Determination of the optical thickness and effective particle radius of clouds from transmitted solar radiation measurements*

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Abstract A method is presented for determining the optical thickness (τ_c) and effective particle radius (r_e) of stratiform cloud layers from transmitted solar radiation measurements. A detailed study shows that the cloud optical thickness and effective particle radius of water clouds can be determined from transmission function measurements at 0.75 and 2.13 μm, provided that the scaled optical thickness $\tau'_{0.75} > 1$ and $r_e > 5$ μm. The wavelengths adopted by our study are similar to the channels of the moderate resolution imaging spectrometer (MODIS). The proposed method is invalid for optically thin clouds since transmission at 2.13 μm is less sensitive to r_e. The retrieval errors of $\tau'_{0.75}$ and r_e monotonically decrease with increasing τ_c. For clouds having $\tau'_{0.75} \geqslant 2$, the retrieval errors of $\tau'_{0.75}$ and r_e are below 10% and 20%, respectively. Transmissions at 0.75 and 1.65 μm can also be used to retrieve τ_c and r_e.

Keywords: **transmitted solar radiation, ground-based retrieval, cloud optical thickness, cloud effective particle radius.**

Climate change is an important issue concerned by governments and scientists. Due to the lack of knowledge, many uncertainties still exist in simulating the past climate and predicting the future climate[1]. Most energy of the earth comes from the sun. When the climate system is equilibrium, the absorbed solar energy is equal to the energy emitted by the earth and atmosphere. Any disturbance factor (radiative forcing factor) breaking the equilibrium will result in climate change. Positive radiative forcing induces the warming of the earth surface and the lower atmosphere, and negative radiative forcing induces the cooling. In the past decades, global warming has been evidenced by many observations, and it has resulted in the climate change. The greenhouse gases and aerosols are thought to be the most important factors leading to the global warming. They both can change the balance of the earth's energy budget and further change the climate[1].

Aerosols produced by the natural process (e.g. dust and volcanic eruption) and anthropogenic process (e.g. fossil burning biomass) have significant effects (direct and indirect effects) on the earth's radiation budget. The direct effects of aerosols are that aerosols directly scatter and absorb the solar radiation and thermal infrared emission. The indirect effects of aerosols are that aerosols serve as the CCN (cloud condensation nuclei) to change the cloud microphysical properties, and then affect the cloud fraction and radiative properties. Anthropogenic aerosols may result in higher albedo of the cloud, and then the solar energy absorbed by the earth will decrease[2,3]. These effects may compensate for the global warming caused by the increase of CO_2[4].

Cloud is a key factor of the earth's radiation budget and water cycle, and plays an important role in the earth climate system[5]. On the one hand, cloud can absorb and scatter the incident solar radiation (cooling ground). On the other hand, cloud can absorb and emit the long wave radiation (warming ground). The net effect of clouds on radiation is determined by the above two effects. The cloud radiative properties depend on many factors, such as cloud fraction and distribution, water vapor and aerosol dis-

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tribution, cloud height and geometry thickness, water content and cloud microphysical properties. The major uncertainty in predicting future climate is the interaction between cloud and radiation. Cloud is a significantly potential error in the climate simulation. The sign of cloud feedback to radiation is an uncertain problem since the results produced by different models are not in agreement[1].

In order to study the interactions between cloud, radiation and climate, and to determine the cloud feedback mechanism in the climate system, one has to study the relationship between microphysical and radiative properties of cloud. It is well known that one can determine the important optical parameters, such as β_{ext}, ω_0 and g, using Mie theory for a given cloud particle distribution. However, the Mie calculation is very time consuming and inappropriate to be incorporated in GCM models. Thus, parameterization method is expected to describe the radiative properties of water cloud by some feature parameters related to the cloud particle distribution. In the ranges of solar spectra and terrestrial spectra, the cloud optical properties primarily depend on the effective radius and it is insensitive to details of the cloud particle distribution. Many schemes about how to parameterize the cloud optical properties using the water content (optical thickness) and effective particle radius have been developed[6—8]. In addition, the dependence of cloud shortwave properties on details of the cloud particle distribution is minimum when using the effective particle radius as parameter to represent the cloud particle distribution[9].

In the past decades, many studies have been carried out to determine the cloud optical thickness and effective particle radius. According to the platform on which these studies are based, these methods can be divided into space-based (aircraft or satellite) and ground-based retrievals.

