Evaluation of mitigation strategies to improve pedestrian comfort in a typical Mediterranean city

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1. Introduction

Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment' (ISO, 1990). Outdoor thermal comfort in urban spaces is known to be an important contributor to people's health. Since the 1980s, studies of thermal comfort in the outdoor environment have grown in number because of increased attention for pedestrians in urban canyons, plazas and squares (Taleghani et al., 2015). Outdoor thermal comfort is mainly related to thermo-physiology, i.e. physiology and heat balance of the human body (Höppe, 2002) that is directly affected by meteorological conditions. In particular, in the Mediterranean area, the main bio-meteorological stress is related to the summer period during which heat waves are frequent: as an example the European heat-wave during summer of 2003 was estimated to have caused up to 70.000 excess deaths during a four month period in central and western Europe (Robine et al., 2008).

One of the most widespread interventions to improve thermal comfort in the Mediterranean area is incorporating green infrastructure into the urban built-space. This is gaining popularity as a cost-effective and long term measure for mitigating climate change impacts associated with built infrastructures (Hamdouch and Depret, 2010; Llausàs and Roe, 2012; Schäffler and Swilling, 2013).The majority of vegetation studies on buildings have focused mainly on the assessment of thermal comfort (Berkovic et al., 2012; Santamouris, 2012; Berry et al., 2013). The effect of vegetation on microclimate strongly depends on atmospheric condition (local climate) as demonstrated by Alexandri and Jones (2008). Nevertheless, air temperature distribution within a city and its time evolution depend on different concomitant aspects, including meteorological factors (wind speed and direction, humidity, cloud cover) and urban related parameters, such as building density, morphology and material, traffic, heating sources etc. (Tablada et al., 2009; Yang et al., 2010). Thus, thermal comfort may vary within the hours of the same day. The effects of vegetation on microclimate and comfort can be evaluated by using environmental modelling (Perini and Magliocco, 2014). Much effort has been done in determining the role of vegetation on urban microclimates, with several experimental and numerical studies (Buccolieri et al., 2011; Pappaccogli et al., 2014; Tiwary and Kuman, 2014).

Within this context, this work aims to demonstrate the effectiveness in reducing thermal stress in urban spaces by incorporating green infrastructure (trees) in urban spaces. The CFD-based ENVI-met (v3.1) is employed and is evaluated against field measurements held during summer 2012 in Lecce (south Italy). Specifically, three different case-studies of a Mediterranean climate were simulated, namely a typical summer day (10 August), a summer hot and dry day (5 August) and a high humidity condition (20 August) for which some thermal comfort indices (namely the Mean Radiant Temperature MRT and the Predicted Mean Vote PMV) are evaluated. Mitigation strategies of thermal stress were then assessed through the simulation of green infrastructures in two study sites.

2. Methodology

2.1 Meteorological measurements

The study area is Lecce, a medium size city in south Italy. During a 51-day long measurement campaign from July 21 to September 9 2012, air temperature was measured in two study sites (Figure 1a,b) using standard thermistor probes PB-5001 assembled with Tinytag TGP-0073 by Gemini data loggers. The thermal sensors (yellow triangles in the figure) were mounted at 4-6m height above ground level to be representative of the urban canyon conditions. More details are given in Maggiotto et al. (2014). Figure 1c,d show the observed temperature time evolution for the selected days. Both sites show a rapid increase in temperature during the first hours, a long plateau (3–4 hours) and then a slow decrease. From the profiles it is evident that 5 August was the hottest among all, while 20 August experienced the lowest temperatures (and high humidity); 10 August was representative of the temperature averaged over the whole meteorological campaign.

A statistical analysis was then carried out to quantify ENVI-met performance in reproducing the temperature distribution on the selected days (Di Sabatino et al., 2011). Table 1 shows the correlation coefficient, the Root Mean Square Error and the Hit Rate (calculated for 1°C and 2°C) for the two study sites. The statistical analysis shows large correlation coefficients R, low RMSE values and large HR (except that 5 August) indicating an acceptable performance of ENVI-met. The worse performance found for 5 August was due to the inability of the model in predicting highest temperatures during the daylight hours (not shown here).

