UHI EFFECT IN THE CITY OF PADUA: SIMULATIONS AND MITIGATION STRATEGIES USING THE RAYMAN AND ENVIMET MODEL

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Abstract

The UHI phenomenon was studied in a medium size city in the North-East of Italy and the results are reported in this paper. Experimental measurements were carried out during the summer of 2012, measuring the main thermo-hygrometric variables by mobile survey and also the mean radiant temperature in characteristic sites of the city area: the historic centre, high and low density populated residential zones, the industrial zone and the rural zone. Two simulation models were used in order to calculate the effect of some mitigation strategies on UHI intensity and outdoor thermal comfort indexes for four typical days of the year.

Introduction

Urban environment is characterized by some typical features: high density of population and buildings, high energy consumption and shortage of green areas. A main consequence is the urban heat island phenomenon (UHI), that is the systematic higher air temperature of the urban environment as compared to the rural one. Depending on the climate type, UHI may be welcome (in winter it may reduce heating loads) or, conversely, in a warmer cli-mate it may increase cooling loads and also mortality rates. The main outcomes are as follows (Lazzarin 2011):

- deterioration of the summer outdoor thermal comfort conditions;
- an increase of buildings energy consumption for cooling;
- a consequent increase of polluting emissions.

Literature on the UHI effect is very rich (Oke 1973, 1981, 1982; Santamouris 2001; Arnfield 2003; Corburn 2009). Landsberg

(1981) studied urban canyons, while Montavez et al. (2000) evaluated the effect of the thermal properties of building materials. Other authors studied the impact of the lack of green areas in cities, but with large extensions of waterproof surfaces that limit the evapotranspiration effect (Takebayashi & Masakazu 2007; Imhoff et al. 2010) instead. Also, the effects of higher albedo of building surfaces (Akbari & Konopacki 2005) and the effectiveness that small urban rivers may have in mitigating the phenomenon (Hathway & Sharples 2012) have been evaluated.

The urban heat island effect results from a lot of causes that interact with one another, according to the particular situation of each city. Briefly, the main factors are the following:

- the structure of urban canyons that affect the shortwave radiation heat exchange capacity of urban surfaces towards the sky;
- the typically low albedo of urban surfaces which increases the heat absorbed by buildings, pavements, roads and roofs;
- the anthropogenic heat produced by heat engines of motor cars and condensation heat from coolers;
- the greenhouse effect which is amplified by higher pollutant concentration in the urban atmosphere;
- the shortage of green areas which increases the sensible heat exchange with the air and decreases the evaporative cooling effect due to the lack of evapotranspiration of trees and grass.

UHI has been studied worldwide (for example Athens, London, Berlin, Vancouver, Montreal, New York, Tokyo, Hong Kong) since the sixties of the past century. Some recent works are related to experimental measurements (Yang et al. 2010; Thorsson et al. 2011; Emmanuel & Krüger 2012; Shahidan et al. 2012), others to simulation and prediction models both of the UHI phenomenon itself (Mirzaei & Haghighat 2010, 2012) and of its consequences for indoor comfort and energy consumption of buildings (Bueno et al. 2012; Mirzaei et al. 2012).

In Italy, only a few studies are available for some major cities like Bologna (Zauli Sajani et al. 2008), Milan (Bacci & Maugeri 1992), Florence (Petralli et al. 2006, 2009, 2011) and Rome (Fabrizi et al. 2010). Very little data is available concerning the existence of the urban heat island phenomenon in medium size cities, the most widespread in Italy, for example: Modena (Bonafè 2006) and Trento (Lora et al. 2006; Giovannini et al. 2011), and none in the Veneto Region in the North-East of Italy. The University of Padua has been studying Padua's UHI effect since 2010. In previous works the authors have described the results of the 2010, 2011 and 2012 measurement campaigns carried out by the research group of the Department of Environmental Agronomy and Crop Productions and by the authors themselves (University of Padua) (Busato et al. 2014; Noro et al. 2014). In this paper, the activities developed by the authors' research group within the framework of the European Project 'UHI' (Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon – 3CE292P3) are described, reporting on the simulation of UHI in Padua. The main tasks of the campaign of measurements previously conducted were, at first, to investigate the presence of the UHI effect in Padua. This paper reports instead on the estimation of the possible correlation between the main variables (later described) by the use of two simulation models in order also to investigate the effect of possible mitigation strategies in characteristic sites of the city.

