Radiative Properties of Stratocumulus Clouds: Influence of Stochastic Geometry

G. A. Titov and E. I. Kasyanov
Institute of Atmospheric Optics
Siberian Branch of the Russian Academy of Sciences
Tomsk, Russia

Introduction

To improve radiation codes of climate models and methods of remote sensing, one needs to know the influence of stochastic geometry and inhomogeneous internal structure on the radiative properties of stratocumulus clouds (Sc).

The horizontal distribution of the liquid water path (optical depth) of marine Sc is well approximated by a two-dimensional random field with lognormal distribution and power-law spectrum (Cahalan and Snider 1989). To describe the observed distributions of optical depth, both cascade (Marshak et al. 1994) and spectral (Prigarin and Titov 1996), cloud models have been developed. The cascade model was used to study the sensitivity of the mean albedo of Sc to horizontal inhomogenety of the liquid water path (Cahalan et al. 1994). The spectral model (Titov 1997) was used to study the horizontal transport and solar absorption. A significant drawback of the models considered is their use of the simplest geometry as a plane-parallel cloud layer.

In this work, we present a comparative analysis of the influence of inhomogeneity of the liquid water path and the height of the upper boundary of Sc on the radiative properties as well as on the accuracy of cloud absorption retrieval.

Cloud Models

1. A plane-parallel layer of thickness ΔH with random horizontal distribution of optical depth will be called the WP model. The optical depth τ_{WP} (extinction coefficient σ) has a one-dimensional lognormal distribution (mean $\langle\tau_{WP}\rangle$ and variance $D_{\tau_{WP}}$) and a power-law spectrum (exponent 5/3).

2. A WP model, in which the upper boundary H is an independent Gaussian process (mean $\langle H\rangle = \Delta H$ and variance $D_H = (\Delta H/3)^2$) with exponential correlation function (correlation radius 2.75 km), will be called the GWP model. Since the random processes are independent, we have $\langle\tau_{GWP}\rangle = \tau_{WP}$.

3. A plane-parallel, horizontally homogeneous layer with geometrical thickness H_{pp} and optical thickness τ_{pp} will be called the PP model. For comparing radiative properties of different models, we assumed that $H_{pp} = \Delta H$ and $\tau_{pp} = \langle\tau_{WP}\rangle = \langle\tau_{GWP}\rangle$.

The algorithm of simulating optical depth τ_{WP} and τ_{GWP} was as follows. The continuous realizations of the processes τ_{WP} and τ_{GWP} were divided into $N = 2^{12} = 4096$ pixels of the same horizontal size $\Delta x = 0.05$ km. In the WP model, for each pixel we determined the optical depth τ_{WP} (i), i = 1,...N, as a value of the random process τ_{WP} at the point $x_i = i \times \Delta x$, and then calculated the extinction coefficient $\sigma(i) = \tau_{WP}(i) / \Delta H$. In the GWP model, for each pixel we also determined the top boundary height $H(i)$ as a value of the continuous realization of the Gaussian process at the point x_i, and then calculated the optical depth $\tau_{GWP}(i) = \sigma(i) \times H(i)$, i=1,...N. In simulating τ_{WP} and τ_{GWP}, we used parameter values most typical for marine Sc: $\Delta H = 0.3$ km, $\langle\tau_{WP}(x)\rangle = 13$, and $D_{\tau_{WP}} = 29$.

The radiative properties of each pixel were calculated using the Monte Carlo method and periodic boundary conditions. The scattering phase function was chosen to correspond to Ñ1 cloud and wavelength 0.69 µm. The transmittance was calculated at the level of the cloud base boundary; while albedo was calculated at the level of the cloud top boundary (plane z=ΔH) in the PP and WP models, and at the level of the maximum top boundary height (plane z = H_{max}) in the GWP model. For the realization constructed, $H_{max} = 0.57$ km. The influences of the underlying surface and the aerosol-gaseous atmosphere on the radiative characteristics of marine Sc were not considered. Radiative flux calculations are presented for the solar zenith angle of 60°. The mean relative computation error was ~1%.

