Numerical modelling of radiative and energetic balances in the urban canopy layer

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Abstract

In stable atmospheric conditions wide urban areas are normally affected by the well known phenomenon called *heat island*, characterised by a temperature distribution increasing from surrounding rural areas to the centre of the town. The connected heating processes in the canopy layer depend on general meteorological conditions and local properties of the surface. During the day the evolution of the heat island is quite complex but, since it happens only in conditions of strong meteorological stability, the dominant phenomena have a vertical development, while horizontal transfer processes can be neglected. For these reasons the problem can be effectively modelled by a uni-dimensional model, applied to the single cells into which the surface is divided. In the present case, for the metropolitan area of Milano (Italy) (30×30 km²), the surface has been divided into 10^6 cells, 30×30 m² each. A system of four equations has been chosen dealing with: 1) the energetic balance at the building surface; 2) the energetic balance at the soil surface; 3) the sensible heat fluxes at the building top and 4) the latent heat fluxes at the building top. The input data for these equations are the meteorological observed parameters, like air temperature and humidity, cloudiness and wind intensity, and some surface properties, deduced by Landsat TM multrispectral images such as albedo, vegetation cover, type of buildings. The model has been implemented by a parallelized code. Output values, for every cell, are: 1) the soil and building surface temperature; 2) the air temperature and humidity at the top of the buildings and in the canopy layer, at an intermediate level between the soil and the buildings top. Convergence of the method and optimality of the solutions has been tested heuristically, through the study of sensitivity of the output with respect to variations of the input data.

1 Introduction

The study of the phisics of the atmosphere has recently greatly developed due to the growing number of numerical models and the improving performances of the computing systems.

The models employed in this kind of research can be split up into three categories, depending on the application area, namely:

- global models, dealing with the general atmospheric circulation (at the planetary or hemispherical scale);
- regional or local models, related to the meteorological phenomena typical of local scales, such as extra-tropical cyclones, fronts, sea-land breezes;
- microscale models for the boundary layer, related to the flux between the earth surface and the lower layers of the atmosphere.

Microscale models need an adequate description of the surface parameters, especially kind of soil, vegetation cover, distribution and type of the buildings, local hydrography.

The model developed in this paper belongs to the family of the Urban Canopy Layer Models (UCLM) and aims to simulate the *urban heat island* phenomenon. It takes into account the sensible and latent heat transfer and the conductive processes among atmosphere, buildings and soil in an urban context.

The heating processes in the canopy layer depend on meteorological conditions and local properties of the surface. The behaviour of the heat island is generally complex but, since it happens only in conditions of meteorological stability, the vertical fluxes are dominant, while horizontal, advective transfer processes can be neglected. For these reasons the heat island can be effectively modelled by a uni-dimensional model, separately applied to the single cells into which the investigated area is divided. Without dynamic and advective contributions, the cells do not interact with each other; therefore the balance is imposed at a single point in each cell, representing the average properties of the cell itself. Parameters describing soil, buildings and atmosphere are dealt with separately; the physical quantities solved for are: the temperatures at the interfaces of soil and buildings and the air temperature and humidity in the canopy layer.

Figure 1 describes three fundamental levels, namely: the soil ($z = 0$), the average height of buildings in the cell (z_1) and a height representative of the atmosphere above the urban canopy (z_2), where the influence of the canopy becomes negligeable.

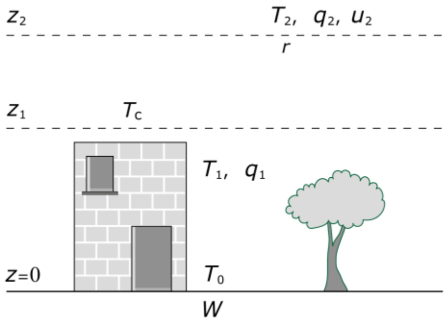


Figure1: The urban context for a single cell.

The other symbols in fig.1 indicate the following quantities:
T_2 , q_2 , u_2 are temperature, specific humidity and wind intensity at the level z_2, 100 m above soil;
T_c is the temperature at the level z_1;
T_1 , q_1 are the temperature and the specific humidity inside the urban canopy;
T_0 , W are the temperature at soil level and the relative humidity inside the soil.