Target area description

Padua is a city in the Veneto Region, northern Italy. It is the capital of the province of Padua and the economic and communications hub of the area. Padua's population is 214,000 (as of 2011). The city is picturesque, with a dense network of arcaded streets opening into large communal piazze, and many bridges crossing the various branches of the Bacchiglione, which once surrounded the ancient walls like a moat. Padua experiences a climate that is

in transition between humid subtropical and Mediterranean (Köppen climate classification between Cfa and Csa/Csb) characteristic of Northern Italy, made milder by the near Adriatic sea. The industrial area of Padua was created in 1946, in the eastern part of the city; now it is one of the biggest industrial zones in Europe, having an area of 11 million m^2. Here there are the main offices of 1,300 industries employing 50,000 people.

The city of Padua is quite sensitive to initiatives concerning the protection of the environment, human health and energy conservation. During the last decade, the Municipality has been involved in different European Projects (Life Siam – n. LIFE04 ENV/IT/000524, Life 'South-EU Urban ENVIPLANS', Belief – Building in Europe local intelligent energy forums, LIFE-PARFUM); initiatives like the arrangement of the Energy Plan and the Climate Plan have been adopted in order to give practical tools to reduce energy consumption and to introduce adaptation and mitigation strategies to climate change.

All these climatic and environmental characteristics of the territory can promote interest in the study of the heat island effect of the city of Padua.

Experimental measurements in previous work

The goal of the field survey was a first characterization the UHI phenomenon in a medium-sized city like Padua (Noro et al. 2014). This kind of study needs the availability of some meteorological data, the main being dry-bulb temperature and relative humidity. Within the framework of the UHI Project we used two methods for data acquisition:

- two stationary meteorological stations, situated in urban and rural zones of the territory, that logged data at fixed time steps during a long time period;
- mobile surveys, with the measurement instrumentation installed on a vehicle running through the territory from the rural to the urban zone, in order to log data continuously.

Data from the stationary logging were supplied by ARPAV (Regional Agency for Environment Protection in Veneto), providing measurements of hourly mean values of dry-bulb air temperature and wind velocity at 2 m above the ground in the period 01/01/1994-12/31/2011. The two meteorological stations are Orto Botanico (urban zone of the city) and Legnaro (rural zone, 8.5 km far) (Fig. 1). The former is located inside a botanical garden and thus its characteristics are probably difficult to be classified in a standard 'local climate zone' (LCZ) (Stewart & Oke 2012), while the latter is an LCZ D. The elevation of both is around 10 m above sea level. The Orto Botanico station is the only meteorological station in the city centre and is used by ARPAV and all the local Administrations to collect meteorological data concerning the urban zone.

Figure 1. Geographical position of the two meteorological stations

Source: Google Earth.

The yearly means of the monthly mean values of the maximum, mean and minimum daily temperatures were calculated on the basis of meteorological data: they were respectively 0, 0.5 and 1.5°C higher in the Orto Botanico station (city centre) with respect to the Legnaro station (countryside) (Noro et al. 2014). Since minimum values were typically found in night measurements, it can be said that the urban heat island in Padua was most intense at night and more evident in summer (around 2°C in July). Furthermore, the authors calculated that the differences between daily

maximum temperatures of the two stations were on average very small during the period 1994-2011, but this was the result of the compensation of the negative difference during the first period (1994-2000) and the positive difference during the following one. This trend can be read as being due to the increasing presence of a day-time heat island effect, which could explain, in some way, the increasing trend of cooling degree days in the urban zone of the city (Noro et al. 2014).

Furthermore, experimental data were logged by mobile surveys from 26 July 2012 to 9 August 2012, some of them in double sessions: day-time (during late afternoon) and night-time session (between 1 and 4 h after sunset in order to investigate the phenomenon during its potentially maximum intensity). Dry-bulb air temperature, relative humidity and solar global radiation on the horizontal, with a time step of 5 s, were the main variables measured by the mobile station equipped on a vehicle. UHI intensity was determined by the difference between mobile measured air temperature and the value recorded at the same time by the reference ARPAV rural fixed meteorological station of Legnaro.

