On the Absorption, Reflection and Transmission of Solar Radiation in Cloudy Atmospheres

KUO-NAN LIOU

Department of Meteorology, University of Utah, Salt Lake City 84112

(Manuscript received 18 September 1975, in revised form 20 January 1976)

ABSTRACT

Band-by-band calculations have been carried out to evaluate the reflection, absorption and transmission of solar radiation by cloud layers and model cloudy atmospheres in the entire solar spectrum. The radiation transfer program is based on the discrete-ordinate method with applications to inhomogeneous atmospheres. The gaseous absorption in scattering atmospheres is taken into account by means of exponential fits to the total band absorption based on laboratory measurements. Thick clouds such as nimbostratus and cumulonimbus reflect 80–90% and absorb 10–20% of the solar radiation incident upon them. The reflection and absorption of a fair weather cumulus with a thickness of 0.45 km are about 68–85% and 4–9%, respectively. A thin stratus, whose thickness is 0.1 km, reflects about 45–72% and absorbs about 1–6% of the solar flux incident on the cloud top. The reflection of a 0.6 km thick altostratus is about 57–77%, with a larger absorption of 8–15%. A number of aircraft observations reveal that clouds may absorb as much as 30–40% of the solar flux incident upon them. Since the maximum absorption of clouds resulting from theoretical calculations is only 20%, certain clouds in the atmosphere are likely to consist of hydrophobic absorbing aerosol particles.

1. Introduction

Clouds occupy regularly over about 50% of the planet earth. They absorb and scatter the incoming solar radiation, while emitting thermal infrared radiation according to their temperature. The transfer of radiation through cloud layers depends on the particle phase, concentration, size and size distribution, all of which determine the properties of the volume single-scattering albedo and phase function. In addition, the cloud thickness is also a significant parameter whose change strongly influences the absorption, reflection and transmission of radiation. The amount of energy absorbed and/or emitted represents one of the prime sources determining the stability of cloud layers and is further associated with atmospheric motion.

In recent years, the reflection and absorption of incident solar radiation by clouds have begun to be extensively investigated. Aircraft measurements have revealed that clouds may absorb as much as 20–40% of the solar radiation incident upon them (see, e.g., Drummond and Hickey, 1971; Reynolds *et al.*, 1975). However, the mechanism responsible for this large absorption and its variability are mainly unknown. It is the purpose of this paper to investigate from a theoretical point of view the absorption, reflection and transmission of solar radiation in model cloudy atmospheres.

A radiation scheme has been developed by which the absorption of water vapor in the near-infrared regions of the solar spectrum can be inserted into the transfer program for inhomogeneous cloudy atmospheres (Liou and Sasamori, 1975). The incorporation of water vapor absorption in scattering atmospheres is accomplished by a series of exponential fits to the total absorptivity of each H_2O band on the basis of laboratory measured data[1] (Howard *et al.*, 1956).

Three-layer model atmospheres are constructed. They consist of cloudless atmospheres above and below a single cloud layer, and with gaseous absorption in all three layers based upon representative model atmospheres suggested by McClatchey *et al.* (1971). Clouds are classified into six types (London, 1957; Sasamori *et al.*, 1972) whose base heights and thicknesses are obtained from climatological data. The observed particle-size distribution and number density for each type of clouds are employed to calculate single-scattering properties of cloud particles from Mie scattering theory.

The basic transfer method is based on the discrete-ordinate method for radiative transfer (Liou, 1973) with further applications to inhomogeneous atmo-

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[1] As described by Liou and Sasamori (1975), in incorporating the gaseous absorption into the scattering layer, the effect of pressure dependence of absorption in an inhomogeneous atmosphere has been taken into consideration. However, since the use of exponential fits is based on a physical argument, we do not have satisfactory checks on its accuracy by a numerical means unless "exact" line-by-line calculations including cloud effects have been carried out.

