The Effect of Cloud Scattering on the Absorption of Solar Radiation by Atmospheric Dust

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ABSTRACT

When non-absorbing scatterers (e.g., cloud drops) are added in an absorbing layer (e.g., a dust layer), the optical paths of the radiation will be greatly changed if the scattering component is optically thick. The absorption will thus be altered. Results are given of numerical computations to determine the effect of non-absorbing cloud drops on the absorption of radiation by a dust layer. Absorption is found to be decreased for low angles of incidence and increased for higher angles of incidence.

1. Introduction

Some measurements of shortwave radiation have suggested a significant absorption of solar radiation by cloud layers, whereas laboratory measurements of absorption coefficients indicate that water absorbs only a negligible proportion of incident shortwave radiation. To date no convincing explanation of this apparent contradiction has been given.

If neither the air nor the liquid water absorbs appreciably, one must give consideration to the effect of particles, i.e., "dust," in absorption. Robinson and Drummond (1971) for example, have reported that up to about 5% of incident solar radiation was absorbed by airborne particles in the atmosphere over the area of the BOMEX experiment. If non-absorbing scattering particles were introduced into such an absorbing layer, the absorption would be expected to change as a result of the changes of direction following scattering. It is possible that an enhancement of absorption could result from the angular redistribution in scattered radiation. The present paper will present and discuss briefly results of computations made to investigate that question.

2. Physical state of dust particles in cloud

Only a small fraction of all airborne particles participate directly in cloud formation by acting as nuclei for the condensation process. Present evidence (Twomey, 1971) suggests that the particles which do thus act are soluble, probably ammonium sulfate, and therefore most probably not effective absorbers of solar radiation. It is likely that airborne particles which do absorb are larger, "black" particles which are insoluble and if combustion products possibly hydrophobic. Such particles will initially be found in the air between the cloud drops but as time goes on some of them will coagulate with cloud drops through diffusion and diffusiophoresis. The fractional rate of diffusive coagulation of particles of radius a with N [cm^{-3}] droplets of radius r is $K(a,r)N$ [sec^{-1}] if K is the coagulation coefficient; the values for the latter are given by Fuchs (1964) for a and r in the range 10^{-7} to 10^{-3} cm. For $a=10^{-5}$ and $r=5\times10^{-4}$ cm, for example, K takes the value 72×10^{-10} cm^3 sec^{-1}. If there are 500 cloud droplets cm^{-3}, it follows that a fraction of only 3.6×10^{-6} sec^{-1} of the particles coagulate with cloud droplets. In the case of diffusiophoresis, Goldsmith *et al.* (1963) give the relation

$$u=1.9\times10^{-4}\frac{dp}{dx},$$

where u is the diffusiophoretic speed of a particle in a vapor pressure gradient of dp/dx [mb cm^{-1}]. Converted to vapor concentration n [molecules cm^{-3}] and pressure [dyn cm^{-2}] units the relation becomes

$$u=1.9\times10^{-7}\frac{dp}{dx}=1.9\times10^{-7}kT\frac{dn}{dx},$$

so that with ν particles [cm^{-3}] a single drop growing by condensation accretes particles at the rate

$$4\pi r^2 u\nu=7.6\pi r^2 kT\nu\frac{dn}{dr}\times10^{-7},$$

while it collects water molecules and grows at the rate

$$\frac{dM}{dt}=4\pi r^2 Dm_0\frac{dn}{dr} \tag{1}$$

(M the mass of drop, D the diffusion coefficient of water vapor, and m_0 the mass of a water molecule). If there are N drops per unit volume, the cloud liquid water content $W=NM$ and

$$\frac{1}{\nu}\frac{d\nu}{dt}=-7.6\pi r^2 kTN\frac{dn}{dr}\times10^{-7}. \tag{2}$$

From (1) and (2), we have

$$\frac{1}{\nu}\frac{d\nu}{dt}=-1.9\times10^{-7}\frac{kT}{Dm_0}\frac{dW}{dt}.$$

Substitution of numerical values for k, T, D, m_0 gives

$$\frac{1}{\nu}\frac{d\nu}{dt}\approx-10^3\frac{dW}{dt}.$$

Hence $\nu\approx\nu_0\exp(-10^3 W)$. Since W is typically of order 10^{-6} gm cm^{-3} or less, the effect of diffusiophoresis is slight, only about one-thousandth of the particles having been removed during cloud formation.

