Soil Albedo and Soil Surface Shape at Various Illumination Conditions

Jerzy CIERNIEWSKI
Department of Soil Science and Remote Sensing of Soils, Adam Mickiewicz University
61-680 Poznań, Poland

and

Tomasz GDALA
Mathematics and Computer Science Faculty, Adam Mickiewicz University
61-614 Poznań, Poland

ABSTRACT

The hemispherical-directional reflectance model [1], was used in this paper to study albedo variation of soil and rocky surfaces, taking the surfaces geometry and its illumination conditions into consideration. Virtual surfaces, characterized by three geometrical parameters, were used for modeling soil surface albedo. They represent uncultivated desert surfaces, smooth and very rough, as well as cultivated ones with soil aggregates randomly dispersed and with a furrow microrelief. The spectral albedo of these surfaces was calculated from their hemispherical-directional reflectance *HDR* data, generated by the model for all possible directions for illumination conditions at a wide range of the solar zenith angle θ_S between 10° and 80° and the optical thickness of the atmosphere τ varied from 0.1 to 15, relating to clear sky and completely overcast conditions, respectively. Results of the studies show that albedo of soil and rocky surfaces clearly depends on their shape. The albedo behavior depends on the way how it is calculated from the *HDR* data. If it is computed as measured by a pyranometer, that is as the ratio of the reflected and incident fluxes, both sensed by horizontally situated detectors, the larger irregularities of the surfaces, the higher variation of the albedo. If the albedo is computed as a bispherical coefficient, as the proportion of the reflected flux to the incident one, where energy of the lower, as well as the upper radiation environments is not projected to the horizontal plane, the larger irregularities of the surfaces, the lower variation of the albedo.

Keywords: Soil, Albedo Variation, Hemispherical-Directional Reflectance, Geometrical model

INTRODUCTION

The land surface albedo, is an quantitative parameter characterizing the earth surface interactions with shortwave electromagnetic radiation. The albedo, as a dimensionless term, expresses the ratio of the total shortwave (0.3-3 μm) radiant exitance of reflected energy by a surface in all directions within the surrounding 2π solid angle (i.e., hemisphere) to the total downwelling irradiance. Because the albedo is a parameter which characterizes intrinsic properties of a given surface, as well as its illumination conditions, it also depends on the solar zenith angle and the atmosphere state, i.e., cloudiness and contents of aerosols and their quality. An angular distribution of sky radiation for a clear and clean atmosphere is unequal. Ground measurements, carried out in a desert region of the state of New Mexico, show that the sky is very bright near the sun in the so-called aureole [2]. The sky is a relatively bright along the horizon, while it is the darkest in the quadrant opposite to the sun. The variation of the sky radiance intensity becomes lower when sun elevation raises. Kondratyev [3] has mentioned that the variation could be practically negligible for higher than 60° sun elevation angles. Amount of the diffuse light in the global skylight, which coming to the earths surfaces, varies with cloudiness. When the sky is completely overcast, the radiance distribution is almost even with its weak monotonic drop from the zenith to the horizon. The diffuse skylight intensity depends on the optical thickness of the atmosphere τ. Kondratyev [3] examining the albedo variation of grass surfaces in the sun elevation function in the relation to the proportion of diffuse to global sky radiation *D/G* has showed, using the diagram, that the relationship is non-linear. The higher the proportion of the diffuse radiation component, the lower the albedo for a given value of the sun elevation. For sun elevation angles higher than 40°, the albedo does not change more than 1-1.5% if the *D/G* varies from 0.1 to 1.

Some of the earth surfaces like vegetation essentially modify themselves with seasons. Vegetation vary with its consecutive growth stages, changing its moisture content and area proportion to a soil background. The albedo of vegetation surfaces varies during a day. Kondratyev [3] quantitatively describes it as its increase of about 0.1-0.5% per each 10° of the sun elevation decrease. The author has also noticed that the relation is asymmetrical. Mayor *et al*. [4] explained it as an effect of vegetation moisture changing during a day. They wrote that afternoon, albedo of vegetation surfaces can increase by 20% relatively to its morning counterpart.

