Characteristics of Small Tropical Cumulus Clouds and Their Radiative Impact

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Introduction

Clouds have a profound influence on the climate system via radiative effects, latent heating, and precipitation, as well as a strong impact on satellite remote sensing. Small cumulus clouds present an especially vexing problem. They are difficult to measure and model, and their inhomogeneity confounds efforts at simple parameterization. Cloud sizes are important to radiative fluxes (Kite 1987) and entrainment/detrainment, but they are seldom modeled realistically. Studies have shown that size distributions exhibit easily described functional forms. For example, Cahalan and Joseph (1989) and Kuo et al. (1993) found a dual power law distribution in Landsat-derived cloud fields. Others (e.g., Wielicki and Welch 1986) have found exponential distributions. Clouds generally have highly irregular shapes. These may be described with an area-perimeter relation and a characteristic fractal dimension (e.g., Lovejoy 1982). Cloud spatial distributions are important for radiative fluxes, both in the shortwave (Aida 1977) and in the infrared (Killen and Ellingson 1994), and they may reflect fundamental convection mechanisms (e.g., Randall and Huffman 1980, and Mapes 1993). Some studies have shown cumulus cloud fields to be regular (Ramirez and Bras 1990), while others have shown them to be clustered (Zhu et al. 1992). Tropical clouds provide a great deal of energy to the atmosphere via latent heating, and their precipitation is important to hydrology and ocean surface buoyancy. It is unclear, however, what scales are required for clouds to form precipitation. To account for their effects on radiative fluxes, climate models often parameterize clouds in terms of average cloud fraction and liquid water content. Cloud fraction is, in turn, frequently based upon relative humidity thresholds (Kiehl 1992), although it is uncertain how justified this assumption is.

This study investigated the characteristics of small tropical cumulus clouds and their impact on their environment. The goal was to uncover useful information with application to radiative transfer simulation, large-scale modeling, and remote sensing.

Data Description

This study used a wide variety of data sets to examine the characteristics of tropical boundary layer cumulus clouds. High-resolution MODIS(a) Airborne Simulator (MAS) data and space shuttle photographs provided cloud field statistics for the investigation of cloud structural and spatial parameters. Aircraft underflights provided additional cloud size information, gave an indication of required cloud scales for precipitation, and measured the clouds' shortwave radiative forcing. Soundings from ships supplied vertical profiles of relevant parameters. Shipboard lidar and soundings probed for correlations among relative humidity, cloud fraction, and cloud base. Except for the space shuttle photographs, the data were obtained during the Tropical Ocean Global Atmosphere-Coupled Ocean/Atmosphere Response Experiment (TOGA COARE) in late 1992 and early 1993 in the tropical western Pacific and during the Central Equatorial Pacific Experiment (CEPEX) in early 1993.

Cloud Morphology

Data from the MAS, collected during 5 days and 22 flight legs from the National Aeronautics and Space Administration's (NASA) ER-2 aircraft, and five photographs from the space shuttle provided detailed 2-D cloud field statistics. A joint infrared-visible threshold detected the clouds in the MAS images, while a subjective visible reflectance threshold detected clouds in the shuttle photographs. Several statistical analyses were applied to the cloud fields thus derived.

Cloud size distributions were best modeled by a double power law of the form $n(D) = aD^{-b}$, with a clear break diameter between the two regimes. The larger clouds had a larger exponent (b) than the smaller clouds (Figure 1a). The area-perimeter relation $P \sim \mathrm{sqrt}(A)^{FD}$ showed the same break diameter (Figure 1b). The larger clouds had a larger fractal dimension (FD) than the smaller clouds, meaning they had

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(a) Moderate Resolution Imaging Spectroradiometer

