EFFECTS OF HORIZONTAL ORIENTATION ON THE RADIATIVE PROPERTIES OF ICE CLOUDS

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Received April 6, 1984

ABSTRACT

Transfer of radiation through cirrus consisting of non-spherical ice crystals randomly oriented in a plane (2D model) is solved by using the discrete-ordinates method. The model is employed to determine the radiative flux properties and the intensity distribution of cirrus for both solar and thermal infrared radiation. Comparison of the 2D cloud model with the conventional 3D cloud model, i. e., randomly oriented in a three- dimensional space, shows that the preferential orientation of ice crystals has a substantial effect on the cloud solar albedo. The difference in the cloud albedo computed from the two models can be as large as 8% for a cirrus of 2 km thickness. On the thermal infrared side, although the flux emission for cirrus is less affected by the orientation of ice crystals, the difference in the upward radiance using 2D and 3D models is also significant.

I. INTRODUCTION

It has been well-known that the interaction of cirrus with solar and terrestrial infrared radiation plays an important role in the radiation energy budget of the earth-atmosphere system. The Investigation of radiation transfer through cirrus in the past generally assumed that cirrus is composed of assembled ice crystals randomly oriented in a three-dimensional space (see, e. g.,[1]) so that the scattering phase function may be handled using the conventional radiative transfer theory. However, studies of the micro-structure of cirrus and cirrostratus by Weickmann (1949)[2], Heymsfield and Knollenberg (1972)[3] and Heymsfield (1975)[4] revealed that the primary, crystalline forms found in those clouds are columns, bullets and plates whose major axes are much longer than their minor axes. Jayaweera and Mason (1965)[5] studied the behavior of freely falling cylinders in viscous fluid and found that if the ratio of diameter to length is less than unity, cylinders would fall with their long axes horizontal. Observations by Ono (1969)[6] also indicated that columnar crystals tend to fall with their major axes parallel to the ground while plates fall with their major axes in a horizontal plane. Lidar measurements of ice clouds carried out by Platt (1968)[7] further confirmed the preferred orientation of platetype crystals. Therefore, it appears necessary to investigate the radiation properties of randomly oriented non-spherical ice crystals in a horizontal plane. Recently, Stephens (1980)[8] carried out some transfer analyses involving cylinders oriented in a horizontal plane utilizing the scattering program developed by Liou (1972)[9].

In this paper we wish to study the difference of the radiative characteristics for ice crystals randomly oriented in a horizontal plane and in a three-dimensional space. In the following section we will present the basic equation and assumptions used to approximate the single scattering parameters. An outline of the solution to this equation is also given. Section III summarizes calculation results using two wavelengths representing solar visible and terrestrial infrared radiation. In this section, a comprehensive comparison of the radiative properties between ice crystals randomly oriented in a horizontal plane and in a three-dimensional space is made. Finally, conclusions are given in Section IV.

II. RADIATIVE TRANSFER EQUATION AND SINGLE-SCATTERING MODEL

Because the scattering of light by a non-spherical particle depends on the direction of incoming and outgoing radiation as well as on the orientation of the particle with respect to the incoming beam, the basic transfer equation governing a sample of non-spherical particles having a horizontal orientation differs from the conventional radiative transfer equation. For an axisymmetrical particle (such as a cylinder) with its major axis randomly oriented in the horizontal plane, the extinction and scattering sections σ_e and σ_s depend on the incident zenith angle, while the scattering phase function is a function of both the incident and emergent zenith angles. Thus, the basic equation governing the azimuthally averaged intensity may be expressed by[10]

$$\mu\frac{dI(u,\mu)}{du}=-\sigma_e(\mu)I(u,\mu)+\frac{1}{2}\int_{-1}^{1}\sigma_s(\mu')\bar{P}(\mu,\mu')I(u,\mu')d\mu'+S(u,\mu). \tag{1}$$

