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Agnese Salvati, Helena Coch Roura y Carlo Cecere

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URBAN HEAT ISLAND PREDICTION IN THE MEDITERRANEAN CONTEXT: AN EVALUATION OF THE URBAN WEATHER GENERATOR MODEL

SALVATI, Agnese[1]
COCH ROURA, Helena
CECERE, Carlo

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Palabras clave: Clima urbano; modelo de clima; simulación energética; contexto urbano

Structured Abstract

The lack of urban-specific climate data is, today, one of the major limits for an accurate estimation of the building energy performance in the urban context. The urban climate is substantially modified by the “heat island” effect that determines an increase of the air temperature compared to the surrounding rural areas. By contrast, the weather data used to run the energy simulations normally refer to rural or suburban weather stations, causing relevant errors in the energy assessment, especially in hot climates.

This study aims at evaluating the accuracy of the "Urban Weather Generator" (UWG), a model developed for generating urban weather files from rural weather data in order to improve the accuracy of the building energy simulations in the urban context.

To this purpose, the model predictions have been compared to actual observations in different urban sites in Rome and Barcelona. The comparisons have been conducted for one year of observations for each site, focusing the analysis on summer and winter months. The model accuracy has been assessed through statistical analysis of the average error.

Results show that the UWG model is able to capture the general trend of the urban temperature. The accuracy of the prediction increases for urban sites located in a rather homogeneous urban fabric in terms of building density and vegetation coverage. In these situations, the model allows a good prediction of the urban air temperatures with low computational requirement and it can be a useful tool to improve the accuracy of urban energy analysis.

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[1] Agnese Salvati: Sapienza University of Rome DICEA Department – SOS_UrbanLab, Faculty of Engineering, via Eudossiana 18, 00184 Roma, Italy. Contact email: agnese.salvati@uniroma1.it

1. Introduction

Cities are complex physical systems, whose functioning affects large scale phenomena, such as global climate change, and local scale phenomena, as the urban heat island intensity and the building energy performance or the thermal comfort in indoor and outdoor spaces.

As the main source of greenhouse emissions and energy consumption, cities are also the heart of the actual environmental issue. One of the clearest consequences of the indiscriminate urbanization produced in the last centuries is the increase of the air temperature in the urban areas. This phenomenon is referred to as "Urban heat island" (UHI) and it has been documented for cities all over the world (Dorer and Allegrini, 2012). Many studies have been conducted in the Mediterranean zone, in Greece, Italy, Spain, Portugal and Turkey (Santamouris, 2007). In this context the UHI is found to range between 1°C and 10°C.

The intensity of the UHI in Barcelona (Spain) has been firstly investigated by Moreno-Garcia (1994), who reported an average annual temperature difference between the city centre and the airport site of 1.4 °C and a temperature gap with respect to the minimums of 2.9 °C.

Several studies have been carried out also in Rome, Italy (Bonacquisti et al., 2006; Colacino and Lavagnini, 1982; Pelliccioni et al., 2012). According to Bonacquisti et al. (2006), the average UHI intensity in Rome is about 3 °C, with a maximum of 4,2 °C in August.

The temperature increase in the urban areas is mainly due to extensive soil sealing, building density and presence of anthropogenic heat sources which alter the water cycle, the wind regime and the radiative exchanges between the earth's surface and the atmosphere compared to a rural environment (Oke, 1987). As a consequence, the UHI exacerbates the effects of climate change and heat waves, posing a serious threat to the citizens' health and comfort. Nevertheless, it also causes a relevant increase of the energy consumption for space cooling, above all in hot and temperate climates as the Mediterranean one (Akbari and Konopacki, 2005; Allegrini et al., 2012; Crawley, 2008; Kolokotroni et al., 2012; Santamouris, 2014).

Urban heat island, comfort and energy performance are thus intimately related (Givoni, 1998; Moonen et al., 2012; Salvati et al., 2015). However, despite the evidence of the phenomenon and the seriousness of its consequences, the UHI effect is still regularly omitted in the practice of energy simulation. In effect, the standard weather files used to run the energy calculation normally refer to climate data gauged at weather station located outside the urban area, as the airports. This approximation entails relevant errors in the energy demand calculation, especially for residential buildings; according to Bueno et al. (2012), a typical 4 K daily-maximum UHI effect can determine a 20% error in the assessment of the cooling demand for residential buildings. The error can be even bigger when it comes to urban scale energy analysis.

Given that the building sector is responsible for a substantial part of the global energy consumption and emissions (Pérez-Lombard, Ortiz, and Pout, 2008), a correct evaluation of the buildings' performance in the urban context is a preliminary necessary requirement to reduce its environmental impact. To this aim, architects and planners must necessarily integrate their background with a wider body of knowledge and tools, able to describe the energetic and climatic dynamics that take place at urban scale, as the urban heat island effect.

Thus far, established building energy models are commonly used to simulate the energy performance at building scale (Crawley et al., 2008). However, the climate data currently used to run the calculation are obtained from weather stations located in open areas and outside the city (airports). The major limitations for an adequate prediction of the energy performance in the urban context is thus the lack of urban specific climate data (Alexander et al.,2015; Bueno et al., 2013).To fil this gap, recent studies have analysed the effect of the urban microclimate on the energy performance with *computational fluid dynamic* (CFD) models, coupled with energy models (Allegrini et al., 2012; Bueno et al., 2011; Yang et al, 2012). However, the level of computation required for these techniques is of much greater order and expense than the building thermal simulation and the procedure is difficult to repeat.

By contrast, several *urban surface energy balance models* (or Urban Canopy Models) have been developed to describe the energy fluxes between the urban surface and the atmosphere with low computational requirement (Grimmond et al. 2010). Among them, the Town Energy Balance (TEB) scheme by Masson (2000) is one of the most established. Furthermore, simplified building energy models have been implemented in urban canopy models to capture the energy interrelationships between the buildings and the urban climate,(Bueno et al., 2012b; Kikegawa et al, 2003). Nevertheless, not even these implemented models are suitable for a direct application for architectural purpose, as they are targeted to disciplines such as climatology and their outputs are not compatible with current building energy models.