Bare soil surfaces change their albedo, too. Already thirty five years ago Kondratyev [3], discussing albedo variation of dry soil surfaces, the stony and the loamy, has reported that during a day when the sun elevation increases from 10° to 60°, their albedo decreases from 0.22 to 0.12 and 0.34 to 0.18, respectively. It is the consequence of their illumination variation. A soil surface reflectance increases with a decrease of soil particle size. Smaller aggregates have a more spherical shape, but larger ones have an irregular shape with a higher number of inter-aggregate spaces and cracks, where the incident light is trapped [5]. Irregularities of soil surfaces are ones of the most unstable soil properties. They are the highest after tillage treatments and progressively decreases with rainfall. The higher the roughness of the soil surfaces, the lower their brightness. Obukhov and Orlov [6] have maintained that structureless soils reflect from 15% to 20% more light than soils having a well-developed structure. Kondratyev and Fedchenko [7] found that this crust developed on soil clods of diameter from 5 to 15 cm, resulting in an increase of soil reflectance of about 10%-15%.

Soil surface irregularities, caused by the soil texture, aggregates and microrelief configuration, that are large compared with the wavelengths and are opaque cast shadows on those surfaces. Variation of the shadows viewing by sensors is a basic reason of the soil non-Lambertian behavior in the optical domain. Soil surfaces, like many natural objects, do not reflect incident wave energy equally in all directions. The soil reflectance vary due to the directions of its illumination and observation. Shaded soil fragments reflect many orders-of-magnitude less than sunlit ones. Cultivated soil surfaces, with dominant diffuse features, reflect more light if a source of direct beams, like the sun, is higher above them. They usually reflect more light from backscattering directions near the zenith and azimuth position of the sun, which gives the lowest proportion of their shaded fragments. However, these surfaces reflect less the energy from the extreme forwardscatter direction near the horizon, from which the highest fraction of their shaded parts is visible. Nearly bare soils of different surface roughness collected by Kimes and Sellers [8] exhibit those features. Milton and Webb [9], examining the influence of cultivation practices on the direct reflectance of sandy soils of different moisture, observed that ploughing considerably decreased soil reflectance. It was the effect of the increase in soil surface moisture, as well as in soil surface roughness. They also found that the peak of backscatter radiation became less pronounced at a low solar zenith angle. Weak symptoms of a forwardscattering character of the reflectance of cultivated bare soils was noticed by Irons and Smith [10]. The results of their studies show that the roughest ploughed soil surface of a fine-loamy texture, scattered radiation forward as strongly as the smoothest surface. The relatively larger shadowing of the roughest soil in compensation for its strong forwardscatter was given as the reason of the effect. Laboratory results presented by Coulson [11] show that desert soil materials like gypsum sand and beach quartz sand display a high reflectance with a strong forwardscatter maximum for the visible and near-infrared range. The directional reflectance of these soil surfaces clearly vary with the angle of the incident radiation. The highest reflectance was recorded at a grazing angle of 78.5°. Shoshany [12], analyzing hemispherical-directional reflectance data sets of desert stony pavements and rocky surfaces in Australia, found that most of the surfaces exhibited an anisotropic reflection with clear backscatering component. The backscatter, as well as the forwardscatter, regime in soil reflectance have been noticed by Deering *et al.* [13]. They have demonstrated it on the examples of an alkali flat bare soil and dune sand surface.

The two hemispherical radiation environments, one incoming and one outgoing, can be described by the bidirectional reflectance distribution function *BRDF*. The *BRDF* is described as the ratio of the radiance reflected by the surface to the incident irradiance from only one source of illumination. Similarly, with only one source of the incident radiation, the bidirectional reflectance factor *BRF* is defined. The factor is described as the radiance reflected by the surface to the radiance which would be reflected by a perfect Lambertian panel, both under the same illumination and viewing conditions [14]. In field conditions, the limitation of only one the direct solar source of radiation would mean an elimination of the diffuse sky radiation. Because it is unreal, for reducing the sky radiation influence, the directional reflectance measurements, taken on a day with a clear sky, under thin and stable aerosol conditions, for wavelengths for which the sky radiance can be neglected, are recommended [15]. Sets of the directional reflectance measurements, related to a specific distribution of the sun and the sky irradiation, cannot be combined with the other sets taken at different atmospheric conditions. Abdou *et al*. [16] and Strub *et al*. [17] suggest that practical data about the directional reflectance behavior of different objects that have been collected so far, require the use of the hemispherical-directional reflectance factor, rather than the bidirectional reflectance approach, because the incident irradiance consist of a mixture of direct solar and non-isotropic diffuse illumination.

