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Numerical estimation of the effective albedo of an urban canyon

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With 12 Figures

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Summary

The paper focuses on the absorption of shortwave radiation in an urban street canyon. To test the effective albedo of the canyon an analytic solution of the multiple reflection problem is applied. The infinitesimally long canyon is divided into slices and a matrix of view factors for the slices is defined. Incoming shortwave radiation includes direct and diffuse parts and shadowing effects are included in the analysis. The model is validated against Aida's (1982) scale model data and measurements in a real canyon. The results demonstrate a rapid decrease of the effective albedo as the canyon aspect ratio (its height to width, H/W) are increased. It is also shown that diurnal changes of the effective albedo can be very complex depending on the particular combination of H/W ratio, surface reflectivity and canyon orientation.

1. Introduction

Absorption of shortwave radiation by the surface is an important factor determining the energy budget of any site. Excluding flat, unobstructed surfaces, radiation absorbed after infinite reflections between surfaces must be considered in addition to the incoming direct solar beam and diffused sky radiation. In some cases, e.g. a forest floor, deep canyons, caves, or ground floor rooms in a densely built-up area, the reflected radiation component becomes the most important light source. Information concerning the radiation flux incident after multiple reflections can be obtained from direct measurements, but in some situations numerical estimation schemes are needed. Unfortunately, for many sites, especially in the presence of vegetation, this is an extremely difficult task because of the complex radiation geometry involved. In such situations the energy absorbed after an infinite number of reflections is usually estimated with the aid of a photon-tracking method based on a Monte Carlo simulation approach.

Estimating the solar energy absorbed by a city is of fundamental importance in order to simulate the local climate alteration due to urban development. A convenient measure of a town's influence on the shortwave radiation balance is the mean albedo of the target area. The albedo of a town is usually lower than that of its surroundings not only because of the low albedo of building materials but also because of enhanced radiation absorption due to multiple reflections between urban structures (Oke, 1982). Herein the total albedo, including both effects, is called an "effective albedo" in contrast to the parameter that characterises a surface's reflectivity, which is called a "surface albedo". Valuable data of the albedo for real towns have been obtained from aircraft, satellite and high tower measurements (White et al., 1978; Brest, 1987; Offerle et al., 2003). An alternative approach is to numerically simulate this parameter. Because of complex town geometry, the great variety of urban structures must be reduced to a few conceptual forms suitable for generalized urban climate modelling. An effective method of town geometry generalization is offered by the concept of an urban canyon (Nunez and Oke, 1976). The idea of an infinite canyon allows one to reduce radiation trapping to a two-dimensional problem. One of the first attempts to model the interaction of solar radiation with urban structures comes from the work of Craig and Lowry (1973) and Terjung and Louie (1973), but their scheme considered only the first reflection. Other early works completely ignore all reflections (Noilhan, 1981). The recent work of Tsangrassoulis and Santamouris (2003) also considers only an initial reflection, but the influence of angular reflectance of the glass surfaces (windows) is analysed. Many numerical simulations of radiation processes in built-up environments have been presented by Arnfield (1976, 1982, 1989). In his approach successive reflection events are evaluated numerically until changes of the mean irradiance emerging from the canyon top drops below a specified amount between events. Similar iterative calculations of the radiation damping due to multiple reflections between urban structures are presented by Chimklai et al. (2004). Other work based on the Monte Carlo style of simulation allows one to calculate an effective canyon albedo after a large but finite number of reflection events (Aida and Gotoh, 1982; Kondo et al., 2001; Sailor and Fan, 2002). Some recent works solve the full geometric series to arrive at the radiation absorption in environments with complex geometry (Verseghy and Munro, 1989; Masson, 2000; Harman et al., 2004; Bozonnet et al., 2005). Such numerical models of radiation trapping by urban structures could not be easily validated until the work of Aida (1982), who used a scale model to investigate the influence of the urban surface geometry on the effective albedo. The experimental data of Aida have been used to validate several different numerical schemes (Aida and Gotoh, 1982; Sievers and Zdunkowski, 1985; Arnfield, 1989; Masson, 2000; Kondo et al., 2001). Recently, a similar experiment was conducted by Kanda et al. (2005) who also developed a numerical model of albedo for regular building arrays.

The work reported here focuses on the influence of urban canyon geometry on the effective albedo of the system. The study uses a method to calculate the radiation absorbed by a facet after an infinite number of reflections to and from other facets. The next section, shows that for a finite number of facets with prescribed view factors and incoming irradiances the problem can be reduced to the solution of the matrix equation. Then the method is applied to construct a model of the interactions of diffuse and direct solar radiation within an urban canyon. The accuracy of the model is verified using Aida's results and radiation fluxes measured in a real urban canyon. Finally, the influence of the canyon geometry on its reflectivity is studied with the aid of proposed model.

The model given here belongs to the group of models which solve the full geometric series to analyse radiation absorption in environments with complex geometry. The basic idea of the scheme is similar to the method used by Masson (2000), but his analysis was restricted to multiple reflections between only two facets, representing the road and walls forming a symmetric urban canyon. The generic method for the full solution of the exchange of diffuse radiation in a closed system of surfaces, is that originally developed by Sparrow and Cess (1970). It was applied to the study of radiation exchange in an urban canyon by Verseghy and Munro (1989) and Harman et al. (2004). So far, this methodology has not been used to study urban canyon albedo as a function of canyon orientation and H/W ratio with a model which includes facet subdivisions. Further, it shows the little understood diurnal changes in the effective albedo of a canyon. The model which applies exact solution of the multiple-reflection problem is a new tool for detailed study of these processes. It can be easily modified to include other cases such as having a different albedo for each wall/street slice or an angularly dependent albedo in first reflection. Preliminary results of the procedure have been analysed by Fortuniak (2002) and shown to be identical to Monte-Carlo simulations (Pawlak and Fortuniak, 2002).

2. The multiple reflection problem

The scheme presented here analytically finds the total shortwave radiation absorbed after an infinite number of reflections by a single facet of the object whose geometry can be simplified to n facets with defined view factors by solving a set of n linear equations. Beside incoming irradiances the input parameters required are the values of albedo and the view factors for all reflecting facets. The radiative flux densities are assumed to be uniform across each facet and the air between facets is assumed to be non-absorbing. The incident radiation for each facet includes both diffuse and direct solar radiation (with shadowing). Reflection is assumed to be Lambertian and identical values are used for the albedo of both direct and diffuse solar radiation. The view factor, $\psi_{\text{emitter,receiver}}$, is defined as the fraction of radiation emitted (reflected) by one facet (emitter) that is intercepted by another (receiver).

