

An investigation on the radiant heat balance for different urban tissues in Mediterranean climate: a case study

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Abstract. The outdoor radiant field is a key aspect to determine outdoor comfort conditions for humans, especially in urban areas. In order to unveil the dependence of the radiant field on the features of the urban fabrics, this study analyses the space distribution of the Mean Radiant Temperature (T_{MRT}) and the radiant field in various urban tissues of the city of Catania (Italy) in a typical Mediterranean climate. The study is based on simulations through the Solar and LongWave Environmental Irradiance Geometry model (SOLWEIG) implemented in UMEP. Results show that the worst conditions occur in areas with moderately deep urban canyons, abundant impervious surfaces and lack of vegetation: here, the T_{MRT} can easily reach 78 °C while in more than 80% of the area it exceeds 60 °C. By modelling the time trends of the shortwave and longwave radiant heat fluxes perceived by a pedestrian, it has been possible to observe that the highest contribution to the outdoor radiant field comes from the downward solar irradiance. However, the downward and upward longwave radiant flux closely follows: this suggests the importance of providing shading rather than using highly reflective surfaces that can exacerbate heat stress by means of the increased reflected shortwave radiation.

1. Introduction

Urban heat stress is becoming more intense and frequent in developed countries because of the rapid urbanization and global warming processes taking place at unprecedented pace. As a consequence, overheating affects people living within cities not only in terms of increased cooling energy demand of buildings [1], but also with regard to the thermal conditions they experience outdoors [2].

In this light, extremely hot weather occurrences are of concern with respect to people's comfort, health risks and mortality [3]. Various studies initially focused their attention on air temperature (T_A) as the main climate variable related to heat stress [4-5]; however, it is now well acknowledged that the main cause of heat stress in summer conditions is the radiant thermal environment. As such, the mean radiant temperature (T_{MRT}) is the most appropriate parameter to characterize the effects of the radiant thermal environment on humans [6]. In fact, although spatial variations in T_A are rather small during the day within an urban area, the T_{MRT} shows large spatial variations [7-8] that are mainly determined by shadow patterns generated by obstructing objects (e.g., buildings and trees) and by different thermal and radiative properties of construction materials (i.e., albedo and thermal emissivity). As an example, during clear summer days T_{MRT} near sunlit walls at noon and early afternoon is significantly higher than T_A because of the high amount of direct and reflected shortwave radiation from the neighbouring surfaces hit by the sun, while at night – when the shortwave radiation is absent – T_{MRT} is



almost equal to the T_A . Many studies have thus analysed heat stress in cities from the radiant energy balance perspective [9-10], while also focusing on the appraisal of specific mitigation technologies such as cool materials [11], urban greenery [12-13] and shading [14].

The objective of the present study is to investigate the spatial variation of T_{MRT} as determined by the various radiant heat forces caused by different urban geometry layouts, construction materials properties and vegetation patterns in a warm and humid Mediterranean city. Three different urban areas in the city of Catania (Italy) are selected as the study sites and analysed by means of the Multi-scale Environmental Predictor (UMEP) software [15] through the dedicated Solar and Long Wave Environmental Irradiance Geometry (SOLWEIG) model [16]. The outcomes of this investigation are intended to providing insights on the magnitude of the heat stress phenomena and on their localization, while also suggesting potential mitigation measures to decision makers.

2. Outdoor comfort simulations and the SOLWEIG model

The mean radiant temperature is defined as “the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” [17]. As such, it accounts for the shortwave and long wave radiant exchange of a standard human body with its surroundings and it is the main meteorological variable governing the human energy balance outdoors [9].