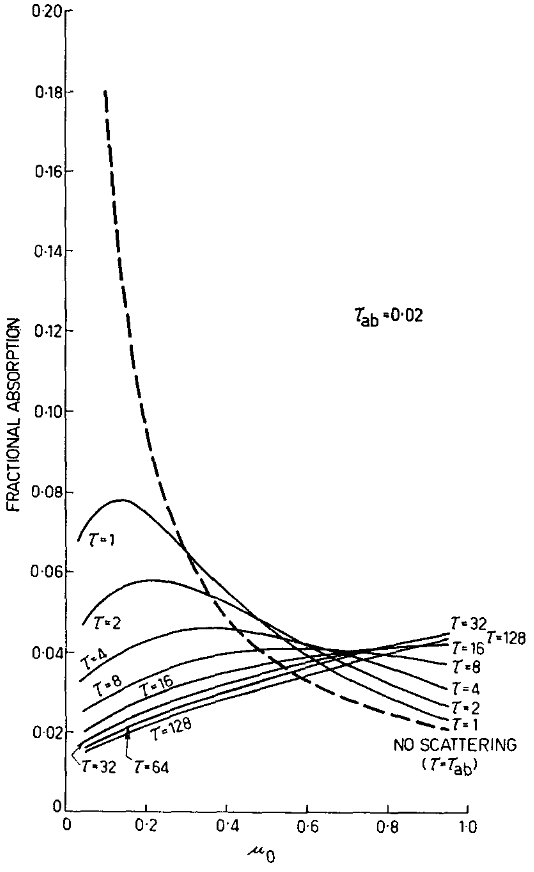

Fig. 1. Absorption vs μ_0 (cosine of zenith angle of incident radiation) for an absorbing layer of optical thickness 0.02 intermixed with non-absorbing scatterers to give a total optical thickness τ. Curves are shown for $\tau=0$, 1, 2, 4, 8, 16, 32, 64 and 128.

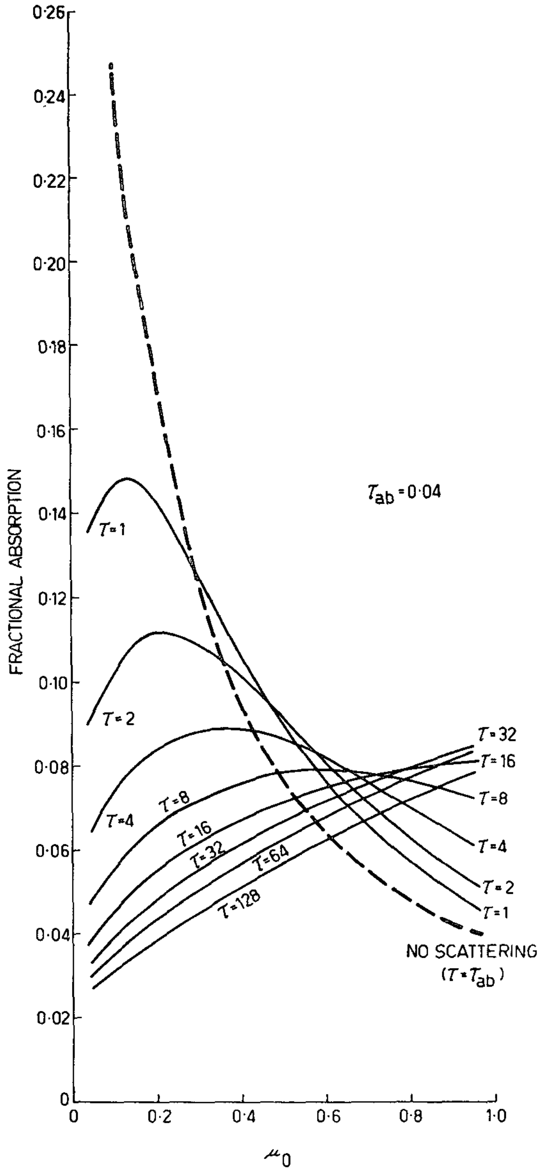

Fig. 2. Same as Fig. 1 except for an absorbing layer of optical thickness 0.04.

It follows that it is reasonable to assume that most of the absorbing particles will be found in between the cloud drops, so that the absorption coefficient within the cloud would be nearly the same as that in a cloudless layer with the same dust content.

