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Cloud Optical Parameters as Derived from the Multispectral Cloud Radiometer

Teruyuki Nakajima† and Michael D. King

Laboratory for Atmospheres, Goddard Space Flight Center, NASA,
Greenbelt, MD 20771, USA

1. Introduction

There are several studies on the simultaneous determination of cloud optical thickness and mean droplet size as derived from multispectral radiometers (Twomey and Cocks, 1982; Curran and Wu, 1982; Arking and Childs, 1985). These studies are very important to elucidate the cloud microphysical structure. As pointed out by many investigators (e. g. Rossow *et al.*, 1985; Wu, 1985), however, many factors bother the successful retrieval when we apply these methods to real data. Therefore, many ground truth experiments are required in order to test the validity of these methods. Here, we have analyzed the data taken in the marine stratocumulus intensive field observation component of the First ISCCP Regional Experiment (FIRE), conducted off the California coast in July, 1987 using the Multispectral Cloud Radiometer (MCR).

The MCR has six near-infrared channels and one 10.7 μm-channel (Curran *et al.*, 1981). The first channel (λ = 0.754 μm) has proven to be very useful for estimating the cloud optical thickness (King, 1987). Adding the additional two wavelengths (λ = 1.645, 2.160 μm), we are able to estimate the mean droplet size (Curran and Wu, 1982). Arking and Childs (1985) also studied a similar problem using the 0.73 and 3.7 μm channels of the NOAA/AVHRR. In spite of these pioneering works, there seem to be insufficient systematic studies of the efficiency of the algorithms. For this purpose, we have performed numerous simulations of the reflected radiation from clouds using an improved radiation calculation algorithm (Nakajima and Tanaka, 1988). Results of the simulation and an application of our algorithm to the MCR data are presented in Sections 2 and 3, respectively.

2. Retrieval algorithm

For the purpose of analyzing the three MCR near-infrared channels outside water vapor and oxygen absorption bands (λ= 0.754, 1.645 and 2.160 μm), we investigated the characteristics of the numerically simulated bidirectional re-

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† Permanent affiliation: Upper Atmosphere and Space Research Laboratory, Faculty of Science, Tohoku University, Sendai 980, Japan.

flectivity of plane-parallel earth-cloud systems. The variables we examined were the optical thickness (τ) and the mode radius of cloud droplets (r_m), defined by the following log-normal cross-section spectrum:

$$\frac{dC}{d\ln r} = C_0 \exp\left[-(\ln r - \ln r_m)^2/(2\sigma^2)\right], \quad (1)$$

where C is the geometric cross section of droplets; r is the particle radius; σ is the log-dispersion of the spectrum. Investigating the first and second moments of several model size spectra of cloud droplets, it is found that σ can be fixed at 0.35 for most problems even including aerosol polydispersions. The following points are clarified as a results of the numerical simulation:

(1) As a first approximation, the cloud optical thickness τ at λ= 0.754 μm can be determined from the reflected radiation at this wavelength. The retrieval is stable, because the cloud reflectivity increases monotonically with increasing optical thickness and the dependence on the droplet size is relatively small.

(2) Using the cloud optical thickness determined in step (1), the cloud droplet mode radius r_m is estimated from an absorbing channel, i.e., 1.645 or 2.160 μm radiation. The optical thickness dependence is small as absorption increases.

(3) Iterating steps (1) and (2) or investigating these steps for several pre-assumed particle radii, we can have an optimum set of τ and r_m. We have developed two methods for the simultaneous retrieval of cloud optical thickness and mode radius, a bispectral method and a multispectral method. The bispectral method uses the two channels of 0.754 and 2.160 μm. This method is hardly affected by the vertical inhomogeneity of the cloud microphysics, but tends to be marred by noise in the absorbing channel. Also, this method can have multiple-solutions of r_m, as demonstrated in Fig. 1. For simplicity we show in Fig. 1 a mode radius dependence of the cloud spherical albedo at λ = 2.16 μm for τ = 8, 16 and 32. Figure 1 shows that the profiles are a peaked function of mode radius with a peak around r_m= 2–3 μm. Thus, for example, a measured reflectance at 2.16 μm, given an optical thickness derived from the 0.754 μm channel, could be produced by one of two possible mode radii. Therefore, it is very important to set a suitable minimum droplet radius for the algorithm. On the other hand, the multispectral method uses all three channels. The optimum value of r_m is determined in this method so as to minimize the following root mean square deviation between the observed and theoretical values:

$$\chi^2 = \sum_{n=2}^{3} \left[\frac{R_n^c(\tau, r_m)}{R_n^m} - 1 \right]^2, \tag{2}$$

where $n = 2$ stands for the second channel (1.645 μm) and $n = 3$ for the third channel (2.160 μm); superscripts c and m stand for theoretical (computed) and measured values, respectively. In the above equation, τ is determined from the first channel (0.754 μm), as in the bispectral method. This method is relatively insensitive to noise in any individual channel and we can have a unique solution for r_m, potentially different from the bispectral method. But this method fails in some case of vertical inhomogeneity. We have adopted both methods for the sake of diagnosing the soundness of the retrieval.