The difficulties in the soil surface hemispherical-directional reflectance measurements arouse interest of their modeling.

The latest geometrical model, worked out by this paper authors [1], predicting the hemispherical-directional reflectance for soil or rocky surfaces of a given roughness under conditions of outdoor illumination, was used for studying soil albedo variation, taking geometry of the surfaces and its illumination conditions into consideration.

METHODS

The model simulates a rough soil or rocky surface as a geometrical creation similar to beads merging into each other. This virtual surface is characterized by three parameters *a*, *b* and *c*. The *a* and *b* describe its height variation along the *x*-axis and the *y*-axis, by the amplitude of the sinus function. The *c* expresses the disturbance in the height position in relation to that determined by only the *a* and *b* parameters. The virtual surface, as an opaque object, is illuminated by a hemispherical light source created by a number of point sources of given light intensities, equally spread on the hemisphere. Irregularities of the surface make impossible to completely illuminate it by all the light point sources. It is assumed that for outdoor conditions the ratio of the direct solar irradiance to the global irradiance for clear sky conditions changes with the sun's position, described by the solar zenith θ_S and azimuth ϕ_S angles, and the optical thickness of the atmosphere τ attributed to the wavelength. Distribution of the hemispherical light energy is described by the formula, taking also into account: the minimum amount of the energy, an amplification of the energy near the horizon, the concentration of the solar aureole and the energy at the darkest part of the hemisphere light in the quadrant opposite the sun. All these quantities are expressed by the constants, similarly as in the equation of Grant *et al.* [18]. The light energy is scattered from the surface, in accordance the quasi-Lambertian function, being a combination of the Lambertian scattering and the quasi-specular one. The distribution of the surface reflectance, as viewed from all the possible directions, can be described for all the possible illumination conditions expressed by the θ_S, ϕ_S and τ.

The root mean square error, assessing the accuracy of the model under clear sky conditions for the wavelengths from 450 nm to 1750 nm, does not exceed 0.1 for smooth and rough surfaces with their irregularities dispersed randomly and 0.14 for cultivated soil with a furrow microrelief [1].

Five virtual surfaces were used here for soil surface albedo variation analysis. These surfaces, were chosen as equivalents of real soil and rocky surfaces with a possible different shape.

RESULTS

These virtual surfaces represent uncultivated surfaces located in the Negev desert, the one smooth silty and the two rough rocky surfaces, as well as the two cultivated ones located in an agricultural field near Beer-Sheva in Israel. The latter are developed from the heavy soil material with furrows and only with soil aggregates randomly dispersed. The three of them, as representing the uncultivated surfaces, the smooth (SBs) and the rough (MRr), as well as the cultivated with a furrow microrelief (BSh), are presented with their virtual equivalents in Fig. 1.

