of output folder names and timings. The study area was modeled using a domain size of 135*135*20 grids (i.e. x-grids*y-grids*z-grids), corresponding to a grid size of 1.5 m*1.5 m* 3.0 m. Building floors were considered to have 3m height whereas, the height of the base floor was considered as 4.5m high; 7 nesting grids were also set around the model domain area, in order to assure numerical stability [91]. The ground properties of the nesting grids are those of concrete pavements so as to approximate in a realistic way the surfaces on the boundaries of the study area. Simulation start time was set to 00:00 and the total runtime was 24 hours. Concerning the meteorological boundary conditions, wind speed, wind direction, hourly values of Tair and RH, used for the forcing along with the mean monthly value of soil temperature were obtained from the meteo station of the Aristotle University. A summary of the meteorological conditions in the model boundaries is provided in Table 1; the thermal properties of the various construction materials based on the ISO standard 10456 [92].

In the framework of this study, the investigated scenarios refer to the following four cases:

- **Case A**, corresponding to current conditions for urban ground surfaces in which asphalt and concrete pavements have reached their maturity and the albedo value is set to 0.12 and 0.30 respectively.
- **Case B**, referring to the replacement of conventional asphalt and concrete pavements with the corresponding cool ones, having design albedo values of 0.40 and 0.70 respectively. The increase of albedo was considered to occur after painting the outer asphalt and concrete pavement layer with a light grey and light beige paint respectively; the considered design values of cool materials albedo were based on values reported in the existing literature ([36], [93])
- **Case C**, corresponding to a first aging scenario, 12 months after the construction;according to the reported values of Lontorfos et al. [49], the albedo of asphalt and pavements was decreased by 40% and 15% respectively. Given that the study area is in the city center, increased pedestrians and vehicles circulation is expected.
- **Case D**, corresponding to a second, less optimistic aging scenario, 12 months after construction. According to the reported values of Kyriakodis et al. [29] and Alchapar et al. [71], the albedo of asphalt and pavements was decreased by 50% and 20% respectively, compared to the design values.

Regarding emissivity, no changes were considered due to weathering process over a year. The later hypothesis was based on the reported results provided by Alchapar et al.[71] who estimated the aging of cool colored concrete pavements by reporting changes on albedo and emissivity occurred within a year. The obtained monitoring results showed zero changes on emissivity for the majority of the samples while a maximum modification of 5% was reported for the rest of the samples. In the same vein, Synnefa et al. [39] performed measurements of albedo and infrared emissivity for 10 prototypes of cool materials for urban applications, exposed on natural weathering. The acquired measurement results indicated that in 3 months, the albedo reduction was of 5% but no changes in infrared emissivity occurred. The optical properties of the ground surface materials used in each investigated case study are summarized in Table 2.

5. Results and Discussion

5.1. ENVI-met model evaluation

Fig.6i and 6.ii present the comparison of the diurnal evolution of both Tair and RH values respectively, for the 22th of July 2016. Regarding Tair values, it can be seen that the model tends to generally underestimate day-time temperatures and over-estimate part of night time (i.e. from 00:00 to 2:00) and morning (i.e. 7:00-11:00) temperatures, a feature that has also been reported in previous studies ([96], [97]); yet, the absolute differences between observed and modeled Tair never exceed 1.80°C. Apart from potential inaccuracies on the determination of the model geometry, vegetation etc., the observed deviations may occur due to fact that the air temperatures on the model boundaries are issued from a meteo station outside the study area, neglecting thus the higher air temperature inside the urban district (as seen in section 3.1). In addition, the effect of multiple reflections and the entrapment of longwave radiation along with the anthropogenic heat release from air conditioners, transportation and other human activities, are not considered during the microclimate simulation.

The quantitative evaluation of the ENVI-met model was performed through the calculation of various difference metrics such as the Root Mean Square Error (RMSE), including its systematic (RMSEs) and unsystematic components (RMSEu), the Mean Absolute and Bias Errors (MAE and MBE) and the index of agreement *d*. The frequently used RMSE, summarizes the mean difference between the predicted values (P) and the observed ones (O); the smaller the value, the better the model's performance. Yet, an important disadvantage is that large errors have a great influence on the overall square error than the smaller errors do [98]. The MBE corresponds to the average of all differences between the estimated and the observed values and indicates whether the model consistently underestimates (negative MBE value)or overestimates (positive MBE value) the observation [99]. Regarding the MAE, it represents the average over the test sample of the absolute values of residuals while the index of agreement concerns a standardized measure of the degree of the model's prediction error, varying between 0 and 1 [98]. The magnitudes of the calculated difference errors for Tair and RH (Table 3) can be considered as acceptable, if compared with the corresponding values already reported in the literature ([56], [100]) . Furthermore, the fact that the Tair systematic error is higher that the unsystematic one, suggest that the improvement of model design or the adjustment of input would lead to even better agreement between simulated and observed values.

