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Article

Evaluating Mitigation Effects of Urban Heat Islands in a Historical Small Center with the ENVI-Met® Climate Model

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Abstract: Urban morphology and increasing building density play a key role in the overall use of energy and promotion of environmental sustainability. The urban environment causes a local increase of temperature, a phenomenon known as Urban Heat Island (UHI). The purpose of this work is the study of the possible formation of an UHI and the evaluation of its magnitude, in the context of a small city, carried out with the ENVI-met® software. For this purpose, a simulation was needed, and this simulation is preparatory for a monitoring campaign on site, which will be held in the immediate future. ENVI-met® simulates the temporal evolution of several thermodynamics parameters on a micro-scale range, creating a 3D, non-hydrostatic model of the interactions between building-atmosphere-vegetation. The weather conditions applied simulate a typical Italian summer heat wave. Three different case-studies have been analyzed: *Base Case*, *Cool Case* and *Green Case*. Analysis of the actual state in the *Base Case* shows how even in an area with average building density, such as the old town center of a small city, fully developed UHI may rise with strong thermal gradients between built areas and open zones with plenty of vegetation. These gradients arise in a really tiny space (few hundreds of meters), showing that the influence of urban geometry can be decisive in the characterization of local microclimate. Simulations, carried out considering the application of green or cool roofs, showed small relevant effects as they become evident only in large areas heavily built up (metropolis) subject to more intense climate conditions.

Keywords: urban heat island; ENVI-Met®; cool roof; green roof

1. Introduction

The strong increase in urban development created a complex phenomenon of rising importance known as urban heat island (UHI): an UHI is a strong overheating of a densely built up area compared to its rural surroundings. Several studies have been carried out on this topic [1,2]: an overview of the literature is available in [3,4]. Moreover, in recent years, the mutual influence of UHI and urban layout [5] or thermal comfort [6,7] has been analyzed, along with mitigation technologies.

The main tools of mitigation available consist of a "technologic" employment of vegetation in urban areas (green technology) [8,9] and the application of materials with peculiar radiative features for roofs and pavements (cool technology) [10]. These solutions have different impacts not only related to the mitigation potential but also regarding the economic tradeoff of an installation [11].

This article analyzes the microclimate in an average urban area of a small city like Teramo (Abruzzo region, Italy) by means of the ENVI-Met® software, a modeling tool of computational fluid dynamics (CFD), evaluating some relevant meteorological parameters. The simulated zone includes a densely built up area and a vegetated area, that could be assumed as reference like it would be a rural surrounding. Although the considered area is quite small, due to the resolution of the model, results show a microclimate alteration, which suggests the rising of a UHI.

The simulation has been repeated considering the application of cool and green roofs, and the results obtained have been compared with existing situations: advantages and disadvantages of the software have been pointed out.

2. Basis of Applied Method

ENVI-met® is a software that allows three-dimensional non-hydrostatic modeling of building-air-vegetation interactions, especially, but not exclusively inside an urban environment. A typical time-space resolution of the model is 10 s/0.5–10 m [12–17]. Possible employment includes several fields, as urban climatology, architecture, building design, energetic and environmental planning.

ENVI-met® is freeware, but is not Open Source. The last available version is v.3.1; although a v. 4.0 beta exists, which introduces significant changes and implementations to the modeling possibilities. It has not been officially released yet, but is available to selected groups for scientific purpose. Therefore, we used v. 3.1.

ENVI-met® is a prognostic model based on the fundamental laws of fluid dynamics and thermodynamics, including simulation of several phenomena: heat flux around and between buildings;

heat and steam exchange at soil level and between walls, turbulence, thermo-hygrometric exchange in vegetation, bioclimatology, fluid dynamics of small particles and polluting species.

The calculating model includes:

- Shortwave and longwave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation;
- Transpiration, evaporation and sensible heat flux from the vegetation into the air including full simulation of all plant physical parameters (e.g., photosynthesis rate);
- Surface and wall temperature for each grid point and wall;
- Water- and heat-exchange inside the soil system;
- Calculation of biometeorological parameters like Mean Radiant Temperature or Fanger's Predicted Mean Vote (PMV) Value;
- Dispersion of inert gases and particles including sedimentation of particles on leaves and surfaces [12].

ENVI-met® takes into consideration the interplays between buildings, vegetation and various surface coverings, all affecting the atmospheric conditions. The model is complex similarly to the real environment. ENVI-met® consists of five model groups:

- The atmospheric model, which calculates the air movement, three-dimensional turbulence, temperature, relative humidity and takes into account obstacles such as buildings and vegetation. The maximal height of the model is 2500 m. The variation of radiation due to vegetation and shading is also considered.
- The surface model, which calculates the emitted long wave, and the reflected short wave radiation from the different surfaces, taking into account the incident long and shortwave radiation. It considers the albedo of the surfaces, the shading in function of the solar path and calculates the water vapor evaporation from the vegetation and the transpiration from the soil, taking into account the air flow-modifying effect of the vegetation. It is adapted to model flat surfaces.
- The vegetation model, which calculates the foliage temperature and the energy balance of the leaves taking into account the physiological and meteorological parameters. The vegetation is characterized by the normalized leaf area density (LAD) and the normalized root area density (RAD). The evaporation rate and the turbulence calculation are based on the airflow fields around the vegetation and the tree shape. The evaporation rate at the leaf surface, regulated by the stomata, is affected by the heat exchange between the leaf and its environment. The absorption characteristics of the foliage are calculated in function of the sunpath and the projected shade.
- The soil model, which calculates the thermo and hydrodynamic processes that take place in the soil. This model takes into account the combination of the natural and artificial surfaces of the urban quarter considered and it can also calculate heat exchanges between a water body and its environment.
- The biometeorological model, which is able to calculate the PMV index from the meteorological data [18].

More details on the software and its intrinsic laws are available at [12].

The analysis has been carried out modeling an area of the old town center of Teramo, a small city (population 60,000, elevation 265 m). The city has a semi-continental temperate climate, with average seasonal temperatures of 5.5 °C (winter) and 25 °C (summer). The model simulates a typical heat wave for this city (intense solar radiation and absence of cloudiness) during the statistically hottest summer days, assuming uniform temperature and humidity.

The modeled area has the following dimensions: width 385 m (left-right in Figure 1) and length 285 m (up-down). The chosen area shows good presence of vegetation around the main square, while the old town center (on the right) has a typical urban canyon layout: narrow roads and tall buildings.

Figure 1. Aerial view of the chosen area. The view is rotated of 32.50° to the North.

The model has been created with the Area Input file editor of the ENVI-met® rotated of 32.5° counterclockwise, according to the main direction of development of the roads. The area has been rendered with a 80 × 80 × 30 (x-y-z) grid, keeping the following spacing:

- dx = 4.50 m;
- dy = 3.50 m;
- dz = 1.20 m.