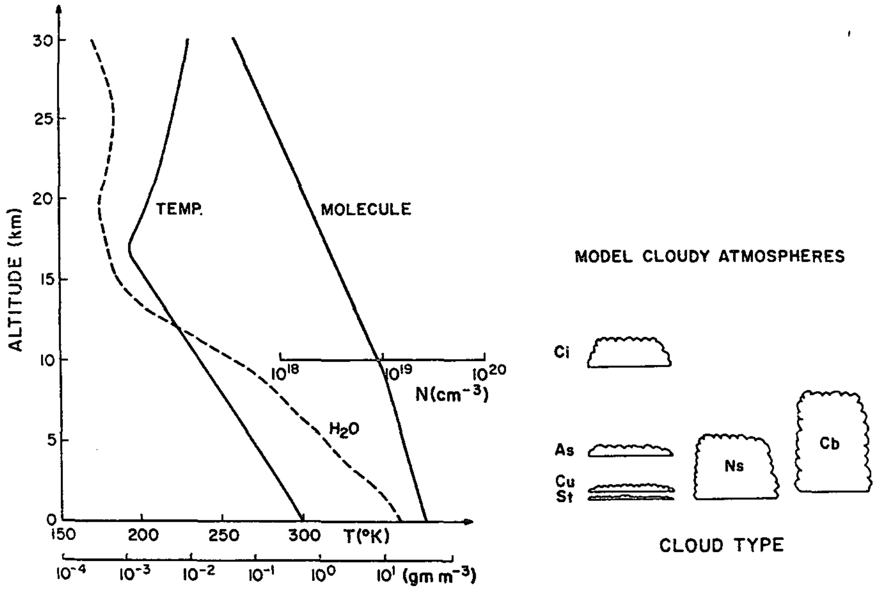

FIG. 1. Model cloudy atmospheres employed in this study. The temperature, water vapor density and molecular concentration profiles are for a mean tropical atmosphere. The climatological base heights and thicknesses of six cloud types are shown on the right-hand side.

spheres (Liou, 1975). Band-by-band calculations (Liou and Sasamori, 1975) are carried out for the absorption, reflection and transmission of solar radiation in model cloudy atmospheres. The computed reflection and absorption of the incident solar radiation by clouds are compared with those obtained by aircraft measurements published by Drummond and Hickey (1971) and Reynolds *et al.* (1975).

2. Model cloudy atmospheres

The climatological data for a tropical atmosphere tabulated by McClatchey *et al.* (1971) are employed in this study. The parameters include the height, pressure, temperature, molecular density and water vapor density which were given at 1 km height intervals up to 25 km (Fig. 1).

Clouds are divided into six types whose base heights z_b and thicknesses Δz_c are given in Table 1. The mean temperatures of clouds are obtained by averaging the temperatures of the cloud top and base. From the mean cloud temperature T, the vapor pressure e may be evaluated based on saturated conditions. Furthermore, from the equation of state, the water vapor density within a cloud is

$$\rho_w = e/(R_w T), \tag{1}$$

where $R_w = 4.168 \times 10^6$ ergs K^{-1} g^{-1}. And the water vapor path length is given by

$$\Delta u_c = \rho_w \Delta z_c. \tag{2}$$

We tabulate all the relevant parameters in Table 1.

The observed particle size distributions for fair weather cumulus (Cu), cumulonimbus (Cb), stratus (St), nimbostratus (Ns) and altostratus (As) are based on the observations by Battan and Reitan (1957), Weickmann and aufm Kampe (1953), Singleton and Smith (1960) and Diem (1948), respectively. The number density N for each type of water cloud is listed in the last column of Table 1. The wavelength-dependent real and imaginary parts of the refractive indices for water are taken from values tabulated by

TABLE 1. Cloud parameters.

Cloud types	z_b (km)	Δz_c (km)	T (K)	e (mb)	Δu_c (g cm^{-2})	N (cm^{-3})
Low cloud (Cu, Sc)	1.7	0.45	288	17.044	0.577	300
Middle cloud (As, Ac)	4.2	0.6	274	6.566	0.311	450
High cloud (Ci, Cs, Cc)	4.6	1.7	234	0.144	0.023	0.1
Nimbostratus (Ns)	1.4	4.0	280	10.013	3.098	330
Cumulonimbus (Cb)	1.7	6.0	270	4.898	2.357	75
Stratus (St)	1.4	0.1	291	20.630	0.154	178

Irvine and Pollack[2] (1968). On the basis of the above information Mie scattering computations (see, e.g., Liou and Hansen, 1971) may be made to obtain the volume scattering and absorption cross sections and the phase function.

