N90-28238

Spectral Absorption of Marine Stratocumulus Clouds Derived from *In Situ* Cloud Radiation Measurements

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1. Introduction

A multiwavelength scanning radiometer has been used to measure the angular distribution of scattered radiation deep within a cloud layer at discrete wavelengths between 0.5 and 2.3 µm. The relative angular distribution of the intensity field at each wavelength is used to determine the similarity parameter, and hence single scattering albedo, of the cloud at that wavelength using the diffusion domain method. In addition to the spectral similarity parameter, the analysis provides a good estimate of the optical thickness of the cloud *beneath* the aircraft. In addition to the radiation measurements, we obtained microphysical and thermodynamic measurements from which the expected similarity parameter spectrum was calculated using accepted values of the refractive index of liquid water and the transmission function of water vapor.

In this paper, we present an analysis of the results obtained for a 50 km section of clean marine stratocumulus clouds on 10 July 1987. These observations were obtained off the coast of California from the University of Washington Convair C-131A aircraft as part of the First ISCCP Regional Experiment (FIRE). We will present a comparison of the experimentally-derived similarity parameter spectrum with that expected theoretically from the cloud droplet size distribution measured simultaneously from the aircraft. The measurements and theory are in very close agreement for this case of clean maritime clouds.

2. Results from observations on 10 July 1987

On 10 July 1987 the C-131A flew a tightly coordinated mission with the ER-2 aircraft, consisting of continually flying legs of 145 km in length. The C-131A was primarily making cloud radiation and cloud microphysics measurements deep within the cloud layer, whereas the ER-2 was flying well above the clouds. Figure 1 illustrates the zenith and nadir intensities as a function of distance (time) for measurements obtained inside clouds near the central portion of one of these flight lines. These data, corresponding to ob-

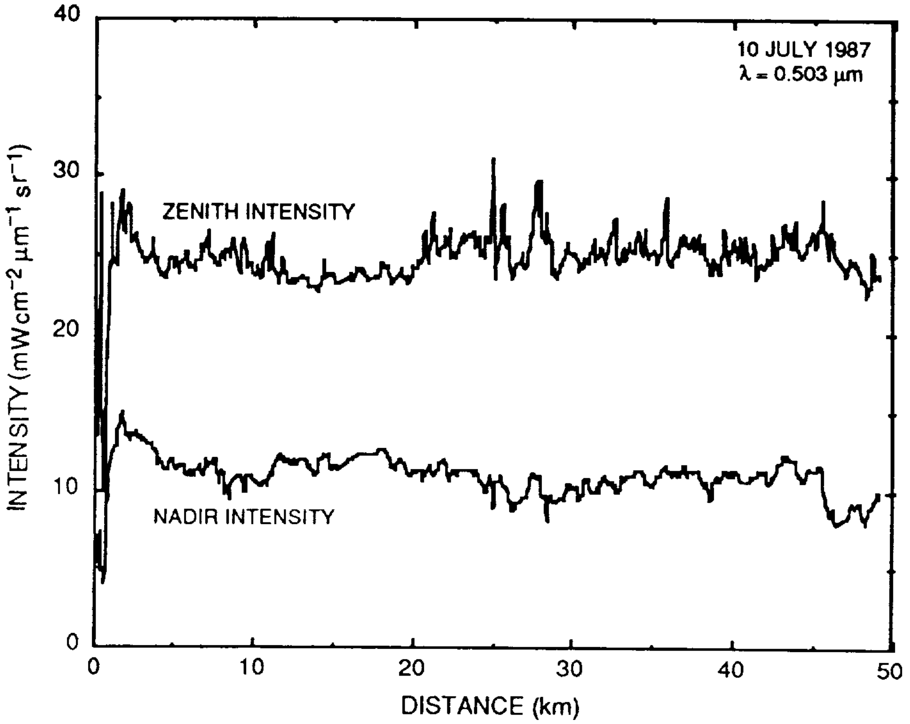

Fig. 1. Zenith and nadir intensities as a function of distance along the flight track for measurements obtained inside the clouds between 9:41 and 9:51 PDT. These measurements were obtained at a wavelength $\lambda = 0.503$ μm.

servations obtained with the cloud absorption radiometer (King et al. 1986) at $\lambda = 0.503$ μm, show that the zenith and nadir intensities were quite uniform within these clouds. A careful examination of Fig. 1 suggests that the data near the start of the flight line are too optically thin to have a diffusion domain, as evidenced by very low zenith and nadir intensity measurements. Furthermore, the measurements near 24.9 and 28.0 km, though probably in a cloud of sufficient optical thickness to have a diffusion domain, were obtained too near the cloud top, so the zenith measurements were contaminated by directly transmitted solar radiation.

