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Absorption of insolation by land surfaces with sparse vertical protrusions

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ABSTRACT

Absorption of insolation by land surfaces is analyzed, applying a previously developed model of a plane with sparse protrusions, in which r_l and r_c are Lambertian reflectivities of the soil-plane and of the protrusions, respectively, and s is the projection on the vertical plane of protrusions over a unit area. The effective daylong absorption of insolation by this type of surface increases with latitude, sharply for dark protrusions, gradually if the reflectivity of the protrusions is equal to that of the soil-plane.

Inasmuch as the absorbed insolation is transferred to the atmosphere at a different rate by the protrusions than by the soil, the daylong absorption at equinox by the protrusions and by the soil-plane are analyzed separately, as functions of r_l, r_c, s and of the latitude. The dependence on the solar zenith angle of the partitioning of the surface absorption between these two components of our complex surface implies that its effective thermal inertia varies with time of day, season and latitude. Surface models, such as the one discussed, are required to interpret the various measurements of bidirectional reflectivity and/or albedo into a data set appropriate for climate studies, specifying (i) the surface albedo as a function of the direction of its irradiation, and (ii) the partitioning of the absorbed insolation into that by the protrusions, and that by the soil (from which the effective surface thermal inertia can be appropriately assessed). Measurements of s in a global survey over all the continents are needed.

1. Introduction

The solar heating of our planet is through absorption at the surface and in the atmosphere. Inasmuch as about 2/3 of the solar heating is by surface absorption, studies of the surface characteristics that bear on the absorption deserve as much attention as those of the atmosphere. The absorption processes are time-of-year dependent: in the atmosphere, mainly through the seasonal changes in the cloud cover, and at the surface, mainly through the changes in the snow cover and in the vegetation characteristics. The seasonal variability in the surface albedo is especially pronounced at latitudes 60 to 70° (both S and N), where the reported differences between late local summer and winter are in the 0.3 to 0.5 range (Kukla and Robinson, 1980).

Measuring the surface albedo and its changes is a relatively simple task if the surface behaves as a Lambert plane. The reflected radiance is then independent of the viewing direction and of the direction of the surface irradiation. Measurement of a radiance for any direction of observation when multiplied by π yields the reflected flux. For an unchanging surface, the albedo remains a constant; this single-value parameter does not change if the direction of the irradiation changes. Thus, one measurement of a reflected radiance or of a reflected flux, in addition to one measurement of the flux impinging on the surface, establishes the albedo. Not only are the measurements easy, but the calculations are also simple. In calculating the solar energy absorbed by the surface by summing up the instantaneous products of the surface irradiance that changes continually from sunrise to sunset, and of the co-albedo (absorptivity), the

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constant co-albedo can be taken outside the summation sign[1].

A planar representation of the earth surface is widely used in meteorological/climatological calculations of the absorption of insolation. A discerning look at almost any natural landscape puts in doubt the adequacy of this representation, with the exception of sandy deserts, playas, and generally, areas of bare soil. Landscape photographs in textbooks on the geography of plants (see, for instance Polunin, 1960; Gleason and Cronquist, 1964) suggest readily that plants generally protrude from the plane of the soil. Most ecosystems therefore constitute complex surfaces and are thus non-Lambertian reflectors. The non-Lambertian characteristics of vegetated areas have been recognized and quantitatively assessed by Monteith and Szeicz (1961) for grass and by Stewart (1971) for forests, for instance.

The absorptivity/reflectivity of a complex surface depends on the direction of the irradiating beam. It can be simply stated that a complex surface presents to the irradiating beam its different aspects at different times. The reflectivity at each aspect is determined not only by the reflectivities of the materials, but also by the three-dimensional configuration in which a reflection from one element of the structure can be intercepted by another element. This effect is often referred to as photon-trapping.

In agricultural meteorology, the absorption of the solar radiation by a plant canopy is studied by nonplanar models. For widely spaced bushes, the representation as vertical protrusions from the soil is the standard and quite obvious practice (Jackson and Palmer, 1972; Allen, 1974; Fuchs et al., 1976). Analyzing the absorption by a plants–soil system using a plane with protrusions representation appears appropriate for many surfaces, such as stubble field, savannah, urban areas, taiga, and tundra. This approach is not currently the common practice in meteorological/climatological modeling for any terrain type, probably because representation as a Lambert plane is considerably simpler.

For non-Lambertian surfaces a measurement of a bidirectional reflectivity in one direction does not convey information about the albedo (even the "instantaneous" albedo at the time of the measurement) because the radiances in all other directions remain unspecified. This question is quite significant today, inasmuch as many of the satellite measurements are of this nature. One needs to resort to some auxiliary information or assumptions, to determine the "instantaneous" albedo.

