Simulation of Solar Radiative Transfer in Cumulus Clouds

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Current radiation codes of general circulation models (GCMs) are still largely based on plane-parallel models, which unsatisfactorily describes the radiative effects of cumulus clouds because their optical characteristics are highly variable both vertically and horizontally. Updated GCM parameterizations of the interaction of radiation with cumulus clouds will use newer Atmospheric Radiation Measurement (ARM) data and more realistic radiative transfer models. In this work we present a 3-D model of radiative transfer which is used to study the relationship between the spatial distribution of cumulus clouds and fluxes (albedo and transmittance) of visible solar radiation.

In the visible spectrum, the scattering by water droplets can be assumed conservative, and the mean albedo $\underline{R}$ and transmittance $\underline{Q}$ are related by formula $\underline{R} + \underline{Q} = 1$, expressing the low of energy conservation. We let the clouds occupy some spatial domain shaped as parallel piped with thickness ΔH and with a square base of side length Xl. In the horizontal plane we divide the domain into cells (pixels) of equal size Δl, and for each of these calculate the albedo $R_{i,j}$ and transmittance $Q_{i,j}$ $i,j = 1,...,nx$ where $nx = \frac{Xl}{\Delta l}$ is the number of cells along each of the coordinate axes OX and OY. The total number of cells is nx^2. If the domain is a part of a plane-parallel cloud, then, on account of the homogeneous boundary conditions, the equality $Q_{i,j} + R_{i,j} = 1$, i,j=1,...,nx, holds in each of the cells. Will the same equality hold in the cumulus cloud case? What consequences will the horizontal inhomogeneity of cumulus clouds have on the spatial distribution of uniform incident solar flux? The mathematical simulation results we present below answer somewhat these questions, as well as make it possible to obtain the probability densities and energy spectra of albedo and transmittance in statistically inhomogeneous cumulus clouds.

Model of Cumulus Clouds and Method of Solution

The stochastic geometry of cumulus clouds is, to date, poorly understood. To avoid expensive computations, we use a simple model of cumulus clouds generated by Poisson point fluxes in space. Cumulus clouds are approximated by inverted, truncated paraboloids of revolution with height H equal to diameter D. The latter has the exponential distribution function $f(D) \sim \exp(-\alpha D)$, $D_{min} \le D \le D_{max}$. Optical parameters (extinction coefficient, single scattering albedo, and scattering phase function) are assumed constant within the cloud. The radiation effects of atmospheric aerosol and underlying surface are neglected for simplicity.

A computer realization of cloud field for $\Delta l = 0.1$ *km*, $nx = 64$ ($nx^2 = 4096$ and $Xl = 6.4$ *km*), $\alpha = 2$, $D_{min} = 0.03$ km, $D_{max} = 1.2$ km, and for a cloud fraction of $\underline{N} = 0.5$ is presented in Figure 1a. If a cell belongs to a group of (two or more) clouds, its optical thickness is calculated for the largest cloud in the group. In this realization, maximum cloud thickness is $\Delta H = 1.174$ *km*.

The 3-D transfer equation was solved subject to cyclical boundary conditions assuming that the layer $0 \le z \le \Delta H$ is filled by a given cloud field realization. The 2-D albedo and transmittance fields were computed by Monte Carlo (MC) method using one or more hundred million trajectories that ensured no more than 2% relative error. The transmittance was determined at the lower (plane $z = 0$) and the albedo at the upper (plane $z = \Delta H$) cloud boundary. Details of the cumulus cloud model and the MC algorithms are given in Titov (1990) and Zuev and Titov (1995).

2-D Albedo and Transmittance Fields

All calculations below employ Henyey-Greenstein scattering phase function with an asymmetry factor of 0.843 (typical of wavelengths 0.3 - 3.0 µm). The azimuthal solar angle measured from OX-axis is zero.