There exist various models able to predict the T_{MRT} outdoors, among which the Solar and Long Wave Environmental Irradiance Geometry (SOLWEIG) is one of the most accurate and reliable [6, 9]. SOLWEIG estimates the T_{MRT} at a height of 1.1 m above ground (representing the height of the centre of gravity for a standing person) through the classic Stefan-Boltzmann’s equation:

$$T_{mrt} = \left(\frac{R}{\varepsilon_p \cdot \sigma} \right)^{1/4} - 273.15 \text{ (}^\circ\text{C)} \quad (1)$$

Here, $\varepsilon_p = 0.97$ is the thermal emissivity of the human body, $\sigma = 5.67 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ is the Stefan-Boltzmann constant and R is the mean radiant flux density ($\text{W} \cdot \text{m}^{-2}$). The latter is defined as the sum of all shortwave (K_i) and long wave (L_i) radiant fluxes reaching the human body – and absorbed by it – from all four cardinal directions, as well as from upward and downward directions:

$$R = \alpha_p \cdot \sum_{i=1}^6 (K_i \cdot F_i) + \varepsilon_p \cdot \sum_{i=1}^6 (L_i \cdot F_i) \quad (2)$$

In Equation (2), α_p is the shortwave absorption coefficient of the human body ($\alpha_p = 0.70$) and the terms named F_i are the angular factors corresponding to all six directions, whose values are set to 0.22 for each cardinal direction and to 0.06 for upward and downward directions, respectively.

The calculation of the shortwave (K_i) and long wave (L_i) radiation components from the six directions is performed according to different analytical expressions that are not reported here for the sake of brevity. The reader can find further details in [16].

3. Case study urban areas and simulation settings

Three study areas are selected within the metropolitan district of Catania (LAT. 37°26’ N, LON. 15°04’ E, 10 m a.s.l.), an Italian city with a hot and humid climate experiencing sunny days for most of the year. Figure 1 reports the localization of the three study areas, along with the main weather variables recorded during the three consecutive hottest days of 2019 at the airport weather station of Catania Fontanarossa that are selected for carrying out the simulations in SOLWEIG.

As it is possible to observe, peak temperatures of about 35 °C are achieved during the first two days (T , solid red line in Figure 1). On the other hand, relative humidity greatly oscillates during the same days from the lowest value of 12% recorded on the 7th of August to the peak value of 82% achieved on the 9th of August (RH, blue dashed line in Figure 1). As far as solar irradiance is concerned (G , yellow solid line in Figure 1), the selected days have clear sky conditions, and as such they show a regular pattern and similar peak values (about 900 $\text{W} \cdot \text{m}^{-2}$) in the global horizontal irradiance.