The model cloudy atmosphere is considered to be plane-parallel with variations only in the vertical direction. It is further divided into several sub-layers according to the cloud location. With all this information, analyses and computations for the absorption and scattering processes in model cloudy atmospheres may be carried out.

3. Definitions of the radiative properties of atmospheres and clouds

As described by Liou and Sasamori (1975), the radiation scheme deals with the transfer of radiation in an absorption band which is divided into several sub-spectral regions. To obtain the reflection (local albedo) and absorption of the atmosphere or the cloud for the entire solar spectrum, proper summation over the fluxes in each sub-spectral region weighted by the appropriate percentage of solar flux is required.

a. Entire atmospheres

The reflection γ may be defined as the ratio of the reflected flux at the top of the atmosphere to the incident solar flux perpendicular to the stratification of the atmosphere. Thus, for each spectral band

$$\gamma_i=\begin{cases}\sum_m F_m^{\uparrow}(0)w_m/(\mu_0 f_{\Delta\lambda_i}), & \text{for H}_2\text{O bands}\\ F_i^{\uparrow}(0)/(\mu_0 f_{\Delta\lambda_i}), & \text{otherwise}\end{cases}\tag{3}$$

where $f_{\Delta\lambda_i}$ denotes the amount of solar flux in the ith spectral band, m is the number of the sub-band interval according to the exponential fit, μ_0 denotes the cosine of the solar zenith angle, and w_m is the weight of solar flux in the m sub-band interval. We note that w_m is independent of the direction of radiation fluxes.

The reflection of the earth-atmosphere system for the entire solar spectrum is to be evaluated by summing all the spectral reflection weighted by the appropriate percentage of the solar flux within each band interval as

$$\gamma=\sum_i \gamma_i f_{\Delta\lambda_i}/S_0,\tag{4}$$

where S_0 is the solar constant. Note that we have divided the solar spectrum into 0.5, 0.7, 0.94, 1.1, 1.38, 1.87, 2.7 and 3.2 μm bands.

In addition to the reflection, it is equally important to study the total absorption within the atmosphere due to both water vapor and cloud particles. Its value may be obtained by the net flux divergence between the top and bottom of the atmosphere whose optical depth is τ_N. For the ith absorption spectral interval, we have

$$\alpha_i=\begin{cases}\sum_m [F_m(\tau_N)-F_m(0)]w_m/(\mu_0 f_{\Delta\lambda_i}), & \text{for H}_2\text{O bands}\\ [F_i(\tau_N)-F_i(0)]/(\mu_0 f_{\Delta\lambda_i}), & \text{otherwise.}\end{cases}\tag{5}$$

The total absorption within the atmosphere due to solar radiation is therefore

$$\alpha=\sum_i \alpha_i f_{\Delta\lambda_i}/S_0.\tag{6}$$

b. Cloud layers

Similar to the above definitions, the reflection (or local albedo) of a cloud layer may be defined as the ratio of the reflected flux to the incident solar flux normal to the cloud top. Hence, the reflection for each spectral band is

$$\gamma_i^c=\begin{cases}\sum_m F_m^{\uparrow}(\tau_t)w_m/[\sum_m F_m^{\downarrow}(\tau_t)w_m], & \text{for H}_2\text{O bands}\\ F_i^{\uparrow}(\tau_t)/[F_i^{\downarrow}(\tau_t)], & \text{otherwise}\end{cases}\tag{7}$$

where τ_t denotes the optical depth at the cloud top. The reflection of a cloud layer for the entire solar spectrum is given by

$$\gamma^c=\sum_i \gamma_i^c f_{\Delta\lambda_i}/S_0.\tag{8}$$

Moreover, the absorption of solar flux within a cloud layer can be evaluated from the net flux divergence between the top and bottom of that cloud. For each spectral band, it is defined as