The scaled optical thickness between the aircraft flight level and the base of the clouds was derived by applying the diffusion domain method to all scan lines of Fig. 1 that satisfied the diffusion domain criteria (see King et al. 1989 for details). Figure 2 illustrates the optical thickness $\tau_c - \tau$ as a function of distance, where we converted scaled optical thickness to optical thickness using the asymmetry factor $g = 0.8579$ applicable to this wavelength ($\lambda = 0.503$ μm) and derived for the measured cloud droplet size distribution. Of the 1000 scan lines presented in Fig. 1, 611 passed the restrictive selection criteria described in King et al. (1989). Among those measurements excluded from our analysis were the optically thin scans at the beginning of the time series and the measurements that were contaminated by the sun (at distances of 24.9 and 28.0 km). As expected, the measurements between 11.5 and 19.4 km that had a

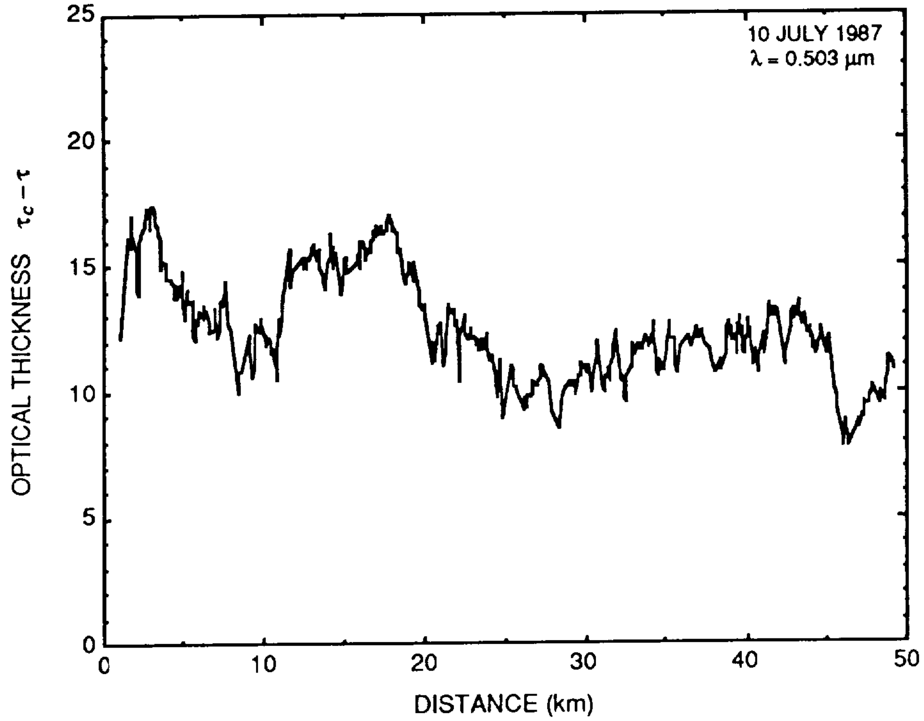

Fig. 2. Optical thickness beneath the aircraft for all measurements of Fig. 7 that satisfy the diffusion domain criteria.

relatively low zenith intensity and relatively high nadir intensity correspond to a region of large optical thickness beneath the aircraft.

Given the surface reflectivity and optical thickness (or scaled optical thickness) of an individual scan at a specified wavelength, the intensity ratio $I(\tau, -1)/\ I(\tau, 1)$ is reduced solely to a function of similarity parameter s. Utilizing formulas summarized in King et al. (1989), we were thus able to calculate the intensity ratio as a function of similarity parameter and match this functional relationship with the measured intensity ratio to derive a value of the similarity parameter for a given measurement and wavelength.