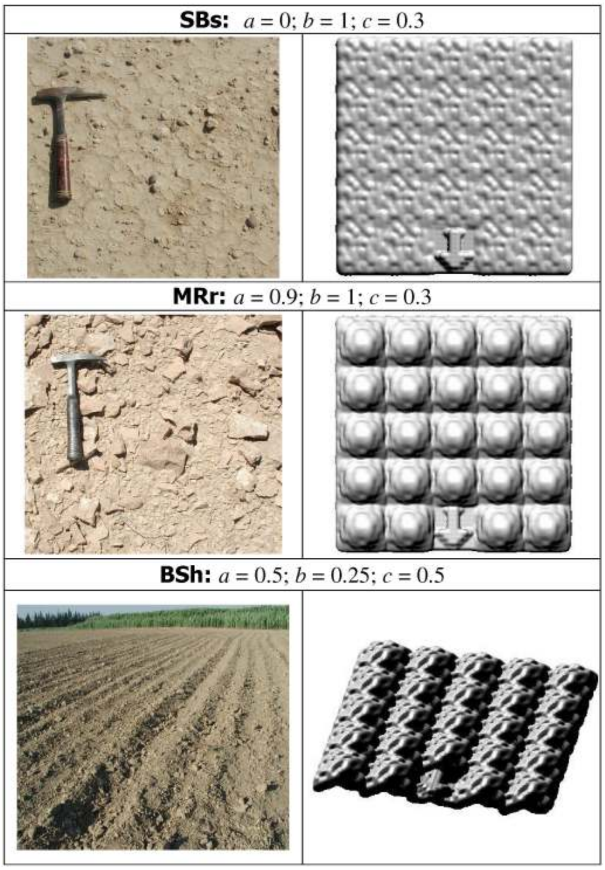

Fig. 1.View of the studied surfaces and their virtual equivalents: the desert smooth silty (SBs) and the very rough rocky (MRr), as well as the cultivated with furrow microrelief (BSh). The symbols *a*, *b* and *c* are the geometrical parameters of the virtual surfaces. The arrow shows the North direction.

This cultivated surface, *Calcic Xerosols*, developed from sandy loam, was prepared by a cultivator which shaped furrows with the 10 cm depth and the distance between their successive tops of 60 cm. All the virtual surfaces are similar to their real equivalents. The virtual surface simulating the cultivated surface with furrow (BSh) has clearly directional shape, expressed by the parameter $0<b<1$. The cultivated and the uncultivated surfaces, with their height irregularities randomly dispersed, are characterized by the virtual surfaces with the b=1. Furthermore, the greater the roughness of the real surfaces, the greater that of their virtual equivalents. The virtual surface of the relatively smooth surface (SBs) is described by a=0 and b=1, deformed only by the disturbance parameter c=0.3.

These virtual surfaces were used as the input data sets to predict the hemispherical-directional reflectance *HDR* of the analyzed surfaces. Their *HDR* was generated by the model for all possible view directions, described by the zenith θ_V and horizontal ϕ_V angles, at a wide range of the solar zenith angle θ_S between 10° and 80° and the atmosphere thickness τ varied from 0.1 to 15, relating to clear sky and completely overcast conditions, respectively. The examples of the *HDR* distributions of the chosen surfaces, presented in Fig. 2, show them only for the θ_S 20° and 80° and the τ 0.1 and 2. These τ values, describing the atmosphere state with the low and the high proportion of the diffuse light component respectively, cause a clearly different distribution of the sky radiation. In consequence of the τ=0.1, the high contrast between sunlit and shaded fragments of the studied surfaces is observed. However, for the τ=2 this contrast is very low. The *HDR* distributions are normalized to the nadir viewing. Variation of the θ_V is marked by concentric circle lines surrounding the nadir point (θ_V=0°) at 10° increments spread on the top of the graphs. These distributions are positioned with respect to the geographical North direction (N) marked at their bottom.

The rough surfaces, the cultivated (BSh), as well as the uncultivated (MRr), demonstrate a high variation of their *HDR*, while the smooth surface (SBs) shows the lowest. This relationship becomes stronger at the higher θ_S, and lower τ. All the analyzed *HDR* data exhibit a backscattering character, although these characterizing the smooth surface (SBs) at high θ_S angles also demonstrate specular features.

Generating the *HDR* data for the examined surfaces at given illumination conditions and then calculating the albedo for them, it was assumed that they are located at the same place. It enable us to specify the identical position of the sun for all studied surfaces at a chosen date. The date of 12th July and the place with geographical coordinates of 31.3°N and 34.7°E, when and where the *HDR* data from the cultivated surfaces were collected to test the model mentioned above, were chosen to the studies.

