JP1.8 A BI-SPECTRAL NEAR-INFRARED METHOD FOR INFERRING THE VERTICAL VARIATION OF CLOUD DROPLET EFFECTIVE RADIUS

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1. INTRODUCTION

One of the important cloud microphysical parameters is the droplet effective radius (DER), which influences the Earth's climate through its effects on radiation balance, hydrological cycle, and cloud and climate feedbacks. Cloud DER has been incorporated into climate models in an ad hoc manner, mainly due to the lack of systematic observations. Most climate models incorporate the DER information acquired from aircraft measurements at local experiments, usually limited to daytime, mid-latitudes, and over land or coastal areas (Slingo et al. 1982; Stephens and Platt 1987; Albrecht et al. 1995; Twomey and Cocks 1989; Rawlins and Foot 1990; White et al. 1995; Dong et al. 1997). There is a dearth of observations concerning the DER vertical variability, which remains as a critical gap in the treatment of clouds in climate models. Thus, routine satellite observations of clouds are required to gain a better knowledge on the vertical structure of cloud DER both at local and global scales and to understand its radiative effects on climate.

Many studies on the retrieval of cloud DER from satellite observations have been devoted to the spectral measurement at the nominal 3.7 μm wavelength from the Advanced Very High Resolution Radiometer (AVHRR) (Arking and Childs 1985; Coakley et al. 1987; Han et al. 1994; Platnick and Twomey 1994; Nakajima and Nakajima 1995). The fundamental basis of these retrieval methods is that the 3.7-μm spectral reflectance has a large dependence on DER. However, due to its large absorption by cloud droplets, the 3.7-μm reflectance is only susceptible to the DER variation near cloud top (Platnick 2000). As a result, the 3.7-μm retrieval is only valid for homogeneous DER vertical profiles. For inhomogeneous DER profiles, its retrieval may only represent a shallow layer near the cloud top and not the bulk property of the cloud.

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Satellite observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) of the Earth Observing System (EOS) (King et al. 1992) provide opportunities for retrieving cloud DER vertical variations by using multi-spectral near-infrared (NIR) measurements at 1.65, 2.15 and 3.75 μm. Since clouds formed by adiabatic or pseudo-adiabatic cooling often display a trend of near-linear increase in DER with height, an assumption of a linear DER profile should be valid. Among such category of clouds are a large number of low-level stratus and stratocumulus clouds observed in many experiments reviewed by Miles et al. (2000). From satellite observations, these stratiform clouds, like marine stratocumulus, can cover large areas of hundred thousands of kilometers and last for several days (Coakley and Baldwin 1984), which play an important role in determining the Earth radiation budget (Hartman et al. 1992). With very weak vertical motion, the growth of droplet size in stratiform clouds is mainly due to condensation rather than coalescence. As a result, for non-precipitation, stratus clouds often display an increase in liquid water content with height, which is driven by an increase in droplet size. Yet, the increase is close to linear (Miles et al. 2000). In light of such a linear DER variation, this study explores the potential of using coincident bi-spectral NIR satellite observations to retrieve an optimum linear DER profile. The retrieved linear DER profiles are compared with those retrieved from ground-based radar reflectivity measurements.

2. THE RETRIEVAL METHODOLOGY

The retrieval method employs the lookup-table technique that determines the linear DER profile by comparing the observed NIR reflectances with model calculations. As conventional, the retrieval procedure has two steps: 1) forward radiative transfer calculations and 2) the inversion retrieval procedure.

2.1 Forward Radiative Transfer Calculations

Large sets of reflectance lookup tables were calculated at the MODIS 0.63, 1.65, 2.15, and 3.75-μm bands by employing an adding-doubling radiative transfer routine (Chang and Li 2002). The radiative transfer calculations were conducted for various conditions of cloud optical depths and linear DER vertical profiles. The linear DER profile is assumed to be a linear function of the within-cloud optical depth (τ'), which is given by

$$r_e(\tau') = r_{e1} + (r_{e2} - r_{e1})\frac{\tau'}{\tau_{\text{total}}}, \quad (1)$$

where τ_{total} is the total cloud optical depth at 0.63-μm band and r_{e1} and r_{e2} are two ideal boundary DERs at cloud top ($\tau' = 0$) and cloud bottom ($\tau' = \tau$), respectively. The DER is defined by (Hansen and Travis 1974)

$$r_e = \frac{\int \pi r^3 n(r) dr}{\int \pi r^2 n(r) dr}, \quad (2)$$

and the lognormal size distribution is used for $n(r)$.