In terms of relative humidity, important deviations up to 18% occurred for a few time steps during daytime, resulting in RMSE and MAE error values of 10.24% and 7.70% respectively. The reported differences between measured and simulated RH are mainly attributed to the fact that the study area is strongly influence by the sea breeze and the corresponding dryer and cooler air, introduced inside the urban canyons, a phenomenon that cannot be reproduced by the model.

At this point, it has to be mentioned that experimental values of ground surface temperatures, enabling the evaluation of the model for an additional microclimatic parameter, are not available due to limitation of resources; hence, previous studies assessing cool asphalt's applications in dense urban areas of Greece, have shown that the model can accurately reproduce the diurnal profile of the parameter with differences between onsite measurements and simulations not exceeding the range of 0.30 °C to 0.80 °C ([29], [49]). Similar low errors and high correlation coefficients between modeled and experimental surface temperatures were also found in previous scientific studies conducted in Asia ([101], [102]), Europe [103] and U.S.A [104]. Based on the above-mentioned remarks, the ENVI-met model can be considered as a reliable tool for further microclimatic analysis, 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 ones.

5.2. Cool materials effect on surface temperature

The investigation of the cooling potential for both new and aged cool materials application was carried out for 15:00, when the peak difference between Tair recorded at the meteo station and the study area was observed (i.e. 2.20 °C). As a result, it is at that time of the day that the maximum cooling effect of high albedo materials was expected. In terms of the solar exposure of the study area during this time step, the ground surfaces of North-South (N-S)f Papandreou and Voga and canyons were mostly shaded while in the East-West (E-W) Pittakou canyon, ground surfaces were fully exposed to solar radiation.

Fig.7 presents (a) the absolute values of the simulated Tsurf, occurring for the current conditions and after the application of cool materials, both for the design (Case B) and the aged (Case C and Case D) albedo values, and (b) the corresponding Tsurf modification due to cool materials' application. It can be seen that the application of cool materials with the design albedo values (Case B) contributed to major Tsurf modifications of 5.0 °C - 7.0 °C and 6.0 °C - 9.0 °C for the all the exposed parts of asphalt street and pavements respectively, with a maximum Tsurf difference reported in cross road areas, being exposed to solar radiation since early the morning. The obtained results agree with the findings of the studies of Kyriakodis et al.[29] and Carnielo and Zinzi [103] in which the achieved surface temperature difference between conventional and cool asphalts was evaluated using experimental measurements. It should be emphasized that, in the existing studies that experimentally evaluated the effect of cool materials on the improvement of the local thermal environment, the assessment of the achieved Tsurf reduction is mainly performed via simultaneous measurements in samples covered by conventional and cool materials. In this way, the climatic boundary conditions during the experimental campaign are the same ([103], [105], [106]) Yet, when it comes to the achieved Tair reduction due to the large-scale application of cool materials, its evaluation is performed via simulation means ([29], [103], [28]). This is because the measurement of Tair before and after the cool materials' application would involve different metrological conditions during the measurement campaigns. A direct comparison is thus not possible.

To continue, lower Tsurf changes, close to 1.0 °C - 3.0 °C were reported for parts of the ground surfaces, being kept in shadow by building volumes (see Case A-Case B diagram). The achieved Tsurf cooling potential is attributed to the significantly higher amounts of reflected solar radiation and the consequent lower absorption by asphalt and concrete paving materials of Case B; increasing the asphalt's albedo by 0.28 resulted in a rise of the reflected shortwave radiation by 75%, compared to the current conditions (i.e. Case A), yet, the assumption of a progressive loss of solar reflectance due to aging and weathering process, resulted in a lower amounts of the reflected shortwave radiation; for the cool materials of Case C, in which the asphalt' and concrete pavements albedo is lower by 0.16 and 0.10 than the 'design' case B (and higher by 0.12 and 0.30 compared to Case A) the reported rise of reflected shortwave radiation has now reached 50%, compared to the current conditions. As a result, higher amounts of solar radiation were henceforward absorbed, contributing to less prominent Tsurf modifications close to 1.0 °C - 2.0 °C and 3.50 °C -7.0 °C for the unprotected asphalt and concrete pavements ground surfaces (Case A-Case C diagram). Finally, the aging scenario of Case D, in which the asphalt' and concrete pavements albedo are higher by 0.08 and 0.26 compared to Case A, revealed (a) similar asphalt Tsurf modifications with Case C and (b) lower cooling potential for the concrete pavements, where the maximum Tsurf reduction was 5.50 °C, almost 40% lower than the respective max value achieved with the 'design' materials of Case B.

5.3. Cool materials effect on air temperature

Fig.8i depicts the absolute values of the Tair distribution at 15:00, for different heights inside the main urban canyons of the study area. More precisely, Tair data for Pittakou and the lower part of Kalliga street canyons, are derived from Y-Z cross diagrams, while the X-Z cross sections provide the vertical profile of Tair for Papandreou street, the upper part of Kalliga street and the Voga canyon (see location of cross sections in Fig.1iii). Air temperature simulation results, are given for all 4 analyzed cases (i.e. current conditions and cool materials' application with the design and aged albedo values), starting from the ground level till 56.0m height, which is the upper limit of the model domain.

