Albedo and Transmittance of Inhomogeneous Stratus Clouds

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A highly important topic of recent concern has been the study of the relationship between the statistical parameters of optical and radiative characteristics of inhomogeneous stratus clouds. This relationship is important not only because it can be used to derive geophysical information (cloud spatial structure, within-cloud turbulence, etc.), but also because the radiation codes of general circulation models (GCMs) need improvement.

A cascade model has been created at the Goddard Space Flight Center (GSFC) to treat stratocumulus clouds with the simplest geometry (plane-parallel layer) and horizontal fluctuations of the liquid water path (optical thickness). These fluctuations were modeled by one-dimensional lognormal distribution and power-law spectrum (Cahalan 1989; Cahalan et al. 1994). It was shown that the area-average albedo depends essentially on the spatial distribution of optical thickness, and not only on its mean value.

Real stratus clouds have odd and irregular upper boundaries. Thus a question arises: How strongly does the stochastic geometry of clouds influence the statistical characteristics of albedo and transmittance of visible solar radiation? In the present work, this question is settled using the GSFC model extended to include the random upper boundary of the cloud layer.

Cloud Model

Current literature on stratus clouds contains no data on simultaneous measurements of the distributions of cloud liquid water and height of the cloud upper boundary, thus the relationship between microphysical and geometrical cloud characteristics has not been experimentally justified. For this reason, we have suggested that the cloud liquid water path and the height of the cloud upper boundary are independent random fields.

The statistical characteristics describing the fluctuations of the upper boundary are obtained from laser sensing of stratus clouds over the Barents and Norwegian seas in October-November 1987. The experimental data processed to date indicate that the stratus cloud upper boundary can be modeled to a first approximation by Gaussian homogeneous isotropic field with exponential correlation function (Andrianov et al. 1994). The correlation radius as determined at e^{-1} level is $2 \div 2.5\,\mathrm{km}$.

Below we use the following abbreviations:

- LWP model describes the fluctuations of liquid water path (optical thickness) in plane-parallel cloud layer. The LWP fluctuations have one-dimensional lognormal distribution and power-law spectrum.

- CUB model describes the fluctuations of the cloud layer upper boundary. The CUB fluctuations are assumed Gaussian process with exponential correlation function.

- LC model is the superposition of LWP and CUB models and describes both the fluctuations of liquid water content (extinction coefficient) and cloud layer upper boundary.

Notation used for statistical characteristics of optical depth (τ), albedo (R), transmittance (Q), etc., includes subscript (for a model), overbar (for the area average), and symbol Var (for a variance) (e.g., $\bar{R}_{LWP}$ and $\mathrm{Var}R_{LWP}$ denote the area-average and the variance of albedo in LWP model).

For simplicity and to reduce computer time, we consider one-dimensional models, that is those in which the optical depth, albedo, and transmittance are random processes. The algorithm of simulating LWP, CUB, and LC realizations is based on the method of “spectrum randomization” (Mikhailov 1978, 1983) which consists in essence of the following:

1) LWP Model - Plane-parallel layer with thickness ΔH = 0.3 km and length L = dx x N = 204.8 km is divided into N = 2^{12} pixels with equal horizontal sizes dx = 0.05 km. For each of the pixels, we simulate the optical thickness τ_{LWP} using one-dimensional lognormal distribution (τ_{LWP} = 13, Varτ_{LWP} = 25.1) and power-law spectrum (with exponent, β = 5/3). Each pixel, then, is assigned the extinction coefficient $\sigma(i) = \tau_{LWP}(i) / \Delta H, > i = 1,N$.

2) CUB Model - Height of the upper boundary, H(i), i = 1,N, is simulated with one-dimensional Gaussian distribution (H = 0.3 km, VarH = 0.01 km^2) and exponential correlation function (correlation radius 2.5 km). The optical thickness of each pixel is given by

$$\tau_{CUB}(i) = \frac{\tau_{LWP}}{\Delta H} \text{ x } H(i) = \frac{13}{0.3} \text{ x } H(i), \; i = 1,N \qquad (1)$$

3) LC Model - Each pixel has the extinction coefficient $\sigma(i)$, thickness H(i), and optical thickness $\tau_{LC}(i)$ = $\sigma(i)$ x H(i), i = 1,N. Owing to the independence of the random processes considered, $\tau_{LC} = \tau_{LWP} = 13$.

