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IMPLEMENTATION OF ENERGY FLUXES IN EULAG WITH A NEW 3D SHADOW MODEL

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Abstract: The last generation of the mesoscale meteorological model try to incorporate urban characteristics, like as Urban Canopy Model (UCM) as a module added to the mesoscale meteorological model WRF (Weather & Research Forecasting system) (NCAR and others). The UCM approach is a good initial and ideal approach to develop micro urban meteorological simulations over urban domains. However, the real urban structures are not simply geometric shapes and have no uniformity. Micro urban simulations require high detailed information. In order to take into the count the building morphology. we have used a Computational Fluid Dynamics (CFD) model named EULAG.

The CFD model will be used in combination with a mesoscale meteorological model, WRF, to provide boundary and initial conditions. EULAG model do not include the fluxes calculation. We have included the energy fluxes calculation into the system for urban and natural cells.

The net radiation play an important role in the energy balance equation and it is affected by the shadows, reflections and reemission by the walls of the buildings. A new three-dimensional urban solar radiation model (SHAMO) which has been developed by the authors of the present contribution. It has been developed to calculate short wave radiation over urban high resolution grids. Sky view factor and reflections are calculated using a three-dimensional ray tracking method. Some details about the speed-up of the algorithm will be presented in this paper. Direct and diffuse radiation partition is made taking into account the solar zenith angle and the sky conditions (cloudless conditions or cover conditions).

We present results of the simulation obtained by using the EULAG-UCM model, with the new 3D shadow model. The radiation model is coupled with the heat transfer equations from UCM, which use the resistance network approach. The data produced by the urban solar radiation model has been used in large scale numerical experiments to simulate turbulent fluxes for urban areas; in this contribution over Madrid (Spain) city. We have applied a modified version of the EULAG (UCAR) micro scale model (CFD) which includes an energy balance equation to obtain the urban atmosphere/biosphere energy exchange. Results of the micro scale simulations and sensitivity analysis related to the solar radiation approach will be presented in this paper.

Key words: Urban energy fluxes, shadow model, urban solar radiation, 3d buildings, sky view, reflections

INTRODUCTION

The urban energy exchange is a fundamental issue for urban scale meteorological simulations. It is necessary to calculate the transfer of the energy and momentum between the urban surface and the atmosphere with more realistic urban geometry. Urban energy fluxes can be obtained applying the surface energy balance equation. One term of the energy balance equation is the net radiation, which depends of the short wave radiation.

In urban scale meteorological simulations, the short wave radiation plays an important role. The models to calculate the solar radiation over urban environments have to take into account the shadows and reflections. . In some cases the net radiation between buildings could be substantially higher than that received in the roof surface, demonstrating that the radiation is trapped inside of the canyons. These effects can be simulated with a simplified geometry of the buildings, this approach is included in the Urban Canopy Model (UCM) , National Centre for Atmospheric Research (NCAR, US) (Kusaka H. et al, 2001) The simplified urban geometry consists of a two-dimensional approach with symmetrical street canyons with infinite length. It was included as a module into the mesoscale meteorological model Weather & Research Forecasting system (WRF) developed by NCAR and others. (Michalakes, J., S. et al, 2001).

The UCM approach is a good initial and ideal approach to develop micro urban meteorological simulations over urban domains. However, the real urban structures are not simply geometric shapes and have no uniformity. Micro urban simulations require high detailed information about spatial and temporal distribution of short wave radiation taking into account the three-dimensional building morphology of the city and the change of solar positions, as well as the effects of multiple reflections and shading in an urban canopy.

In order to include the building morphology in the urban environment with a very high spatial resolution in the WRF-UCM structure, we have used a new model specifically devoted for Computational Fluid Dynamics (CFD) applications named EULAG (UCAR, US) (Smolarkiewicz, P. K., and L. G. Margolin, 1997). The computational effort needed to simulate 3D building morphology with a few meters spatial resolution by using WRF-UCM is prohibited. So, the boundary information is produced by WRF-UCM with high spatial resolution (200 m) and sent to EULAG simulation (after including our flux balance and SHAMO model) to produce detailed (4 m spatial resolution) surface flux maps.

CFD model is a numerical model that solves the Navier-Stokes equations at high resolution (meters) and explicitly resolves the buildings. The ability of CFD models to reproduce microescale airflow behaviour in urban areas has been tested extensively in the last years..

