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Cloud Optical Parameters as Derived from the Multispectral Cloud Radiometer

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1. Introduction

Simultaneous measurements of the liquid water content and particle size have assumed an important role in cloud physics as they help elucidate the mechanism of cloud particle formation and the mechanism of air mass-mixing in stratus clouds. Such measurements can reveal the modification of cloud air masses by anthropogenic aerosol particles (Coakley et al. 1987, Durkee 1989). Studies of the climatic impact of these modification processes on cloud microphysics seems to be urgent for understanding mechanisms of climate change. GCM simulations can be improved by introducing a parameterization of cloud optical properties in terms of integrated liquid water content (liquid water path) and particle size (Slingo 1989).

Motivated by the above mentioned circumstances, we have been developing remote sensing techniques for simultaneously retrieving the cloud optical thickness and effective particle radius, from which the liquid water path can be inferred. Nakajima and King (1989a) have shown a good agreement between the effective radius derived from *in situ* cloud microphysics observations and that derived from reflected solar radiation measurements, with a slight overestimation occurring in the remote sensing method. Also Durkee (1989) found a good correlation between the *in situ* value of the effective particle radius and the cloud reflectance at 3.7 μm.

In this paper we will present statistical features of the cloud optical thickness (or liquid water path) and effective particle size for marine stratocumulus clouds. These results have been obtained during four days (7, 10, 13 and 16 July 1987) of observations with the Multispectral Cloud Radiometer (ER-2) and Thematic Mapper (Landsat-5) during the First ISCCP Regional Experiment (FIRE).

2. Results

The optical thickness (τ_c) and effective particle radius (r_e) for 7, 10, 13 and 16 July 1987 have been retrieved by analyzing reflected solar radiation mea-

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surements at the 0.754, 1.65 and 2.16 μm channels of the MCR onboard the NASA ER-2 aircraft. The algorithm used to derive these parameters has been described by Nakajima and King (1989b). We have also applied the same method to data obtained from band 2 (0.56μm) and 7 (2.22 μm) of the Landsat-5 Thematic Mapper on July 7 and 16.

The areas used in the present analysis are approximately 30 km × 100 km for the MCR data, and 150 km × 150 km for the Thematic Mapper. *In situ* cloud liquid water content and effective radius were obtained from measurements obtained with the Johnson-Williams (JW) liquid water content meter and three different PMS cloud probes (FSSP, OAP-200X and OAP-200Y) on board the University of Washington C-131A aircraft.

Figure 1 shows comparisons between the remote sensing-derived values of the effective radius and the *in situ* values, where we have partitioned the results into three different cloud optical thickness ranges, *i. e.*, $5 \leq \tau_c < 10$, $10 \leq \tau_c < 15$ and $15 \leq \tau_c < 20$. The remote sensing values have been adjusted to the cloud center where the C-131A was flying (see Nakajima and King 1989b for details), and the data with $\tau < 5$ have been omitted because of the uncertainty in the retrieval for optically thin clouds. From the results presented in this figure we see that for thin clouds ($5 \leq \tau_c < 10$) the remote sensing values are in excellent agreement with the *in situ* values. As the cloud optical thickness increases, however, the remote sensing values become progressively larger than the *in situ* values for $r_e \leq 10$ μm, and vice versa for $r_e > 10$ μm. The former phenomenon is likely related to the so-called cloud absorption anomaly in the near infrared region (NIR), *i. e.*, the cloud looks darker than the theoretical expectation from *in situ* microphysical parameters (*e.g.*, Stephens and Platt, 1987). On the other hand, the latter phenomenon is caused by the drizzle mode particles which can be measured by the PMS-OAP cloud and precipitation probes. The remote sensing values have only a weak sensitivity to these drizzle mode particles which tend to exist relatively low in the clouds.