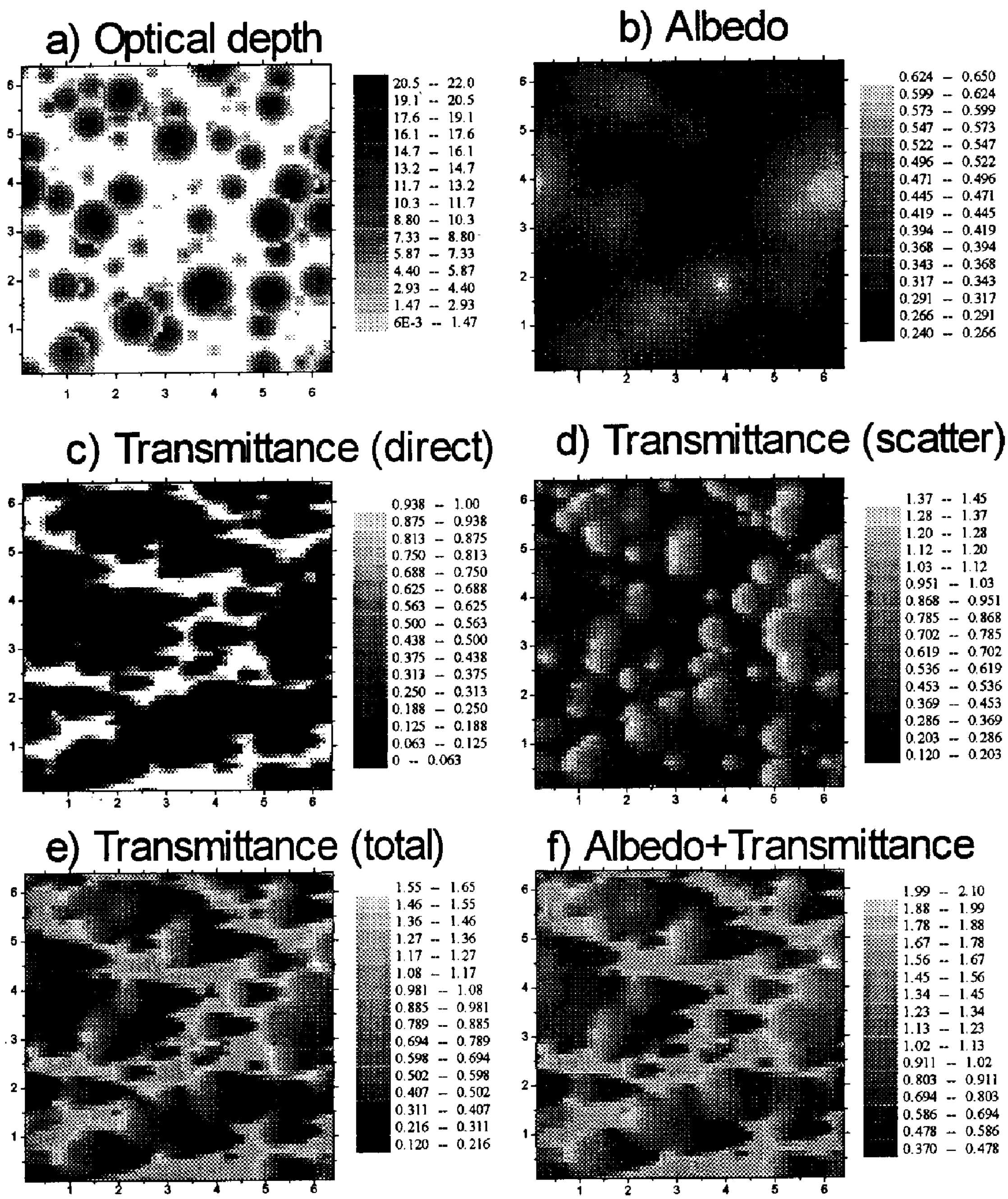

Figure 1. 2-D fields of optical depth (a), albedo (b), transmittance of direct (c), diffuse (d), and total radiation (e), and albedo plus transmittance (f), for the cloud fraction N = 0.5, pixel horizontal size of 0.1 km, extinction coefficient $\sigma = 20\ \mathrm{km}^{-1}$, and solar zenith angle $\xi = 60^\circ$.

Multiple scattering plays a dominant role in the formation of radiation field in clouds, leading, in particular, to the fact that the albedo R and diffuse transmittance Q_s reach appreciable values even in noncloudy cells (Figures 1b and 1d). In the given cloud field realization, clouds vary in thickness from 0.033 km to 1.174 km. Radiative field, reflected by a single cloud, spreads in the space and overlaps with the radiative fields of other clouds, before reaching the plane $z = \Delta H$ to give albedo. Owing to the spread and overlap effects, the albedo is essentially smoothed out in the horizontal plane, so that the many details are effectively masked, thus complicating the visual reconstruction of the real pattern of cloud spatial distribution from known albedo values (Figures 1a and 1b). The tops of the most massive clouds are distinctly observed because for these, the effects above are not sufficiently strong. The albedo varies from 0.24 to 0.65, the mean and the variance being 0.33 and 0.0039, respectively.