3. Computational method

The method used was the matrix method of layer superposition described by Twomey *et al.* (1966)—this is in all major respects identical to the doubling method introduced by van de Hulst (1963) and applied by Hansen (1969, 1971) and others. In these methods the scattering properties of a thick layer of optical thickness τ, single scattering albedo $\bar{\omega}$, and scattering phase

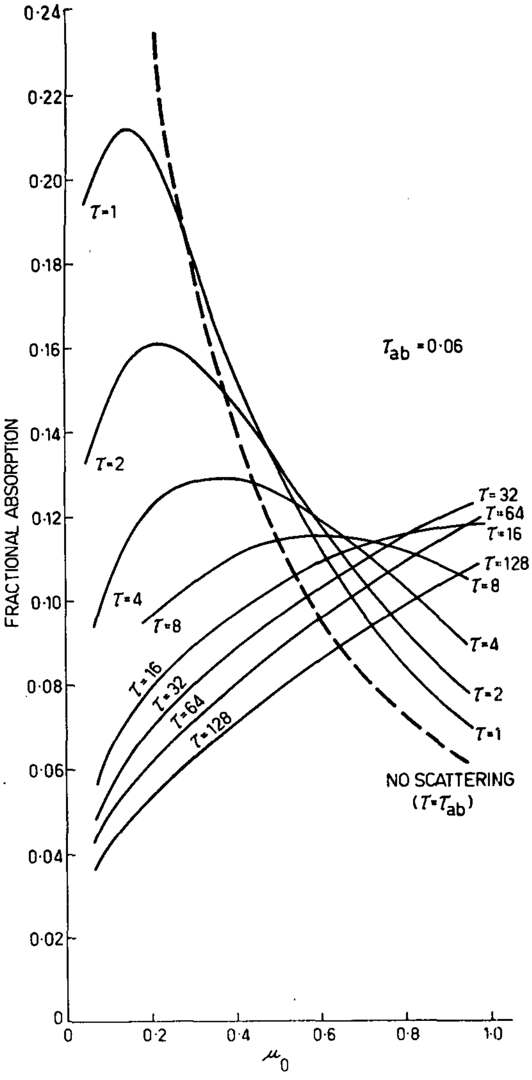

FIG. 3. Same as Fig. 1 except for an absorbing layer of optical thickness 0.06.

function p or phase matrix **P** is derived by starting with a thin layer of thickness $\Delta\tau$; for the thin layer the reflection and transmission function (or matrix) can be written down immediately from the phase function (matrix). The method then proceeds by superimposing layers of progressively greater thickness until the required final thickness is reached: the simplest application proceeds by superposition of equal layers so that the thickness is doubled at each step and after m successive superpositions a layer of thickness τ is built up from the initial thickness $2^{-m}\tau$.

If cloud forms in a layer which in the dry state was purely absorbing with optical thickness τ_a, then the effect of cloud formation is to change from a layer with $\tau=\tau_a$, $\tilde{\omega}=0$ to a layer with $\tau=\tau_a+\tau_c$, $\tilde{\omega}=\tau_c/(\tau_a+\tau_c)$ (here τ_c is the scattering optical thickness due to the non-absorbing cloud drops; for most visible clouds $\tau_c \gg 1$). For each pair of values for τ_a and τ_c, the doubling method was used to proceed from a thin layer with thickness $2^{-m}(\tau_a+\tau_c)$ and single scattering albedo $\tau_c/(\tau_a+\tau_c)$ to a layer with thickness $\tau_a+\tau_c$. Even though only the absorption vector was needed a complete set of transmission and reflection matrices had to be calculated at each step to provide the data needed in the following step.

4. Results

The variation of absorption with the cosine of angle of incidence μ_0 for various values of τ_c is shown in Fig. 1 for an absorbing optical thickness $\tau_a=0.02$ (i.e., approximately 2% of the incident energy absorbed at normal incidence). It is apparent that the effect of