Using such a linear DER profile, infinitesimal cloud layers with varying DER were superimposed in the adding-doubling radiative transfer calculations. For fast radiative transfer calculations, the adding-doubling calculations adopted variable cloud optical depth layers to deal with the DER vertical inhomogeneity. The superimposition starts with very thin optical depth layers near the cloud top and then adopts progressively thicker layers towards the cloud bottom. The intervals of cloud optical depth adopted are $\Delta\tau_k = 0.5$ for k = 1–8 ($\tau_{\text{total}} = 4$ at k = 8), $\Delta\tau_k = 1$ for k = 9–12 ($\tau_{\text{total}} = 8$ at k = 12), $\Delta\tau_k = 2$ for k = 13–16 ($\tau_{\text{total}} = 16$ at k = 16), $\Delta\tau_k = 4$ for k = 17–20 ($\tau_{\text{total}} = 32$ at k = 20), $\Delta\tau_k = 8$ for k = 21–24 ($\tau_{\text{total}} = 64$ at k = 24) and $\Delta\tau_k = 16$ for k = 25–28 ($\tau_{\text{total}} = 128$ at k = 28), where k denotes the kth layer from cloud top downward in the adding procedures.

Figure 1 shows the simulated NIR reflectances at 1.65 and 3.75 μm, which were calculated for a cloud layer of $\tau_{\text{total}} = 20$ using different r_{e1} and r_{e2} for various linear DER profiles. It is seen that the NIR reflectances depend on both the cloud-top r_{e1} and the linear variance towards r_{e2}. Since the larger the DER the more the absorption, the reflectance dependence on r_{e2} decreases as r_{e1} increases. Also, since the longer the wavelength the faster the reflectance saturation, the 3.75-μm reflectance displays much less sensitivity to variation in r_{e2}, as opposed to the 1.65-μm reflectance. Thus, an independent DER retrieval inferred from the 1.65-μm channel conveys DER information at a larger depth within cloud than the retrieval from the 3.75-μm channel. Such reflectance dependence on both r_{e1} and r_{e2} lays the foundation for retrieving the linear DER profile.

2.2 The Retrieval Procedure

The proposed linear-DER retrieval method starts with a procedure similar to the conventional one by following an iterative procedure to retrieve cloud optical depth and DER from the 0.63-μm visible reflectance measurement and a NIR reflectance measurement, for example, at either 1.65 or 3.75 μm. During this retrieval procedure, the DER profile was assumed to be constant with no vertical variations (i.e., the difference $r_{e2}-r_{e1} = \Delta r_e = 0$). However, for cloud DER having inhomogeneous vertical variations, the retrieved DER obtained using 1.65-μm measurement will differ from that obtained using 3.75-μm measurement. This is due to the fact that photon transports significantly deeper inside a cloud at 1.65 μm than at 3.75 μm.

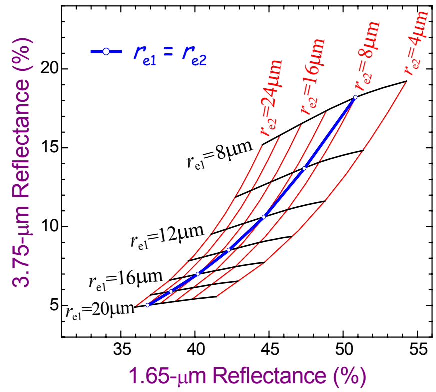

Fig. 1 Theoretical NIR reflectances at 1.65 and 3.75 μm for various r_{e1}-r_{e2} linear DER vertical variations.