1 Space-based and ground-based retrievals

1.1 Space-based retrieval

There are many studies of determining the cloud optical thickness and/or effective particle radius from multiwavelength radiometers boarded on aircrafts or satellites. The underlying principle of these techniques is that the reflection function of clouds at a nonabsorbing channel in the visible wavelength region is primarily a function of the cloud optical thickness, whereas the reflection function at a water (or ice) absorbing channel in the near-infrared range is primarily a function of cloud particle size[4, 10, 11].

The reflection function, $R_\lambda(\mu, \mu_0, \phi)$, is defined by

$$R_\lambda(\mu, \mu_0, \phi) = \frac{\pi I_\lambda(\mu, \mu_0, \phi)}{\mu_0 F_{0\lambda}} \tag{1}$$

where $I_\lambda(\mu, \mu_0, \phi)$ is the reflected intensity at the top of the cloud layer, measured by the radiometer carried by aircraft or satellite, μ_0 is the cosine of the solar zenith angle, μ is the cosine of viewing zenith angle, ϕ is the relative azimuth angle between sun azimuth angle and viewing azimuth angle, $F_{0\lambda}$ is the incident solar radiation at the top of atmosphere, and subscript λ is the wavelength.

β_{ext}, ω_0 and g are parameters of the cloud radiative properties and are all pertain to the particle size and wavelength. In fact, many studies have shown that these parameters can be well presented by a function of a similarity parameter s, and the scaled optical thickness[12] τ_c':

$$s = \left(\frac{1-\omega_0}{1-g\omega_0}\right)^{1/2} \tag{2}$$

$$\tau_c' = (1-g)\tau_c \tag{3}$$

The similarity parameter considers the dependences of ω_0 and g on the particle size. The smaller the particle size is, the stronger the scattering is. The similarity parameter approaches to unit one as absorption increases. The scaled optical thickness is related to the optical thickness. In the water vapor window where $\lambda \leqslant 1.0\,\mu m$, scattering is conservative and s is almost 0. Therefore, s and τ_c' can be determined by R_λ in this range of wavelength (Fig. 1(a)). At wavelengths of 1.65 μm and 2.13 μm, where water vapor absorption is negligible, R_λ and s are sensitive to the effective particle radius. The effective particle radius can be determined using either of these two wavelengths (Fig. 1(b), (c)).

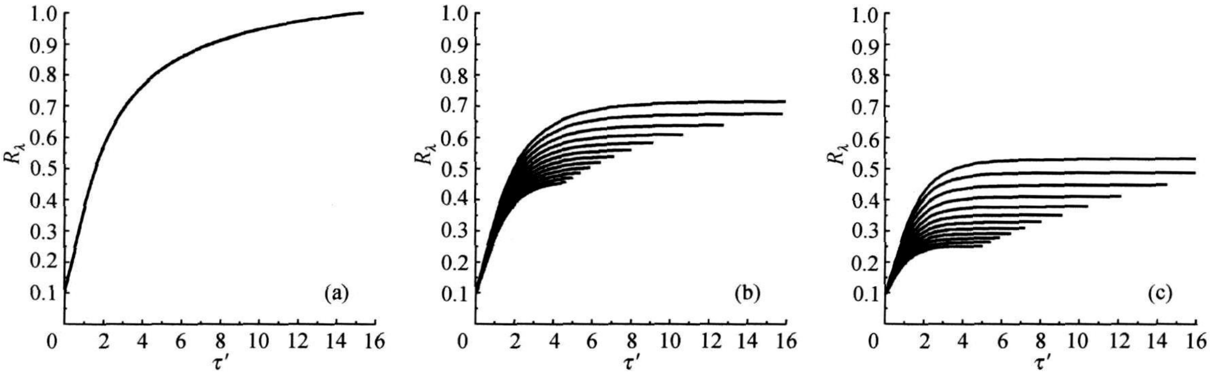

Fig. 1. Relationships between reflection function and scaled optical thickness. (a) $\lambda = 0.75\ \mu m$; (b) $\lambda = 1.65\ \mu m$; (c) $\lambda = 2.13\ \mu m$.

Many instruments boarded on satellite are equipped with visible and near infrared channels to measure the reflected intensity at the top of cloud layer. For instance, 0.65 and 2.13 μm (plus 3.75 μm) channels are adopted by MODIS, which is boarded on the Terra and Aqua, the satellites of EOS (earth observing system) program of USA. The cloud optical thickness and effective particle radius are then determined by the reflected solar radiation measurements[13].

