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The Impact of Geometrical Effects on Calculated Value of Albedo on the Heterogeneous Environmental Interfaces

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Abstract: The albedo of the interface is an important parameter for the calculation of the radiation fluxes in environmental studies. The problem arises when the surface is a heterogenous one. There have been developed various manners to calculate the aggregated albedo. Our previous research has indicated, however, existence of a geometrical effect related to the fact that different parts of the interface may have different heights. In these studies we have offered the general approach to the calculation of the flux that is lost due to the absorption on the vertical lateral boundaries. We derived analytically the expressions for this loss coefficient which for some ideal urban geometries coincides with Oke's sky-view factor. The aim of this paper is to elaborate the effect for more complex geometry. The number of geometries allowing easy analytic solutions is rather restricted, so it was necessary to develop an efficient numerical procedure. In this paper we expose so called ray-trace MC approach, then we use it to test the known analytical solutions and combine it with a parameterisation scheme (LAPS). An example of central geometry is considered in this study. It is assumed that the region consists of two-patch grid-cell with a square geometrical distribution and different heights of its parts. Simulations were done for several patch areas, with different horizontal dimensions and heights ("propagating building") as well as for different surface types. The multiple scattering effect and the dependence of the albedo on the zenithal angle of the incident radiation were neglected. The derived expression for the albedo is compared with the conventional approach. Changes in albedo lead to a significant change in partitioning of the energy at environmental interface. The most remarkable changes are in values of sensible and latent heat fluxes, and surface temperature. Their values are calculated using LAPS parameterisation scheme and then compared to the values obtained with a conventional parameterisation of the albedo.

Keywords: Albedo; Environmental interface; Parameter aggregation; Urban modelling.

1. INTRODUCTION

Surface albedo is a fundamentally important meteorological parameter. Through its influence on the energy balance of the Earth, and thus indirectly on many other factors (fluxes of momentum, energy, carbon-dioxide, moisture etc.), albedo became a key variable in the parameterization of the land-surface radiative transfer over the grid cell in numerical modelling.

Nowadays, one of the basic tasks in order to obtain more precise parameterization of physical processes is determination of albedo over heterogeneous areas. There have been developed various manners to calculate the aggregated albedo [Dickinson, 1983, Delage et al., 1999, Mihailovic et al., 2001]. The most common approach usually used is a simple arithmetical averaging to determine the albedo as the grid cell-average albedo. According to physics based analysis, a significant deviation of the albedo is observed from that calculated by simple averaging.

In our previous work shown in Kapor et al. [2002] and Mihailovic et al. [2004] we have proposed a new method for aggregating the albedo over a very heterogeneous surface in land surface schemes for use in environmental models. The basic assumption of our research is that geometrical factor plays an important role in albedo calculation. We have demonstrated that even the same material at different heights might produce interesting effects.

After a brief description of our previous work, in this paper we will present a simulation aimed to illustrate our further work, concentrated on elaboration of this effect using more complex geometries.

2. SHORT REVIEW OF PHYSICAL BASIS OF AGGREGATION

2. 1 Introduction (basic assumptions)

In our aforementioned studies we have proposed a new approach for aggregating the albedo over a very heterogeneous surface. For the simplicity we analysed two-patch grid-cell with a simple geometrical distribution and different heights of its components. We supposed that the basic constituent of the albedo, coming from the grid-cell, describes the diffuse, homogeneous single scattering of incoming radiation from a given surface. The multiple scattering effect and the dependence of the albedo on the zenithal angle of the incident radiation were also neglected.

Our main idea was relied upon the fact that a part of radiation reflected from the lower surface is completely absorbed by the lateral sides of the surface lying on a higher level. We introduced a “loss coefficient”, flux that is completely lost due to the absorption on the vertical lateral boundaries. Its definition is conceptually analogous with Oke’s sky-view factor [Oke, 1987], especially for some ideal urban geometries. The derived expression for the albedo of the particularly designed grid-cell is compared with the conventional approach, using a common parameterization of albedo over the same grid-cell as used by Delage et al. [1999].