Figure 3 illustrates the similarity parameter as a function of distance for four wavelengths of the CAR determined in this manner. The similarity parameter s, defined as $s = [(1 - \omega_0)/(1 - \omega_0 g)]^{1/2}$, is a function of the asymmetry factor g and the single scattering albedo ω_0. The tendency for the similarity parameter to decrease with increasing distance, especially noticeable at 1.64 and 2.20 μm, is due to a modest decrease in the effective radius of the cloud droplets over this distance and not to a decrease in the absorption content of the cloud droplets themselves. Due to the use of a filter wheel to measure the intensity field in channels 8-13, diffusion domain measurements were obtained in this time interval for between 71 and 87 scans, depending on filter position, in contrast to 611 for the first seven, simultaneously sampled, channels.

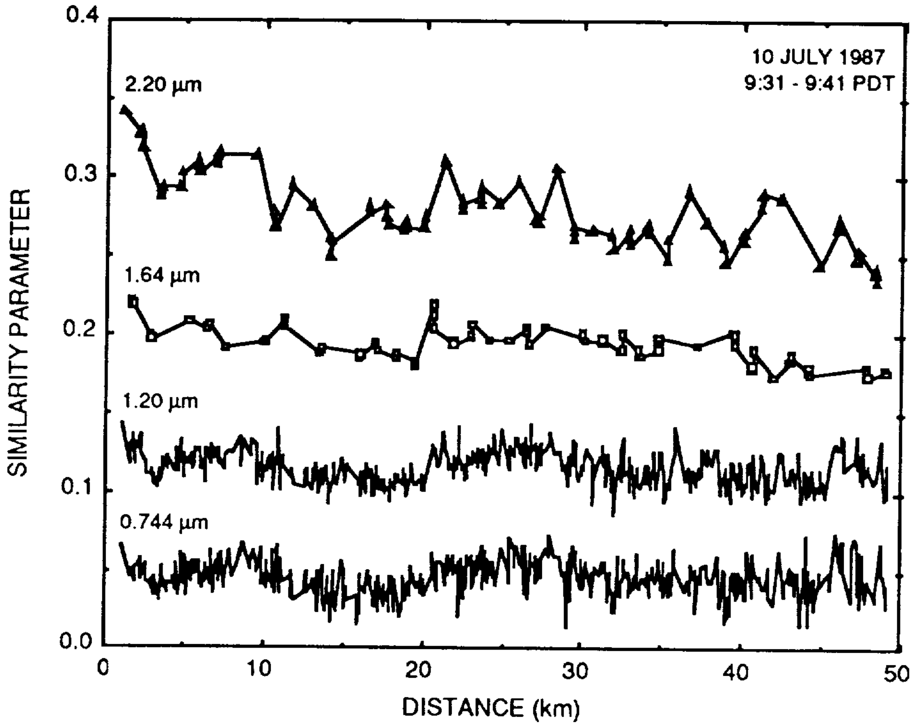

Fig. 3. Similarity parameter as a function of distance for four wavelengths of the cloud absorption radiometer.

Figure 4 illustrates the mean and standard deviation of the spectral similarity parameter for all thirteen channels of the CAR obtained from aircraft measurements on 10 July 1987. Although the conversion from s to ω_0 is not unique, due to the moderate spectral variation of g, we have provided a single scattering albedo scale in this figure as a matter of convenience. This scale, shown on the right-hand side of Fig. 4, is strictly applicable at λ = 0.754 µm. Based on profile ascents and descents following these measurements, the stratocumulus cloud layer was determined to be 440 m thick with a cloud base at 490 m.

In addition to the experimental results obtained using the CAR, Fig. 4 illustrates calculations of the similarity parameter as a function of wavelength for a cloud composed of water droplets only (solid curve) and droplets plus saturated vapor at 10.3°C (dashed curve). The water droplet computations were based on a combination of Mie theory and complex angular momentum theory (Nussenzveig and Wiscombe 1980) applied to the measured cloud droplet size distribution. The water vapor computations, on the other hand, were based on assuming the cloud to be composed of saturated vapor and applying the necessary pressure and temperature scaling to obtain an equivalent absorber amount (w = 0.41 g cm^{-2}). The water vapor transmission functions were then computed for this cloud layer at a resolution of 20 cm^{-1} using LOWTRAN 5 (Kneizys et al. 1980). The absorption optical depths thus ob-