An interesting implementation of the TEB scheme is the Urban Weather Generator (UWG) by Bueno et al. (2013). The UWG model creates urban weather files using rural temperatures as input. This model is especially useful to the architectural sector as its computational cost is on the same order of an energy simulations run, the output weather file is compatible with the most popular energy models and the most relevant input parameters can be derived from GIS databases available for many cities in the world.

This paper presents an evaluation of the UWG accuracy regarding the urban air temperature prediction for different sites in two Mediterranean cities. Firstly, the model components and the data required for the simulation are described. Then the UWG prediction is compared to the actual air temperature observations obtained from urban weather stations in Rome and Barcelona. In particular, the model is evaluated for its ability to improve the energy simulation accuracy in the urban context. So the UWG prediction is compared to both the urban air temperature and the airports air temperature, which is normally used for standard climate databases. The statistical analysis of the model performance is thus presented and discussed. Finally, some recommendations for a proper use of the tool and the limits for its applicability are drawn as conclusion.

2. Model description

The UWG was developed by Bueno et al. to calculate hourly values of urban air temperature given the weather data measured at stations located in rural or sub-urban areas (Bueno et al., 2013). The model is based on the Town Energy Balance scheme of Masson, including a building energy model derived from EnergyPlus algorithms (Bueno et al., 2011; 2012b). So far, the UWG has been evaluated against field data from Basel (Switzerland), Toulouse (France) and Singapore, showing an average error of about 1K (Bueno et al., 2013; 2014).

The model consists of four calculation components: the “Rural Station Model", the "Vertical Diffusion Model", the "Urban Boundary-layer model" and the "Urban Canopy and Building Energy Model". Using the rural climate data as input, the model calculates the hourly air temperature in the urban canyon, given a parametric description of the urban area. The UWG calculation is based on the *urban surface energy balance*, taking into account for the reciprocal interactions between buildings and the urban climate. In particular, the urban canopy energy balance accounts for (Bueno et al., 2013):

1. The heat fluxes from walls, windows and the road
2. The sensible heat exchange between the canyon air and the upper atmosphere layer
3. The heat fluxes due to the building cooling and heating systems (exfiltration, waste heat from heating, ventilation and air-conditioning equipment)
4. Other anthropogenic heat sources
5. The radiant heat exchange between the canyon air and the sky

The solar radiation received by walls and road is calculated with the equations used in TEB scheme (Masson, 2000), considering an average oriented urban canyon. The longwave radiation among walls, road, urban canyon air and the sky is computed by linearization of the Stefan–Boltzmann equation, accounting for the transmittance of the urban canyon air and assuming only one bounce of radiative heat fluxes between surfaces (Bueno et al., 2013).

To perform the calculation, UWG need two input files:

1. A rural hourly weather file in EnergyPlus format (.epw)
2. A xml file that describes the characteristics of the reference urban site.

The xml file includes 4 categories of parameters, which refer to different scales: "Reference site", "Urban Area", "Building" and "Elements".

The "Reference site" parameters describe the latitude, longitude and the radius of the reference city. The "Urban area" category includes the urban morphological parameters, the ratio of trees coverage and the amount of anthropogenic heat from traffic. The morphological parameters are very relevant on the energy balance calculation (Salvati, Cecere, & Coch, 2016), so they must be computed with particular attention. The morphological parameters are three:

- *Average building height:* the average building height in the urban area, normalized by building footprint
- *Site coverage ratio*: the ratio of the building footprint to the urban site area
- *Façade-to-site ratio*: the ratio of the vertical surface area (wall) to the urban site area

The "Building" parameters describe the typical features of the buildings in the urban area: the type, set points and efficiency of heating and cooling systems, the façade glazing ratio, the average floor height, internal gains, ventilation and infiltration. The most significant parameters in this category are the temperature set points, especially the cooling set point, as it determines the building energy consumption and, proportionally, the waste heat released into the atmosphere. Finally, the "Elements" parameters describe the thermal and radiative properties of the canyon's surfaces: vegetation coverage, albedo, emissivity, thermal conductivity, volumetric heat capacity and thickness. These properties are required for each element of the canyon (road, roof, wall) and for the rural station site.

3. Model evaluation: methodology and data source

The model evaluation is carried out considering different urban sites in Rome and Barcelona. The analysis is aimed at assessing the accuracy of the UWG prediction and its ability to improve the building energy assessment for the Mediterranean urban context.

To this aim, urban and rural weather stations have been identified in the two cities in order to compare the observed urban air temperatures with the UWG predictions. The chosen urban sites in Rome and Barcelona are similar for what concern land use and building density and morphology.

The validation methodology consists of three steps. Firstly, a “rural weather file” (epw format) is created from the hourly temperature data measured at the rural stations. Then the rural weather file is used as input for the UWG calculation, along with the xml file that describes the areas in which the urban weather stations are located. Finally, the estimated urban temperatures are compared to those measured at the urban meteorological stations and the statistical error of the predictions is evaluated. The model is evaluated with the specific aim of identifying whether its prediction is able to improve the accuracy of the building energy performance assessment in urban areas. The object of the evaluation is thus the accuracy of the predicted monthly average diurnal cycle of the urban air temperature with respect to the urban actual observations and the rural temperature. The reference rural stations are located at the airports of the two cities, which are the sites from which meteorological data are commonly derived for energy simulation purpose.

3.1 Reference weather stations

Rome and Barcelona are classified in the map of Köppen-Geiger as temperate climate, with hot and dry summers. They are located at very close latitude, respectively to 41.9 ° N Rome and 41.4 ° N Barcelona. The seasonal average trend of the temperature is very similar in the two cities, with a slightly bigger temperature range in Rome. The daily and yearly temperature range is smaller in Barcelona due to the direct thermoregulatory effect of the sea. Rome is about 20 km distant from the coast, so the effect of the sea on the climate is weaker, but still significant.

