A New Parameterization Scheme for Shortwave Radiative Properties of Water Clouds

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ABSTRACT

A new parameterization scheme for the shortwave radiative properties of water clouds is presented, using versatile cloud drop size distributions (DSDs). As for single-scattering properties, a new parameterization for cloud optical thickness τ is proposed by using the separation of the dependence of τ on the total number of the DSDs, the cloud thickness, and the liquid water content, combined with equivalent radius. The cloud bulk radiative properties are obtained from the delta-Eddington approximation for our cloud models. It is shown that the flux reflectivity, transmissivity, and absorptivity are uniquely fitted by a dimensionless parameter χ or the cloud optical thickness τ. The parameterization is compared with other schemes. The features and potential use of the scheme are discussed.

1. Introduction

It is well known that clouds play an important role in the water cycle, local weather, earth radiation budget, and local and global climate. In modern weather and climate forecasting and general circulation models (GCMs), it is imperative to take into account the radiation effects of clouds, a task which must be parameterized in a certain manner, as it is too ambitious an undertaking to consider all influences of the cloud macro- and microphysics. Over the past two decades, many parameterization schemes have been proposed for the shortwave and infrared radiation of clouds (e.g., Stephens 1978; Liou and Wittman 1979; Slingo and Schrecker 1982; Stephens et al. 1984; Slingo 1989; Tsay et al. 1989; Rockel et al. 1991). Stephens (1978), Liou and Wittman (1979), and Stephens et al. (1984) have shown that the shortwave properties of clouds depend strongly on the liquid water path (LWP) and solar zenith angle, and that this dependence can be parameterized. Moreover, a significant dependence of the properties on drop size distribution (DSD) was found, and the simple relationships for the optical thickness, single-scattering albedo, and asymmetry factor of cloud drops as functions of the cloud LWP and equivalent radius of the DSD were given by Slingo and Schrecker (1982, hereafter SS). On the basis of the SS scheme, the cloud bulk radiative properties were further parameterized by Slingo (1989). In addition, to obtain a unified treatment of both solar and terrestrial radiation, an extension of the SS scheme for the solar spectrum was made for the terrestrial spectrum as well by Tsay et al. (1989).

Since cloud optical properties are strongly dependent on LWP and respective DSD, a more realistic simulation of the interaction between clouds and radiation and a more flexible and accurate parameterization scheme are required. In this study, a new parameterization scheme for the optical thickness and for the radiative properties of water clouds in the solar spectrum is proposed by using some new DSDs and microphysics and more compact and simple formulas. The parameterization is compared with other schemes and some aspects are discussed.

2. Cloudy atmosphere models

Since our objective is to investigate the impact of water cloud micro- and macrocharacteristics on the shortwave radiative transfer, only the atmospheric molecular scattering and absorption are taken into account, while the influence of the atmospheric aerosols is ignored. In the solar spectrum from 0.3 to 8.7 μm, the principal absorbing gases are water vapor H_2O, ozone O_3, and carbon dioxide CO_2. The O_3 absorption is mainly in the visible Chappuis band. The H_2O absorption has seven important bands whose central wavelengths are 0.9, 1.1, 1.38, 1.87, 2.7, 3.2, and 6.3 μm. Seven CO_2 absorption bands are located at 1.4, 1.6, 2.0, 2.7, 4.3, 4.8, and 5.2 μm. Some of these CO_2 and H_2O absorption bands are superposed or overlapped, which does not give rise to many errors because CO_2 absorption is usually negligible compared with that of H_2O.

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The U.S. standard atmosphere is used. A constant mixing ratio of 330 parts per million by volume (ppmv) is taken for CO_2. Temperature and pressure corrections in the CO_2 absorption are made with the formulas given in LOWTRAN 7 (Kneizys et al. 1988). The H_2O absorption is calculated by Liou and Sasamori's (1975) method, and O_3 absorption is obtained from Lacis and Hansen's (1974) parameterization.

