Parameterization of Longwave Optical Properties for Water Clouds①

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(Received January 8, 2001; revised March 27, 2001)

ABSTRACT

Based on relationships between cloud microphysical and optical properties, three different parameterization schemes for narrow and broad band optical properties in longwave region for water clouds have been presented. The effects of different parameterization schemes and different number of broad bands used on cloud radiative properties have been investigated. The effect of scattering role of cloud drops on longwave radiation fluxes and cooling rates in cloudy atmospheres has also been analyzed.

Key words: Water cloud, Long wave radiation, Optical property, Parameterization, Climate model

1. Introduction

Cloud is a main regulator of the earth's climate. Through radiative, latent and convective forcing mechanisms, cloud affects the state of atmospheric motion and the climate. As to the radiative role of clouds, it has the "albedo effect" to cool and "greenhouse effect" to heat the earth–atmosphere system, respectively. The unbalance between these two roles of clouds is of fundamental importance in climate change. Simulations with 19 general circulation models (GCMs) show that only due to the different treatments of clouds in models, the cloud feedback role may vary in the range from medium negative to strong positive (Cess et al., 1990). In fact, the uncertainty in the treatment of cloud roles in GCMs has become a severe obstacle for giving reliable prediction in the study of possible climate change. To consider the effect of droplet size distribution on cloud optical properties in GCMs, simple linear parameterization schemes have been developed for shortwave and longwave optical properties of water clouds by Slingo and Schrecker (1982), Sligo (1989), Tsay et al., (1989) under the 'large droplet' approximation with the equivalent radius as model parameter. In addition, a non–linear parameterization scheme for cloud optical properties has been developed by Hu and Stamnes (1993). Based on the relationship between optical and microphysical properties of water clouds with different droplet size distributions, we have presented three parameterization schemes for cloud optical properties in longwave region. One of them includes both the equivalent radius and mean radius as model parameters for a better consideration of the effect of abundant small cloud droplets usually existing in water clouds. The other two schemes only consider the equivalent radius as single model parameter.

①This work was supported by National Key Basic Research Development Program (G1999043400) and the National Natural Science Foundation of China (Grant No.49675248).

2. Parameterization of cloud optical properties

The entire longwave region from 100 cm^{-1} to 3000 cm^{-1} is divided into 206 spectral intervals for narrow band parameterization, and eight intervals or one interval for broad band parameterization. The parameterization schemes of cloud optical properties for broad band are similar to those for the narrow band (Wang and Zhao, 2000). The following schemes are for extinction coefficient β_e, single scattering albedo ω_0 and asymmetry factor g.

(1) one–parameter linear scheme:

$$\frac{\beta_e}{\mathrm{LWC}} = a_1 + b_1 / r_e \ , \tag{1}$$

$$1 - \omega_0 = a_2 r_e + b_2 \ , \tag{2}$$

$$g = a_3 r_e + b_3 ; \tag{3}$$

(2) one–parameter non–linear scheme:

$$\frac{\beta_e}{\mathrm{LWC}} = a_1 r_e + b_1 + c_1 / r_e + d_1 / r_e^2 \ , \tag{4}$$

$$1 - \omega_0 = a_2 r_e + b_2 + c_2 / r_e + d_2 / r_e^2 \ , \tag{5}$$

$$g = a_3 r_e + b_3 + c_3 / r_e + d_3 / r_e^2 \ ; \tag{6}$$

(3) two–parameter scheme:

$$\frac{\beta_e}{\mathrm{LWC}} = a_1 r_e + b_1 + c_1 / r_e + d_1 / r_e^2 + e_1 r_m + f_1 r_m / r_e \ , \tag{7}$$

$$1 - \omega_0 = a_2 r_e + b_2 + c_2 / r_e + d_2 / r_e^2 + e_2 r_m + f_2 r_m / r_e \ , \tag{8}$$

$$g = a_3 r_e + b_3 + c_3 / r_e + d_3 / r_e^2 + e_3 r_m + f_3 r_m / r_e \ . \tag{9}$$

Where, r_e and r_m are respectively effective radius and mean radius of cloud drop size distributions, LWC is the cloud liquid water content. The coefficients in the equations for narrow band are determined by Mie theory for different cloud drop size distributions and least square method.