The reference rural weather stations are located at the airports, respectively Barcelona El Prat Airport for Barcelona and Rome-Ciampino GB Pastine Airport for Rome. Actually, these sites do not totally conform to Oke’s description of “rural site”, given the proximity to the sea in Barcelona airport and the presence of urbanization in both sites. However, as already mentioned, the standard weather databases normally refer to the airport weather stations. This choice is thus aimed at assessing how much the urban temperatures differ from those that are normally used for energy simulations purpose. The hourly values of air temperature, humidity, wind speed and direction are available for both stations from the web site www.wunderground.com (Code LEBL for El Prat Airport station and code LIRA for Ciampino airport station).

Three urban weather stations are used as reference to carry out the comparison with UWG calculation: one in Barcelona, referred to as "Raval", and two in Rome, referred to as

"Boncompagni" and "Arenula". All of them are located in the city centre and approximately at the same distance from the corresponding rural station. (Figure 1)

The three weather stations differ for the sensor position, which is located at roof level in the case of Raval and Boncompagni and near the ground level in the case of Arenula. This is a substantial difference, because the roof level stations measure the air temperatures in the *roughness sublayer*, above the average heights of the buildings, while the street level station records the air temperatures at about 2 m from the ground, into the *urban canopy layer*. The thermic gradient from ground level to roof level is considerable, as a result of different radiative fluxes and wind regimes (Di Bernardino et al., 2015; Xie et al, 2007), so we expect a different temperature trend from the two kind of stations.

The UWG is a surface energy balance model, so it estimates the average homogeneous temperature into the canyon. The evaluation of the model using temperature data from roof level and ground level allows thus to identify whether the model predicts better the temperatures into the canopy layer or in the roughness sublayer.

Figure 1. **Weather stations localization in Barcelona and Rome**

Source: Self processing of BING maps images

Table 1. **Reference urban weather stations characteristics**

Weather station	Dist. from Airport (Km)	Dist.from sea (Km)	Height of the sensor (m)	Position
Raval (BCN)	13	1.3	33 a.s.l.	Roof top
Boncompagni (RM)	13	25	72 a.s.l.	Roof top
Arenula (RM)	13	24	31 a.s.l.	Ground level

Source: METEOCAT data for Raval station and ARPA data for Boncompagni and Arenula stations

A brief description of the main features of the three urban weather stations is reported hereafter.

Raval station is located in the ancient core of the city (figure 3), quite near the sea. The structure of the district is very dense and compact, composed of irregular blocks and narrow streets, mostly pedestrian. The typical canyon aspect ratio (height/width) is about 3. Trees and vegetation are scarce in the area. The intended use is primarily residential, with the exception of the northern area, where universities and museums are concentrated. The district is very close to the sea, just 1.3 km from the port, and at 13 km distance from the airport. The weather station is part of the “Meteorological service of Catalunya” (METEOCAT) network and it is located on the top of one university building (Faculty of Geography and History). The hourly temperature data for Raval have been supplied by METEOCAT for the whole year 2013. According to Steward and Oke’s classification (2012), the district matches the Urban Climatic Zone 2.

Boncompagni station is located in the city centre of Rome (figure 4). The structure of the area dates back to early twentieth century and it is composed of large and compact blocks on a wider street network compared to Raval texture. The buildings are quite tall (about 7 floors) and the canyon aspect ratio is about 1.5. The tree coverage is low near the weather station, but at approximately 500 m in North-West direction there is the big park of Villa Borghese. According to Oke and Steward's classification, the district matches the Urban Climatic Zone 2. The meteorological station belongs to the network of the “Regional Agency for Environmental Protection of Lazio Region” (ARPA Lazio) and it is located on the roof of ARPA building. The station is equipped with ultrasonic anemometer (USA1 SCIENTIFIC), Rain Gauge (VRG 101), Thermo-hygrometer (HMP 45AC) and Radiometer (CNR1). The hourly temperature data for the year 2013 were provided by ARPA.

The Arenula station (figure 5) was located in Largo Arenula during the period of observation, in the old city center (the station has been moved in Piazza Cairoli later on). The neighborhood is mixed-use, with large presence of offices, retail spaces, accommodation facilities and institutional buildings along with residential buildings. The district is built on a dense medieval urban structure, mainly made up of courtyard buildings. The urban canyons are particularly high and narrow, with an average aspect ratio of 2.5. The district is one of the most compact and densely built area of the city. The vegetation is mostly concentrated near the Tiber river, at about 500 m distance from the point of measurement. Arenula station was part of the air quality monitoring network of ARPA. The temperature sensor was located at about 2 m above ground level. For Arenula station, the hourly temperature data refer to the year 2003.

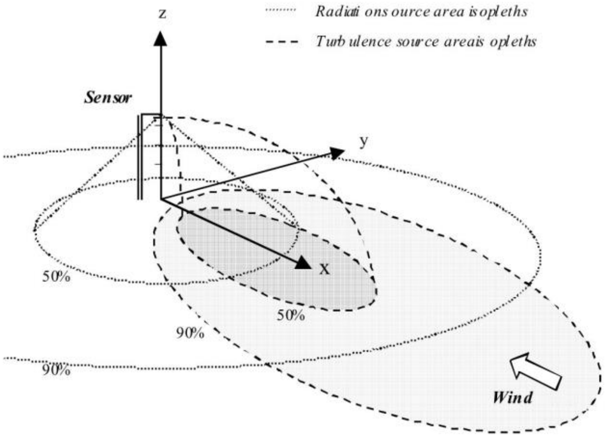
3.2 Model set up

For each urban reference site, a UWG run has been performed, in order to compare the model prediction to the actual air temperature observations. To this aim, rural weather files were created (.epw format) from the hourly temperatures recorded at the rural weather stations. Then, for each reference urban site, the parameters required for the xml input file were calculated.