To designate the means and variances of albedo R, transmittance T, absorptance A, and horizontal transport E, we used angular brackets $\langle \cdot \rangle$ and the symbol D, respectively. A subscript stands for a cloud model. For instance, $\langle E_{GWP} \rangle$ and $D_{E_{GWP}}$ represent the mean and variance of horizontal transport in the GWP model.

Radiative Properties

To estimate the influence of the stochastic geometry of upper boundary and inhomogeneous internal structure of Sc on the mean radiative fluxes, we used

$$\Delta F_{WP} = F_{pp} - \langle F_{WP} \rangle$$

$$\Delta F_{GWP} = F_{pp} - \langle F_{GWP} \rangle \quad (1)$$

where F denotes the radiative characteristics R, T, A, and E. The differences ΔF_{WP} and ΔF_{GWP} are the deviations of $\langle F_{WP} \rangle$ and $\langle F_{GWP} \rangle$ from F_{pp} caused only by inhomogeneous internal structure and joint fluctuations of liquid water content and top boundary height, respectively.

The value of ΔR_{GWP} is roughly two times larger than ΔR_{WP} both in the case of conservative scattering (Figure 1a) and in the presence of absorption by cloud droplets (Figure 1b). It can therefore be concluded that the influences of the inhomogeneous internal structure and stochastic geometry on the mean albedo are comparable. This conclusion is also valid for transmittance. The stochastic geometry of upper boundary weakly affects the mean absorption of Sc (Figure 1b).

From Figure 2, we see that, for the WP and GWP models, the variances of τ, R, T, and A differ by as much as a factor of two. Therefore, the inhomogeneous internal structure and stochastic geometry have comparable contributions to the variances D_τ, D_R, D_T, and D_A. Of note is the very important result that $D_{E_{GWP}}$ exceeds $D_{E_{WP}}$ by more than an order of magnitude. This means that the variance of horizontal transport is determined primarily by the stochastic geometry.

Horizontal Transport and Absorption

Usually the absorptance is determined as the difference between the net fluxes measured at cloud top and base boundaries. This means that one can find only an inferred absorptance $A' = A + E$. If the horizontal transport and real absorptance are comparable in the order of magnitude, the inferred absorptance, A', will substantially diverge from the real one, A. We propose two approaches which allow us to remove the influence of horizontal transport and improve estimates of the real cloud absorption from field data (Titov 1997).

Space Averaging

A realization of F is divided into 2^{12-nx} nonoverlapping intervals of the same length $\Delta L(nx)$. For each interval we determine the mean value $F_j(nx)$, $j=1,...,2^{12-nx}$, where F denotes the radiative characteristics R, T, A, and E. If, after averaging over space, $E_j(nx) \approx 0$, then a reliable estimate of the mean absorptance $A_j(nx)$ can be obtained. The inequalities $|E_{WP}(nx)| \le 0.01$ and $|E_{GWP}(nx)| \le 0.01$ hold at averaging scales $\Delta L(nx)$ on the order of 6 km and 30 km (Figure 3), respectively. This means that the fluctuations of top boundary height act to degrade the accuracy of retrieving cloud absorption by approximately a factor of five.

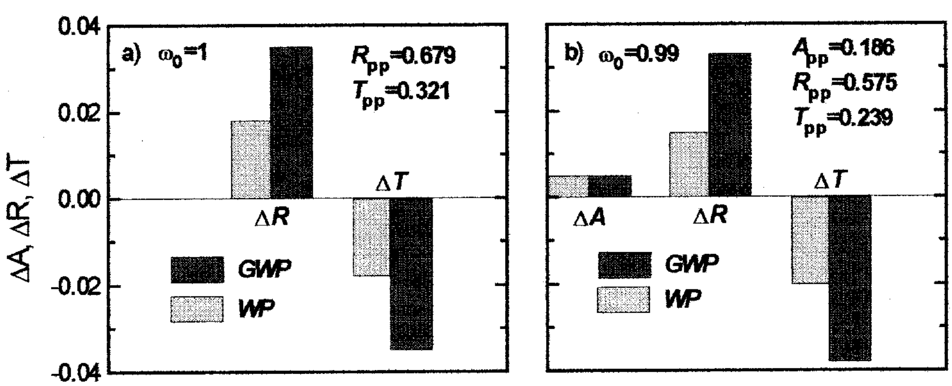

Figure 1. The differences ΔR, ΔT and ΔA, corresponding to two models, with (a) $\omega_0 = 1$ (pure scattering) and (b) $\omega_0 = 0.99$ (absorption by water droplets).