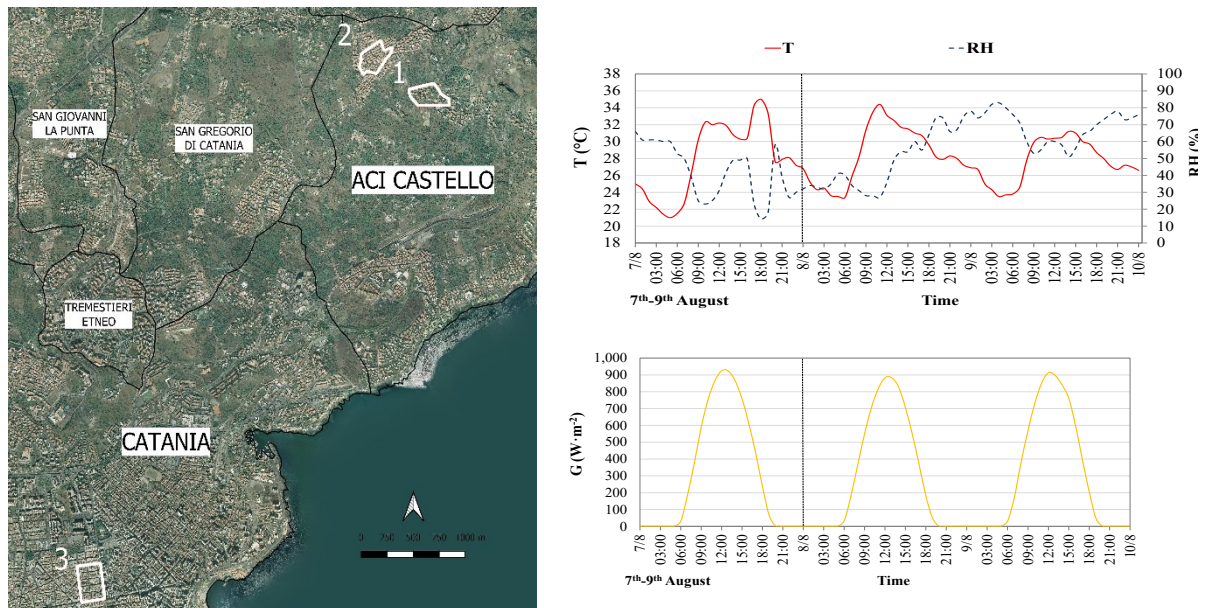


Figure 1. Aerial view of the three study areas and main weather variables recorded during the simulation days (7-9 August 2019)

The morphometric characteristics and land cover fractions of the different study areas are reported in Table 1. These areas have been selected because they show different geometric properties, as summarized by their average canyon ratio (i.e., the ratio between the average building height to the average street width), and different land covers. Various points of interest (POIs) are selected to derive detailed values of the most important radiant heat components that make up the radiant heat balance on the human body. The characteristics of such POIs are shown in Table 2, which reports on their optical (i.e., albedo and thermal emissivity) and geometric (i.e., sky view factor SVF) properties. It is worth noting that SOLWEIG allows considering only an average value of the albedo of walls, which has been set to 0.4 in all three areas.

Table 1. Morphometric and land cover characteristics of the study areas

Area	Avg. building height [m]	Avg. street width [m]	Avg. canyon ratio [-]	Building surface [%]	Impervious surface [%]	Bare soil [%]	Trees [%]	Grass [%]
#1	8.3	15	0.55	31	27	4	36	2
#2	9.4	10	0.94	46	46	2	2	4
#3	21.45	12	1.79	42	56	0	2	0

Table 2. Characteristics of the selected points of interest (POIs)

Point of interest	Land cover	Thermal emissivity ϵ [-]	Avg. ground albedo [-]	Avg. SVF [-]
P1	Bare soil	0.94	0.25	0.97
P2	Paved	0.95	0.15	0.47
P3	Paved	0.95	0.15	0.40
P4	Paved	0.95	0.15	0.12

4. Results and Discussion

In order to give an idea of the spatial variability of T_{MRT} , Figure 2 reports the values calculated for each study area on the 8th of August at 14:00 in a false colour scale, along with the identification of every POIs within them. As it is possible to see, the area showing the highest T_{MRT} values is area #2 with peaks of around 78 °C, followed by area #3 and area #1 in order. This can be explained by the

fact that in area #2 the streets width is comparable with the buildings height (i.e., the average canyon ratio is of about one), and as such pedestrians are directly exposed to solar radiation since buildings do not provide adequate shading. On the other hand, the geometric configuration of area #3 with its courtyards and taller buildings contributes to lowering T_{MRT} values, especially in proximity of the east facing facades that show values in the range of 40 °C to 55 °C. The lowest T_{MRT} values, found in the range of 30 °C to 50 °C, are instead reported for area #1 thanks to the higher rate of pervious surfaces (about 42% of the total) and the significant amount of vegetated area (38% of the total) almost evenly distributed over the entire area.