Here, for simplicity we have omitted the wavelength-dependent subscript. In Eq. (1), $\mu=\cos\theta$, θ the emergent angle, and the vertical path length is defined by

$$u=\int_0^z n(z')\mathrm{d}z', \tag{2}$$

where n is the particle number density which is assumed to vary only in the z-direction. $S(u,\mu)$ represents the radiation source function which has the form

$$S(u,\mu)=\begin{cases}\frac{F_0}{4}\sigma_s(-\mu_0)\bar{P}(\mu,\mu_0)\exp[(u_1-u)/\mu_0], & \text{for solar}\\ [\sigma_e(\mu)-\sigma_s(\mu)]B(T), & \text{for infrared}\end{cases} \tag{3}$$

where μ_0 is the cosine of the solar zenith angle θ_0, F_0 the solar flux density at the top of the atmosphere and $B(T)$ the Planck function. The azimuthally averaged scattering phase function is defined by

$$\bar{P}(\mu,\mu')=\frac{1}{2\pi}\int_0^{2\pi}P(\pi/2,\mu,\mu',\Delta\phi)\mathrm{d}\Delta\phi. \tag{4}$$

If $\sigma_e(\mu),\sigma_s(\mu)$ and $P(\mu,\mu')$ are known, then Eq. (1) can be solved by mean of the discrete-ordinates method for radiative transfer (see, e. g., [11]) However, numerical programs for the calculation of these single-scattering parameters for randomly oriented ice crystals in a horizontal plane have not been developed for the incorporation into the radiative transfer equation at this time. Thus, it is necessary to make appropriate approximations for these single-scattering parameters so that transfer calculations may be carried out.

In their study on the transfer of visible radiation through a cumulus, Danielson et al. (1969)[12] have shown that the transmission and reflection of a cloud whose phase function is characterized by the Henyey-Greenstein function have similar values to those using the Mie scattering phase function subject to the condition that both phase functions have the same asymmetry factor. The Henyey-Greenstein phase function is given by

$$P(\theta)=\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}, \tag{5}$$

where g is the asymmetry factor and θ the scattering angle. In view of the above finding, we postulate that it may also be applied to the scattering phase function for non-spherical particles. In addition, we assume that the asymmetry factor for ice crystal randomly oriented in a horizontal plane is a function of the cosine of the incident zenith angle only. Thus, the azimuthally averaged phase function can be determined by using Eq. (4). Physically, the scattering phase function $p\ (\mu,\mu')$ represents the redistribution of radiation energy streams from the μ' direction to the emergent direction denoted by μ and it should satisfy the following normalization constraint

$$\frac{1}{2}\int_{-1}^{1}\bar{P}(\mu,\mu')\mathrm{d}\mu=1. \tag{6}$$

For ice crystals randomly oriented in a horizontal plane, the extinction and scattering cross-sections as a function of the incident angle should be symmetrical with reference to the horizontal plane so that $\sigma(\mu)=\sigma(-\mu)$. All these functions can be expanded by a Legendre polynomial of even order, i. e.,

$$\sigma(\mu)=\sigma_0+\sum_{i=\mathrm{even}}\alpha_i P_i(\mu), \tag{7}$$

where σ_0 corresponds to the scattering parameter for ice crystals randomly oriented in a three-dimensional space. Using a two-term approximation, we can derive the coefficient α_2 from σ_0 and the scattering paramaters corresponding to the normal incident case σ_N. Utilizing the geometric ray tracing program developed by Cai and Liou (1982)[13], we have computed the extinction and scattering cross-sections for hexagon columns having a length and diameter of 300 and 120 μm, respectively, randomly oriented in a three-dimensional space and in a horizontal plane with normal incidence. Calculations were carried out for 0.55 and 10.6 μm wavelengths and results are depicted in Table. 1. The index of refraction for ice at these two wavelengths are 1.31 and 1.097—0.134 i (Schaaf and Williams, 1973)[14].

The radiation boundary conditions imposed on the solar radiation transfer through cirrus are that there is no downward diffuse radiation at the cloud top and no upward diffuse radiation at the cloud base. Thus, we write

$$\begin{cases} I(u_1,-\mu)=0, \\ I(0,\mu)=0, \end{cases} \quad \mu>0 \tag{8}$$

For thermal infrared radiation transfer, we assume that there is no intervening atmosphere between the cloud and the surface and that the underlying surface is a black body. Thus, the radiation boundary conditions can be written as

$$\begin{cases} I(u_1,-\mu)=0, \\ I(0,\mu)=B(T_s), \end{cases} \quad \mu>0, \tag{9}$$