Since the schemes of Stephens (1978), Stephens et al. (1984), SS, and Slingo (1989) were based on only an eight-drop spectra, a wider range of observed and/or synthetic spectra is needed to study the impact of the cloud microphysics on the solar radiation. Thus, for our model clouds, which are composed of the spherical liquid water drops, nine model DSDs are constructed based on a modified Γ function, which is expressed by

$$n(r) = Cr^{\alpha}\exp(-\beta r^{\gamma}) \qquad (1)$$

$$C = \frac{\gamma\beta^{(\alpha+1)/\gamma}}{\Gamma[(\alpha+1)/\gamma]}, \qquad (2)$$

where C is a normalization constant, and α, β, and γ are drop spectral parameters. The nine DSDs may be divided into three types: (a) monomodal, expressed directly by Eq. (1); (b) bimodal, expressed by two weighted modified Γ functions; and (c) long tail, expressed by a weighted modified Γ function with one constant. Some parameters of the nine DSDs are given in Table 1. Tsay et al. (1989) have simulated a multimode size distribution to resemble the distribution at cloud top. Obviously, our model DSDs are more multiple and versatile than those of Tsay et al. (1989).

The cloud layer with various thicknesses is positioned at different heights in the troposphere. The horizontal and vertical homogeneities are assumed for extended clouds based on Welch and Cox's (1980) study. Welch et al. (1980) and other authors have shown that the radiative properties of vertically developed clouds (e.g., cumulus and cumulonimbus) are quite different from those of extended stratiform clouds. Cumulus and cumulonimbus model clouds are examined here to determine the influence of drop density, cloud thickness, and size spectral shape on the radiative properties of clouds.

3. Parameterization of model clouds

a. The optical thickness

The single-scattering properties—that is, the extinction coefficient β_e, single-scattering albedo ω_0, and asymmetry factor g—of model clouds are calculated by the Mie theory in the solar spectral region from 0.3 to 4.7 μm. This spectral region is chosen because the UV radiation flux arriving at the troposphere is very weak due to the stratospheric O_3 absorption, and the solar radiation in the wavelength region $\lambda > 4.7$ μm is less than 0.05%. The optical constants of liquid water are taken from Hale and Querry (1973). For practical purposes, the extinction coefficient of all model clouds is averaged in the solar spectral region from 0.3 to 4.7 μm:

$$\bar{\beta}_e = \frac{1}{4.7 - 0.3}\int_{0.3\,\mu m}^{4.7\,\mu m} \beta_e(\lambda)d\lambda. \qquad (3)$$

TABLE 1. Some parameters of nine drop size distributions as well as their equivalent radii r_e and liquid water contents.

Type	α	γ	r_e (μm)	W_1 (g m^{-3})
Stratus 1 (St1)	2.0	1.2	7.39	9.04×10^{-4}
Stratus 2 (St2)	2.0	1.3	4.95	2.83×10^{-4}
Stratocumulus 1 (Sc1)	2.0	1.3	6.92	7.75×10^{-4}
Stratocumulus 2 (Sc2)	2.0	1.3	14.84	7.63×10^{-3}
Altostratus (As)	2.0	1.2	8.21	1.36×10^{-3}
Nimbostratus 1 (Ns1)	2.0	0.65	14.95	4.80×10^{-3}
Nimbostratus 2* (Ns2)	2.0	1.3	3.5	4.06×10^{-3}
Cumulus (Cu)	2.0	1.2	11.61	3.51×10^{-3}
Cumulonimbus** (Cb)	4.5 (8.0)	0.45 (1.2)	29.39	3.51×10^{-2}

* Long tail: composed of weighted Sc1 and constant 1/24; weighting coefficients are 0.76 and 0.24, respectively.