When facet i with albedo α_i is irradiated by the solar radiation flux $K{\downarrow}_i$ (direct and diffuse radiation from the sky: $K{\downarrow}_i = S_i + D_i$), the energy absorbed at the time of this reflection event is given by:

$$A_i(0) = (1 - \alpha_i) \cdot K{\downarrow}_i. \tag{1}$$

The reflected radiation, $R_i(0) = \alpha_i \cdot K{\downarrow}_i$, irradiates other facets so the energy absorbed after the first reflection can be calculated as:

$$A_i(1) = A_i(0) + \sum_{j=1}^{n} (1 - \alpha_i) \cdot \psi_{ji} \cdot R_j(0) \tag{2}$$

(because $\psi_{jj} = 0$ it is not required to include point $j \neq i$ in the summation of the above notation).

After k reflections:

$$A_i(k) = A_i(0) + \sum_{j=1}^{n} (1 - \alpha_i) \cdot \psi_{ji} \cdot \sum_{\kappa=1}^{k} R_j(\kappa - 1). \tag{3}$$

In the limit, $k \to \infty$, this equation permits calculation of the energy absorbed after an infinite number of reflections, but the sum:

$$\sum_{\kappa=1}^{\infty} R_j(\kappa) \equiv \Sigma R_j \tag{4}$$

must be determined. To obtain this one can write the reflected part of the incoming solar radiation as:

$$R_i(0) = \alpha_i \cdot K{\downarrow}_i. \tag{5}$$

and the reflected part of the radiation incoming from other facets in the k-th reflection:

$$R_i(k) = \sum_{j=1}^{n} \alpha_i \cdot \psi_{ji} \cdot R_j(k - 1). \tag{6}$$

The total radiation reflected by the facet after k reflections:

$$\sum_{\kappa=1}^{k} R_i(\kappa) = R_i(0) + \sum_{j=1}^{n} \alpha_i \cdot \psi_{ji} \cdot \sum_{\kappa=1}^{k} R_j(\kappa - 1), \tag{7}$$

gives in the limit case, $k \to \infty$:

$$\Sigma R_i = R_i(0) + \sum_{j=1}^{n} \alpha_i \cdot \psi_{ji} \cdot \Sigma R_j. \tag{8}$$

Thus, the radiation, $\mathrm{S}R_i$, reflected by i-th facet after an infinite number of reflections might be found as a solution of:

$$\begin{pmatrix} 1, & -\alpha_1\psi_{21}, & -\alpha_1\psi_{31}, & \ldots, & -\alpha_1\psi_{n1} \\ -\alpha_2\psi_{12}, & 1, & -\alpha_2\psi_{32}, & \ldots, & -\alpha_2\psi_{n2} \\ \vdots & \vdots & \vdots & & \vdots \\ -\alpha_n\psi_{1n}, & -\alpha_n\psi_{2n}, & -\alpha_n\psi_{3n}, & \ldots, & 1 \end{pmatrix} \times \begin{pmatrix} \Sigma R_1 \\ \Sigma R_2 \\ \vdots \\ \Sigma R_n \end{pmatrix} = \begin{pmatrix} R_1(0) \\ R_2(0) \\ \vdots \\ R_n(0) \end{pmatrix}. \tag{9}$$

In consequence, the energy flux, A_i, stored in this process by the i-th facet is given by:

$$A_i = A_i(0) + \sum_{j=1}^{n} (1 - \alpha_i) \cdot \psi_{ji} \cdot \Sigma R_j. \tag{10}$$

This allows calculation of the total energy absorbed by the system as well as its effective albedo.

3. The urban canyon radiation model

In the model the scheme given above is used to calculate the effective albedo of an infinitely long urban canyon. The canyon elements (walls and road) are divided into equally wide slices (facet-subdivisions). The number of slices to be used and their surface albedos are the input

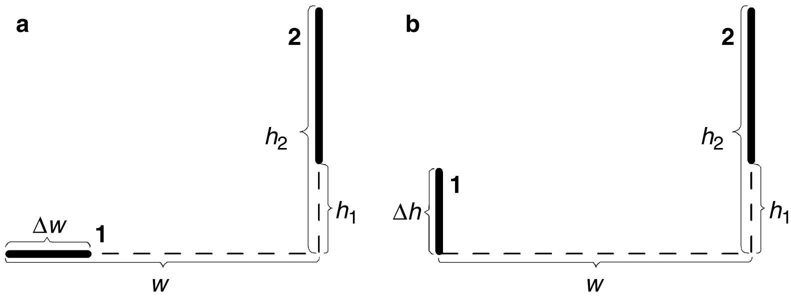

Fig. 1. Symbols used in calculations of view factors for two perpendicular (**a**) and parallel (**b**) slices of a long urban canyon

parameters of the model. The sensitivity of the model to the number of slices is discussed in Sect. 4. The other input parameters are the Sun's coordinates (height and azimuth), the canyon's geometric properties (height of walls, road and roof widths, canyon azimuth) and values of the incoming direct and diffuse radiation on a horizontal surface. For each slice, the view factors of other elements and the incoming shortwave radiation are computed as described below. The albedo of the system including its roofs is calculated as a simple weighted average of the albedo of the canyon and the roofs with weights proportional to the canyon and building widths.

3.1 View factors

In general, the determination of the matrix of view factors of all reflecting elements is a difficult task. Either empirical methods (Steyn, 1980; Grimmond et al., 2001; Fortuniak, 2000) or numerical methods (Johnson and Watson, 1984, 1985; Steyn and Lyons, 1985) are used. In the approach given here view factors are calculated analytically by solving equations for perpendicular and parallel slices. This is possible because the urban canyon is characterised by relatively simple geometry and only two cases of mutual surface orientations are to be considered: perpendicular and parallel. For an infinitesimal (in width) road element within a distance W from a wall of height H, a wall view factor is:

$$\psi_{1H} = 0.5\left(1 - \frac{W}{\sqrt{H^2 + W^2}}\right) \tag{11}$$

If the road element is Δw in width, the averaged wall view factor can be calculated as an integral of this formula. Moreover, if a receiver is not the whole wall but a slice within heights h_2 (upper) and h_1 (lower) (Fig. 1a), the average view factor can be found as:

$$\psi_{12} = \frac{h_2}{2w}\left(\sqrt{\left(\frac{h_1}{h_2}\right)^2 + \left(\frac{w}{h_2}\right)^2} - \sqrt{\left(\frac{h_1}{h_2}\right)^2 + \left(\frac{w-\Delta w}{h_2}\right)^2} + \sqrt{1 + \left(\frac{w-\Delta w}{h_2}\right)^2} - \sqrt{1 + \left(\frac{w}{h_2}\right)^2}\right). \tag{12}$$

Because of symmetry, the same formula can be used for the calculation of the road and sky view factors for wall elements.