1.2 Ground-based retrieval

The space-based retrieval can obtain the cloud optical and microphysical properties on a larger space scale. However, more theoretical studies and observations are required to assess the retrieval method and to validate the results, since many theoretical hypotheses and approximations can affect the soundness of the retrieval. In addition, satellite retrieval cannot satisfy the requirements of long term and continuous observation, since cloud develops and changes very rapidly. Therefore, ground-based retrieval is a necessary supplement to the space-based retrieval. Many projects/programs are designed to develop the ground-based retrieval techniques, such as ARM (atmospheric radiation measurements), which focuses on collecting the long term ground-based data and using these data to retrieve important meteorological parameters, including the cloud optical thickness and effective particle radius. Fruitful results have been achieved[14—18].

The conventional method of ground-based retrieval is to use visible band to infer the cloud optical thickness and to employ liquid water path (L_{WP}) measured at microwave band to determine the effective particle radius.

The cloud optical properties weakly depend on details of PSD (particle size distribution) when using r_e as the feature parameter to demonstrate PSD[8,9]. In other words, if keeping r_e constant, the cloud optical properties are very similar when using different functions, such as Γ and log-normal distribution, to represent PSD.

In this study, we use the following log-normal distribution to represent the PSD of boundary layer stratus

$$n(x) = \frac{N}{\sqrt{2\pi}\,\sigma_x}\exp\left[-\frac{1}{2}\left(\frac{x - x_m}{\sigma_x}\right)^2\right] \qquad (4)$$

where $x = \ln r$, r is the cloud drop radius, $x_m = \ln r_m$, r_m is the modal radius, σ_x is the log width, and N is the total number of cloud drops in unit.

Then, τ_c, L_{WP}, and r_e can be derived as follows:

$$\tau_c = Q_e \pi r_m^2 \exp(2\sigma_x^2) N \Delta Z \qquad (5)$$

$$L_{WP} = \rho_w\left[\frac{4}{3}\pi r_m^3 \exp(9\sigma_x^2/2)\right] N \Delta Z \qquad (6)$$

$$r_e = \int_0^\infty r^3 n(r)\mathrm{d}r \Big/ \int_0^\infty r^2 n(r)\mathrm{d}r = r_m \exp(5\sigma_x^2/2) \qquad (7)$$

where ΔZ is the cloud geometry thickness, ρ_w is the density of water, and Q_e is the extinction coefficient.

In Eq. (5), if the cloud drop size is much larger than the wavelength of incident radiation, Q_e is very close to constant 2 (in the visible range, this condition can be satisfied).

Using Eqs. (5), (6) and (7), one can write r_e as

$$r_e = \frac{3L_{WP}}{2\tau_c \rho_w} \qquad (8)$$

Eq. (8) shows that r_e can be determined by τ_c and L_{WP}. This ground-based retrieval technique requires to simultaneously measure the radiation at visible and microwave band.

In the past field experiments (e.g. FIRE), both cloud reflection and transmission were measured. There are dozens of paper about how to simultaneously retrieve cloud optical thickness and effective particle radius using reflectance. However, only a few paper is about how to retrieve the cloud optical thickness using transmission[19].

This paper is to present a procedure for inferring the optical thickness and effective particle radius of stratiform cloud layer from multiwavelength transmitted solar radiation measurements. The wavelengths adopted by our study are similar to the channels of MODIS. It will be demonstrated that it is feasible to retrieve the cloud optical and microphysical properties from transmission. From the above introduction we know that the space-based and ground-based retrievals use reflection and transmission, respectively. The scattering angle of reflection with respect to the cloud layer is different from that of transmission. However, both reflection and transmission contain information of cloud. In this paper, we will follow the strategy of satellite remote sensing to study how to determine the cloud optical thickness and effective particle radius with transmitted solar radiation. This will be very helpful for the validation of MODIS related products.

2 Theoretical background

The underlying principle of space-based retrieval methods is that the reflection function of clouds at a nonabsorbing channel in the visible wavelength range is primarily a function of the cloud optical thickness; whereas the reflection function at a water (or ice) absorbing channel in the near-infrared range is primarily a function of cloud particle size. In this section, we will study the features of transmission function in the visible and infrared ranges.

The definition of transmission function $T_\lambda(\mu, \mu_0, \phi)$ is

$$T_\lambda(\mu, \mu_0, \phi) = \frac{\pi I_\lambda(-\mu, \mu_0, \phi)}{\mu_0 F_{0\lambda}} \tag{9}$$

where $I_\lambda(-\mu, \mu_0, \phi)$ is the transmitted intensity at the bottom of cloud layer, which can be measured by ground-based radiometer, the minus sign means I_λ is downward, opposite to the positive direction (zenith). The meanings of other symbols are the same as those in $R_\lambda(\mu, \mu_0, \phi)$.