The xml file describes all the features of the urban area that directly affects the weather station measurement. This “area” is known as “footprint” or “source area” of the weather station and it depends on the wind speed and direction and on the height of the sensor (figure 2). More precisely, quoting Oke: “The source area of a sensor that derives its signal via turbulent transport is not symmetrically distributed around the sensor location. It is elliptical in shape and is aligned in the upwind direction from the tower” (Oke, 2006, p.7).

So the source area changes during the day and year, according to the variation of the wind direction. In the urban context, the circular area that most characterizes the wind regimes and the turbulent heat transport is equal to about 500m (Oke, 2006; Stewart and Oke, 2012). It is to highlight that this general situation may be substantially modified within the urban canopy layer, due to the complex geometry of the three-dimensional urban surface that causes blockage or channelling of the flows. In effect, the detailed calculation of the "footprint" area of a meteorological station is still an open problem, as it depends on the wind direction and speed that assume a very variable trend during the day and the year, especially in a urban context (Kljun et al., 2004; Schmid, 2002).

Figure 2. **“Footprint” or “source area” of the measurement**



Source: Oke, T. R. (2006). Initial guidance to obtain representative meteorological observations at urban sites

The weather station footprint has been calculated in a simplified way in this study, considering the part of a 500 m radius circular area centered in the station and aligned in the dominant upwind directions (figure 3, 4 and 5). The dominant wind directions in Rome are from North in winter time and from South-West in summer, while in Barcelona the wind comes from North-West in winter and from South-Southwest in Summer[2]. Only in the case of Arenula, given the sensor height of about 2m from the ground, all the 500 m circular area has been considered as footprint; because the wind speed and direction are substantially modified by the geometry and the density of the built environment.

The calculation of the urban morphological parameters was performed through the construction of detailed digital models of the footprints areas with AutoCAD®, starting from GIS data elaborated with the open source software gvSIG (Asociacón GvSIG, 2015). The digital models have allowed the computation of all the vertical and horizontal surfaces and thus the calculation of the three morphological parameters required by UWG.

The "tree coverage" has been computed on aerial images derived from Google Earth and elaborated with AutoCAD®. For the three urban sites, this parameter varies from 7 to 12%.

For what concern the "anthropogenic heat from traffic", an average value has been identified in the work of Pigeon and Sailor (Pigeon et al., 2007; Sailor, 2011). In particular the anthropogenic

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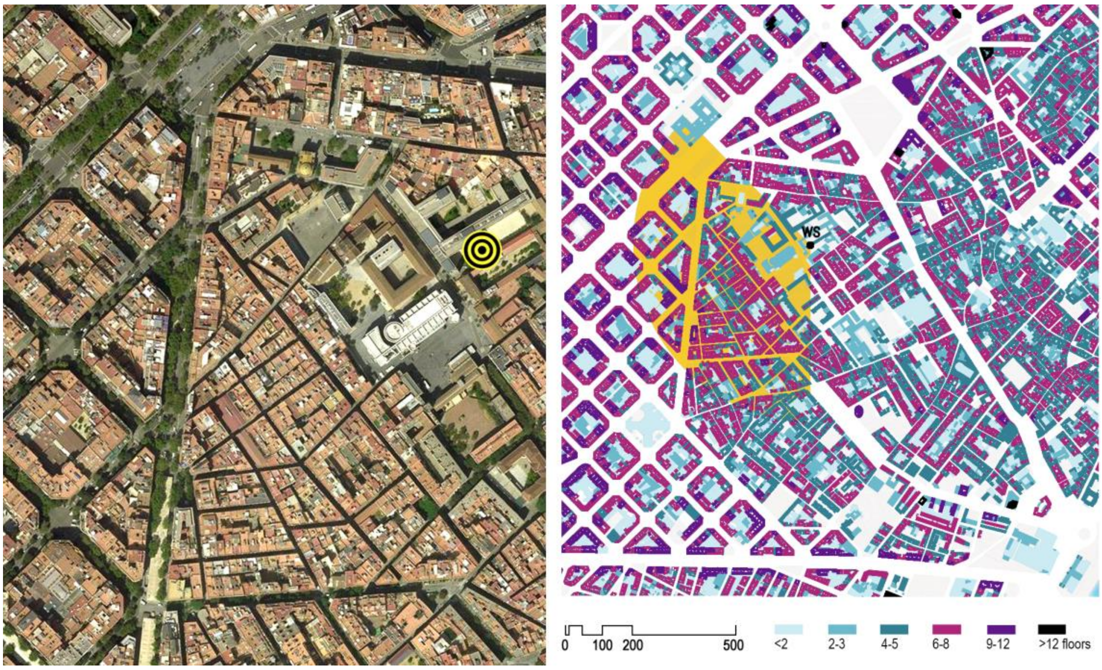
[2] The dominant wind directions in the urban areas refer to data from the meteorological observatory "Collegio Romano" in the centre of Rome and from the meteorological station of Raval in Barcelona.

