Impact of urban albedo on microclimate and thermal comfort over a heat wave event in London

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Abstract: This work investigates the potential of increasing the surface albedo of roads and buildings' facades for mitigating thermal stress in London over heatwave events. The results are based on microclimate simulations with ENVImet (V4.4.3), validated using air temperature and radiation data (incoming and reflected) measured in a case study area of London. The comparison shows that ENVImet can accurately estimate the reflections within urban canyons in most cases and slightly overestimates the peak air temperature in urban canyons. The validated model is used to assess the impact of surface albedo on the Physiological Equivalent Temperature (PET) at the street level, considering the meteorological conditions of the heat wave on 29th June 2019. The results show that, at London's latitude, increasing the albedo of facades has a negligible impact on the thermal environment at the street level. Conversely, reducing the reflectivity of facades and increasing the reflectivity of roads reduces the hours of extreme heat stress and lowers the PET values during the hottest hours of the day. This result can be explained by the impact of facades' albedo on the multiple reflection of solar radiation within urban canyons.

Keywords: Urban Albedo; reflective materials; outdoor thermal comfort; heat waves; urban microclimate

1. Introduction

Urban environments play a crucial role in the challenges posed by the current climate crisis. Since the unfortunately famous heat wave of 2003, which caused thousands of deaths in Europe (Public Health England, 2019), the health risks associated with heatwaves have become clear, especially in cities.

In cities, the risks posed by higher global temperatures and by the increase in frequency, severity, and duration of heat waves are amplified by local urban climate phenomena such as the heat island effect (Li and Bou-Zeid, 2013; Founda *et al.*, 2015). Furthermore, urban population is growing all over the world (World Bank, 2014), increasing the number of inhabitants exposed to heat-related health risks at any latitude (Inostroza, Palme and De La Barrera, 2016). For this reason, mitigation and adaptation strategies play an important role in improving the thermal response of urban environments and reducing the population exposure under extreme weather events. This is particular relevant in urban areas with high building density and scarce vegetation, which experience the maximum UHI intensity (Kolokotroni and Giridharan, 2008; Lemonsu *et al.*, 2015; Salvati *et al.*, 2019).

One cause of the heat island effect is the ability of urban fabrics to absorb and store heat during daytime, due to the thermal and optical properties of materials and the urban surface geometry that causes multiple reflections of solar radiation (Yang and Li, 2015; Oke *et al.*, 2017). The use of green infrastructures and high albedo materials can contribute to mitigate the UHI by reducing solar absorption and heat storage (Santamouris, 2014; Alchapar, Cotrim and Correa, 2017; Gunawardena, Wells and Kershaw, 2017; Giridharan and

Emmanuel, 2018; Imran *et al.*, 2018). Green infrastructure helps retaining water in the urban environment and dissipating heat through the evaporation process. Surface albedo, which is defined as the ratio of the shortwave radiation reflected by a surface to the shortwave radiation reaching that surface, can contribute to lower urban surface temperatures by reflecting more of the incoming ration toward the sky.

However, in an urban context, the ratio of solar radiation reflected toward the sky depends on both the surface albedo of materials and the geometry of urban canyons. For this reason, the concept of urban albedo was introduced. The urban albedo (UA) is defined as the ratio of the outgoing to the incoming shortwave radiation at the upper edge of the urban canopy layer (Yang and Li, 2015). UA is different from surface albedo since its value depends on both the photometric properties of materials (i.e. surface albedo) and the geometry of the urban surface. In fact, in an urban fabric the incoming radiation undergoes multiple reflections between urban surfaces (facades and roads) and, at every incidence, a portion is absorbed by the incident surface while another portion is reflected towards other urban surfaces. For this reason, the effectiveness of high albedo materials in improving outdoor thermal comfort in complex urban geometries is still under investigation and it may vary depending on urban geometry (Yang *et al.*, 2016) and latitude (i.e. solar altitude).

Many studies indicated a positive impact of increasing the reflectivity of roads on UHI intensity and outdoor thermal comfort (Wang and Akbari, 2016; Salata *et al.*, 2017; Santamouris *et al.*, 2018). Conversely, some studies highlighted that the use of high reflective materials may have a negative impact on summer thermal comfort (Erell, Pearlmutter and Boneh, 2012; Alchapar and Correa, 2016), due to the increase of reflections within urban canyons and the consequent increase of mean radiant temperatures. Furthermore, Nazarian et al. (Nazarian *et al.*, 2019) showed that high reflective walls can increase the building energy use in high-density urban areas in Singapore, due to the increase of solar radiation transmitted into the neighbouring buildings.

This study investigates the potential of high albedo materials for facades and pavements for mitigating heat stress over a heatwave event at London latitude (lat 51.5º N). A real residential area is used as a case study. Different scenarios are investigated and their impact on the street level air, mean radiant and surface temperatures, and physiological equivalent temperature (Hoppe, 1999) is discussed. The analysis is based on microclimate simulations using the ENVImet program.