$$\alpha_i^c=\begin{cases}\sum_m [F_m(\tau_t)-F_m(\tau_b)]w_m/[\sum_m F_m^{\downarrow}(\tau_t)w_m], & \text{for H}_2\text{O bands}\\ [F_i(\tau_t)-F_i(\tau_b)]/F_i^{\downarrow}(\tau_t), & \text{otherwise}\end{cases}\tag{9}$$

where τ_b denotes the optical depth at the cloud base. The total absorption within a cloud layer for the entire solar spectrum, therefore, is

$$\alpha^c=\sum_i \alpha_i^c f_{\Delta\lambda_i}/S_0.\tag{10}$$

4. Results

a. Theoretical calculations

The inhomogeneous cloudy atmosphere is divided into three layers consisting of cloudless atmospheres above and below a single cloud layer. Each layer is

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[2] There are new observed results for the imaginary parts of the refractive indices for ice (Schaaf and Williams, 1973; Bertie *et al.*, 1969) and for water (Hale and Querry, 1973). Results obtained by Hale and Querry in 1973 apparently deviate insignificantly from those summarized by Irvine and Pollack in 1968.

considered to be homogeneous with respect to the single-scattering albedo and the phase function. The spectral solar flux at the top of the atmosphere is taken from the table in *Astrophysical Quantities* (Allen, 1963, p. 272). Band-by-band calculations are carried out for the transfer of solar radiation in inhomogeneous cloudy atmospheres based on the discrete-ordinate method for radiative transfer. The final resulting absorption, reflection and transmission for the cloud layer and the entire atmosphere are obtained according to the formulas defined in Section 3. We have chosen a surface albedo of 0.1 in the following presentations.

Fig. 2 shows the normalized phase functions of a fair weather cumulus for various wavelengths in the solar spectrum. It is assumed that the phase functions and extinction cross sections of cloud particles are constant in each spectral band. Phase functions and extinction cross sections have also been calculated for cloud types mentioned previously. These single-scattering properties are then incorporated into the transfer program.

Before we present some results for the reflection, absorption and transmission of solar radiation in cloudy atmospheres, we note that the imaginary parts of the refractive indices for water in the 0.5 and 0.7 μm bands are about 10^{-9} to 10^{-7}, resulting in slight absorption by cloud droplets. Furthermore, there are other absorbers in the solar spectrum in addition to water vapor, namely, oxygen, ozone and carbon dioxide. According to parameterization calculations by Sasamori *et al.* (1972) for a zonally averaged tropical atmosphere, oxygen and carbon dioxide together are responsible for only about 1.5% absorption, while absorption due to ozone, which is an important absorber primarily in the stratosphere, is about 3%. Since clouds are normally of tropospheric origin, we shall neglect the absorption contribution caused by ozone, oxygen and carbon dioxide in the discussion of cloud reflection, absorption and transmission. We anticipate that the neglect of these three minor absorbers will cause no more than 1% error in the resulting cloud absorption.

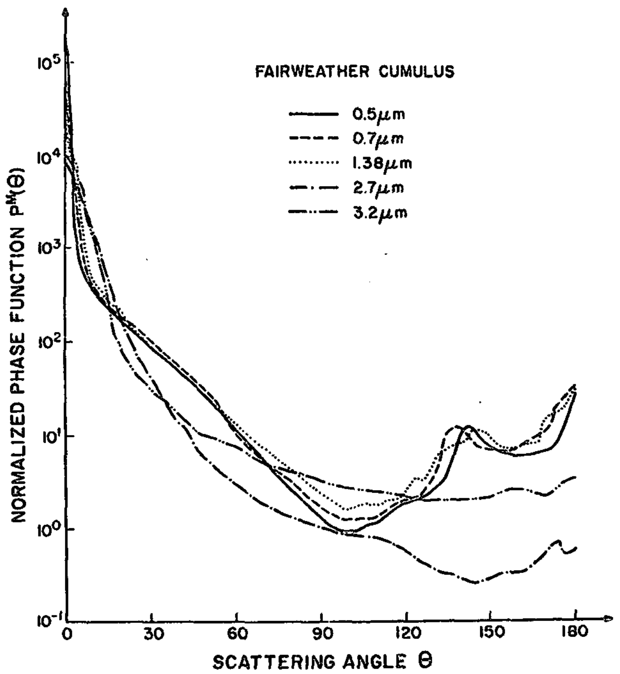

Fig. 2. Normalized phase functions of a fair weather cumulus as functions of the scattering angle for various wavelengths in the solar spectrum.

