Computations of the Absorption of Solar Radiation by Clouds

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(Manuscript received 9 October 1975, in revised form 23 February 1976)

ABSTRACT

Using published data for water vapor absorption and for absorption by liquid (or ice) water, the absorption of solar radiation by clouds was computed for several representative cloud models. Absorption was found to approach 20% of the solar flux for the more absorbing and thicker clouds. There were systematic differences between continental and maritime clouds, the latter absorbing more for the same cloud thickness—an effect produced by the greater absorption efficiency of the larger maritime drops.

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1. Introduction

It is generally recognized that clouds are crucial to the reflection of solar radiation and to the emission and absorption of infrared radiation and, as such, are very important in atmospheric energetics. Recently, more attention has been given to the role of clouds in the absorption of solar energy. The traditional view that absorption by clouds could be neglected is hardly supported by recent measurements (e.g., Rosenberg *et al.*, 1974; Reynolds *et al.*, 1975; Drummond and Hickey, 1971), which suggest that direct absorption of solar radiation in clouds is an important heat source in the troposphere. This heating is, of course, realized at the expense of surface heating, since in the absence of cloud absorption the surface would have absorbed some of the radiation, but nonetheless it is of obvious importance.

The purpose of the present contribution is to outline the methods and results of a numerical computation of cloud absorption which took into account the spectral variations of absorption by water vapor and liquid water and the effects of cloud scattering.

2. Computational scheme

The starting point for the calculations was the tabulated spectral liquid water absorption data of Irvine and Pollak (1968) and the spectral water vapor absorption data of McClatchey *et al.* (1970). There were four main steps in the calculations.

(i) The two tables were merged into one using linear interpolation of the variables tabulated or graphed in the original works, to obtain both quantities at common wavelengths.

(ii) The absorption and scattering properties of cloud drops as a function of drop size were calculated using Mie theory. Polydispersity of drop size was taken into account by integrating over the range of drops using a distribution which is in good approximate agreement with measured cloud distributions in the lower atmosphere. In fact, a Gaussian distribution with a relative dispersion $\sigma/\bar{r}$ of 0.2 was used. However, it was found that the distribution used was not too important, so long as it was not very narrow; observed distributions are found to give values of $\sigma/\bar{r}$ ranging up from 0.2, smaller values being rare (Warner, 1969). Any reasonably wide distribution irons out the maxima and minima characteristic of scattering by a single sphere and leaves quite a smooth dependence on average size.

Having completed the scattering computations, one has the extinction and scattering optical thicknesses $\Delta\tau_e$ and $\Delta\tau_s$ for the liquid (or ice) component in a small-volume element of the cloud. Water vapor contributes only to the absorption and extinction and its contribution was calculated by assuming vapor saturation at the prescribed temperature and obtaining the appropriate transmittance for a 1 km path from the data of McClatchey *et al.* The total scattering optical thickness τ_s for a 1 km layer is influenced only by droplet scattering. The extinction optical thickness, on the other hand, is contributed to by droplet scattering, droplet absorption and vapor absorption; writing τ_v for the absorption optical thickness of a 1 km path of water vapor, and τ_a for the absorption optical thickness for the drops, one has

$$\tau=\tau_s+\tau_a+\tau_v.$$

For any wavelength one can calculate the total optical thickness $\tau(\lambda)$ and also obtain a single scattering albedo $\tilde{\omega}_0(\lambda)$ in the form $\tau_0=\tau_s/\tau$. The total optical thickness τ varies only slightly with λ and the average size of the droplet, but $\tilde{\omega}_0(\lambda)$ varies strongly with both wavelength (Fig. 1) and droplet size—the solid curve in Fig. 1 relates to a maritime-type cloud (25 droplets cm^{-3}) and the broken curve to a continental-type cloud (200 droplets cm^{-3}) at the same temperature and containing the same liquid water (0.33 g m^{-3}). Evidently, a sizable influence of cloud type is found, as well as the