When collecting radiation nearly to the horizon on all sides, through a "2π" aperture, the upwelling flux is measured, and not a radiance in a single direction. Most aircraft and tower measurements use this approach. Such measurements lead directly and correctly to an "instantaneous" albedo. However, if the albedo depends on the direction of irradiation, it is difficult to translate one, two, or even several such measurements into an effective albedo for the daylong insolation on the day of the measurement. It is even more difficult to calculate the effective albedo for a month or a season. In our opinion, it is through simple surface models that the different measurements of the bidirectional reflectivity and of the "instantaneous" albedo, at different times of day or on different days, can be translated into a data set meaningful in meteorological/climatological studies.

There is one additional and important point why we should resort to modeling of the surface. The solar energy absorbed by plants that protrude from the plane of the soil is transferred to the atmosphere much more readily than the energy absorbed by the soil. The rate of exchange of both the sensible and the latent heat, especially at an onset of wind, can be much higher for the protrusions than for the soil. Thus, the partitioning of the solar energy absorbed at the surface into soil absorption and protrusions absorption is significant in meteorological studies for formulating the surface–atmosphere interactions. The suggested partitioning is an attempt to formulate the interactions on the basis of a variable albedo *and* a variable thermal inertia. Information on this partitioning is not provided if the surface albedo is represented by a single parameter.

We first present a plane with protrusions reflectivities model developed previously. Subsequently, we calculate the absorption at the

[1] This holds for the spectral surface albedo or co-albedo, used with the spectral surface irradiance. Surface albedo averaged for the entire solar spectrum applies only for a given spectral distribution of the surface irradiance, unless the spectral albedo is constant in all the bands. This spectral distribution generally changes as a function of the solar zenith angle and the atmospheric conditions. A fuller discussion of this problem area is presented elsewhere (Otterman, 1983).

surface[2] from a direct solar beam at equinox, as a function of latitude. It should be stressed that the model was developed to analyze sparse protrusions. It is not appropriate for terrain types such as a dense forest.

2. The hemispheric reflectivities and the absorptivities of plane with sparse protrusions

Under arid conditions, plants grow as isolated tussocks or bushes, to draw moisture from the large interstices. A simple representation has been specifically developed for monitoring arid steppe regions from satellites (from zenith; Otterman, 1981a). The plants are modeled as thin vertical cylinders. The model is specified by only one geometrical parameter s, which is the product of height, diameter and number of cylinders per unit area (s is dimensionless). The soil and the cylinder mantles (the area of the vertical protrusions) are assumed as of a definite Lambertian reflectivity: r_i for the soil interstices and r_c for the cylinders.

The shadow cast on the horizontal plane of the soil by a single cylinder or several cylinders with a projection s on a vertical plane is $s\eta_0$, where $\eta_0 = \tan \theta_0$ and θ_0 is the solar zenith angle. It means that a fraction $1 - s\eta_0$ of the solar beam is intercepted by the soil and a fraction $s\eta_0$ by the cylinders. This holds true as long as the shadow of one cylinder does not fall in part on another cylinder. With lengthening shadows, this model (Otterman, 1981a) becomes inaccurate and eventually breaks down at large solar zenith angles.

Overlapping of shadows can be taken into account if these fractional direct fluxes are expressed by exponentials in $-s\eta_0$, rather than by the linear terms. The fractional direct flux is then $\exp(-s\eta_0)$ on the soil and $1 - \exp(-s\eta_0)$ on the cylinders; see Otterman (1981b) for a derivation where random distribution of plant-to-neighbor distances and azimuths is assumed.

A radiation pencil reflected from the soil at a zenith angle θ is assumed to reach the atmosphere without interception by the protrusions with a probability $\exp(-s \tan \theta)$, that is, with the same probability that an irradiating beam along an opposite direction will strike the soil. Integrating over all the pencils of radiation that constitute the fractional flux $r_i \exp(-s\eta_0)$ reflected from the soil, the fraction $I(s)$ of that flux intercepted by the protrusions is given as:

$$I(s) = 2 \int_0^{\pi/2} \cos \theta \sin \theta [1 - \exp(-s \tan \theta)] d\theta, \qquad (1)$$

where $\cos \theta/\pi$ represents a reflected radiation pencil, $2\pi \sin \theta \, d\theta$ is the differential solid angle, and where π cancels out.

Thus, the soil-to-cylinders reflection contributes $I(s) r_i \exp(-s\eta_0)$ to the fractional flux on the cylinders. Neglecting cylinder-to-cylinder reflection, half of the flux reflected from the cylinders escapes to the atmosphere and the other half impinges on the soil. The first cylinders-to-soil reflection therefore contributes $[1 - \exp(-s\eta_0)] \times r_c/2$ to the fractional flux on the soil-plane. Because of these assumptions, the model is not appropriate for dense protrusions.