Similarly, an average view factor for parallel elements (slices of opposite walls) of an urban canyon (Fig. 1b) is found to be:

$$\psi_{12} = \frac{w}{2\Delta h}\left(\sqrt{1 + \left(\frac{h_2}{w}\right)^2} - \sqrt{1 + \left(\frac{h_1}{w}\right)^2} + \sqrt{1 + \left(\frac{h_1 - \Delta h}{w}\right)^2} - \sqrt{1 + \left(\frac{h_2 - \Delta h}{w}\right)^2}\right). \tag{13}$$

Substituting $\Delta h = W$ (canyon width), $h_1 = 0$, $h_2 = W$, and $w = H$ (height of walls) allows to calculate an average sky view factor for the road:

$$\psi_{RS} = \sqrt{\left(\frac{H}{W}\right)^2 + 1} - \frac{H}{W}. \tag{14}$$

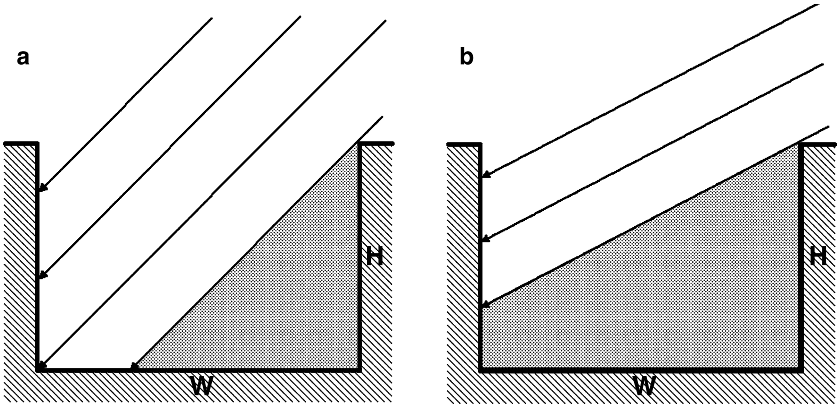

Fig. 2. Solar radiation received in a canyon in the case of high (**a**) and low (**b**) solar elevation (canyon perpendicular to the solar beam for simplicity)

Formula (12) with substitutions $\Delta w = H$, $w = H$, $h_1 = 0$, $h_2 = W$ gives an averaged sky view factor for the walls:

$$\psi_{WS} = \frac{1}{2}\left(\frac{H}{W} + 1 - \sqrt{\left(\frac{H}{W}\right)^2 + 1}\right) \Big/ \left(\frac{H}{W}\right) \quad (15)$$

Equations (14) and (15) are the same as those given by Noilhan (1981).

3.2 Incoming radiation

To calculate the energy stored by a slice, information about the incoming radiation is required. Because of shadow effects, the direct solar beam and diffuse sky radiation are computed separately.

Let S be the direct solar radiation received by a horizontal surface for a solar azimuth Ω and solar elevation angle β. For a canyon geometry defined by its width (W), azimuth (Ω_C) and with a building height (H), the shadow part of the canyon is determined by geometrical relations. If the canyon is parallel to the direction of the solar beam, only the road is irradiated by direct solar radiation. Otherwise, two cases must be considered: high and low solar elevation (Fig. 2). In the case of a high sun, $\beta > \arctan(H/W \cdot \sin(\Omega - \Omega_C))$, the road is partially illuminated and one of the two walls is in shadow (Fig. 2a). The width of the shadow part of the road is given by:

$$w_c = H \cdot \cot(\beta) \cdot \sin(\Omega - \Omega_C)$$

In the case of a low sun (Fig. 2b), the road is no longer illuminated and the height of the shadow part of the irradiated wall is:

$$h_c = H - W \cdot \tan(\beta) / \sin(\Omega - \Omega_C)$$

In the presented model, direct solar radiation is assumed zero for the shadow parts of wall and road. The irradiances of the sunlit slices of road and wall are $S_r = S$ and $S_w = S \cdot \cot(\beta) \cdot \sin(\Omega - \Omega_C)$, respectively.

The diffuse sky radiation on a horizontal surface, D, allows one to calculate the energy absorbed in this form by the road and walls. Assuming the diffuse sky radiation to be isotropic the diffuse radiation, D_r, for a road element can be calculated by multiplying D by the sky view factor, $\psi_{r,\mathrm{Sky}}$, of the element: $D_r = D \cdot \psi_{r,\mathrm{Sky}}$. Similarly, the diffuse radiation, D_w, for a wall element is given by: $D_w = D \cdot \psi_{w,\mathrm{Sky}}$.

The input values of direct and diffuse radiation for a horizontal surface can be obtained either from measurements or simulations. The calculations given here use the algorithm proposed by Davies et al. (1975).

4. Model validation

Before conducting validation the sensitivity of the results to the number of slices per facet (wall

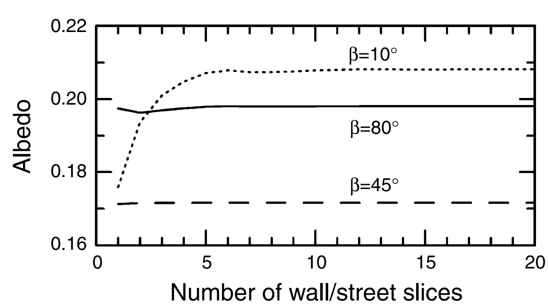

Fig. 3. Estimated effective albedo of an urban canyon with its axis oriented perpendicular to the solar azimuth with $H/W = 1$ as a function of the number slices per facet (wall or street)

or street) was tested with different combinations of the other input parameters (H/W ratio, street azimuth, surface albedo, diffuse/direct radiation ratio). For example Fig. 3 shows the effective canyon albedo as a function of the number of slices for a canyon with $H/W=1$, oriented perpendicularly to the solar azimuth. The results depend slightly on the number of slices. Only for the case of a low sun does having more slices improve the results. However, when the number of slices exceeds 5 the results converge towards a fixed value. This is due to a solar shading effect. For a low sun direct solar radiation irradiates only the upper part of the wall. According to the model formulation, the reflected radiation is assumed to be uniform across the slice. If only one slice per wall is used radiance reflected to the sky by the first reflection is underestimated (because the sky view factor for the whole wall is lower than for its upper part). As a consequence a one slice per facet model underestimates the effective canyon albedo and using more slices improves results. In other simulations the results converged for 5 slices per facet as in the presented case. Only for a very low solar elevation (below 10°) would more slices be necessary, but because of the low total irradiance for a low sun the error introduced by limiting the number of slices is unimportant relative to other uncertainties within the total energy budget. Because of this, in all of the results presented herein estimations with no less than 5 slices per facet are used (5 slices per wall for $H/W<1$ or 5 slices per street for $H/W=1$). Most of the examples given here were rerun using a larger number of slices per facet, but differences were negligible.