** Bimodal: composed of two weighted modified Γ functions; weighting coefficients are 0.6 and 0.40.

We define a dimensionless parameter χ_1 as

$$\chi_1 = \frac{kW_1}{r_e}, \qquad (4)$$

where the coefficient $k = 1000$ m^3 μmg^{-1}, W_1 is the LWC of normalized DSD, and r_e is the equivalent radius, which is given by

$$r_e = \frac{\int_0^{\infty} \pi r^3 n(r)dr}{\int_0^{\infty} \pi r^2 n(r)dr}. \qquad (5)$$

The broadband optical thickness may be expressed as

$$\tau = N\bar{\beta}_e H_c, \qquad (6)$$

where H_c is the cloud thickness (km) and N is the total number of cloud droplets in unit volume (cm^{-3}). By using nine normalized DSDs, a parameterization relation between $\bar{\beta}_e$ and χ_1 is fitted as

$$\bar{\beta}_e = a\chi_1^b, \qquad (7)$$

where $a = 1.59$, $b = 0.947$, and the maximum fitting error is about 2%.

b. The bulk radiative properties

In our radiative transfer model, the whole atmosphere is divided into 20–30 layers depending on the cloud thickness. Since we do not examine the radiative flux profile, it is not necessary to take more sublayers into account.

According to Zdunkowski et al. (1967), the solar spectrum is divided into nine spectral intervals. The optical constant for the ith spectral interval (from λ_1^i to λ_2^i) is given by

$$\bar{m}_i = \frac{\int_{\lambda_1^i}^{\lambda_2^i} m_{\lambda_i} B_\lambda(T) d\lambda}{\int_{\lambda_1^i}^{\lambda_2^i} B_\lambda(T) d\lambda}, \tag{8}$$

where $B_\lambda(T)$ is the Planck function, which at $T = 5777$ K corresponds well to solar constant $S = 1367$ W m^{-2} (Iqbal 1983).

The bulk radiative properties of clouds—that is, the reflectivity R, transmissivity $\mathcal{T}$, and absorptivity A—are defined as

$$R = \sum_{i=1}^{9} S_i \left[\frac{F_i^\uparrow(\tau_t^i)}{F_i^\downarrow(\tau_t^i)}\right]$$

$$\mathcal{T} = \sum_{i=1}^{9} S_i \left[\frac{F_i^\downarrow(\tau_b^i)}{F_i(\tau_t^i)}\right]$$

$$A = \sum_{i=1}^{9} \frac{S_i[F_i(\tau_t^i) - F_i(\tau_b^i)]}{F_i^\downarrow(\tau_t^i)}, \tag{9}$$

where $F_i^\uparrow$, $F_i^\downarrow$, and F_i denote the upward, downward, and net fluxes for the ith spectral interval, respectively, which are calculated by using delta-Eddington approximation (Joseph et al. 1976; Wiscombe 1977); S_i is the ratio of the incident flux in the ith interval to the flux in the entire shortwave spectrum; and τ_t^i and τ_b^i are the optical thickness in the ith interval at the cloud-top Z_t and cloud-base height Z_b, respectively. Values for Z_t and Z_b are calculated by

$$\tau_t^i = \tau_{\text{air}}^i(Z_t)$$

$$\tau_b^i = \tau_c^i + \tau_{sa}^i + \tau_{\text{air}}^i(Z_b), \tag{10}$$

where τ_{air}^i is the optical thickness of the clear atmosphere, including the molecular scattering and absorption; τ_{sa}^i the optical thickness of saturated water vapor within clouds; and τ_c^i the optical thickness of cloud drops.

A dimensionless parameter is employed in the radiation parameterization, which is defined as

$$\chi = \frac{W}{\rho_w r_e}, \tag{11}$$

where W denotes the cloud LWP and ρ_w is the water density.

As to the parameterization of the reflectivity, a segmental fitting is used in order to have the lower order in the polynomials. There is a discontinuity between two segments with quite little difference. In both low and high segments, the two fitting equations are, respectively,

$$R_1 = a_{10} + a_{11}\chi + a_{12}\chi^2 + a_{13}\chi^3 + a_{14}\chi^4 + a_{15}\chi^5 \quad (\%) \tag{12a}$$

$$R_2 = a_{20} + a_{21}\chi + a_{22}\chi^2 + a_{23}\chi^3 \quad (\%), \tag{12b}$$

where the values of the coefficients are $a_{10} = 2.4169$, $a_{11} = 8.183$, $a_{12} = -0.4826$, $a_{13} = 1.528 \times 10^{-2}$, $a_{14} = -2.4145 \times 10^{-4}$, $a_{15} = 1.4831 \times 10^{-6}$, $a_{20} = 61.851$, $a_{21} = 0.2196$, $a_{22} = -1.1605 \times 10^{-3}$, and $a_{23} = 2.1618 \times 10^{-6}$. The maximum fitting error is less than 6%.