Figure 2. Spatial distribution of mean radiant temperature in the study areas on August 8th at 14:00 and identification of POIs

Further insights come from Figure 3: here, the curves describe the cumulated frequency of the T_{MRT} values occurring over the entire area at a selected point in time. As it is possible to observe, at 14:00 T_{MRT} is higher than 60 °C – i.e. the threshold over which heat-related mortality risks increase by 10% in people aged over 80 [3] – in about 80% of Area #2, while the corresponding figures for Area #3 and Area #1 are 60% and 48% respectively. However, in a less extreme situation – e.g. at 18:00 of the same day (Figure 3, right-hand panel) – T_{MRT} is below 50 °C in every point of the three areas, thus suggesting the major role played by direct sunlight. Interestingly, at 18:00 Area #3 now shows the lowest T_{MRT} values: actually, deep urban canyons are favoured when the sun height is low.

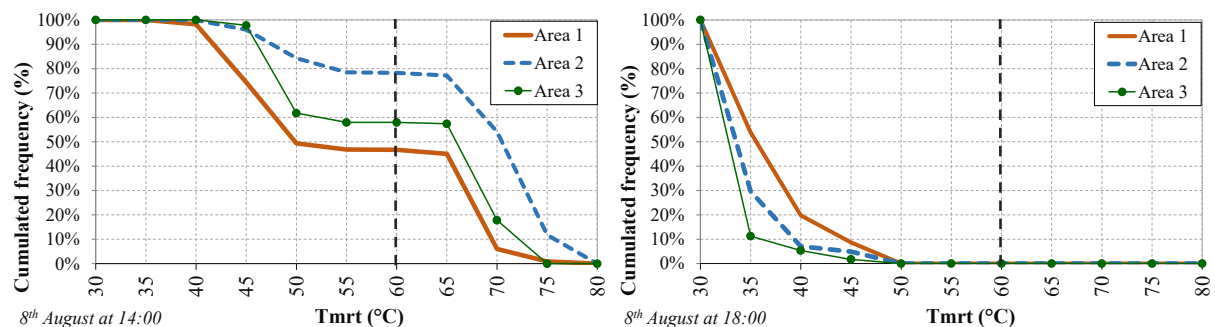


Figure 3. Spatial cumulated distribution of the mean radiant temperature in the study areas on August 8th at 14:00 (left) and 18:00 (right)

In order to verify this issue, the magnitude of the radiant heat forces acting on the different POIs is plotted against the corresponding T_{MRT} values in Figure 4. Here, what immediately emerges is the predominance of the downward shortwave radiation from the sky (K_{DOWN} , red solid line) during daytime, with peaks of around $900 \text{ W}\cdot\text{m}^{-2}$ between 13:00 and 14:00 for POIs P1, P2 and P3: in these points, which are always sunlit during daytime, T_{MRT} closely follows the pattern of K_{DOWN} . By contrast, when the POI is shaded for most of the time, L_{UP} and L_{DOWN} turn out to be the predominant radiant forces. This is the case of P4, placed below a tree, except during the short time interval (around

11:00) where sun rays coming from east hit the POI and determine a sudden (but short) increase in K_{DOWN} and T_{MRT} . As a general rule, both longwave terms range between 400 and 600 $W \cdot m^{-2}$: L_{UP} is mainly determined by the high rate of heat absorbed by the ground – and then re-emitted in the longwave range – whereas L_{DOWN} is due to the infrared radiation directly coming from the sky and eventually reflected from the facades.

Finally, the lowest contribution to T_{MRT} comes by the shortwave radiation reflected by the ground (K_{UP} , orange dashed line), which in each POI peaks below 200 $W \cdot m^{-2}$ at the same time of K_{DOWN} . In this case, the albedo of the ground plays a key role; however, in all points the albedo is similar and very low (see Table 2), as usual for ground surfaces. In P1, where bare soil has a slightly higher albedo (0.25) than paved ground (0.15), K_{UP} is consequently higher than in the other points, but it still has a minor role. Notwithstanding this, it is worth noting that the simplification imposed by SOLWEIG of considering a fixed albedo value for all the facades can undermine not only the prediction of the shortwave radiation coming from the four cardinal directions when the POI is close to one or more façades, but also that of K_{UP} that accounts for the same facades' reflection. On the other hand, the magnitude of the long wave radiation coming from the four cardinal directions is comparable to L_{UP} and strongly depends on the POIs' sky view factor (i.e., proximity to building facades).