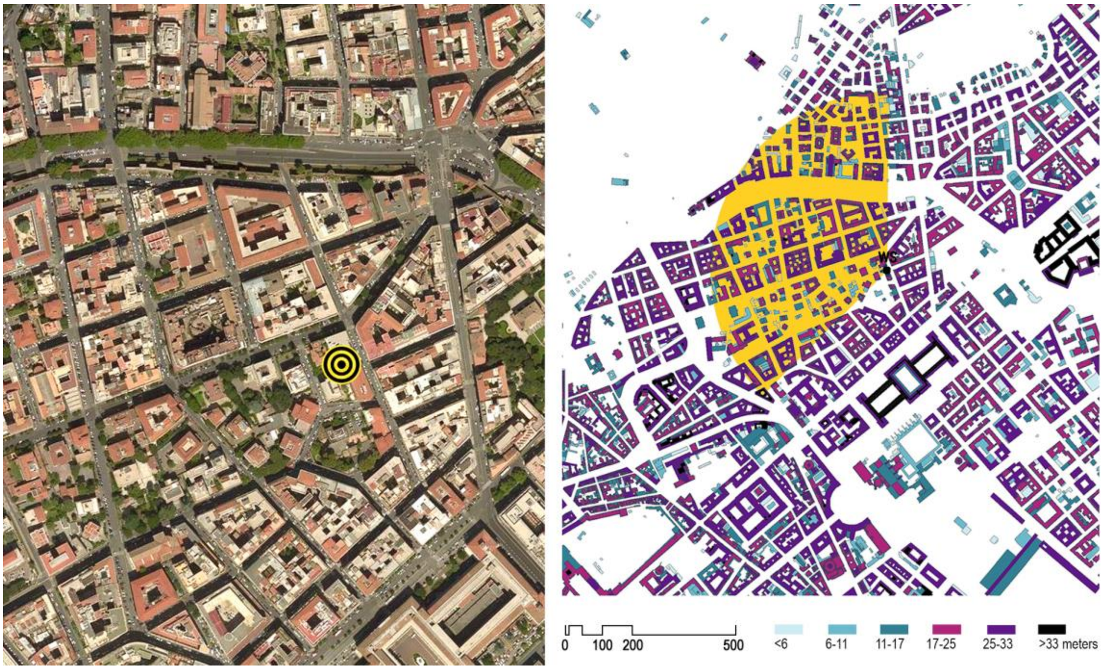
heat calculated for Toulouse (8 W/m2) has been chosen as reference for both Rome and Barcelona urban sites.

Figure 3. **Raval (Barcelona) weather station position and footprint**



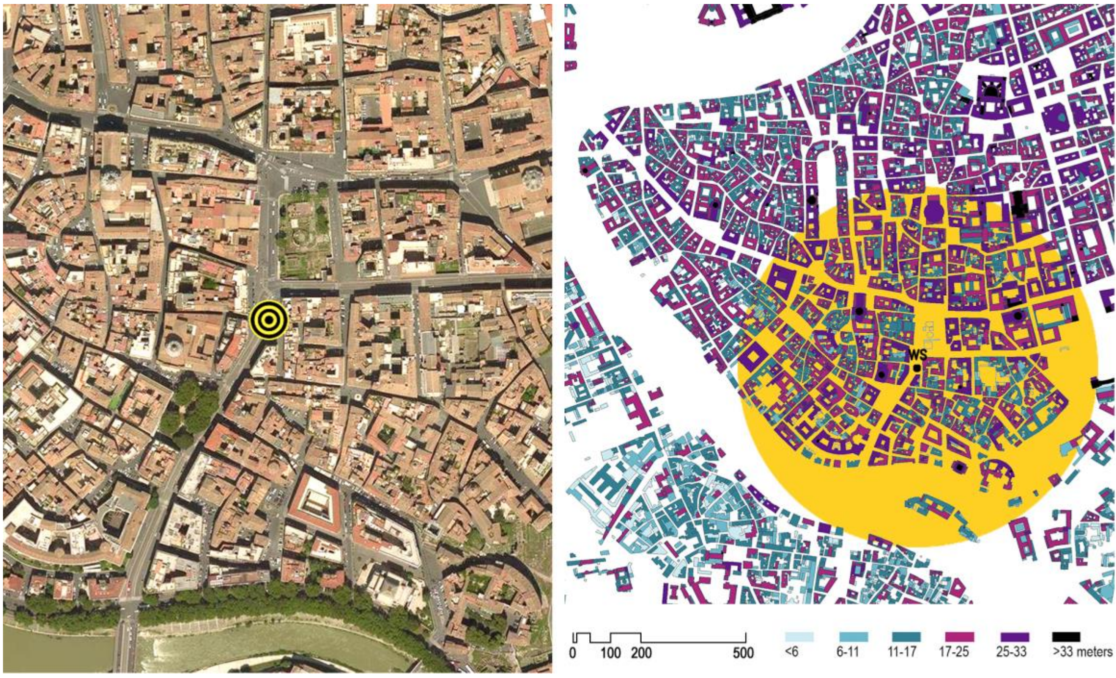
Source: Self processing of GIS data by software gvSIG 2.2.

Figure 4. **Boncompagni (Rome) weather station position and footprint**



Source: Self processing of GIS data by software gvSIG 2.2.

Figure 5. **Arenula (Rome) weather station position and footprint**



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ource: Self processing of GIS data by software gvSIG 2.2.

The other source of anthropogenic heat, the buildings, is taken into account in the UWG calculation according to the typical characteristics of the buildings in the area (architectural features, building construction, technology and systems operation). The building construction type in the three urban sites is similar in terms of thermal behavior: masonry construction with high thermal inertia and low insulation (wall transmittance is considered about 1.5 W/mq K).

A very important parameter of the "Building" category is the cooling set point, because it directly determines the amount of waste heat released into the canyon. The three urban sites are characterized by mix use: residential, offices and commercial. To take into account this heterogeneity in terms of air conditioning use, a quite high daily cooling set point has been chosen as input (26°C), while during the night the air conditioning has been supposed to be off.

Other parameters of the "Building" category, which are less important on the urban heat island intensity, are the façade glazing ratio, the internal gains and the ventilation and infiltration values. For the three urban sites, the chosen values are 0.3 for the façade glazing ratio and 0.5 ACH for ventilation and infiltration. For what concern the internal gains, a differentiation has been made according to the prevalent use of the area. For Via Arenula, which use is mainly commercial and offices, a value of 30 W/mq and 5 W/mq has been used for daytime and night-time, respectively. For Via Boncompagni and Raval, which use is mainly residential, the chosen values are 2 W/mq for daytime and 5,8 W/mq for night-time.

Finally, for the three urban sites, which are similar in terms of claddings and colors, the values of albedo and emissivity for the walls, roads and roofs have been identified according to the literature (Gartland, 2008). A more detailed description of the input parameters for each site can be found in table 2.

The "vegetation coverage" parameter, that falls into "Elements" category, is significant only for the rural site. In this case a 500 m radius circular area centered in the weather station has been considered to compute the vegetation coverage ratio in the two airport sites (Figure 3).