2. Methods

This study is based on microclimate simulations using the software ENVImet (V4.4.3), validated with air temperature and solar radiation data measured in a residential area of London. ENVImet is a microclimate simulator able to calculate high-resolution spatial and temporal distribution of microclimate variables within an urban domain (Bruse and Fleer, 1998; Huttner and Bruse, 2009).The accuracy of ENVI-met estimations of air temperature and reflections within urban canyon is assessed comparing the modelled microclimate outputs with the measured data.

The impact of materials reflectivity of facades and roads on outdoor thermal comfort is assessed in terms of hourly PET changes under heatwave conditions.

2.1. Air temperature and radiation measurements

An area of approximately 100m by 100m in a London borough is used as case study for this analysis. The area has typical characteristics of residential neighbourhoods in London, with low rise terraced houses cladded with bricks and plaster (Figure 1).

An air temperature sensor was installed in a radiation screen at 5m height on a lamppost in the case study area (Figure 1 c). A bluetooth temperature, humidity and dew point sensor beacon and data logger is used with temperature resolution of 0.1ºC and accuracy of 0.3ºC, with maximum 0.4ºC at -10ºC to +75ºC.

Spot measurements of the incoming and reflected solar radiation in different points within the canyons of the study area were performed on the 23rd of May 2019, under clear sky conditions (Figure 1 a, b and d). An albedometer composed of two pyranometers pointing one upward and the other one downward was used to measure the incoming radiation from the upper hemisphere and the reflected radiation from the lower hemisphere at three levels within canyons: at the street level (1.2m height), at the 2nd floor level (5m height) and at the eaves level (10m height). A cherry picker was used to carry out the measurements at the different heights (figure 1 b and d).

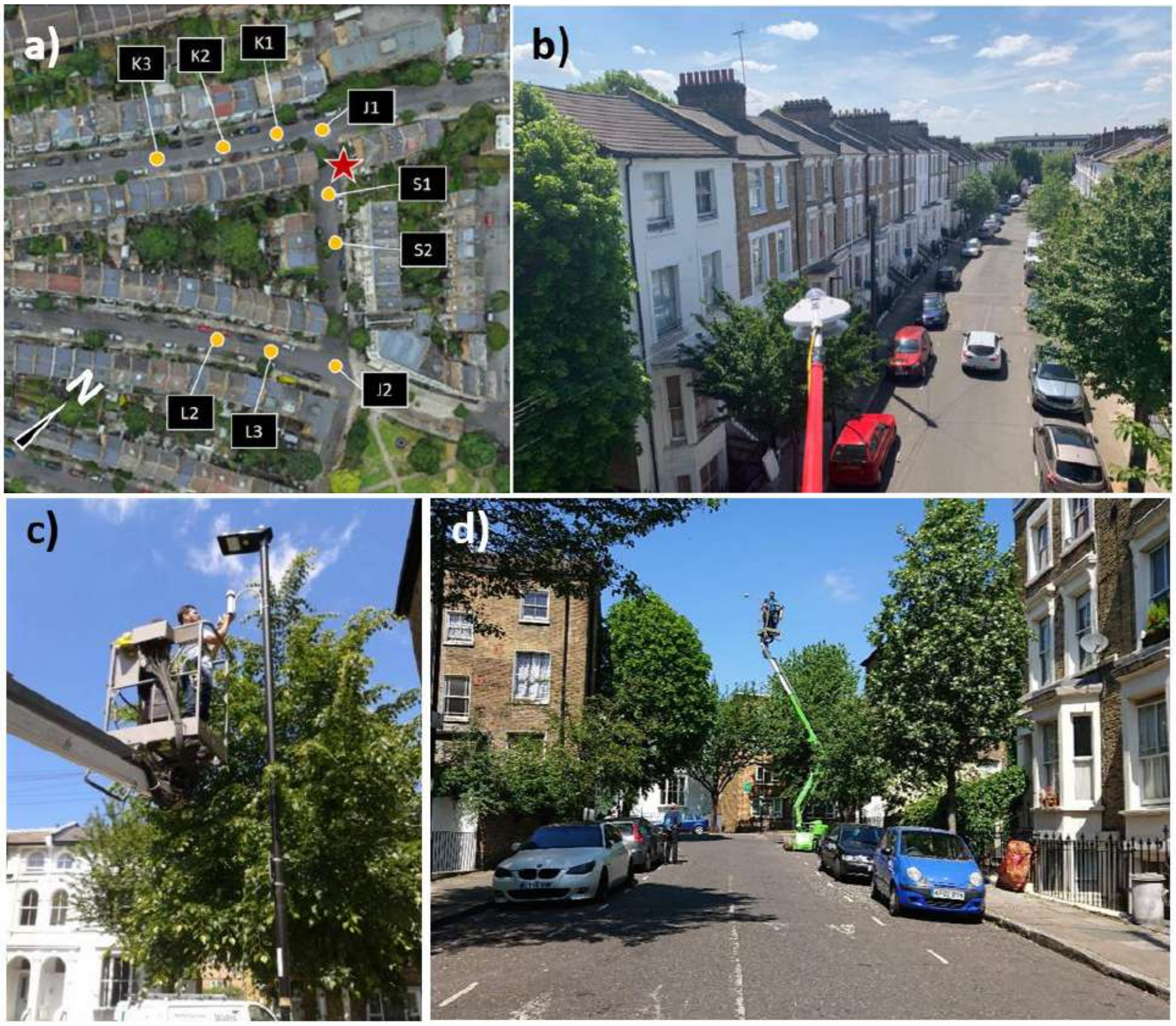

Figure 1 : a) Radiation measurement points in three roads (K_Rd, S_Rd and L_Rd); b) albedometer and radiation measuring at eaves level; c) installation of the temperature sensor on the lamppost; d) cherry picker used for the radiation measurements

