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Key Parameters for Urban Heat Island Assessment in A Mediterranean Context: A Sensitivity Analysis Using the Urban Weather Generator Model

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Abstract. Although Urban Heat Island (UHI) is a fundamental effect modifying the urban climate, being widely studied, the relative weight of the parameters involved in its generation is still not clear. This paper investigates the hierarchy of importance of eight parameters responsible for UHI intensity in the Mediterranean context. Sensitivity analyses have been carried out using the Urban Weather Generator model, considering the range of variability of: 1) city radius, 2) urban morphology, 3) tree coverage, 4) anthropogenic heat from vehicles, 5) building's cooling set point, 6) heat released to canyon from HVAC systems, 7) wall construction properties and 8) albedo of vertical and horizontal surfaces. Results show a clear hierarchy of significance among the considered parameters; the urban morphology is the most important variable, causing a relative change up to 120% of the annual average UHI intensity in the Mediterranean context. The impact of anthropogenic sources of heat such as cooling systems and vehicles is also significant. These results suggest that urban morphology parameters can be used as descriptors of the climatic performance of different urban areas, easing the work of urban planners and designers in understanding a complex physical phenomenon, such as the UHI.

1. Introduction

Urban Heat Island (UHI), is one of the most profound climatic modification linked to urbanization, being reported and theorized since the seminal studies of Oke during the 80's [1]. However, regardless the relevant advances in the understanding of urban climate, the relative weight of urban variables such as impervious materials, urban form, anthropogenic heat sources and the like contributing to the general UHI effect remains unclear, needing more empirical research. This shortcoming also constrains the development of predictive studies with lower levels of uncertainty.

Research carried out by Ryu and Bak [2], Salleh et al. [3], Perini and Magliocco [4], Palme et al. [5] have highlighted the fundamental contribution of urban form and anthropogenic heat generation on the UHI effect; the findings also highlight that the presence of impervious materials and the reduction of vegetation drive the diurnal UHI. UHI intensity has been predicted using four different kinds of climate models, as proposed by Kolokotsa [6]: 1) Computational Fluid Dynamics (CFD) models (e.g. FLUENT model), 2) Urban Thermal Environment (UTE) models (e.g. ENVIMET model), 3) Mesoscale models



(e.g. Urban Weather Generator, Weather Research Forecasting and Mitigation Impact Screening Tool models) and, 4) Local Climate Zones (LCZ). These models differ in calculation approaches and accuracy of results. CFD and UTE are more accurate in calculation, but the spatial extension of the simulation is limited, since they require high computational power and time. LCZ and Mesoscale models are less detailed and more uncertain; nevertheless, they have the advantage to be representative of a whole neighbourhood or even of a whole city.

The Urban Weather Generator (UWG) model has been developed by Bueno et al. [palme], coupling an atmospheric model with a Building Energy Model (BEM). The advantage of using UWG is that it produces a modified weather file compatible with the most common BEMs. The model accuracy has been evaluated for different urban contexts, such as Singapore [8] Boston [9], Tolosa [7], Rome and Barcelona [10]. Preliminary sensitivity studies on this tool have been developed by Nakano [11], Palme et al. [5] and Salvati [12], considering different geographic locations.

This paper presents a detailed sensitivity analysis of UWG variables considering the Mediterranean context as reference, in order to identify the relative weight of the major urban parameters responsible for the UHI intensity in this geographic context. The selected parameters are of high interest for urban designers and planners, as they could use these results to understand direct links between the morphological features of the built environment and the complex physical phenomenon of the UHI.

2. Methodology

The influence of different urban parameters on the UHI intensity was tested carrying out sensitivity analyses with UWG model (v1.0). The model calculates hourly values of air temperature in the urban canyon using two input files: 1) a rural weather file (. epw format) and 2) an XML file which describes the area where the canyon is located.