In the current conditions, the highest ambient Tair values, above 30.0 °C were reported in the places of the study area being fully exposed to solar radiation during the afternoon, such as the Pittakou street canyon and the upper area of Kalliga

Street. In areas where the building volumes contributed to the canyon surfaces' shading (i.e. Voga and lower parts of Kalliga canyon), the obtained Tair values were slightly lower and around 29.5 °C. Regarding the cooling potential of high albedo materials, the obtained simulation results lead to the following remarks:

- For the design values of albedo: (See Case A-Case B cross sections, Fig.8ii).

The maximum Tair reduction was reported at the pedestrian height (i.e. at 1.5 - 2.0 m), close to the ground level. In all parts of street canyons being exposed to solar radiation, regardless of the orientation, increasing the albedo of the asphalt and concrete pavements by 0.28 and 0.40 respectively led to a cooling effect of around 0.50 °C -0.60 °C, while the respective modification was around 30% lower in the shaded areas. The maximum Tair reduction of 0.80 °C at 1.5 m height was reported in the crossroad of Pittakou and Papandreou street, a place receiving solar radiation since the early morning. The acquired results comply with findings of previous studies, indicating that the application 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 of lower importance ([55], [57], [107]).

The cooling effect remained rather stable till the height of 4.50 m, corresponding to the lower part of the first building floor. From this point, the ambient air cooling potential progressively dropped by around 8% for every additional floor height (i.e. 3m), reaching values around 0.35ºC-0.43ºC for heights between 7.5-10.5 m (level of 2nd building floor) and 0.25 °C - 0.35 °C for 16.5 - 19.5 m (level of 5th building floor) in Papandreou and Kalliga Canyons. For Pittakou street canyon, the respective values were 0.40 °C - 0.50 °C and 0.30 °C - 0.40 °C for level of 2nd and 5th building floor level correspondingly. Finally, in all canyons, at the roof top level (i.e. at 22 - 25 m height) the achieved Tair reduction is significantly low, reaching values around 0.20 °C -0.25 °C.

- For the aging scenarios:

In the first aging scenario (See Case A - Case C cross sections, Fig. 8ii) an albedo reduction by 40% and 15% for asphalt and pavements respectively, was considered as a consequence of weathering and aging (see Table 1). Simulation results for the aged cool materials revealed a major decrease of their cooling potential after the considered solar reflectance degradation, even at the pedestrian level. More precisely, the achieved Tair modification at 1.5 m height, fluctuated between 0.28 °C - 0.35 °C in Pittakou, Papandreou and the upper area of Kalliga street canyons and around 0.20 °C -0.25 °C in Voga canyon, being almost 50% lower than the Tair cooling, achieved with the design albedo values. The same magnitude of reduction was also reported for the peak temperature decrease at 1.5 m, which was now found close to 0.40 °C. The latter findings are due to the higher amounts of sensible heat, being henceforward released towards the air, as a consequence of the lower albedo value and the induced higher solar radiation absorption in the ground surface materials. More specifically, the sensible heat release from the asphalt surface towards the ambient air was reduced by almost 35% for the 'design' cool materials compared to the base case, while the respective reduction for the aged cool materials (1st aging scenario) was around 12%.

Concerning the vertical profile of Tair cooling, the analysis again showed a rather stable value of Tair reduction till 4.5m and from that point, a decrease of the cooling potential around 6%-8% per 3 m (i.e. per building floor level) was found. Thus, a Tair change of 0.25 °C -0.30 °C and 0.18 °C - 0.22 °C was found for between 7.5 - 10.5 m (level of 2nd building floor) and for 16.5-19.5 m (level of 5th building floor) respectively, in Papandreou, Pittakou and Kalliga Canyons. The latter Tair differences are around 30% lower than the corresponding modifications achieved with the design values of albedo Again, in all canyons, the reported Tair cooling at the last floor, at the rooftop level is very limited and only close to 0.16 °C -0.18 °C.

Regarding the second aging scenario (See Case A-Case D cross sections, Fig. 8ii), an additional 10% and 5% loss of albedo values for cool asphalt and pavements respectively, led to even higher drop of the cooling effect of the high albedo materials; for the latter aged albedo values (i.e. 0.20 for the asphalt and 0.56 for the concrete pavement), the transfer of sensible heat flux from ground surfaces towards the nearby air layers was only decreased by almost 8% compared to the base case, resulting in rather minor cooling of the ambient air. The results suggested a maximum Tair reduction at 1.5m up to 0.25 °C in Pittakou and the upper part of Kalliga street, around 55% lower that the corresponding value for the 'new' cool materials with the design properties. Similarly to Case C, the loss of the high albedo materials' cooling potential per height of building floor (i.e. 3 m) 'is 6% - 8% resulting in insignificant reductions of Tair in the middle and upper canyon heights.