In Milan, located in the Po Valley, a wide plain of the Northern Italy, the climate is characterized by very frequent and persistent conditions of atmospheric stability, favourable to the development and growth of the urban heat island. The UCLM model has been implemented in order to integrate satellite images [1], Fortran codes and meteorological data. The study of metropolitan climatology is indeed profitably carried out only by means of a multidisciplinary approach that includes the selection of relevant input data, the parametrisation of physical processes [2] and the graphic elaboration of results.

2 The model

2.1 The area and the input data

The region chosen for the study is a square area of side 30 km including Milan and its suburbs. This area is divided by a regular square mesh of dimension between 30 m and 1500 m, depending on the simulation purpose and modality. All input data are averaged on each cell of the mesh and considered as values taken on at the central point of the cell. The relevant parameters for the cell are the thermic and hygrometric responses. There are two classes of input data, namely:

- parameters related to urban and rural properties;
- meteorological data related to the general synoptic conditions.

Local properties of the area at study were reconstructed by means of remote sensing techniques on the basis of Landsat TM satellite images [3]. Such images were converted into numerical matrices; their entries were elaborated in such a way that, as a final result, it was possible:

- to detect 7 different land cover classes and their coverage percentage in the examined area (table 1);
- to single out the building density σ_c (that is the ratio built area to total area), albedo and vegetation index (NDVI); there is a remarkable correlation between the highly built up areas of Milan and the lowest albedo values;
- to assign specific emissivity (table 2) and mean height values of the buildings; each cover class is characterized by a specific kind of buildings with different height and material.

Table 1: Cover classes based on spectral responses in Landsat TM channels

Soil cover classes	Coverage percentage
1. Residential buildings	35
2. Industrial areas	15
3. Recent industrial areas (highly reflective)	5
4. Vegetation	21
5. Water	1
6. Wet rural areas (rice fields, watered meadows, etc.)	5
7. Rural areas (bare fields)	18

Table 2: Emissivity values of different soil cover classes

Soil cover classes	Emissivity
1. Residential buildings	0.9
2. Industrial areas	0.85
3. Recent industrial areas (highly reflective)	0.8
4. Vegetation	In function of NDVI
5. Water	0.9
6. Wet rural areas (rice fields, watered meadows, etc.)	0.95
7. Rural areas (bare fields)	0.85

The input meteorological data for the urban area result from the surface measurements recorded by the Milano-Duomo Meteorological Observatory; for the rural areas, the data employed were collected by radiosoundings made at Milano-Linate Meteorological Centre.

2.2 The town modelling and the radiation balance

The urban environment has been modelled as an ordered set of square blocks, grouped in bigger blocks spread uniformly in all the directions, according to the radial plan of Milan, and separated by *urban canyons*. An urban canyon is a simple model of a main road: the buildings are aligned with continuity along its sides.

The urban area is subdivided into square cells of given side. The buildings in each cell are assumed of equal height (the average of the real heights, kindly provided by the local authorities). Several parameters can be chosen to describe the town in terms of its thermal behaviour, but our aim is to take into account the energetic balance relative to the surfaces of the buildings and of the ground together with the sensible and latent heat fluxes. Both radiation and heat fluxes are deeply affected by the geometric structure of the town. Let us consider a single building, *i.e.* a parallelepiped with square basis of side t and height h. Let A be the sum of the lateral and top surfaces of the building. During light hours, the building shades a portion A_h of the ground, depending on its dimensions and on the zenithal and azimuthal angles, θ and φ respectively (fig. 2).

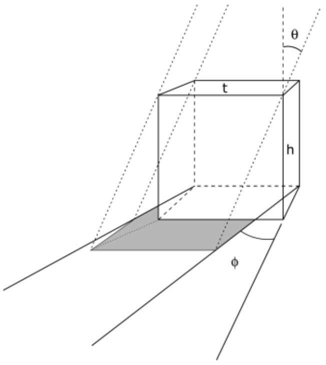


Figure 2: The shadow projected by a building.

We define the *shape factor* S_f as

$$S_f = A_h/A.$$

This factor has a minimum value at noon and maximum values at sunrise and sunset.

We also define the view factor Ψ_{21} as the portion of the radiation emitted by a surface ΔA_1 which is intercepted by another surface ΔA_2 (fig. 3).