The sensitivity analysis was performed by changing systematically the value of one parameter at a time in the XML file and assessing the impact on the resulting UHI intensity. Eight parameters were tested: 1) the city radius, 2) the urban morphology, 3) the tree coverage, 4) the anthropogenic heat from vehicles, 5) the building's cooling set point, 6) the heat released to canyon from HVAC systems, 7) the wall construction properties and 8) the albedo of vertical and horizontal surfaces.

The tested values for the eight parameters were identified according to the range of variability observed in Rome and Barcelona, being representative of significant urban areas in Mediterranean climate. However, some values are aimed at providing broader assessment, like the city radius. The input rural weather file used in the simulations refers to Rome-Ciampino (Lat. 41.47, Long.12.34. This approach makes evident the trend of the monthly average UHI intensity according to the variability of the single parameters in the Mediterranean climate.

2.1. Range of variation of urban parameters in the Mediterranean context

The eight parameters selected for the study contribute to the UHI intensity through different physical processes, which modify the amounts of the energy budget in the urban canyon with respect to the rural environment [1]. The links between the urban parameters and the commonly hypothesized causes of UHI are reported in figure 2. The eight parameters correspond to four different scales, as reported in table 1: 1) "Reference site", the entire urban area, 2) "Urban area", area of approximately 500 m radius surrounding the urban canyon, 3) "Building", the typical building of the canyon and, 4) "Elements", the wall, road and roof of the urban canyon. Table 1 summarises the test values chosen for each parameter.

2.1.1. City radius. The value of the city radius is used in UWG for the calculation of the advection flux in the "Urban Boundary layer" (UBL). Therefore, five values of city radius were tested in order to

consider a wide range of city dimensions, from small towns (1,500m radius) up to megalopolis (20,000m radius). The values for Rome and Barcelona are 6,500m and 4,500m, respectively.

2.1.2. Urban Morphology. Urban morphology contributes to the UHI intensity through multiple effects: the shortwave radiation absorption is increased because of multiple reflections into the canyon; the turbulent sensible heat transfers out of the canyon is reduced due to reduction of wind speed and the long-wave radiation loss from within the canyon is reduced due to the low sky view factor determined by surrounding buildings [13]. UWG considers three parameters of urban morphology: 1) Average building height (m), which expresses the average height of buildings in the urban area, normalised by building footprints; 2) Site coverage ratio (m^2/m^2), which is calculated as the ratio of the built area to the urban site area and; 3) Façade to site ratio (m^2/m^2), which is given by the ratio of the vertical surface area (walls) to the urban site area. The range of variability of the three parameters has been explored considering five urban textures representative of the range of urban densities in the Mediterranean context [14]; the reference textures are Borrel y Soler, Barceloneta and Raval of Barcelona and Don Bosco and Prati of Rome (figure 1). The three parameters have been calculated over simplified digital models, obtained through a process of normalisation and replication of the typical urban blocks present in each texture [15]. The sensitivity analyses have been carried out performing five simulations, changing concurrently the three parameters, in order to calculate the UHI intensity for the different urban textures.