The cloud transmissivity $\mathcal{T}$ and absorptivity A are parameterized as

$$\mathcal{T} = 246.2\chi^{-0.86873} \tag{13}$$

$$A = 12.33\chi^{0.11585}. \tag{14}$$

The fitting errors are generally less than 10%. As the cloud transmissivity and absorptivity depend not only upon the cloud characteristics but also upon the atmospheric gas absorption, especially water vapor absorption in the clouds, the fitting accuracy for $\mathcal{T}$ and A is not so minute as that for R.

If the optical thickness τ of Eqs. (6) and (7) is used in the radiation parameterization, the fitting formulas for the cloud reflectivity, transmissivity, and absorptivity are given as

$$R_1 = 3.8462 + 3.8183\tau - 9.3979 \times 10^{-2}\tau^2 + 1.0648 \times 10^{-3}\tau^3 - 4.5147 \times 10^{-6}\tau^4 \quad (\text{for } \tau \leqslant 75) \tag{15a}$$

$$R_2 = 47.262\tau^{-0.085} \quad (\text{for } \tau > 75) \tag{15b}$$

$$\mathcal{T} = 509.6\tau^{-0.928} \tag{16}$$

$$A = 11.93\tau^{0.114}. \tag{17}$$

When $\tau = 75$, the difference between Eqs. (15a) and (15b) is 0.3%. The fitting errors reach 10%, which are larger than those of Eqs. (12)–(14). This means that the use of χ is slightly better than that of τ for the parameterization of the bulk radiative properties.

4. Comparisons and discussions

a. The optical thickness

Figure 1 shows the comparison between the optical thicknesses calculated by Mie theory and those calculated by the parameterizations including both Slingo's (1989) and our schemes. The cloud data are mainly taken from our nine model clouds, and some are taken from the stratiform cloud values of Stephens (1979). It is obvious from Fig. 1 that our parameterization scheme for the cloud optical thickness [Eqs. (6) and (7)] is better than that of Slingo (1989). Moreover, the fitting coefficients a and b in Eq. (7) are obtained on the basis of our nine model clouds. But

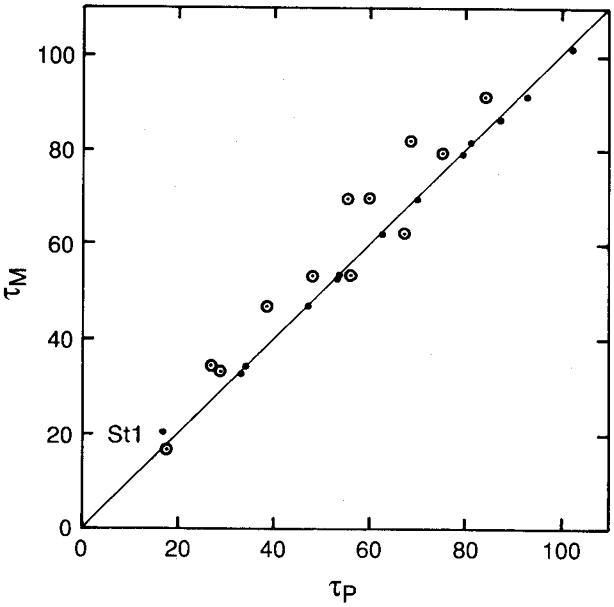

FIG. 1. Comparison of the cloud optical thicknesses calculated by Mie theory (τ_M) with parameterization schemes (τ_P). The dots denote the present study results. The "⊙" symbol denotes Slingo's (1989) parameterization scheme. The dot denoted St1 indicates that the data of cloud type St1 in Stephens (1979) were used.

that the dot points almost lie on the straight line in Fig. 1 demonstrates that our DSDs contain Stephens's (1979) cloud spectra. There is only one scattered dot near the origin, which corresponds to Stephens's (1979) cloud type St1. Its DSD shape is very different from the shape of the modified Γ function.