The urban land surface models UCM and the Unify Noah Land-Surface Model (NOAH) (Chen, F. and J.Dudhia, 2001) have been coupled with the CFD model EULAG. EULAG allows including a 3D GIS structure to estimate the wind and temperature in a 3D grid with a very high resolution. EULAG model does not include the flux calculation, so, it is necessary to include the energy fluxes into the system in order to have surface patterns of sensible, ground and latent heat fluxes with high spatial resolution in an urban environment, so we have developed this section. When the grid cell has a non-urban land-use type (natural), the NOAH land-surface model approach is applied into EULAG and in case of an urban grid cell, the UCM scheme is used to calculate the fluxes. The fluxes implemented into EULAG are capable to produce information related to urban microclimate, heat island effects, air conditioning system design analysis and low energy building designs.

IMPLEMENTATION OF ENERGY FLUXES

In this section, we explain how the fluxes are integrated into the EULAG CFD model. Meteorological, radiation information and surface exchange coefficient are provided by the mesoescale model WRF. The urban/natural surface scheme (NOAH/UCM) is applied over high resolution grid cells using detailed data of winds and temperature from EULAG.

New skin temperature is estimated applying the Similarity Theory and the Energy balance equation:

$$Rn - H - L - G = 0 \tag{1}$$

where, Rn is the net radiation which includes the short and long wave; H is the sensible heat flux; L is the latent heat flux and G is the ground heat flux.

$$H = \rho\ c_p\ k \frac{u_*}{\psi_h}(\Omega - \Omega_0) \tag{2}$$

where

Ω = Air temperature Ω_0 = Air temperature at roughness length height. ρ = Air density

c_p = Heat capacity of dry air k = 0.4 (von Karman constant) ψ_h = Heat integrated universal function

u_* = friction velocity

From Similarity we obtain u_* and ψ_h using two levels, $Z_{wrf} - Z_{eulag}$. The latent heat flux is calculated as:

$$L = \rho\ E1\ k \frac{u_*}{\psi_h}(q - q_0) \tag{3}$$

where

$\rho =$ air density $q_0 =$ WRF surface specific humidity (at roughness length).

$El =$ heat capacity of vaporation.

$q = 0.622 * ES(PS$(saturation pressure)-0.378*ES(saturation vapor pressure)).

Ground heat flux:

$$G = \text{Thermal conductivity}*\left(\frac{\Omega(surface) - \Omega(layer\ 1)}{(depth/2)}\right) \tag{4}$$

Radiation budget:

$$Rn = (1-\alpha)short\_wave\_radiation + \text{emissivity}*long\_wave\_radiation\ - \sigma\Omega^4 \tag{5}$$

Short wave and long wave radiation is affected by the shadows and reflections

The NOAH land-surface model uses a latent heat flux partition into three different fluxes: canopy water, direct soil and total plant evaporation. The NOAH model calculates the ground heat flux with the thermal diffusivity, the sensible heat flux (SH) using the following approach:

$$SH = \frac{CH*CP*SFCPRS}{R*T2V}*(TH2 - T) \tag{6}$$

Where CH (m s-1) is the surface exchange coefficient (coming from the surface scheme); SFCPRS is the surface pressure; T2V is the virtual temperature (coming from the EULAG model); TH2 is the potential temperature (coming from the EULAG model) and CP and R are constants. The latent heat flux is divided into EC (canopy water evaporation), EDIR (direct soil evaporation) and ETT (total plant evaporation. These values are calculated through the Penman method. Finally, the change in soil moisture content is calculated through the precipitation, runoff and evaporation (the infiltration is calculated as precipitation minus runoff).

SHAMO SHADOW MODEL

A new 3D urban solar radiation model has been developed by the authors, the final solar radiation has been calculated as:

$$FSR_{i,m} = \sum FSR_{k,m-1} * ALB * FREFLECTION \tag{7}$$

where, FSRi,m is the final solar radiation in the grid cell i, after m reflections; FSRk,m-1 is the final solar radiation in the grid cell j after m-1 reflections; the ALB is the surface albedo and finally, FREFLECTION is the reflection factor. If m=0 the initial solar radiation is ISR (No reflections yet). The variables to be calculated to have a full description of the total short wave solar radiation in every grid cell are: sun location (x, y, z), shadows, sky view factor, direct & diffuse solar radiation, reflections and finally total solar radiation in every grid cell. The process continue by an iterative process until FSR < 1% ISR. The ISR is calculated as:

$$ISR = FSHADOW * DIRSR + FSKY * DIFSR \tag{8}$$

where, FSHADOW is the building shadow effect. The FSHADOW=1 in case the grid cell is receiving full solar radiation and the SHADOW=0 in case the grid cell is full in a shadow; DIRSR is the direct solar radiation (W/m2), DIFSR is the diffuse solar radiation (W/m2) and FSKY is the sky view factor (0-1). From every grid cell, a straight line between sun and the grid cell is traced. From the grid cell, we follow the straight line and if a building is found, the FSHADOW is set to 0, If not, FSHADOW is set to 1. The sun position is calculated by using the declination angle (d), the zenith angle (z) and the hour angle (w) and the celestial coordinate system is applied by using the solar altitude angle (α) (90º -z) and the solar azimuth angle (y) in a way that:

$$\cos y = \frac{\sin(\alpha)\sin(w) - \sin(d)}{\cos(\alpha)\cos(w)} \tag{9}$$

The Cartesian coordinates for the sun's position are calculated as:

$$x = r\ \cos(\alpha)\ \sin(y) \qquad y = r\ \cos(\alpha)\ \cos(y) \qquad z = r\ \sin(\alpha) \tag{10}$$

In Figure 31, we show an example of the Madrid shadows in 1 km x 1 km domain (our experiment) with 4 m spatial resolution on June, 28, 2008, 07:00 GMT (left) and 18:00 GMT (right) using our SHAMO shadow module. White areas are buildings, purple areas are shadow and brown are sun areas. The results are agreed with the sun movement.

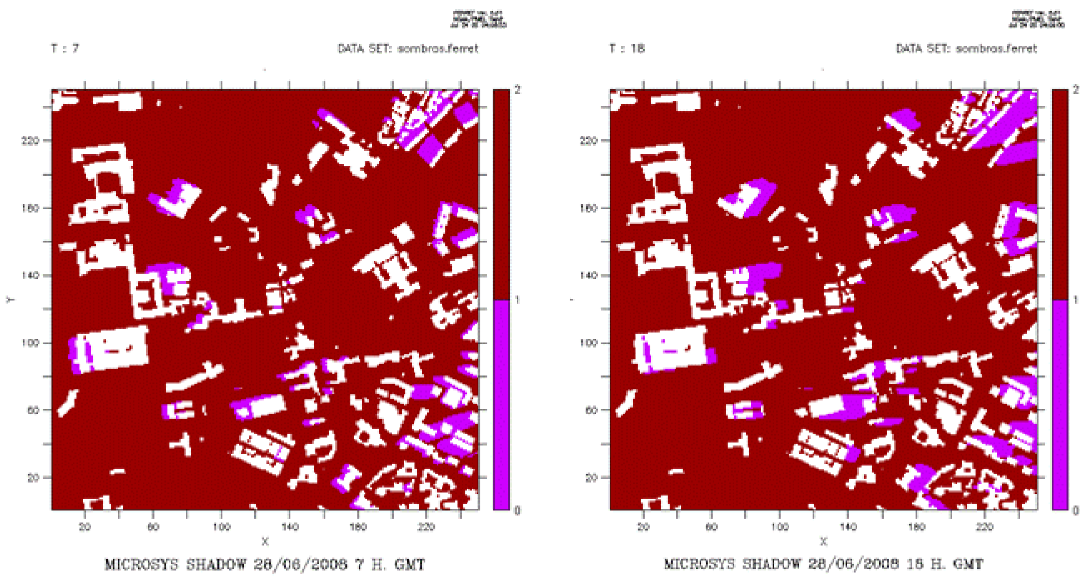

Figure 31: Shadow module (SHAMO MODEL) results on June, 28, 2008 over a domain of 1 km x 1 km with 4 m spatial resolution. Left 7H and right 17H. White areas are buildings. (0 = Shadow and 1 = Sun).