2.2. ENVImet model calibration and PET estimations for changing materials

An ENVImet model of the area was built to simulate the microclimate and thermal comfort implications of changing the reflectance of roads and facades in the case study area. A base model corresponding to the current situation was built based on field surveys, GIS data (Ordnance Survey, 2018) and satellite data (Google Earth) for urban geometry and vegetation.

A survey of materials was conducted to estimate the reflectivity and emissivity properties of facades, paving and road materials to be used in the ENVImet model. The reflection coefficients and material distribution of the base model are reported in table 1. The reflection coefficients of the materials have been estimated using digital photography techniques and the London Urban Micromet data Archive 'LUMA' (Kotthaus *et al.*, 2014). The distribution of materials on the different facades was calculated based on site surveys and google earth visualizations and reproduced with the same ratio in the ENVImet model.

Table 1. ENVImet base model material reflectivity and distribution

Material & reflectivity coefficients		**K_rd**		**S_Rd**		**L_Rd**	
Façade (divided by orientation)		**ESE**	**WNW**	**SSW**	**NNE**	**SSE**	**NNW**
Red Bricks	r= 0.32	9%	40%		69%	8%	4%
Yellow bricks	r= 0.43	25%		33%		31%	33%
painted brick	r= 0.2	9%					
Dark paints	r= 0.08			3%	1%		
White painted bricks	r= 0.56	38%	35%	40%	17%	33%	42%
Clear glass	r= 0.05	19%	25%	24%	13%	28%	22%
Roads							
Tarmac	r= 0.19	100%		100%		100%	

Table 2. ENVImet scenarios tested

Scenarios	**A1 - High reflectivity facades**	**A2 - Low reflectivity facades**	**A3 - High reflectivity Roads**	**A4 – Combined scenario**
Facades	r = 0.6	r = 0.1	as base case	r = 0.1
Roads	as base case	as base case	r = 0.5	r = 0.5

The ENVImet mesh size, area size and simulation parameters were defined according to the criteria developed in a previous work for the same urban area which led to the best air temperature accuracy estimation (Salvati and Kolokotroni, 2019). The ENVImet model correspond to an area of 200m by 200m (mesh size of 2m), so as to include the upwind urban area that affect the temperatures in the point of measurement and avoid border effects on the results (Salvati and Kolokotroni, 2019).(Salvati and Kolokotroni, 2019).

The simulations have been performed in "full forcing mode", using the 30min frequency air temperature and relative humidity data measured by the bluetooth sensor on the 29th of June 2019 as forcing conditions. The use of local air temperature observations as forcing conditions was found to provide the best accuracy in ENVImet estimations (Salvati and Kolokotroni, 2019). A buffer time of 12hrs was considered for model pre-conditioning.

ENVImet air temperature accuracy was assessed by comparing the simulation results at the point corresponding to the sensor location measuring air temperature. All the simulations have been performed using the advanced IVS radiation algorithm for reflection calculation.

The accuracy of ENVImet in the calculation of reflections within the urban canyons was also assessed. To this aim, an ENVImet simulation was forced using the incoming solar radiation data measured on the 23rd of May 2019 on site and the IVS method for radiation transfer. The ENVImet radiation output "Reflected shortwave radiation lower hemisphere" (Figure 4) was compared with the reflected radiation measured on site in three urban canyons at different heights (figure 1).

The validated model has been used to test the potential microclimate impact of high albedo and low albedo materials for paving and building facades. Four scenarios have been simulated, changing the surface albedo of facades and roads as reported in table 2. The surface albedo values for the scenarios "high reflective facades" and "high reflective roads" were set to 0.6 and 0.5 respectively; these are common values found in the scientific literature on high albedo materials for microclimate mitigation.

The impact of the different scenarios on the thermal environment has been assessed in terms of air temperature and mean radiant temperature at 1.5m height at different points within the three main streets of the studied area. The physiological equivalent temperature (Hoppe, 1999) – PET – has been used for assessing the impact of the canyon materials' surface albedo on the outdoor thermal comfort. The correlations between PET, mean radiant temperature, surface temperatures and solar radiation received by the urban surfaces in each scenario is also discussed. This highlights whether high albedo materials are effective in mitigating heat risks in typical urban settings in London.

3. Results

3.1. Measured reflections in urban canyons

The measured incoming and reflected radiation within the three case-study urban canyons are reported in figure 2. The three canyons have the same geometry ratio (i.e. ratio of the building heights to the street width) of approximately 0.75 and different orientation and material distribution as reported in table 1.

