Absorption of Solar Radiation in Broken Clouds

V. E. Zuev, G. A. Titov, and T. B. Zhuravleva
Institute of Atmospheric Optics
Russian Academy of Sciences
Tomsk, Russia

Introduction

It is recognized now that the plane-parallel model unsatisfactorily describes the transfer of radiation through broken clouds and that, consequently, the radiation codes of general circulation models (GCMs) must be refined. However, before any refinement in a GCM code is made, it is necessary to investigate the dependence of radiative characteristics on the effects caused by the random geometry of cloud fields. Such studies for mean fluxes of downwelling and upwelling solar radiation in the visible and near-infrared (IR) spectral range were performed by Zuev et al. (1994a,b).

In this work, we investigate the mean spectral and integrated absorption of solar radiation by broken clouds (in what follows, the term “mean ” will be implied but not used, for convenience). To evaluate the potential effect of stochastic geometry, we will compare the absorption by cumulus ($0.5 \leq \gamma \leq 2$) to that by equivalent stratus ($\gamma << 1$) clouds; here $\gamma = H/D$, H is the cloud layer thickness and D the characteristic horizontal cloud size. The equivalent stratus clouds differ from cumulus only in the aspect ratio γ, all the other parameters coinciding. The spectral absorption $P(\lambda)$ of stratus clouds partially covering the sky is calculated with high accuracy by the formula

$$P(\lambda) = N \text{ x } P_{lay}(\lambda) + (1 - N) \text{ x } P_{cle}(\lambda) \qquad (1)$$

where *N* is the cloud fraction, and $P_{cle}(\lambda)$ and $P_{lay}(\lambda)$ are the spectral absorptions by clear sky and plane-parallel overcast, respectively. Obviously, the same formula applies to the calculation of integrated absorption as well.

Models of the atmosphere and the methods of spectral flux calculations in the near-IR have been sufficiently discussed by Zuev et al. (1994a,b) and Titov et al. (1995). It should only be recalled that the atmosphere is assumed to extend vertically from 0 to 16 km and that the clouds are contained in the 1-1.5 km layer; also that only the absorption by water vapor and carbon dioxide is considered. The spectral absorption is calculated by assuming that the unit solar flux is incident on the top of the atmosphere in direction $\vec{\omega}_{\oplus} = (\xi_{\oplus}, \varphi_{\oplus})$, with $\xi_{\oplus}$ and $\psi_{\oplus}$ the zenith and azimuthal solar angles. To change to the absolute values, results for spectral absorption must be multiplied by $\pi S_{\lambda} \cos\xi_{\oplus}$, where πS_{λ} is the spectral solar constant.

Since the optical thickness of atmospheric aerosol is considered to be much smaller than that of the clouds, any absorption difference between cumulus and stratus clouds will primarily result from multiple scattering in clouds. So we can restrict ourselves to the discussion of absorption by the cloud layer alone. In addition, owing to the small optical thickness of above-cloud atmosphere, the scattering of radiation reflected from the cloud layer can be neglected. This implies that the incident solar radiation on the cloud top is independent of the cloud type.

Spectral Absorption

As is well known, the absorption by cloud particles (water droplets) increases with the increase of the fraction of diffuse radiation and the mean multiplicity of scattering, as well as with the decrease of the single scattering albedo. From the above definition of equivalent stratus clouds, it is obvious that only the first two of these factors depend on cloud type. For fixed pressure, temperature, and concentration, the absorption by atmospheric gases is determined by the value of photon mean free path in clouds. We begin the discussion of calculation results with the simplest case when the albedo of underlying surface, A_s, is zero.

Radiation may escape through the sides of cumulus clouds, so that the mean multiplicity of scattering and the photon mean free path in cumulus are less than in stratus. When the sun is in zenith, the fraction of diffuse radiation is the same for both cloud types, thus the absorption in stratus, $P_{St}(\lambda)$, exceeds the absorption in cumulus, $P_{Cu}(\lambda)$ (Figure 1).

Except for large zenith solar angles ($\xi_{\oplus} > 80^{\circ}$), the fraction of diffuse radiation in stratus depends very weakly on $\xi_{\oplus}$, whereas in cumulus it rapidly grows with increasing $\xi_{\oplus}$. For cumulus, this leads to an increase in absorption, which may compensate for the effect caused

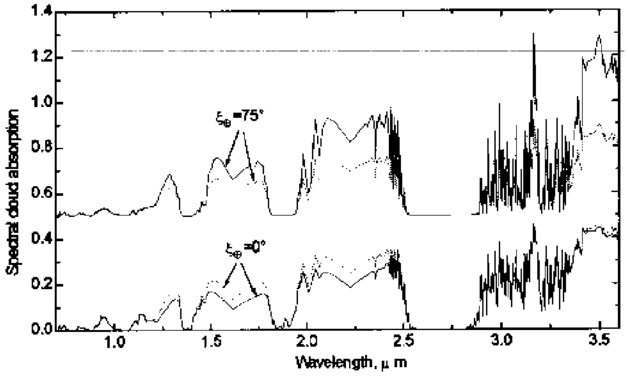

Figure 1. The dependence of spectral absorption in cumulus (solid) and stratus (dots) on solar zenith angle with N = 0.5, $\sigma_{0.71\,\mu m}$ = 30 km^{-1}, D = 0.25 km, A_s = 0.0. For convenience, values of cloud absorption for $\xi_{\oplus}$ = 75° are exaggerated by 0.5.

