# SIMULATION OF THE INCREASE OF THE SOLAR RADIATION INTENSITY NEAR THE EARTH'S SURFACE UNDER CLOUDY CONDITIONS

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*Effects of stratus and cumulus cloudiness on radiation regime of the atmosphere are studied. Monte Carlo method is used to simulate the increase of the mean solar radiation intensity near the earth's surface as a result of screening the outgoing radiation by the cloudy layer. The decrease of albedo of the atmosphere–surface system as a result of multiple surface absorption under cloudy conditions is studied as well.*

The two effects of concern here, namely, the increase of solar radiation intensity near the earth's surface and the decrease of the atmosphere–surface system albedo result from the specific radiation regime of the cloudy atmosphere allowing multiple light reflection between the clouds and the surface.

Let $\Phi(r, \omega)$ denote the intensity of radiation at a point $r$ in the direction $\omega$. Then the mean intensity of radiation at the point $r$ is $J(r) = (4\pi)^{-1}\int_{\Omega}\Phi(r, \omega)\mathrm{d}\omega$, where $\Omega$ is the unit sphere of directions. To see how cloudiness affects the mean intensity of radiation in the atmosphere and the albedo of the atmosphere–underlying surface system, we assume the following model. Let the solar incidence upon the atmosphere with the cloudy layer be a plane-parallel flux of unit power. Let $\theta$ denote the angle between positive $Z$ direction and the direction of incidence, $\pi/2 \le \theta \le \pi$. Upon interaction with the atmospheric layer, photons are reflected in upward direction with the probability $A(\theta)$, absorbed with the probability $P(\theta)$, and transmitted through the atmospheric layer with the probability $T(\theta) = 1 - A(\theta) - P(\theta)$ (the optical properties of the atmospheric layer with clouds are assumed homogeneous and isotropic in the $XY$ plane). Radiation transmitted by the cloudy layer interacts with the surface.

For simplicity, the underlying surface is assumed to reflect photons lambertianly (i.e., isotropically and independent of the incident direction) with the probability $Q$, and absorbs it with the probability $1-Q$. Surface-reflected photons again interact with the atmospheric layer, being resent back to the surface with probability $A(\varphi)$, absorbed with the probability $P(\varphi)$, and transmitted through the layer in upward direction with the probability $P(\varphi)$. Here $\varphi$ is the angle between positive $Z$ direction and the direction of photon reflected from the surface, $0 \le \varphi \le \pi/2$. Photons returned back to the surface again interact with it, and so forth. Within the model assumed one easily finds

$$A = A(\theta) + T(\theta)QT_*/(1 - QA_*); \quad (1)$$

$$P_A = P(\theta) + T(\theta)QP_*/(1 - QA_*); \quad (2)$$

$$P_S = T(\theta)(1 - Q)/(1 - QA_*); \quad (3)$$

$$4\pi\cdot J_1 = T(\theta)/(1 - QA_*) + T(\theta)Q/(1 - QA_*); \quad (4)$$

$$4\pi\cdot J_0 = 1 + A; \quad (5)$$

$$A_* = \int_0^{\pi/2} A(\varphi)\sin(\varphi)\mathrm{d}\varphi,\ T_* = \int_0^{\pi/2} T(\varphi)\sin(\varphi)\mathrm{d}\varphi,$$

$$P_* = \int_0^{\pi/2} P(\varphi)\sin(\varphi)\mathrm{d}\varphi.$$

Here $A$ denotes the albedo of the atmosphere–surface system, $P_A$ is the fraction of radiation absorbed by the atmospheric layer, $P_S$ is the fraction absorbed by the surface, $A + P_A + P_S = 1$, $J_0$ is the mean intensity above the atmospheric layer, and $J_1$ is the mean intensity near the surface.

*Remarks*. (1) The first term in Eq. (4) describes the total illumination from above, while the second one is the illumination from below.
(2) In the case of nonabsorbing surface and atmospheric layer,

$$J_1/J_0 = T(\theta)/T_*.$$

Computations were performed for stratus and cumulus cloudiness in the visible wavelength range $0.4 \le \lambda \le 0.71$ μm. Photon interaction with the clear atmosphere and absorption by clouds were not considered. Clouds were considered to be a scattering medium with the scattering coefficient $\sigma = 30\ \mathrm{km}^{-1}$. Scattering phase function is that of *C1* cloud from

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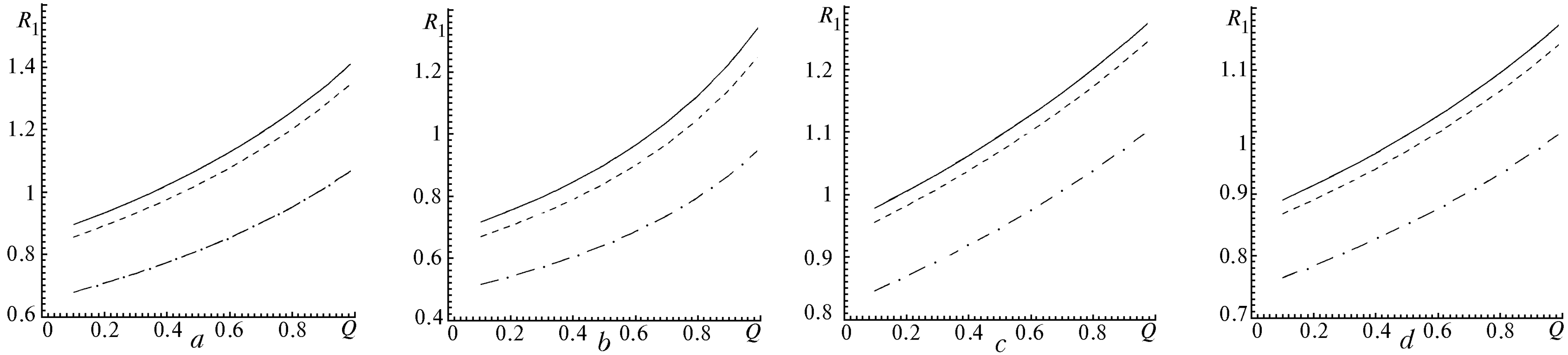