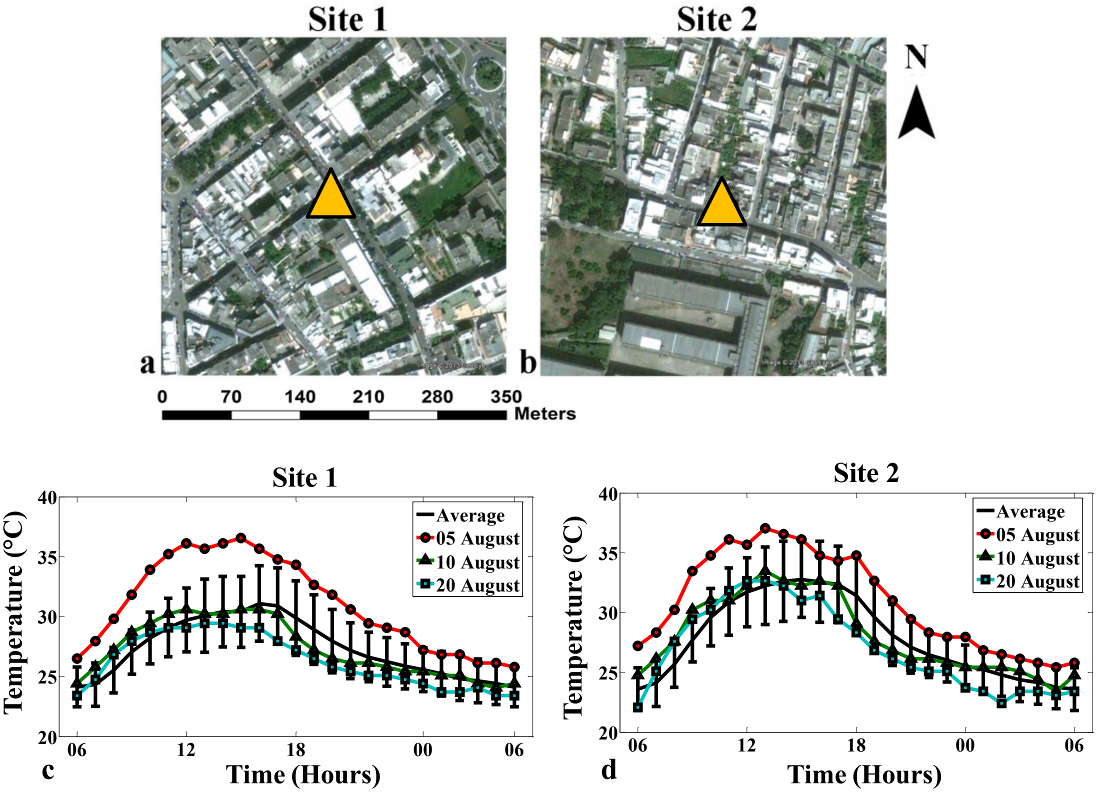

Fig. 1 Aerial images of (a) Site 1 and (b) Site 2 (from Google Earth). Yellow triangles represent the location of the thermal sensors. Profiles of observed temperatures for three selected days (5, 10, 20 August) and temperatures averaged over the measurement campaign for Site 1 (c) and Site 2 (d).

	R			RMSE			HR (1°C)			HR (2°C)		
	5 August	10 August	20 August	5th August	10th August	20th August	5th August	10th August	20th August	5th August	10th August	20th August
Site 1	0.94	0.94	0.89	0.40	0.16	0.21	0.21	0.79	0.54	0.50	1.00	1.00
Site 2	0.90	0.93	0.88	0.49	0.33	0.44	0.21	0.58	0.29	0.38	0.67	0.67

Tab. 1 Results of statistical analysis (correlation coefficient, Root Mean Square Error, Hit Rate).

2.2 Numerical modelling

ENVI-met simulations were done using a computational domain size of 494m x 494m for each site, which was meshed by 247 x 247 square cells of 2m x 2m. Within the domain, the nested study site occupied an area of 350m x 350m meshed by 175 x 175 square cells ("base case" in Figure 2). The study site was nested in a chessboard patterned computational domain which allowed the selection of two types of soil surfaces. Loamy soil and asphalt were set for all the sites in order to better capture the nocturnal evapo-transpiration effects (Maggiotto et al., 2014). Initial and boundary conditions are summarized in Table 2. Specifically, to calculate the thermal comfort indices (Mean Radiant Temperature MRT and Predicted Mean Vote PMV), we set three parameters (walking speed, energy exchange and clothes thermal resistance) which reproduced people that wear light summer clothes, standing or doing a light activity (e.g. shopping).