The albedo α of the analyzed soil and rocky surfaces were calculated from their *HDR* and sky radiance data predicted by the model as: the bispherical factor (A) and the factor, where both parts of the radiance, the reflected and the incident, are projected on the flat horizontal plane (B), like measured by a pyranometer (Fig. 3). This second way (B) of the albedo calculation essentially reduces the influence of the reflected and incident radiance coming obliquely to the sensors. The α variation of these surfaces is presented as the function of the solar zenith angle θ_S at the range from 10° to 80° and the optical thickness of the atmosphere τ varied from 0.1 to 5. The asymptotical shape of the relationship for higher values of the τ, analysed up to the τ=15, enable us to narrow its range in the figure 3 to the values between 0.1 and 5.

Results of the studies show that the α variation of the studied soil and rocky surfaces clearly depends on their shape and their illumination conditions. The α variation is much more sensitive to the illumination conditions, if the α is calculated according to the procedure A than the B.

- If the albedo is determined by the A formula, the larger irregularities of the surfaces, the lower the α variation in the function of the solar zenith angle θ_S and the atmosphere optical thickness τ. The α variation does not vary essentially for τ values higher than 3. The minimal albedo variation in the τ function is expected for θ_S angles between 60° and 65°. For θ_S lower than the critical ones, the higher the τ up to 0.5, the higher the α, while for higher τ than 0.5, the higher the τ, the lower the α. For θ_S higher than these critical values, the higher the τ, the higher the α.
- If the albedo is obtained by the B formula it is opposite, i.e., the higher irregularities, the higher the α variation. The albedo variation does not vary with respect to the τ for its values higher than 2. The influence of the atmosphere optical thickness τ is minimal at the solar