The resolution is an average within the suggested values (minimum 0.5 m – maximum 10 m) [12–17] and is a reasonable compromise between accuracy and calculation time. A more accurate resolution would imply a larger model, taking into account that the maximum dimensions allowed by the software are 250 × 250 × 30 cells.

The grid has a fixed spacing at the x and y axis, while it is telescopic at the z axis (1.20 m is a mean value), with a thicker grid near the ground, allowing a better accuracy for edge effects. The maximum height of the model is therefore 36 m (1.20 × 30 m). To achieve numeric stability, this value will be at least double of the height of the tallest building in the model (in this case 15 m) [12,19].

There are 40 buildings in the model, many of them having common walls, with a height between 3 and 15 m, 10 m being the mean value. For the modeling of the vegetation, three different plant types have been employed:

"T1": tree 10 m tall, dense foliage, leafless base;

- "H2": thick bush , 2 m tall;
- "xx": grass, average density, 50 cm tall.

Soil has been modeled with traditional pavement for the whole area, with the notable exception of the main road, covered in dark granite.

3. Case Studies

For evaluating the impact of the main tools in order to diminish the urban microclimate effects, three different configurations have been considered in the model:

- *Base Case*: the model has been kicked off applying standard values of urban environment, especially regarding radiative properties of buildings:

  \- *Albedo roofs* = 0.3;
  \- *Albedowalls* = 0.2.

- *Cool Case*: it has been assumed that all the roofs have been covered with high-reflectance material:

  \- *Albedo roofs* = 0.9;
  \- *Albedo walls* = 0.2;

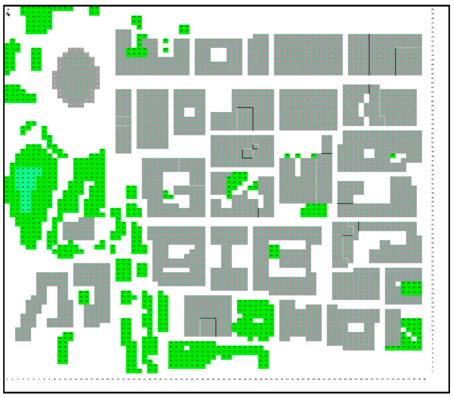
  In order to build this simulation in ENVI-met® the same Input files of the *Base Case* have been employed, modifying only the Configuration File, which contains all the parameters set to the model (see Figure 2);
- *Green Case*: a green roof, consisting of an average density 50 cm tall grass has been applied to all buildings. Radiative properties are almost the same as *Base* Case: the walls (and their albedo) are the same, while grass typical albedo is 0.26. In this case, not only a different Configuration File (as for the *Cool* Case) has been used but also a different Area Input file has been created, in order to include the newly added vegetation. A green roof is modeled into the software firstly by creating the building and then by creating vegetation in the cell that represents top-roof. The modified model is depicted in the following figures, both referred to the Green Case domain. Figure 3a) is a snapshot of the area input file, where the vegetation is defined but cannot be seen, while Figure 3b) is a 3D view taken from the output of the model.

All other main parameters have been left unchanged, in order to evaluate only the effect of the described cases on the urban microclimate. All the simulations have been started on 20 July 2013, representing strong (but not anomalous) summer heat wave for that city, with complete uniformity of temperature and wind velocity. The minimum simulation time, as suggested in ENVI-met® guide [12], is 6 h. Many authors used one day of simulation [5,15,16], other authors used in [13] a 45 h long simulation [13], while in [20] the simulated period is 5 days. In our work, the simulation elapsed time is 72 h (three days). All simulations start at 6:00 a.m. (default value, also suggested by the ENVI-met® guide [12]), thus the end was at 6:00 a.m., 23 July.

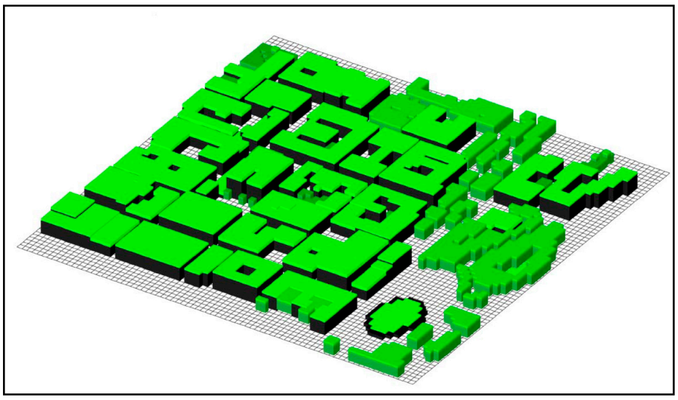
Figure 2. Configuration File written for simulation.

```
% ---- Basic Configuration File for ENVI-met  Version 3 ---------------
% ---- MAIN-DATA Block -------------------------------------------------
Name for Simulation (Text):                       = teramo base
Input file Model Area                             =[INPUT]\prova teramo def.in
Filebase name for Output (Text):                  =teramo base
Output Directory:                                 =[OUTPUT]
Start Simulation at Day (DD.MM.YYYY):             =20.07.2013
Start Simulation at Time (HH:MM:SS):              =06:00:00
Total Simulation Time in Hours:                   =72.00
Save Model State each ? min                       =60
Wind Speed in 10 m ab. Ground [m/s]               =3
Wind Direction (0:N..90:E..180:S..270:W..)        =0
Roughness Length z0 at Reference Point            =0.1
Initial Temperature Atmosphere [K]                =298
Specific Humidity in 2500 m [g Water/kg air]      =7
Relative Humidity in 2m [%]                       =60
Database Plants                                   =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --)
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the description)
         ( This file is created for ENVI-met V3.0 or better )

[SOILDATA] _____________________________________Settings for Soil
Initial Temperature Upper Layer (0-20 cm)    [K]=298
Initial Temperature Middle Layer (20-50 cm)  [K]=295
Initial Temperature Deep Layer (below 50 cm) [K]=292
Relative Humidity Upper Layer (0-20 cm)         =50
Relative Humidity Middle Layer (20-50 cm)       =60
Relative Humidity Deep Layer (below 50 cm)      =70
[NESTINGAREA]________________________________Settings for nesting
Use aver. solar input in nesting area (0:n,1:y) =1
Include Nesting Grids in Output (0:n,1:y)       =0
[SOLARADJUST] _________________________________
Factor of shortwave adjustment (0.5 to 1.5) =1.0

[BUILDING]___________________________________Building properties
Inside Temperature [K]                          = 300
Heat Transmission Walls [W/m²K]                 =1.50
Heat Transmission Roofs [W/m²K]                 =4
Albedo Walls                                    =0.2
Albedo Roofs                                    =0.3

[CLOUDS] _____________________________________
Fraction of LOW clouds (x/8)                   =0
Fraction of MEDIUM clouds (x/8)                =0
Fraction of HIGH clouds (x/8)                  =0
[PMV] ________________________________________Settings for PMV-Calculation
Walking Speed (m/s)                             =0.3
Energy-Exchange (Col. 2 M/A)                    =116
Mech. Factor                                    =0.0
Heattransfer resistance cloths                  =0.5
```

Figure 3. The model adopted for the *Green Case*. It is similar to that employed in other cases but buildings have been covered with a 50 cm tall grass layer. (**a**) snapshot of the area input file; (**b**) 3D view taken from the output of the model.