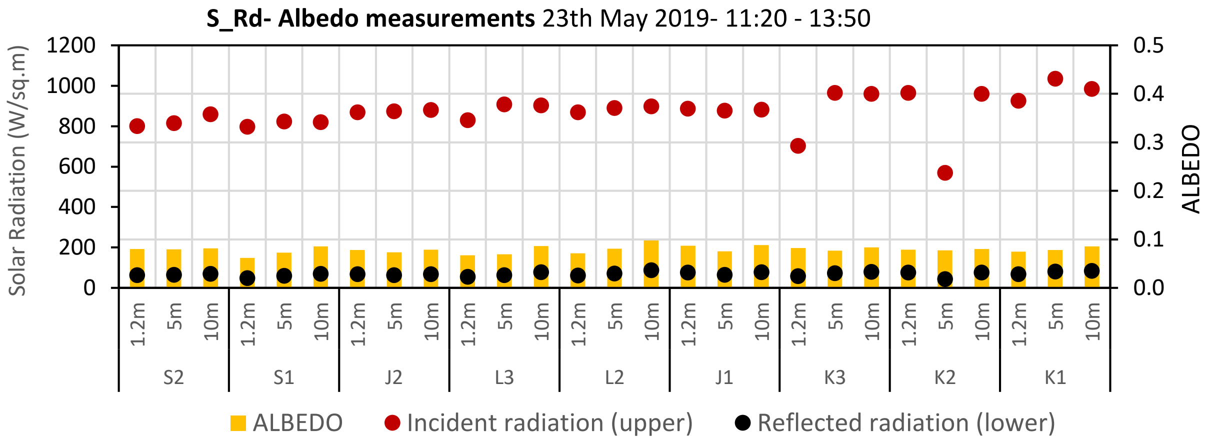

Figure 2 Measured incoming (incident) and outgoing (reflected) radiation and urban albedo values within urban canyons in the case study area

The radiation measurements showed that, for a datum geometry, the reflections are not influenced by street orientation and materials distribution. Also, the measured reflections did not vary with measurement height, being approximately the same value at the street level (1.2m height), 2nd floor height (5m agl) and eaves level (10m agl) as reported in figure 2. Therefore, the measured urban albedo, namely the ratio of the measured outgoing to the incoming radiation, showed very small variation. At the street level, the UA varied between 0.06 and 0.09, with an average value of 0.08. At the 2nd floor, the UA was even less variable, with a maximum and minimum value of 0.08 and 0.07 and an average value of 0.08. At the eaves level, the UA varied between 0.1 and 0.08, with an average value of 0.09. The highest values of UA (0.1) was recorded at point L2, namely in the street with the façade that received more radiation at the time of measurements (South-South East oriented façade).

3.2. Accuracy of ENVImet estimations: air temperature and reflected radiation

The accuracy of ENVImet in estimating air temperature is strongly related to the meteorological forcing conditions used in the simulation (Salvati and Kolokotroni, 2019). Therefore, to obtain the best accuracy, the local air temperature measured at 5m height in the studied area was used to force the simulation. The simulated day was the 29th of June 2019, when London experienced a heat wave with temperatures up to 35.6 ºC in the case study area (figure 3).

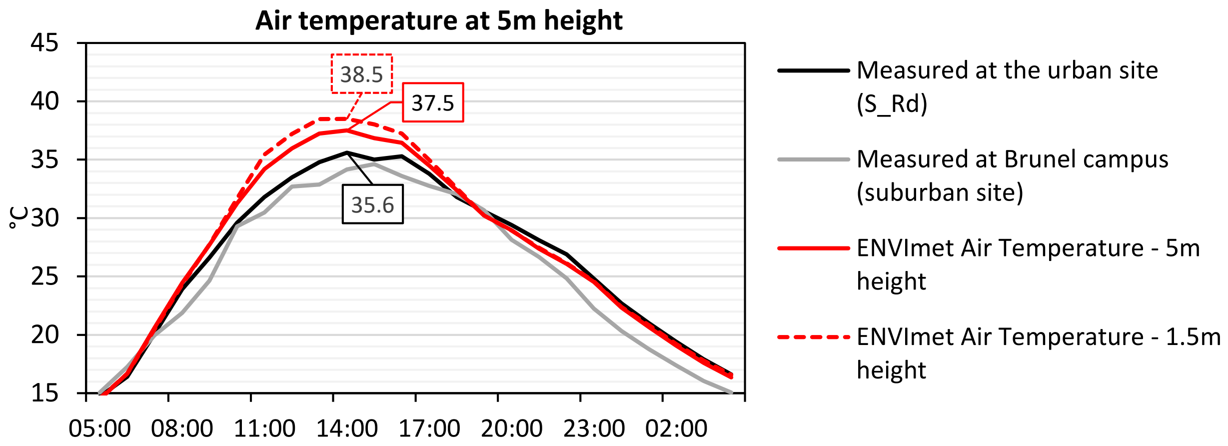

Figure 3 Comparison of measured and estimated air temperature over the 29th June 2019 heat wave event in London

Figure 3 compares ENVImet air temperature estimations to the measured data. The comparison shows that air temperature is overestimated by ENVImet between 12:00 and 16:00. The maximum overestimation reaches about 2 °C at 14:00, when the temperature recorded by the sensor was about 35.6 ºC while ENVImet estimates 37.5 ºC. At the street level (1.5m height) ENVimet estimates a further increase up to 38.5 ºC, which probably is similarly overestimated of about 2°C. The RMSE over the 24hr of heatwave day is about 1.18 °C, which is in line with previous ENVImet works (Salata et al., 2016; Salvati and Kolokotroni, 2019).