Figure 2 shows comparisons of the liquid water path (gm^{-2}) estimated from the remote sensing quantities as

$$W_{remote} = 2 r_{center} \tau_c / 3, \tag{1}$$

and by the *in situ* measurements as

$$W_{in\ situ} = w_m \Delta z, \tag{2}$$

where r_{center} is the effective radius derived from remote sensing after adjustment for vertical inhomogeneity (Nakajima and King 1989b), τ_c the remote sensing-derived cloud optical thickness, w_m the measured liquid water content from the JW liquid water content meter, and Δz the cloud geometrical

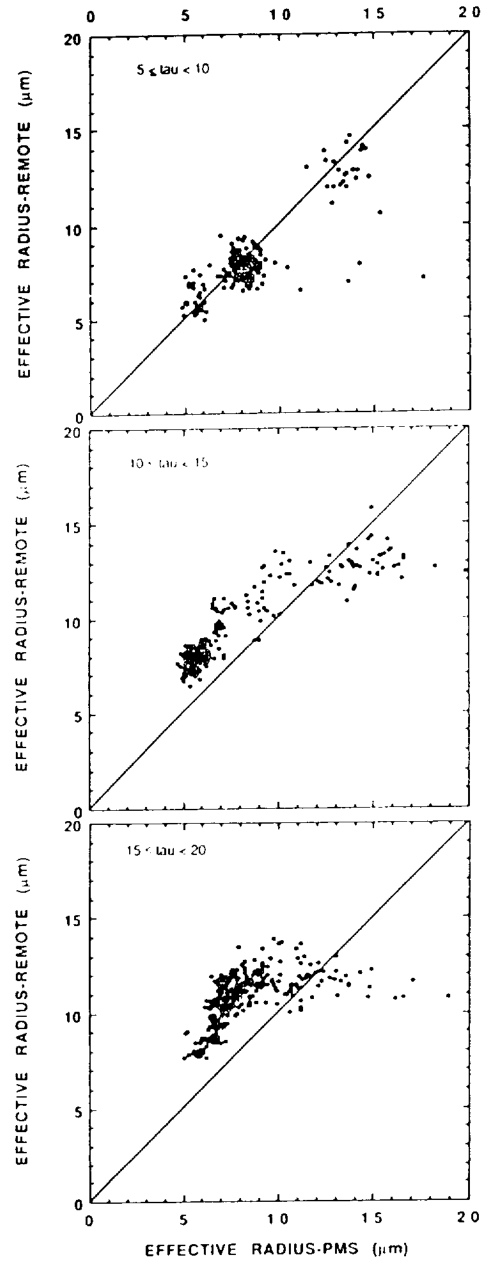

Fig. 1. Scatter diagrams comparing the *in situ* effective radius with the remote sensing effective radius. Three different optical thickness range cases (*i. e.*, $5 \leq \tau_c < 10$, $10 \leq \tau_c < 15$ and $15 \leq \tau_c < 20$) are shown in three separate panels.

thickness. The geometric thickness of the cloud has been estimated as an equivalent thickness which gives the liquid water path obtained by integrating vertical profiles of the liquid water content.

Although there is large uncertainty in the estimation of Δz, we observe a tendency to underestimate the liquid water path retrieved from our remote sensing method by 20% to 40%. From Eq. (1), together with Figs. 1 and 2, we conclude that the remote sensing optical thickness is somewhat *smaller* than