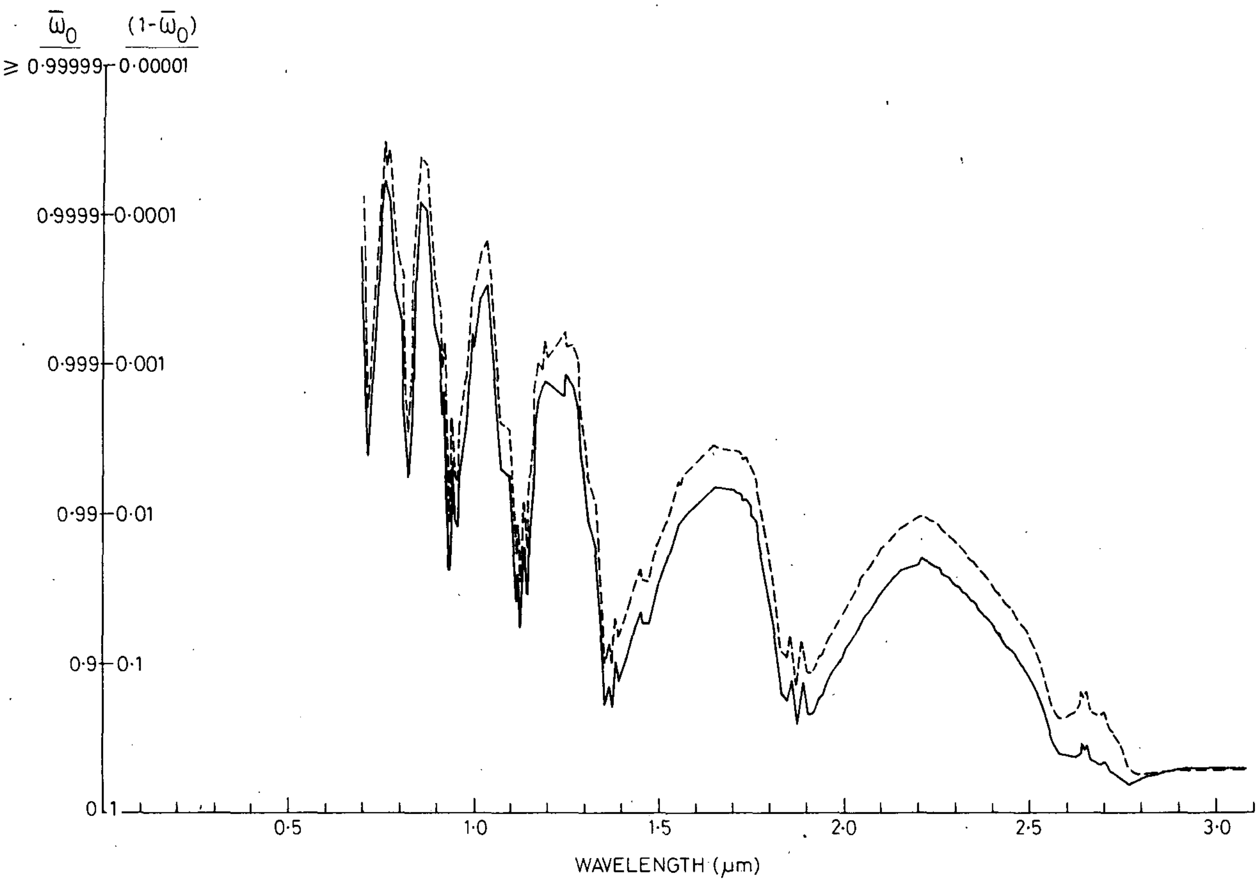

FIG. 1. Spectra of the single scattering albedo $\bar{\omega}_0$ as a function of wavelength.

strong spectral dependence caused by the spectral variation of liquid, solid and vapor absorption coefficients.