Examples of the one-dimensional distributions and energy spectra of optical depth are presented in Figure 1. The distribution mode in the LC model is shifted toward smaller optical thicknesses and is about 30% smaller, while the distribution itself is broader (Varτ_{LC} $\approx$ 2 x Varτ_{LWP}) (Figure 1a).

Figure 1b is a log plot of the energy spectrum of optical thickness, E(τ, k), versus bin number k, which is related to the spatial frequency f_k as f_k = k/L = k/(dx x N), with L the length of the realization processed. The smoothing of energy spectrum was performed by sliding summation over 59 points of nonsmoothed spectrum. In the spatial frequency range under consideration, the energy spectrum E(τ_{CUB},k) has a near flat (on a log plot) section, which can be approximated by E(τ_{CUB},k) ~k $-\beta_{CUB}$, with β_{CUB} = 2.0; that is, $\beta_{CUB} > \beta_{LWP}$ and E(τ_{CUB},k) falls off faster than E(τ_{CUB},k). Since the variance of τ_{LWP} is 1.5 times that of τ_{CUB}, the energy spectrum E(τ_{LC},k) differs little from E(τ_{LWP},k).

Albedo and Transmittance

Albedo and transmittance are computed in each pixel by the Monte Carlo method, employing, in particular, the Maximal Cross-Section Method (Marchuk et al. 976). The calculations are made for overhead sun and Heneye-Greenstein scattering phase function with an asymmetry parameter of 0.843. Impact of the underlying surface

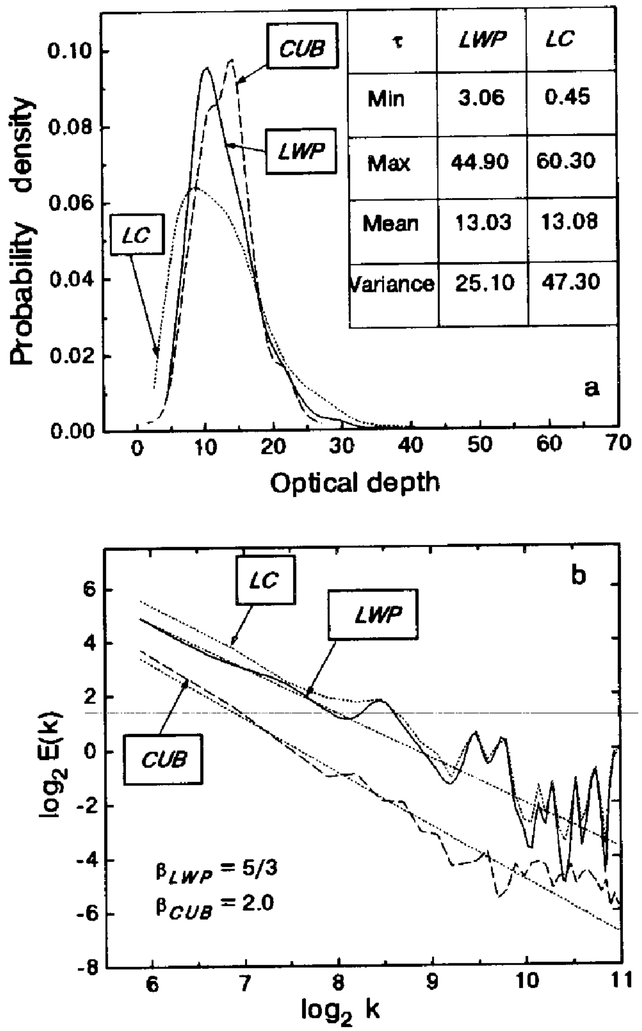

Figure 1. Probability density (a) and energy spectrum (b) of optical depth.

and aerosolatmosphere was not considered. In order to evaluate the extremely possible impact of the cloud top stochasticity on solar radiation transfer in inhomogeneous stratus clouds, R_{LC} and Q_{LC} were calculated with Var H = $(H/3)^2$ = 0.01 km^2. Minimum and maximum (H_{max}) cloud top heights were, respectively, 0.014 and 0.646 km. The albedo R_{LWP} was determined at height z = ΔH, while R_{LC} was at the maximum height of the cloud upper boundary (plane z = H_{max}). The transmittances Q_{LWP} and Q_{LC} were calculated at the level of the cloud lower boundary (plane z = 0). The relative computation error was within 1%.

Below we present the calculation results which illustrate the influence of the effects, caused by the stochastic geometry of stratus cloud upper boundary, upon the statistical characteristics of albedo and transmittance. We note that these effects, missing completely in the LWP model, are most important for cumulus clouds and are sufficiently discussed in Titov (1990) and Zuev and Titov (1995).