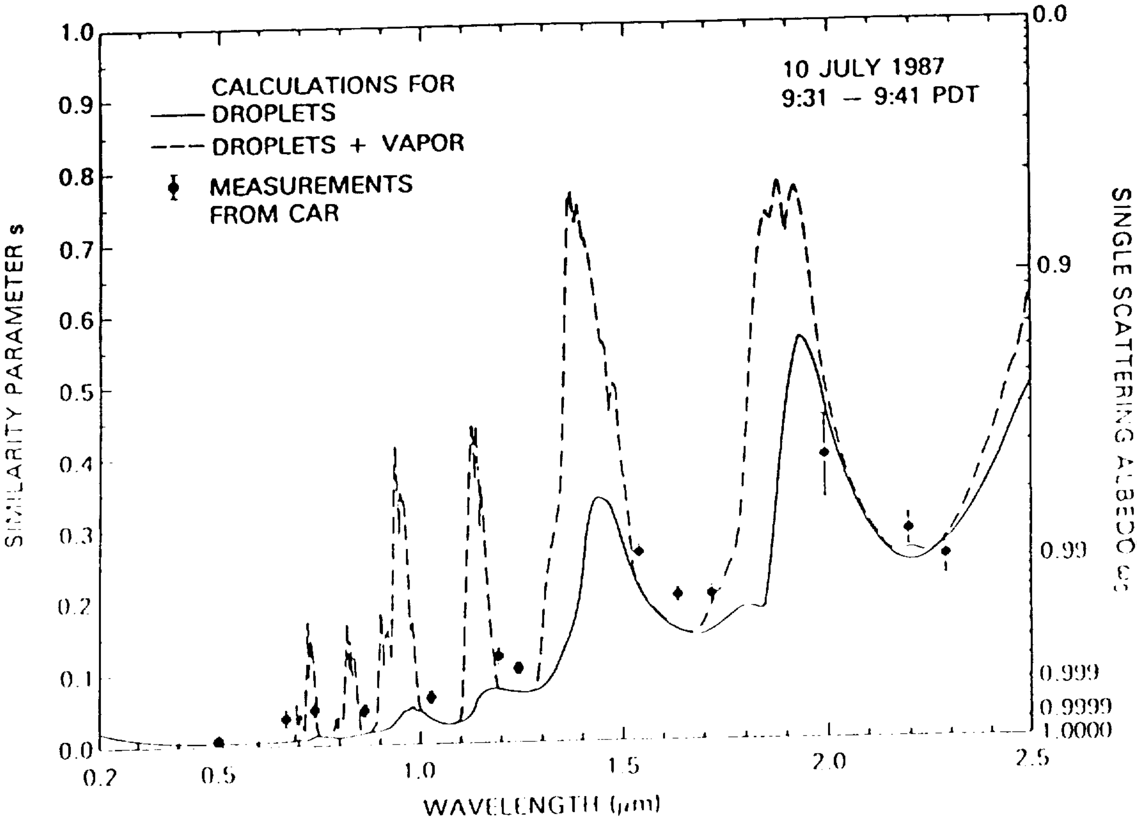

Fig. 4. Calculations of the similarity parameter as a function of wavelength for water droplets alone (solid line) and drops plus vapor (dashed line) for the cloud droplet size distribution and water vapor conditions of the marine stratocumulus cloud of 10 July 1987. The single scattering albedo scale is valid at λ = 0.754 μm, where the cloud asymmetry factor g = 0.848. The measurements derived from the cloud absorption radiometer (solid circles with error bars) are averages of the similarity parameter derived by applying the diffusion domain method to the 50 km section of this cloud.

tained were combined with the corresponding optical properties for cloud droplets, where we further assumed that the total cloud optical thickness τ_c = 16 at a wavelength of 0.754 μm.

The very close agreement between the measurements and theory shows that, *in this case,* the absorption of solar radiation by the clouds can be accounted for largely by the droplets and that the large drops (drizzle) did not produce significant "anomalous absorption." Based on these results we are forced to conclude that "anomalous absorption," as discussed by Twomey (1976), Davies et al. (1984) and Stephens and Tsay (1989), was not significant in the marine stratocumulus clouds that we sampled on 10 July 1987.

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