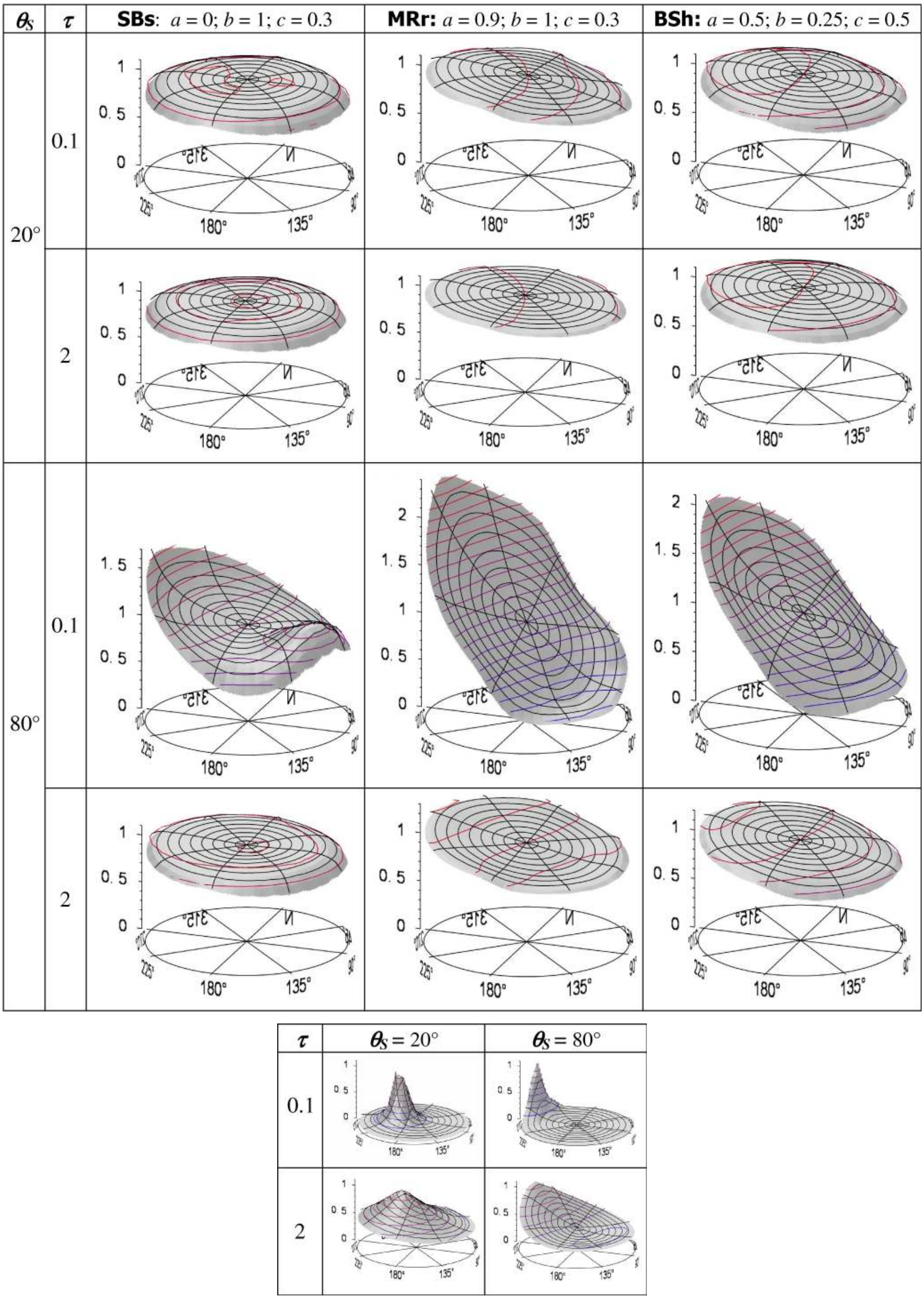

Fig. 2. Distributions of the normalised hemispherical-directional reflectance *HDR* of the desert silty (SBs) and rocky (MRr) surfaces and the cultivated one with the furrows microrelief (BSh), generated for chosen illumination conditions defined by the optical thickness of the atmosphere τ and the solar zenith angle θ_S. The sky radiation distributions connected with the selected illumination conditions, normalized to its maximum values, are presented at the bottom of the figure. The symbols a, b and c are the geometrical parameters of the virtual surfaces.