The accuracy of ENVImet calculation of reflections and UA within urban canyons is reported in Figure 4.

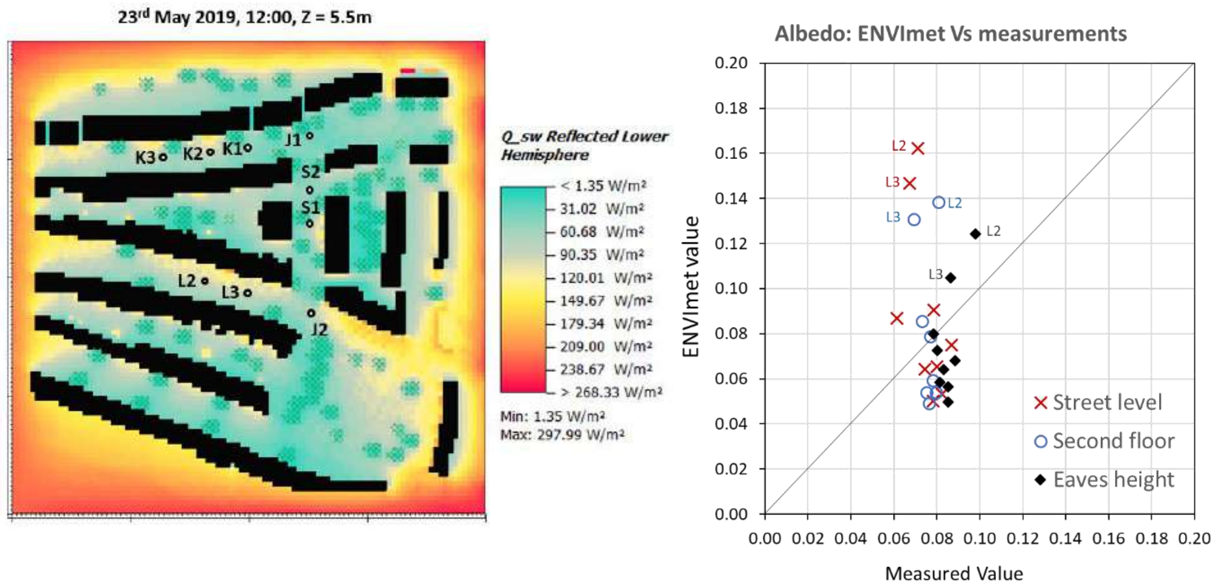

Figure 4 on the left: ENVImet Reflection estimations in the simulated domain. On the right: comparison between the ENVImet urban albedo estimated values and the measured urban albedo values.

The simulation results indicate a good estimation of the reflections within urban canyons for most of the points except for points L2 and L3, where urban albedo is overestimated by ENVImet. This is due to an overestimation of the canyon reflections in these points, in particular at the street level and at the second-floor level. This means that ENVImet probably overestimates the canyon reflections in canyon with facades that receive high solar radiation. For all the other points, the UA estimation is very accurate and always below 0.1. It should be noted that this accuracy was reached only using the advanced IVS algorithm for radiation transfer. When the simplified method for reflection calculation is used, the reflections within urban canyons are all the same and overestimated compared to the measurements.

3.3. Impact of materials reflectivity on outdoor thermal comfort

The impact of the four scenarios tested (table 2) on the PET value at street level is reported in figure 5. The PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Hoppe, 1999). In other terms, the PET value corresponds to the temperature of an indoor environment with no direct solar irradiation, wind velocity equal to 0.1 m/s, mean radiant temperature equal to air temperature and relative humidity of about 50% at Ta=20°C which would determine the same thermal sensation than the outdoor environment.

The PET has been calculated with the Biomet (4.4.3) module of ENVImet, based on the microclimate outputs of the microclimate simulations for each scenarios. The heat stress scale reported in figure 5 refers to Matzarakis and Mayer classification (1996).