(**a**)



(**b**)

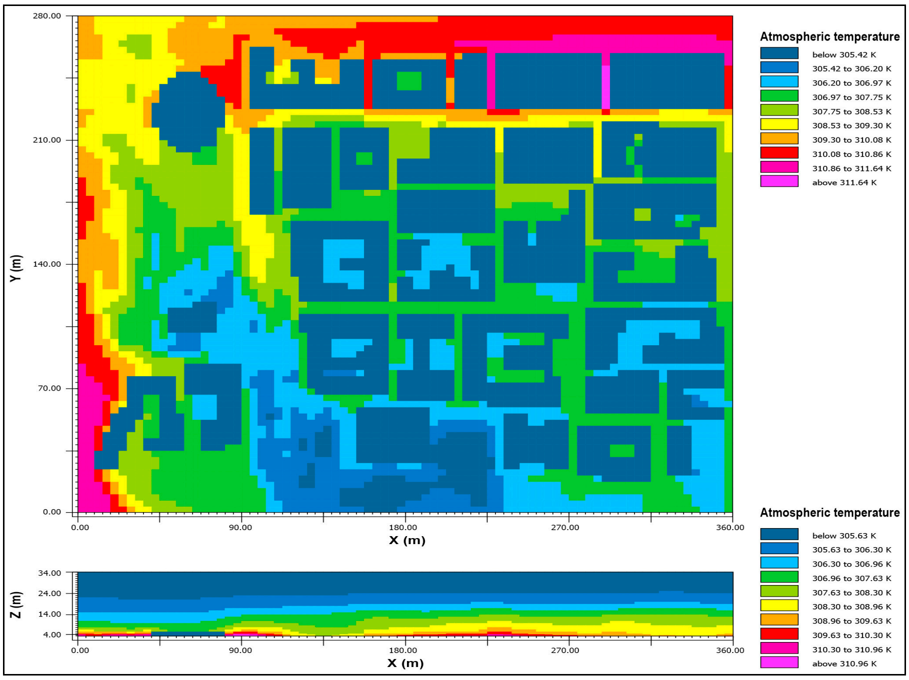
4. Results

In the following section, the most significant calculated parameters are shown: atmospheric temperature, relative humidity and wind velocity for the three cases previously described. The results are all related to the third day of simulations, because it was less influenced by initial uniformity. Furthermore, considering the gradual increase of thermal stress in a heat wave, the third day is also the most affected by the UHI development phenomenon (both daytime and nocturnal UHI). In all the illustrated results, edge values have been discarded, since they are affected by the boundary conditions set by the model. In fact, boundary conditions are set by the software in order to achieve numerical stability of the model, but they do not represent the physical boundary of the area. Discarded values are those from the first three rows of grid cells. Furthermore, results obtained in the upper part of the model have not been included in our evaluations: the model, in fact, does not include buildings standing in that zone because they would have been partially modeled due to the end of the modeling grid. Therefore, as can be seen comparing Figures 1 and 3a, the modeled area does not represent the real urban zone, because there are buildings which could not have been included, since part of them would have exceeded the limits of the model area. Enlarging the model area would have caused the same problem, due to other adjacent buildings.

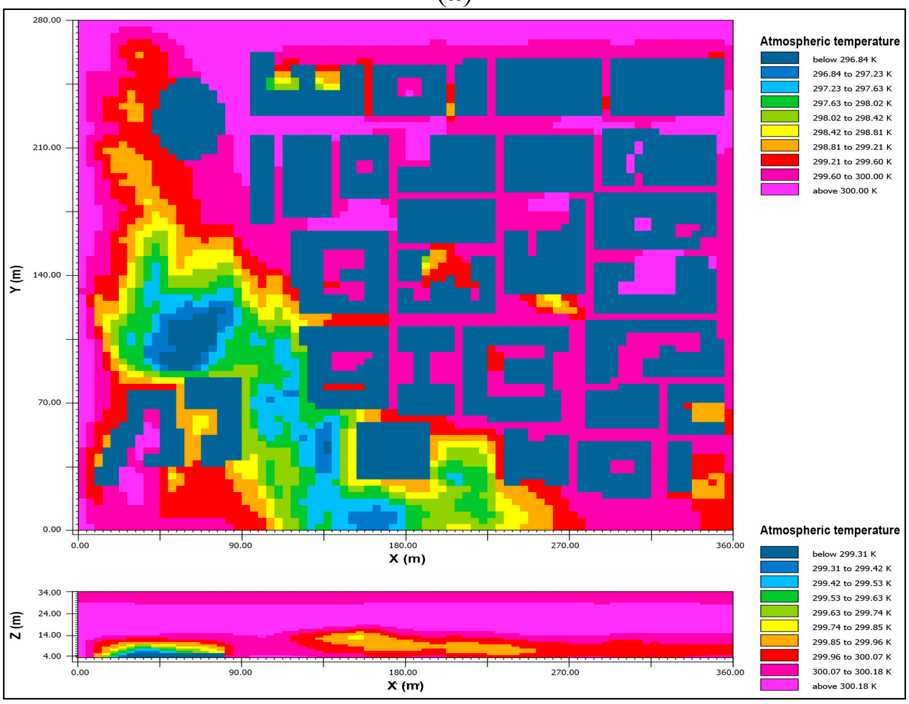
4.1. Atmospheric Temperature

In the following figures (Figures 4–7), thermal maps of the analyzed area are shown, considering the warmest moment of the day and for comparison the half day after.

Figure 4. Atmospheric temperature in "Base Case", x-y view at z = 1.20 m and x-z view at y = 220.5 m at (**a**) 2:00 p.m., 22 July 2013 (**b**) 2:00 a.m., 23 July 2013



(**a**)



(**b**)

For horizontal views (x-y) all data are shown at pedestrian level - height z = 1.20 m (representing what people could perceive). In addition, an x-z view is shown at y = 220.5 m (relative to the old town center main road).