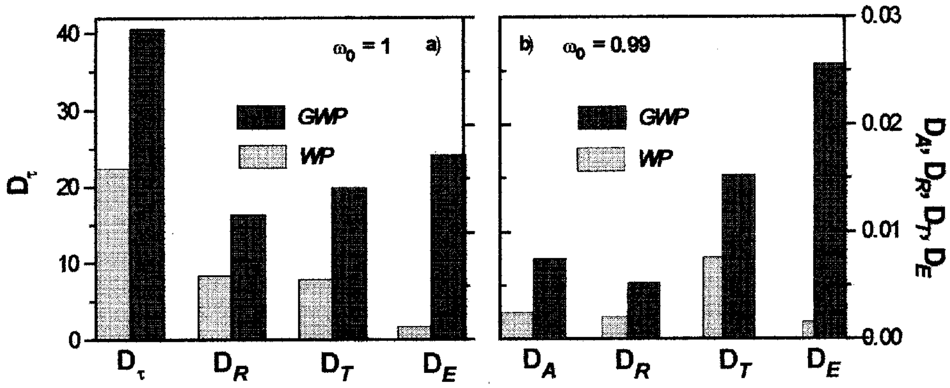

Figure 2. The variances of (a) optical depth D_τ, (a,b) albedo D_R, (a,b) transmittance D_T, (b) absorptance D_A, and (a,b) horizontal transport D_E, corresponding to two models, with (a) ω_0 = 1 (pure scattering) and (b) ω_0 = 0.99 (absorption by water droplets).

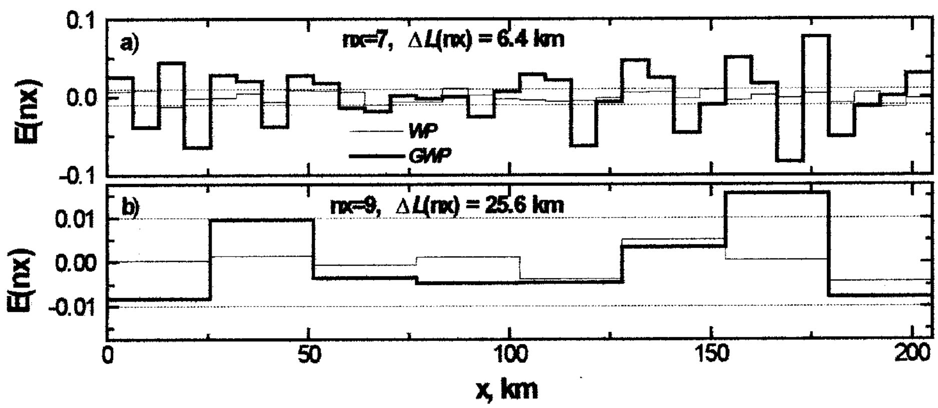

Figure 3. Dependence of horizontal transport E(nx), as corresponding to two models, on the length of the averaging interval ΔL(nx) with ω_0 = 0.99 (absorption by water droplets); (a) ΔL(nx) = 6.4 km, (b) ΔL(nx) = 25.6 km.

Visible and Shortwave Fluxes

We use 1) simultaneous visible ("vis") and near IR ("ir") measurements of albedo and transmittance (since $A_{vis} = 0$, then $E_{vis} = 1 - R_{vis} - T_{vis}$); and 2) a linear regression between E_{vis} and E_{ir}, i.e. $E_{ir} = b \times E_{vis}$. The coefficient b is evaluated using a mathematical simulation.