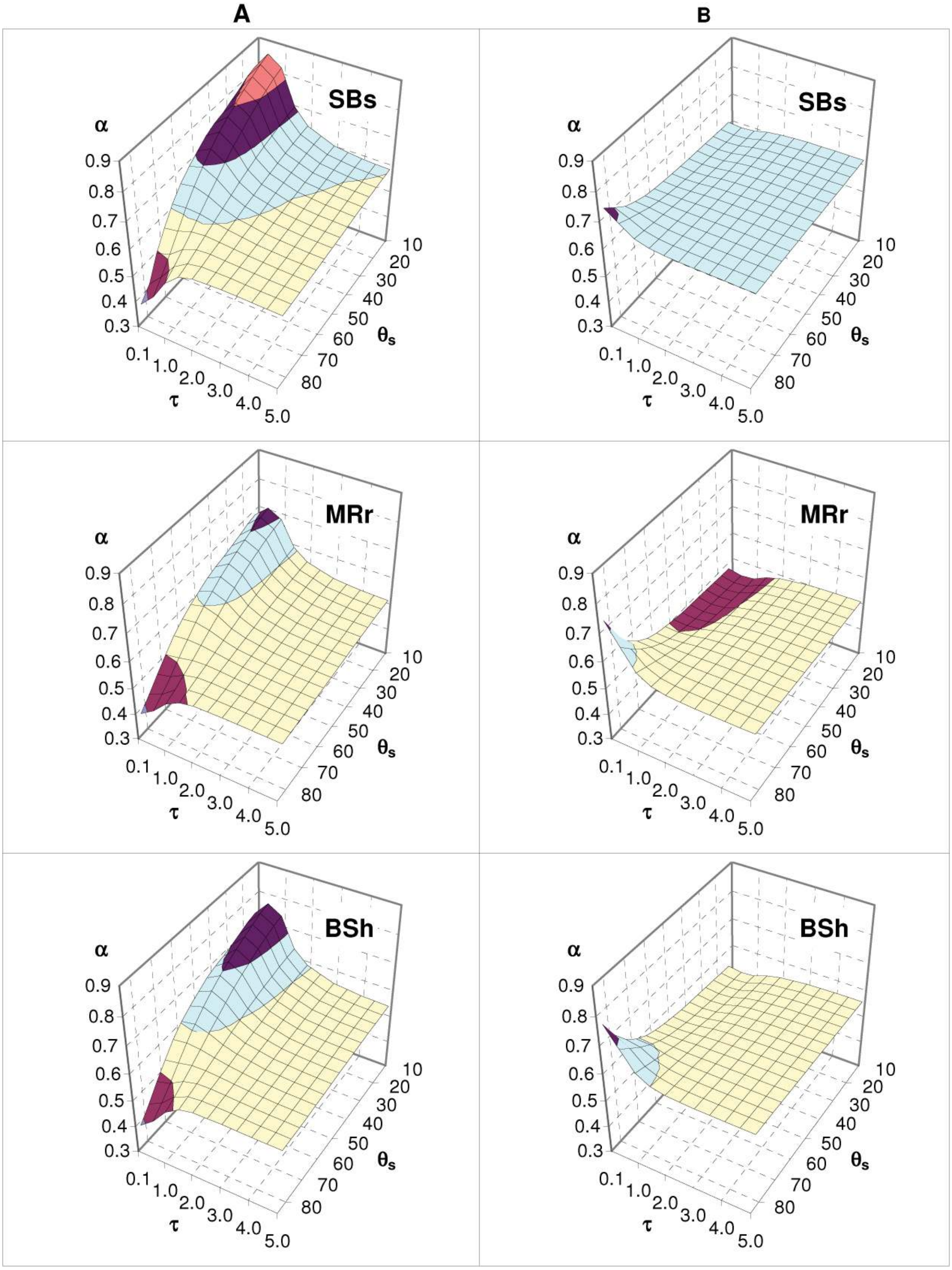

Fig. 3. Distributions of the albedo for the desert silty (SBs) and rocky (MRr) surfaces and the cultivated one with the furrows microrelief (BSh) in the function of the optical thickness of the atmosphere τ and the solar zenith angle θ_S, calculated from their reflected (*HDR*) and the incident sky radiance distributions as: the bispherical factor (A) and the factor, where the reflected radiance and the incident one, are projected on the flat horizontal plane (B).

- zenith angle θ_S of about 60°. For lower θ_S angles than this critical one, the higher the τ, the higher the α. For higher θ_S angles than this critical value this relation becomes opposite, i.e., the higher the τ, the lower the α.

CONCLUDING REMARKS

The results of our studies enable us to deeply understand the influence of soil and rocky surfaces shape and their illumination conditions on the albedo variation of these surfaces. The clearly higher sensitivity of the soil surface albedo calculated as the bispherical factor to the surface illumination conditions in comparison to the albedo computed like is measured by a pyranometer suggests testing the first one as the parameter to studies on energy transfer between soil, vegetation and atmosphere, as well as on climate studies at global and regional scales. Precision of Soil-Vegetation-Atmosphere Transfer Schemes (SVATS) and Global Climate Models (GCMs) strongly depends on an accuracy with which the surface albedo can be specified. Sellers [19] determines this accuracy requirement as ±2% for current GCMs. Users of the GCMs frequently assume insufficient precision of the albedo values, deriving them from inappropriate study results, where they are rather treated as invariable quantity [20]. Perhaps, the use of appropriate values of the albedo, selected to illumination conditions characterizing studied processes, will enable us to improve their modeling.

REFERENCES

[1] J. Cierniewski, T. Gdala, A. Karnieli. “A hemispherical-directional reflectance model as a tool for understanding image distinctions between cultivated and uncultivated bare surfaces”. **Remote Sensing of Environment**. Vol. 90. 2004. pp. 505-523.

[2] R.S. Fraser. „Interaction mechanisms – within the atmosphere (chapter 5)”. **Manual of Remote Sensing**. Vol. I. New York: American Society of Photogrammetry. Falls Church. 1975. pp. 181-233.

[3] K. Kondratyev. **Radiacyonnye kharakteristiki atmosfery i zemnoy powerkhnosti**. Leningrad: Gidrometeorologiczes-koye Izdatelstwo. 1969.