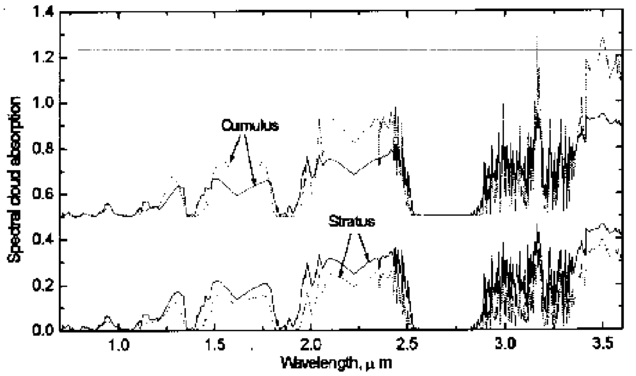

Figure 2. Same as in Figure 1 but for spectral cloud absorption with $\xi_{\oplus}$ = 0° (solid) and $\xi_{\oplus}$ = 75° (dots). For convenience, values of cumulus cloud absorption are exaggerated by 0.5.

by the decrease of the mean multiplicity of scattering and photon mean free path.

Thus, there are two opposite effects whose net result can be determined by expanding the spectral absorption in series in scattering multiplicities (orders). Obviously, the *n*th term of the expansion is proportional to $w_{\lambda}^{n-1}(1-w_{\lambda})$. When the single scattering albedo approaches unity, a major contribution to the spectral absorption will come from high scattering orders. Low scattering orders are more important contributors to the absorption by cumulus, while higher orders are of more importance in stratus. At wavelengths $\lambda \leq 1.2$ μm, water droplets absorb weakly ($w_{\lambda} \geq 0.999$). For such w_{λ} values, the increasing diffuse fraction may not compensate for the effect of decreasing mean scattering order and photon mean free path; as a result, for $\xi_{\oplus} > 0°$, the spectral absorption in cumulus is less than that in stratus (Figure 1). The situation is reverse for $\lambda \geq 1.2$ μm, in which case the water droplets strongly absorb ($0.485 \leq w_{\lambda} \leq 0.999$).

The differences in spectral absorption between stratus and cumulus clouds (the other parameters coinciding) have been discussed above. Now let us discuss the dependence of spectral absorption on solar zenith angle, for each of the cloud types. To this end we modify Figure 1 somewhat to obtain Figure 2. As zenith solar angle grows, the incident solar radiation upon the cloud top is increasingly depleted by the gaseous absorption and aerosol extinction; in addition, the cloud albedo increases, and the mean scattering order and mean path length of reflected photons both decrease. For these reasons, the absorption by stratus clouds decreases as $\xi_{\oplus}$ increases. A more complicated pattern is observed in the cumulus clouds case. For a moderate gaseous absorption, the increasing fraction of diffuse radiation dominates over the other effects mentioned above, so that the cumulus cloud absorption increases. For a strongly absorptive case, the dependence is reversed.

Let us suppose now that the underlying surface reflects according to Lambert's law and has the albedo $A_s > 0$. This surface can be viewed as a diffuse source whose power is proportional to $A_s Q(\lambda)$, with $Q(\lambda)$ the spectral transmittance at the surface level. Obviously, only in the case of a weak to moderate droplet and gaseous absorption will the source be powerful enough to affect noticeably the spectral absorption by clouds. Radiation reflected from the surface can interact with the sides of numerous cumulus clouds (i.e., may be scattered and absorbed). Quantitatively, this means that the fraction of radiation passing in gaps (holes) between clouds will be much less in cumulus than in stratus clouds. As a consequence, cumulus clouds absorb more radiation reflected from the surface than the stratus cloud do.

Integrated Absorption

By integrated absorption we mean the quantity

$$P = \frac{\int_{0.7\mu m}^{3.6\mu m} \pi S_{\lambda} P(\lambda) \cos\xi_{\oplus} d\lambda}{\pi S \cos\xi_{\oplus}} \text{ x } 100\%, \qquad (2)$$

where π S = 1353 W/m^2 is the integrated solar constant. Major contributors to the integrated absorption are those spectral intervals in which $P(\lambda)$ and πS_{λ} are sufficiently large. Clearly, the behavior of integrated absorption is dominated by the dependence of spectral absorption on problem parameters, so some obvious cases will be given without comments. Recall that the wavelength interval 0.7 -1.2 µm comprises ≈ 30% of the incident solar flux on the top of the atmosphere, while for the 1.2-2 µm and 2-4 µm intervals the percentages are ≈15% and 5%, respectively.