4.1.1. Base Case

- 22 July 2013, 2:00 p.m.: the old town center main road and its crossing roads are the hottest zones, due to the presence of the urban canyon layout; as can be seen in Figure 4a, surroundings, which are less densely filled with buildings and have more vegetation, suffer milder effects. Maximum temperature is 312.5 K (39.3 °C), while minimum, recorded in densely vegetated areas, is 304.5 K (31.3 °C). Thus, maximum thermal gradient is 8 K;
- 23 July 2013, 2:00 a.m.: an atmospheric urban heat island is clearly sketched (Figure 4b), with the area filled with buildings clearly warmer than open and vegetated areas. The atmospheric temperature is rather homogeneous inside the old town center, with a peak of 300.2 K (27.0 °C), while the minimum temperature, again recorded in southwest green area, is 296.3 K (23.1 °C), with a difference of almost 4 K. In the main road view, small warmer spots are present, close to buildings top, caused by thermal release of roofs which is higher than that of the walls (roofs usually have higher transmittance, and in other works simulation have been carried out with this assumption [13,17,20].

To better understand temperature oscillation simulated by the software, and in order to compare modelled temperature on different parts of the area, we selected three different points and plotted an hourly temperature profile among the simulation period, using temperatures output by the software. Results are shown in Figure 5. This will also be a future reference for the *in situ* campaign. Points characteristics are described in Table 1, where midway and end way are referred to the model scale.

Figure 5. Hourly temperature profile of selected spots.

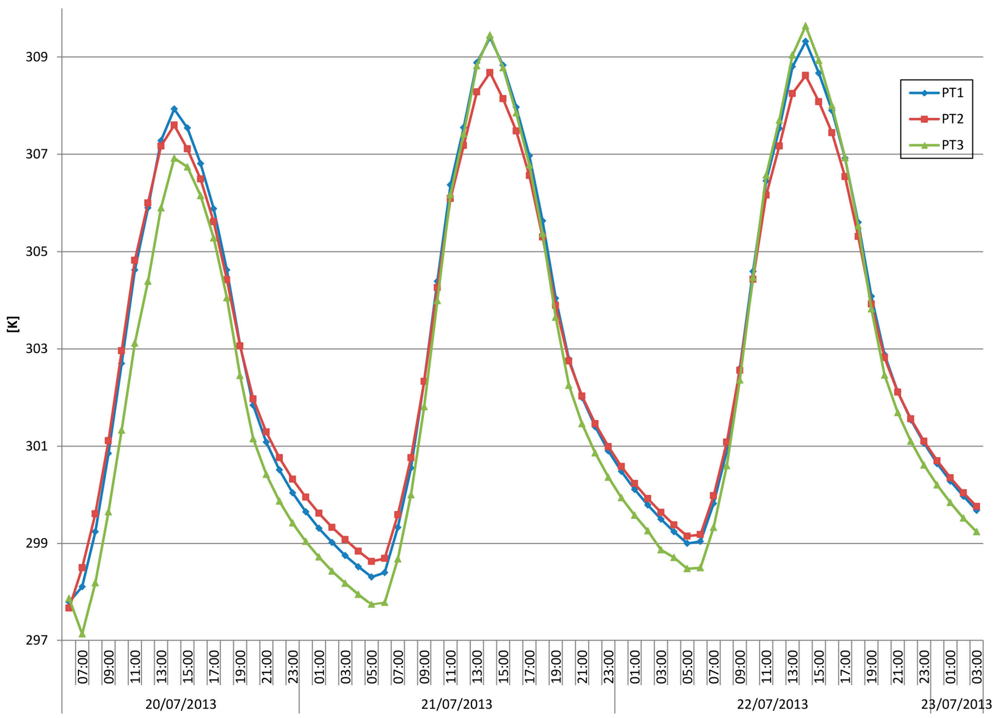
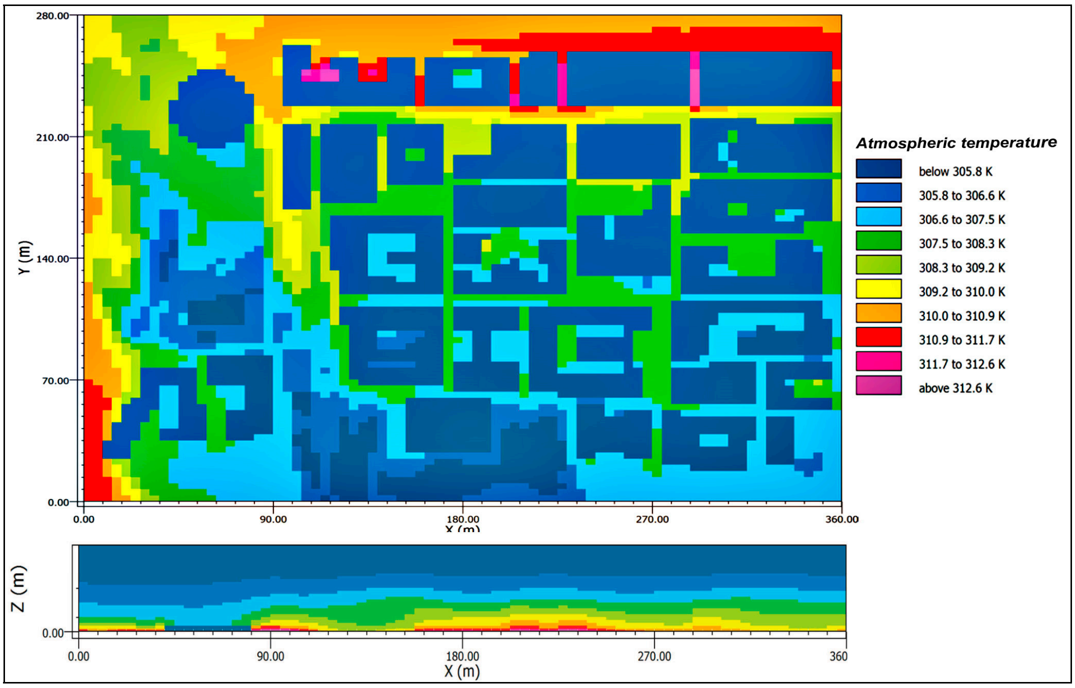