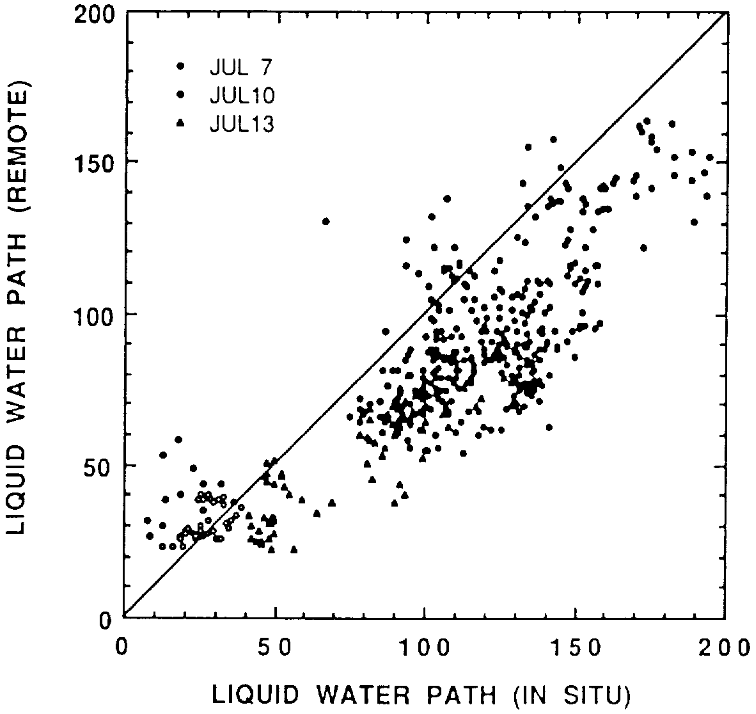

Fig. 2. Comparison of the liquid water paths derived from *in situ* measurements and estimated from remote sensing methods.

the expected value from *in situ* measurements by ~50% for thick clouds with $\tau \approx 20$ and $r_e \sim 8$ μm, roughly corresponding to the case for 10 July 1987. For such thick clouds the channel 1 (λ = 0.754 μm) intensity is mostly sensitive to the optical thickness, with little sensitivity to particle radius, and thus the intensity at λ = 0.754 μm is significantly smaller than the expected value from *in situ* measurements.

Although there is some discrepancy between the *in situ* and remote sensing values of W and r_e, it is worthwhile to examine the correlation between these two quantites, especially given the recent interest in parameterizing the shortwave radiative properties of clouds in terms of these two parameters (Slingo 1989). Figure 3 shows two dimensional histograms of W and r_e for the four days of our observations. The five contour lines for each day show the 10, 30, 50, 70 and 90% occurrence levels. Other than 10 July, the contour lines are confined in a rather small area having the different peaks depending on days. The composite pattern of all contours with different days shows a weak positive correlation between W and r_e. The rough tendency may be expressed as

$$r_e \simeq 0.333\, W^{1/4}. \qquad (3)$$

A similar comparison for *in situ* quantities is shown in Fig. 4. Since we have relatively large particles on 7 July and very large drizzle particles on 10 July,

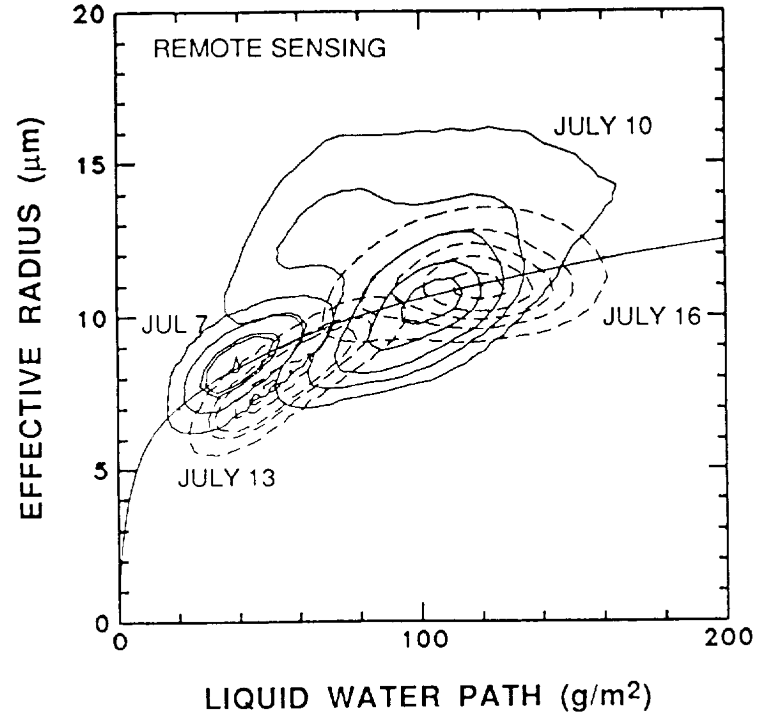

Fig. 3. Joint probability density function for the liquid water path and the effective radius derived from reflected solar radiation measurements. Five contour lines for each day shows 10, 30, 50, 70 and 90 % occurrence levels. The solid continuous line fits the rough tendency of the contours.