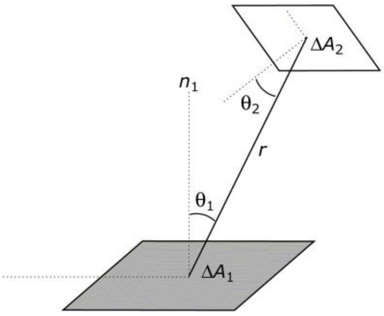


Figure 3: View factor geometry for two surfaces

It can be sown that if the positions of the surfaces ΔA_1 and ΔA_2 are as in fig. 3, the value of Ψ_{21} is

$$\Psi_{21} = \frac{\cos(\theta_1)\cdot \Delta A_2 \cdot \cos(\theta_2)}{\pi \cdot r^2},$$

depending only on the geometrical features and independent of the thermal properties.
Finally we define the sky as an immaginary horizontal surface at the level of 100 m above the ground, where, on the basis of measured data, the interactions between the town and the atmosphere become negligible. Thanks to this sort of lid of the city, the radiation emitted by a surface is totally intercepted by other surfaces: the ground, the sky, the neighbouring vertical surfaces.
The heat fluxes among the buildings (roof and walls), the soil and the sky have been estimated both in the long- and short-wave balance. In our assumptions all the builndings in the cell are of the same height, the view factors are reciprocally the same (that is $\Psi_{12} = \Psi_{21}$) and an urban canyon is defined by walls, ground and sky. A detailed parametrization of all the fluxes was presented in [4]. For short- and/or long-wave fluxes, schematized by an arrow, the following processes are studeid: sky → canyon; sky → ground; building → sky; roof → sky; wall → ground; wall → sky; ground → sky; ground → wall.

2.3 The energy balance and the mathematical structure of the model

The UCLM model is based on the solution of a system of four independent equations, concerning the different types of heat transport and storage. The terms involved are computed at the levels described in fig. 1. The equations are:

$Q_c = Rn_c - H_c + Qa_c$ Energetic balance at the building surface (1)

$Q_g = Rn_g - H_g - \lambda E_g + Qa_g$ Energetic balance at the soil surface (2)

$H_a = H_g + H_c$ Sensible heat fluxes at the building top (3)

$E_a = E_g$ Latent heat fluxes at the building top (4)

where (suffixes c and g stand for the building and soil values, respectively, while a stands for the air in the canopy): Q_c and Q_g are the conduction heat fluxes, Rn_c and Rn_g are the net radiation terms, H_a , H_g , H_c are the sensible heat fluxes, Qa_c and Qa_g are anthropogenic heat terms, E_a and E_g are the sensible heat fluxes, λ is the soil heat conductivity.

The four unknown quantities are:
T_c , the temperature at buildings top;
T_0 , the temperature at the soil;

T_1 , the temperature inside the urban canopy;
q_1 , the specific humidity inside the urban canopy.

3 The application

3.1 Input

The static data are latitude, height above the sea level and Landsat images, that provide: land cover class, building density, albedo, emissivity, vegetation cover index, anthropogenic heating, canopy and soil conductivity, soil roughness lenght. The dynamic parameters are: month, day of the month, solar time, cloudiness, soil relative humidity, air pressure at surface, air temperature at 2 m above ground, air specific humidity at level z_2 , wind intensity at level z_2 , top of the surface layer (z_2 ~100 m above the ground), soil temperature, air temperature inside the canopy layer (at level z_1), air specific humidity inside the canopy layer (at level z_1), temperature of the building surface.
All values are computed at the centre of each cell and interpreteded as average relative to the whole cell.

3.2 Computing method

Some *first step values*, $T_{0,\mathrm{o}}$, $T_{1,\mathrm{o}}$, $T_{\mathrm{c,o}}$ and q_1 must be provided (see fig.1). The subscripts "o" indicate that the set of the four values represents the same starting conditions for all the cells of the entire area.
The method is based on an iterative procedure starting from the first step values and from the four deviations computed by means of eqs (1) to (4), defined as:

$$D_1 = Q_\mathrm{c} + H_\mathrm{c} - Rn_\mathrm{c} + Qa_\mathrm{c} \tag{5}$$

$$D_2 = Q_\mathrm{g} + H_\mathrm{g} + \lambda E_\mathrm{g} - Rn_\mathrm{g} - Qa_\mathrm{g} \tag{6}$$