According to the channels of MODIS, we chose 0.75, 1.65 and 2.13 μm to study the sensitivities of $T_\lambda(\mu, \mu_0, \phi)$ to τ_c and r_e. These wavelengths are in the water vapor window and can avoid the effects of water vapor absorption.

The particle size of terrestrial water cloud is between 5 and 10 μm in most cases[10]. In this study, we calculated the transmission function and scaled optical thickness of stratiform cloud layers with different water contents and $5 \leqslant r_e \leqslant 16$ μm at wavelengths of 0.75, 1.65 and 2.13 μm.

Fig. 2 illustrates the relationship between transmission and scaled optical thickness at $\lambda = 0.75$ μm. For $\tau'_{0.75} \geqslant 1$, $T_{0.75}$ monotonically decreases with increasing $\tau'_{0.75}$ and has no dependence on r_e. When $\tau'_{0.75} < 1$, $T_{0.75}$ is dependent on r_e. Therefore, if $\tau'_{0.75} \geqslant 1$, one can solely determine $\tau'_{0.75}$ by the measured transmission at 0.75 μm.

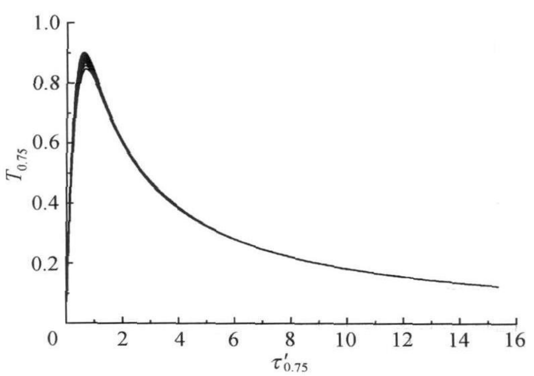

Fig. 2. Relationships between transmission and scaled optical thickness ($\lambda = 0.75$ μm, the solar zenith angle $\theta_0 = 30°$, $5 \leqslant r_e \leqslant 16$ μm, the viewing zenith angle $\theta = 180°$ (Nadir)).

Fig. 3 demonstrates the transmission (at wavelengths of 1.65 and 2.13 μm) as a function of the scaled optical thickness for stratiform cloudy layers containing various values of effective particle radius (only $r_e = 5, 8, 11, 14$ μm are shown). From Fig. 3 (a) we can see that, for $\tau'_{2.13} \geqslant 1$, $T_{2.13}$ and $\tau'_{2.13}$ are sensitive to r_e. These curves are in the same pattern, but with different values. For $\tau'_{2.13} < 1$, their dependences on r_e are weak. Similar results for 1.65 μm can be seen in Fig. 3(b).

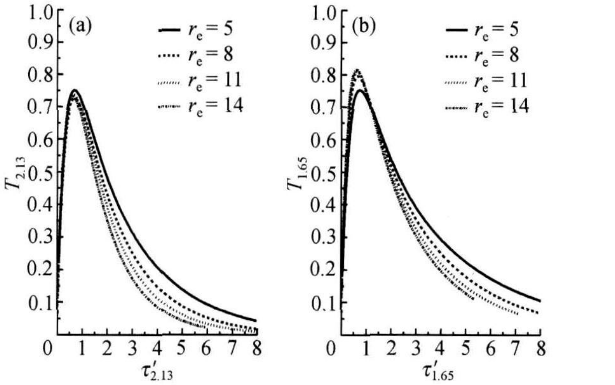

Fig. 3. Relationships between transmission and scaled optical thickness at wavelengths of (a) 2.13 μm and (b) 1.65 μm (Calculation conditions are the same as that in Fig. 2.)

Therefore, if the scaled optical thickness $\tau'_{2.13}$ (or $\tau'_{1.65}$) can be obtained, then r_e can be determined by the transmission $T_{2.13}$ (or $T_{1.65}$).

In summary, the transmission function is only related to the scaled optical thickness and independent of the effective particle radius in the visible range, whereas it is only related to the effective particle radius in the near-infrared range. These features show that it is possible to retrieve the optical thickness and effective particle radius of stratiform cloud layers using transmission function.

3 Method

From Section 2 we know that the effective particle radius r_e can be determined by the transmission function $T_{2.13}$ (or $T_{1.65}$), and the scaled optical thickness $\tau'_{2.13}$ (or $\tau'_{1.65}$). Since the retrieval principle for 1.65 μm is the same as 2.13 μm, we will take 2.13 μm as an example in the following study. $T_{2.13}$ can be measured directly with ground-based radiometer. However, $\tau'_{2.13}$ is dependent on r_e and cannot be obtained directly. In fact, we can use $\tau'_{0.75}$ to infer $\tau'_{2.13}$.