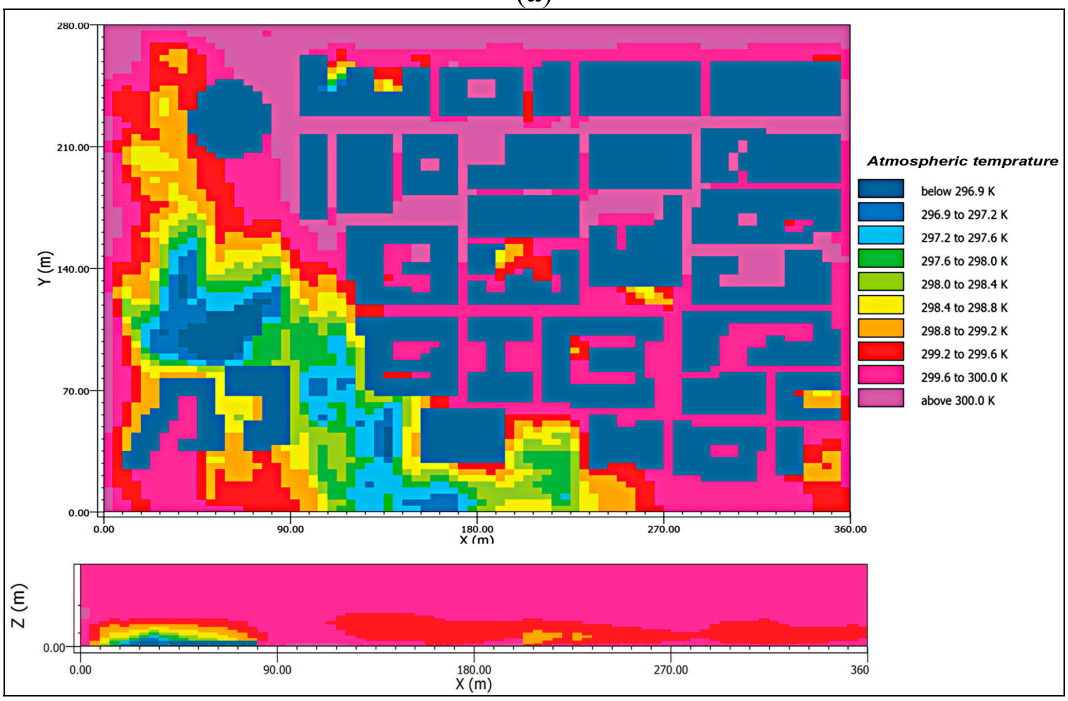
Table 1. Location of spot selected for hourly temperature profile.

Locations' Characteristics.		
Point	**Name**	**Characteristics of Selected Location**
1	Corso San Giorgio (main road–midway)	Dense urban area, well frequented
2	Corso San Giorgio (main road–end way)	Dense urban area, well frequented
3	Viale Crucioli	Public park, vegetated

Figure 6. Atmospheric temperature in "Cool Case", x-y view at z = 1.20 m and x-z view at y = 220.5 m at (**a**) 2:00 p.m., 22 July 2013 (**b**) 2:00 a.m., 23 July 2013.



(**a**)



(**b**)

During the nighttime, the temperature in the vegetated area (PT 3) is always lower than the one on PT 1 and PT 2 of about (at 5 a.m. difference of respectively of 0.57 K and 0.89 K on 21 July, 0.52 K and 0.67 K on 22 July, and 0.45 K and 0.54 K on 23 July).

During the daytime, however, temperature in the vegetated area is higher than PT 1 and PT 2 (at 2 p.m. difference of respectively of 0.05 K and 0.77 K on 21 July, 0.32 K and 1.02 K on 22 July). This confirms the microscale effect of the vegetated area, and the possible development of an UHI in the city, since even the small area considered shows local important temperature differences. Thus, it is reasonable to think of possible mitigation interventions.

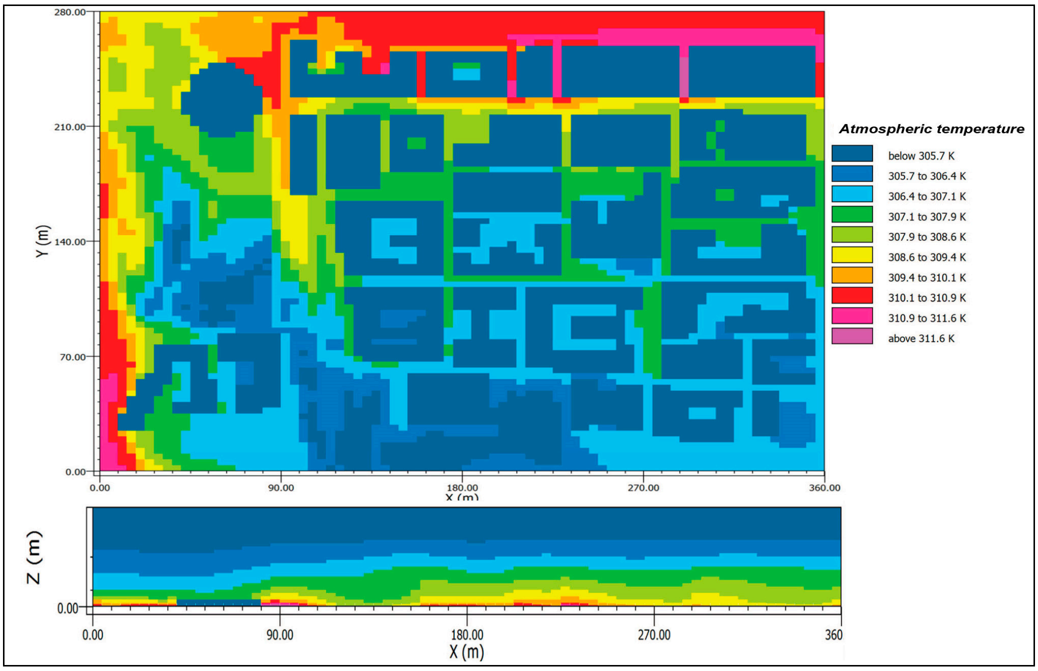
4.1.2. Cool Case

- 22 July 2013, 2:00 p.m.: the atmospheric temperature (shown in Figure 6a) is really uneven with strong differences between built up areas and the green zone. Nevertheless, a general decrease in the temperature is recorded (0.5 K on average). Maximum temperature, in the urban canyon near main road, is 313.4 K (40.2 °C). Minimum temperature is 304.9 K (31.7 °C), as usual recorded in the vegetated area, and is higher than *Base Case*—One of the possible causes of this phenomenon is the increased diffuse radiation (due to the higher albedo of buildings), that could interfere with adjacent buildings or trees foliage, and cause indirect drawback like the increase of thermal load on pedestrians [21,22]. In our model, however, the height of the trees is smaller or at least equal to that of the roofs, with the only exception being a 3 m high building standing in the lower center part of the model. Therefore, the view factor between trees and roof is close to zero, and therefore the effect of roof reflection toward trees is minimal. This is confirmed by our model, which shows that solar diffuse radiation difference between cool and base case is minor than 10^{-4} W/m^2. Another possible cause is the alteration of wind velocity, but in our model, wind velocity difference between cool and base is negligible, as it is less than 0.1 m/s. The possibility of local temperature increase, however, has been highlighted in previous works [23,24] and may be ascribed to vertical and horizontal mixing changes (not evaluated in the present work).
- 23 July 2013, 2:00 a.m.: the atmospheric urban heat island is fully developed, with uniformity of values in the buildings area (see Figure 6b). There is not any substantial change with respect to the *Base Case*, since the utmost temperature difference between the two cases is 0.25 K, also due to the lack of irradiation. Minimum recorded temperature is 296.5 K (23.3 °C) while the maximum is 300.1 K (26.9 °C), with a thermal gradient of 3.6 K.