Figure 6. **Rural Weather station's source areas for the input parameters calculation**

Source: Self processing of GooglEarth image

Table 2 **Most relevant parameters used for the simulation**[3]

	Raval	**Boncompagni**	**Arenula**
Reference Site			
Latitude [°]	41.4	41.47	41.47
Longitude[°]	2.2	2.34	12.34
Urban Area			
Average Building height [°]	16.7	20.1	19.9
Site coverage ratio [--]	0.63	0.45	0.49
Façade-to-site ratio [--]	2.19	1.66	1.44
Tree coverage [%]	8	12	7
sensible anthropogenic heat [W/m^2]	8.0	8.0	8
Building			
Daytime cooling set point [°C]	26	26	26
Nighttime cooling set point [°C]	35	35	35
Daytime heating set point [°C]	20	20	20
Nighttime heating set point	20	20	20

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[3] A complete definition of all the parameters involved in the calculation can be found here http://urbanmicroclimate.scripts.mit.edu/uwg_parameters.php

[°C]			
Elements			
Wall albedo	0.25	0.25	0.25
Wall materials and thickness	Brick, plaster 43 cm	Brick, plaster 43 cm	Brick, plaster 43 cm
Roof albedo	0.25	0.25	0.25
Roof materials and thickness	Hollow-brick slab, screed, insulation, tiles, 38cm	Hollow-brick slab, screed, insulation, tiles, 38cm	Hollow-brick slab, screed, insulation, tiles, 38cm
Road albedo	0.08	0.08	
Rural			
Albedo	0.25	0.15	0.15
Emissivity	0.92	0.96	0.96
Vegetation coverage [%]	20	48	48

4. Results and discussion

The analysis of the UWG performance has been carried out using two statistic measures commonly used to determine the accuracy of climate and environmental models: the *Root Mean Square Error* (RMSE) and the *Mean Bias Error* (MBE). The error measure is based on the comparison between the predicted temperatures and the observed temperatures for a reference year. In particular, the model accuracy has been evaluated with respect to the monthly-average diurnal cycle of the urban air temperature, considering summer and winter months.

The Root Mean Square Error (RMSE) is calculated as the square root of the mean-square error, which is the sum of the "*x*" individual squared errors divided for "*x*". This measure, which removes the sign from the error, identifies the average magnitude of the error.

The Mean Bias Error (MBE), instead, is given by the difference between the model-predicted mean and the observed mean, respectively. In this measure the sign of the error is not removed, so the MBE indicates the average over or under-estimation of the model predictions with respect to the observations. Both measurements have the same dimension of the variable of interest, °C in this case.

In figure 7, the monthly average diurnal cycle[4] of the urban temperature observed at Raval weather station is reported in comparison with the UWG prediction and the airport temperature. Statistical results of this comparison are presented in Table 3.

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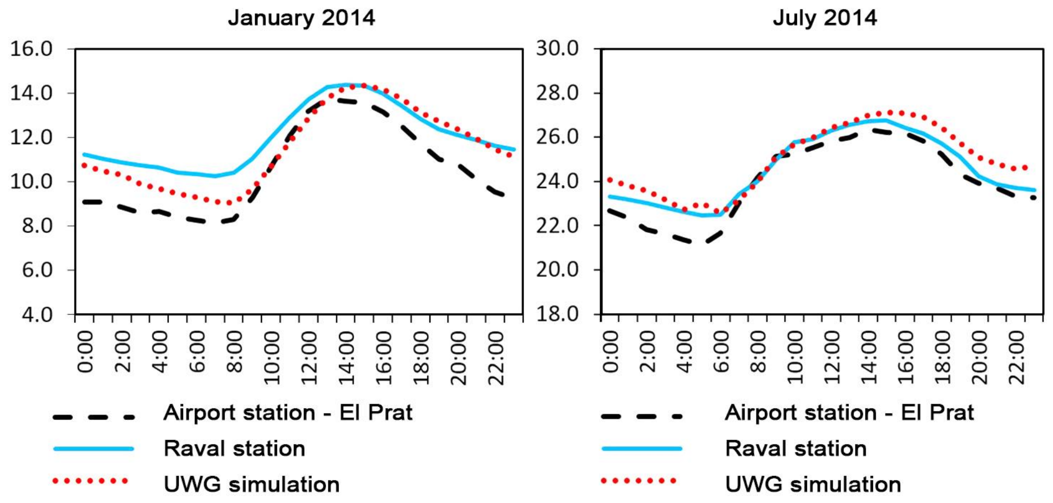
[4] The Coordinated Universal time (UTC) is used in the graphs; the local time zone is UTC+1 in winter and UTC+2 in summer for both Barcelona and Rome.

Figure 7. **Monthly-average diurnal cycle of urban air temperature calculated by the UWG and observed at Raval Station**



Source: Self-elaboration of the results

Table 3. **Statistical results of this comparison for Raval (Barcelona)**

	MBE	RMSE	Monthly Avg. Obs UHI
December	-1.3	1.42	2
January	-0.5	0.77	1.5
February	0.7	0.86	1.4
June	0.1	0.41	0.9
July	0.4	0.56	0.6
August	0.7	0.79	0.1

