Observations of Regional and Local Variability in the Optical Properties of Maritime Clouds

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Introduction

White and Fairall (1995) calculated the optical properties of the marine boundary layer (MBL) clouds observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) and compared their results with the results obtained by Fairall et al. (1990) for the MBL clouds observed during the First International Satellite Climatology Program (ISSCP) Regional Experiment (FIRE). They found a factor of two difference in the optical depth versus liquid water relationship that applies to the clouds observed in each case. In the present study, we present evidence to support this difference. We also investigate the local variability exhibited in the ASTEX optical properties using measurements of the boundary layer aerosol concentration.

Optical Properties Algorithm

We used solar irradiance measurements from a pyranometer to calculate the transmission coefficient, Tr, as a function of solar zenith angle, θ. We then used the plane-parallel radiative transfer parameterization of Stephens et al. (1984) to obtain values of albedo, Re, and optical depth, τ. Details are given by Fairall et al. (1990). A laser ceilometer provided measurements of the overhead cloud fraction, *f*. Microwave radiometric data were used to calculate the liquid water path (LWP).

The plane-parallel assumption is reasonable for the FIRE transmission data since $f \simeq 1$ was observed much of the time. However, the bulk of the data collected during ASTEX pertains to broken clouds. To complicate matters further, the values of *f* and LWP were measured using upward-looking, narrow field-of-view instruments (i.e., the ceilometer and radiometer), whereas the values of Tr were based on pyranometer measurements that are hemispheric. Therefore, we modified the ASTEX transmission data using the algorithm of Chertock et al. (1993) [their Equations (7) and (8)]. The algorithm accounts for cloud fraction (i.e., $f \neq 1$) and the zenith angle dependence of cloud fraction, $f(\theta)$.

We investigated the relationship between optical depth and liquid water because this relationship is often used to parameterize the radiative effects of clouds in large-scale models. For example, Stephens (1978) has shown that $\tau = (3/2)\mathrm{LWP}/(\rho_w, r_e)$, where r_e is the effective radius and ρ_w is the water density. Alternatively, Fairall et al. (1990) have shown that for a lognormal droplet size distribution and a linear profile of liquid water $\tau \propto N^{1/3}$, where N is the cloud droplet number concentration.

Results

Figure 1 shows τ versus LWP for ASTEX and FIRE. We used diurnal averages for the ASTEX data to compensate for the sampling inadequacies mentioned above. The lower bounds used for the plot are consistent with the approximate lower limits on the accuracy of our values for τ and LWP. White and Fairall (1995) placed more confidence in the ASTEX optical properties obtained from measurements taken near solar noon because then the instruments are matched to the upward looking case. If we consider only these points in Figure 1, we can place a line through the ASTEX data that lies roughly a factor of two beneath the FIRE line.

A possible explanation for this difference would be that r_e and N were different for the two cases. For example, FIRE took place much closer to a densely populated coastline than ASTEX. Because continental aerosols are generally smaller than maritime aerosols, we might expect FIRE to have a

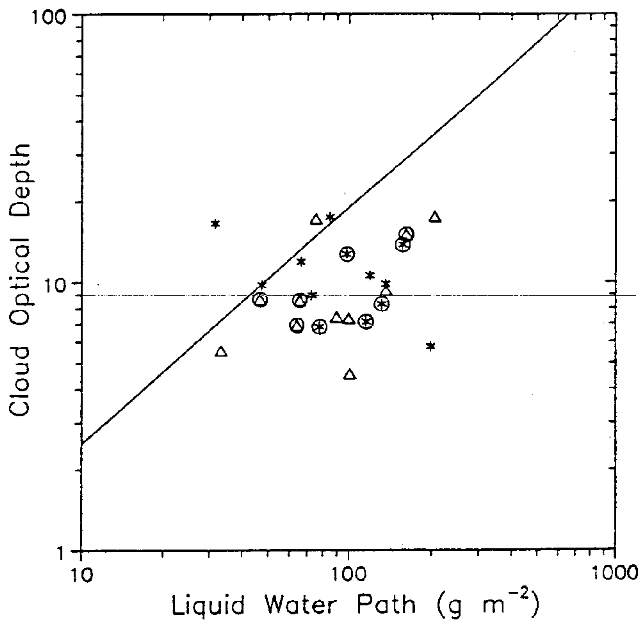

Figure 1. Cloud optical depth versus liquid water path. The symbols plot diurnal averages derived from ASTEX ship data (asterisks) and ASTEX island data (triangles). The line shows the relationship for FIRE (Fairall et al. 1990). The circles classify data derived from measurements taken near solar noon ($\theta \leq 15°$).

higher mean concentration of the smaller aerosols, which would lead to a smaller mean r_e and a larger optical depth for a given LWP. Satellite observations do indicate a higher cloud albedo near the California coast (Minnis et al. 1992), consistent with greater concentration of cloud condensation nuclei (CCN) associated with continental aerosol sources.