2.2 Analytical treatment

The average albedo over the grid-cell divided into two subregions with different albedos, according to conventional approach is given as

$$\overline{\alpha}_c = \alpha_1\sigma_1 + \alpha_2\sigma_2 \tag{1}$$

while our analytic treatment for calculating the average albedo over this grid is

$$\overline{\alpha}_n = (1-k)\alpha_1\sigma_1 + \alpha_2\sigma_2 \tag{2}$$

α_i is corresponding albedo of particular patch. σ_i is fractional cover, calculated as a ratio of patch’s area S_i and total grid cell area $S\left(\sigma_i = S_i / S, i = 1,2\right)$. k is before mentioned loss coefficient, which can be derived from the following relation

$$k = \frac{\left(\dfrac{dE}{dt}\right)_l}{\left(\dfrac{dE}{dt}\right)_h} \tag{3}$$

The denominator shows the amount of flux emitted from the lower surface into the upper space, while the numerator is a part of total energy coming from lower horizontal surface towards lateral surface. The expression to calculate the radiant energy flux dE/dt was taken following Liou [2002].

The amount of emitted flux reaching the vertical lateral boundary is defined as a sum of all infinitesimal amounts of radiant flux emitted from the infinitesimal surface element $dxdy$ (centred around the point with position vector $\vec{r}$) confined in the solid angle $d\Omega$ under which the element $dxdy$ „sees“ the lateral surface, shown shaded in Figures 1 and 2. Since the flux of radiation that reaches the vertical boundary surface is completely lost, according to our basic assumptions, the contribution of the radiation reflected from the lateral surface is not taken into account of the total reflected flux of radiation.

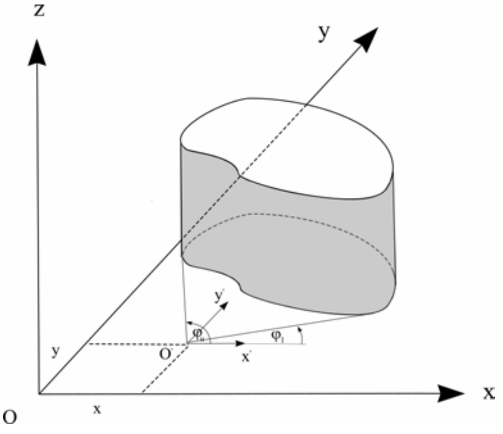

Figure 1. Definition of the boundaries for the integration over the local azimuthal angle

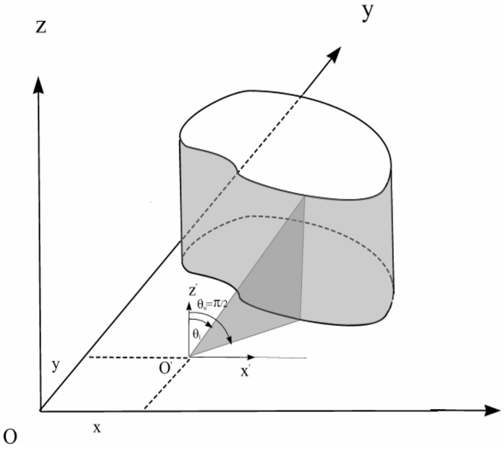

Figure 2. Definition of the boundaries for the integration over the local zenithal angle

The boundaries of the integration for a given point are determined over the azimuthal (φ_l, φ_u) and zenithal (θ_l, θ_u) angles in terms of the x, y coordinates, as it is shown in Figures 1 and 2. The subscripts l and u denote lower and upper boundary, respectively. Accordingly, the equation that calculates a part of total energy coming from lower horizontal surface towards lateral surface is given in the following form

$$\left(\frac{dE}{dt}\right)_l = I \iint\limits_S dxdy \int_{\varphi_l(\vec{r})}^{\varphi_u(\vec{r})} d\varphi \int_{\theta_l(\vec{r},\varphi)}^{\theta_u(\vec{r},\varphi)} \cos\theta \sin\theta d\theta \tag{4}$$

I is the total intensity of radiation obtained from the monochromatic intensity by integrating it in the range of the whole spectrum. $\cos\theta$ describes the direction of the radiation stream, while $\sin\theta d\theta d\varphi$ is the element of solid angle within which our differential amount of energy is confined to. The amount of flux emitted from the lower horizontal surface into the upper space is calculated as $(dE/dt)_h = IS_l\pi$. The loss coefficient k we need for calculating the average albedo can be evaluated combining Equations (3) and (4).