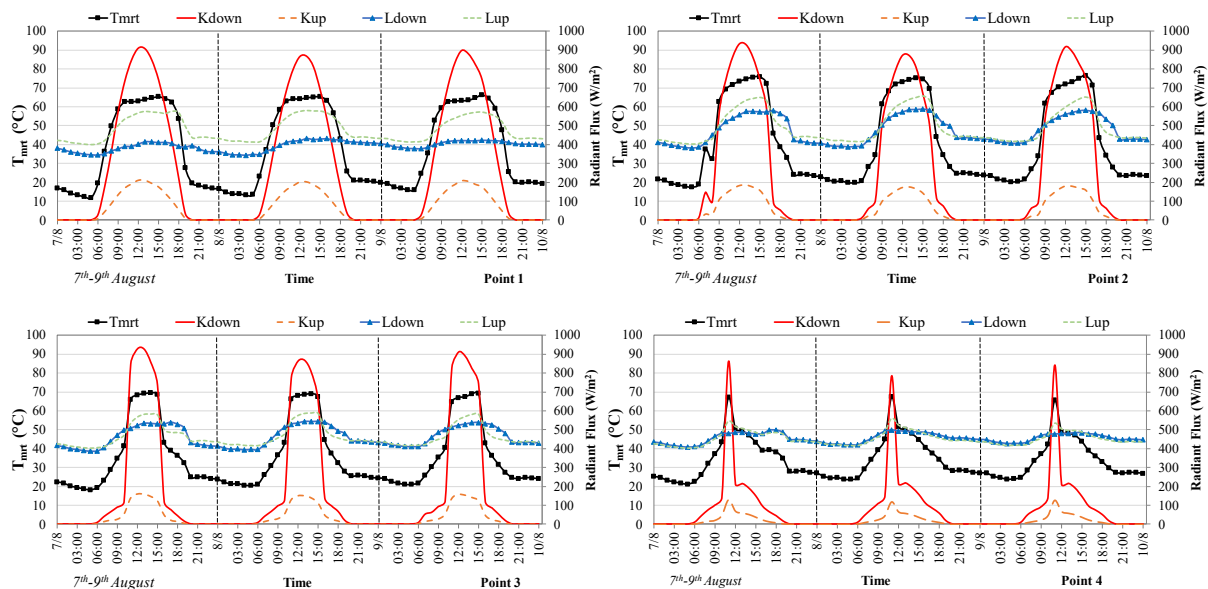


Figure 4. Radiant energy balance and mean radiant temperature profile for POIs during three consecutive warm days

5. Conclusions

The analysis of the mean radiant temperature (T_{MRT}) and the outdoor radiant heat fluxes in SOLWEIG for different urban tissues of the Mediterranean city of Catania (Italy) allowed identifying the main sources of heat stress for pedestrians. In particular, the T_{MRT} has peaks around 78 °C in urban areas with a canyon ratio close to the unity, a high amount of impervious surfaces and lack of greenery. Although less warm, also areas with a good amount of pervious surface (about 42%) are found to suffer from high T_{MRT} , with more than 50% of such areas showing a T_{MRT} value higher than 60 °C (threshold for increased mortality risk for the elderly) in the early afternoon of a particularly hot day. The detailed analysis of the radiant heat fluxes exchanged with pedestrians allowed identifying the incoming shortwave radiation, followed by the upward and downward long wave radiation, as the main causes of thermal discomfort of people. Thus, mitigation actions should be planned with the goal of reducing such radiant heat fluxes through appropriate shading of the walkable paths, rather than by increasing the albedo of vertical surfaces or horizontal surfaces. However, the possibility of using only a fixed albedo value for all the facades in SOLWEIG can undermine the predictions of the longwave