*FIG. 1. Ratio of the mean radiation intensity for the cloud layer—surface system to that in the absence of clouds;* $\theta_0 = 0°$ *(solid line),* $\theta = 30°$ *(dashed line) and* $\theta_0 = 60$ *(dot-and-dash line); stratus cloud layer* 50 *(a) and* 100 m *(b) thick and cumulus clouds at* $h_0 = 100$ m, $n_0 = 0.9$, $d_0 = h_0$ *(c) and* $h_0 = 200$ m, $n_0 = 0.7$, *and* $d_0 = h_0$ *(d).*

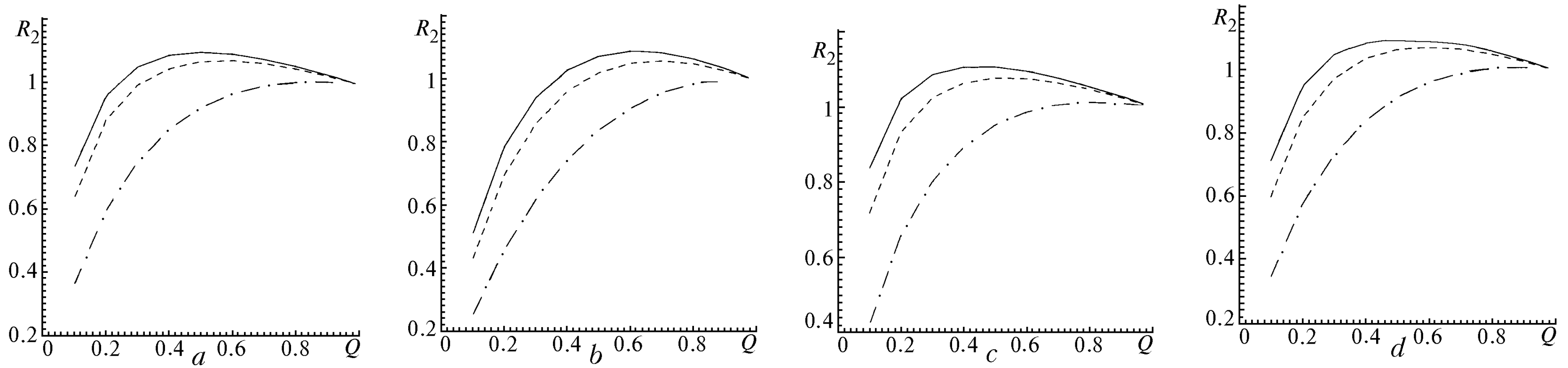


*FIG. 2. Ratio of the albedo in the absence of clouds to that for the cloud layer—surface system:* $\theta_0 = 0°$ *(solid line),* $\theta_0 = 30°$ *(dashed line) and* $\theta_0 = 60°$ *(dot-and-dash line); stratus cloud layer* 50 *(a) and* 100 m *(b) thick and cumulus clouds with* $h_0 = 100$ m, $n_0 = 0.9$, *and* $d_0 = h_0$ *(c) and* $h_0 = 200$ m, $n_0 = 0.7$, *and* $d_0 = h_0$ *(d).*

Ref. 1 (with the asymmetry factor of 0.86). Monte Carlo method was used to calculate $A(\varphi)$ and $T(\varphi)$ which values were then used in formulas (1)–(5). Cumulus clouds were simulated with a Gaussian model from Ref. 2 whose input parameters were cloud fraction $n_0$, mean cloud thickness $h_0$, and characteristic cloud diameter $d_0$. Photon trajectories were simulated by the method of Maximal Cross Section.

Simulation results are presented in Figs. 1 and 2. Computed were the ratio of the mean intensity near surface to that in the absence of clouds, $R_1 = 4\pi J_1/(1 + Q)$, and the ratio of albedo in the absence of clouds to that of the cloud layer–surface system. Figure 1 demonstrates $R_1$ value in excess of unity (the increase of the mean intensity of solar radiation when clouds are present) for a wide range of $Q$ and $\theta$ in cases of quite thin cloud layers. For higher cloud layers, $R_1 > 1$ only when the probability of surface reflection is near unity. Maximum $R_1$ value was 1.54 for stratus and 1.76 for cumulus.

We note that for cumulus clouds, the total illumination $J_1$ was taken as average over space. (For a treatment of spatially inhomogeneous radiation field transmitted through the broken clouds, see Ref. 3).

The decrease of albedo of the clouds–surface system relative to the cloudless case also takes place ($R_2 > 1$) for thin cloud layers and for a wide range of $Q$ and $\theta$ values (see Fig. 2). The results of the simulation suggest that, due to multiple light reflection between clouds and surface, the system albedo may be reduced by as much as 10%.

## ACKNOWLEDGMENTS

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