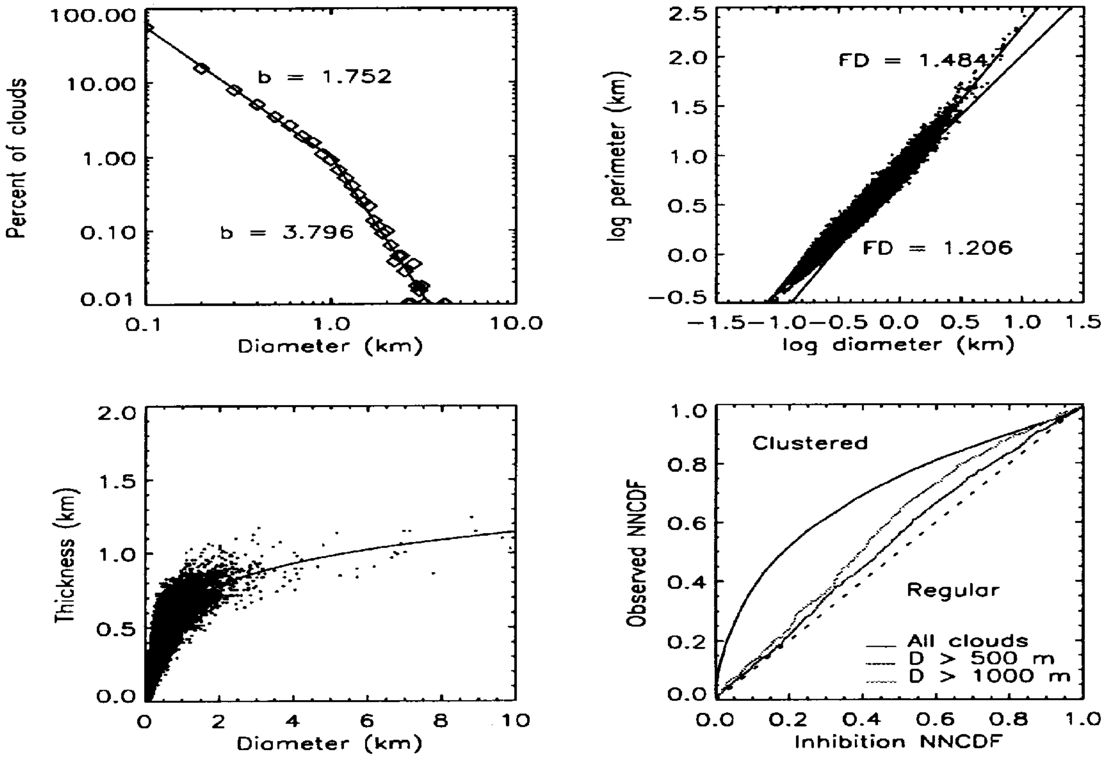

Figure 1. Results from field of nearly 40,000 clouds in ER-2 MAS data from 11 March 1993, showing (a) size distributions, (b) area-perimeter relation, (c) thicknesses, and (d) nearest neighbor common data format (CDF) comparison.

longer, more ragged perimeters. Plots of cloud thickness vs. diameter (Figure 1c) were also best fit by a double power law, with fractional exponents, and they also showed a clear break diameter. All of these suggest that there may be a fundamental mechanism separating cloud scales, such as the maximum size of individual convective elements. Cloud spatial distributions showed clear signs of clustering at all scales (Figure 1d), which supports the idea that there is some mechanism favoring the growth of cumulus clouds in groups.

Precipitation

Time series data from 9 days and 30 flight legs from the National Center for Atmospheric Research (NCAR) Electra aircraft were used to determine the required scales for cumulus precipitation. Temporarily low values of downwelling shortwave radiation indicated clouds in the time series. Taken together, these low periods provided a rough cloud fraction and cloud size distribution. Rainwater detected concurrently in the 2D-P probe data showed which clouds were precipitating. For the full data set, precipitating clouds ranged in size from 1100 m to 8600 m (Figure 2).

About 40% of the clouds larger then 3000 m were found to precipitate. Some precipitating clouds showed only light rain, while others, such as the 8600-m cloud, showed heavier sustained rain. There are great difficulties in accurately inferring 2-D field statistics from 1-D data, and this study did not address these issues in great detail. Also, cloud shapes tend to be highly irregular, so these results are, at best, a rough estimate. However, it seems safe to conclude that only the larger, and thus deeper, boundary layer cumuli possess the necessary conditions to foster the formation of precipitation.

Cloud Fraction/Relative Humidity

Models typically parameterize average cloud fraction using relative humidity. A joint analysis of ceilometer and sounding data from the R/V *Moana Wave* tested this assumption. During the 53 hours with low broken clouds and a released sounding, ceilometer cloud fraction and median cloud base were compared with 4 relative humidity values, both at levels and layer-averaged. These humidity values were also compared with the corresponding values for the