The model is evaluated with the measured albedo data given by Aida (1982), who manufactured an urban structure models with numerous concrete cubic blocks (0.15 m on each side) laid out on a concrete foundation (3 × 3 m). Four geometric arrangements were employed in his study. Model 0 was the reference flat base of concrete. Models 1 and 2 were a north–south (NS) and east–west (EW) oriented street canyons with a height to width ratio $H/W=1$ and equal roof and street widths. Model 3 contained NS and EW canyons that intersect. The albedo of the system for all four models was evaluated by independent observations of the reflected global radiation using two experimental procedures. In the scrap and build method, the models were built and demolished in turn throughout two days (15 June 1978 and 3 December 1977). In the standing method, one of the above models was built in advance in case of fine weather and after a one-day experiment was scrapped and rebuilt into a new model.

Figure 4 gives a comparison of the albedo values measured by Aida in a scrap and build method (data digitized from Aida's paper) with the effective albedo computed with the aid of the present model. The angular dependence of the surface reflectivity observed for a flat surface (model 0) is incorporated into the model by adjusting (polynomial fit) the roof albedo to Aida's measurements for model 0. Road and wall reflections are supposed to be isotropic and the albedo

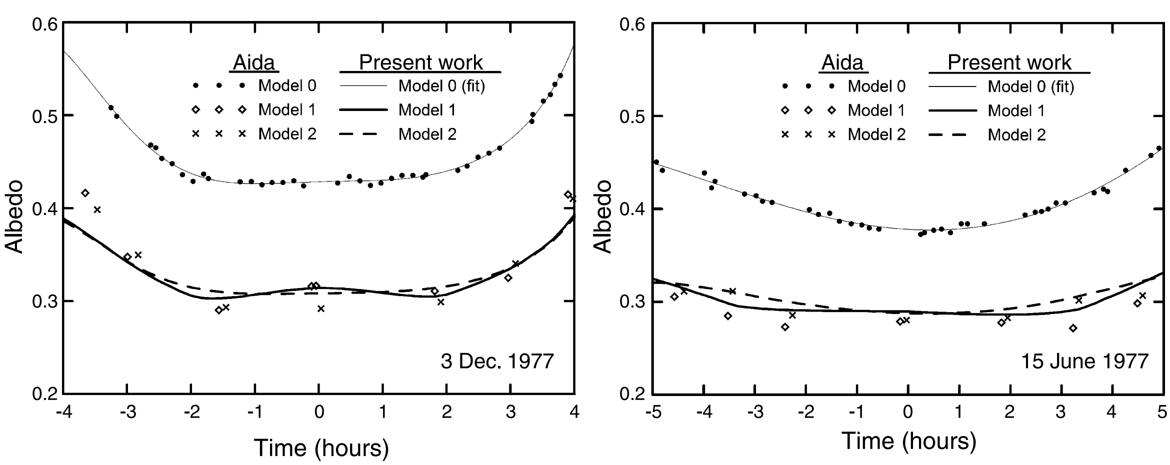

Fig. 4. Urban albedo as measured by Aida (1982) in a scrap and build method (dots) and as parameterized by the present model (lines)

Table 1. Statistical measures of the model fit to the data of Aida

Aida's method and canyon orientation	RMSE	MBE	*d*	*r*
Scrap and build				
NS	0.018	0.013	0.944	0.972
EW	0.019	0.017	0.931	0.976
Standing (roofs included)				
NS	0.015	0.010	0.825	0.690
EW	0.015	0.011	0.704	0.513
Standing (roofs excluded)				
NS	0.028	0.019	0.446	0.298
EW	0.030	0.022	0.440	0.617
Standing (roof excluded; albedo angular depend in first reflection)				
NS	0.028	0.018	0.316	0.302
EW	0.033	0.024	0.375	0.365

RMSE Root mean squared error; *MBE* mean bias error; *d* Willmott's index of agreement (Willmott, 1981); *r* correlation coefficient

for these slices is taken as a constant, equal to 0.40. The model was run for the latitude of the Aida's experiment (35°28′ N). The results demonstrate very good agreement with measurements, both for winter and summer simulations. Modelled and measured values are highly correlated and average errors produced by the model are about 1–2% (Table 1). The model adequately reproduces not only a general increase of radiation absorption due to multiple reflections but also the diurnal changes of the effective canyon albedo. The high albedo for the case of a low solar elevation can be attributed to the influence of the angular dependence of the roof albedo, but the increase around noon for the case of the NS canyon is a result of the canyon geometry. The model is also able to reproduce differences between NS and EW canyons.

The simulation of the diurnal changes in urban albedo observed by Aida for NS and EW canyons in the standing method also shows high consistency between the measured and modelled values (Fig. 5). The clear bend that separates the almost constant values of albedo for a small solar zenith angle, $Z < \sim 45°$, from the linear increase of this parameter for the low sun in the case of a NS oriented canyon is well reproduced by the model. For the case of the EW canyon the model fits the data very well for high solar elevations ($Z < \sim 55°$). More significant discrepancies are evident for a low sun, but in this case the measurements themselves differ between the morning and evening hours. The high correspondence between the model and the Aida data (Table 1) is to certain degree caused by using a curve-fitted roof albedo. In Aida's experiment the roofs cover 50% of the area and the actual canyon albedo (without the roof) can be easily extracted. Figure 6 presents a model fit to such data. Both forenoon and afternoon measurements are placed on the same axis. In this case the statistical goodness of fit is much lower (Table 1), but the data itself does not show a clear dependence on solar zenith angle, especially for angles above $\sim 55°$.