Based on this model and considering only one cylinders-to-soil and one soil-to-cylinders reflection calculated in the previous paragraph, the in situ absorptivity ν_i of the soil (the absorptivity, $1 - r_i$, times the fractional flux on the soil) for the direct solar beam is

$$\nu_i(s,\eta_0,r_i,r_c) = (1 - r_i) \{\exp(-s\eta_0) + r_c[1 - \exp(-s\eta_0)]/2\}, \qquad (2)$$

and the in situ absorptivity ν_c of the protrusions is

$$\nu_c(s,\eta_0,r_i,r_c) = (1 - r_c) [1 - \exp(-s\eta_0) + I(s) r_i \exp(-s\eta_0)]. \qquad (3)$$

The hemispheric reflectivity R (spectral albedo) of the protrusions/soil-plane system, $R = 1 - \nu_i - \nu_c$, is

$$R(s,\eta_0,r_i,r_c) = r_i \exp(-s\eta_0)[1 - I(s)(1 - r_c)] + r_c[1 - \exp(-s\eta_0)](1 + r_i)/2 \qquad (4)$$

Whereas the reflectivity of a Lambert plane does not depend on the direction of the irradiation, R changes from $r_i[1 - I(s)(1 - r_c)]$ when $\theta_0 = 0$ to $r_c(1 + r_i)/2$ when $\theta_0 \to 90°$. For any θ_0, R is lower than that of a Lambert plane (when the reflectivity

[2] In a section below, we compute and discuss ratios of daylong absorption by a plane with sparse protrusions to that by a Lambert plane. It is certainly not implied that the use of the one-parameter albedo, such as tabulated by Kukla and Robinson (1980), is in error in the same ratios, or in error at all. The one-parameter monthly albedo *can* represent an appropriate climatic average for a surface, whether it is planar or complex. We do suggest that the task of deriving such appropriate climatic average albedo is difficult for a complex surface.

of the Lambert plane equals r_l) unless the protrusions reflect *much* more strongly than the soil-plane, that is, unless $r_c > 2r_l/(1 + r_l)$. The reduction in the reflectivity for sun near the horizon is obviously more pronounced if r_c is lower than r_l.

The photon-trapping effects in the structure of a nonplanar surface depend on the configuration, but also on the magnitude of the reflectivity of the materials. It is quite easy to demonstrate this point: if the reflectivity of all the materials is zero, the reflectivity of a complex surface equals that of a planar surface constructed with the same materials. Thus, there is no photon-trapping effect. We analyze the photon-trapping effect, comparing the absorptivity of a complex surface with that of a Lambert plane. The comparison of the absorptivities can be more directly meaningful for climate studies, especially if the surface is bright and thus a small percentage change in the reflection corresponds to a large percentage change in the absorption. The absorptivity ν_h of our plane with sparse protrusions for $\theta_0 \to 90°$, when $r_c = r_l = r$, is $[2 - r(1 + r)]/2$. The absorptivity ν_u of Lambert plane is $1 - r$. Their ratio

$$\frac{\nu_h}{\nu_u} = \frac{2 - r(1 + r)}{2(1 - r)} = \frac{2 + r}{2} \tag{5}$$

is 1 for $r = 0$ (as discussed above), increases linearly with increasing r, and tends to 1.5 for a large r. Caution should be exercised in applying this equation in the case of r approaching 1, because the third and higher reflections, for which we failed to consider the absorption, become non-negligible. Nevertheless this equation points to the dependence of the photon-trapping in a complex structure on the value of the reflectivity of the materials. This dependence is assessed in a later section by daylong integration of the absorption at the surface for the latitude of 60°.

The hemispheric reflectivity R and the in situ absorptivities ν_l and ν_c of our protrusions/soil-plane surface can be calculated only if the direction of the irradiance is specified. We calculate it for the direct beam only. In Fig. 1, ν_l, ν_c and R are graphed as specified by eqs. (2), (3), and (4), respectively, as a function of θ_0, the zenith angle of the solar beam. These 3 functions obviously add up to 1 at any θ_0. The plots are for $s = 0.2$ and $r_l = 0.5$, and for two values of r_c: $r_c = 0$ in Fig. 1A, and $r_c = r_l = 0.5$ in Fig. 1B. We note that the reflectivity R is always lower than the reflectivity 0.5 of the soil-plane. In the absence of the protrusions, the soil-plane would constitute a Lambertian surface with a reflectivity r_l. The reflectivity R decreases sharply with increasing zenith angle θ_0 if the protrusions are dark, $r_c = 0$, as in Fig. 1A; the decrease with θ_0 is only gradual if $r_c = r_l = 0.5$, as in Fig. 1B. The in situ absorptivity of the protrusions increases with