Besides the mobile surveys, in situ measurements were performed in some characteristic sites of the city area along the path, in order to measure air temperature and humidity, wind velocity and mean radiant temperature. Consequently, these data were processed using the RayMan model (Matzarakis et al. 2007, 2010) in order to calculate some outdoor thermal comfort indexes: the Predicted Mean Vote (PMV), the Physiological Equivalent Temperature (PET) and the new Standard Effective Temperature (SET).

All the results and discussion on the experimental measurements were reported on (Noro et al. 2014). Here we focused on the following step of the work: what kinds of strategy can be adopted in a representative area of the fabric of the city of Padua in order to mitigate the UHI effect?

UHI mitigation strategies by simulations

Thermal comfort by Rayman simulations

Many mitigation measures can be adopted and have been proposed by various researchers: they could be classified as measures that could only be implemented during the design and planning stage (e.g. sky view factor and building material) and those that could also be implemented after the design and planning stages (e.g. green areas and roof spray cooling) (Rizwan et al. 2008). The RayMan model was used in order to quantify possible increases in thermal comfort as a consequence of some possible mitigating measures of both types. The RayMan model is a simulation tool for the estimation of radiation fluxes and mean radiant temperature (T_{mr}) and other variables, compatible with Windows®, that can analyse complex urban structures and other environments. The main inputs of the model relate to outdoor environment conditions: dry-bulb air temperature and relative humidiy (RH), wind velocity, Bowen ratio (ratio of sensible over latent heat flux in evapotranspiration, fixed at 1.5) and cloud cover (fixed at 1 okta). Other inputs are the albedo and emissivity of surfaces, fixed respectively at 0.30 and 0.95, typical values for an urban environment.

A slightly warm PMV was obtained for via Rinaldi (Padua old town) and in via Pindemonte (high density population residential zone) (Fig. 1): here the modification in thermal comfort with some characteristics of the site was evaluated by RayMan. The following limitations in the RayMan analysis must be highlighted:
- emissivity is considered the same for all the different kinds of surfaces;
- consequences of higher albedos cannot be correctly evaluated: the lower surface temperature would not be estimated as it is given by the air temperature (input of the software).

For these reasons the simulations concerned topology modifications only (height and distance of buildings, presence of green areas); obviously these are mitigation strategies that can be implemented during the design and planning stage only. Table 1 reports the results for via Rinaldi considering a different layout of buildings:

- the actual situation;
- maximum height of buildings limited to 6 m;
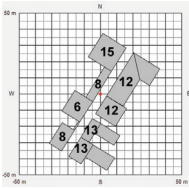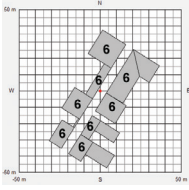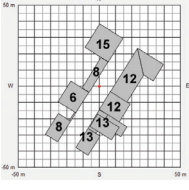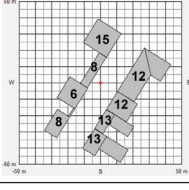- doubling or tripling the street width.

Every simulation was repeated using the same values of environmental variables as measured during the experimental sessions (air temperature and RH, wind velocity). Results in Table 1 show an increase in Sky View Factor (SVF) thus allowing a more effective nightly cooling of surfaces and a decrease of T_{mr}. In particular, limiting the maximum height of buildings to 6 m or doubling the street width to 11 m would generate nearly the same results (i.e., a decrease by 1°C in T_{mr}, by 0.1 in PMV and by 0.5-0.7°C in PET) because the increase of the SVF would be much the same (respectively 0.31 and 0.35). A significant increase in SVF in the third case of Table 1 would allow a decrease of T_{mr} by about 2.5°C.