Considering the variation of thermal radiation with wavelength, the broad band optical properties, the extinction coefficient β_e, single scattering albedo ω_0 and asymmetry factor g, are determined from narrow band optical properties weighted by Planck function,

$$\beta_e = \sum_i \beta_e(i) w(i) \ ,$$

$$\omega_0 = \sum_i \omega_0(i) \beta_e(i) w(i) / \sum_i \beta_e(i) w(i) \ ,$$

$$g = \sum_i g(i) \omega_0(i) \beta_e(i) w(i) / \sum_i \omega_0(i) \beta_e(i) w(i) \ ,$$

$$w(i) = \int_{\delta v_i} B(v, T) dv \Big/ \int_{\Delta v} B(v, T) dv \ ,$$

where, $B(v, T)$ is the Planck function, v and T are wavenumber and temperature respectively. $w(i)$ is the weight of Planck radiative energy in i–th narrow band δv_i included in a broad spectral interval Δv. The coefficients in broad band parameterization models can be determined from the coefficients of narrow band parameterization models by taking the weight of Planck radiative energy in each narrow band into consideration. The spectral intervals in

ARPS model (Chou and Suarez, 1994) are used in broad band parameterization with eight intervals. They are: 1) 3000.0–1900.0 cm^{-1}, 2) 1900.0–1380.0 cm^{-1}, 3) 1380.0–1100.0 cm^{-1}, 4) 1100.0–980.0 cm^{-1}, 5) 980.0–800.0 cm^{-1}, 6) 800.0–540.0 cm^{-1}, 7) 540.0–340.0 cm^{-1} and 8) 340.0–10.0 cm^{-1}. Table 1 shows the root mean square errors of optical properties in different intervals calculated with broad band parameterization models for 124 different cloud drop size distributions. It can be seen that the two-parameter scheme is of best accuracy. The one-parameter non-linear scheme is also quite accurate and the linear model has relatively large errors.

Table 1. Root mean square errors of optical properties calculated with broad band parameterization models

Eqs.	Root mean square error (%)								
	One band model	8 band model							
		band 1	band 2	band 3	band 4	band 5	band 6	band 7	band 8
One-parameter linear scheme									
(1)	6.97	0.32	8.27	11.61	9.32	5.29	5.46	7.56	5.82
(2)	2.79	4.04	2.97	4.75	5.88	3.47	2.46	3.06	3.40
(3)	1.90	0.93	0.52	1.22	1.82	2.53	3.98	5.98	9.67
One-parameter non-linear scheme									
(4)	2.32	3.40	2.96	3.28	2.97	1.95	1.88	2.48	2.23
(5)	0.60	2.95	2.25	2.07	1.54	0.70	0.55	0.63	0.78
(6)	0.39	0.46	0.25	0.27	0.37	0.42	0.79	1.92	5.50
Two-parameter scheme									
(7)	0.70	3.44	1.26	1.81	1.56	0.61	0.40	0.82	0.99
(8)	0.32	1.48	1.18	1.50	0.92	0.29	0.22	0.34	0.33
(9)	0.23	0.44	0.16	0.23	0.24	0.26	0.51	1.03	1.48

3. The effect of different number of broad bands on cloud radiation

In order to see the effect of different number of bands used in the calculation of cloud optical property on the cloud radiation property, the cloud optical properties in four layers of an inhomogeneous stratus (Table 2) are computed with Mie theory for 206 narrow bands, eight broad bands and one broad interval in longwave region, respectively. Then the longwave