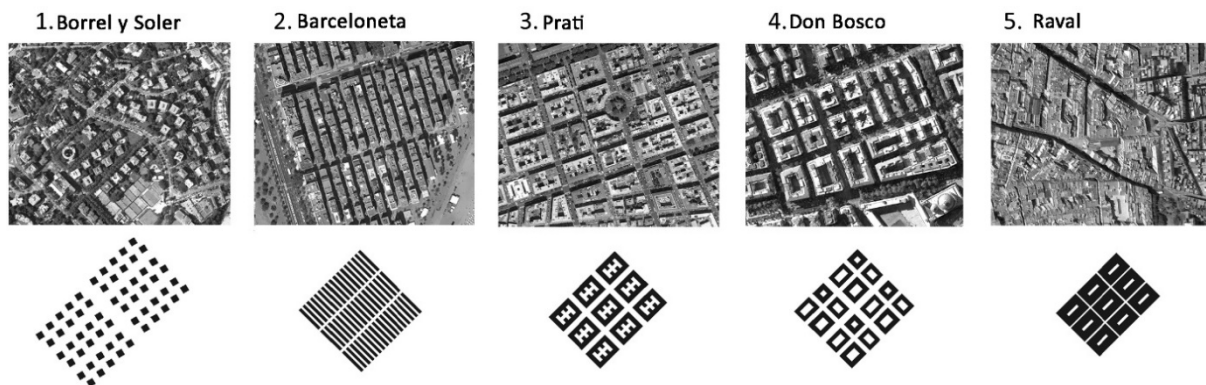


Figure 1. Urban textures of Barcelona (Borrel y Soler, Barceloneta, Raval) and Rome (Prati, Don Bosco) and normalised digital models used for the calculation of the Urban Morphology parameters

2.1.3. Tree coverage. The tree coverage is calculated as the ratio of the horizontal area occupied by trees to the urban site area. This parameter is used by UWG to calculate the latent heat flux in the urban area and the percentage of shaded surface in the canyon. The test values for this parameter have been estimated on the same sample of urban textures, where a range of tree coverage between 5% (in Raval) and 28% (in Borrel y Soler) was measured.

2.1.4. Anthropogenic heat from vehicle. The anthropogenic heat from traffic is a constant input value for UWG. The test values for this study have been calculated according to the formulation of Sailor and Lu [16], considering statistics of "daily vehicle distance per capita" [17] and population density of Italian cities. According to this analysis, the heat released by vehicles ranges between a minimum of 3 W/m^2 , for low traffic levels such as during night time, up to 30 W/m^2 during peak hours in high-density areas. The average urban value has been assumed equal to 8 W/m^2 based on previous research [18, 19].

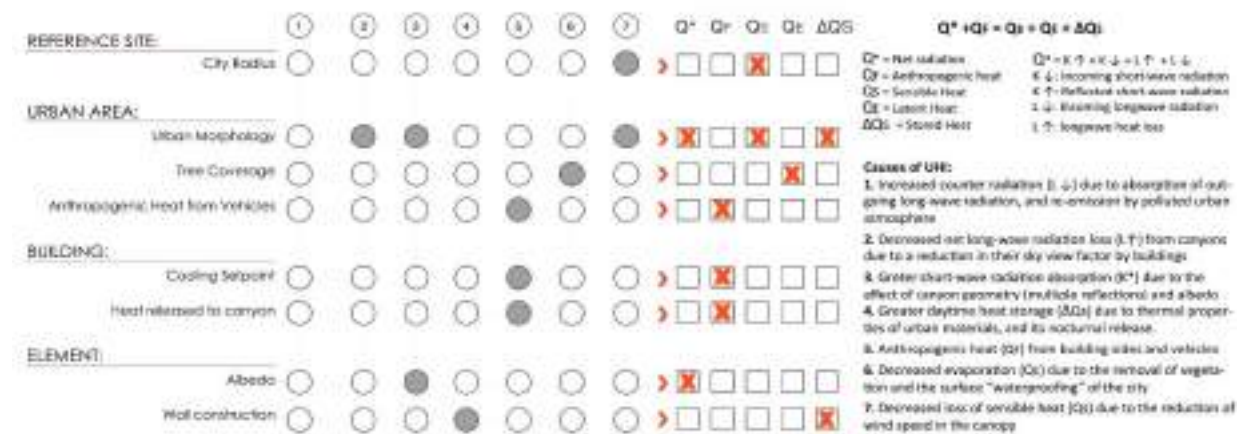


Figure 2. Relationships between the urban parameters and the 7 hypothesized causes of UHI

2.1.5. Building’s cooling set point. The cooling set point is a fundamental parameter used by UWG to calculate the building’s energy performance and so the heat released into the canyon. It is expressed in °C and corresponds to the building’s temperature setting during summer time. The sensitivity analyses have been performed for values from 22°C to 26°C and a value equal to 35°C which indicates the absence of mechanical cooling. The average urban value has been established to 26°C. This is a quite high value, aimed at considering that not all the buildings have air conditioning systems in the Mediterranean context.