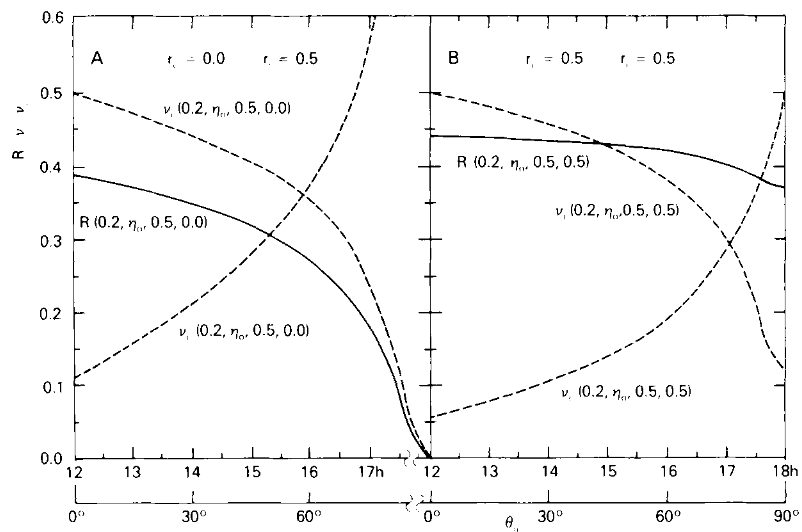

Fig. 1. The hemispheric reflectivity R (s,η_0,r_l,r_c) of the protrusions/soil-plane system, the in situ absorptivity of the protrusions ν_c (s,η_0,r_l,r_c), the in situ absorptivity of the soil ν_l (s,η_0,r_l,r_c), all as a function of θ_0 (or the time of day for equinox, at the equator); $s = 0.2$; Fig. 1A: $r_l = 0.5$, $r_c = 0$; Fig. 1B: $r_c = r_l = 0.5$.

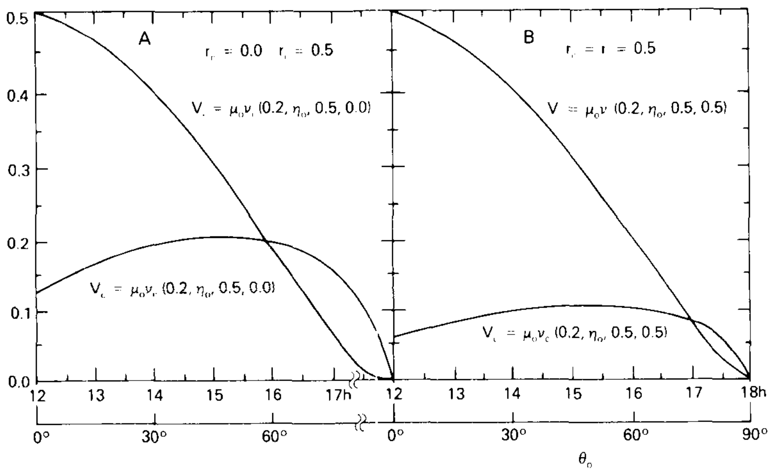

Fig. 2. The rate of absorption of the insolation μ_0 by the protrusions $V_c = \mu_0 v_0 (s,\eta_0,r_l,r_c)$ and by the soil $V_l = \mu_0 v_l (s,\eta_0,r_l,r_c)$ as a function of θ_0 (or the time of day for equinox, at the equator): $s = 0.2$; Fig. 2A; $r_c = 0$, $r_l = 0.5$; Fig. 2B; $r_c = r_l = 0.5$.

increasing θ_0, very steeply if the protrusions are dark, Fig. 1A, less steeply if $r_c = r_l$, Fig. 1B. The in situ absorptivity of the soil decreases with θ_0 and becomes quite small at large zenith angles.

We noted in Fig. 1 that the in situ absorptivity of the protrusions is much larger than that of the soil at large zenith angles. At such angles the insolation is low. Thus, we should examine whether the rates of the absorption are significant. This question is addressed in Fig. 2, where the absorption rates from the direct solar beam, $V_l = \mu_0 v_l$ by the soil-plane and $V_c = \mu_0 v_c$ by the protrusions, are plotted versus θ_0. For $s = 0.2$, the rates of absorption by the protrusions are especially significant if the protrusions are dark, $r_c = 0$, Fig. 2A. The rates in this case are about twice as large, for a given zenith angle, than those in the case $r_c = r_l = 0.5$, Fig. 2B. In both cases, the plots suggest that the rates of absorption by the protrusions are about the same at $\theta_0 = 75°$ as at high noon, $\theta_0 = 0°$. On a closer inspection, if atmospheric scattering/absorption are considered, this can be shown to be a somewhat crude approximation.