Source: Self-elaboration of the results

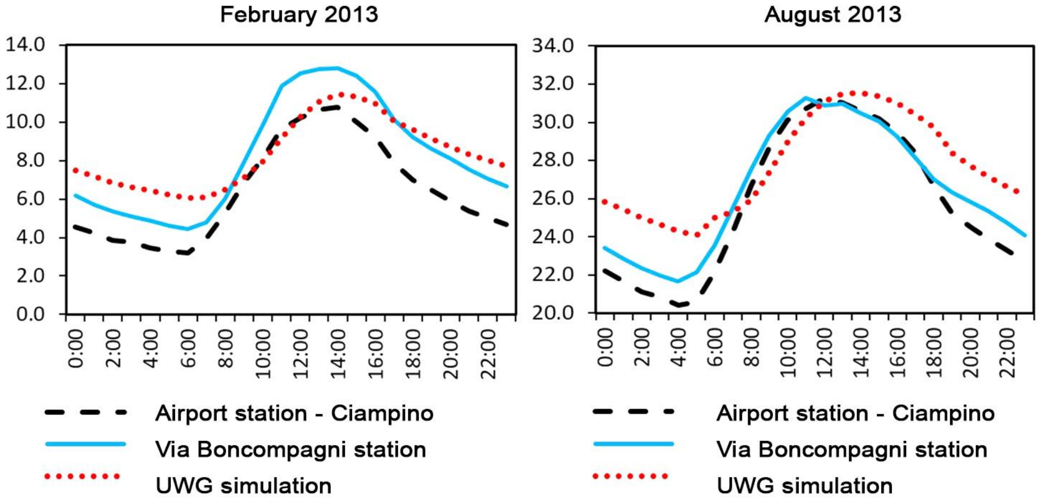
As shown in the graphs in figure 7, the UWG is able to capture the average daily trend of the urban heat island effect. The RMSE between the model predictions and the observations is 0.77 in January and 0.56 in July, where the average daily-maximum UHI intensity is 2.2°C and 1.3°C, respectively. The model maximum error occurs in December, when the RMSE is 1.42 and the daily-maximum UHI intensity is 2°C (table 3). In the 2014, the maximum UHI intensity in Raval was recorded exactly in December, with a daily maximum of 2.8 C°. In this case, the model underestimates the urban temperature, as shown by the negative MBE in table 3.

From the same table it can be seen a similar underestimation of the urban temperatures in January and an overestimation during February and all the summer months. It has to be highlighted that the most relevant error in the prediction is the one for August, when the monthly average UHI intensity recorded at Raval station is only 0.1°C, while the UWG prediction is 0.8°C. This error highlights the inability of the model to capture the effect of the sea breeze, that is particularly beneficial on the air temperatures during summer period in the Spanish coastal city.

Raval weather station, which is located on the top of one of the tallest building of the neighbourhood at only 1,3 Km distance from the sea, is particularly affected by the sea breeze; as a consequence, the air temperature is quite constant during the central part of the day (12:00-18:00 local time) and very close to the airport temperature. This phenomenon is underestimated by UWG, even though the input rural weather file used to run the simulation took into account the increase of the wind speed due to the sea breeze. However, this inaccuracy was predictable, as the UWG model does not take into account the proximity to water bodies or other geographical features that can affect the city climate at macroscale. Despite this, the model error ranges between 0.4 °C and 1.4 °C, in line with previous evaluation studies (Bueno et al., 2013, 2014).

The same comparison has been conducted for the model predictions and the observations taken in Via Boncompagni (Rome) during 2013. The monthly average diurnal cycles of the urban temperature for February and August are reported in figure 8; the observations at Boncompagni weather station are compared to the UWG predictions and the airport temperature. Statistical results of this comparison are presented in Table 4. In this case the model accuracy is worse compared to Raval; the RMSE is high, ranging between 1.2°C and 2.1 °C.

Figure 8. **Monthly-average diurnal cycle of urban air temperature calculated by the UWG and observed at Via Boncompagni Station**



Source: Self-elaboration of the results

Table 4. **Statistical results of this comparison for Via Boncompagni (Rome)**

	MBE	RMSE	Monthly Avg. Obs UHI
December	0.87	1.51	1.1
January	0.74	1.20	0.9
February	0.17	1.36	1.8
June	1.11	1.84	0.9
July	1.51	2.10	0.5
August	1.23	1.90	0.8

Source: Self-elaboration of the results

Figure 9**. Villa Borghese park proximity to Boncompagni weather station**

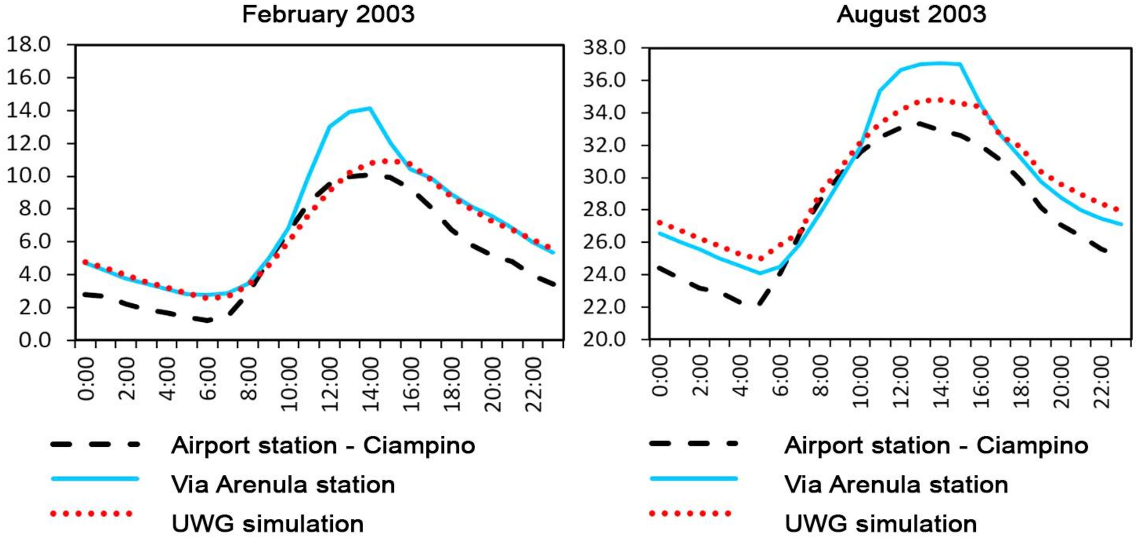
Source: Self processing of GooglEarth image

As in the case of Raval, the errors are more relevant for the summer predictions, in which the model systematically overestimates the urban temperature (table 4). This over prediction can be partially explained in the light of some features of the weather station area. As explained in paragraph 3.2, the weather station measurement depends on its "source area", or footprint, which is affected by the height of the sensor and the wind speed. The footprint areas in this study have been calculated as a portion of the 500 m circular area surrounding the weather stations, as suggested by the literature in this field.