(iii) The next step was the calculation by the doubling method of the multiple scattering properties of an extended horizontal layer of optical thickness $\tau=2^n\tau_0$. The starting value τ_0 was 2^{-10} and the doubling procedure for absorption was as described in Twomey (1975), using a range of values of $\bar{\omega}_0$ and a phase func-

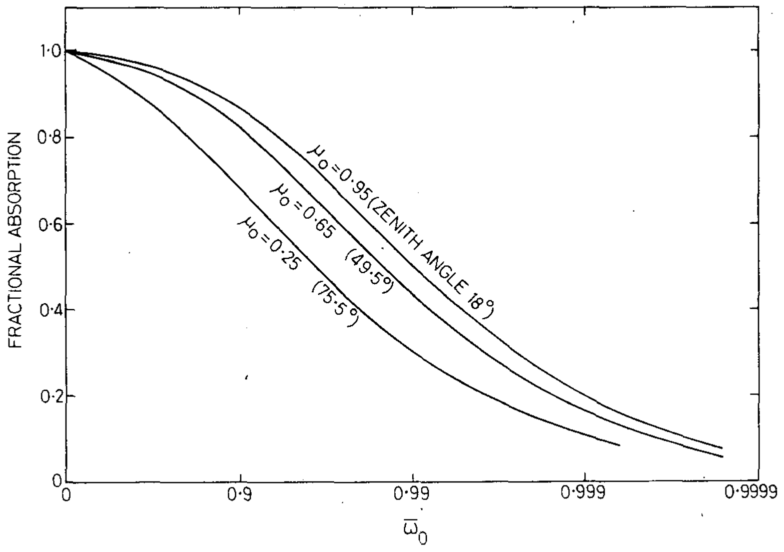

FIG. 2. Relationship between fractional absorption and $\bar{\omega}_0$ for a cloud 1 km deep (for the oceanic case, $\tau=32$).

tion (scattering diagram) given by Mie scattering from the cloud droplets (integrated over size). For any direction of incident zenith angle $\cos^{-1}\mu_0$, one can plot absorption uniquely against $\bar{\omega}_0$, to obtain curves such as those shown in Fig. 2. There is no absorption for $\bar{\omega}_0=1$ (conservative scattering) and an absorption of $1-\exp(-\tau/\mu_0)$ for $\bar{\omega}_0=0$ (no scattering). The curves will be slightly different for other scattering diagrams but the difference is very small for $\tau\gg1$. [van de Hulst (1970) has shown that for thick ($\tau\gg1$) layers the scattering and absorptive properties of a layer are determined almost exclusively by τ, $\bar{\omega}_0$ and the asymmetry-factor $\overline{\cos\theta}$, other details of the scattering diagram being almost irrelevant; furthermore, for most terrestrial clouds $\overline{\cos\theta}$ shows only slight variation—for the various lower-level clouds used in these calculations the range of $\overline{\cos\theta}$ was only from 0.82 to 0.86.]

The multiple scattering calculation is essentially exact but implicitly it assumes exponential absorption, which is not followed by water vapor absorption at the resolution used by McClatchey *et al.* (1970). This is the only simplifying approximation made in the present set of computations, and of course it was for this reason that transmittances for a 1 km path were used above.

(iv) Having obtained the single scattering albedo $\bar{\omega}_0$ as a function of wavelength and absorption as a function of $\bar{\omega}_0$, it is possible to determine the energy absorbed in any wavelength interval $\lambda\rightarrow\lambda+\Delta\lambda$ in the form $S(\lambda)a(\lambda)\Delta\lambda$, where $S(\lambda)\Delta\lambda$ is the incident solar energy density in the wavelength interval and $a(\lambda)$ is the fractional absorption corresponding to the single scattering albedo $\bar{\omega}_0(\lambda)$. To obtain the total energy absorbed one must evaluate

$$\int_{\lambda_{\min}}^{\lambda_{\max}} S(\lambda)a(\lambda)d\lambda.$$

$\lambda_{\min}$ needs to be no greater than 0.3 μm and $\lambda_{\max}$ no smaller than 2.5 μm in order to cover adequately the range of incoming solar radiation into the troposphere, but there is general agreement that water in any form does not absorb appreciably below 0.7 μm; thus for computation $\lambda_{\min}=0.7$ μm was adopted. Such an integration involves a very large number of quadrature points because of rapid changes of $\bar{\omega}_0(\lambda)$ with wavelength and for this reason an equivalent but slightly less direct procedure was adopted, as follows.