Table 2 Scattering Parameters for Solar and Infrared Wavelengths

λ (μm)	Extinction ($\times 10^{-4}$ cm²)			Scattering ($\times 10^{-4}$cm²)		
	σ_0	σ_N	α_2	σ_0	σ_N	α_2
0.55	5.6527	6.8795	1.2288	5.6527	6.8795	1.2288
10.6	5.6527	6.8795	1.2288	2.9991	3.5177	0.5186

where $B(T_s)$ is the Planck function of the surface temperature, T_s. The solution of Eq. (1) subject to Eq. (8) or Eq. (9) can be derived based on the principle of the discrete-ordinates method for radiative transfer which has been documented rather comprehensively in Liou (1973)[10,11]. Hence, the detailed mathematical derivation will not be given here.

III. RESULTS AND DISCUSSION

First, we present calculation results on the solar flux transfer. The flux transmission $t(\mu_0)$ andreflection $r(\mu_0)$ are defined by

$$\left.\begin{aligned} t(\mu_0)&=F^{\downarrow}(z_b)/\pi\mu_0F_0 \\ r(\mu_0)&=F^{\uparrow}(z_t)/\pi\mu_0F_0 \end{aligned}\right\}, \tag{10}$$

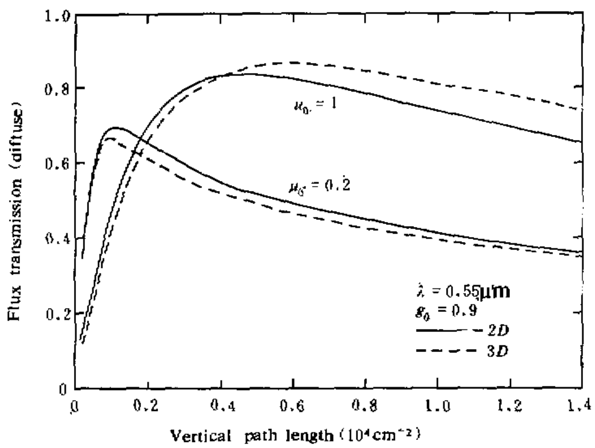

Fig. 1. The solar flux transmission as a function of the vertical path length for 2D and 3D cloud models.

where z_t and z_b denote the cloud top and base heights, respectively, $\pi\mu_0F_0$ represents the solar flux perpendicular to the plane-parallel stratification, and $F^{\downarrow}(z_b)$ and $F^{\uparrow}(z_t)$ are downward and upward diffuse fluxes at the cloud base and top, respectively. In reference to the analysis described by Stephens (1980)[8], the asymmetry factors for ice crystals having 3D random orientation and 2D random orientation with normal incidence are taken to be 0.9 and 0.85, respectively.

Fig. 1 shows the flux transmission as a function of the vertical path length for two solar incident angles. According to the definition of vertical path length, it is proportional to the cloud geometrical thickness if the particle number density is uniform in the vertical direction. Using a number density of 0.05 cm^{-3}, the abscissa in Fig. 1 is equivalent to the cloud thickness ranging from 0 to 2.8 km, which corresponds to the vertical optical depth from 0 to 9.6. In Fig. 1, it is seen that when the cloud is optically thin due to, either a low particle concentration or a small thickness, the difference produced by 2D and 3D models is insignificant. As the vertical optical length increases, the difference becomes noticeable. For $\mu_0=1$, the 2D flux transmission is larger than the 3D value for path lengths less than about 0.4×10^4 cm^{-2}, whereas for larger vertical path lengths, the relative magnitude of two flux transmission values reverses. This is because in the normal incident case ($\mu_0=1$), the scattering and extinction cross-sections for 2D orientation crystals are larger than those for 3D counterparts (see Table 1). However, for a low sun with a μ_0 of 0.2, the flux transmission for the 2D case is consistently larger than that for the 3D case. The reason for the variation of the flux transmission as a function of the vertical path length is that when μ_0 is greater than $1/\sqrt{3}$, which is the root of the Legnedre polynomial of second order, the scattering cross-section for 2D orientation crystals is smaller than that for 3D orientation crystals. It is evident, therefore, that the solar radiative properties of cirrus are governed by the single scattering parameters which are directionally dependent on the solar incident angle. For very large vertical path lengths, there is no apparent difference between the flux transmission values for 2D and 3D cases. Clearly, the effects of multiple scattering due to large optical depths overwhelm the directional dependence of radiation streams.