2.1.6. Heat released to canyon from HVAC systems. The "heat released to canyon" indicates the amount of wasted heat from cooling system that is exhausted into the urban canyon and/or in the urban boundary layer. So, this parameter describes whether the cooling system is composed of outdoor units on the facade or centralised units located on the rooftop. The parameter ranges between 0 and 1; the value 0 means that there is no waste heat release into the canyon, while the value 1 means that all the waste heat is released into the canyon. The tested values are 0, 0.5 and 1, assuming 0.5 as the average urban value.

2.1.7. Wall construction properties. As regards the thermal properties of urban materials, in UWG each layer of walls, roads and roofs, is characterised by thermal conductivity (W/m^1K^1), volumetric heat capacity (J/m^3K^1) and thickness (m). Considering the properties of building materials and the common construction technologies in the Mediterranean context, the main difference is given by the density and thickness of the element's materials, which determine its inertia and ability to store heat. Therefore, two types of walls have been tested: load bearing walls and light weight walls. The former are typical of masonry constructions, with high thermal inertia and heat capacity, while the latter are light weight layered elements which ensure insulation from outdoor environment but have low thermal capacity. Details on the tested materials and thickness of the two types are given in table 1.

2.1.8. Albedo of vertical and horizontal surfaces. The last parameter tested was the albedo of walls, roads and roofs surfaces. The albedo, also known as reflection coefficient, is the ratio of reflected radiation from the surface to incident radiation upon it. Its value, which ranges between 0 and 1, is mainly linked to the colour of surface. Many studies [20] highlighted that an increase of albedo would have a significant mitigation effect on urban air temperature. However, the range of variation of the albedo of urban materials is quite low; according to literary review [21], the average values are between 0.2 - 0.5 for walls (from light-coloured to dark-coloured plasters or coatings), 0.04 - 0.2 for roads (from fresh asphalt to worn asphalt) and 0.1 - 0.35 for roofs (including bituminous membranes, tiles or floorings). The sensitivity analyses have been conducted for this range of values. The three values of

albedo of walls, roads and roofs have been changed together to simulate the effect of dark, medium or light colours, as reported in detail in table 1.

Table 1. The tested values of the eight urban parameters used in the sensitivity analysis. The average values are in bold.

| Scale | Urban Parameters | Tested values | | | | |
|----------------|--|--|---------------------------------|--|-------------------|--------------|
| Reference site | 1) City Radius (m) | 1. 1,500 | 2. (Barcelona) 4,500 | 3. (Rome) 6,500 | 4. 10,000 | 5. 20,000 |
| Urban Area | 2) Urban Morphology | 1.Borrel y Soler | 2.Barceloneta | 3.Prati | 4.Don Bosco | 5.Raval |
| | Average Building Height (m) | 15 | 16.5 | 19.5 | 25.5 | 19.5 |
| | Site coverage ratio (m ² /m ²) | 0.2 | 0.52 | 0.49 | 0.43 | 0.8 |
| | Facade-to-site ratio (m ² /m ²) | 0.63 | 2.23 | 1.43 | 1.68 | 1.38 |
| | 3) Tree coverage (%) | 1.Low 5 | 2.Average 12 | 3.High 28 | | |
| | 4) Anthropogenic heat from Traffic (W/m ²) | 1.low 3 | 2.Average 8 | 3.high 15 | 4.pick hour 30 | |
| Building | 5) Cooling set point | 1.No cooling 35° | 2.High 26° | 3.Medium 24° | 4.Low 22° | |
| | 6) Heat released to canyon | 1.HVAC Units on rooftop 0 | 2. Average 0.5 | 3.HVAC units on facade 1 | | |
| Element | 7) Wall construction | 1.Heavy Wall | | 2.Light Wall | | |
| | Layers material | plaster-masonry-plaster | | plaster-hollow brick-air-insulation-hollow brick-plaster | | |
| | Thickness (m) | 0.02-0.5-0.01 | | 0.02-0.08-0.05-0.07-0.12-0.01 | | |
| | Conductivity (W/mK) | 1.0-0.72-1.0 | | 1.0-0.37-0.026-0.034-0.37-1.0 | | |
| | Volumetric heat capacity (J/m ³ K) | 14*10 ⁵ -1612800-14*10 ⁵ | | 14*10 ⁵ -930000+1206+49000+930000 +14*10 ⁵ | | |
| | 8) Albedo | 1.ligh colours wall 0.5 | 2.Medium 0.35 | 3.dark colours 0.2 | | |
| | | road 0.2 | 0.08 | 0.04 | | |
| | | roof 0.35 | 0.25 | 0.1 | | |