The random upper boundary of stratus clouds produces a considerable increase in the variance of optical depth, so that $\mathrm{VarR}_{LC} \approx 1.7 \times \mathrm{VarR}_{LWP}$ and $\mathrm{VarQ}_{LC} \approx 2 \times \mathrm{VarQ}_{LWP}$. The mean albedo and transmittance, however, are almost unaffected (~3% change). The probability density of R_{LC}, unlike that of R_{LWP}, is distinctly bimodal (Figure 2a), which might be explained by the increase of the variance of optical depth. To verify this suggestion, we have calculated the albedo and transmittance for the LWP model with $\mathrm{Var}\tau_{LWP} = \mathrm{Var}\tau_{CUB}$.

The results are tabulated in the figures in parentheses (Figure 2) and show that, for fixed values of the mean and variance of optical depth, the mean and variance of albedo and transmittance depend on the cloud model only weakly. For such variations of the variance of optical depth, the probability density of R_{LWP} is not distinctly bimodal. This means that the effects caused by the stochastic cloud geometry are responsible for the bimodal behavior of the probability density of R_{LC}.

As is well known, there is a "scaling break" in the energy spectrum of reflected intensity (Barker and Davies 1992) and albedo (Cahalan and Snider 1989) on the space scales of several hundred meters. Our results support this fact and show that the energy spectrum of transmittance is "broken" as well (Figure 3). The explanation is that the multiple scattering significantly smoothes out the radiation field at space scales on the order of ten photon mean-free pathlengths.

The difference is appreciable between energy spectra of albedo, $E(R_{LC}, k)$ and $E(R_{LWP}, k)$, while being negligible between $E(Q_{LWP}, k)$ and $E(Q_{LWP}, k)$. The former is attributable to the fact that the radiation field reflected by a given pixel "spreads" in the space before reaching the plane $z = H_{max}$, to give albedo; in addition, it overlaps with radiation fields reflected by neighboring pixels. The two effects are 1) the stronger the energy spectra of albedo, the larger the difference between H_{max} and the cell height, and 2) both act to smooth out the spatial distribution of albedo.

In summary, the results presented above show that, for fixed values of the mean and variance of optical depth, the effect of the stochastic geometry of the upper boundary of inhomogeneous stratus clouds upon the mean and the variance of albedo and transmittance can be neglected. The probability density and energy spectrum of albedo are highly sensitive to the variations of the stratus cloud upper boundary.

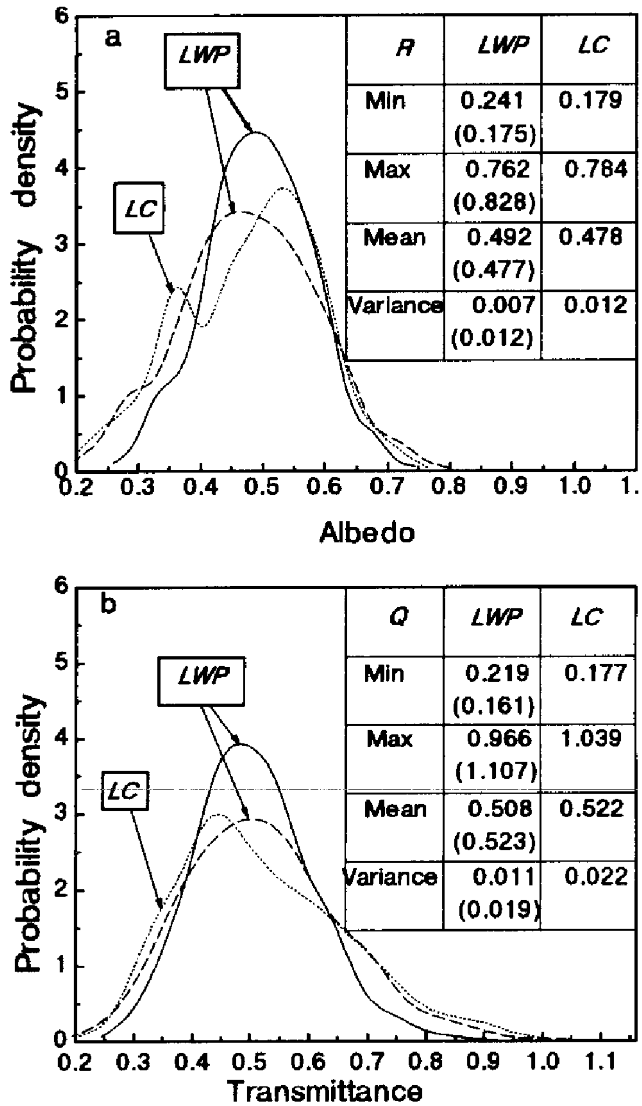

Figure 2. Probability density of albedo (a) and transmittance (b). Solid line shows $\mathrm{Var}\tau_{LWP}$ = 25.1, dashed line shows $\mathrm{Var}\tau_{LWP}$ = 47.3.