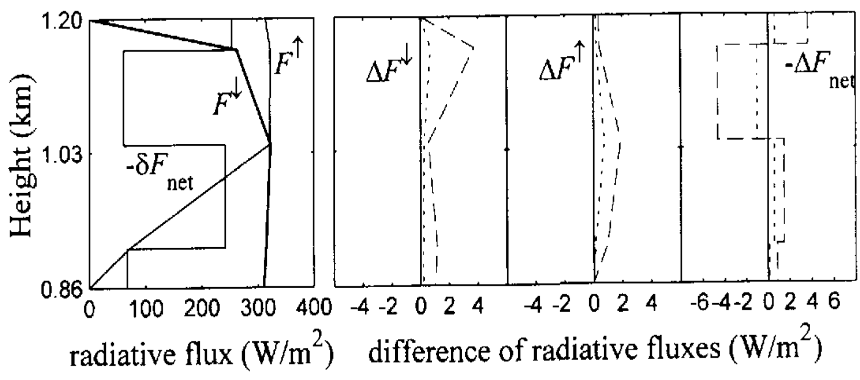

Fig. 1. Radiative fluxes and absorbed radiation in cloud for 206 narrow bands (left) and differences of radiative fluxes and deviation of absorbed radiation for different numbers of broad band compared with 206 narrow bands (right, one-band, dashed; eight-band, dotted).

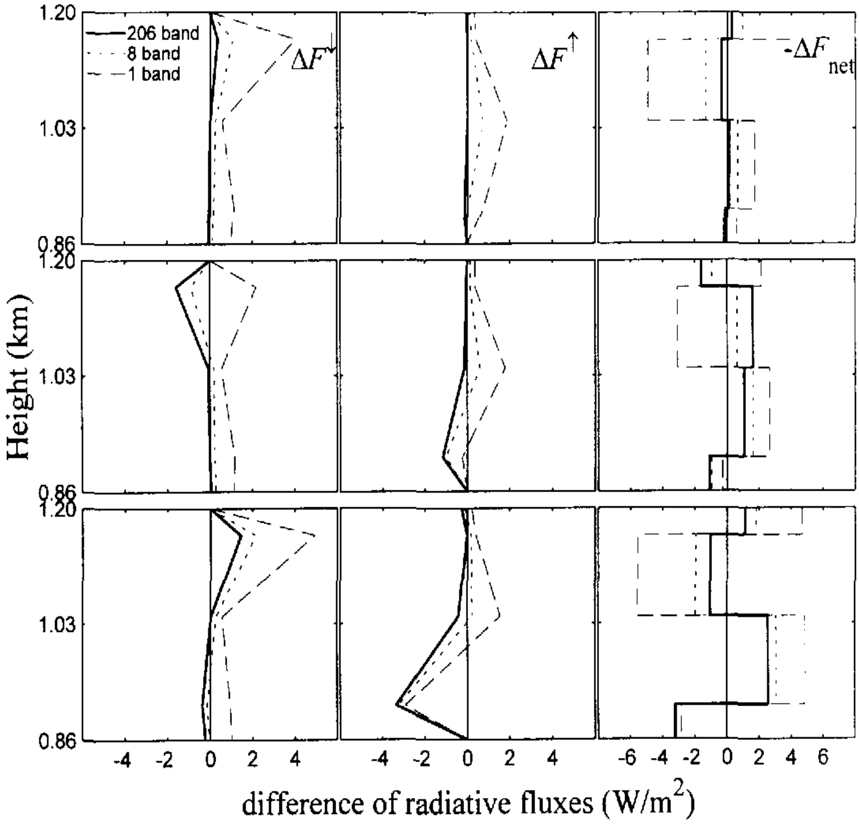

Fig. 2. Differences of longwave radiative fluxes in cloud obtained with different parameterization models (two-parameter, top; one-parameter non-linear, middle; one-parameter linear, bottom) and with different number of spectral bands (206-band, solid; one-band, dashed; eight-band, dotted).