The graphs in Figs. 1A and 2A are for $r_c = 0$. The approximation $r_c = 0$ is appropriate during the periods when the ground is still (or already) covered by snow, but with the trees free from snow. These conditions generally prevail at a snow boundary, that is, the expansion/shrinking of the snow cover occurs under such conditions.

3. Determination of the protrusion parameter *s* for four ecosystems

An ungrazed range in arid Utah has been selected as a test site for determining *s* by remote sensing. Reflectivities of the surface–atmosphere system over this site computed from nine Landsat passes from January to December 1976, show a reflectivity decrease of nearly 30% in the 0.8–1.1 μm band from the June highs to the winter (both January and December) lows.[1] The reflectivities in the other bands (shorter wavelengths) follow a comparable pattern but the winter decreases are somewhat smaller. Such seasonal decreases in the reflectivity to zenith for an effectively unchanging terrain, and also their wavelength dependence,[2] are compatible with the increased shadowing by the protrusions as represented in our model. Landsat is a sun synchronous satellite, that is, its passages occur throughout the year at essentially the same local time, at 09.30 a.m. At this time the solar zenith angle over Utah is much larger in winter

[1] The reflectivities of a playa, a few kilometers from this ungrazed range, remain essentially constant throughout the year.

[2] The seasonal changes in the reflectivity measured from the satellite are smaller at the shorter wavelength because the scattered component of the surface irradiance (Rayleigh scattering) is larger.

than in summer. Best estimate of r_l, for each of the four spectral bands of Landsat, using the equation for the reflectivity to the zenith (not presented here) leads to a determination of the protrusion parameter s as well as of r_l. This measurement of s yields $s = 0.10$ with only small deviations from one spectral band to another (Otterman, 1981c).

In a similar study, the parameter s was determined for a fenced area (exclosure) in the northern Sinai, using data from four Landsat passes in the 1975 to 1979 period. The strong recovery of the vegetation when grazing was stopped in the exclosure, produced a plane with protrusions situation (Otterman, 1981a). The surrounding terrain, severely overgrazed, can be approximately described as a planar surface of bare sands. Using the ratio of the radiance measured by Landsat over the exclosure to that measured over the surroundings, Otterman and Robinove (1982) determined s to be about 0.18.

The absorption of the insolation by the taiga (boreal forest) is of special interest, because it covers large areas at the high northern latitudes. An aerial photograph taken near Hudson Bay (59.5° N), with trees showing up dark against a white background of snow on the ground, was especially useful. The parameter s was found to range from 0.3 to 0.5. This range of s can be thought as appropriate for *some* areas of the taiga, just south of the tundra, where tree-to-neighbor distances are relatively large.

The fourth ecosystem for which we assess the parameter s is the Thetford Forest, Norfolk, U.K. This approximate determination is based on the measurements by Ford (1976) on an experimental site that contained 387 trees. At the time of the measurements, in 1970, these Scots pines were about 40 years old. Ford (1976) reports the average vertical projection of a live crown as 10.9 m^2 and the average space per tree as 9.95 m^2. Dividing the first area by the second, we obtain $s \simeq 1.1$. In this determination of s, we neglect the contribution to s of the trunk and the dry branches below the live crown. This value of s indicates that the Thetford forest is too dense to be modelled as a plane with sparse protrusions.

4. Numerical results of modeling the absorption at the surface at equinox

Daylong absorption at the surface from the direct solar beam at equinox is computed by numerical integration, and the results are presented in Figs. 3, 4, and 5. The direct solar beam is represented as $\mu_0 = \cos\theta_0$. For equinox, we have $\mu_0 = \cos\theta_0 = \cos z \cos t$, where z is the latitude and t is time measured from the local noon in $\pi/12$ radians per hour. The daylong absorption by the soil is

$$\bar{V}_l(s,z,r_l,r_c) = \int_{-\pi/2}^{\pi/2} \mu_0(z,t)\, \nu_l(s,\eta_0,r_l,r_c)\,\mathrm{d}t, \qquad (6)$$

where the in situ absorptivity of the soil ν_l is defined by eq. (2), and similarly the daylong absorption by the protrusions is

$$\bar{V}_c(s,z,r_l,r_c) = \int_{-\pi/2}^{\pi/2} \mu_0(z,t)\, \nu_c(s,\eta_0,r_l,r_c)\,\mathrm{d}t, \qquad (7)$$

where ν_c is defined by eq. (3).