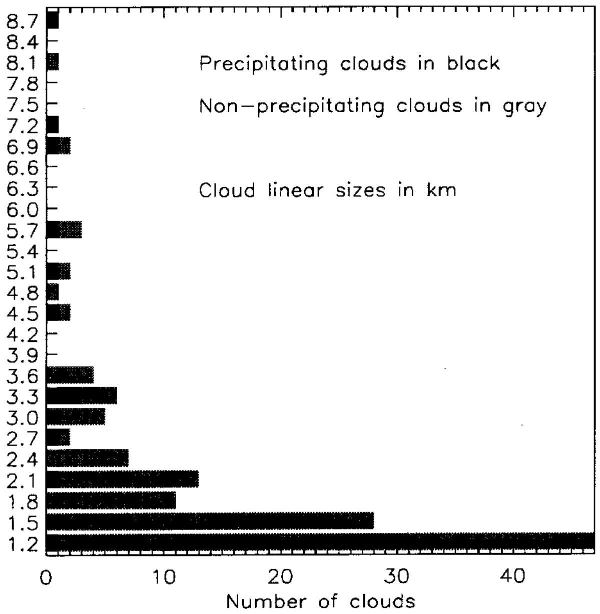

Figure 2. Precipitating and non-precipitating clouds from TOGA COARE and CEPEX Electra time series.

46 hours with clear skies. There was essentially no correlation between cloud fraction and humidity. Not surprisingly, there was a negative correlation between cloud base and humidity. Also, the average humidity values varied by less than 1°C between the cloudy and clear cases, well within the standard deviations. These results suggest that there may be no straightforward way to parameterize cloud fraction by relating it to or thresholding it from standard thermodynamic variables, such as relative humidity.

Shortwave Forcing

Time series of downwelling shortwave radiation data from 9 days and 28 flight legs from the NCAR Electra aircraft were used to examine the magnitude of shortwave forcing from small cumulus clouds. The data were corrected for aircraft pitch and roll, and then a multi-step scheme (Long 1996) picked out the most likely clear points. A fitted function of cos(SZA) estimated the unforced shortwave, and this was compared with the data values to obtain the shortwave forcing. This was normalized to the noon value and averaged for each leg. Finally, the cloudy points were determined and the flight leg cloud fraction computed.

Not surprisingly, greater cloud fraction led to greater shortwave forcing. A plot of these two quantities (Figure 3) was reasonably well fit by a quadratic, especially when data from the two field missions were considered separately. Flight legs from TOGA COARE tended to have greater shortwave forcing for a given cloud fraction than those from CEPEX. This may indicate a real geographic difference, as TOGA COARE took place in a warmer, moister region then CEPEX. It is often said that for accurate climate modeling, radiative fluxes must be known to within 10 W/m^2. In this Electra data, even for very low cloud fraction, the shortwave forcing produced by small cumulus clouds almost always exceeded this arbitrary threshold.

Conclusion

The morphology of the observed cloud fields—size distributions, fractal dimensions, and thicknesses—exhibited a clear break in scale invariance and could all be modeled with simple functional forms. Spatially, these cloud fields were clustered at all scales. Only the larger cumuli appeared to precipitate. Relative humidity did not appear to be correlated with cloud fraction, nor did it vary appreciably between clear skies and those with small cumulus. Shortwave radiative forcing was never negligible and was greater in the TOGA COARE region. These factors are relevant to radiative transfer, satellite remote sensing, and large-scale modeling. More work is required to determine the importance and exact nature of these effects.

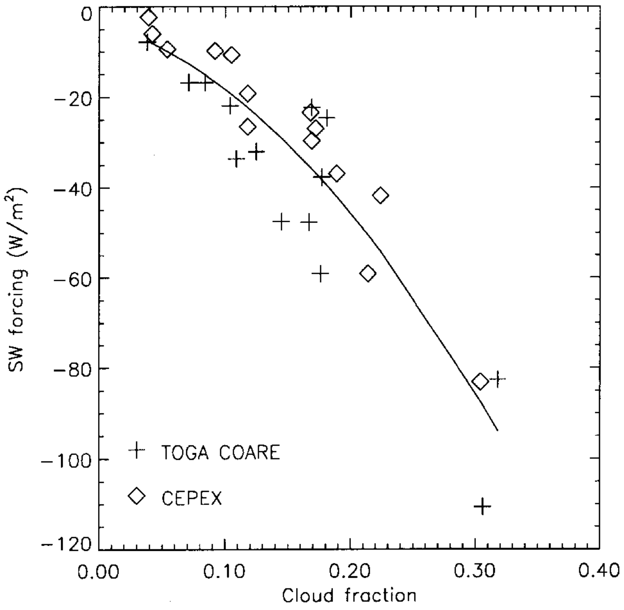

Figure 3. Shortwave forcing vs. cloud fraction in TOGA COARE and CEPEX Electra time series.

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