[4] S. Mayor, W.L. Smith, L. Nguyen, T. A. Alberta, P. Minnis, C.H. Whitlock, G.L. Schuster. “Asymmetry in diurnal variation of surface albedo”. http://techreports.larc.nasa.gov /ltrs/pdf/NASA-96-igars-sm.pdf.

[5] N. A. Michajlova, D.S. Orlov. **Opticheskie svoystva pochv i pochvennych komponentov**. Moskva: Nauka. 1986.

[6] A.I. Obuchov, D.S. Orlov. “Spektralnaya otrazatelnaya sposobnost glavneysykh tipov pochv i vozmoznost ispolzovaniya diffuznogo otrazenija pri pochvennykh issledovaniyakh”. **Pochvovedenie**. 1964. pp. 28:83-94.

[7] K.Y. Kondratyev, P.P. Fedchenko. “Vliyaniye obrabotki na spektralnye otrazatelnye svojstva pochvy”. **Pochvovede-nie**. Vol. 12. 1980. pp. 47-53.

[8] D.S. Kimes, P.J. Sellers. “Inferring hemispherical reflectance of the Earth’s surface for global energy budget from remotely sensed nadir or directional radiance values”. **Remote Sensing of Environment.** Vol. 18. 1985. pp. 205-223.

[9] E.J. Milton, J.P. Webb. “Ground radiometry and airborne multispectral survey of bare soils”. **International Journal of Remote Sensing**. Vol. 18. 1987. pp. 3-14.

[10] J.R. Irons, J.A. Smith. “Soil surface roughness characterization from light scattering observations”. **Procidings of 10th Annual International Geosciences and Remote Sensing Symposium, May 20-24, Washington DC**. Vol. II: 1990. pp. 1007-1010.

[11] K.L. Coulson. “Effect of reflection properties of natural surfaces in aerial reconnaissance”. **Applied Optic**. Vol. 5. 1966. pp. 905-917.

[12] M. Shoshany. “Roughness-reflectance relationship of bare desert terrain: An Empirical study”. **Remote Sensing of Environment.** Vol. 45. 1993. pp. 15-27.

[13] D.W. Deering, T.F. Eck, J. Otterman. “Bidirectional reflectance of selected desert surfaces and their three-parameter soil characterization”. **Agricultural and Forest Meteorology**. Vol. 52. 1990. pp. 71-90.

[14] E.J. Milton. “Principles of field spectroscopy”. **Remote Sensing Yearbook**. Vol. 1988-1989. 1989. pp. 79-99.

[15] S.R. Sandmeier. “Acquisition of bi-directional reflectance factor data with field goniometer”. **Remote Sensing of Environment**. Vol. 73. 2000. pp. 257-269.

[16] W.A. Abdou, J.E. Conel, S.H. Pilorz, M.C. Helmlinger, , C.J. Brugge, B.J. Gaitley, W.C. Ledoboer, J.V. Martonchik. “Vicarious calibration. a reflectance-based experiment with AirMISR”. **Remote Sensing of Environment**. Vol. 77. 2001. pp. 338-353.

[17] G. Strub, M.E. Schaepman, Y. Knyazikhin, K.I. Itten. “Evaluation of Spectrodirectional alfalfa canopy data acquired during DAISEX’99”. **IEEE Transactions on Geoscience and Remote Sensing**. Vol. 41. 2003. pp. 1034-1042.

[18] R.H. Grant, W. Gao, G. M. Heisler. “Photosynthetically-active radiation: sky radiance distributions under clear and overcast conditions”. **Agricultural and Forest Meteo-rology**. 82. 1996. pp. 267-292.

[19] P.J. Sellers. “Remote Sensing of the land surface for studies of global change”. **International Satellite Land Surface Climatology Project Report.** Columbia, MD: NASA/GSFC. 1993.

[20] P. Lewis, M.J. Barnsley. “Influence of the sky radiance distribution on various formulations of the earth surface albedo”. **Proceeding 6th International Symposium on Physical Measurements and Signatures in Remote Sensing, Val d'Isére, France, January 17-21, 1994**. 1994. pp.707-715.