The transmittance S of direct radiation passing through holes between clouds is unity (the direction of the sun is cloud-free); and at oblique sun angles, the cloud shadows are clearly seen (Figure 1c). Optically thin cells, localized near cloud bottom and directly sunlit, are able to transmit much radiation without scatter, smearing somewhat shadow boundaries. The diffuse transmittance Q_s is maximum for those cells which have small (roughly 2-3) optical thickness and are not screened by surrounding clouds (i.e., which are reached by the incident solar radiation without interaction with the clouds [Figure 1d]). Interestingly, Q_s for such cells can be markedly greater than unity, owing to the radiation striking the neighboring, optically thicker cells. However, through multiple scattering, the Q_s "slides down" to these optically thinner cells, thus adding to their transmittances. Certainly, there exist cells with small (0.1-0.2) Q_s values, which are either far apart from the clouds or fall within the shadow zones of the most massive of them. As a result, the Q_s may vary by more than order of magnitude (from 0.12 to 1.45) with the average being 0.42.

The transmittance of total radiation, $Q = S + Q_s$, is given in Figure 1e and varies from 0.12 to 1.65, with the mean being 0.67 and variance being 0.1839. The smallest Q values occur in the cells shaded by most massive cumulus clouds. For cells located in cloud gaps S= 1 and, due to the diffuse contribution, the inequality $Q > 1$ always holds. Clearly, this inequality will also hold for those cells where $Q_s > 1$. The $Q > 1$ values have long been obtained by field measurements (Timanovskaya and Feigelson 1970); however, no such theoretical estimates of Q were previously reported, as far as we know.

The simulation results indicate that the albedo and transmittance of cumulus have large horizontal gradients. As a result, the law of energy conservation holds only on averages, for the whole spatial domain under consideration, but in each cell the sum $Q_{ij} + R_{ij}$, i,j=1,...,nx, may substantially differ from unity, ranging from 0.37 to 2.10 (Figure 1e). The horizontal inhomogeneity of radiant fluxes in cumulus can affect appreciably such atmospheric processes as underlying surface heating, cloud dynamics, and photochemical reactions, among many others.

Independent Pixel Approximation (IPA)

This approximation neglects the net horizontal photon transport and uses the plane-parallel model for each pixel (cell) (Cahalan 1989; Cahalan et al. 1994). In other words, radiative properties of each cloud pixel depend only on its own vertical optical thickness, not on the optical thickness of neighboring pixels. In the case of plane-parallel stratocumulus clouds with nonuniform distribution of optical depth, the IPA has reasonable accuracy if only the horizontal size of the pixel exceeds its thickness and is much larger than photon mean free paths in clouds. Otherwise, mean-albedo biases of up to 10-20% result. In the IPA, the albedo R_{IPA} and transmittance Q_{IPA} can be calculated for each pixel using the approximation derived by King and Harshvardhan (1986) for conservative scattering:

$$\begin{aligned} R_{IPA}(\tau;\xi_\oplus,g) &= 1 - Q_{IPA}(\tau;\xi_\oplus,g), \\ Q_{IPA}(\tau;\theta,g) &= \frac{\delta(\xi_\oplus) + \left[1-\delta(\xi_\oplus)\right]\exp\left[-\tau/\left|\alpha(\xi_\oplus)\right|\right]}{1+\gamma(g)\tau} \end{aligned} \qquad (1)$$

where τ is the pixel optical thickness, ξ is the solar zenith angle, and g is the asymmetry parameter. Below we use the following values of the functions $\delta(\xi)$ $\alpha(\xi)$, $\gamma(g)$: $\delta(60^\circ) = 0.8$, $\alpha(60^\circ) = 0.8$ and $\gamma(0.43) = 0.11$.