2.3 Numerical approach

Beside analytical treatment, we expose a version of Monte Carlo approach. Since the number of simple geometries which allow easy analytic solutions is rather restricted, it was necessary to develop an efficient numerical procedure for calculating the loss coefficient. We made a direct system simulation using a well known „ray tracing“ MC method.

The essence of MC „ray tracing“ method is to retrace a ray destiny. The light transport equation is solved using MC methods to simulate the propagation of light in a scenery. Monte Carlo simulation is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. By using random inputs, the deterministic model is turned into a stochastic one. Result is obtained in the limits of large number of numerical experiments.

As we mentioned, the main idea is to follow the appropriately chosen ray of light, after it had undergone diffuse, homogeneous single scattering from the lower surface of the grid-cell. Averaging the observed behaviour over a large number of followed light paths, we determine the value of "loss-coefficient" k within a given grid-cell geometry.

More precisely, we guide our numerical experiment as follows. We generate first two random numbers r_1 and r_2 uniformly distributed in the interval (0,1) in order to randomly sample the point $A(x, y)$ which belongs to the lower surface and represents a point of intercept of this surface and the incoming beam. Then we choose a random direction in upper half-space (θ, φ) [with $\theta \in (0, \pi/2)$; $\varphi \in (0, 2\pi)$] to simulate trace of scattered beam. The case was positive for absorption if diffusively scattered beam would reach the vertical boundary. This procedure was repeated $N = 10^6$ times and the "loss-coefficient" was estimated as

$$k = N_a / N \tag{5}$$

where N_a is number of cases which were positive for absorption and N is number of conducted numerical experiments.

The first test of the method was to reproduce the analytical results for the simplest geometry ("step-like"patch) Kapor et al. [2002], Mihailovic et al. [2004]. After successful reproduction for various parameters of the patches, we concluded that the MC ray-tracing method application is justified in this case.

3. NUMERICAL TEST

In this study we have considered an example of central geometry. For the simplicity, it is assumed that the region consists of two-patch grid-cell, a grid-cell of size L and „propagating building" with the edge l and height h, taking a different values, simulating the propagation of that area over the grid-cell. The basis of building is a square centred at the center of cell.

In our study the dimension of a grid-cell is $100 \times 100\,m$. The fractional cover of the central area is $\sigma = (l/L)^2$, while for the rest of the cell is $1 - (l/L)^2$. Calculations of albedo were done using reduced dimensionless quantities $\hat{l}$, defined as l/L ratio and $\hat{h}$, defined as h/L ratio. Depending on the variations of the reduced length $\hat{l}$, we have calculated values of average albedo according to both, conventional and our approach. These values were utilized then as average values of albedo in prognostic equation for evolution of the surface temperature over heterogeneous grid-cell. The mentioned prognostic equation is

$$C_g \frac{\partial T}{\partial t} = R_{net} - H - \lambda E - G \tag{6}$$

where T is surface temperature [K], t is time [T], C_g is effective heat capacity (heat capacity per unit area) [M/KT^2], R_{net} is net radiation [M/T^3], H is sensible heat flux [M/T^3], λE is latent heat flux[M/T^3], and G is soil heat flux [M/T^3]. (Here, standard meteorological terminology is used. Actually, using the correct terminology, all these are not fluxes, but flux densities). Net radiation, as a sum of incoming and outgoing radiation, could be determined through the following terms

$$R_{net} = (1 - \alpha) R_{short} + R_{long} \tag{7}$$

where R_{short} is a shortwave radiation [M/T^3] and R_{long} is a total longwave radiation [M/T^3]. The surface fluxes aggregation approach was applied to obtain the mean surface fluxes over heterogeneous grid-cell, while fluxes over particular area were obtained from

LAPS (Land Air Parameterization Scheme). This land surface scheme was designed to be run either as a standalone model or as the part of an atmospheric model, Mihailovic et al. [2001]. The analyzed period in our case was one day, with time step of 10 min.