Starting from the base case, the mitigation strategy consisted of planting trees within street canyons ("mitigated" hereinafter). Overall 417 trees have been added in Site 1 (which corresponds to an increase of 32% with respect to the existing green area) to the and 497 (which corresponds to an increase of 49% with respect to the existing green area) in Site 2 (Figure 2). All the planted trees have been chosen from ENVI-met database (T1 database plants code), i.e. tree were 10m high with very dense foliage (with a maximum Leaf Area Densty LAD value of 2.180) and leafless base.

Fig. 2 ENVI-met areas input for Site 1 (a) and Site 2 (b) showing the base cases on the left and the mitigated cases (by trees) on the right. Red circles identify areas were trees have been added for mitigation purposes.

	5 August	10 August	20 August
Wind speed (m/s) at 10m	1.0	1.5	1.0
Wind direction (°) at 10m	118	300	238
Initial air temperature (°C)	27	24	23
Relative humidity at 2 m (%)	57	67	83
Soil data: initial temperature (°C) and relative humidity (%) of upper layer 0-0.2m	35 40	29 40	29 40
Soil data: initial temperature (°C) and relative humidity (%) of middle layer 0.2-0.5m	35 50	29 50	29 50
Soil data: initial temperature (°C) and relative humidity (%) of deep layer below 0.5m	33 50	27 50	27 50
Walking speed (m/s)	0.8		
Energy-exchange	0.93		
Clothes thermal resistance (clo)	0.5		

Tab. 2 Initial and boundary conditions used in ENVI-met simulations.

3. Results

In Figure 3, ENVI-met profiles of MRT for Site 1 and Site 2 are shown. MRT is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. It has a strong influence on thermophysiological comfort indexes such as Physiological Equivalent temperature (PET) and Predicted Mean Vote (PMV) (Fanger, 1982). Data refers to 1m high model receptors located at the same position of the thermal sensors. We remind here that the street canyon investigated at Site 1 is characterized by a south-west/north-east orientation, while the one at Site 2 is oriented along the east-west direction.

From the figure it can be noted that during the night the conditions are similar because of the absence of the global radiation, while during the day the picture is very different.

Specifically, at Site 1 the base case (Figure 3a) showed a peak of MRT during the hottest hour (i.e. from 13:00 to 15:00) up to 70°C, while a plateau occurred during all the other hours. No significant differences among the three days were found. In the mitigated case, MRT values decreased during the hottest hours, with a decrease of 30°C on 5 August (-43% with respect to the base case), 25°C on 10 August (-38%) and 15°C on 20 August (-15%) at 15:00. The mitigation strategy was thus more effective in decreasing the MRT during the warmer and drier day.

At Site 2 MRT peaks occurred from 9:00 to 17:00 in the base case. This was due to the street orientation that implied a long exposure to direct solar radiation at the building façade where the thermal sensor (and receptor) was positioned. Overall, MRT profiles were quite similar for all the days investigated, with values comparable to those at Site 1. In the mitigated case, MRT values decreased during the hottest hours, with a decrease of 27°C on 5 August (-38% with respect to the base case), 25°C on 10 August (-36%) and 16°C on 20 August (-23%) at 15:00 (hottest hour). Overall, due to the street orientation, the most significant contribution of the mitigation strategy was that of decreasing the number of hours showing MRT peaks, which were however similar to those found in the base case.