Much larger albedo biases are expected for cumulus clouds whose geometries are fundamentally different from plane-parallel because the effects associated with their stochastic geometry (shading and multiple scattering between clouds) profoundly influence the solar radiative transfer. From (1), the 2-D fields R_{IPA} and Q_{IPA} follow the distribution of optical thickness (Figure 1a) and, therefore, visually they are quite dissimilar to their MC counterparts, R and Q fields (Figures 1b and 1e). In particular, R_{IPA} and $Q_{s,IPA}$ have zero values in the pixels located in gaps (holes) between clouds, and Q_{IPA} never exceeds 1. In addition, IPA fails to describe the shading effects.

The MC versus IPA comparison in cumulus is performed by calculating

$$\Delta R = \frac{R - R_{IPA}}{R} \times 100\%$$
$$\Delta Q = \frac{Q - Q_{IPA}}{Q} \times 100\% \qquad (2)$$

The IPA underestimates albedo for pixels located in gaps (holes) between clouds, and vice versa, for the other pixels (Figure 2a). The IPA-calculated mean and variance of albedo are, respectively, 0.25 and 0.0807. Compared with the MC values above, the IPA gives about a factor of 1.5 lower mean albedo and 20 times higher variance. This implies that the radiative interaction of pixels and the effects of stochastic geometry effectively smooth out the reflected field of solar radiation. The transmittance Q exceeds Q_{IPA} in the pixels located in the optically thin cells near cloud base or in cloud gaps, both directly sunlit (i.e., not shaded by clouds [Figure 2b]). As expected, $|\Delta Q|$ assumes maximum values in the pixels located in cloud gaps and shaded by clouds. Values of Q may be far in excess of 1, so the variance of Q is two times that of Q_{IPA}.

Summarizing, the results above clearly demonstrate that IPA unsatisfactorily describes the radiation effects of cumulus clouds.

Currently the lack of experimental data on stochastic cumulus clouds represents a major obstacle for developing 3-D radiative transfer models for cumulus clouds. Hopefully, more data will come from the ARM Program, which will help to improve the existing models and, if necessary, to develop newer, more realistic ones for treating the interaction of solar and thermal radiation with cumulus clouds.

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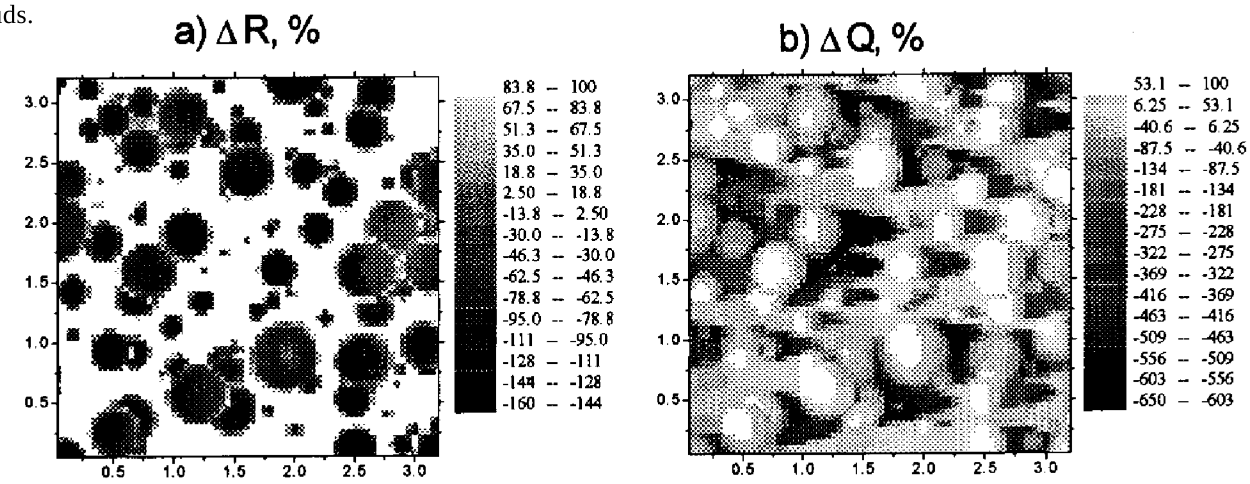

Figure 2. 2-D fields ΔR and ΔQ for cloud fraction N = 0.5, pixel horizontal size of 0.1 km, extinction coefficient $\sigma = 20\ km^{-1}$, and solar zenith angle $\xi = 60^{\circ}$.