The angular dependence of the roof albedo on the solar zenith angle suggests also that this effect might be observed for the walls and street. Simulations with a surface albedo that includes an angular dependence for the first reflection event (Fig. 6 – dashed line) shows some visual improvement. This conclusion is not fully confirmed by the descriptive statistics presented in Table 1. Again, this is probably because of poor

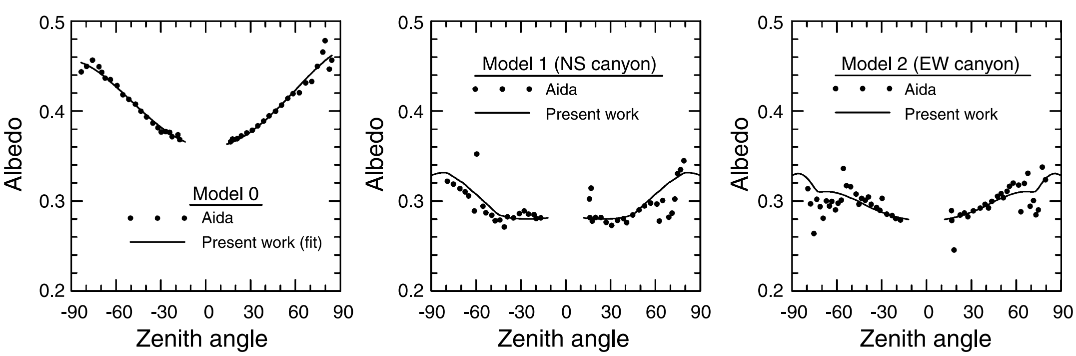

Fig. 5. Urban albedo as measured by Aida (1982) in a standing method (dots) and as parameterized by the present model (lines) for summer observations (negative Z values indicate measurements before noon)

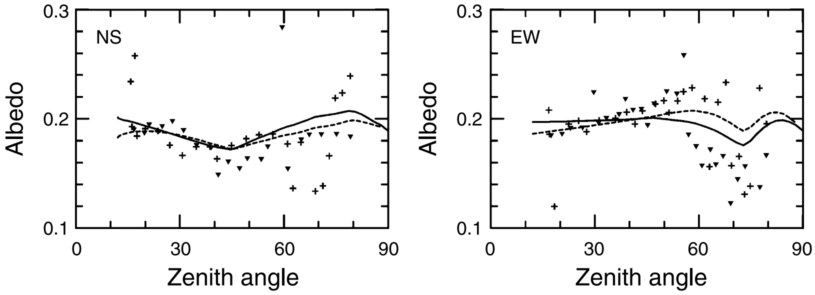

Fig. 6. Urban albedo as measured by Aida (1982) in a standing method after extraction of the roof component and its modelled values for NS and EW canyons. Measurements made before noon (triangles) and afternoon (crosses) shown separately. Solid line – model with constant wall and street albedo ($\alpha = 0.4$). Dashed line – model with albedo having angular dependence for the first reflection

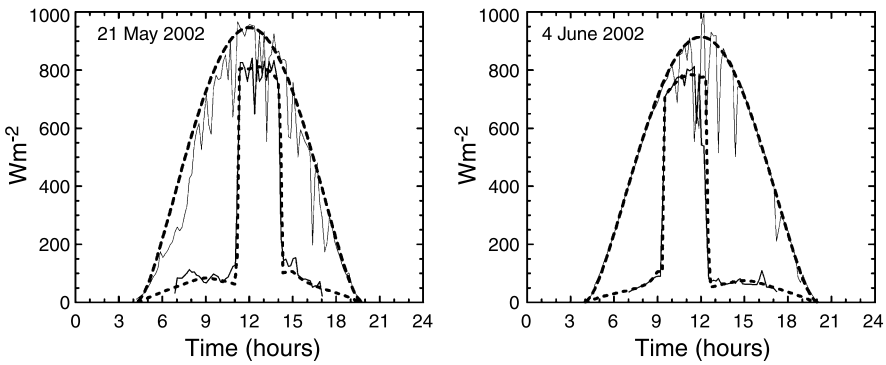

Fig. 7. Measured (solid lines) and modelled (dashed lines) total solar irradiance at roof level and in the urban canyon in Łódź at Piotrkowska street

representation of cases with Z > ~55°, but other possible sources of inaccuracy can be mentioned. For example, the increased surface albedo for high Z might be a result of a spectral dependence of the surface albedo and of daily changes in the spectrum of incoming solar radiation; reflection may also not be Lambertian, etc. It is not possible to include all these effects both because of way the model is formulated and because of lack of experimental data. To avoid unnecessary complications all other simulations are made with assumption of a constant (angularly independent) surface albedo of the facets.

Field measurements in a real world urban canyon provide additional data for model validation. The diurnal variation of the total solar radiation in an urban canyon was measured in Łódź in the summer of 2002 for a few one day experiments (Podstawczynska and Pawlak, 2003). A Kipp and Zonen CM11 pyranometer mounted on at 1.8 m on a mast was placed in the urban canyon for a whole day at a time, from sunrise to sunshine. In the cases analyzed (May 21st and June 4th – Fig. 7), the radiation was recorded in a NS oriented urban canyon 2 m away from the east (21 May) and west (4 June) walls. The street was 18 m wide with $H/W = 1.1$. As a reference, a second CM11 pyranometer measured radiation on the roof of a 17 m high building. Both stations were situated in the centre of the old town and were separated by about 1.5 km. Detailed information regarding the surface albedo of the walls and the road are not available, so in simulations the values $\alpha_w = 0.3$ and $\alpha_r = 0.1$ were used. These were considered reasonable values based on tables in the literature. In these simulations 18 slices per street and 20 per wall were used to estimate total irradiance for the slice corresponding to the distance of the pyranometer from the wall. The scheme of Davies et al. (1975) slightly underestimated the incoming solar radiation for 21 May using climatological means for the optical properties of the atmosphere). Values for this day were multiplied by a factor of 1.05 to obtain a better representation of the input. A comparison of measured and modelled irradiance in the urban canyon (Fig. 7) shows the method reproduces the real world values well. The modelled total irradiance in the canyon fits the data for the street irradiated by direct solar radiation as well as in the hours when the pyranometer is in shadow. The simulations were made for a street slice width of 1 m, whereas pyranometer's elevation was 1.8 m. An additional simulation for 2 m lower walls was conducted (not shown) to check if that changed the results. The results remained similar to those presented with slightly longer time of solar illumination (comparable to the line width on Fig. 7. It should be noted that the lack of detailed information concerning the albedos of the facets and their angular dependence reduces the value of this verification.

Other studies (Pawlak et al., 2005) show the results given by the proposed scheme are identical to Monte Carlo simulations based on the photon tracking method. This gives further confidence in the validity of the model.