The FSKY & FREFLECTION variables are calculated as follows: a) 3D tracking method b) casting rays from a hemisphere located on the centre of each grid cell c) final point of each ray is located as:

$$X = k\ \cos(\sigma)\ \ Y = k\ \sin(\sigma)\ \ Z = (r^2 - k^2)^{\frac{1}{2}} \tag{11}$$

σ: Ray direction angle [0,180º] k : Ray Height [0,r].

d) counting the number of rays that collide with the building grid cells e) the minimum number of rays is 35000 in a 1 km x 1 km experiment domain, f) the fraction of rays that collide with the building grid cells is the reflection factor (FREFLECTION), g) (1-FREFLECTION) rays are not reflected. This is the sky view factor (FSKY), h) We designed a full parallel approach due to the high computing demand. The computer time with 1 CPU and 34752 rays is 95 minutes; with 50 CPU's and 34752 rays, the CPU time is 2.40 minutes and finally for 50 CPU's and 135014 rays, the CPU time is 6.50 minutes.

The global total radiation is calculated as the direct plus the diffuse solar radiation. The diffuse solar radiation is calculated as the global radiation obtained from the WRF/UCM model multiplied by the turbidity factor. It is defined as the relation between extraterrestrial solar radiation and the incoming solar radiation over the horizontal plane. The turbidity factor is calculated as follows:

$$TF = MIN(1, 1/A) \qquad A = MAX(0.1, B) \qquad B = 2.1 - 2.8 * LOG(LOG(SOLTOP/GLOBAL)) \tag{12}$$

$$SOLTOP = 1370 * DAYFACTOR * \cos(zenith) \tag{13}$$

The ratio DIRECT/DIFFUSE solar radiation depends on the solar zenith angle and the sky conditions (cloudiness). Under high cloudiness conditions and small solar angles the ratio is close to 0.5 and with large solar angles, the ratio is close to 0.2.

RESULTS AND DISCUSSION

A sensitivity study has been developed to try to assess the differences in model outputs about energy fluxes (surface results) by a simple shadow model (UCM SHADOW MODEL) and the new 3d shadow model (SHAMO) implemented. The EULAG domain is limited to 1 km x 1 km with 100 m in height. Our objective is to have a 4 m surface resolution simulation. The vertical resolution is also fixed to 4 m. The EULAG model estimates the wind and temperature at 2 m in height (4 m cubes).

We will show the results to two significant hours of the day June 28, 2008, at 7:00 (sunrise), and 18:00 (sunset),.The differences on sensible heat flux, Figure 32, and on ground heat flux, Figure 33 , between the detailed 3D shadow model and the simple shadow model (MICROSHADOW – CANYONSHADOW). The differences on sensible heat flux and ground heat flux are very important for both models,

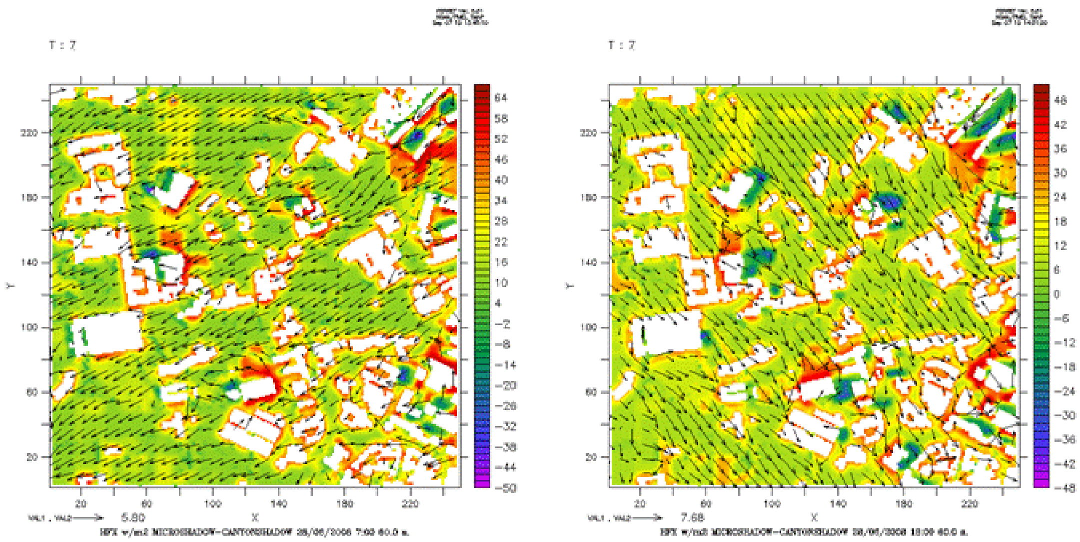

Figure 32: Differences between the sensible heat flux (W/m2) obtained by the detailed shadow model (MICROSYS SHADOW) (SHAMO) and the simple shadow model (CANYONSHADOW) (UCM) on June, 28, 2010 at 07h00 GMT (left) and 18h00 GMT (right) after 60 s simulation time of EULAG model.