There is additional evidence suggesting the mean r_e was different for FIRE and ASTEX. Han et al. (1995) have computed cloud droplet sizes for FIRE using the ISCCP data analysis. Their results show r_e = 8 µm for FIRE. This is an estimate of the r_e near cloud top. Frisch et al (1995) show that profiles of modal radius, r_m, can be retrieved from vertical profiles of radar reflectivity and microwave radiometer measurements of the LWP by assuming a cloud droplet distribution shape and characteristic width. They retrieved r_m = 8-12 µm near cloud top during ASTEX. By taking the ratio of the third to the second moment of their assumed lognormal distribution, it can be shown that $r_e = 1.36\ r_m$. The observed values of r_m then translate into values of r_e ranging from 11-16 µm, which is consistent with a factor-of-two difference in optical depth.

We investigated the impact of aerosols on the optical depth of the ASTEX clouds using shipboard measurements of condensation nuclei (CN). Here, we must make the assumption that the particle concentration measured at the surface is directly proportional to the number of activated CCN. Figure 2 shows 10-min values of ASTEX optical depth data plotted for two ranges of aerosol concentration. Although there is a significant amount of scatter, most of the ASTEX data with "low" CN concentrations (i.e., less than 200 cm^{-3}) lie below the FIRE line, while much of the ASTEX data with "high" CN concentrations (i.e., greater than 800 cm^{-3}) lie above the FIRE line. The low CN concentration data have an average concentration of 131 cm^{-3} and on average lie a factor of 0.7 below the FIRE line. The high CN concentration data have an average concentration of 1128 cm^{-3} and, on average, lie a factor of 1.4 above the FIRE line. If we assume $\tau \propto N^{1/3}$, then the average ratio of aerosol concentrations would change the optical depth by a factor of $(1128/131)^{1/3} = 2.0$. This value agrees with the observed change in optical depth (i.e., 1.4/0.7 = 2.0)

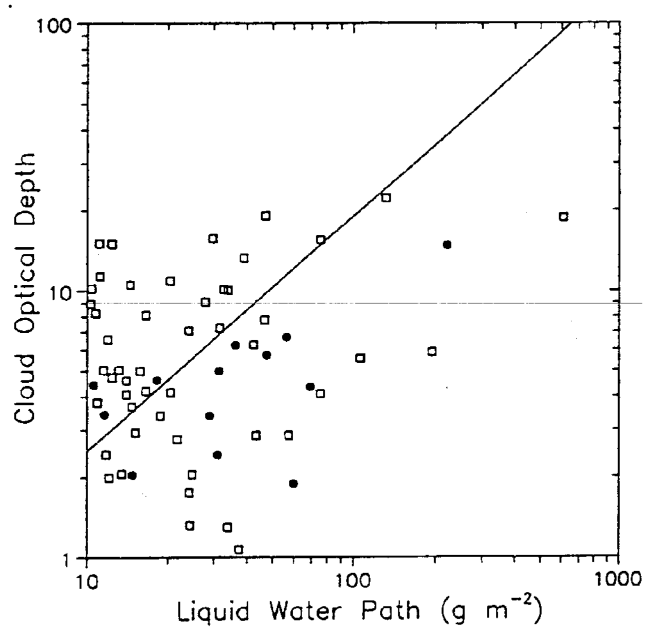

Figure 2. Cloud optical depth versus liquid water path. The ASTEX 10-min, ship-based data are plotted for instances of condensation nuclei concentration greater than 800 cm^{-3} (squares) and less than 200 cm^{-3} (solid circles). The line is for the FIRE relationship (Fairall et al. 1990).

Summary

Using cloud optical properties deduced from surface-based measurements of the transmission coefficient and a radiative transfer model, we investigated the relationship between optical depth and liquid water for ASTEX and compared our result with the result obtained for FIRE. Our comparison indicated the ASTEX clouds formed in significantly cleaner air masses on average than the FIRE clouds. Independent droplet-size information deduced from radar and satellite observations also suggest that the ASTEX cloud droplets were on average a factor-of-two larger than the FIRE cloud droplets. An investigation into the impact of boundary layer aerosol concentration on cloud optical depth implied a factor-of-two change in the τ versus LWP relationship associated with a factor-of-eight variation in CN concentration observed just within the ASTEX data set, a direct demonstration of the so-called Twomey effect.

Acknowledgments

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