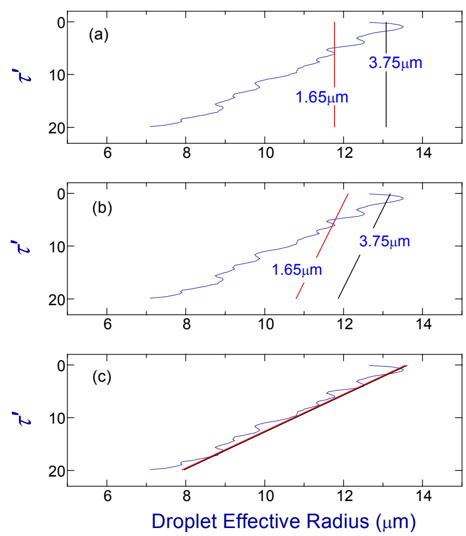

Fig. 2 Schematic illustration of the bi-spectral NIR retrieval procedures using 3.75- and 1.65-μm channels for retrieving an optimum linear DER profile.

The difference between the two DER retrievals from 1.65 and 3.75 μm can thus be used to determine the slope (Δr_e) of the linear DER profile. Thus, the proceeding retrieval is improved by replacing the constant DER profile with the new (r_{e1}, r_{e2}) linear DER profile.

Figure 2 shows the schematic illustration of the bi-spectral NIR retrieval procedure. Fig. 2a shows the original retrievals by assuming a constant DER vertical profile. For the case of a nearly linear decrease of DER from cloud top to cloud bottom, the resulted retrievals give $r_{e1} = r_{e2} = 13.1$μm with the use of 3.75-μm and $r_{e1} = r_{e2} = 11.7$μm with the use of 1.65-μm. Fig. 2b shows that using a linear DER profile with fixed slope (i.e., Δr_e = 13.1–11.7μm = 1.4μm), the resulted retrievals give r_{e1} = 13.1μm and r_{e2} = 11.7μm with 3.75-μm and r_{e1} = 12.1μm and r_{e2} = 10.7μm with 1.65-

μm. With increasing Δr_e, the two retrieved linear DER profiles capture more closely the trend of the DER vertical variations as shown in Fig. 2c.

3. COMPARISONS WITH GROUND-BASED RADAR MEASUREMENTS

The bi-spectral linear-DER retrieval method was applied to the MODIS satellite observations overpass at the Oklahoma Southern Great Plain (SGP) Central Facility site of the US/Department of Energy's Atmospheric Radiation Measurement Program (ARM). The retrieved linear DER profiles were compared to the ground-based retrievals using radar reflectivity measurements (Dong and Mace 2002). The ground-based radar retrieval method utilizes reflectivity profiles measured by millimeter radar together with cloud liquid water path derived from microwave radiometer measurements, from which the vertical profiles of cloud liquid water content and DER were retrieved. For the ground radar retrievals, two different methods of Dong and Mace (2002) and Frisch et al. (1995) were employed and compared with the MODIS satellite retrievals. Figure 3 shows the ground radar retrieved vertical profiles of DER and the extinction coefficient for two stratus cloud cases observed on (a) April 4 and (b) May 31, 2001 at ARM SGP site. The profiles were average of a 15-minute span at near MODIS passing time. In general, the DER decreases with height on April 4, but increases on May 31. The radar retrieved DER from Dong and Mace's are on average larger than Frisch et al's by 2 μm.

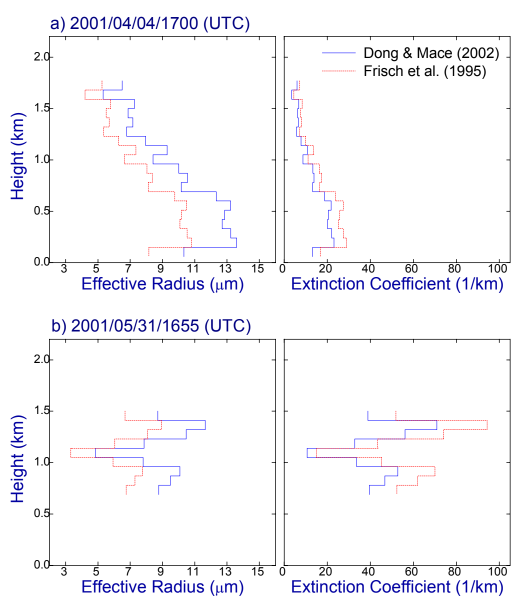

Fig. 3 Ground-based radar retrieved vertical profiles of DER (left column) and extinction coefficient (right column) on a) April 4 and b) May 31, 2001 at ARM SGP site.