Using this procedure, the footprint of Boncompagni station turned out to be a completely built area (figure 4) on which the required parameters to run the simulation have been calculated. However, the 80 hectares park of Villa Borghese stands just beyond the 500 m distance from the weather station, in North-West direction (figure 9). It is thus reasonable to think that it could affect the measurement of the weather station, mitigating summer temperature. So, once again, the inability to take into account relevant geographic features in the proximity of the studied area, as water bodies or large parks, determines a significant error in the model predictions. These results suggest to pay particular attention when computing the input parameters, above all for non-homogeneous urban context in terms of building density and vegetation coverage.

Finally, the model predictions have been compared to the measurements taken at street level in Via Arenula, during 2003. In figure 10 the monthly average diurnal cycles of the urban temperature for February and August are reported. Statistical results of the comparison between the model predictions and the observations are presented in Table 5.

Figure 10. **Monthly-average diurnal cycle of urban air temperature calculated by the UWG and observed at Via Arenula Station**



Source: Self-elaboration of the results

Table 5. **Statistical results of this comparison for Via Boncompagni (Rome)**

	MBE	RMSE	Monthly Avg. Obs UHI
December	-0.05	0.63	1.2
January	-0.10	0.56	1.1
February	-0.65	1.43	1.8
June	0.56	1.56	1.8
July	0.25	1.28	1.8
August	0.08	1.25	1.9

Source: Self-elaboration of the results

In February the RMSE of the model is 1.43°C, with a monthly UHI intensity of 1.8 °C. The maximum daily UHI intensity is quite higher than the previous cases, reaching 4.1 °C at 15:00 local time (UTC+1), as it can be seen from the graph in figure 7. Similarly, in August the RMSE of the model is 1.25 °C, with a monthly UHI intensity of 1.9 °C and a maximum UHI daily intensity of 4.4 °C occurring between 16:00 and 17:00 local time (UTC+2). In effect, as clear from the graphs, the magnitude of the error is very different for the hottest hours of the day compared to late afternoon and night. During the afternoon and the night, the urban temperature calculated by UWG is very similar to the actual observation, with an error near to zero in the time period from 16:00 to 10:00. Conversely, the maximum daily UHI intensity, which occurs between 14:00 and 15:00 UTC, is never detected by the model.

Such systematic error for this time period suggests that the model does not adequately consider the contribution of the radiative trapping on the canyon air temperature increase. Nevertheless, the model prediction for Arenula site is quite good and very close to the average monthly UHI intensity during all the year. These results should be analysed in the light of the position of the temperature sensor in Via Arenula, which was at about 2 m from the ground. This means that the measurement was affected also by the proximity to the overheated urban surfaces (road, walls) and from anthropogenic heat sources, as traffic. As expected, the UWG is not able to take into account site specific variables that can modify the climate at microscale; the model is based on the average-oriented canyon parametrization and estimates average values of the air temperature, supposed homogenous into the urban canyon. In effect, comparing the MBE between the model prediction and the observations, it can be seen a systematic overestimation of the temperature with respect to the roof level measurements (Boncompagni and Raval) and an underestimation with respect to the road level measurements (Via Arenula).

5. Conclusions

This study presented an evaluation of the UWG model, by comparing the predicted urban temperatures to hourly observations in different urban sites. The results show an average RMSE between the modelled and observed air temperatures ranging between 0.5 and 1.5°C, in line with previous analysis.

The model performance decreases for non-homogeneous urban contexts in terms of building density and vegetation, as in Via Boncompagni, Rome. In effect, the accuracy of UWG calculation strongly depends on the location of the urban site within the city and on its features. The model prediction is more accurate when the urban site is located in a fairly central position and in a rather homogeneous urban district, above all for what concern building density.

In the case of Raval in Barcelona and Via Boncompagni in Rome, the UWG model was not able to take into account the proximity to the sea or to the Park of Villa Borghese; these approximations contributed to the inaccuracy of the prediction, leading to an overestimation of the urban temperature, especially in summer.

However, the UWG prediction was able to capture the average daily trend of the urban heat island effect, so it can actually allow a significant improvement of the energy simulations in the urban context, giving more accurate urban weather file with respect to the airport temperature that is still currently used.

The most accurate prediction of UWG was the one for Via Arenula, in Rome. In that case the UWG calculation significantly reduced the error in the urban temperature estimation if compared to rural meteorological data. However, there was a systematic error for what concern the central hours of the day that suggests an underestimation of the diurnal radiative trapping.

Conversely, the model tends to overestimate the urban temperature with respect to the roof level observations (Via Boncompagni and Raval). This happens because it cannot adequately simulate the beneficial effect of the wind and the sea breeze, which is considerable above the roof level.

In general, the model performs better for urban sites characterized by low wind conditions, where the UHI intensity is mainly due to the canyon geometry and to the anthropogenic heat release. This condition can be met in several urban contexts, above all in the Mediterranean compact city where the building density determine a "skimming flow" regime and a low interaction between the canyon air and the above layers of atmosphere. On the contrary, the results for a coastal neighborhood (e.g. Barceloneta in Barcelona) would be completely unreliable, because the wind channeling and speed assume, there, a determining role on the UHI intensity. So the UWG can undoubtedly allow more accurate energy simulations, but it is not able to estimate the microclimate at the street level, that depends from site specific characteristics and singularities. However, the microclimate at street level is more relevant to the thermal comfort assessment rather than to the building energy analysis. The buildings' energy performance in the urban context is related to the average trend of the canyon air temperature, so the improvement made by UWG is significant, above all in the light of the simplicity and rapidity of the simulations.

For a proper use of the UWG model, some considerations must be made before running the simulation: the urban site must be rather homogeneous in terms of building density and vegetation coverage and the input parameters must be computed on the correct "source area", according to the dominant winds. With those precautions, the UWG can be a useful tool for modeling the urban temperature and perform more realistic energy analysis.

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