When $\tau'_{0.75} \geqslant 1$, $T_{0.75}$ monotonically decreases with increasing $\tau'_{0.75}$ and is independent of r_e (Fig. 2). Hence, we chose $r_e = 5$ μm to fit the curve. The fitting result is

$$T_{0.75} = a \times (1 - e^{(-\tau'_{0.75}/c1)})^b \times e^{(-\tau'_{0.75}/c2)} + d \tag{10}$$

where a, b, $c1$, $c2$, d are the fitting parameters.

Fig. 4(a) shows the relationships between $\tau'_{2.13}$ and $\tau'_{0.75}$ for various values of r_e (only $r_e = 5, 8, 11, 14$ μm are shown). The curves in Fig. 4(a) can be fitted with the following linear equation

$$\tau'_{2.13} = K(r_e)\tau'_{0.75} \tag{11}$$

where K is the slope of fitting curve, and it is a function of r_e.

Fig. 4(b) gives the relationship between $K(r_e)$ and r_e. They can be fitted with the following linear equation

$$K(r_e) = 1.571 - 0.018 r_e \tag{12}$$

Therefore, $\tau'_{2.13}$ can be inferred from $\tau'_{0.75}$ using Eq. (11) and Eq. (12) for a given r_e.

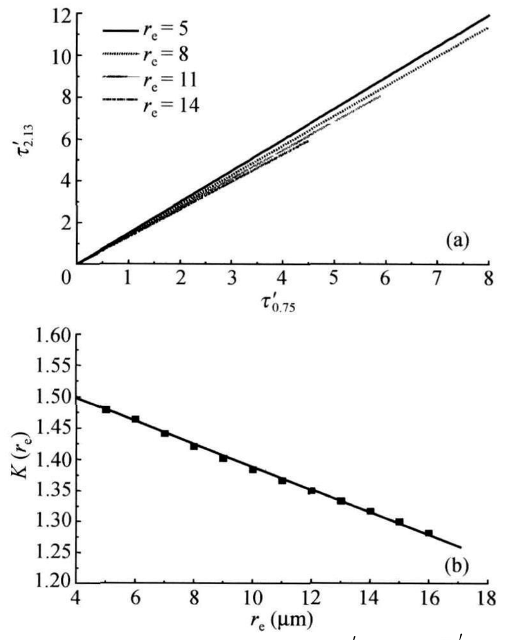

Fig. 4. Relationships between (a) $\tau'_{2.13}$ and $\tau'_{0.75}$; (b) $K(r_e)$ and r_e.

Similarly, we can fit the curves of $T_{2.13}$ and $\tau'_{2.13}$ for various values of r_e. Fig. 5(a) illustrates the fitting curves of $T_{2.13}$ and $\tau'_{2.13}$ (only $r_e = 5, 8, 11, 14$ μm are shown). The fitting function is in the form of

$$T_{2.13}(r_e) = A(r_e) \times (1 - e^{(-\tau'_{2.13}/C1(r_e))})^{B(r_e)} \times e^{(-\tau'_{2.13}/C2(r_e))} \tag{13}$$

From Eq. (13) we can see that the fitting parameters, A, B, $C1$, and $C2$, are also functions of r_e. Their relationships with r_e are shown in Fig. 5(b). The equations are

$$A(r_e) = 0.798 + 0.075 r_e - 0.002 r_e^2 \tag{14}$$

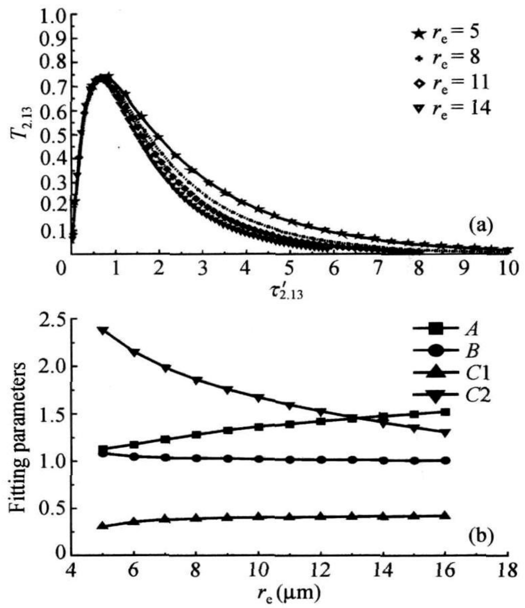

Fig. 5. Relationships between (a) $T_{2.13}$ and $\tau'_{2.13}$; (b) fitting parameters and r_e.