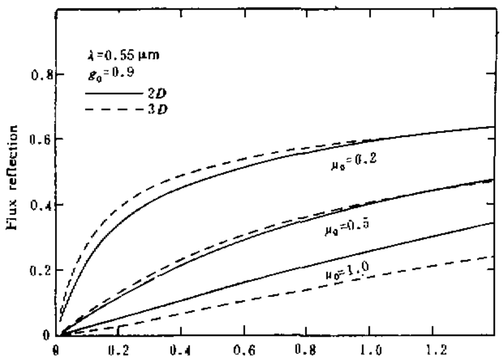

Fig. 2. Same as Fig. 1, except for the solar flux reflection (albedo).

In Fig. 2 is shown the flux reflection (albedo) of cirrus as a function of the vertical path length for three solar incident angles. A common feature of these curves is the increase of the reflection value with the path length. As pointed out previously, the orientation effect depends on the incident solar zenith angle. When $\mu_0=1$, crystals randomly oriented in a horizontal plane reflect more sunlight than those randomly oriented in 3D space. The difference as hown in this figure, increases monotonically with the increasing vertical path length. As much as 8% difference for a 2 km thick cirrus is seen. When $\mu_0=0.5$ and 0.2, we see a reversed trend. It should be noted that when $\mu_0=1/\sqrt{3}$, the scattering cross-section of the 2D and 3D models have the same value. Thus, the resulting reflection values differ slightly due to the multiple scattering effect.

Moreover, we wish to investigate the effects of 2D and 3D crystal orientation on the transfer of terrestrial infrared radiation. In this study, the surface temperature is taken to be 300 K and the cloud temperature is assumed to be 237 K. The asymmetry factors for 3D and 2D randomly oriented crystals at the 10.6 μm wavelength are assumed to be 0.8 and 0.75, respectively. For the flux transfer, the infrared emissivity and transmissivity are defined by

$$\left.\begin{aligned} \varepsilon^f &= F_1^\uparrow(z_t)/\pi B(T_c) \\ T^f &= F_2^\uparrow(z_t)/F_2^\uparrow(z_b) \end{aligned}\right\}, \tag{11}$$

where $F_1^\uparrow(z_t)$ is the infrared flux emergent from the cloud top, which is attributed to the emission by the cloud itself. $F_2^\uparrow(z_b)$ and $F_2^\uparrow(z_t)$ are infrared fluxes reaching the cloud base and leaving the cloud top, respectively, without the contribution of the cloud emission. Since there is no atmosphere between the surface and the cloud in this analysis we have $F_2^\uparrow(z_b)=\pi B(T_s)$.

Fig. 3 compares the infrared flux transmissivity and emissivity for crystals with 2D and 3D orientations as a function of the vertical path length. The infrared flux transmissivity computed from both models decreases rapidly with the increasing vertical path length. For a 2 km thick cirrus, the flux transmissivity value is very small indicating that the infrared radiation is largely absorbed within the cloud. Also, we note that the flux reflectivity ($R^f = 1-\varepsilon^f-T^f$) in this case is about 6%, which is due to the scattering of large ice crystals. As shown in this figure, the flux emissivity of cirrus increases monotonically with the path length, and reaches an asymptotic value. The asymptotic flux emissivity values are about 0.93 and 0.96 for 2D and 3D cloud models, respectively. The different orientation of ice crystals results in only a slight difference of 2—3% in the infrared radiative properties of the cirrus.

Since there is no preferential incident direction in the transfer of terrestrial infrared radiation in the atmosphere, the azimuthally averaged intensity is an adequate representation of the radiation field for a plane-parallel cloudy atmosphere. Thus, the solution of Eq. (1) may be utilized to examine the effect of the ice crystal orientation on the infrared intensity (radiance) transfer. The intensity emissivity and transmissivity are defined by

$$\left.\begin{aligned} \varepsilon(\mu) &= I_1^\uparrow(z_t,\mu)/B(T_c) \\ T(\mu) &= I_2^\uparrow(z_t,\mu)/I_2^\uparrow(z_b,\mu) \end{aligned}\right\}, \tag{12}$$

where $I_1^\uparrow(z_t,\mu)$ is the upward radiance emergent from the μ direction resulting from the internal thermal emission of the cloud itself. $I_2^\uparrow(z_b,\mu)$, $I_2^\uparrow(z_t,\mu)$ are radiances reaching the cloud base and leaving the cloud top in the μ direction, respectively, which is generated by the external radiation source. From Eq. (9), we have $I_2^\uparrow(z_b,\mu)=B(T_s)$, where T_s is the surface temperature.