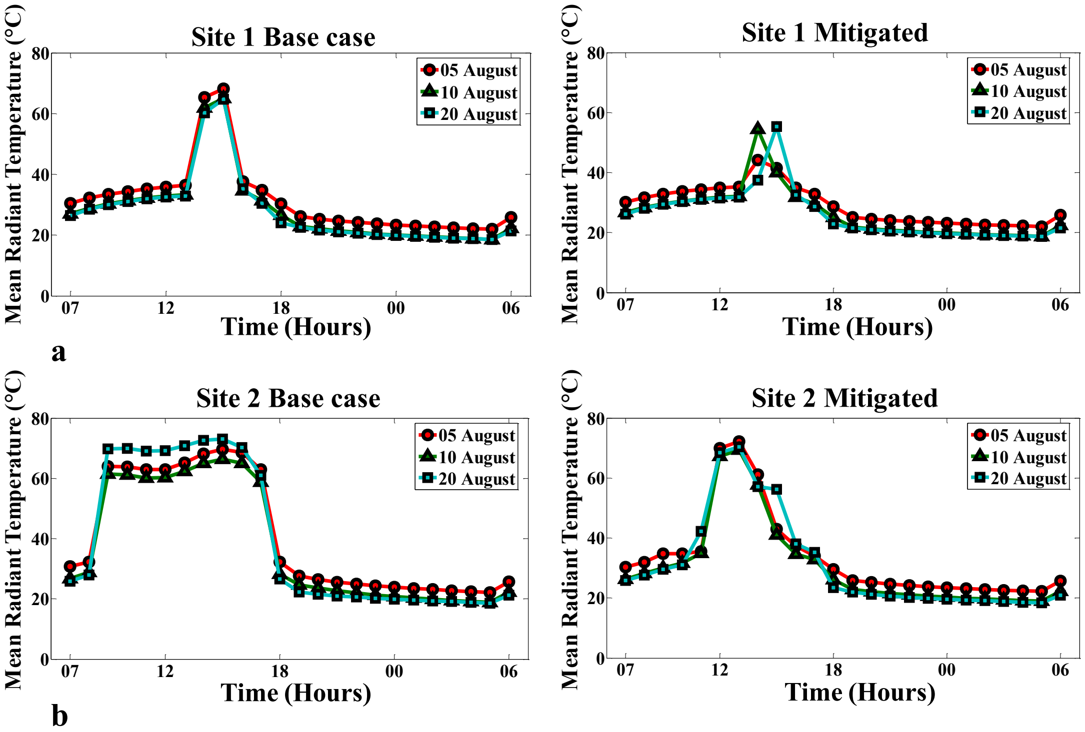

Fig. 3 ENVI-met profiles of Mean Radiant Temperature for Site 1 (a) and Site 2 (b) with the base case on the left and the mitigated case (by trees) on the right.

Figure 4 shows, as an example, ENVI-met maps (at 2m) of PMV at Site 1 and Site 2 for the base case and the mitigated case on 5, 10 and 20 August during the hottest hour (15:00). The PMV is probably the best known human thermal comfort model. Initially conceived for indoor applications, it is based on Fanger's comfort model and relates the energy balance of the human body with the humans thermal impression. PMV was originally developed for steady-state indoor situations, but by extending the energy flux related parts of the model with solar and longwave radiation and allowing wind speeds above an indoor room situation, PMV can also be applied to outdoor situations (see e.g. German VDI 3787 Part 2, 2008). Normally, the PMV scale is defined between -4 (very cold) and +4 (very hot) where 0 is the thermal neutral (the most comfortable condition) value.

From the figure it can be noted that the 5 August experienced the highest values of PMV (above +4) at both sites. Slightly lower values of PMV were found on 10 August and 20 august (high humidity). As expected from the MRT analysis, the influence of trees was to lower PMV, even though the effect was confined to the streets subjected to the mitigation strategy (see Figure 2). Overall, PMV patterns were mainly influenced by shadows of buildings, still suggesting the crucial role of the street orientation.

Specifically, at the receptor location in the mitigated streets at Site 1 PMV values decreased of maximum 3.42 on 5 August (-42% with respect to the base case), 2.99 on 10 August (-67%) and 2.94 on 20 August (-70%) at 15:00. The mitigation strategy was thus more effective in decreasing the PMV during the humid day. The same occurred at Site 2, where PMV values decreased of maximum 1.61 on 5 August (-27% with respect to the base case), 1.4 on 10 August (-30%) and 1.57 on 20 August (-34%).

4. Conclusions

The CFD-based ENVI-met code was used to evaluate the effectiveness of mitigation strategies for the improvement of pedestrian comfort at two different neighborhoods of Lecce, a medium size city of south Italy. Model simulations were compared with field measurements collected during summer 2012 using both direct comparisons and statistical indices. Once validated, ENVI-met results were used to estimate the Mean Radiant Temperature (MRT) and the Predicted Mean Vote (PMV) to assess the influence of trees on thermal comfort at the investigated sites.