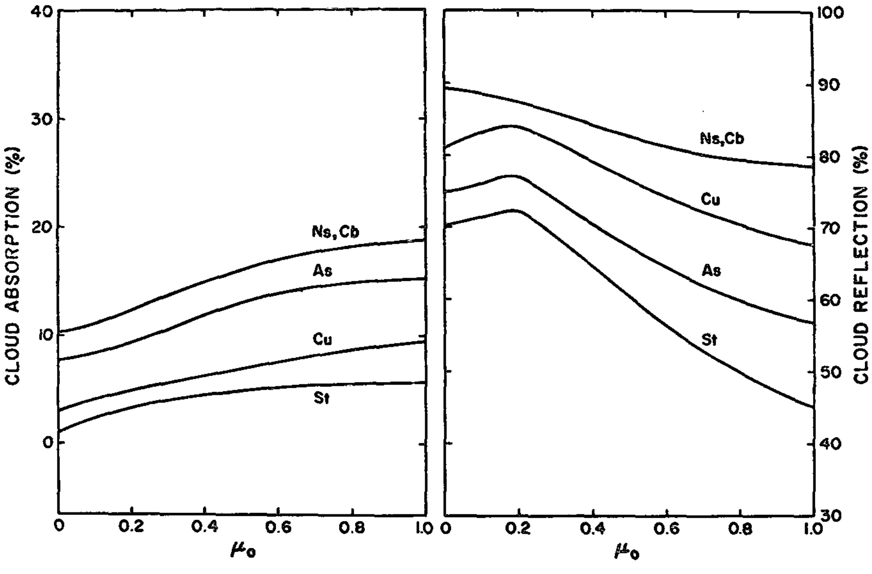

Fig. 3. The absorption and reflection of solar radiation by five cloud layers as functions of the cosine of the solar zenith angle.

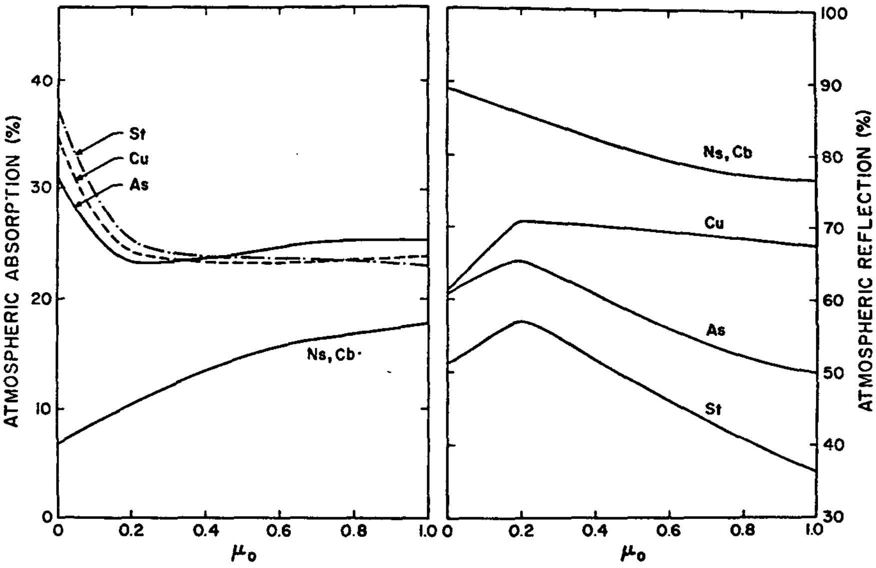

FIG. 4. The total absorption and reflection of solar radiation by five cloudy atmospheres as functions of the cosine of the solar zenith angle.