A similar analysis was developed for via Pindemonte (high density population residential zone):

- considering the actual situation;
- increasing the street width from 15 to 25 m;
- limiting the maximum height of buildings to 12 and 6 m;

Table 1. T_{mr} and thermal comfort indexes in via Rinaldi (Bowen ratio = 1.5, cloud cover = 1 okta, clothing = 0.5 clo, activity level = 80 W above the basal metabolism) for different disposition of buildings

		SVF	Date	T_{mr}	PMV	PET
Actual situation		0.18	27-Jul	27.1	1.2	28.0
			30-Jul	25.9	0.8	26.7
			31-Jul	26.0	0.8	26.7
6 m buildings height max		0.31	27-Jul	26.0	1.1	27.5
			30-Jul	24.8	0.7	26.2
			31-Jul	24.8	0.7	26.2
Double street width		0.35	27-Jul	25.8	1.1	27.4
			30-Jul	24.5	0.7	26.0
			31-Jul	24.5	0.7	26.0
Triple street width		0.48	27-Jul	24.6	1.0	26.8
			30-Jul	23.3	0.6	25.5
			31-Jul	23.4	0.6	25.5

- having a garden in front of the point of measurements instead of an apartment building.

The results can be seen in Table 2. A limitation of the maximum height of buildings to 6 m would be the action with the most relevant effect. The mean radiant temperature was shown to decrease by 2.6°C and PMV by 0.2. Anyway, the night effects of an increased SVF were probably underestimated by Ray-

Table 2. T_{mr} and thermal comfort indexes in via Pindemonte (Bowen ratio = 1.5, cloud cover = 1 okta, clothing = 0.5 clo, activity level = 80 W above the basal metabolism) for different disposition of buildings

		SVF	Date	T_{mr}	PMV	PET
Actual situation		0.29	27-Jul	24.9	0.6	25.3
			30-Jul	24.3	0.5	25.3
Street width enlarged by 10 m		0.38	27-Jul	24.2	0.5	25.0
			30-Jul	23.6	0.5	24.9
12 m buildings height max		0.45	27-Jul	23.6	0.5	24.7
			30-Jul	22.9	0.4	24.6
6 m buildings height max		0.6	27-Jul	22.3	0.4	24.2
			30-Jul	21.7	0.3	24.1
Green in front		0.56	27-Jul	22.7	0.4	24.4
			30-Jul	22.1	0.3	24.2

Man, because the mean radiant temperature and so PMV and PET were calculated by knowledge of air temperature (input) that is actually expected to decrease when SVF increases. Also, the effect of having a green area (last solution of Tab. 2) was probably underestimated because the model does not consider the cooling effect due to evapotranspiration.

UHI mitigation strategies for built areas by envimet simulations

The measures just described can be suggested both in new and built areas, in case of redevelopment of an existing urban area. Within the framework of the European Project UHI, the authors conducted simulations using the ENVImet model (Bruse & Fleer 1998) in order to quantify the effect of selected mitigation actions (usable in already built areas) in one of the previously analysed sites (via Pindemonte).

ENVImet is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in an urban environment with a typical resolution of 0.5 to 10 m in space and 10 s in time. The modelled area is described in Figure 2 and Figure 3. The main area is a 99 x 70 x 30 grid (in a x, y, z three dimensional reference system), with a 5 x 5 x 3 m grid dimension. An appropriate number of nesting grids (five) has been set in order to minimize boundary effects. Four specific points of interest have been identified in the zone to characterize the air temperature (at 2 m above ground) during 24 hours, from 6 am to 6 pm. Simulations lasted 72 hours, but only the last 24 hours were considered for the results. The daily mean air temperature of the days before the start of simulation (Tab. 3) were used as initial air temperature at 6 am. As requested by the Project, four characteristic days (suggested by the Work Package Leader and common to all Project Partners) representative of the four seasons were considered. Simulations used the default values of ENVImet except for the ones reported in Table 3.