5. Model application

The main objective of the scheme given here is to estimate the effective albedo of an urban canyon. It enables one to test the implications of using different combinations of the surface albedo of walls and the street, the height to width ratio and the ratio of diffuse to direct solar radiation. For simplicity only a canyon without roofs is analysed herein.

First, the effective albedo of the urban canyon was calculated for two values of surface reflectivity: $\alpha = 0.4$ (the same for walls and road) and $\alpha = 0.8$. Separate simulations for direct and diffuse radiation were provided for a canyon perpendicular to the solar azimuth (Fig. 8a). There is no need to run for a canyon parallel to the solar beam because the results repeat those for $\beta = 90°$. The trapping of direct beam radiation was tested for different solar elevations from $\beta = 10°$ to $\beta = 90°$. A very strong influence of geometry on the absorption of the solar radiation is observed. For low solar elevation, an increase in the H/W ratio results in a very rapid drop in the effective canyon albedo for small H/W, but the lines kink for $H/W = \tan(\beta)$ (when the road becomes totally shaded). Beyond that the reduction of the effective albedo due to geometry is much less rapid, especially for low values of surface albedo. The decrease of the effective canyon albedo for high solar elevations is more regular. The influence of geometry is different for a different surface albedo – for $\beta = 90°$ the effective albedo of the canyon with $H/W = 5$ is 89% lower than for a flat surface in the case of $\alpha = 0.4$, whereas for $\alpha = 0.8$ it is only 76%. Similarly, the reduction of the albedo for a low sun case ($\beta = 10°$) is more significant for $\alpha = 0.4$ (47%) than for $\alpha = 0.8$ (34%). For a low sun, the influence of the geometry is less significant because only the upper narrow band of wall is irradiated and a large fraction of the radiation escapes to

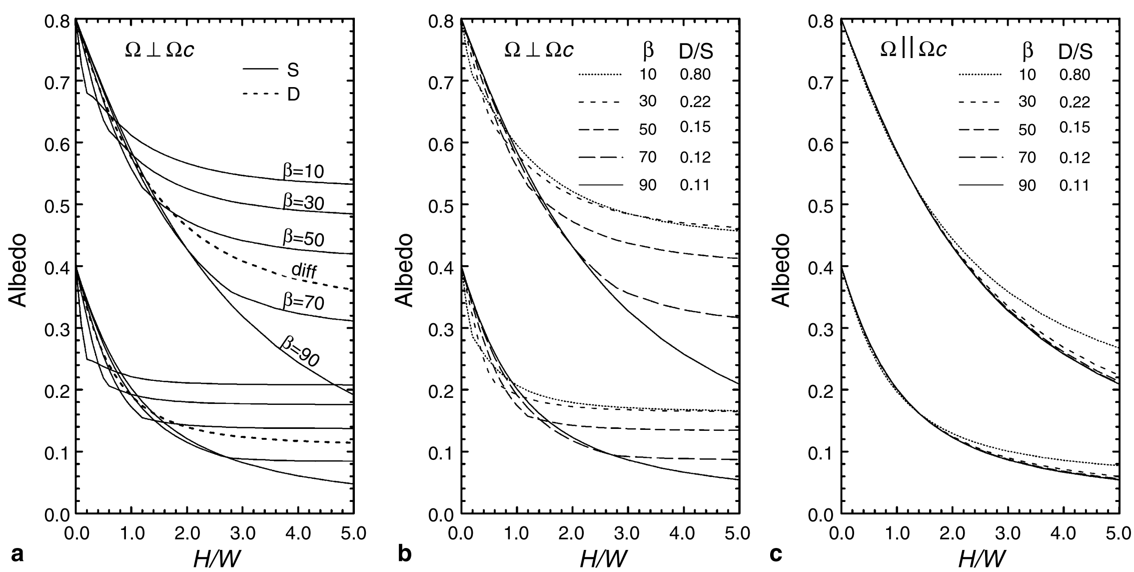

Fig. 8. Estimated effective albedo of an urban canyon for different solar elevation angle (β) as a function of the H/W ratio: **a** separate estimates for direct (S) and diffuse (D) radiation for a canyon perpendicular to the solar azimuth; **b**, **c** estimates for total radiation (i.e. the sum of S and D) with D/S depending on solar elevation

the sky after the first reflection. The same relations are valid for diffuse shortwave radiation – high surface albedo results in a smaller percent increase of canyon absorption with H/W.

A similar but more realistic example is given in Fig. 8b and c. Two cases of canyon orientation are considered: perpendicular and parallel to the solar azimuth, but the total incoming irradiance is composed of direct and diffuse parts with the ratio depending on the solar elevation (the fraction of direct radiation increases with elevation). In the case of a canyon oriented perpendicular to solar azimuth (Fig. 8b), a high fraction of diffuse radiation for the low sun case decreases the effective canyon albedo in comparison with results for a direct beam. The effect is so strong that almost no differences are observed for the trapping processes for $\beta = 10°$ and for $\beta = 30°$. For a high solar elevation, the direct beam irradiates mostly the bottom of canyon (street) and it is reflected many times before a photon escapes from the canyon. Diffuse radiation illuminates mainly the portions of the canyon with the largest sky view factors (the upper parts of the canyon) and a large part escapes after the first reflection. Therefore the trapping of total diffuse radiation is lower than in the case of the direct beam. Simulations for the canyon parallel to the solar azimuth (Fig. 8c), when only the street is irradiated by a direct beam, clearly show the role of diffuse radiation – a higher fraction of diffuse radiation increases the effective albedo of the canyon.

The previous simulations assume the albedos of the buildings and the road are equal, which is rarely the case in the real world. When buildings are painted white and the street is covered by a dark material (e.g. asphalt), the reflection of the radiation from the walls can raise the albedo of the system (in comparison with the road albedo) – see Fig. 9. For a low solar elevation case, the albedo of the system rises together with the increase of the H/W ratio, as long as the whole wall is irradiated – the wall is an additional radiation source and an increase of the H/W ratio enhances this source. The rest of the canyon is illuminated by weak diffuse radiation (direct irradiance of the road is small because of shading and the result of multiplying by $\sin(\beta)$ on sunlit parts). For the high sun case, most of the radiation illuminates the road and the walls additionally absorb a part of the reflected radiation. In effect, the growth of the H/W ratio results in an albedo reduction. On cloudy days (when diffuse radiation dominates) the effective albedo of the whole system can be either higher or lower than the road albedo depending on the height of walls and their surface albedo.