Fig.9 depicts the achieved Tair decrease in the middle of Pittakou street canyon (position 1, Fig.1iii) and also in front of a building façade of the canyon (position 2, Fig.1iii), at different distances from the ground, as a result of cool materials' applications. Given that the cooling energy needs of a building are strongly influenced by the microclimatic conditions reported in immediate vicinity of its façades ([108], [91]) potential changes on Tair are generally expected to play an important role on the calculated cooling energy loads. The results indicate similar magnitudes of cooling effect in the middle of the canyon and in front of the building façade. For the latter case, the cooling potential of the new, 'clean' cool materials presented an average drop of 8.40% per 3 m height, with maximum achieved Tair reductions reported close to the ground level (i.e. 1.5 - 4.5m). On the other hand, the aged cool materials of Case C resulted in a minor temperature decrease of the ambient air near the building façade, with values ranging from 0.27 °C to 0.20 °C at 7.5 m and 19.5 m respectively, while the average reported cooling loss was close to 7.2% per 3 m height. Finally, similar low magnitudes of Tair cooling in front of the building façade were reported for Case D where the achieved Tair drop at the height of 10.5 m from the ground was lower than 0.20 °C.

6. Main conclusions

In this study, the current microclimatic conditions along with the effect of high albedo materials on the improvement of the outdoor thermal environment of an urban district of Thessaloniki were investigated, under hot summer conditions. The potential of cool materials applied on the ground surfaces on lowering surface and air temperatures was analysed by simulation means for (a) the design values of solar reflectance and (b) after weathering and aging process, resulting in a degradation of reflectivity. The following remarks can be drawn:

a. Onsite microclimatic measurements suggested higher ambient Tair inside the urban study area, compared to values recorded at the meteorological station, as a consequence of increased building densities, significant anthropogenic heat emissions, high sensible heat release by the impervious construction materials and longwave radiation entrapment, inhibiting the night-time cooling of the urban area.
b. The application of cool materials, having the 'design' albedo values, may result in major Tsurf modifications, reaching 7.0 °C and 9.0 °C for asphalts and pavements respectively. Given the high amounts of reflected solar radiation, the sensible heat transfer towards the air was significantly reduced, resulting in maximum Tair reductions of 0.85 °C, at

1.5 m from the ground; yet, the potential of cool materials on reducing the Tair was found negatively related to height as a respective decrease of 8% per building floor was estimated.

c. A potential degradation of cool asphalts and pavements' albedo as a consequence of weathering, dust and vehicles rubber deposition would provoke a serious reduction of their cooling potential, both for surface and air temperatures. Assuming a 40% and 10% loss of the design solar reflectance values of cool asphalt and pavement led to a max Tair reduction of 0.40ºC, almost 50% lower than the respective Tair cooling, achieved with the design albedo values. Given the decrease of the Tair cooling potential, close to 6%-8% per 3 m (i.e. per building floor level), the acquired Tair modifications at the 5th floor level, did not exceed 0.22 °C.

Implementing high albedo materials on ground surfaces has been widely discussed as a strategy towards the improvement of the outdoor urban thermal environment. Yet, the above-mentioned findings indicate that the accurate evaluation of their contribution on the microclimate's improvement during the whole lifecycle of the material imposes the consideration of the albedo degradation because of weathering and aging. The acquired results also highlight the need for the industry and the academy to direct their efforts in the development of cold materials that will stand the test of time. Moreover, as the buildings' energy demand for heating and cooling purposes is strongly influenced by the microclimatic conditions occurring in its near vicinity, future research will focus on the impact of the achieved outdoor Tair cooling on the buildings' energy needs. The latter knowledge, combined with existing evidence on the cool materials' effect on outdoor thermal comfort is expected to enable a holistic evaluation of their performance on the urban built environment.