$$B(r_e) = 1.149 - 0.020 r_e + 7.110 \times 10^{-4} r_e^2 \quad (15)$$

$$C1(r_e) = 0.178 + 0.036 r_e - 0.001 r_e^2 \quad (16)$$

$$C2(r_e) = 3.331 - 0.235 r_e + 0.007 r_e^2 \quad (17)$$

Note that all the results obtained above are at solar zenith angle $\theta_0 = 30^\circ$. For other solar zenith angles, similar results can be achieved. The fitting functions of each parameter, K, A, B, $C1$, $C2$, are in the same form, but with different coefficient, as shown in Fig. 6(a)—(d).

In order to determine the cloud optical thickness and effective particle radius from transmission, a LUT (look up table), which is related to all the fitting parameters a, b, $c1$, $c2$, d, K, A, B, $C1$, $C2$, can be set up in advance for various solar zenith angles and effective particle radii. Thus, the optical thickness and effective particle radius of stratiform cloud layers can be retrieved following the scheme shown in Fig. 7.

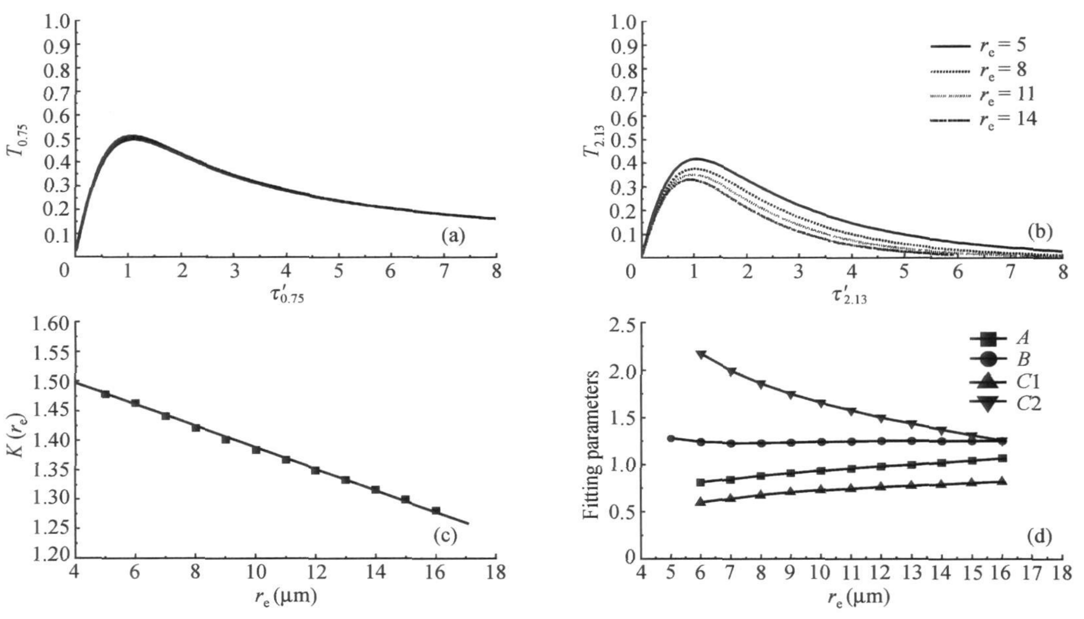

Fig. 6. Retrieval method applied at $\theta_0 = 60^\circ$. (a)—(d) are the relationships between (a) $T_{0.75}$ and $\tau'_{0.75}$; (b) $T_{2.13}$ and $\tau'_{2.13}$; (c) K and r_e; (d) A, B, $C1$, $C2$ and r_e.