(4) The error involved in the retrieval increases in the backward portion of the scattering. The error in r_m increases with decreasing r_m; the errors in τ and r_m increase in the region $\tau < 6$ or $\tau > 100$.

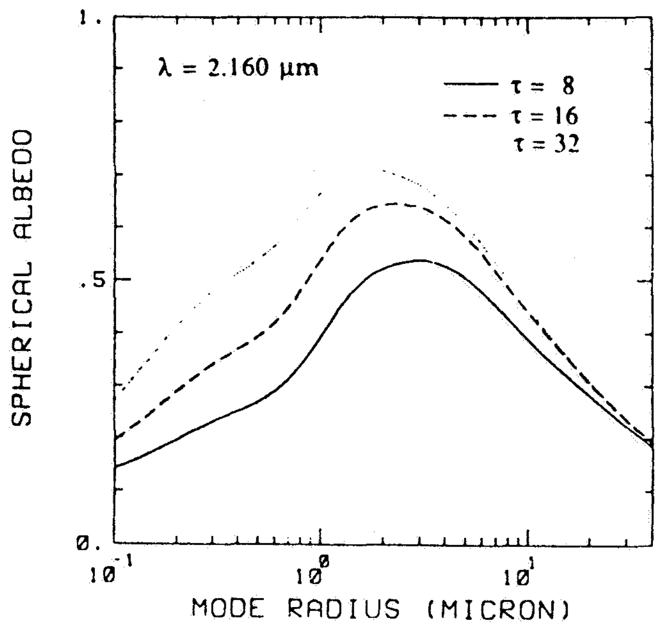

Fig. 1. Spherical albedo of a plane-parallel cloud versus the droplet mode radius at λ= 2.16 μm.

3. Analysis of MCR-data

Since the MCR can produce a 2-D image of the upwelling radiation, we tried to develop a retrieval scheme computationally very efficient. We have generated four tables of bidirectional reflectivity for the scaled cloud optical thickness $\tau^* = (1-g)\tau = 0.4$, 0.8, 1.2 and ∞, where g is the cloud asymmetry factor. Using asymptotic theory for $\tau^* \geq 1.8$ (King, 1987) and computations for $\tau^* < 1.8$, we can interpolate the bidirectional reflectivity with errors less than 2%. Since our intention is to derive effective parameters to describe the radiative characteristics of clouds, we assume homogeneous and plane-parallel stratification for the analysis. According to numerical simulations, τ can be estimated with an error less than 20% and r_m can be estimated at the effective depth of radiation unless the optical thickness and particle radius are too small.

Figure 2 shows contours of the cloud optical thickness derived for the first half of the fourth ER-2-flight line of July 10, 1987 (about 1000 scan lines, 60 km). A photographic print of the original data for this example shows that a band of τ~15 was the edge of a large flat cloud deck spreading ahead of the flight course. The optical thickness varied from 5 to 20 around this edge.

Figure 3 shows the horizontal distributions of τ and r_m along a constant pixel line (solid lines for pixel number 84 and dotted lines for pixel number 252, where the total number of profiles in an active scan is typically 336). Although r_m showed a small monotonic decrease from left to right, the value was remarkably constant with values around 15 μm, in spite of the large change of τ from 5 to 15 around the horizontal distance of 30 km (solid line) and large hole around 40–50 km (dotted line). Although we showed the value of r_m derived by the multispectral method, there was no large difference from the bispectral method except for small optical thickness < 6. For small optical thickness, however, there were some cases when the algorithm selected the smaller branch of the solution depending on the viewing direction, as shown by several steep dips of the mean radius. Since we had a large difference between the results of the multispectral and bispectral methods in this case, there may be large uncertainties in the retrieved value of r_m around these dips (as expected by item (4) in the preceding section). We show the minimized χ^2-value in the multispectral method in the uppermost section of Fig.3. The *rms*-difference between the measured and theoretical values was less than 5%.