Fig. 3 shows the absorption and reflection of solar radiation as functions of the cosine of the solar zenith angle for five cloud types. The absorption and reflection are normalized with respect to the downward flux at the cloud top. Owing to the large geometrical thickness and broad particle spectrum, the cloud-particle optical depths of the nimbostratus and cumulonimbus at a visible wavelength of 0.5 μm are about 500 and 700, respectively. In order to carry out the transfer calculations including water vapor absorption, a double precision sub-program was made to eliminate the exponential over- and under-flow in the computations. Because of these computational procedures, the differences in the resulting radiation parameters between Ns and Cb are found to be negligibly small. Values of the cloud reflection illustrate that Ns and Cb reflect about 80–90% of the solar flux incident upon them. The scattering of cloud particles obviously is responsible for the large reflection. The corresponding absorption within these clouds indicates a value of about 20% when the sun is overhead. Absorption of solar radiation by both water vapor and cloud particles in the near infrared is responsible for the cloud absorption.

Although the geometrical thickness of the cumulus used in this study is only about 0.5 km, large reflection values ranging from 68 to 85% are obtained. About 9% of the solar flux incident upon it is absorbed when the sun is overhead. The reflection and absorption values for a stratus,[3] whose geometrical thickness is 0.1 km, are from 45 to 72% and from 1 to 6%, respectively. Altostratus reflects about 57 to 77% of the solar flux. These values are somewhere in between those of Cu and St. On the other hand, however, the absorption of solar flux by As is greater than that by Cu and St with values ranging from 8 to 15%. The larger absorption, which takes place in the middle cloud, is primarily due to its higher appearance in the atmosphere. In this case, since the concentration of water vapor above the cloud is relatively small, a large portion of solar flux penetrates the atmosphere and is absorbed by the cloud. This evidence indicates that cloud location in the atmosphere is important in determining the absorption of solar radiation energy in the cloud layer. Variations of the cloud absorption obviously depend upon the cloud type which gives the indication of the mean cloud location, thickness and composition (particle sizes and concentration). The effective optical depth is responsible for the cloud reflection. The cloud effective optical depth is determined by a combination of its thickness and composition as well as the solar zenith angle. Optically thick clouds reflect more radiation incident upon them. It is apparent that Cb has the largest optical depth, with St the smallest.

The total absorption and reflection for five entire cloudy atmospheres are shown in Fig. 4. For the Cu case the total atmospheric absorption is about 24% when the sun is overhead, and 35% when the sun is close to the horizon. For the As case, it is interesting to note that, compared with the Cu case, larger absorption occurs when the sun is near the zenith, while

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[3] It should be pointed out that Ns, Cb, Cu and As are optically thick clouds whose optical depths in the visible are all greater than about 30 or so. Hence, the effect of the underlying albedo on their radiative properties is insignificant. For thin stratus whose optical depth in the visible is about 9, our unpublished results reveal that increasing the surface albedo from 0.1 to 0.4 produces maximum increases of 0.005 and 0.09 for the absorption and reflection values, respectively. Thus, the effect of the surface albedo is also small.

smaller absorption takes place when the sun is close to the horizon. The reason for this involves the relatively low appearance of Cu in the atmosphere. When the sun is low, a longer water vapor path length is expected. Consequently, more absorption of solar radiation takes place above the Cu. The atmospheric absorption caused by water vapor in a cloud- and aerosol-free tropical atmosphere is about 18% when the sun is overhead. In this case, absorption by cloud particles accounts for only about 5–8%. Values of the reflection at the top of the atmospheres containing Cu, St and As clouds are smaller compared to those of the clouds alone, because more solar flux is absorbed in the atmospheres above and below the cloud layer. As for the Ns and Cb cases, since clouds dominate the radiation processes, values of the reflection and absorption for cloudy atmospheres are about the same irrespective of the presence of atmospheres above and below the cloud layer.