To estimate the UHI intensity, simulations were extended in the rural zone just outside Padua, in a lateral street of Via Roma (an unpaved dirt patch road in the countryside), at the same point where the experimental

Figure 2. The model area in ENVImet used for the simulations of the 'AsIs', 'Cool pavements' and 'Cool roofs' scenarios. The red numbers identify four characteristic points for which air temperature at 2 m above ground was considered in the study. The grey surfaces are impervious (asphalt, cement, buildings, etc.), the green ones are pervious (green, trees)

Figure 3. The model area in ENVImet used for the simulations of the 'Green ground' and 'Green ground + Cool pavements' scenarios. Explanations as in Figure 2

Table 3. Configuration values in ENVImet

Simulation tool: ENVI-met 3.1
Start Simulation at Day (DD.MM.YYYY): 02.02.2012 Winter; 02.05.2012 Spring; 27.07.2012 Summer; 03.11.2012 Autumn
Start Simulation at Time (HH:MM:SS) = 06:00:00
Total Simulation Time in Hours = 72.00
Wind Speed at 10 m ab. ground [m s^{-1}] = 3
Wind Direction (0:N; 90:E; 180:S; 270:W) = 90
Roughness Length z0 at Reference Point = 0.1
Initial Temperature Atmosphere [K]: 279 K Winter; 290.9 K Spring; 300 K Summer; 282.2 K Autumn
Specific Humidity at 2500 m [g$_{water}$/kg$_{air}$] = 7
Relative Humidity at 2 m [%] = 50
Output: air temperature at 2 m above ground
Building properties
Inside Temperature [K] = 298
Heat Transmission Walls [W m^{-2} K^{-1}] = 1
Heat Transmission Roofs [W m^{-2} K^{-1}] = 2
Albedo Walls = 0.2
Albedo Roofs = 0.3 (all scenarios except 'Cool roofs'); 0.6 ('Cool roofs')
Albedo Pavements = 0.4 (all scenarios except 'Cool pavements'); 0.5 ('Cool pavements')
Albedo Roads = 0.2 (all scenarios except 'Cool pavements'); 0.5 ('Cool pavements')

measurements were conducted during the summer of 2012. Four scenarios were analysed besides the actual one ('AsIs' scenario):

• 'Green ground': increasing the pervious surfaces of the area from 18% to 23% by planting trees (10 m height) within the urban canyon and the main road of the area, and converting an impervious zone – e.g. asphalt car park surface – to a pervious zone by planting grass. The main effects were: Sky View Factor along the streets decreased with the presence of trees; the impervious surface fraction decreased (and pervious surface fraction increased) because the green area increased; albedo slightly increased; other thermo-physical properties of the surfaces/materials remained much the same;

• 'Cool pavements': substituting all the traditional asphalt (albedo 0.2) and concrete (albedo 0.4) (roads and pavements) with 'cool materials', that is materials with

a higher albedo (0.5). The main effects were that albedo significantly increased while other properties remained the same;
- 'Cool roofs': use of 'cool materials' for the horizontal impervious surfaces of roof. In particular, albedo of roofs was increased from 0.3 to 0.6;
- 'Green ground + cool pavements': scenario with both the mitigation actions just described being adopted simultaneously.

The results, in terms of 24 hours of air temperature at 2 m above ground and UHI intensity with respect to Via Roma (rural zone), are reported in Figures from 4 to 7 for point 1 present in Figure 2 (as representative of the area) and for the four characteristic days of the year. Summarizing, the main results were:
- the highest UHI intensity (difference between the 'AsIs' and 'Via Roma' curves per each hour of the day) was clearly
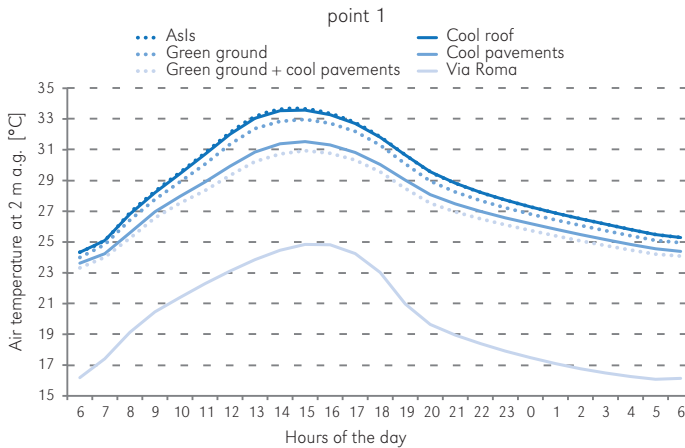