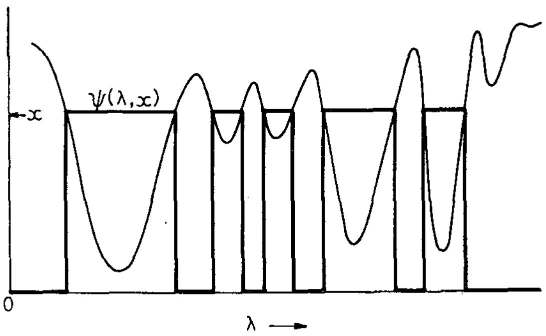

Fig. 3. Determination of wavelength intervals with $\bar{\omega}_0\leqslant x$.

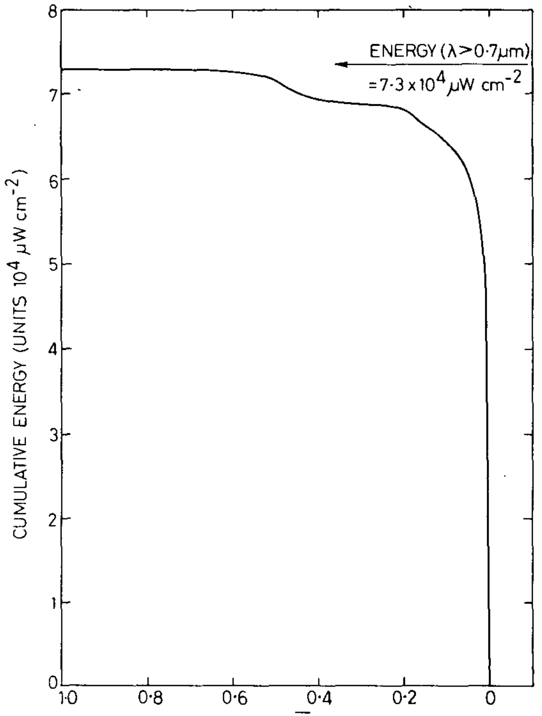

Fig. 4. Cumulative energy vs $\bar{\omega}_0$ for the oceanic cloud case (energy integrated upward from 0.7 μm).

Let $\psi(\lambda,x)$ be a discontinuous function of λ, which is unity when the single scattering albedo $\bar{\omega}_0(\lambda)\leqslant x$ and zero elsewhere; as shown in Fig. 3 it represents a bar-diagram marking the intersections of the horizontal line $\bar{\omega}_0=x$ with the spectral curve $\bar{\omega}_0(\lambda)$. The integral

$$C'(x)=\int_{\lambda_{\min}}^{\lambda_{\max}} S(\lambda)\psi(\lambda,x)d\lambda$$

specifies how much of the incoming solar energy is present at wavelengths such that the single scattering albedo $\bar{\omega}_0\leqslant x$. A typical curve of C' versus single scattering albedo is shown in Fig. 4. Evidently $C'(0)$ equals 0 while $C'(1)$ must equal S_0, the total incoming energy flux. Absorption by the layer and single scattering albedo $\bar{\omega}_0$ are uniquely and monotonically (though inversely) related for any layer thickness for fixed τ and $\cos\theta$, and one can transcribe from $\bar{\omega}_0$ to fractional absorption a and the cumulative curve C' can be uniquely "replotted" against a to obtain curves such as that of Fig. 5. The area $C(a)$ under such a curve from $a=0$ to $a=1$ gives the total energy absorbed. To prove the relationship, it is necessary only to note that

$$\int_0^1 C(a)da=-\int_0^1 a\frac{dC(a)}{da}da.$$

From the definitions $dC(a)$ is the solar energy in-

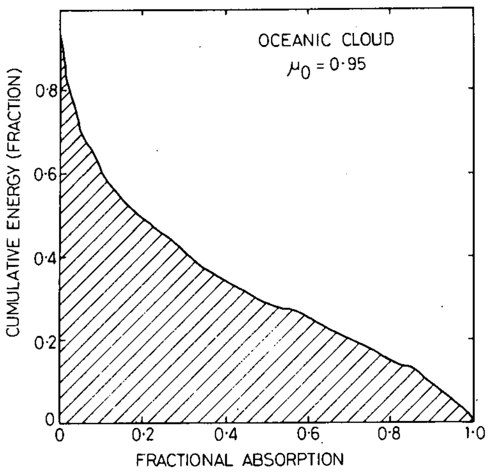

FIG. 5. Cumulative energy (fractional) versus fractional absorption a. The ordinate is the cumulative energy (with $a \geqslant$ indicated value) divided by the solar energy at wavelengths >0.7 μm.