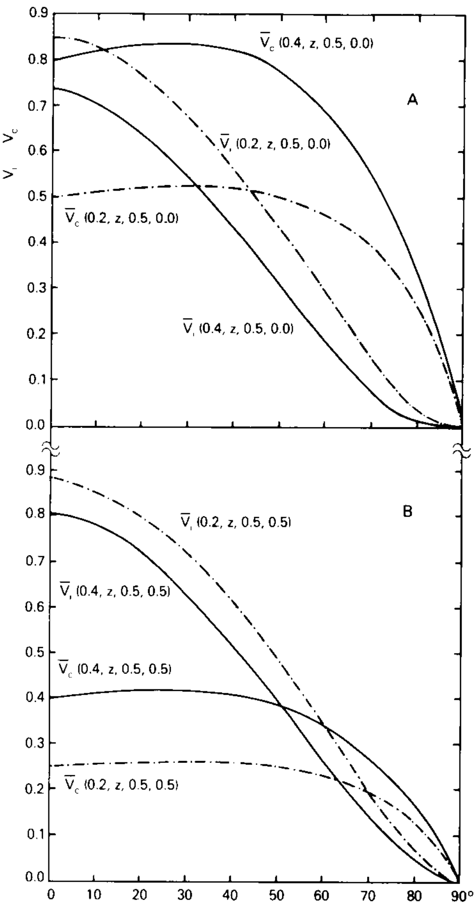

Fig. 3. The daylong integrals of the absorption by the protrusions $\bar{V}_c$ (s,z,r_l,r_c) and by the soil $\bar{V}_l$ (s,z,r_l,r_c) for equinox as a function of z; $s = 0.2$ dotted lines; $s = 0.4$, solid lines; Fig. 3A: $r_l = 0.5$, $r_c = 0$; Fig. 3B: $r_c = r_l = 0.5$.

An insight into how the parameters s, r_l and r_c influence the solar heating for the various latitudes can be gained from the graphs of the absorption by the soil $\bar{V}_l$ and by the protrusions $\bar{V}_c$, versus latitude z, Fig. 3. All the functions $\bar{V}_c$ increase slowly from the equator, reach their peak values in mid-latitudes, 25° to 45°, and subsequently decrease slowly to a latitude of about 60°. At still higher latitudes, the decrease is steeper; however, even at $z = 75°$ the functions $\bar{V}_c$ have appreciable values. The functions $\bar{V}_l$ decrease monotonically from the equator to the pole, slowly until about $z = 15°$ and steeply in mid-latitudes. The relative values of $\bar{V}_c$ and $\bar{V}_l$ depend on s and r_c as well as on the latitude. In all the comparisons of Fig. 3 the same r_l is assumed. When $r_c = 0$, Fig. 3A, for $s = 0.4$, $\bar{V}_c$ is slightly higher than $\bar{V}_l$ at the equator but higher by a factor of two to three in mid-latitudes. For $s = 0.2$, $\bar{V}_c$ is smaller than $\bar{V}_l$ by a factor of about 1.7 at the equator, and the two absorption functions become equal at $z = 38°$. When $r_c = 0.5$, Fig. 3B, at the equator the absorption by the soil $\bar{V}_l$ is much larger that the absorption by the protrusions $\bar{V}_c$. The two functions become equal at $z = 50°$ and at $z = 70°$ for $s = 0.4$ and $s = 0.2$, respectively. In all these four cases of s and r_c, the $\bar{V}_c$ functions are higher or much higher than the $\bar{V}_l$ functions above the 70° latitude.

The effective surface reflectivity for daylong insolation is

$$\bar{R}(s,z,r_l,t_c) = 1 - [\bar{V}_l(s,z,r_l,r_c) + \bar{V}_c(s,z,r_l,r_c)]/\textstyle\int_{-\pi/2}^{\pi/2} \mu_0(z,t)\,\mathrm{d}t. \qquad (8)$$

The reflectivity $\bar{R}$ is graphed in Fig. 4 for two values of s, $s = 0.2$ and 0.4, for $r_l = 0.5$ and for two values of r_c, $r_c = 0.5$ and $r_c = 0$. The data should be compared with a Lambert plane with a reflectivity equal to the reflectivity of the soil-plane r_l (in the absence of protrusions $\bar{R} = r_l$). $\bar{R}$ in the graphs are significantly lower than 0.5. When the protrusions are non-reflecting ($r_c = 0$) and $s = 0.2$, $\bar{R}$ at the equator is 2/3 of r_l; when $s = 0.4$, it is less than 1/2 of r_l. Near the pole $\bar{R}$ goes to zero for either value of s. This holds s true for any non-zero s, if $r_c = 0$. When the reflectivity of the protrusions equals that of the soil-plane, $r_c = r_l = 0.5$, near the equator $\bar{R} \approx 0.43$ for $s = 0.2$ and $\bar{R} \approx 0.40$ for $s = 0.4$. The reflectivities $\bar{R}$ for $r_c = r_l$ decline only slightly with latitude and tend to a value $r_c\,(1 + r_l)/2 = 0.375$ near the pole.