Figure 4. Air temperature at 2 m above the ground during one summer day (from 6 am to 6 am of the following day) at point 1 of the pilot area modelled by ENVImet (asphalt car park surface in front of a block of flats)
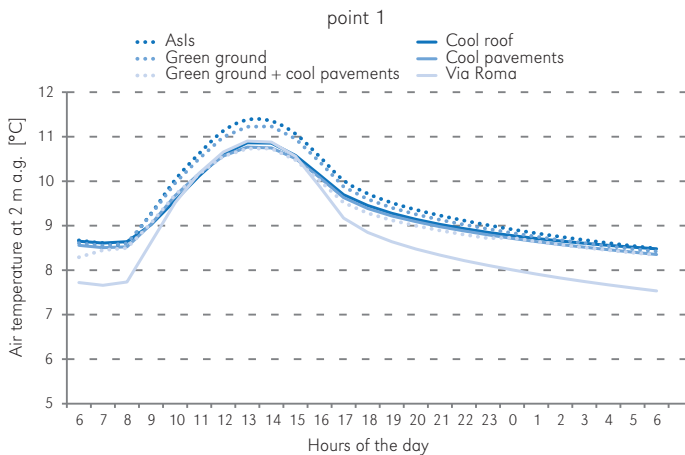

Figure 5. Air temperature at 2 m above the ground during one autumn day (from 6 am to 6 am of the following day) at point 1 of the pilot area modelled by ENVImet
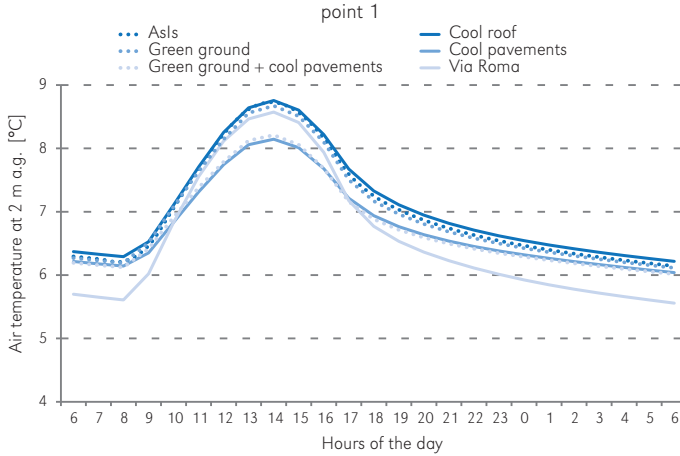
point 1

Figure 6. Air temperature at 2 m above the ground during one winter day (from 6 am to 6 am of the following day) at point 1 of the pilot area modelled by ENVImet
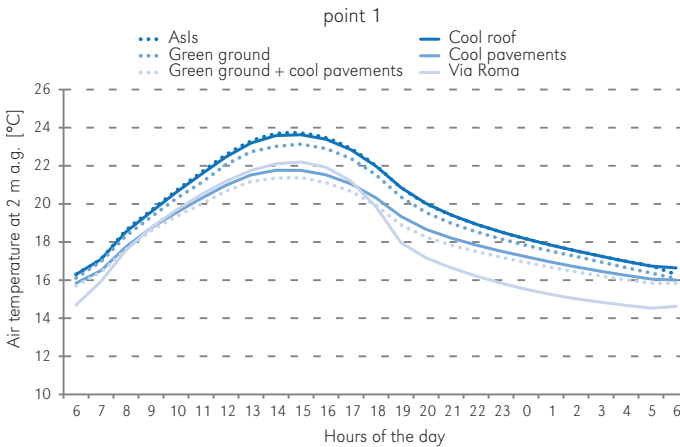
point 1

Figure 7. Air temperature at 2 m above the ground during one spring day (from 6 am to 6 am of the following day) at point 1 of the pilot area modelled by ENVImet

obtained in summer. During the other seasons, the UHI phenomenon was much lower and quite negligible in winter during the central hours of the day;