crement which is absorbed with fractional absorption $a \rightarrow a+da$; hence the last-written integral gives the absorbed solar energy.

Considerable computing time is saved by the procedure just described, since the curves of both C' and fractional absorption as a function of single scattering albedo are both quite smooth, as is the resulting curve of $C(a)$ vs a. In the calculations which have been made 69 values of $\bar{\omega}_0$ were used between 0 and 1 but quite evidently a much smaller number would have sufficed had they been appropriately selected.

3. Discussion of results

The calculations made were carried out over the spectral interval 0.7 to 4.0 μm which contains approximately 50% of the incoming solar radiation. Stair *et al.*'s (1954) solar spectral flux data were used for $S(\lambda)$.

The results indicate an appreciable absorption of solar radiation by clouds, which for a 1 km thickness amounted to between 8 and 17% of the total incoming flux depending on solar elevation and cloud type. For the thickest, most absorbing clouds, the fractional absorption reaches 20%. Representative results are set out in Fig. 6 for a 1 km layer, and show the effect of cloud microstructure and solar angle on absorption. The variation with cloud thickness is shown for typical examples in Fig. 7.

Two assumptions were made in these calculations: 1) exponential absorption by water vapor and 2) neglect of variation of τ and $\overline{\cos\theta}$ with wavelength. During the spectral calculations τ and $\overline{\cos\theta}$ were evaluated and the variation in both was small enough to justify their being treated as constant. The fluctuation in τ for $\tau \approx 32$, for example, was about 1.5 over the whole spectral range 0.7–2.5 μm. For optically thick layers, layer properties vary with τ quite slowly—to quote a typical case, absorption changed from 0.17 to 0.19 when τ was doubled from 32 to 64.

With respect to the second assumption, it is relevant to note that omission of water vapor absorption entirely reduced the maximum calculated absorption by about 0.05 (e.g., from 0.15 to 0.105), indicating the kind of error which grossly incorrect treatment of water vapor absorption can produce. It is planned to extend the computational technique to allow non-exponential absorption and to include CO_2 absorption, but it seems unlikely that the magnitudes of our calculations will be greatly changed.

The absorptions calculated here are only about one-half of the absorption measured by Drummond and Hickey (1971), and only about one-quarter of the larger values reported by Reynolds *et al.* (1975). Rosenberg *et al.*'s (1974) inference from satellite measurements also represents more absorption than is given by the present calculations: values of $\bar{\omega}_0 \approx 0.999$ at 0.744, 0.723 and 0.738 μm and of $\bar{\omega}_0 = 0.99$ at 1.03 μm were cited by Rosenberg *et al.*, which do not agree with the values given in Fig. 1.

Absorptions as large as 0.52, as reported by Reynolds *et al.* (1975), would require either total absorption beyond 0.7 μm or a sizable degree of absorption at