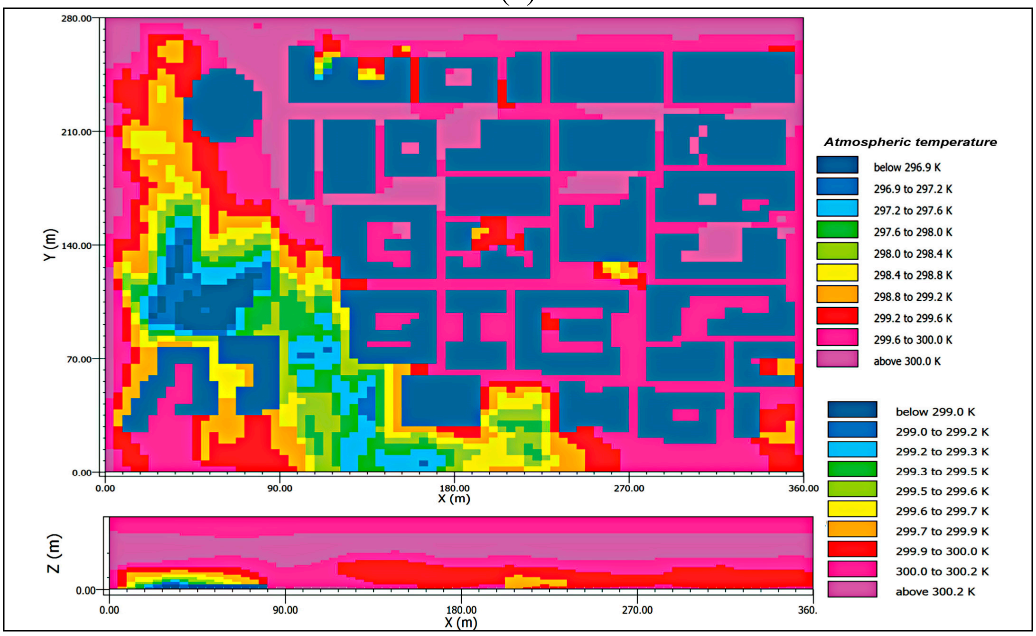
4.1.3. Green Case

- 22 July 2013, 2:00 p.m.: even in this situation there is an improvement compared to the *Base Case* (see Figure 7a). In the built area, temperatures are up to 1.2 K lower than the *Base Case.* The lower temperature is 305 K (31.8 °C), the higher is 312.3 K (39.1 °C), with a difference of 7.3 K;
- 23 July 2013, 2:00 a.m.: there is a nocturnal atmospheric UHI fully developed, with temperature reduction trend of few tenth of K, particularly in the lower right part of the model (Figure 7b). The higher temperature calculated is 300.1 K (26.9 °C), the minimum 296.5 K (23.3 °C), for a difference of 3.6 K.

Figure 7. Atmospheric temperature in "Green Case", x-y view at z = 1.20 m and x-z view at y = 220.5 m at (**a**) 2:00 p.m., 22 July 2013 (**b**) 2:00 a.m., 23 July 2013.



(**a**)



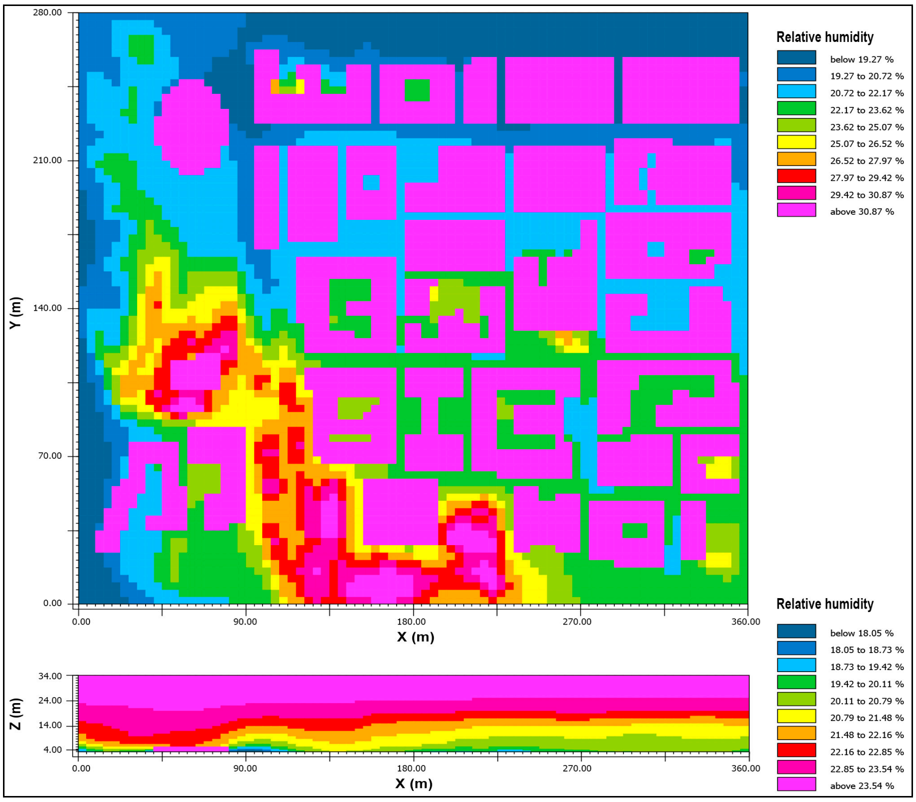
(**b**)