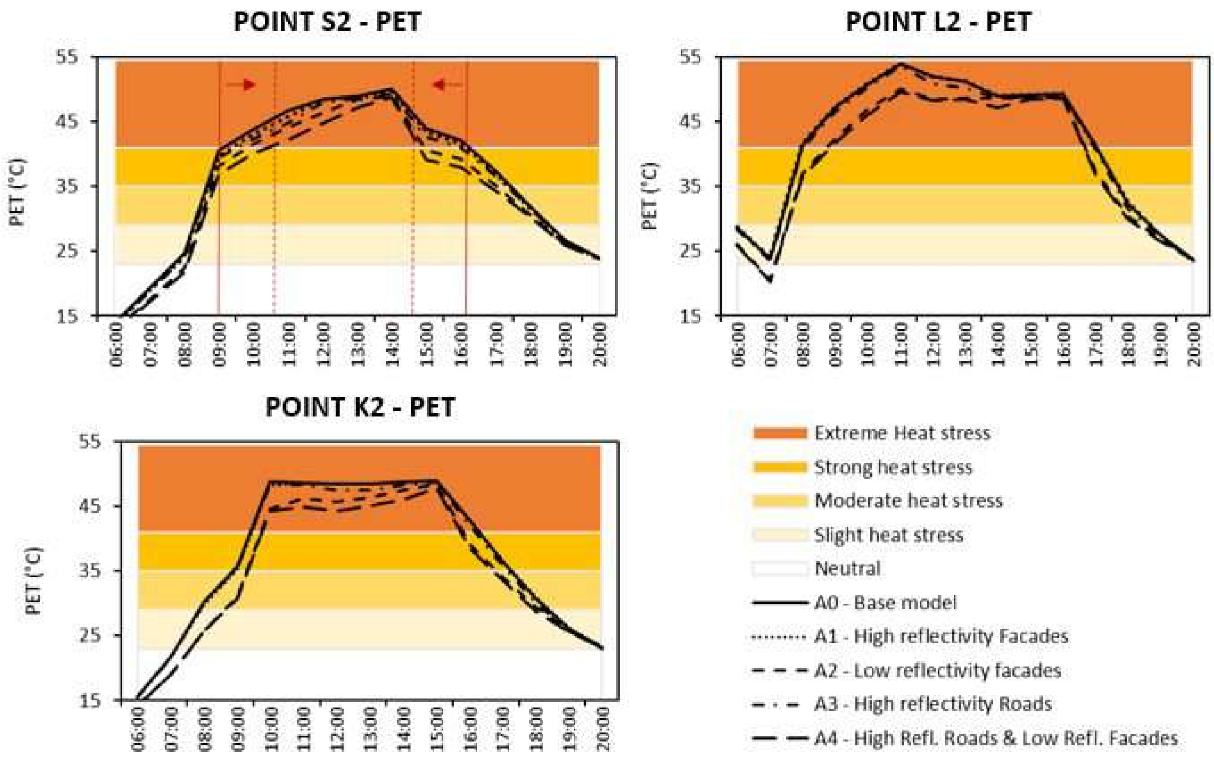

Figure 5 Impact of roads' and facades' materials albedo on the physiological equivalent temperature over the studied heatwave day in London. The location of the three points is reported in Figure 1,a.

The graphs in figure 5 clearly show that none of the scenarios is able to avoid extreme heat stress over the hottest hours of the heatwave day. However, in some cases, the duration of the heat stress time can be reduced. This happens for example at point S2 for the scenario A4, namely a combined scenario with low reflectivity facades and high reflectivity roads. The combined scenario A4 allows reducing the hours of extreme heat stress from about 7 hours in the base case (from 9:00 to 16:00) to about 4 hours (from 10:30 to 14:30).

The combined scenario indicates the ability to reduce heat stress in all the canyons. The highest PET value is reached at point L2, at 12:00. This probably happens because point L2 is located in the canyon with a SSE façade, which receives the maximum radiation in the early hours of the morning, leading to very high heat stress levels. In this canyon, both the scenarios A4 and A2 allow a sensible decrease of the maximum PET. These scenarios have in common a reduced reflectivity of facades. It has to be noted that point L2 is located in the canyon with the highest overestimation of reflections by ENVImet compared to the measurements. Therefore, the impact of surface albedo of materials on the PET value could also be overestimated in this point.

4. Discussion

The results of this study outline the complex relationship between urban variables and outdoor thermal comfort, due to the multiple factors that affect the urban microclimate in real-world urban areas. Increasing the surface albedo of urban materials may have countering effects on urban microclimate and outdoor thermal comfort. On the one hand, increasing the albedo of surfaces determines a decrease of surface temperatures. On the other hand, the consequent increase of reflections within complex urban geometry leads to an increase of solar radiation received by urban surfaces, which may have a negative impact on the outdoor and indoor thermal comfort. The overall balance of these opposite effects depends on the regional climate (i.e. solar elevation and radiation intensity) and the urban canyon aspect ratio (ratio of the height to the width of the street).

The canyon aspect ratio in the case study area is approximately 0.75 (building height equal to 12m and street width equal to 16m). In this kind of geometry, at London's latitude, the simulation results show that increasing the wall albedo does not improve the outdoor thermal comfort while increasing the road albedo has a significant positive impact on the PET index. This result is explained by the impact of the roads' and facades' albedo change on the air temperature and mean radiant temperature at street level, reported in Figure 6. The trends reported in the figure correspond to point S2, but they are similar in all the canyons. In terms of air temperature, changing the albedo of facades does not influence air temperature. A significant decrease of air temperature is instead obtained with the increase in road albedo (scenario A3). On the other hand, for the studied geometry, increasing the reflectivity of facades (scenario A1) has a negligible impact also on the mean radiant temperature. Conversely, a substantial decrease in facade albedo (scenario A2) allows a reduction of the mean radiant temperature at the street level.

Similar results were also reported in other latitudes (Alchapar and Correa, 2016) and can be explained by the impact of the walls' albedo on the multiple reflection of solar ration within urban canyons. In fact, the solar radiation received by the canyon' walls varies significantly for different values of surface albedo, as shown in figure 7. Similar results were found by Levinson (2019), who showed that the wall's solar availability in an urban context may increase up to 30% in deep urban canyons when the albedo of the neighbouring building is raised from 0.25 to 0.6.