3. Results and discussions

3.1. Impact of the single parameters on the UHI intensity

The variation of the monthly average UHI intensity according to the tested values for each of the eight parameters is reported in figure 3.

Regarding the city radius, UWG estimates a higher UHI intensity for the smaller cities, above all during autumn and winter months, while during summer months this parameter is irrelevant. This result is probably linked to the calculation of circulation velocity [7], which determines if the advection flux in the "Urban boundary layer" is driven by the geostrophic wind (forced problem) or by the urban breeze circulation (buoyancy-driven problem). The maximum variation of UHI intensity determined by urban radius variability occurs in September and October, reaching 0.7 °C. However, considering the radius of the two tested Mediterranean urban areas, Barcelona, about 4,500m radius and Rome, about 6,500m, the temperature gap is negligible.

The impact of urban morphology on the UHI intensity is significant during both winter and summer. The maximum difference is recorded in February, when the UHI intensity for the morphology of Raval is up to 2.4°C higher with respect to the one of Borrell Y Soler. The annual average temperature difference between the densest and the rarest urban texture is 1.8°C.

The tree coverage has, instead, an appreciable effect on the UHI intensity only during summer months; the variation of the tree coverage from the lowest value (5%) to the highest one (28%) determines an average decrease of UHI intensity of 0.8°C in July and August. However, it has to be considered that the average value of tree coverage in the Mediterranean urban context is quite low, because the built surface is very high, especially in the city centre. In fact, the difference of UHI intensity between the average case (12% tree coverage) and the worst case (5% tree coverage) is negligible. The analysis of variability of sensible heat from traffic shows significant impacts on the UHI. During the summer, the UHI intensity based on the maximum value of the parameter (30 W/m^2) is more than 1°C higher than the UHI corresponding to the average value (8 W/m^2). Nevertheless, in UWG model this parameter is assumed to be constant over the day, while the maximum value considered in this analysis corresponds to peak traffic hours; during the rest of the day the value would be certainly lower. Therefore, this result may overestimate the impact of heat from traffic on the UHI. In this regard, the possibility to implement the daily trend of heat release from vehicles would improve the accuracy of the UWG predictions.