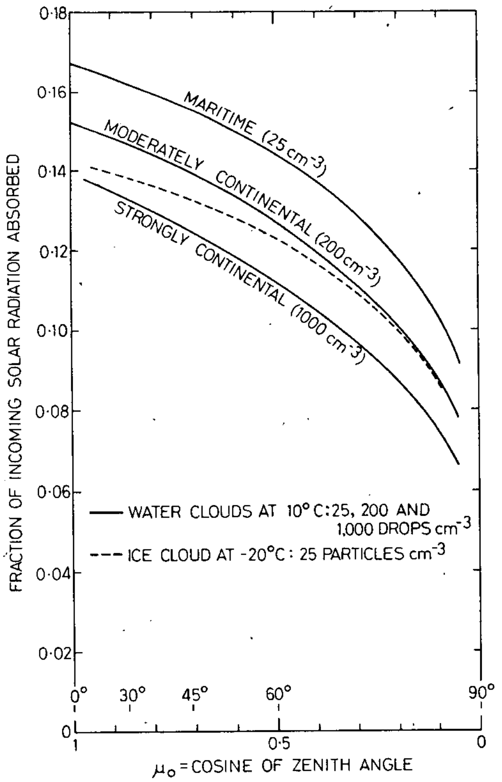

FIG. 6. Fraction of total incoming solar radiation absorbed as a function of solar angle. The angles written above the horizontal axis are values at zenith angle.

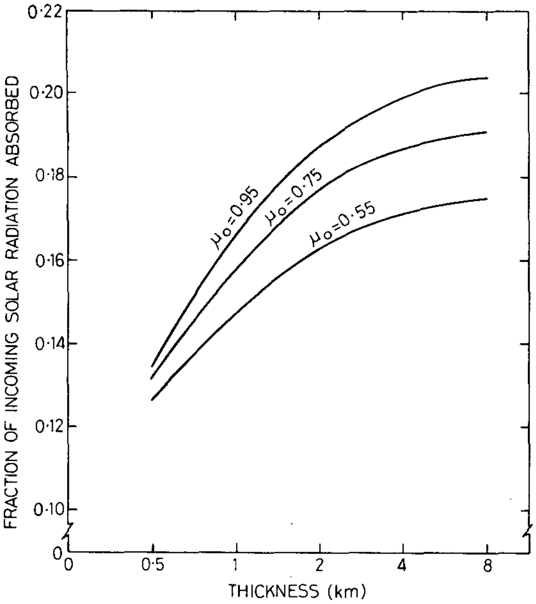

Fig. 7. Absorption as a function of cloud thickness for the oceanic case.

shorter wavelengths. The present calculations do not suggest that absorption by pure water alone can be responsible, while in a previous paper (Twomey, 1972) the writer showed that enhancement of particulate absorption as a result of scattering in clouds could not account for the large absorptions. The question of what could be responsible still remains unanswered.

4. Effect of microstructure

The increased drop concentration in continental clouds as compared to oceanic clouds is known to be caused by the presence in continental air of natural nucleus concentrations systematically higher than those found in maritime air. Manmade pollution would affect cloud drop concentration in the same way. When the drop concentration is increased while holding constant liquid water content and geometric thickness of cloud, there are two radiatively important consequences: (a) the optical thickness of the cloud is increased, which tends to increase absorption, other things equal, and (b) the single scattering albedo is increased, i.e., the drops absorb a smaller fraction of what they scatter, which tends to reduce absorption. The results given here show that the single scattering albedo effect (b) dominates, so that the oceanic clouds, although optically thinner, absorb *more* than the continental clouds. Being optically thinner they also transmit more radiation, so that in two quite separate senses maritime cloudy areas experience more shortwave radiative heating relative to otherwise similar areas with continental clouds. As shown in an earlier paper (Twomey, 1974) 10–20% more of the incoming solar radiation will be transmitted through a 1 km maritime cloud layer as compared with a continental cloud layer of similar depth while the present results show that about 2–3% more of the incoming radiation is absorbed in the cloud layer itself. This represents a systematic difference between continental and maritime cloudy areas which gives a relative tropospheric warming (or more strictly a lesser cooling) in maritime cloudy areas, so far as shortwave solar radiation is concerned.

5. Conclusions

The computations made indicate that a pure water or ice cloud plus the water vapor contained therein will absorb solar radiation to an extent that is appreciable. For a moderately thick (1 km) layer in continental conditions (high nucleus concentrations, giving rise to high droplet concentrations and large scattering cross sections but less efficient absorption) absorption reaches 15% of the incoming solar flux when the sun is near the zenith, falling to about half this value at low solar elevations. For maritime clouds the absorption is about 3% more (of the incoming flux); the computed absorption attained a value of 20% for very thick maritime clouds at high solar elevations.

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