4.2. Relative Humidity

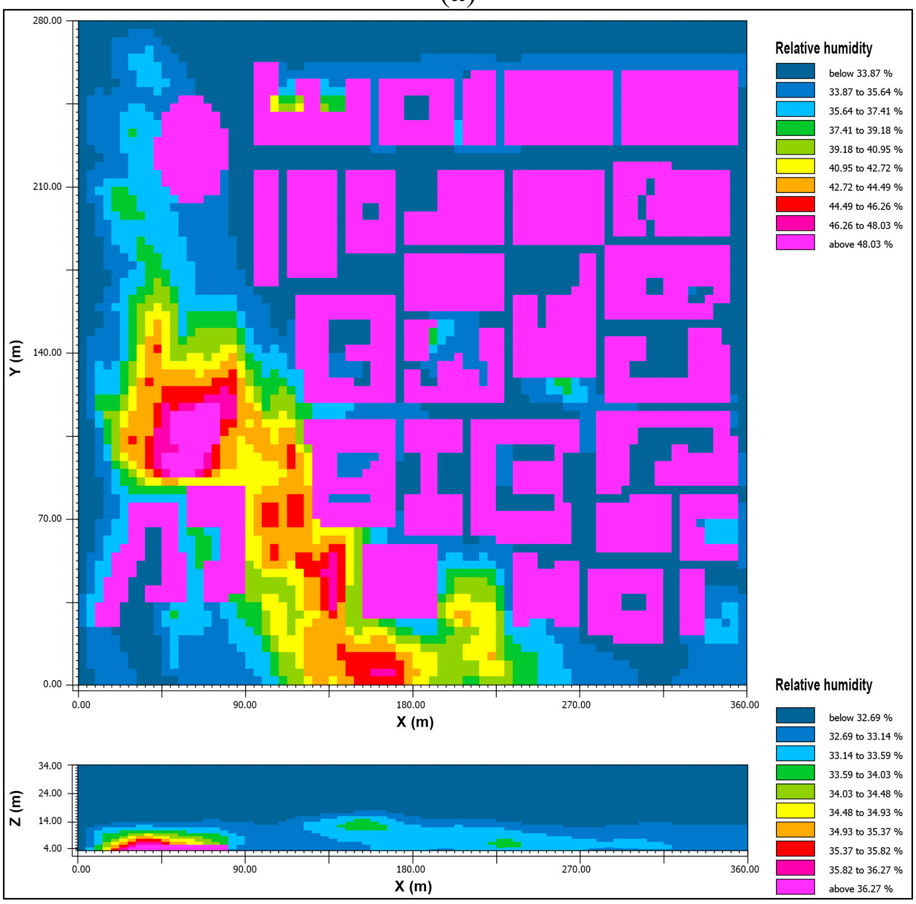
ENVI-met® provides hygrometric values both as specific humidity (g_{water}/kg_{air}) and relative humidity (in percentage): the latter has been used, to maintain coherence with equipment output in our future on site campaign.

Relative humidity is a meaningful parameter in determining thermal urban comfort, because it influences a person's heat perception. A sweltering climate, hot and humid, restrains the natural cooling mechanism of transpiration; a dry climate, for the same reason, grants a better comfort.

Figure 8. Relative humidity "Base case", x-y view at z = 1.20 m and x-z view at y = 220.5 m at (**a**) 3:00 p.m., 22 July 2013 (**b**) 3:00 a.m., 23 July 2013.



(**a**)



(**b**)

In the urban context, beyond the humidity of the air mass on the zone, the main sources of humidity are vegetation and cars (since one of the main products of combustion is water vapor, released by exhaust pipe). However, the software used is not able to evaluate the latter factor, but considering that a huge part of the modeled zone is located in the historical city center, where traffic is forbidden or limited, the error caused is negligible.

Anyway, since the absolute values mentioned above strongly depend on the specific climatic conditions assumed and cannot be considered as typical for the zone, it is interesting to note the humidity distribution in the area, ad to understand which are the driest and dampest areas.

Maps refer to two different timing (respectively 3:00 p.m. and 3:00 a.m.), one view at eye level z = 1.20 m, one view on plane x-z at y = 220.5 m.

Results shown below refer only to *Base Case*, since differences in the other cases are not relevant: the average difference of relative humidity between base case and cool case at 3:00 p.m. ranges between −0.32% and −0.2%, and between −0.18% and −0.16% at 3 a.m.; average difference of relative humidity between base case and green case at 3:00 p.m. ranges between −0.09% and −0.032%, and between −0.07% and 0.04% at 3 a.m.

- 22 July 2013, 3:00 p.m.: there is an overall compensating trend of temperature effect. Colder areas are damper, too (which is not surprising, since these areas are characterized by vegetation and a source of humidity); warmer areas are drier. This fact tends to compensate for itself, and uniform thermal comfort (or discomfort) is perceived, even though humidity difference does not balance the high temperature difference. The maximum value, registered in vegetated area located at the bottom right in Figure 8, equals 33%, whereas the minimum value toward the main street is 18.5%, and it matches with the particular morphology: it is formed by a vegetative nucleus surrounded by three buildings, with less air renewal. The maximum difference calculated is 14.5%, substantial but not high.
- 23 July 2013, 3:00 a.m.: as expected, nocturnal values are higher than daytime ones, even though the distribution of thermo hygrometric values in the zone has no relevant variations. Minimum humidity recorded is 33%, while maximum is 53%; so the highest difference is 20%, greater than the evening one. Even in this case, in absolute terms these values are not high.

4.3. Windiness

The intensity of air currents plays an important role in regulating convective exchanges that happen in the atmosphere, and the heat exchanged between air and vegetation, buildings and people.