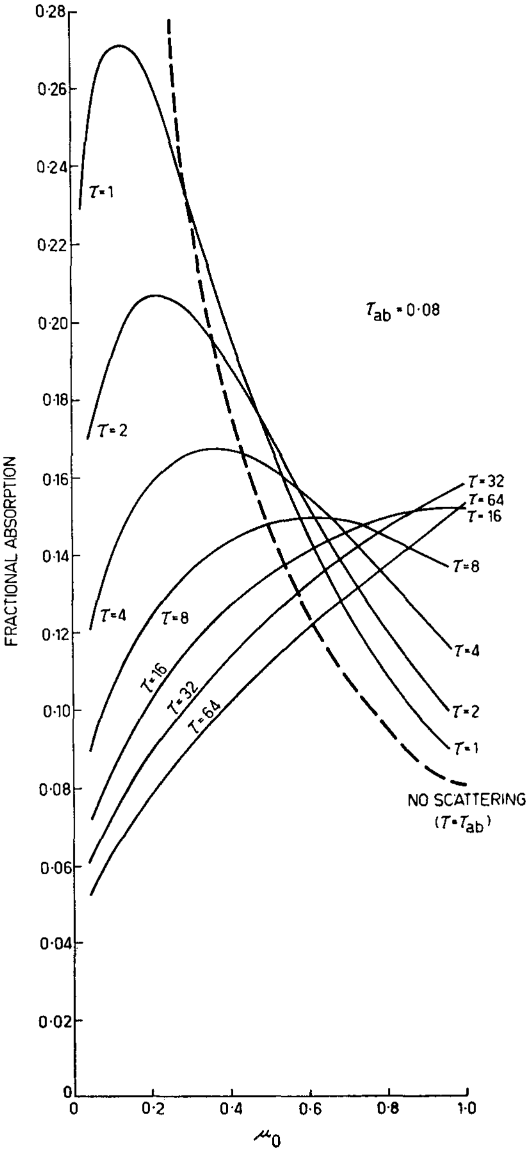

FIG. 4. Same as Fig. 1 except for an absorbing layer of optical thickness 0.08.

introducing the cloud layer is to decrease the absorption for low-incident angles (small μ_0)—this decrease evidently arises from the fact that the introduction of scattering allows some photons to take a shorter route through the absorbing layer—while for near-normal incidence the absorption is increased, by the tendency for path lengths to be increased by scattering. The addition of clouds thick enough to obscure the zenith sun from an observer on the ground ($\tau \approx 8$) approximately doubles the absorption at normal incidence, but for solar zenith angles $\gtrsim 60°$ (elevation angles $< 30°$) absorption is reduced by cloud formation.

Results for absorbing layers of optical thickness 0.04, 0.06 and 0.08 are shown in Figs. 2–4. Again the absorption is increased at high solar elevations and decreased considerably for low elevations. In each of Figs. 1–4 the absorption around normal incidence is approximately doubled when a thick cloud layer is introduced.

The overall effect of cloud formation on absorption is not great when averaged over all incident directions. Considering, for example, the difference between a uniformly illuminated sphere uniformly covered with an absorbing dust layer of optical thickness τ_a and the same layer plus an intermixed scattering layer, one must compare the values taken by $2\int_0^1 a(\mu)\mu d\mu$ if $a(\mu)$ is the absorption for incident zenith angle $\cos^{-1}\mu$. Numerically computed values of $2\int_0^1 a(\mu)\mu d\mu$ are given in the following table for a dust layer of (absorbing) optical thickness 0.08 and $\bar{\omega}=0$ and a scattering cloud layer of optical thickness $\tau = 0, 1, 2, 4, 8, 16, 32, 64$:

τ	0	1	2	4	8	16	32	64
$2\int_0^1 a(\mu)\,\mu d\mu$	0.138	0.140	0.141	0.140	0.140	0.138	0.133	0.124

In the table, as in similar data for other optical thicknesses of the absorbing component, there is little variation of the quantity $2\int_0^1 a(\mu)\mu d\mu$ over a wide range of scattering optical thickness. In other words, the increased absorption at near zenith illumination is fairly accurately cancelled by the decreased absorption for illumination at lower elevations.

5. Conclusions

When averaged globally, the absorption by a dust layer is hardly altered at all by the introduction of scatterers in the layer (such as would occur if a cloud formed in it). However, there is a redistribution of absorbed energy with respect to angle of illumination, with approximately a doubled absorption for close to normal incidence. This effect is large enough to need to be taken into account when experimental observations are being analyzed, but it is not large enough to explain the values of cloud absorption reported for example by Robinson (1958) and by Drummond and Hickey (1971). The latter inferred cloud absorption of 25–30% for thick clouds in the ROMEX area where particle layer absorption was measured at around 5%.

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