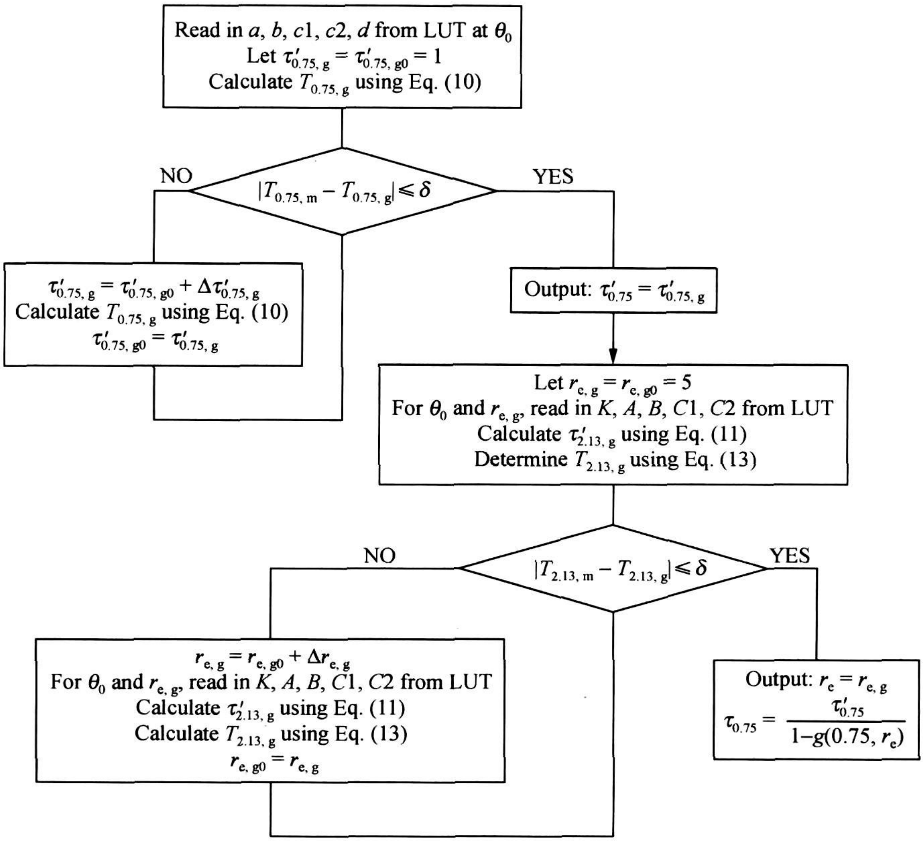

Fig. 7. Flow chart of retrieving cloud optical thickness and effective particle radius using transmission. Subscripts m and g represent the measurement and guessing values, respectively.

4 Error analysis

When the cloud optical thickness and effective radius are determined, it is important to examine the overall uncertainties in $\tau'_{0.75}$ and r_e. These uncertainties arise as a result of errors in the measured transmission function at wavelengths of 0.75, 1.65 and 2.13 μm, as well as uncertainties in the curve fitting. The latter can be avoided with higher fitting accuracy. In fact, the mean fitting error is below 0.1% under the fitting function used by our method. Therefore, we will focus on the discussion of the errors caused by the uncertainties in the measured transmission function ($T_{0.75}$, $T_{2.13}$).

The relative error of function $y = f(x)$ is

$$\delta y = \left| \frac{f'(x)}{f(x)} \right| \delta x \tag{18}$$

Thus, we can derive the analytic expressions of $\delta\tau'_{0.75}$ and δr_e using Eqs. (10), (13) and (18). Fig. 8 illustrates the error in the optical thickness, $\delta\tau'_{0.75}$, arising from a 5% error in the measured transmission function at 0.75 μm ($\delta T_{0.75} = 0.05$). Fig. 9 illustrates the error in the effective radius, δr_e, arising from a 5% error in the measured transmission function at 2.13 μm ($\delta T_{2.13} = 0.05$).

From Fig. 8 we can see that the retrieval error of $\tau'_{0.75}$ monotonically decreases from 20% to 10% when $\tau'_{0.75}$ is in the range of $1 \leqslant \tau'_{0.75} \leqslant 2$; when $\tau'_{0.75} \geqslant 2$, the error decreases to less than 10%.

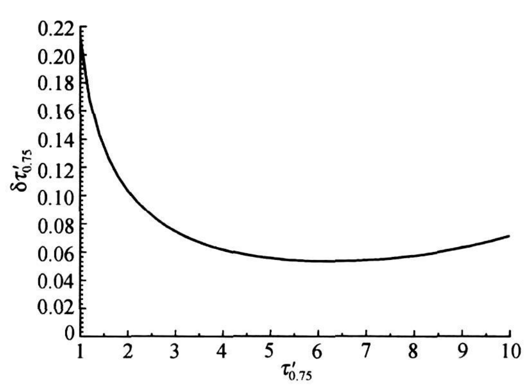

Fig. 8. Retrieval error of $\tau'_{0.75}$ when transmission function at 0.75 μm has 5% error ($\theta_0 = 30°$).