Fig. 5 illustrates the reflection (local albedo) of each individual spectral band at the top of five cloudy atmospheres whose surface albedos are 0.1 when the sun is overhead. For all the cases presented here, the band reflection generally decreases with increasing wavelength in the solar spectrum due to the absorption characteristics of cloud droplets and water vapor. The reflection values for 0.94 and 1.1 μm weak water vapor bands depend strongly on the cloud composition and structure. As for 1.38, 1.87 and 2.7 μm bands, water vapor absorption apparently dominates the radiation processes. The reflection of solar radiation by cloudy atmospheres is the most important parameter in the study of the atmospheric energy budget. In the past, a visible wavelength (e.g., 0.5 or 0.7 μm) was usually employed to evaluate the reflection of solar radiation by clouds (see, e.g., Twomey, 1972; Liou, 1973). As can be easily understood from Figs. 4 and 5 ($\mu_0=1$), if a 0.5 μm wavelength, for instance, is chosen to estimate the reflection values, then an overestimation by as much as 10–15% may be anticipated as compared with those calculated by including all the wavelengths in the solar spectrum.

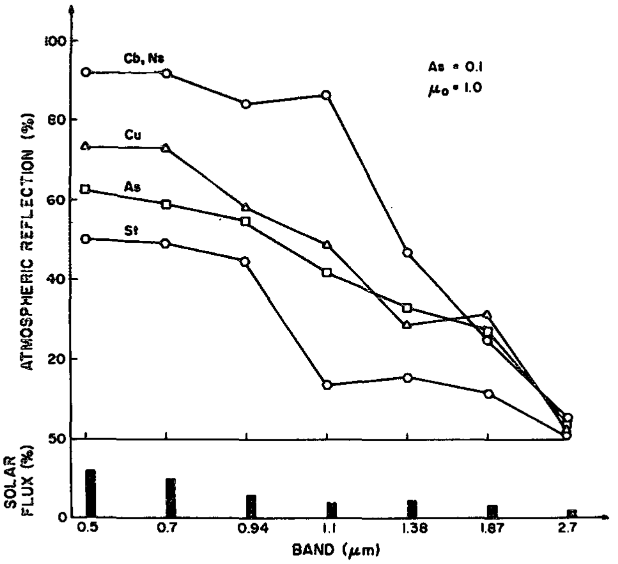

Fig. 5. The reflection of various bands in the solar spectrum by five cloudy atmospheres when the sun is overhead. The lower part of the figure represents the percentage of solar flux in each spectral interval.

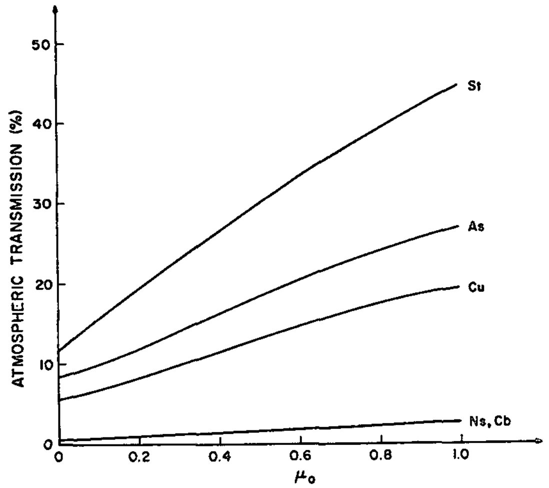

Fig. 6. The transmission (including direct and diffuse components) of solar radiation at the bottom of five cloudy atmospheres. The transmitted solar flux in cloudy atmospheres represents an important energy source available to the earth's surface.

Fig. 6 presents the total transmission, which includes the direct as well as diffuse components, at the bottom of the atmosphere. Only about 1–3% of the solar flux can penetrate an atmosphere containing Ns and Cb clouds. When the sun is overhead, values of the transmission for Cu, St and As atmospheres are about 20, 27 and 45%, respectively. Owing to the increased atmospheric path length the transmission values decrease when the sun moves toward the horizon. The transmitted solar flux represents one of the important energy sources available to the earth's surface.

b. Comparison with observations

Aircraft measurements of the reflection and absorption of solar radiation by cloud layers were reported by Reynolds *et al.* (1975) and Drummond and Hickey (1971). These observations were made when solar elevation angles were greater than 60° (i.e., $\mu_0 > 0.866$). We present in Table 2 the observed reflection and absorption for various cloud types, along with the present theoretical values.