Different combinations of the wall and street albedos can result in a different diurnal course of the canyon albedo, as pointed out by Sievers and Zdunkowski (1985). As an example, simulations for a fixed wall albedo $\alpha_w = 0.4$ and three different values of street albedo $\alpha_r = 0.2$, 0.3 and 0.4 for NS and EW canyon with $H/W = 1$ are shown in Fig. 10. The most striking feature evident is the high sensitivity of the diurnal course of the effective albedo to different combinations of wall and street reflectivity. The albedo of a NS canyon with uniform surface reflectivity ($\alpha_r = \alpha_w = 0.4$) is characterized by a w-shaped diurnal course with high values at noon and minima for solar azimuths of 112° and 248° on June 22nd and 168° and 192° on December 22nd. The minima correspond to the time when one wall is fully irra-

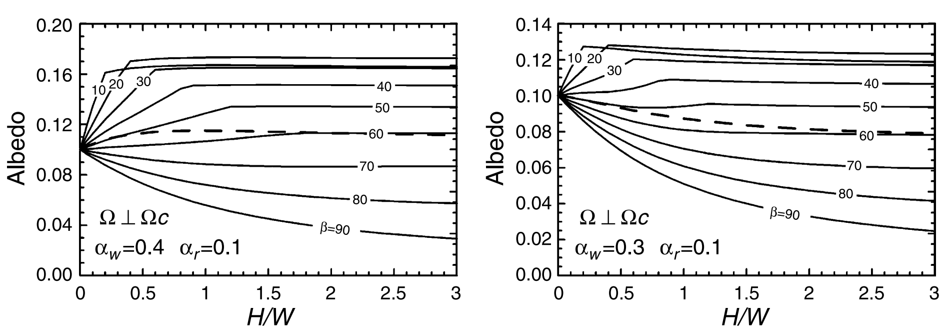

Fig. 9. Estimated effective albedo of an urban canyon for different solar elevation (β) as a function of the H/W ratio on a sunny day (solid line) and on a cloudy day (diffuse radiation only – dashed line) for a canyon perpendicular to the solar azimuth for different values of the wall (α_w) and the street (α_r) albedo

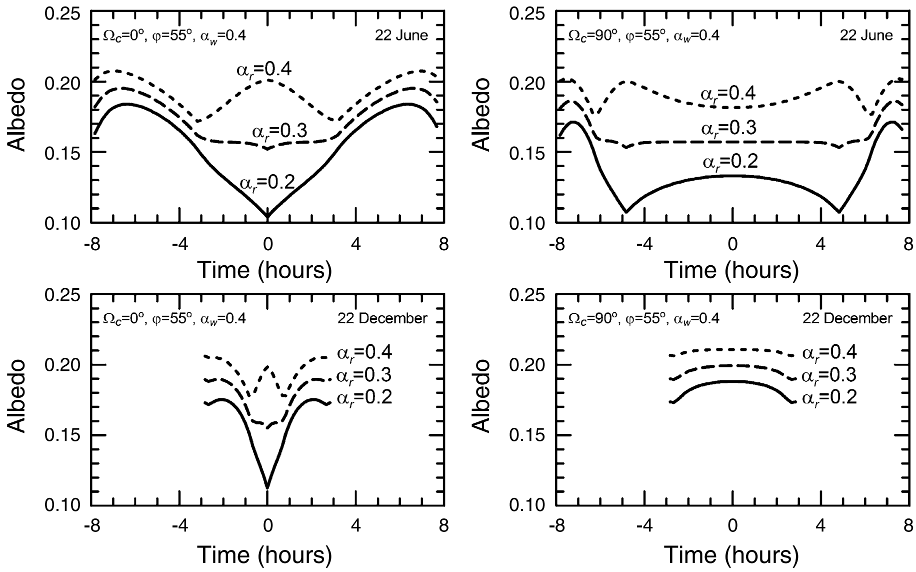

Fig. 10. Estimated diurnal course of the effective albedo of an urban canyon with fixed wall albedo $\alpha_w = 0.4$ and three different street albedos, $\alpha_r = 0.2$, 0.3 and 0.4 for EW and NS canyons having $H/W = 1$ at latitude $\varphi = 55°$ on 22 June and 22 December

diated. Such diurnal variation can be qualitatively explained. For the low sun case only the upper slice of the wall is illuminated by direct radiation. Because of the orientation, its sky view factor (SVF) is close to 0.5. Assuming that all radiation reflected in the canyon is absorbed, an effective albedo for this slice is $\alpha_w/2$. For lower slices the influence of SVF reduces their effective albedo for direct radiation even more strongly – SVF falls below 0.2 for a slice next to the ground (for $H/W = 1$). Thus, in the case of direct radiation only, an increase in the lighted part of the wall results in a decrease of effective canyon albedo. The canyon albedo for diffused radiation stays unchanged, but the role of direct radiation in the total incoming increases as the solar elevation grows, which results in a decreasing effective albedo.

The SVF for horizontal elements in the symmetric canyon is higher than for the vertical ones, thus the effective albedo starts to increase according to the width of the illuminated portion of the road. It is only true for the case of a relatively high road albedo (e.g. in Fig. 10, where $\alpha_r = \alpha_w$). For sufficiently low α_r the effect of an increase of the SVF is reduced or even dominated by increased absorption. This is clearly shown in Fig. 10 (NS canyon) for $\alpha_r = 0.2$. Diurnal changes of the EW canyon albedo are even more complex, especially in the summer. The albedo for uniform surface reflectivity fluctuates in the morning and in the evening, reaching its minimum when one wall is fully irradiated and the solar beam is parallel to the canyon. During the rest of the day the EW canyon albedo slightly decreases towards a minimum at noon. The physical processes governing its diurnal variation are the same as those in the case of a NS canyon. The forenoon and afternoon maxima of the total albedo for $\alpha_r = 0.4$ correspond with its minima for $\alpha_r = 0.2$, because of strong absorption by the road for low α_r. The course between these two times reaches its maximum at noon for $\alpha_r = 0.2$ and it constitutes almost a mirror image of the path for $\alpha_r = 0.4$. The canyon azimuth plays an important role in seasonal changes of the diurnal course of the effective albedo. In the case of a NS canyon, the winter plot is just a compressed version of the summer one. However, the diurnal course of the albedo of an EW canyon differ between seasons, not only quantitatively but also qualitatively. In winter the influence of street reflectivity is much less pronounced and for all analyzed α_r the maximum is observed at noon.