Figure 4 compares the MODIS satellite retrievals with the ground radar retrievals for the two stratus cases shown in Fig 3. The satellite retrievals were averaged over a 15 km x 15 km area over the ARM SGP site. Fig. 4a shows the linear DER profile retrieved by using two different bi-spectral NIR combinations of 3.75-/1.65-μm and 3.75-/2.15-μm. The DER profile retrieved using 3.75-/2.15-μm is closer to the cloud-top DER variations, whereas using 3.75-/1.65-μm it captures more DER variations near cloud bottom. In contrast, Fig. 4b compares the DER retrievals with no vertical variation by using independent NIR channel at 3.75-, 2.15- and 1.65-μm. Apparently, such a single-NIR DER retrieval is inadequate to represent the cloud DER variations for a vertically inhomogeneous cloud layer.

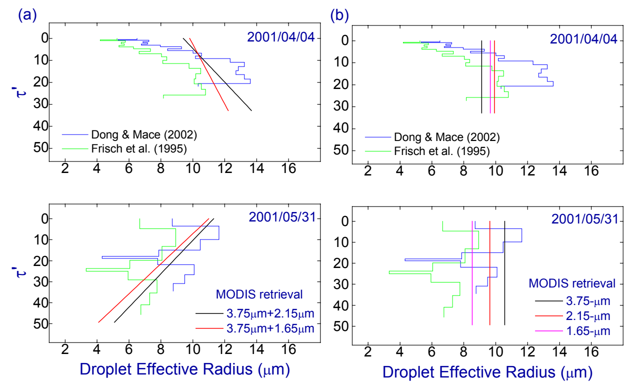

Fig. 4 Comparisons of MODIS-retrieved a) linear-DER and b) constant DER profiles with ground retrievals.

4. SUMMARY AND FUTURE WORK

This manuscript presents a satellite-based retrieval method for inferring the vertical variation of cloud droplet effective radius (DER) by utilizing bi-spectral NIR measurements at, e.g., 1.65, 2.15, and 3.75 μm, available from the MODIS satellite observations of the NASA EOS project. The method is based on the principle that these NIR measurements convey cloud DER information from different heights within a cloud, which is sufficient to allow for the retrieval of a linear DER profile that captures the trend of the DER vertical variations. The method is applicable to low-level, non-precipitating, stratiform clouds as their DER often displays monotonical increase from cloud bottom to cloud top. As such, by comparing the bi-spectral NIR measure-ments to corresponding lookup-tables values generated for various linear DER profiles an optimum linear DER profile can be retrieved. The retrieval method was evaluated and compared to the conventional single-NIR retrieval method by applying both methods to two stratocumulus clouds observed at the ARM SGP site with ground-based radar measurements of the DER vertical profiles. Capable of capturing the trend of DER vertical variations, the retrieved linear DER profiles showed large improvement over the conventional 3.75-μm retrievals. The later are prone to systematic overestimation near cloud bottom.

For future work, we will conduct an extensive validation study to evaluate its performance and investigate its applicability using ARM cloud microphysical data obtained by means of in-situ observations and ground-based remote sensing. The ground-based DER retrievals will utilize radar reflectivity profile and microwave liquid water path measurements. The university of North Dakota Citation aircraft also provided in-situ measurements of cloud microphysics during the ARM cloud Intensive Observing Period (IOP) at SGP site for validating the surface retrievals. Since surface- and aircraft-based measurements only provide samples directly over the site, the complimentary satellite retrievals of cloud properties are important to obtain large-scale and areal mean observations. Satellite retrievals of cloud DER profiles may then be used to better quantify cloud microphysical properties in boundary layer clouds in order to improve cloud parameterizations in climate models.

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