Cloud absorption is determined by the formula

$$A'_{ir} = 1 - R_{ir} - T_{ir} - E_{ir} \approx$$

$$1 - R_{ir} - T_{ir} - b \times E_{vis} \qquad (2)$$

At $\Delta L(2^0)$ = 0.05 km, E_{ir} values show wide "scatter" about the regression line (Figure 4a), so that the real absorptance, A_{ir}, and the inferred one, A'_{ir}, substantially differ (Figure 4c). After averaging E_{vis}, E_{ir}, and the radiative characteristics entering (2) over realization fragments of length $\Delta L(2^3)$ = 0.4 km, a reliable estimate of absorption can be obtained (Figure 4d). This is mainly because, after averaging, the variances of E_{vis} and E_{ir} decrease, and so does the "scatter" of E_{ir} about the regression line (Figure 4b). Thus, by using simultaneous visible and near-IR measurements of albedo and transmittance, one can obtain a reliable estimate of the cloud absorptance A_{GWP} to a maximum spatial resolution of ~0.4 km. For the WP model, such an approach allows one to study smaller-scaled (~0.05 km) fluctuations of absorption (Titov 1997). Therefore, the stochastic geometry of the upper boundary acts to degrade, by as much as an order of magnitude, the maximum spatial resolution to which the cloud absorption can be obtained.

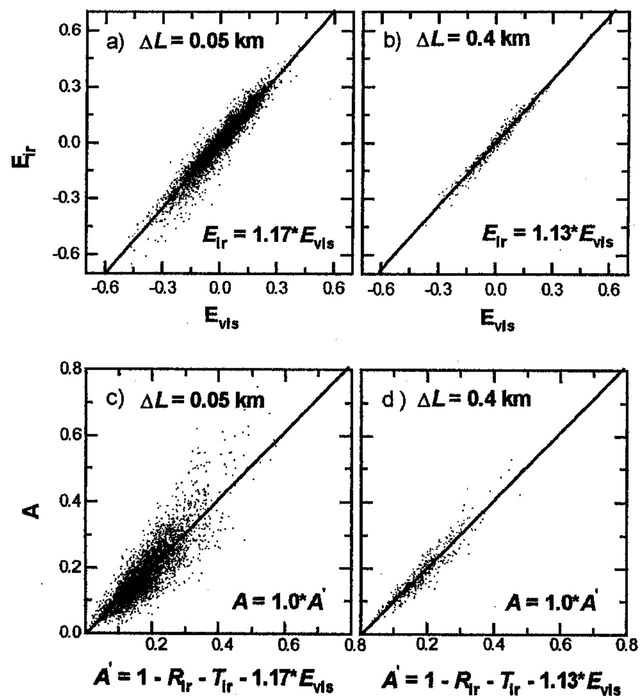

Figure 4. (a,b) A linear regression between E_{ir} and E_{vis}, and (c,d) the real absorptance A_{ir} as a function of the inferred absorptance A'_{ir} for varying spatial resolution: (a,c) ΔL = 0.05 km and (b,d) ΔL = 0.4 km with ω_0 = 0.99 (absorption by water droplets).

Conclusion

The contributions of stochastic geometry and inhomogeneous internal structure to the mean albedo and transmittance are *comparable*. The mean absorption of clouds Sc depends weakly on the stochastic geometry of the upper boundary. Fluctuations of liquid water content and top boundary height have nearly *equal* effects on the variances of albedo, transmittance, and absorptance. The variance of horizontal transport is caused primarily by the stochastic geometry.

If the cloud absorption is estimated by using the net fluxes measured in one spectral interval, then the stochastic geometry degrades the accuracy of absorption retrievals by approximately a factor of five. If the synchronous visible and shortwave measurements of the net fluxes are used, then, due to the stochastic geometry, the maximum spatial resolution of absorption is degraded by about an order of magnitude.

Acknowledgments

The support from the DOE's Atmospheric Radiation Measurement Program (under contract N 350114-A-Q1) and the Russian Fund for Fundamental Research (under grant N 96-05-64275) is appreciated.

References

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.*, **16**, 2434-2455.

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

Marshak A., A. Davis, R. F. Cahalan, and W. J. Wiscombe, 1994: Bounded cascade models as nonstationary multifractals. *Phys. Rev.*, **E49**, 55-79.

Prigarin S. M., and G. A. Titov, 1996: Spectral methods of numerical modeling of geophysical fields. *Atmos. Oceanic Opt.*, **7**, 993-1003.

Titov G. A., 1997: Radiative horizontal transport and absorption in stratocumulus clouds. *J. Atmos. Sci.*, submitted.