- talking about the summer, the highest UHI intensity (9-10°C) was noticed after sunset (8 pm) and till the first sunrise (4 am);
- the same value of 9-10°C for UHI intensity during the day was noticed only for point 2 (1 pm), that is a street canyon (characterized by low SVF and impervious surfaces); for the other points the maximum daily

UHI intensity was always lower than 9°C. This is a significant effect in the summer daytime that was not seen in three remaining cases analysed (Fig. 5, 6 and 7); this is probably due to the very limited air temperature in the rural reference point (via Roma, open countryside) likely caused by very high evapotranspiration of the environment (green, ground and a small river) during summer daytime;

- the best UHI mitigation strategy was the 'Green ground + cool pavements' (Scenar-

io 4) that allowed a 2°C decrease in UHI maximum intensity (but till a nearly 3°C decrease in point 2);

- the 'Cool pavements' mitigation strategy allowed a decrease between 1 and 2°C in UHI maximum intensity in all the points;
- the 'Green ground' mitigation strategy allowed an appreciable decrease of UHI maximum intensity only in point 2 (around 1°C): in all the other points, the positive effect of the action was quite negligible;
- during the day (afternoon) the most effective mitigation actions were 'Green ground' and 'Green ground + cool pavements': they allowed an up to 3°C decrease in UHI intensity;
- during all the other seasons, but especially in winter, the most effective UHI mitigation strategies ('Cool pavements' and 'Green ground + cool pavements') caused a negative effect during the central hours of the day: UHI intensity became negative, that is air temperature in the urban zone was colder (about 0.5°C) than in the rural zone;
- the 'Cool roof' action seemed not to have any effects on mitigation (the 'AsIs' and 'Cool roof' curves substantially overlap). This was probably due to the type of fabric of the city in this area (high density population residential zone) with little difference in the heights of buildings.

It has to be highlighted that such simulation results are obviously subject to some uncertainty. Hedquist et al. (2009) report that simulation outputs for ambient temperature throughout the 24 hour period generally under-predicted the maximum observed temperature and over-predicted the minimum temperature. However, the study confirms that at the time of maximum UHI magnitude (10 pm), the model simulations were most accurate (Hedquist et al. 2009). This smaller diurnal temperature range prediction is similar to the results found in Emmanuel and Fernando (2007) and Chow (2011); it could be a consequence of several limitations of ENVImet, such as its inability to dynamically simulate heat storage for building walls

and roofs by having constant building indoor temperatures with no thermal mass, and simulate regional-scale thermal and turbulence exchanges that may directly influence micro-scale climates. Despite these limitations, the relatively low root mean square errors and mean average errors found by the authors suggest that the model is accurate in simulating time-series temperature data as reported also in other studies (Ali-Toudert & Mayer 2006; Fahmy & Sharples 2009; Yang et al. 2013).

Conclusions

The experimental analyses have highlighted the presence of a non-negligible UHI effect in medium size cities like Padua, also up to 6-7°C, resulting in thermal stress for people living in an urban environment, while there being a thermal comfort situation in rural zones. The UHI phenomenon was very intense in the old town, where covered streets are characterized by high H/W ratio, small SVF and no presence of pervious surfaces. However, in residential areas the UHI intensity was lower on average with a decreasing trend going from more densely populated streets to less densely populated ones. The reasons would be due to the higher SVFs, the lower H/W ratios and the higher presence of green areas. Moreover, the presence of water was shown to contribute to the reduction of UHI intensity.

It is very difficult to think how to mitigate the UHI phenomenon in the city centre (old town), while it is advisable to implement some mitigation strategies in sub-urban zones. Different options were considered suitable for both new areas and already develpoed ones by means of the RayMan and ENVImet models. By the first model, increasing the value of the SVF seems to be the most effective strategy to mitigate the UHI effect, even if the results obtained are probably underestimated because of the calculation method of the model. In the second model, solutions such as planting trees, green areas and using cool materials can mitigate UHI intensity in

a significant way and contribute to the provision of outdoor environments within thermal comfort zones. These kinds of analyses can be useful, above all, in new and developing areas with lower costs and better results than already built ones.

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Editors' note:

Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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