$$D_3 = H_\mathrm{a} - H_\mathrm{g} - H_\mathrm{c} \tag{7}$$

$$D_4 = \lambda E_\mathrm{a} - \lambda E_\mathrm{g} \tag{8}$$

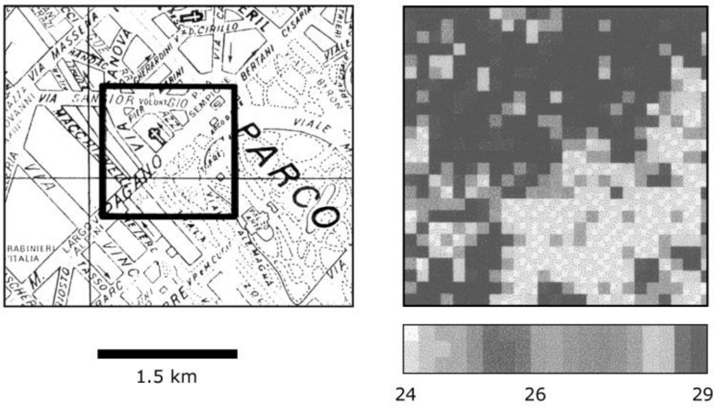
The resulting quadratic deviation is given by

$$D = \{D_1^2 + D_2^2 + D_3^2 + D_4^2\}^{½} \tag{9}$$

The iterative procedure consists of the following steps: D is minimized on each cell, by increasing or decreasing the first step values. At every step a new value of D is determined and the increasing/decreasing process will continue till the minimum value of D becomes quasi-stationary. The four values obtained for T_0 , T_1 , T_c and q_1 are the best fitting temperatures and humidity values obeying the balance law in the given meteorological conditions, and with the givens physical properties of the cell surface.

3.3 Output

Application of the UCLM method provides a map for each of the four variables obtained by the computing procedure by means of some isocontouring techniques. In [4], due to the high number of cells of side 30 m, a limited area was selected (fig. 5), at the centre of Milan, in which both blocks of buildings and a green surface (Parco Sempione) are present. The same situation (1996, August 28th, h 21:00) was considered also for the entire area, by means of cells of side 1500 m (fig. 6) to reduce the computational weight. The temperature distributions in the two cases are obviously quite different, mainly because of the different average values of the parameters on cells of different size.



(a) (b)

Figure 5: City of Milan, heat island at h 21:00 on 1998, August 28th. Square area (1,5x1,5 m²) covering a part of Parco Sempione (a), temperture field in Celsius degrees (b) with cells of side 30 m.

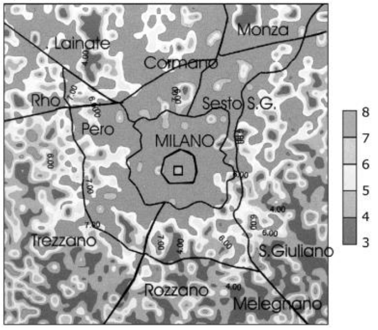


Figure 6: Urban area of Milan (30x30 km²). 1998, August 28th, cells of 1500 m sides. Temperatures at h 21:00 as deviations from the lowest value registered in the area during the day. The smaller square area at the centre represents approximatively the area considered in fig. 5a.

While in fig. 6 the centre of Milan has the warmest temperatures and the field representation is quite uniform, in fig. 5 the discontinuity between built area and Parco Sempione is rather evident, with differences of temperature of about 4° C. This is due to the use of a mesh having 30 m steps instead of the very larger one used for the entire area.

4 Improving the model performance

4.1 Parallelization of the code

The results obtained in [4] were quite satisfactory, since the output temperature field was locally in a good agreement with the values of temperature recorded at 10 meteorological stations in the urban area of Milan. As a major limit, the simulation requested that the field be discretized by a 1500 m sided mesh, so that the recorded temperatures had to be compared with interpolated data.

The desire of using a larger number of cells (10^6) covering the chosen area without increasing the computational effort excessively suggested a significant improvement of the model, obtained through the parallelization of the code. The simulation of the heat island can be more detailed, so that each single temperature recorded at the meteorological stations can be compared with the output of the model for a particular cell.

4.2 Output elaboration and results

The model has been applied in several situations, all of them characterized by conditions of atmospheric stability. The output, e.g. for the temperature, one value for each cell, has been elaborated using ENVI, the same software used to analyse the Landsat images. In such a way, for each situation, a set of temperatures at the centre of the cells has been computed and compared with the temperatures observed. In table 3 the air temperatures obtained for 4 days (2002, May 29th to June 1st), at the indicated times are shown.