Fig. 4 depicts the intensity transmissivity and emissivity for crystals with 2D and 3D orientations as a function of the vertical path length. Although the variation of the intensity transmissivity and emissivity with the path length is similar to that presented in Fig. 3, the effect of the crystal orientation on these radiative properties is much

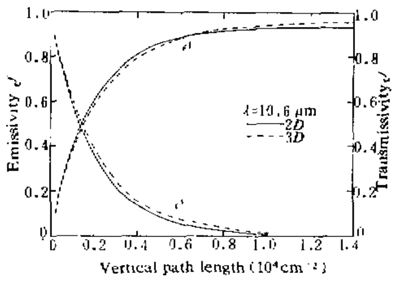

Fig. 3. The infrared flux emissivity and transmissivity as a function of vertical path length for 2D and 3D cloud models.

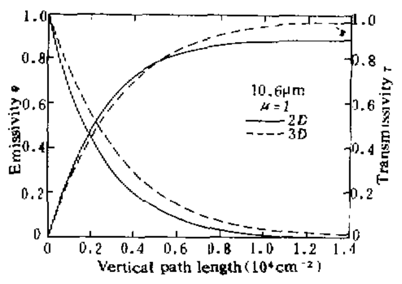

Fig. 4. The intensity emissivity and transmissivity for 10.6 μm wavelength as a function of the vertical path length for 2D and 3D cloud models.

more pronounced. The difference in the transmissivity value for a semi-transparent cirrus and the emissivity value for a thick cirrus between the 2D and 3D cloud models can be as much as 10%. Evidently, this will produce a significant dif-ference in the upwelling radiance. On the basis of the present study, it would appear that the ice crystal orientation property has an important non-negligible influence on the upwel-ling radiance. Thus, from the point of view of the sounding of the cirrus cloud composition and structure from satellites or ground-based radiometers, the horizontal orientation characteristics of hexagonal ice crystals should be considered in the parameterization and retrieval analyses.

IV. CONCLUSIONS

In this paper we have investigated the solar and infrared radiative properties of ice crystals randomly oriented in a three-dimensional space (3D) or in a horizontal plane (2D). The scattering parameters in the 2D case depend on the incident zenith angle. Therefore, the radiative transfer equation involving a 2D cloud model differs from the conventional transfer equation. Applying the discrete-ordinate method for radiative transfer and utilizing simple approximations for the scattering phase function for ice crystals, we have solved the basic equation governing the transfer of solar and infrared radiation through horizontally oriented ice crystals. We have calculated the reflection and transmission properties of a homogeneous and isothermal ice cloud with 2D and 3D orientations and compared their resulting values. We find that for the solar flux transfer the reflection (albedo) is affected significantly by the orientation property of the cloud particles. In general, the difference is most noticeable when the sun is overhead with a value as much as 8%. However, for low solar angles and when thick clouds are involved, the difference between the 2D and 3D cloud models is less significant because the radiative properties of the cloud are dominated by diffuse multiple scattering. For thermal infrared radiation the preferential orientation of ice particles is not extremely important for the cloud flux emissivity. However, it has a profound effect on the upward radiance. For a 0.8 km thick cirrus, the influence of the horizontal orientation of ice crystals on the radiation field decreases the upwelling radiance by as much as 20% when compared with the results derived from the assumption of three-dimensional random orientation. Consequently, it appears necessary to incorporate the radiation contribution caused by the orientation configuration of ice crystals in the parameterization and retrieval of cirrus cloud parameters from the satellite or ground-based radiometers.

We would like to thank Ms. Sharon Bennett for typing and editing the manuscript. The research work contained in this paper is supported by the Division of Atmospheric Sciences, National Science Foundation under Grant ATM 81-09050.

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