Results suggests that the efficiency of trees in improving thermal comfort is mostly confined to the streets with trees and strictly depends on the street orientation which affects direct solar radiation and/or the presence of building shadows. Planting trees for mitigation purposes should thus be carefully evaluated though a comprehensive analysis which involves the influence of the street geometry and position as well as meteorological factors.

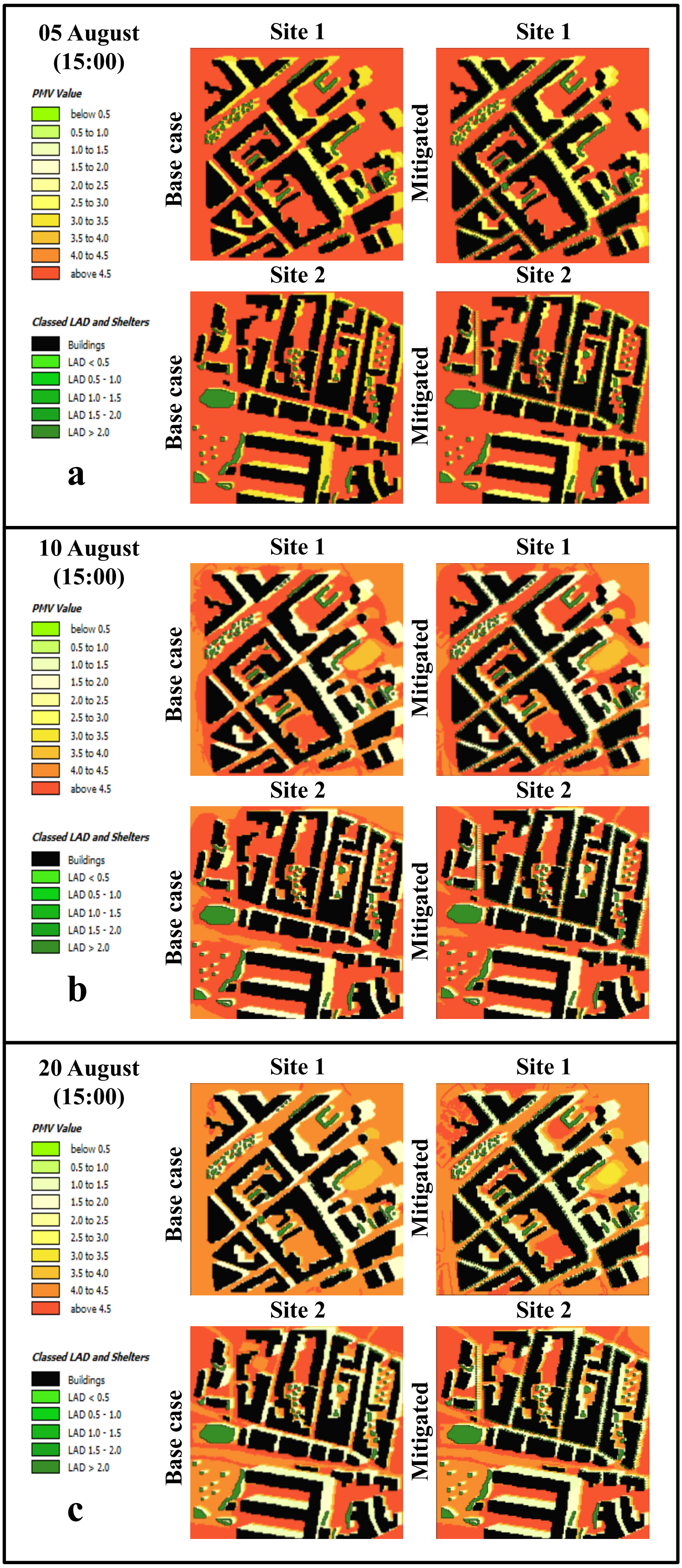

Fig. 4 ENVI-met maps (at 2m) of Predicted Mean Vote for Site 1 and Site 2 with the base case on the left and the mitigated (by trees) case on the right computed for the days of 05 August (a),10 August (b) and 20 August (c).

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