The results show important differences between different grid cells in the experiment model domain. The Northwest area of the domain has a building density lower than the Southeast area of the model domain, so that when running our shadow models the results show higher differences in the latter area

After the results analysis, we can conclude that the positive differences are predominant for the sensible heat flux analysis. These are located around the buildings. At 7:00 AM the differences can be seen in the eastern part of the buildings and at 18:00 on the west part., which is consistent with the actual sun movement. The maximum differences reach values up to 60 W/m2, this is because some areas are being considered as shadow places by the simple shadow model, with values around -20 W/m2. But the new 3d shadow model implemented considers that some rays of sun are coming at this area, with sensible heat flux values of about 40 W/m2.

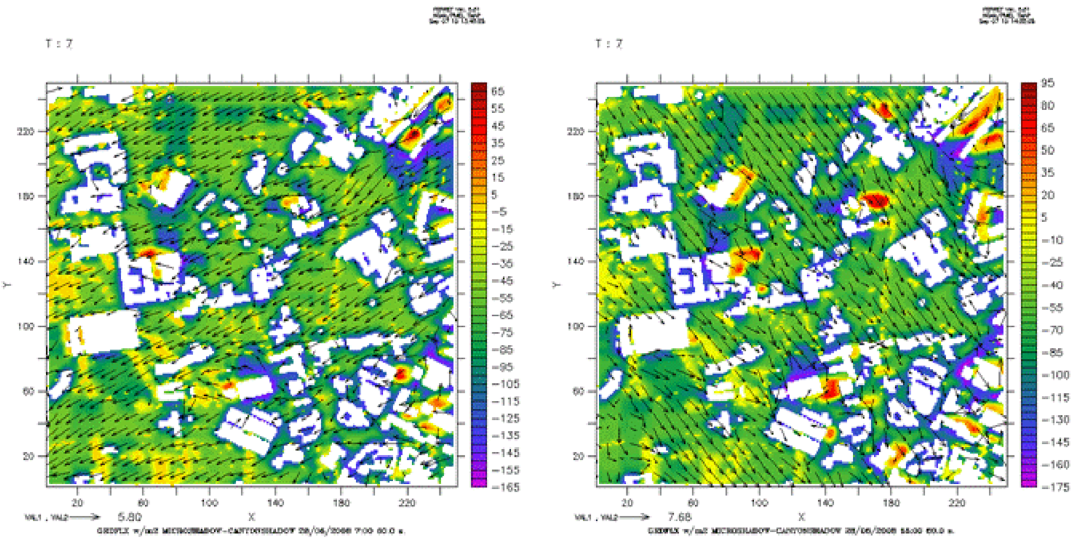

Figure 33: : Differences between the groud heat flux(W/m2) obtained by the detailed shadow model (MICROSYS SHADOW) (SHAMO) and the simple shadow model (CANYONSHADOW) (UCM) on June, 28, 2010 at 07h00 GMT (left) and 18h00 GMT (right) after 60 s simulation time of EULAG model.

The ground heat flux differences follow the same procedure for the sensible heat flux, taking into account the sign convention changes. Positive ground heat flux means that the heat is moving from the ground into the subsoil. The differences are larger than in the case of the sensible heat flux differences because ground heat flux is more sensible to the solar radiation finally reaching each grid cell, which depends on the calculated shadow degree by the shadow model.

The simple shadow model uses street canyons to calculate shadows. If you apply this methodology over an urban area where there is not a clear canyon street, it introduces an uncertainty in the fluxes model, which can be solved by using the new 3D micro- shadow model implemented.

We have implemented the turbulent energy fluxes (sensible, latent and ground) into the EULAG code. We have developed a detailed shadow model to take into account the different reflections of the short wave solar radiation over the buildings in a typical urban environment. The approaches have been developed for a high resolution runs of EULAG in an urban environment (in our experiment with 4 m spatial resolution grid cells).

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