Table 3: Urban area of Milan - 2002, May 31st to June 1st. Temperature values (Celsius degrees) obtained for the four days and the UTC (universal time co-ordinate) indicated (0, 6, 12 and 18). The values refer to the different kind of land cover just previously defined (table 1).

Cover classes	**29 May 2002**				**30 May 2002**				**31 May 2002**				**1 June 2002**			
	0	**6**	**12**	**18**	**0**	**6**	**12**	**18**	**0**	**6**	**12**	**18**	**0**	**6**	**12**	**18**
1	18.1	16.9	20.6	26.1	18.5	17.8	26.8	27.7	22.0	19.0	27.0	29.7	23.0	19.8	28.2	28.6
2	19.2	16.7	21.4	25.5	18.5	18.1	26.4	26.7	21.6	18.9	26.3	27.9	23.0	19.7	27.8	27.8
3	17.7	16.4	20.2	25.2	18.3	17.5	26.1	26.7	21.5	18.8	26.4	28.1	22.7	19.5	27.6	28.2
4	16.3	13.9	21.6	22.1	17.6	15.6	21.0	24.0	20.2	17.9	21.9	24.6	20.3	18.7	23.9	25.5
5	16.1	14.1	21.6	22.2	17.6	15.6	21.3	24.0	20.4	17.9	22.2	24.7	20.4	17.7	24.5	25.5
6	16.2	14.3	21.7	22.5	17.8	15.7	21.1	24.2	20.5	17.9	22.3	24.8	20.5	17.8	24.2	25.7
7	16.2	14.3	21.7	22.5	17.8	15.7	21.4	24.2	20.5	17.9	22.2	24.8	20.6	18.4	24.4	25.6

All the computed values are in a good agreement with the recorded ones at the ten meteorological stations. For example, in table 4 the ten couples of values are compared for 2002, June 1st, at 12 UTC.

Table 4: Urban area of Milan - 2002, June 1st, 18 UTC. Air temperatures computed and measured at the ten stations located over the area.

Station	Location	Computed T (°C)	Measured T (°C)
Marche	N centre of Milan	28.2	28.3
Juvara	E centre of Milan	28.6	28.4
Zavattari	W centre of Milan	28.2	28.0
Brera	Centre of Milan	28.6	28.5
Duomo	Centre of Milan	28.6	28.5
Rho	NW hinterland	27.8	27.4
Agrate	NE hinterland	25.7	25.8
Cassano	E hinterland	25.5	25.6
Tavazzano	SE hinterland	25.6	25.7
Corsico	S hinterland	25.5	25.4

For each situation the computed temperature field can be represented graphically by means of a gray scale. In fig. 7 for instance it can be seen that, because of the heat island, the city center at sunset is about 3 degrees warmer than the southern suburbs. Furthermore, with the accuracy due to the fine mesh (UCLM has 30 m of horizontal resolution), the Parco Sempione is again well represented by a little dark spot.

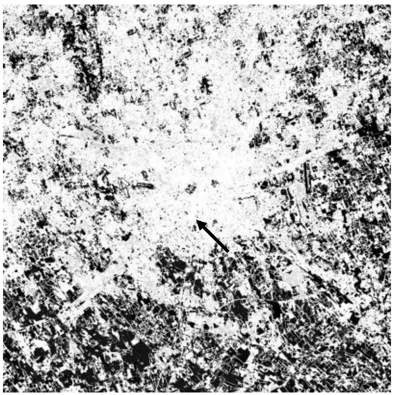


Figure 7: Urban area of Milan - 2002, June 1st, 18 UTC (7 PM local solar time). Air temperature field is presented in a gray scale (colder pixels are the darker ones). The arrow indicates the gray spot related to the green area of the Parco Sempione.

5 Conclusion

According to the simulation results and to their comparison with meteorological data from monitoring stations in Milan, the model UCLM can be considered a useful tool for micrometeorological studies in very complex and heterogeneous urban areas. More generally, an integration of remote sensing techniques, meteorological measurements and modelling turns out to be a valuable method for heat island analysis in different urban settings. The improvement of results was obtained mainly by means of the new parallel computing technique. Thanks to the reduced computational effort for the single cell, experimentation of model UCLM shows that such a diagnostic method can be applied both to observed and forecast meteorological data sets.

Therefore the evolution of the urban heat island can be studied even 48 hours in advance and this is the typical range of the LAM (limited area models), recently chosen since capable of providing predicted meteorological fields in the boundary layer with time intervals of 3-6 hours and horizontal resolution very close to 5 Km.

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