Simulations were done for several patch areas, with different surface types. Accordingly, each of the subregions had different and corresponding albedos. Three situations were analyzed. In all of them, the central area was concrete or rocky land, having the same albedo value 0.30. The other patch of grid-cell, in these three simulations, was covered with grass, orchard and concrete, having albedo values 0.20, 0.15 and 0.30, respectively.

The albedo was calculated taking the following values of the reduced lengths 0.50, 0.70 and 0.870. We wanted to analyze daily temperature profile differences obtained by both approaches in a case of grid-cell covered with each type of surface with 25%, 50% or 75%. Altitude of a central patch was case sensible. In the grass-concrete situation, concrete was 2m high, while grass was 0.5m. Results are shown in Figure 3. In the case of orchard-concrete grid-cell, orchard is taken to be 2.5m high, while concrete 10m. The same height of a central area concrete is applied when both patches were concrete covered. Figures 4 and 5 show the obtained results, respectively.

As we can see from the exposed graphics, aggregated approach in every situation gives a higher daily maximum of surface temperature. The significant difference between temperature profiles obtained by aggregated and conventional approach is noticed in a case of orchard-concrete situation and especially in concrete-concrete case. Temperature depends on albedo value, which has the largest deviation when central area occupies 75% of the grid, since in that case the "loss-coefficient" has the largest value. Figure 6 shows how "loss-coefficient" varies with different values of reduced length and height. Although this geometry was not that simple, we made an analytical calculation, and as we can see in Figures 3-5, the Monte Carlo simulation reproduced the obtained results quite well, which gave a reliable base for further research in a case of more complicated geometry.

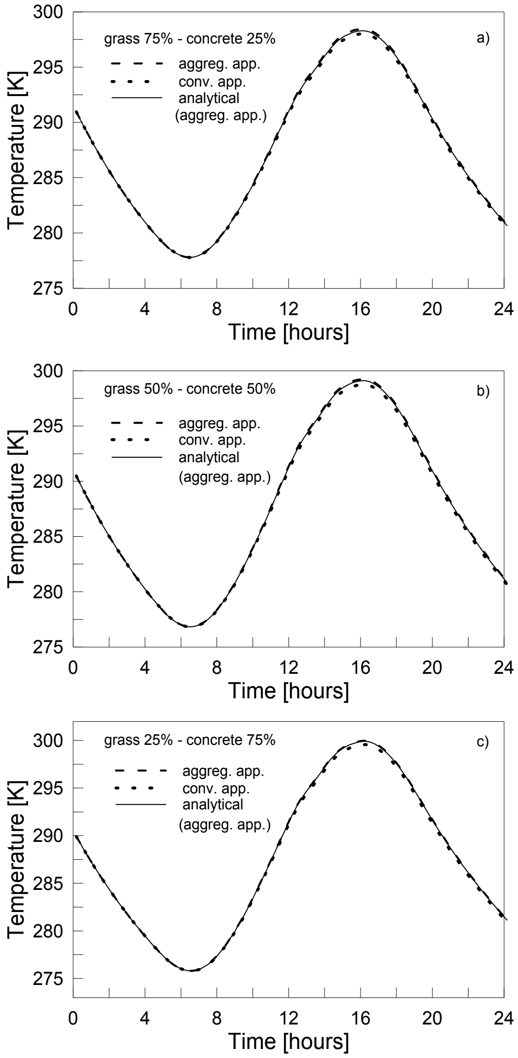

Figure 3. Daily profile of surface temperature in a case of grass-concrete covered grid-cell, with a) grass 75%, b) concrete 50%**,** c) concrete 75% using both approaches

In order to define more precisely the difference between temperature profiles obtained by aggregated and conventional approach, the root mean square error (RMSE) is found. From results depicted in Figure 7 we can see that maximum increase in the temperature and decrease in albedo is for 50-50 area coverage when both patch areas are covered with concrete. In orchard-concrete situation we also obtained a significant RMSE, especially for case when central area occupies 25% of cell.