In Fig. 5, the ratio of the absorption by a plane with protrusions, $\bar{V}_s = \bar{V}_l + \bar{V}_c$, to that by a Lambert surface, $\bar{V}_f(r_l,z) = (1 - r_l)\int_{-\pi/2}^{\pi/2} \mu_0(z,t)\,\mathrm{d}t$, is plotted versus s for $r_c = r_l$ and for $r_c = 0$. In representing open forests, the first set approximates situations when the ground is covered by moss and

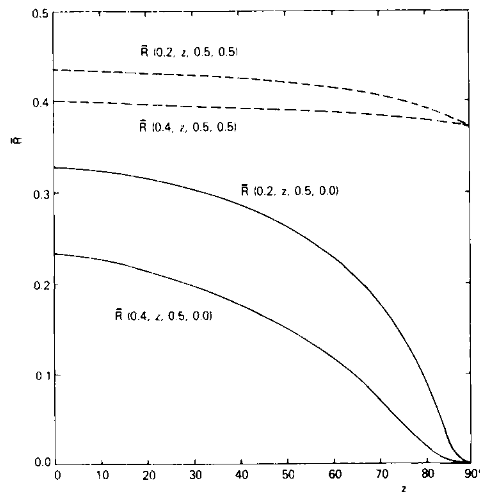

Fig. 4. The average hemispheric reflectivity for equinox $\bar{R}$ (s,z,r_l,r_c) as a function of z, $s = 0.2$ or 0.4; $r_l = 0.5$, $r_c = 0$, solid lines; $r_l = 0.5$, $r_c = 0.5$, dotted lines.

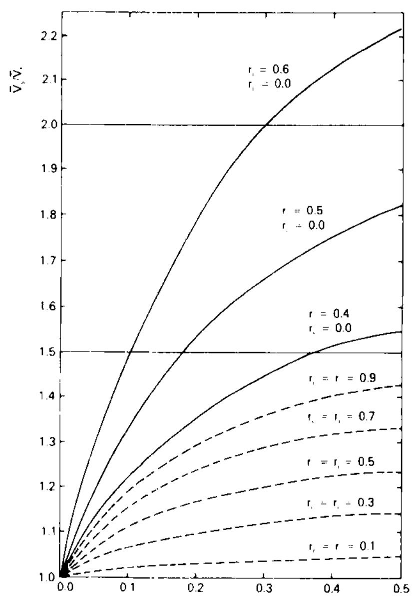

Fig. 5. The ratio of the average daylong absorption by a plane with protrusions $\bar{V}_s$ (s,z,r_l,r_c) to that by a Lambert plane with reflectivity r_l, for equinox, latitude 60°, as a function of s, for various values of r_l; $r_c = 0$, solid lines; $r_c = r_l$, dotted lines.

grass and the second set approximates snow-covered ground with snow-free trees. In the $r_c = r_l = r$ set, for $s = 0.5$ (the upper values of our measurements for the taiga), the $\bar{V}_s/\bar{V}_f$ ratio ranges from 1.05 for $r = 0.1$ to 1.43 for $r = 0.9$. At this value of s, the graphs of the $\bar{V}_s/\bar{V}_f$ ratio vs s are almost horizontal. The ratios are practically equal to the values of the asymptotic solution $(2 + r)/2$ for the irradiation at large zenith angles (or, more accurately, at high values of $s\eta_0$).

In the $r_c = 0$ set, the $\bar{V}_s/\bar{V}_f$ ratios increase from 1.55 if $r_l = 0.4$ to 2.22 if $r_l = 0.6$, in both cases for $s = 0.5$. In this set, the graphs of $\bar{V}_s/\bar{V}_f$ continue to slope strongly at this point of s. For still higher values of s, the reflectivity of our protrusions/soil-plane system is effectively controlled by the reflectivity of the protrusions and the approximation $r_c = 0$ becomes inappropriate even when the protrusions have a very low reflectivity.

5. Discussion and conclusions

Sandy deserts appear to be the only land surface that covers very large areas and which can be approximately treated as a Lambert plane. Vegetated areas can hardly be regarded as planar, because essentially all plants form protrusions from the soil on various scales. An appropriate description of such surfaces requires at least one parameter quantifying the departure from the planar character. The previous study of the arid steppe (Otterman, 1981b) and this paper are attempts to introduce a simple model with such a parameter (our s) and by means of the model to suggest a nonplanar representation of land surfaces in climate studies.