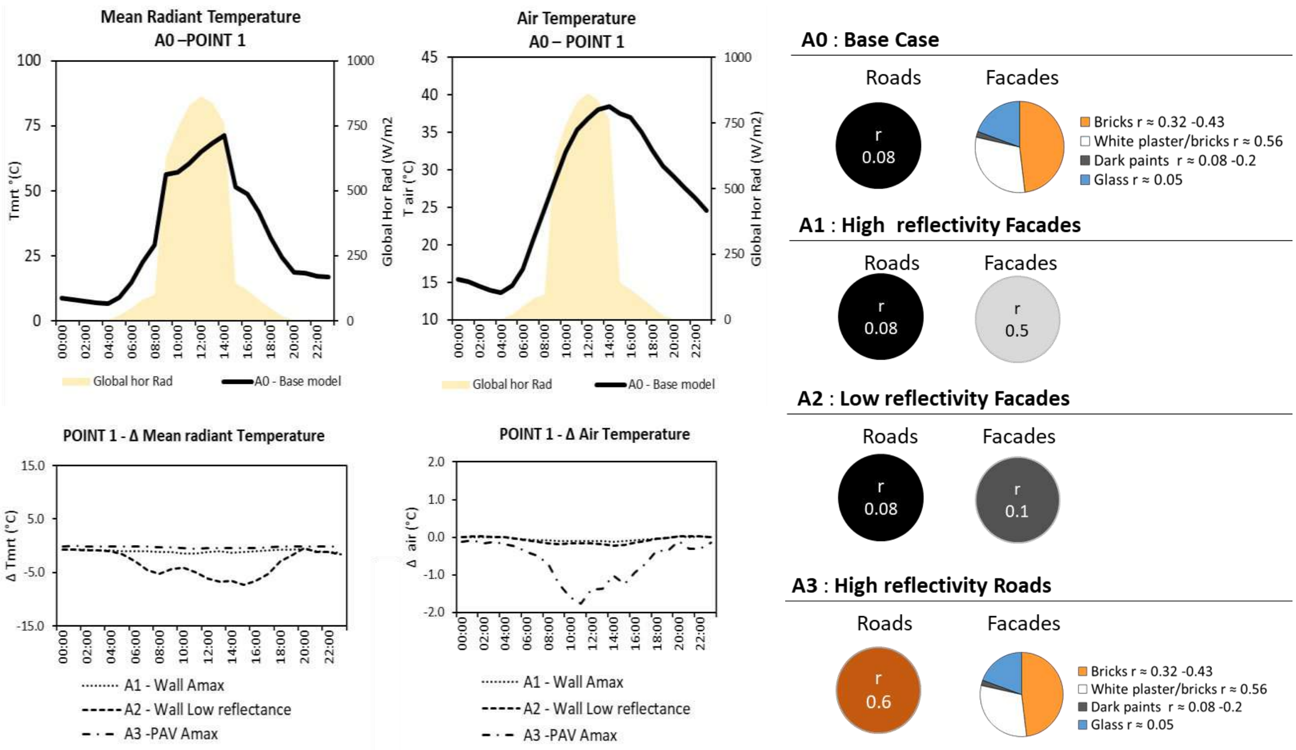

Figure 6 Impact of roads and facades' materials reflectivity on air temperature and mean radiant temperature at street level compared to the current scenario (base case).

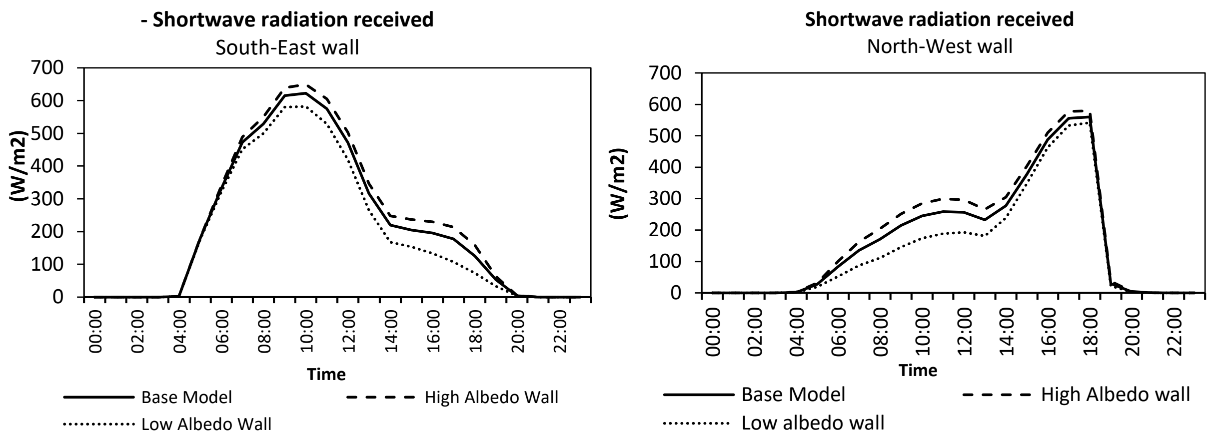

Figure 7 : Shortwave solar radiation received by the South-East (left) and (North-west) wall surrounding point L2 for different scenarios