In addition to surface reflectivity the H/W ratio of the canyon plays an important role in diurnal changes of the total albedo of the canyon (Fig. 11). A shallow NS canyon reflects most of the energy at noon whereas absorption by a deep one is greatest during these hours. This is because at noon only the street is irradiated by direct solar radiation and most of this incoming energy is absorbed in the multiple reflection process. For a deep EW canyon, the same process leads to two minima for the times when the solar azimuth is parallel to the canyon axis ($\sim$5 h be-

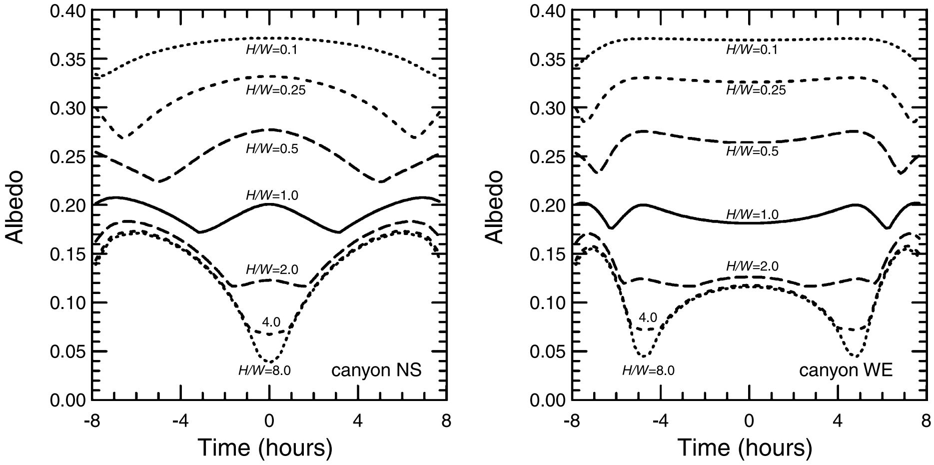

Fig. 11. Estimated diurnal course of the effective albedo of an urban canyon with uniform surface reflectivity $\alpha_w = \alpha_r = 0.4$ and with H/W varying from 0.1 to 8.0 on 22 June for NS (left) and EW (right) canyon at latitude $\varphi = 55°$

fore and after noon). These local maxima are not observed for a shallow EW canyon. The albedo of a shallow EW canyon does not change very much during the day except that it grows fast in the morning and has a similar rate of decrease in the evening, but there is a slight minimum at noon for the moderate H/W case. Differences in the diurnal course of the albedo for NS and EW canyons with a small H/W ratio are not only a consequence of the multiple reflection processes but also of a shadowing effect. A large part of the NS canyon is in shadow in the morning and evening. Only one wall is well irradiated and no more than a half of the reflected radiation escapes to the sky, the rest is involved in the multiple reflection process. This results in a decreased total albedo. At the same time the bottom of the EW canyon is sunlit and a large part of the reflected radiation is directly lost to the sky because of a high sky view factor. At noon, shadowing effects are not so important for a shallow canyon because of the high solar elevation. However, as the H/W ratio increases, the effect becomes significant and a slight minimum appears in these hours for a EW canyon.

The simulation results for a shaded NS canyon seems to contradict with the widely accepted opinion of an increase of the total albedo with increasing solar zenith angle (e.g. Offerle et al., 2003), but it can happen in real cities. For example, Fig. 12 shows the diurnal variation of the albedo measured in Łódź on a high mast (25 m) located on the roof of the new 20 m high University building, which is typical of the roof levels in the surrounding area. The geometry of the neighbourhood nearby is very complex and cannot be simply approximated by a street canyon, but the presence of relatively large courtyards on the west and east sides of the relatively narrow building create a configuration similar to a NS canyon. The course of the albedo shown is typical of that observed at this site on a sunny day. Measurements in another district of Łódź show a typical U-shape diurnal course of the albedo (see Offerle et al., 2003 for more details). At this other site, a similar mast was used and the roof level was approximately the same, but the geometry was dominated by narrow structures with lower SVF.

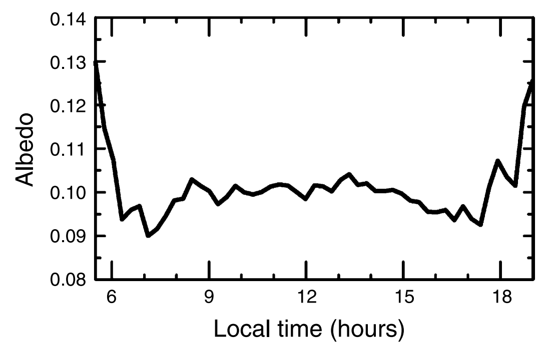

Fig. 12. Example of the diurnal course of the albedo measured in Łódź on the sunny day of 21 June 2005 at 25 m above roof level

6. Conclusions

The model of multiple reflections presented here was used to calculate an effective albedo for long street canyons. The urban canyon structure was chosen for analysis because: it is a common urban structure used in many studies on urban climate; the data necessary for model verification are available in the literature; a simple parameter can be used to describe canyon geometry (the H/W ratio); analytical calculation of the view factors for reflecting faces is relatively easy. However, the subroutine to calculate the absorption of the energy after an infinite number of reflections can also be used in analysis of structures with more complex geometry. In such cases, an analytical calculation of the view factor matrix is more problematic, but it can be done with the aid of methods like the photon tracking technique. If the number of reflecting facets is not too large, the analytic solution of the multiple reflection problem can be less time-consuming than Monte Carlo simulations.

The model presented here performs well in tests using the data of Aida (1982) for – both winter and summer cases. The model reproduces well not only the general dependence of the albedo on zenith angle, but also singularities for different canyon orientations. Agreement with measured irradiance on the floor of a real canyon provides additional evidence of the applicability of the model.

Calculations show that an increase in the H/W radio dramatically decreases the effective albedo of the canyon system, especially with a high sun and low surface reflectivity. The daily variation of the effective albedo of a street canyon depends not only on the H/W ratio but also on the other factors, e.g. the combination of the reflectivity of the street and walls, the azimuth of the canyon, season of the year and the latitude of the location. The cases presented do not cover results for the full spectrum of the possible combinations of these factors, rather they show the most typical, illustrative examples. Because of complexity of the influence of the factors, a separate simulation should be done for each particular case. The model can be used as a tool for such case studies.

It is shown that the model properly analyzes the multiple reflection problem in urban canyons, however, some sources of potential error should be noted. Firstly, the absorption, emission and scattering of the radiation by the air in the canyon have been neglected. Secondly, scattering is assumed to be Lambertian, which is not the case in many real structures (e.g. reflection by windows). Better parameterization of the incoming direct, and especially diffuse radiation could also improve estimates.

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