Current literature on stratus clouds contains no data on the relationship between the statistical characteristics of cloud liquid water and cloud top altitude. For this reason, we suggested that the cloud liquid water path and the height of cloud upper boundary are independent random processes. To develop cloud models which most fully and adequately describe the real inhomogeneous stratus clouds, and to

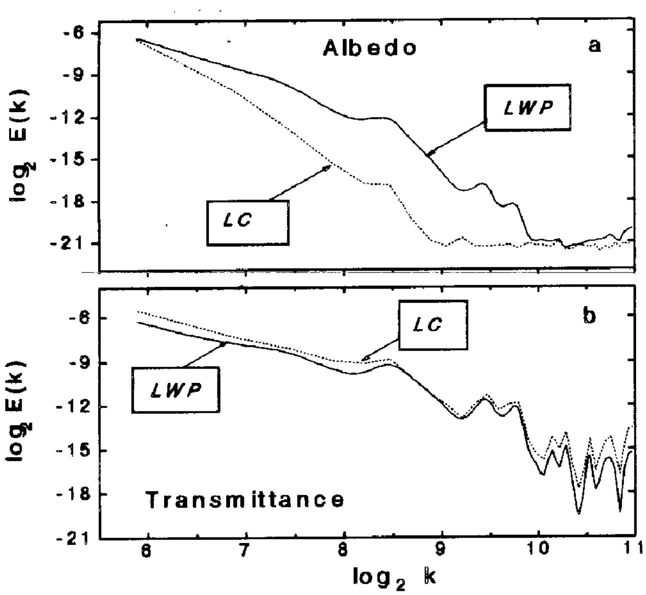

Figure 3. Energy spectrum of albedo (a) and transmittance (b).

elaborate the appropriate solution techniques, will require data on the statistical characteristics of the cloud microphysical and geometrical parameters and the relationship between them. It is hoped that such data will be available from the Atmospheric Radiation Measurement (ARM) Program.

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References

Andrianov, I., I. Penner, G. Titov, and V. Shamanaev. 1994. The determination of fractal dimensionality of the stratus cloud upper boundary from data of laser sensing. In *Interrepublic Symposium, "Atmospheric and Oceanic Optics*," Tomsk, 238-240.

Barker, H. W., and J. A. Davies. 1992. Cumulus cloud radiative properties and the characteristics of satellite radiance wavenumber spectra, *Remote Sens. Environ.*, **42**, 51-54.

Cahalan, R. F. 1989. Overview of fractal clouds. In *Advances in Remote Sensing Retrieval Method*, Deepak Pub., Hampton, Virginia, 371-388.

Cahalan, R. F., W. Ridgway, W. J. Wiscombe, T. L. Bell, and J. B. Snider. 1994. The albedo of fractal Stratocumulus Clouds, *J. Atmos. Sci.*, **51**, 2434-2455.

Cahalan, R. F., and J. B. Snider. 1989. Marine stratocumulus structure, *Remote Sens. Environ.*, **28**, 95-107.

Marchuk, G. I., G. A. Mikhailov, M. A. Nazaraliev, R. A. Darbinjan, B. A. Kargin, and B. S. Elepov. 1976. *Monte Carlo Method in Atmospheric Optics*. Nauka, Novosibirsk.

Mikhailov, G. A. 1978. Numerical construction of the random field with a given spectral density, *Dokl. Akad. Nauk SSSR*, **238 (4)**, 793-795.

Mikhailov, G. A. 1983. Approximate models of the random processes and fields, *Zhurn. Vychisl. Matem. i Matem. Fiz.*, **23(3)**, 558-566.

Titov, G. A. 1990. Statistical description of radiation transfer in clouds, *J. Atmos. Sci.*, **47**, 24-38.

Zuev, V. E., and G. A. Titov. 1995. Radiative transfer in cloud fields with random geometry, *J. Atmos. Sci.*, **51**, 176-190.