Before examining the values in Table 2, it should be emphasized that the theoretical calculations employ the "climatological mean" cloud thicknesses and locations presented in Fig. 1, since the observed data

TABLE 2. Observed and computed reflection (γ^c) and absorption (α^c) of solar radiation for various cloud types.

		Drummond and Hickey (1971)	Reynolds *et al.* (1975)	Liou Present study ($\mu_0=1$)
St, Cu	γ^c	47–56%	37–42%	45–67%
	α^c	—	12–36%	6–9%
As, Ac	γ^c	40%	—	56%
	α^c	15%	—	15%
Cb, Ns	γ^c	—	66%	78%
	α^c	—	31%	19%
Ci, Cs	γ^c	20%	47–59%	—
	α^c	—	13–15%	—

provide no such direct information. We have not been able to carry out the transfer calculations for cirrus clouds because the information on the single-scattering properties of non-spherical ice crystals in the solar spectrum are still lacking. Except for the As absorption value, we see that the computed reflection and absorption values are generally higher and lower, respectively, than those obtained from aircraft measurements. There may be a number of reason for these discrepancies due to the uncertainties in field observations and model theoretical calculations.[4] However, it seems most likely that 1) the differences in the geometrical depth, particle size and concentration between calculations and observations, and 2) the possible existence of absorbing hydrophobic aerosol particles in the cloud layer (Twomey, 1972) are the primary causes for these differences. Point 1) may be solved if a careful and comprehensive field experiment including cloud physics measurements is undertaken. However, point 2) requires knowledge of the refractive indices for aerosols in the entire solar spectrum and the concentration and sizes of aerosols that may exist in the cloud layer.

5. Conclusions

Band-by-band calculations have been carried out to evaluate the reflection, absorption and transmission of solar radiation by the cloud layer and the model cloudy atmosphere in the entire solar spectrum. The reflected solar fluxes at the top of the atmospheres containing cumulus, stratus and altostratus are found to be smaller than those of the clouds alone, owing to the additional absorption by the gases above and below the cloud layer.

Thick clouds such as nimbostratus and cumulonimbus reflect 80–90% and absorb 10–20% of the solar flux incident upon them. Effects of the atmospheres above and below them are shown to be fairly small. The reflection of a fair weather cumulus with a thickness of 0.45 km is found to be about 63–85%, but its absorption is only about 4–9%. A thin stratus whose thickness is 0.1 km reflects about 45–72% and absorbs about 1–6% of the solar flux incident on the cloud top. Reflection of a 0.6 km thick middle cloud is about 57 to 77%. Because of its higher location in the atmosphere, a larger absorption of about 8 to 15% is obtained. On the basis of these calculations, it is evident that the location of the cloud in the atmosphere is important in determining the cloud absorption.

Comparisons with aircraft observations reveal that theoretical calculations yield higher reflection and lower absorption values for most of the water clouds. Although these discrepancies may well be caused by the uncertainties in field observations and model theoretical computations, it appears more likely that water clouds in the lower atmosphere are composed of hydrophobic aerosol particles, which could give rise to more absorption, and subsequently less reflection of solar radiation.

Acknowledgments. A portion of the calculations reported in this paper was carried out by S. Y. Chao. This research was supported by the Atmospheric Sciences Section of the National Science Foundation under Grant DES75-05216. Partial support of this research was also provided by the Air Force Cambridge Research Laboratories under Contract F19628-75-C-0107.

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[4] Theoretical calculations assume that clouds are plane-parallel layers with infinite horizontal dimensions. To a good approximation such an assumption may be applied to cloud systems whose horizontal extents are greater than their vertical developments. Note that radiative transfer in finite cloud layers is one area where further investigation is required.

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