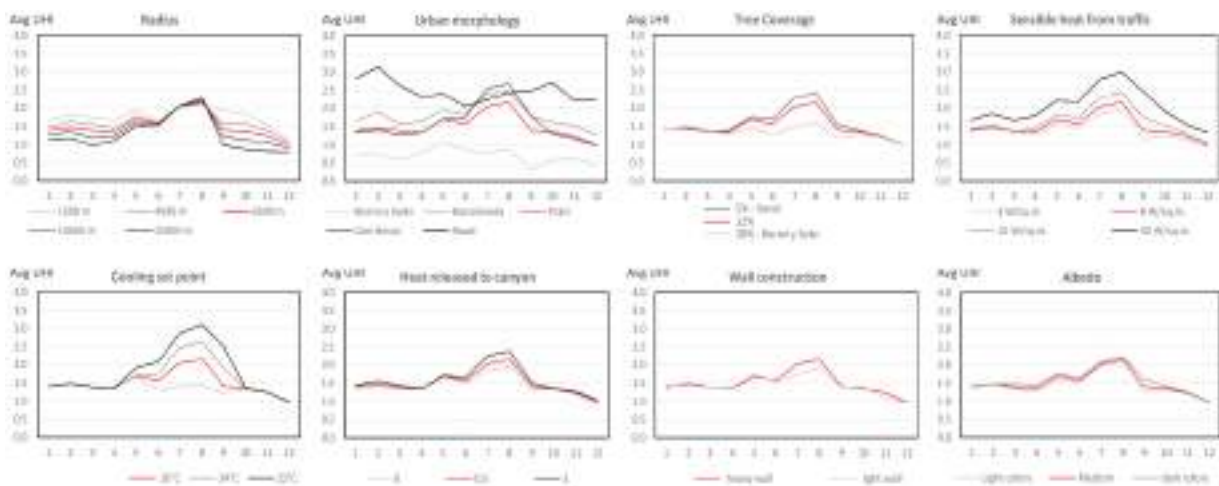


Figure 3. Monthly average UHI intensity according to the variability of the urban parameters.

Another crucial variable affecting the UHI intensity in summer is the presence of cooling systems in buildings; the impact is especially high for low cooling set points. In the hottest month, UWG estimates an increase of the average UHI intensity between 0.8°C and 1.7°C due to anthropogenic heat released by cooling systems. The parameter "heat released to canyon", which defines whether the heat from buildings is exhausted directly into the canyon or not, is less important.

The results also show that the variability of wall's thermal capacity does not affect the UHI intensity during most part of the year. The only appreciable temperature difference is recorded in July, when UWG results indicate a 0.3°C increase of UHI intensity for the walls with high thermal capacity (heavy walls). Therefore, this parameter is not influential on urban climate, in spite of its significance on the indoor thermal balance in summer.

Similarly, UWG calculations do not show any significant impact of the albedo of surfaces on the UHI intensity. This can be explained in the light of the limited variability of albedo values in the urban context. Urban albedo values of approximately 1 would be required for the UHI intensity effect to be reduced substantially; however, it is not likely that these values can be achieved across a whole urban area, where the average values are normally below 0.5.

3.2. Hierarchy of importance of the parameters

A comparative analysis of the results is presented in figure 4 to highlight the relative weight of each parameter on the UHI intensity in the Mediterranean context. The black bars in the graphs indicate the maximum difference of the monthly average UHI intensity determined by the maximum variation of each parameter; the difference varies from less than 0.5 °C to more than 2 °C, depending on the month and the parameter considered.

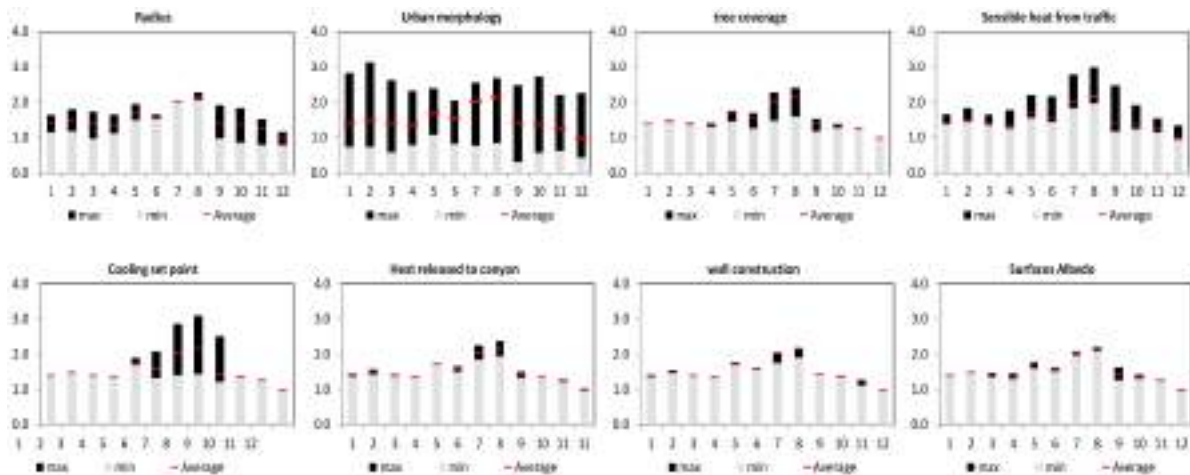


Figure 4. Maximum, minimum and average UHI intensity determined by the maximum, minimum and average value of each parameter

These results indicate a clear hierarchy of importance of the eight analysed urban parameters in terms of their impact on the UHI effect in the Mediterranean context. This is explained by two reasons: 1) the range of variability of certain parameters in the Mediterranean urban context is larger than others and, as a consequence, their impact on the UHI intensity is higher and; 2) some of the "causes" of the UHI are more important than others, and so the related parameters.