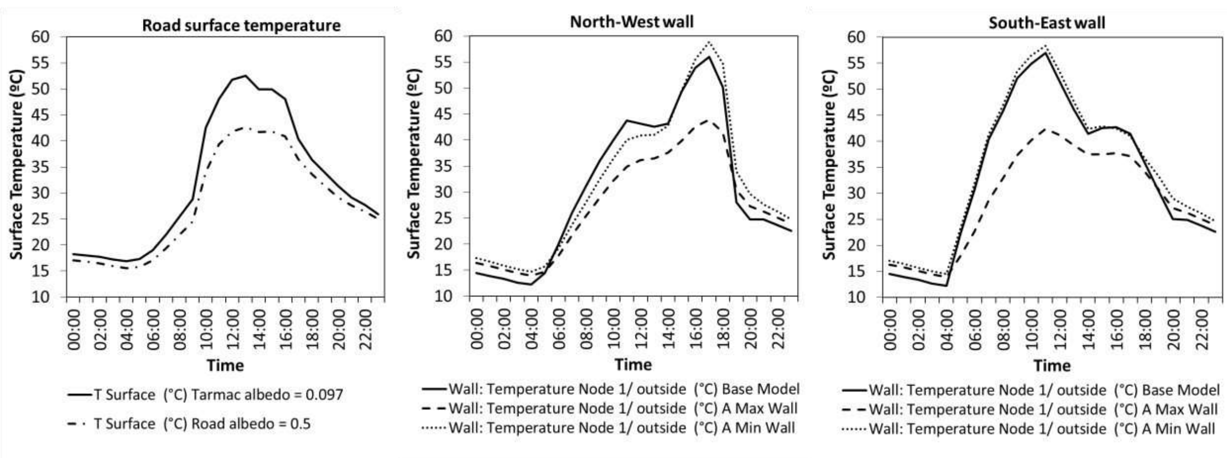

Figure 8 Left: Tarmac surface temperature over the heat wave. Right: surface temperature decrease using a high reflectivity material for paving

The combined scenario of low albedo facades and high albedo roads allowed the maximum improvement of outdoor thermal comfort in the case study area, being beneficial for both street level air temperature and mean radiant temperature. However, in terms of surface temperatures (figure 8), the high-albedo walls show a significant decrease in surface temperature compared to the base case and the low albedo walls. Surprisingly, this change in surface temperature does not entail a similar change in mean radiant temperatures or improved PET values. The same applies for the increase of surface albedo of the road, which entails a significant decrease of surface temperature, but it does not impact the mean radiant temperature at street level (Figure 6).

This could be explained by the fact that ENVImet takes into account all radiation fluxes in the calculation of the mean radiant temperature, including direct and diffuse irradiance, reflected radiation and long wave radiation (Naboni *et al.*, 2019). Therefore, changes in the direct and diffuse irradiance may have a bigger impact on the mean radiant temperature compared to the change in surface temperature of walls and roads. This is supported by other studies on the impact of reflective paving on outdoor thermal comfort, which show that the reduced surface temperature is not enough to offset the increased radiation loads from the surfaces (Erell, Pearlmutter and Boneh, 2012; Yang, Wang and Kaloush, 2015). However, to validate this result, more investigations into the mean radiant temperature calculation method of ENVImet are necessary. The lack of information to fully assess the accuracy of the outdoor thermal comfort estimations was reported also for other tools (Evola *et al.*, 2020). This highlights the need of more experimental data to completely validate these complex simulation tools.

Further developments of this research will include the assessment of the impact of the albedo of urban materials in different urban geometries and in the winter season.

5. Conclusion

This work analyses the potential of changing the albedo of facades' and roads' materials for reducing heat stress in London over heatwave events. The results provide new insights on the relationship between surface albedo and urban albedo and the effectiveness of high albedo materials in improving outdoor thermal comfort in complex urban geometries at London's latitude.

The analysis is based on microclimate simulations with the software ENVImet, validated with experimental data of air temperature and solar radiation measured in a case-study residential area of London. The incident and reflected solar radiation measurements within three urban canyons of the case-study area indicate that, for a datum geometry, the reflections are not influenced by street orientation and materials distribution. In the measured canyons (aspect ratio approximately 0.75), the average urban albedo varied between 0.08 and 0.09. The comparison of reflections measurement with ENVImet estimations showed a good agreement using the detailed IVS method for the computation of reflections.

The validated model was used to assess the impact of changing surface albedo of facades and roads on the outdoor thermal environment. The results showed that increasing the albedo of facades has a negligible impact on the thermal environment, while a substantial decrease of the facades' albedo may have a beneficial impact on the heat stress level during heatwaves, because it determines a decrease of the mean radiant temperature. The results also showed that increasing the albedo of roads allows a decrease of street-level air temperature, with positive impact on the PET value. These findings are relevant for the development of urban planning guidelines for improving thermal comfort and reducing outdoor heat stress under heat wave events in London.

Acknowledgement

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