4. Concluding remarks

We have installed an efficient retrieval scheme for deriving the cloud optical thickness and droplet mode radius; and we have described the behavior of the retrieval error. Generally the scheme can retrieve the optical thickness and mode radius adequately unless they are too small; the use of the forward scattering region is more sound than the use of the backscattering portion.

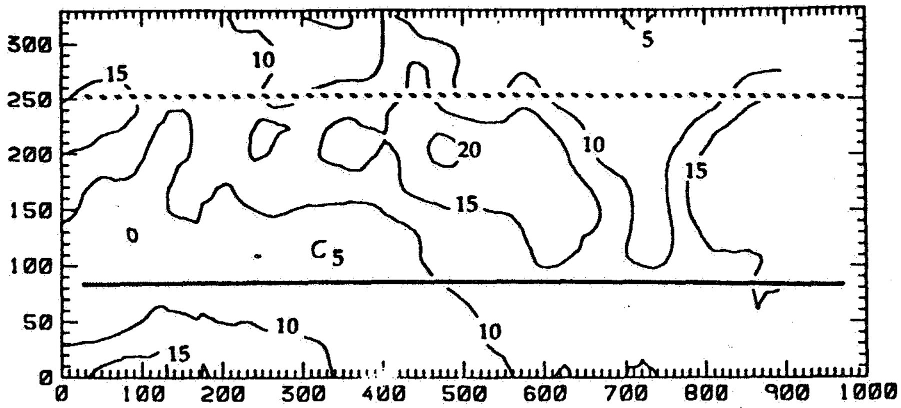

Fig. 2. Cloud optical thickness distribution for the fourth flight line of July 10, 1987. Horizontal and vertical axes are for scan-line and pixel numbers. Bold solid and dotted lines shows the sampling lines for Fig. 3.

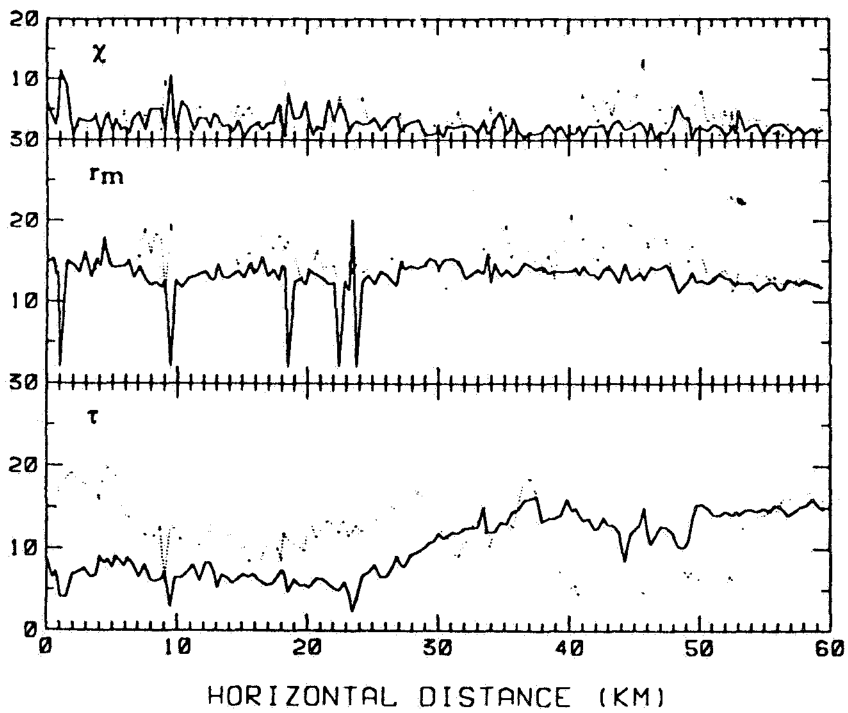

Fig. 3. Cloud optical thickness (τ), droplet mode radius retrieved by the multispectral method (r_m), and χ along the bold solid and dotted lines in Fig. 2.

Applying our method to real data, we have derived the two-dimensional distribution of optical thickness and mode radius for a portion of one of the FIRE marine stratocumulus missions. In this case study, the droplet size showed a more uniform distribution than optical thickness with some correlation between large droplet size and small optical thickness. Although we can find microphysical reasons for these tendencies, we are suspecting that the remotely sensed droplet size may be overestimated. As a future problem, we will compare our results with *in situ* data of the droplet size distribution. Also it will be very important to check several reasons why the droplet radius might be overestimated, e.g., soot contamination, effect of escaping photons from the lateral sides of broken clouds, and so on.

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