According to UWG results, the most important factor is the urban morphology, which determines substantial variations of the UHI intensity throughout the year. Considering that the annual average UHI intensity is about 1.5 °C for the average case, the variability of urban morphology determines changes up to 1.8°C; this means a relative impact up to the 120% of the average UHI intensity.

Another key parameter is the anthropogenic heat from the air conditioning systems of buildings, which significantly increases the UHI during summer. The average impact on air temperature is about 1.3°C, over an average UHI intensity in summer of 1.8°C. So, results indicate that the use of air conditioning systems in the buildings determines a relative change of 72% of the UHI intensity in summer. The anthropogenic heat released from traffic has an appreciable impact on the UHI intensity as well, even if lower than the urban morphology and the cooling systems. The variability of this parameter determines an annual average temperature change of 0.6 °C, which is the 40% of the annual average UHI intensity. A similar impact is determined by the variability of the city radius. However, with regards to this parameter, the results predict higher temperatures in smaller cities, probably due to the methodology adopted by UWG for the calculation of the advection flux in the urban boundary layer. Since there is no validation of this specific calculation module, these results should be further investigated.

The remaining four analysed parameters are much less significant on the UHI intensity. Therefore, according to these results, the most important causes of urban temperature increase in the Mediterranean

context are the physical processes that occur in the urban canyon due to the urban morphology and the presence of anthropogenic sources of heat like traffic and cooling systems.

The fact that the values of tree coverage is less influential on the UHI intensity is consistent with other urban studies [22–26]. Like in the case of albedo, the influence depends on the limited range of variability that these variables have in urban areas; a substantial modification of their values in the entire urban area could produce a more appreciable effect on the UHI intensity. At the same time, it has to be considered that UWG cannot simulate the effect of large water bodies or big parks on urban climate, so these variables have not been included in the study so far. They are matter of future studies, since their effect at urban scale may be significant.

4. Conclusions

This paper analyses the relative impact on the UHI intensity of eight parameters in the Mediterranean context, through sensitivity analyses using the UWG model.

Urban morphology is the parameter having the higher effect over the UHI intensity, causing a relative change up to 120% of the annual average UHI intensity. The anthropogenic heat related to traffic and buildings is also important. The variability of the heat released from vehicles in the urban area determines a 40% change of the annual UHI average. In summer, the presence of cooling systems in buildings is even more significant on the UHI intensity; waste heat produced by cooling systems may determine an increase up to the 72% of the average UHI intensity. All in all, the amount of anthropogenic heat from both vehicles and cooling systems is depending on the density and morphology of buildings in the urban area. Therefore, urban morphology is, indeed, the most important parameter with respect to the UHI intensity. The impact of variability of other parameters is quite negligible on the UHI variation in the Mediterranean context.

These results show that some common mitigation strategies, such as increase of albedo and tree coverage, may be ineffective to reduce the UHI intensity in the Mediterranean context, unless the intervention is able to change the ratio of these variables over a whole urban area; if their values remain, instead, constrained to small urban extensions, the impact on UHI intensity will be weak. This result is in line with other similar urban studies [22–27].

These results also suggest that urban density and morphology parameters could be used as predictors of the UHI intensity in the Mediterranean context, easing the analysis of the phenomenon in the urban areas for planners and urban designers. The knowledge of the temperature distribution according to morphology and density of the urban texture could also help to steer the mitigation interventions in the most affected areas within the city, so as to obtain effective results at urban scale.

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