Table 2. An inhomogeneous cloud with four layers

Layer	LWC (g / m^3)	Thickness (km)	Type**	r_e (μm)	r_m (μm)
1	0.352	0.04	St top	11.29	8.19
2	0.435	0.12	St top	11.29	8.19
3	0.289	0.13	St base	7.33	5.57
4	0.023	0.05	St base	7.33	5.57

* * Cloud drop size distributions (Welch et al., 1980).

radiative fluxes in cloud are calculated with four-stream discrete ordinate method (Fig. 1). In the calculation, the cloud temperature is 275 K and the effects of atmosphere and land surface are omitted. In Fig. 1, $F^{\downarrow}$ and $F^{\uparrow}$ refer to the downward and upward fluxes, δF_{net} is the absorbed radiation, corresponding to 206 narrow bands, ΔF and ΔF_{net} repress the flux difference and deviation of absorbed radiation between with different numbers of broad band and with 206 narrow band, respectively. It can be seen from Fig. 1 that the differences between the results of eight broad bands and 206 narrow bands are rather small, but there are relatively large errors for single band.

4. The effect of different parameterization schemes on cloud radiation

In order to investigate the effect of different cloud optical parameterization scheme on the calculation of radiative transfer in cloud, the optical properties in those cloud layers shown in Table 2 are computed separately with above three schemes for one, eight and 206 bands. Then the longwave radiative fluxes in cloud are calculated with four–stream discrete ordinate method. Compared with the results obtained by Mie theory for 206 narrow bands (left side of Fig. 1), the differences of downward and upward fluxes in cloud, $\Delta F^{\uparrow}$ and $\Delta F^{\downarrow}$, and the deviations of absorbed radiation in cloud layers, ΔF_{net}, are shown in Fig. 2. It can be seen that accurate radiative fluxes and absorption in cloud layers can be obtained with two–parameter scheme for 206 narrow bands and eight broad bands, with one–parameter non–linear scheme, the accuracy is still rather high, and with one–parameter linear scheme, the errors in calculated radiative quantities are relatively large. If only one broad band is used, the errors are larger in all cases.

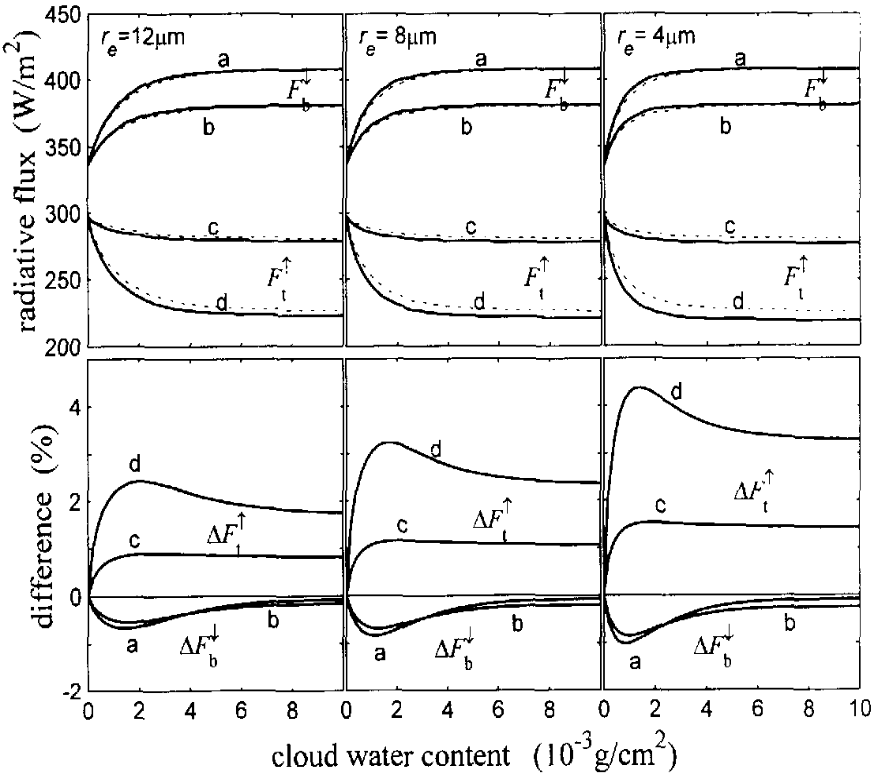

Fig. 3. The radiation fluxes (top) and the flux differences (bottom) from eight–band model for midlatitude summer model atmosphere with low clouds (curves a and c) or middle clouds (curves b and d) and with cloud scattering (solid) or without cloud scattering (dashed).