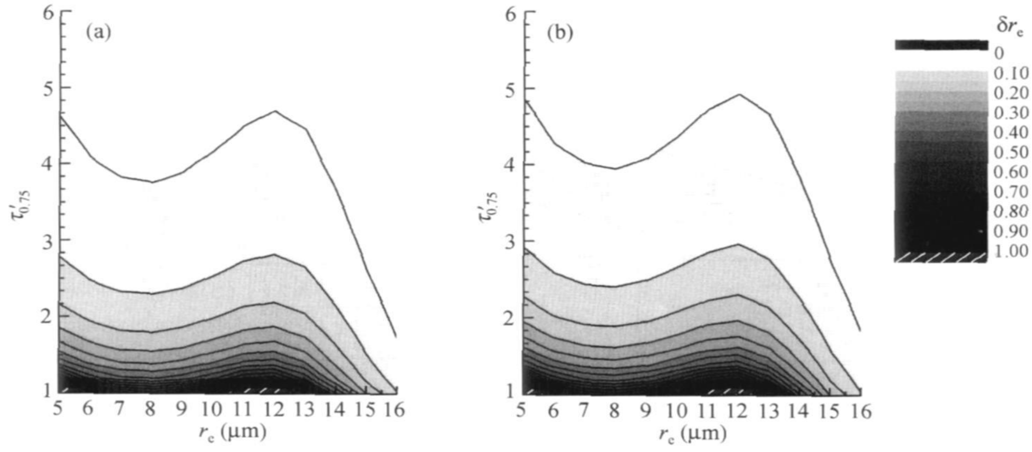

Fig. 9. Retrieval error of r_e when transmission measurement at 2.13 μm has 5% error (solar zenith angle $\theta_0 = 30°$). (a) $\tau'_{0.75}$ has no error; (b) $\tau'_{0.75}$ has 5% error.

Except for $\delta T_{2.13} = 5\%$, we calculated the retrieval errors of r_e when $\delta\tau'_{0.75} = 0$ and $\delta\tau'_{0.75} = 5\%$ since r_e is dependent on both $T_{2.13}$ and $\tau'_{0.75}$. From Fig. 9 we can see that the dependence of r_e on $\tau'_{0.75}$ is relatively small. The retrieval error of r_e monotonically decreases as $\tau'_{0.75}$ increases; and it is relatively large when cloud is optically thin ($\tau'_{0.75} < 1.5$); when $\tau'_{0.75} > 2$, the error decreases to less than 20%.

Note that we made the error analysis at the solar zenith angle $\theta_0 = 30°$. For other solar zenith angles, the tendency and range of the errors are similar.

5 Conclusion

In this paper, a technique has been developed for determining the optical thickness and effective particle radius of stratiform from multiwavelength transmitted solar radiation measurements. The principles, applicable condition of the method and error analysis have been discussed from the theoretical point of view. The wavelengths adopted by our study are similar to the channels of MODIS, which is an important platform to obtain the cloud optical and microphysical properties up to date. The results show that the cloud optical thickness and effective particle radius of water clouds can be determined from transmission function measurements at 0.75 and 2.13 μm, provided that the scaled optical thickness $\tau'_{0.75} > 1$ and $r_e > 5$ μm. The retrieval errors are comparable to that of MODIS. Therefore, both space-based and ground-based retrieval techniques can use the same combination of wavelengths to retrieve cloud optical thickness and effective particle radius. Their results can validate each other. We also design a retrieval scheme for our method. All the empirical parameters needed can be pre-calculated with high accuracy and be stored in a LUT for future retrieval. Transmissions at 0.75 and 1.65 μm can also be used to retrieve τ_c and r_e. The proposed method is invalid for the optically thin clouds since transmission at 2.13 μm is less sensitive to r_e for these clouds.

The major uncertainties in our retrieval arise from the errors in the measured transmission function at wavelengths of 0.75 and 2.13 μm. Under the assumption that transmission measurement has 5% error, we estimated the tendency and range of the retrieval errors. The retrieval errors of $\tau'_{0.75}$ and r_e monotonically decrease as τ_c increases. For clouds having $\tau'_{0.75} \geq 2$, the retrieval errors of $\tau'_{0.75}$ and r_e are below 10% and 20%, respectively. Therefore, our method is valid for the optically thick cloud layer.

Note that the reflection method adopted by MODIS is based on the asymptotic theory approximation and also only suitable for the optically thick clouds. For optically thin clouds, the uncertainty in the surface albedo will affect the retrieval accuracy. Therefore, it is still of interest to research how to determine the cloud optical thickness and effective particle radius for the optically thin clouds. Although we limit the application of our method to the optically thick clouds ($\tau'_{0.75} > 1$), it can be seen that we include the optically thin clouds in the curve fitting. The preliminary analyses have shown that it is possible to apply our method to the optically thin clouds.

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