It is necessary to point out that our parameterization scheme for cloud optical thickness is different from those of Slingo (1989) and Tsay et al. (1989). Our study shows that with the same height and thickness of one type of cloud, the reflectivity R increases with the increase in total number N. In addition, using the same LWP and r_e but different N values of Stephens (1979), the results of calculations are different. This means that the influence of the total number N on cloud radiative properties is significant. Thus, our parameterization of τ is performed for the quantity χ_1 of normalized DSD (i.e., the total number $N = 1$ cm^{-3}) so that separation of the dependence of the optical thickness of clouds on N, H_c, and LWC/r_e may be carried out. As vertically homogeneous clouds are assumed, the dependence of τ linearly on N, and H_c in Eq. (6) and the corresponding points lying on the straight line in Fig. 1 are expected. So far as Slingo's (1989) scheme is concerned, both N and H_c is nonlinear even for assumed vertically homogeneous clouds, and the scatter of Slingo's points along the straight line occurs.

It is known that the real DSD for one type of cloud varies with cloud height, cloud stage, season, and area. The analyses above reveal that our parameterization scheme suits extensively different DSDs, provided that the DSD is not odd.

b. The bulk radiative properties

The characteristics of the reflectivity, transmissivity, and absorptivity of water clouds at a zenith angle at 0° varying with the parameter χ are shown in Fig. 2. We found that when the total number N was too low or too high the regression fit was not satisfactory. Thus, Fig. 2 shows the results are suitable only for the model clouds with $100 \leqslant N \leqslant 300$ cm^{-3}.

Figure 3 depicts the characteristics of the bulk radiative properties of water clouds varying with the optical thickness τ and offers a comparison between our scheme and that of Stephens et al. (1984). Obviously, the features of R, $\mathcal{T}$, and A varying with τ here are similar to those in Fig. 2 with parameter χ as the abscissa; R ($\mathcal{T}$) increases (decreases) with τ or χ, while A increases slightly with τ or χ.

The comparison in Fig. 3 shows that the R ($\mathcal{T}$) values of our scheme are larger (smaller) than those of Stephens et al. (1984). When $\tau < 40$ the differences between the two schemes are relatively large; with τ increasing the differences are diminishing. As for absorptivity A, when $\tau > 40$ both scheme results are very similar, but our values are smaller than those of Stephens et al. (1984) when $\tau < 40$. With τ increasing, however, the A values of Stephens et al. (1984) decrease. These facts are mainly due to different cloud models, especially different DSDs, and different parameterization schemes.

Comparisons between our Eqs. (12)–(14), or Eqs. (15)–(17) and the formulas of Slingo (1989) for R,

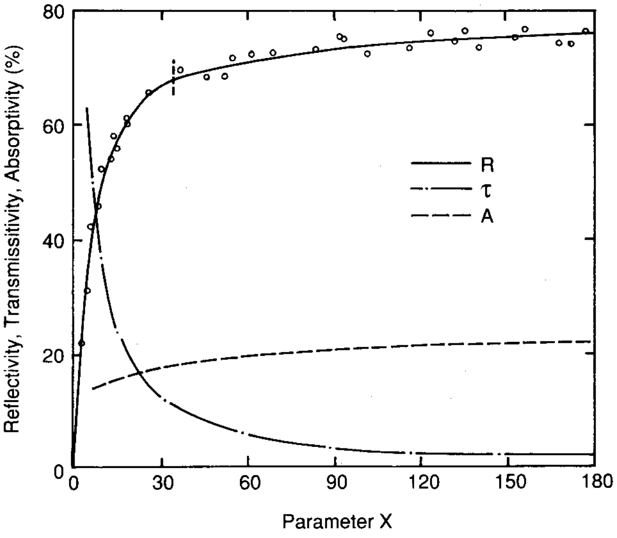

FIG. 2. The bulk radiative properties of eight model clouds (except cumulonimbus) at a zenith angle of 0° vs the parameter χ ($100 \leqslant N \leqslant 300$ cm^{-3}). Small vertical bar indicates the separate point of the fitting segments.