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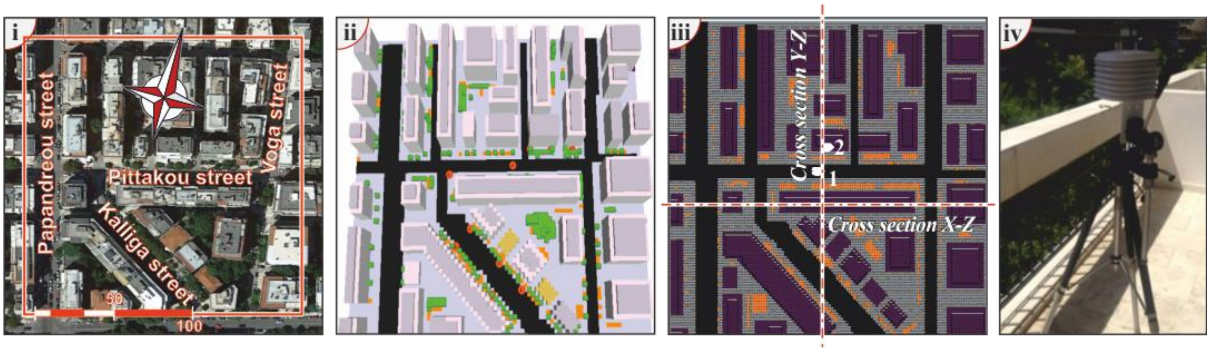
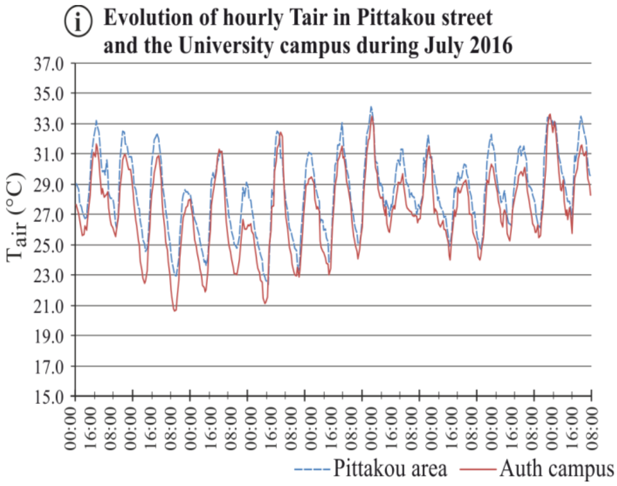


Figure 1: (i) Google earth image of the study area indicating the main street canyons and (ii, iii) area input file introduced in the ENVI-met model, (iv) placement of the logger on the 1st floor balcony of a building in Pittakou canyon

Figure 2:Street views of the main canyons of the study area and indication of the balcony in which the logger was placed (see red arrow)



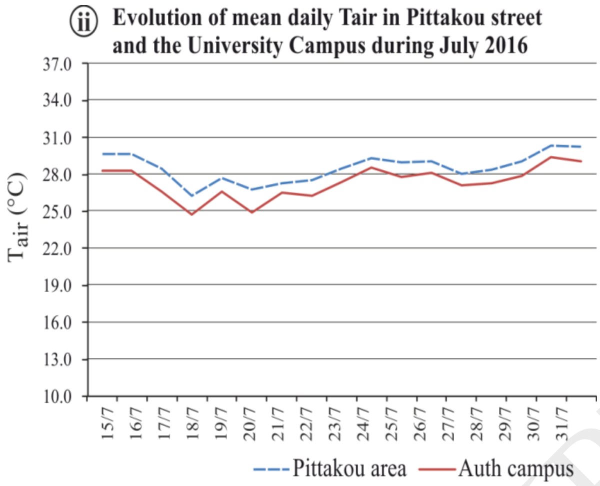


Figure 3: Evolution of hourly Tair and mean daily Tair in Pttakou street amd the meteo station

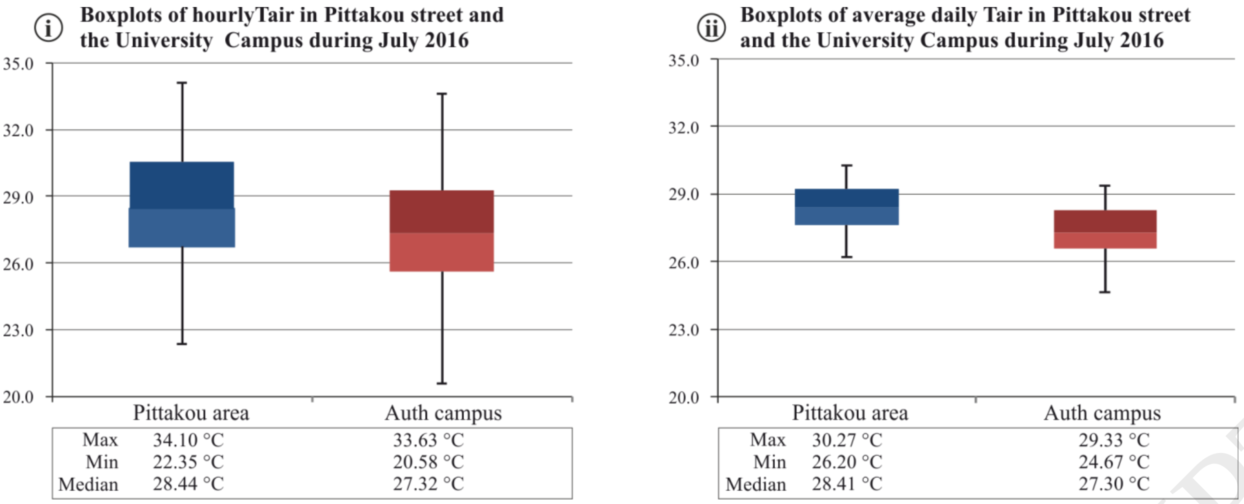


Figure 4: Boxplots presenting values of maximum, minimum, median, 25th and 75th percentile of hourly and mean daily Tair, observed in Pittakou street and the meteo station