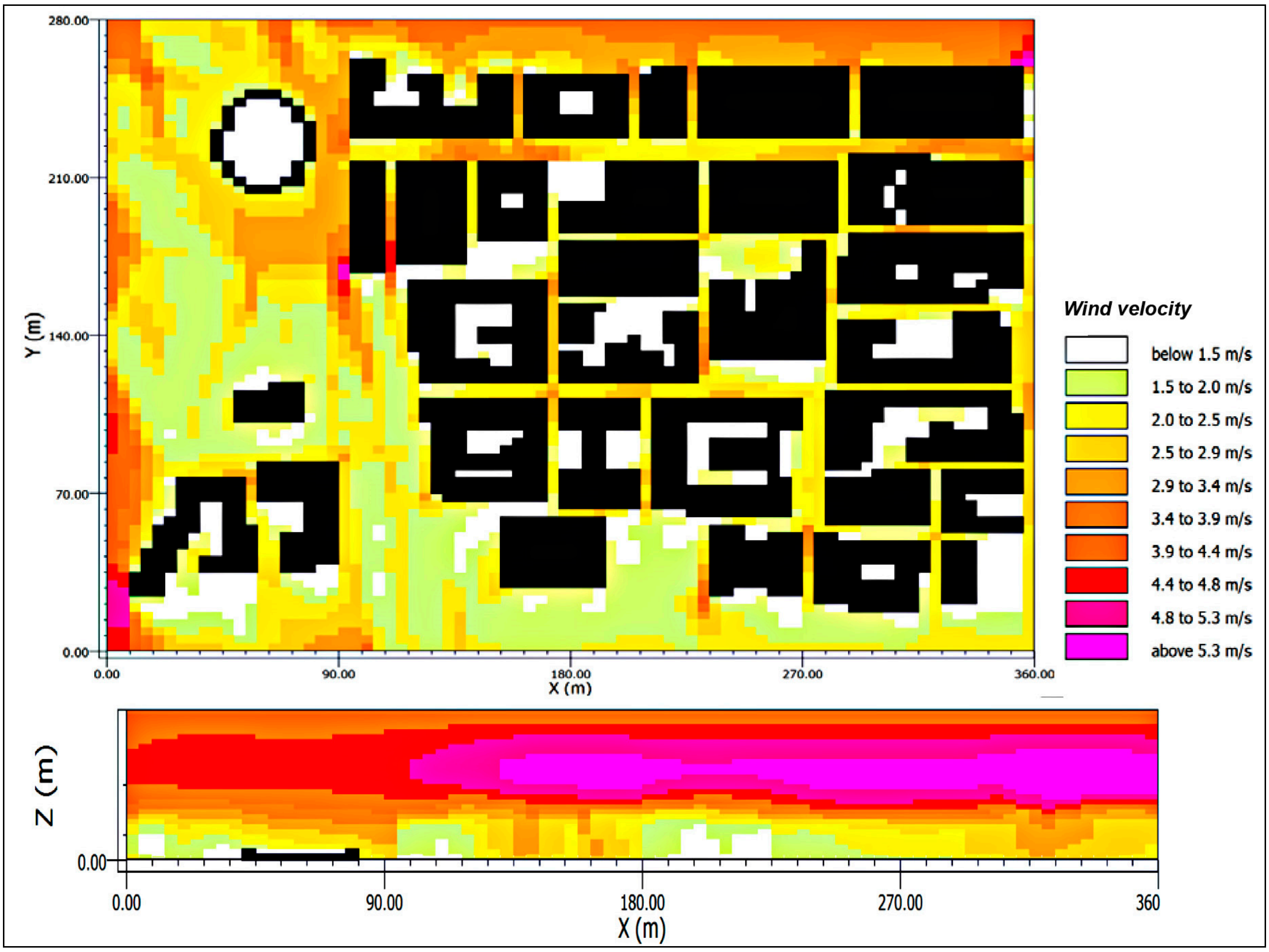
Urban morphology has great influence on local windiness: the existence of barrier enhances superficial roughness and therefore the height of anemometric boundary layer and the specific layout of streets and buildings can create an air preferential direction with high anemometric gradients in tight regions.

For what concerns UHI, high windiness enhances air mixing and tends to uniform different zones temperature, limiting phenomena like heat stagnation point due to still air.

This issue makes cities liable for this phenomenon by the great resistance offered to the air mass that flows through the area. Due to this consideration, this parameter has been chosen to represent the characterization of the microclimate of the selected area.

Figure 9 shows values calculated at 3:00 p.m. of the last day of simulation, only for the base case, since wind distribution is quite the same for the other cases and there are not significant variations with respect to the other cases (the utmost difference is 0.05 m/s between cool case and base case, and 0.38 m/s for between base case and green case). As usual, values are representative of horizontal view at z = 1.2 m, and plane x-z at y = 220.5 m.

Figure 9. Wind velocity, "Base case". 22 July 2013, 3:00 p.m. View x-y at z = 1.20 m and view x-z at y = 220.5 m.



A mean wind velocity equal to 3 m/s has been assumed for simulation setup, with a prevalent direction of 0° North (coincident with the N-S axis).

Wind distribution is consistent with area morphology: wind velocity is low near obstacles or almost still, especially in narrow areas, whereas open spaces have greater wind velocity.

This shape tends to promote the growth of an UHI. An interesting peculiarity is the canalization effect in the main street, large and straight, because it creates a current that, at some points, has velocity higher than 3 m/s.

The minimum value calculated (excluding totally closed areas, as internal buildings' porticoes, and the extreme areas affected by boundary conditions) is 0.2 m/s, whereas the higher is 4.5 m/s, with a maximum difference of 4.3 m/s.

5. Results Discussion and Conclusions

As a main conclusion, the urban microclimate is quite altered even in such a small area, and it is reasonable to think that, for that city, a fully developed UHI may rise. With ENVI-met® it is not possible to simulate the micro-climate of whole cities but only single quarters within, because the maximum number of grid cells of the model is quite limited [15].

Even in an average built area (as the historical city center of a small city like Teramo) a fully developed UHI may occur, with high thermal gradients between built areas and open spaces characterized by vegetation.

The analysis shows differences of up to 8K during hottest hours and greater than 3 K during nighttime.

Moreover, these gradients are established in a few hundreds of meters, confirming that urban geometry is crucial for the characterization of local microclimate.

The analysis of mitigation scenarios by using green or cool roofs have given improvements consistent with those available in literature. For a complete analysis, other factors must be considered: the installations foreseen provide benefits mainly on internal climate of buildings on which they are realized [14], and then consequently on external climate; however, to appreciate relevant effects on the external climate, wide metropolitan areas must be included, but this is not possible with this software, due to its having an inadequate resolution. Results obtained in a small area like the one considered, characterized by few tens of buildings, may appear insignificant or negligible; however, they suggest the possibility to have a fully developed UHI in the whole urban contest.

Furthermore, it is necessary to consider the limits of the software used. It is a powerful tool, since fluid-dynamic computation of atmospheric phenomena requires the solution of a quite complex calculating model, but highlights important deficits, particularly for what concerns building management.

Particularly, the most severe constraint is indoor building temperature, which is unique in all the points of the building, the same for all buildings and is not an output of the simulations, but is an input data necessary to fix boundary conditions for calculating the cell, although recent studies aimed to link ENVI-met to the building energy simulation (BES) program EnergyPlus [14]; a strong constraint is also due to transmittance and albedo values, fixed and identical for all buildings, and the impossibility to take into account anthropogenic heat flux (due, for example, to traffic or air conditioning, as highlighted in [16]). Another software issue is 2.5D modeling, that is the possibility to impose only two boundary conditions in vertical direction [25,26]. Thus, it is impossible to model vertical details like windows, roof slopes, types of shielding or any other architectural peculiarity. Furthermore, ENVI-met® does not model vegetative shielding of vertical surfaces, like green walls.

Another negative point is the duration of calculation time. This is on one side an inevitable and intrinsic factor, since CFD requires brief steps to guarantee consistency and convergence of numerical model used, particularly for the evaluation of turbulence; one the other side, during use the low capability of the software to parallelize process using the power of multiprocessor emerged. For example, a simulation of three days (which is a short amount of time on the meteorological scale) could last up to one month if the model is too big.

Author Contributions

All the authors contributed equally to this work. In particular, Dario Ambrosini, Giorgio Galli and Stefano Sfarra led the research activities, the data analysis and the writing of the paper, Biagio Mancini and Iole Nardi created and run the model.

Conflicts of Interest

The authors declare no conflict of interest.

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