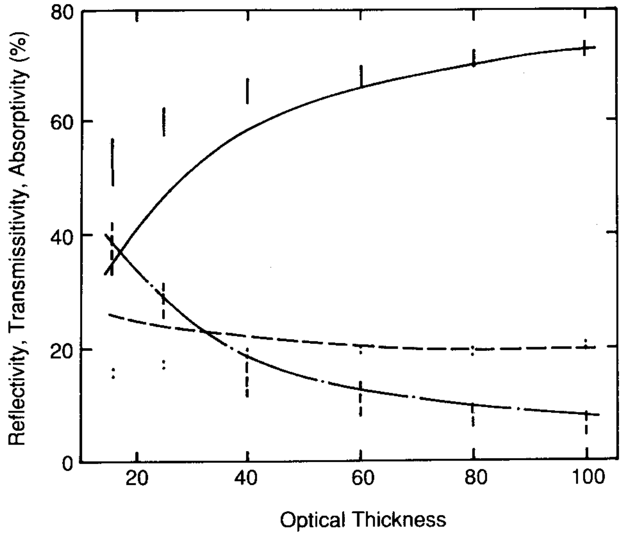

FIG. 3. Reflectivity, transmissivity, and absorptivity of water clouds (%) as function of the cloud optical thickness. Results are shown for the present parameterization, denoted by the vertical bars, and that of Stephens et al. (1984), denoted by the curves. The vertical bars for R are due to different cloud types having different R values for the same τ. The same is true for $\mathcal{T}$ and A.

$\mathcal{T}$, and A were found to be unreliable for lack of enough information on his scheme. However, it is evident that the two schemes have different features. Since the solar radiative transfer in clouds is governed by the optical thickness of the layer, which is very close to the χ value as defined by Eq. (11), it is very natural to use the χ or τ value for the parameterization of flux reflectivity, transmissivity, and absorptivity. We have shown that the cloud bulk radiative properties are uniquely fitted by the dimensionless parameter χ, or τ. Equations (12)–(14), or Eqs. (15)–(17) are simpler than the formulas of Slingo (1989) and are compact enough for dynamic modeling.

5. Conclusions

A new parameterization for the shortwave radiative properties of water clouds has been presented. The analyses indicate that the model DSDs used here are more versatile and suitable for the study of the interaction of cloud microphysics and radiation. As cloud optical thickness is one of the most important variables needed for deriving and depicting cloud radiative properties, the parameterization of single-scattering properties for τ only is performed in the present study. One important new feature of the present scheme is the separation of the dependence of the optical thickness of clouds on N, H_c, and LWC/r_e due to the definition of the parameter χ_1. Thus, more cloud microphysics are considered in our τ parameterization. Moreover, comparisons of the various schemes indicate that our parameterization of cloud optical thickness is better than those of Slingo (1989) and Stephens (1978) and is more applicable to different DSDs.

Another important feature of our scheme is that the cloud bulk radiative properties, R, $\mathcal{T}$, and A, are uniquely fitted by the dimensionless parameter χ or the optical thickness τ. Thus, our parameterization formulas are compact enough for dynamic modeling.

Recently, a number of works have demonstrated the feasibility of the determination of the equivalent radius r_e of clouds from satellite reflectance measurements in the solar radiation (Twomey and Cocks 1989; Nakajima and King 1990) and from the Moderate Resolution Imaging Spectrometer (King et al. 1992). In principle, the remote sensing of other cloud microphysics (e.g., the total number N) could also be expected. Thus, the present parameterization scheme, which has been related to more cloud microphysics, could be used in GCMs.

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