the overall pattern is more complicated than that presented in Fig. 3. If we disregard the drizzle particles, the effective radius is relatively insensitive to the liquid water path. The difference in the sensitive altitude within clouds between *in situ* and remote sensing is at least partly responsible for some of the difference in the tendency shown in Figs. 3 and 4.

3. Concluding remarks

As a result of our investigation, we have observed some interesting relationships between the liquid water path and the effective particle radius. We observed a systematic bias in the effective radius derived by our remote sensing method, with the tendency to overestimate the effective radius increasing as the cloud optical thickness increases. Since this can be a good guideline for solving the NIR cloud absorption anomaly problem, we need to compile more data in order to determine whether this is a general tendency for marine stratocumulus clouds. Although we also found some tendency of underestimating the cloud optical thickness from reflection function measurements, we need to be careful about drawing any conclusions because of the large uncertainty in estimating the liquid water path using Eq. (2).

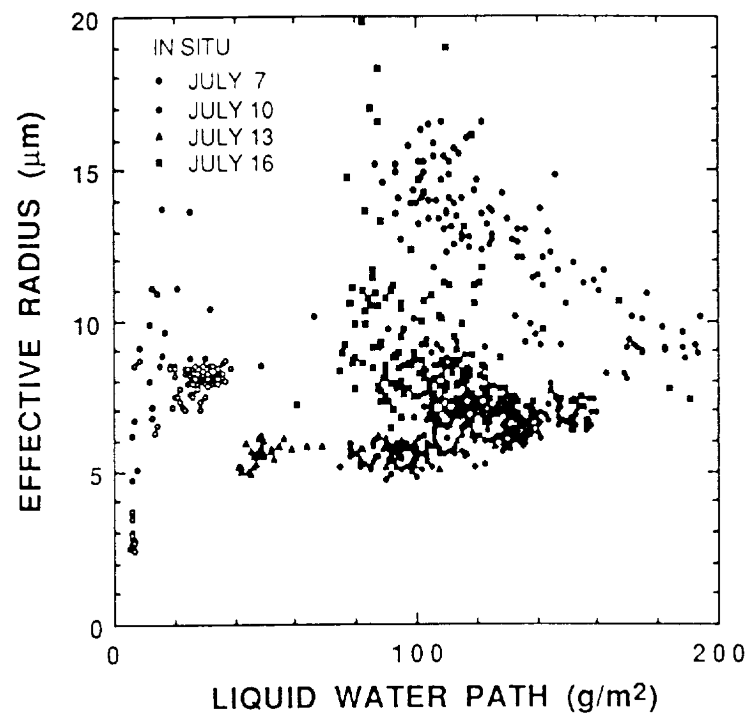

Fig. 4. Comparison of the liquid water path and the effective radius derived from *in situ* measurements.

As for the dependency of the effective radius on liquid water path, we conclude that the effective radius is relatively independent of the liquid water path with some weak positive correlation for clouds lacking significant drizzle development. For reflected solar radiation the existence of drizzle particle is not important, whereas the transmitted solar radiation is expected to have some dependence on drizzle mode particles. Consequently we need to use a vertically inhomogeneous cloud model with a two mode size distribution to produce a consistent cloud radiative model valid for both reflected and transmitted radiation.

Since the above results depend strongly on the calibration of the radiometers and *in situ* instruments, more ground (aircraft) truth will be required to further extend the results shown here.

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