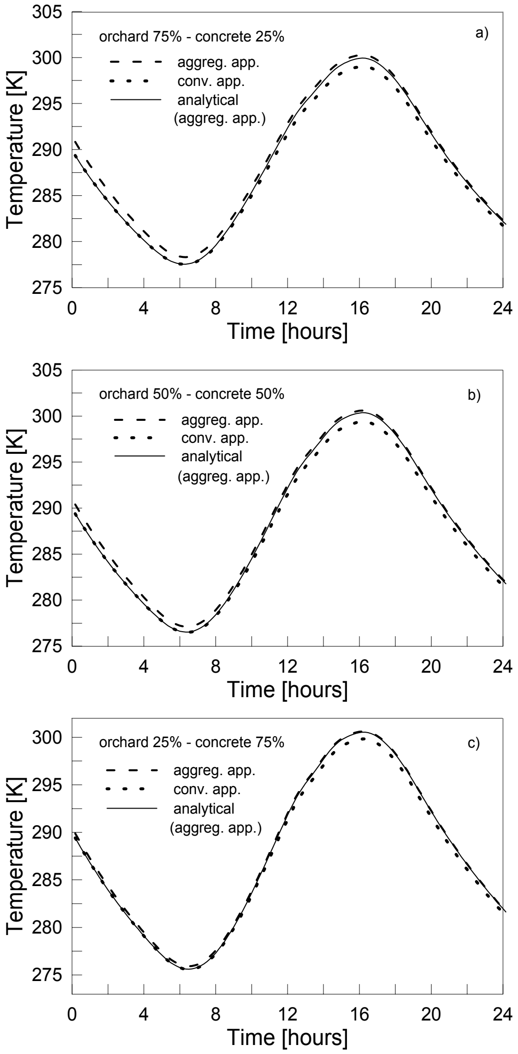

Figure 4. Daily profile of surface temperature in a case of orchard-concrete covered grid-cell, with a) orchard 75%, b) concrete 50%, c) concrete 75% using both approaches

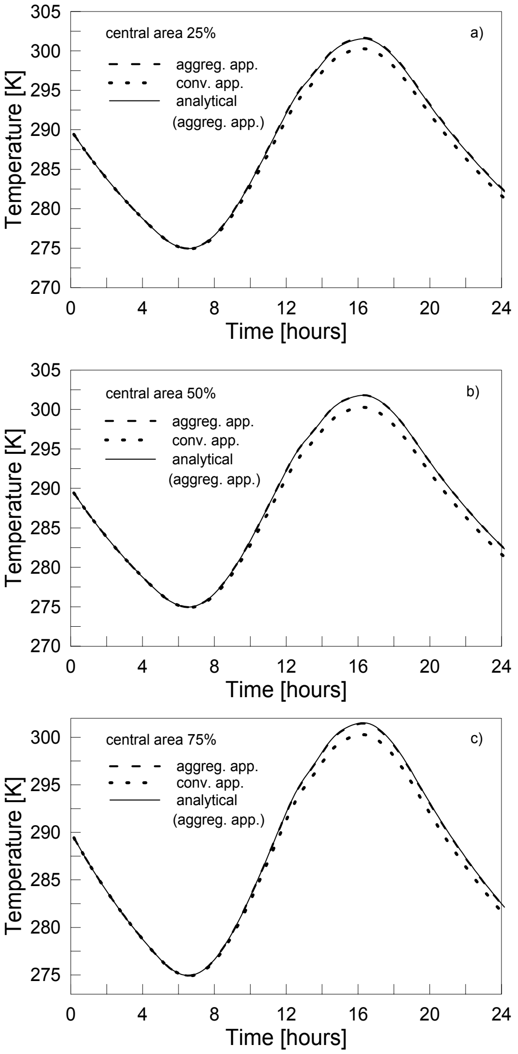

Figure 5. Daily profile of surface temperature in a case of concrete-concrete covered grid-cell, with a) central area 25%, b) central area 50%, c) central area 75% using both