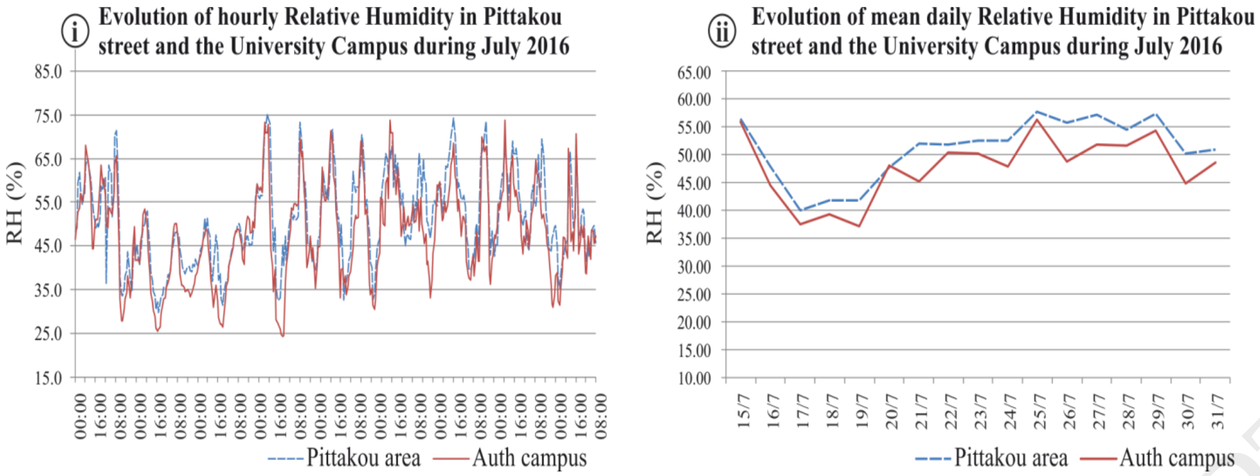


Figure 5: Evolution of hourly RH and mean daily RH in Pttakou street amd the meteo station

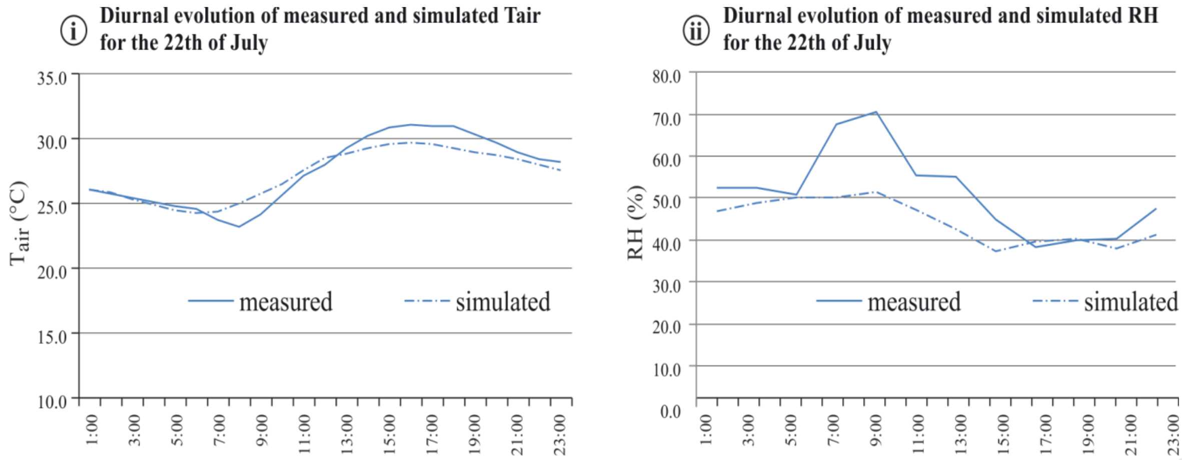


Figure 6: Comparison of measured and simulated Tair and RH values.