Scaling up or down of a complex surface does not affect the proportions in any aspect presented to an irradiating beam. Thus, the actual dimensions of the protrusions in our model have no significance for the absorption of insolation and the model can apply to skyscrapers just as well as to stubble or to the scraggly growth of the tundra. Only when analyzing the surface–atmosphere heat transfer do the dimensions become important, inasmuch as the thermal inertia is a function of the actual dimensions.

The main conclusion emerging from the daylong measurements of plant temperatures and soil temperatures conducted by Otterman (1981b) was that the arid region vegetation, because of its low thermal inertia and high exposure to the wind, yields the absorbed insolation to the atmosphere almost immediately at the onset of a breeze. This rather obvious point provides the motivation for computing and analyzing the two distinct functions, one for the absorption of the insolation by the protrusions, V_c, and the other for the absorption by the soil, V_l. The protrusion parameter s controls the partitioning of the absorption between these two components of the surface for a given solar zenith angle. The dependence of the partitioning on the solar zenith angle indicates that the effective thermal inertia as well as the albedo are time-of-day dependent.

Both the vertical cylinder mantles s and the horizontal plane of the soil are assumed here to be of a specific Lambert law reflectivity, r_c and r_l respectively. The absorption at various latitudes is examined parametrically in terms of s and of these two reflectivities. Some very high reflectivities are included, aiming to represent snow cover. The case $r_c = 0$ is given special attention, because for many ecosystems r_c is much lower that r_l, at least in some spectral bands. In an arid steppe, many plants consist mostly of brown grey stalks and twigs, the reflectivity of which is typically by a factor of about two lower than that of a sandy soil (Otterman, 1981a). The conifers of taiga are dark, and $r_c = 0$ approximates their low reflectivity in contrast to the snow on the ground.

Applying the model to a numerical study of the absorption of the solar energy by the surface, we arrive at these conditions:

(a) The absorptivity of a plane with sparse protrusions is higher than that of a Lambert plane, assuming that the reflectivity of the Lambert plane equals r_l, and that $r_c \leqslant r_l$.

(b) The ratio between the absorption by a plane with sparse protrusions to that by a Lambert plane increases with the zenith angle of the irradiating beam. The increase is steep for a low r_c (represented here as $r_c = 0$). The increase is less pronounced if $r_c = r_l$.

(c) The ratio $\bar{V}_s/\bar{V}_f$ of the daylong absorption by a plane with protrusions to that by a Lambert plane calculated for latitude of 60°, at equinox, increases with a steep slope with increasing s, when s is low. For a higher s (in the range 0.3–0.5) the slope remains fairly steep when $r_c = 0$ but is gradual when $r_c = r_l$ (see Fig. 5).

(d) When $r_c = r_l = r$, the ratios $\bar{V}_s/\bar{V}_f$ at 60°

latitude are much larger for a large value of r than for a low r, as indicated by eq. (5).

The latitude of 60° was selected for the more detailed calculations, because at 60° to 70° N, and constitutes 2/3 of the circumference of the globe. These latitudes merit special attention in climate studies, because the analysis of the absorption under a realistic representation of the surface might lead to a better assessment of the ice/snow albedo feedback.

Because the absorptivity of a plane with protrusions is quite sensitive to the direction of illumination, especially when r_c is much smaller that r_t, it appears worthwhile to reexamine the studies of the Milankovitch theory of the ice ages, such as by Suarez and Held (1979), using a complex surface representation of land areas. The latitudinal and seasonal redistribution *and* redirection of insolation, produced by variation in the orbital parameter of the earth (obliquity, eccentricity and the longitude of perihelion) will produce effects, when calculated for a plane with protrusions, possibly different to those resulting solely from the redistribution assuming a Lambert plane representation.

Our model, eqs. (2), (3), (4) could be introduced today into climate simulation programs only on a "for instance", parametric basis. At the present, data are not available for an adequate characterization of terrain as a complex surface, whether on a global or on a regional scale. Observations over different ecosystems and terrain types appear warranted, to better define the actual surface characteristics of our planet. Combined field, aircraft and satellite measurements programs would be most worthwhile. Daylong observations from a geosynchronous orbit, from the same viewing direction but at various directions of the solar irradiation, appear especially advantageous (Otterman et al., 1983).

Improvements in our model might be necessary for some ecosystems. A parameter could be added to quantify the fractional area of the protrusion tops for savannah and urban areas. An analysis of dense protrusions also based on the three parameters r_t, r_c and s, compatible with this study, appears worthwhile. This study is presented only for the direct solar beam. The direct beam is a reasonable approximation to the surface irradiance only in the infrared part of the spectrum under a clear atmosphere. The effects of the atmosphere on the absorption at the surface of the solar radiation should be analyzed comparatively for the different representations of the surface.

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