5. The effect of cloud drop scattering on longwave radiation transfer

Atmospheric gases and clouds have strong absorption in longwave spectral region with relatively weak scattering, therefore only cloud absorption has been taken into account in some models (e.g. Hunt, 1973; Platt, 1976; Stephens, 1978; Chylek and Ramaswamy, 1982; Chylek et al., 1992; Chou and Suarez, 1994). However the scattering roles of cloud drops are still rather significant in some spectral intervals with higher radiative energy, based on Mie scattering calculation of cloud optical properties in longwave region for different cloud drop size distribution. In order to study the influence of cloud drop scattering on longwave radiative transfer, various low clouds (1–2 km) or middle clouds (5–6 km) with 4, 8 and 12 μm effective radii of cloud drop and with cloud liquid water content varied in the range of 0 to 0.01 g / cm^2 are included in a midlatitude atmosphere model. In calculations, the atmosphere is divided into 70 layers, the thickness of each layer is 0.25 km below 13 km, 1km between 13 and 25 km and 5 km between 25 and 50 km. In radiative transfer calculation, the atmospheric water vapor and CO_2 absorption is calculated with K–distribution method (Chou and Suarez, 1994). In this model O_3 absorption is not included. Cloud optical properties are calculated with one–parameter non–linear model for eight broad bands or one single

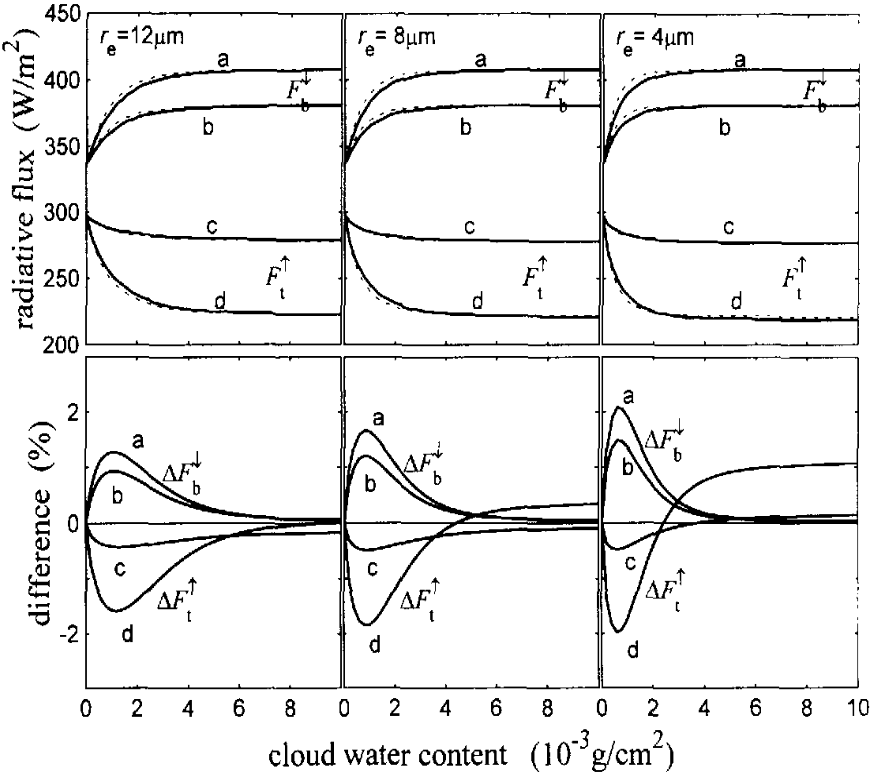

Fig. 4. The same as Fig. 3 except for both one–band model (dashed) and eight–band model (solid) taking cloud scattering into account.

interval. Four-stream discrete ordinate method is used for radiative transfer computation.