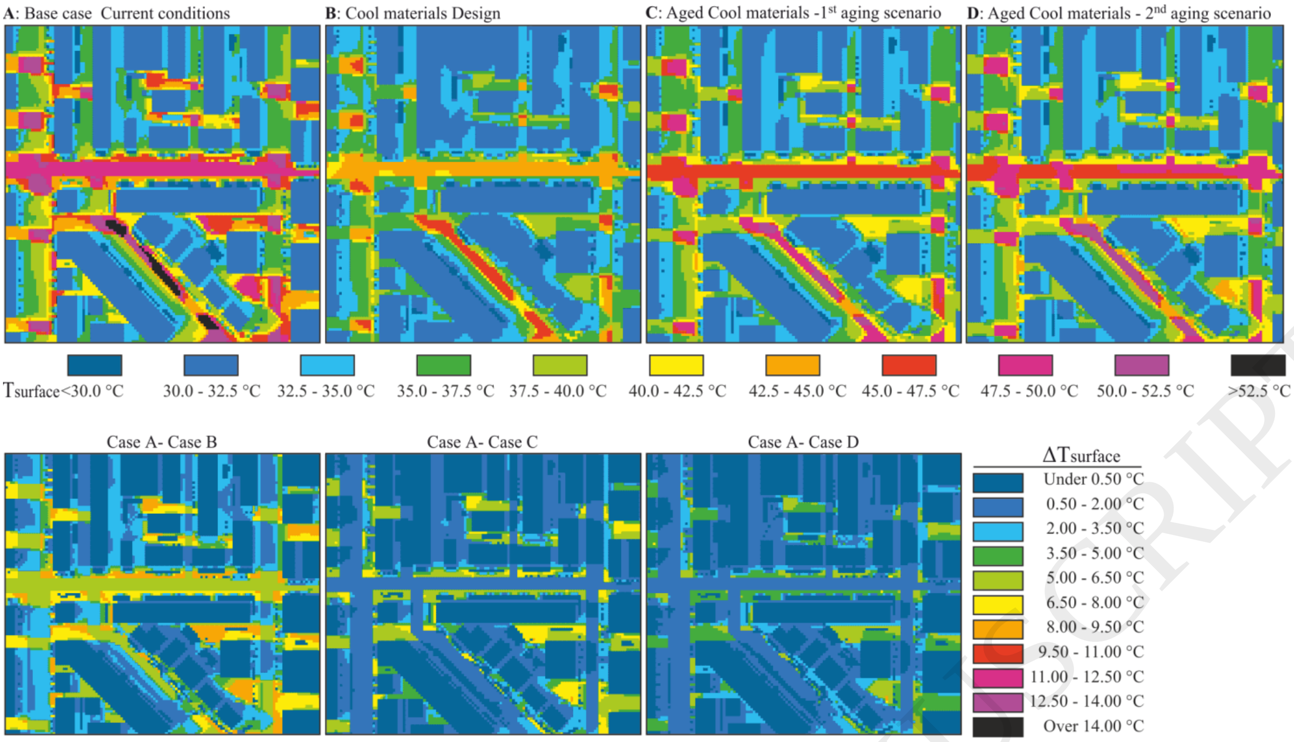


Figure 7:

Absolute values of the simulated Tsurf, occurring for the current conditions (Case A) and after the application of cool materials, for the design (Case B) and the aged (Case C and Case D) albedo values and the respective Tsurf decrease due to cool materials' application, on July22th at 15:00