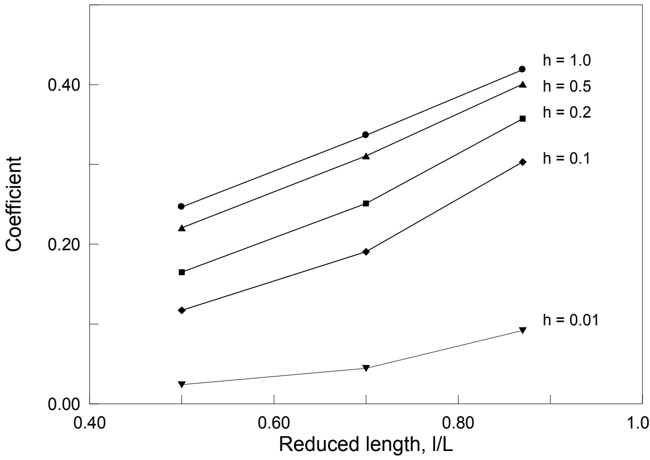

Figure 6. Dependence of "loss coefficient" on reduced length l/L and height h/L

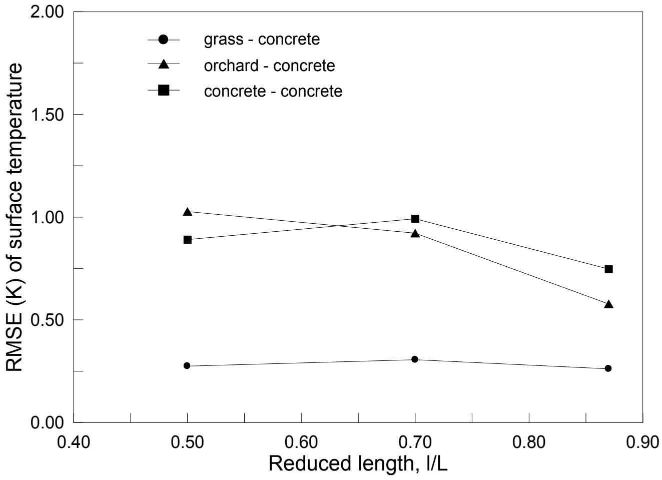

Figure 7. Dependence of RMSE of surface temperature on the reduced length l/L

4. CONCLUSIONS

The aim of this study was to show further achievements related to the new approach for the aggregation of albedo over the heterogeneous grid-cell. We have elaborated the effect for a central geometry for the most general case using only two patches distinguished by relative height of the central one. Simulations were done for different surface types, with different horizontal dimensions and heights.

After a short review of the general approach to the calculation of the flux that is lost due to the absorption on the vertical lateral boundaries, a theory was applied to a simple model of square patches. Because of a rather cumbersome analytical solution, we exposed an efficient numerical procedure, using Monte Carlo ray tracing method, for albedo calculations. Results were compared with the results of the conventional method, but also with the analytical ones, and were applied in a calculation of surface temperature over the heterogeneous area. Sensitivity tests were performed using land surface scheme LAPS to compute the fluxes needed for surface temperature calculations.

Some of the key findings we obtained through this study is that depending on the relative size of the patches and their heights, and especially depending on the surface type, the decrease of albedo can be significant. Accordingly, it also leads to differences (increase) in the surface temperature calculations. This indicates that geometrical effect plays an important role in albedo estimation. Our further work will be converted to a more complex and more demanding geometries.

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