The output of eight broad bands for midlatitude summer model atmosphere with low or middle clouds are show in Fig. 3, in which $F_t^{\uparrow}$ is the upward flux at the top of the atmosphere and $F_b^{\downarrow}$ is the downward flux at surface. The left, middle and right panels in Fig. 3 are respectively for 12, 8 and 4 μm effective radius r_e of cloud drop size distribution. The results show that without cloud scattering, the upward flux is overestimated and downward flux is underestimated. In this case, the flux differences are larger for clouds with smaller effective radius than that with larger one. However, the differences for the downward fluxes become insignificant with the increasing of cloud thickness. The effect of different number of broad bands and cloud scattering on the radiation flux are shown in Fig. 4. The effects of cloud scattering on the cooling rate are shown in Fig. 5. The results in Fig. 5 show that omitting the role of cloud drop scattering may result in obvious deviation of cooling rates in clouds. The single broad band parameterization scheme without considering the variation of cloud optical property with wavelength may produce significant errors in cooling rates in clouds.

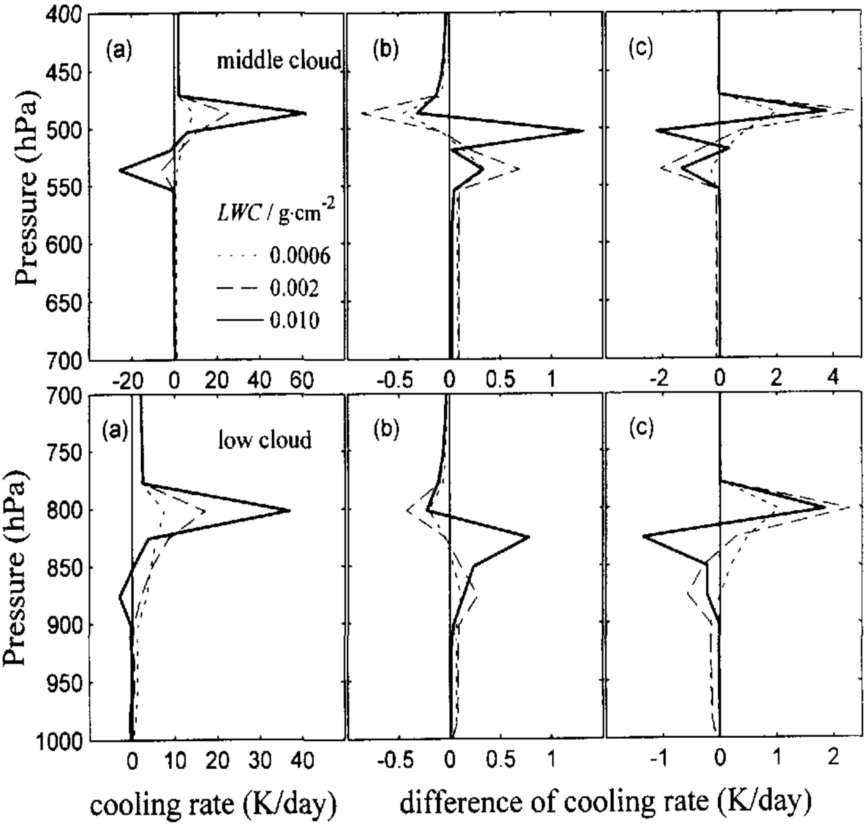

Fig. 5. (a) Cooling rates in the atmosphere by using eight-band parameterization scheme with cloud scattering; (b) cooling rate differences without cloud scattering; and (c) cooling rate differences by using one-band parameterization scheme.

In the case of midlatitude summer model atmosphere with a stratus with cloud top at 1.2 km, the effects of different parameterization methods on the upward and downward flux differences ($\Delta F^{\uparrow}$ and $\Delta F^{\downarrow}$) and cooling rate difference (ΔCR) are shown in Fig. 6. The results in Fig. 6 show that rather accurate fluxes and cooling rates in the atmosphere can be obtained when one-parameter non-linear or two-parameter schemes are applied to the eight-band model with cloud scattering. But when cloud scattering is neglected or only one single broad band is used, significant deviations may appear in the calculation of upward radiative fluxes in the atmosphere above cloud, in downward fluxes and cooling rates within cloud.