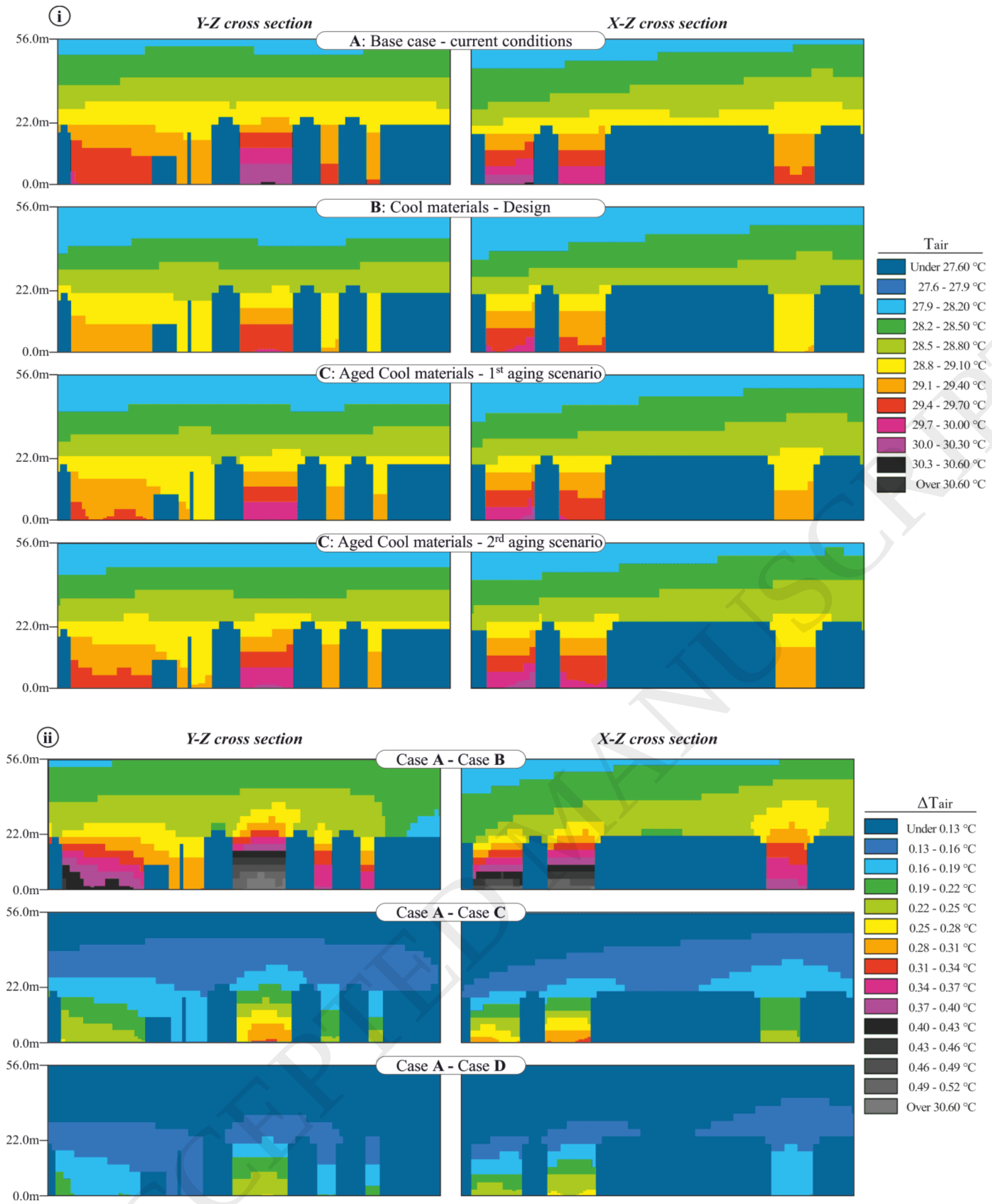


Figure 8: Street canyons cross sections showing the vertical profile of Tair and the cooling potential for the design albedo values (Case B), and two aging scenarios (Case C and Case D) for the 22th of July, at 15:00 a.m

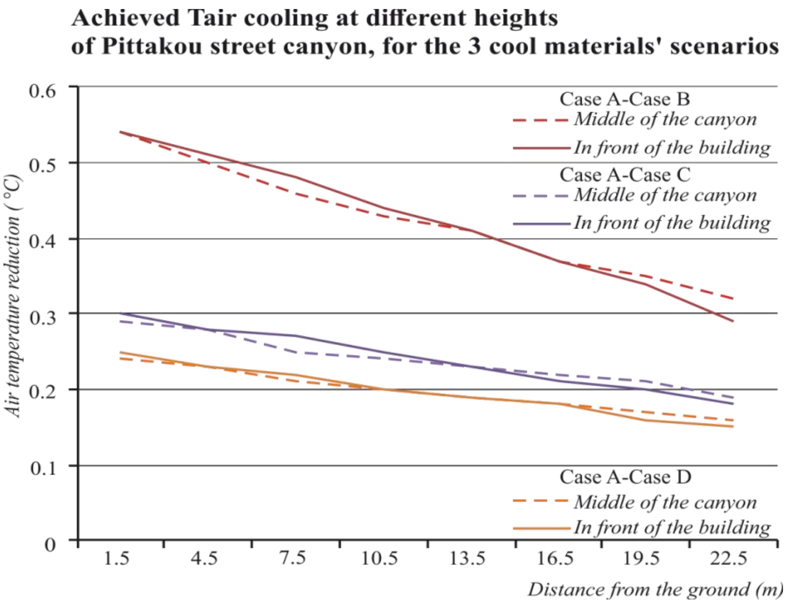


Figure 9: Tair cooling reduction due to cool materials, at different heights of Pittakou street, reported for the different investigated scenarios in the middle of the canyon and in front of a building façade, the 22th of July, at 15:00

Table 1: Meteorological input boundary conditions

Input parameters	22th of July 2016
Mean wind speed at 10m above ground	1.15 m/s
Prevailing wind direction	SW (225º)
Roughness length	0.1*
Air temperature forcing	Hourly data from meteo station
Relative humidity forcing	Hourly data from meteo station
Cloud coverage	No clouds
Specific humidity at 2500m	7g/kg*
Solar adjustment factor	1
Soil upper layer (0-20cm) initial temperature	305 K
Soil upper layer (20-50cm) initial temperature	304 K
Soil deeper layer (below 50cm) initial temperature	293 K*
Soil upper layer (0-20cm) moisture content*	50%*
Soil upper layer (20-50cm) moisture content*	60%*
Soil upper layer (below 50cm) initial moisture content*	60%*

**ENVI-met default values*

Table 2: optical properties of the ground surface materials ([94], [95], [36]

	Asphalt road albedo	Asphalt road emissivity	Concrete pavement albedo	Concrete pavement emissivity
Case **A**: Current conditions	0.12	0.90	0.30	0.90
Case **B**: Cool materials – Design value	0.40	0.90	0.70	0.92
Case **C**: Cool materials- 1st aging scenario	0.24	0.90	0.60	0.92
Case **D**: Cool materials- 2nd aging scenario	0.20	0.90	0.56	0.92

Table 3: Estimated errors between simulated and observed values of Tair and RH

	RMSE	RMSEs	RMSEu	MAE	MBE	d
Tair	1.02 ºC	0.86 ºC	0.61 ºC	0.82	-0.83 ºC	0.94
RH	10.24%	9.60%	3.40%	7.70%	-9.10%	0.97