As the solar zenith angle increases, the integrated cloud absorption P_{Cloud} decreases for stratus and slightly increases for cumulus (Figure 3). The latter is because the spectral absorption in cumulus, $P_{Cu}(\lambda)$, may both increase and decrease with growing $\xi_{\oplus}$ (Figure 2); thus P_{Cloud} consists of two contributions varying in opposite directions with $\xi_{\oplus}$. For $\lambda \leq 2$ µm, and as $\xi_{\oplus}$ grows, there are spectral intervals in which $P_{Cu}(\lambda)$ decreases, and πS_{λ} is sufficiently large there, so these intervals are important contributors, and P_{Cloud} increases little. At the same time, the lower the solar elevation, the higher the integrated absorption due to the above-cloud atmosphere, so the larger the total atmospheric integrated absorption in both cumulus and stratus cases.

The effects associated with finite horizontal extents of cumulus clouds are responsible for the nonlinear (in contrast to stratus case) dependence of integrated absorption on cloud fraction *N* (Figure 4). Maximum differences in integrated absorption between cumulus and stratus clouds occur at intermediate cloud fractions and grow with increasing surface albedo.

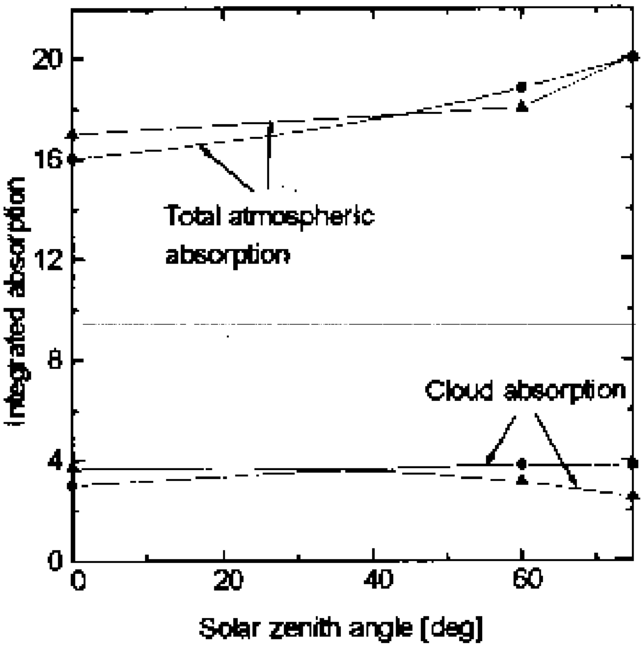

Figure 3. The influence of zenith solar angle on integrated absorption by cumulus (circles) and stratus (triangles) with $\sigma_{0.71\ \mu m}$ = 30 km^{-1}, N = 0.5, D = 0.25 km, A_s = 0.0.

In summary, the results above clearly demonstrate the substantial influence of effects, caused by the stochastic geometry of cloud fields, upon the spectral and integrated absorption of solar radiation in cumulus clouds. Currently we possess an extensive body of results for upward and downward fluxes of solar radiation, which can be viewed as a numerical radiation model of broken clouds. The next step of studies must be directed toward the improvement of now existing GCM radiation codes. This can be done through development of simple techniques for calculating the radiant fluxes in broken clouds, which would be sufficiently efficient and could adequately treat the effects caused by the stochastic geometry of cloud fields. Their accuracy and applicability range can be assessed by means of the developed numerical radiation model of broken clouds.

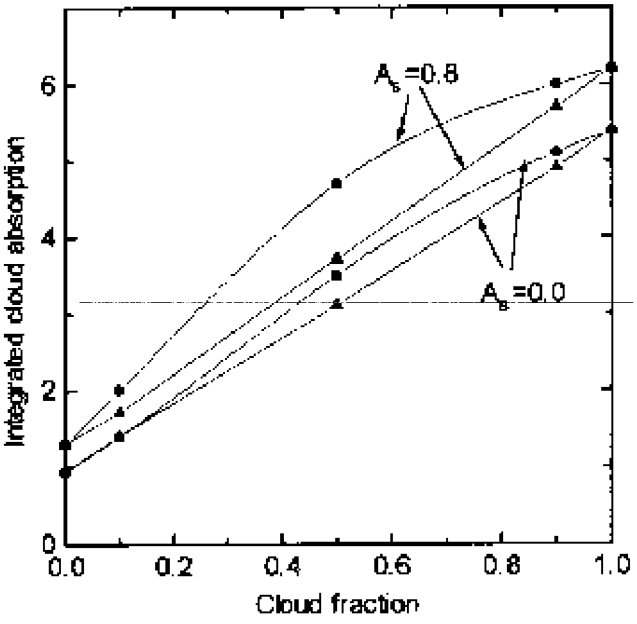

Figure 4. The dependence of the integrated absorption m cumulus (circles) and stratus (triangles) on cloud fraction with $\sigma_{0.71\ \mu m}$, = 30 km^{-l}, D = 1.0 km, $\xi_{\oplus}$ = 60° and for different values of surface albedo A_s.

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