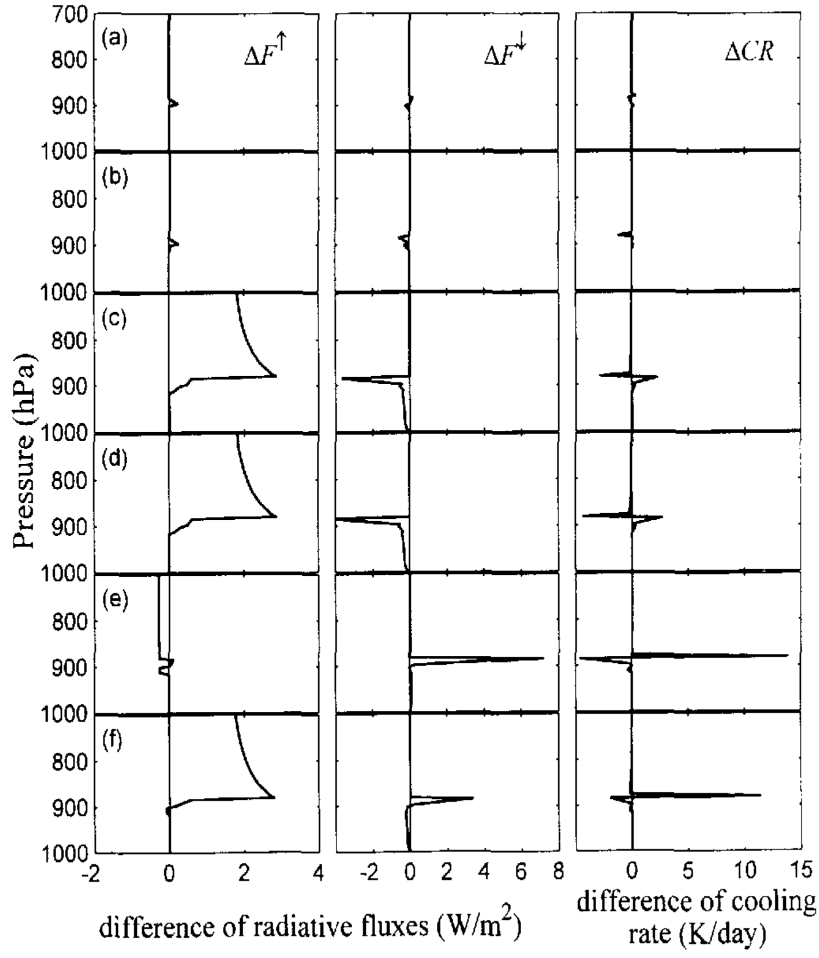

Fig. 6. Differences of radiation fluxes and cooling rates in the atmosphere with a stratus top at 1.2 km. (a) Eight band with scheme (3) and cloud scattering. (b) The same as (a) except for using scheme (2). (c) The same as (a) except for without scattering. (d) The same as (b) except for without scattering. (e) One broad band with scheme (2) and cloud scattering. (f) The same as (e) except for without scattering.

6. Conclusion

Above results reveal that the one-parameter non-linear or two-parameter schemes with eight broad bands can be used for cloud optical property calculation in longwave spectral region with rather good accuracy. The one-parameter linear scheme may lead to relatively large errors. Obvious deviation in cloud cooling rates may occur without taking cloud scattering role into account. In the case of considering cloud scattering, but without taking the variation of cloud optical properties with wavelength into consideration, the single broad band parameterization scheme may also result in significant errors in the cooling rates in cloud.

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水云的长波光学性质参数化

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摘　要

在研究水云的微物理性质与光学性质关系的基础上，提出了三种用于长波区域窄带和宽带水云光学性质计算的参数化方案，研究了应用不同的水云光学性质参数化方案和不同的宽带数目对云辐射性质的影响，分析了云滴的散射作用对有云大气中长波辐射通量和冷却率的影响。

关键词：水云，长波辐射，光学性质，参数化，气候模式