Dependence of Cumulus Anvil Radiative Properties on Environmental Conditions in the Tropical West Pacific

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Introduction

Climate model simulations (Del Genio et al. 1996; Yao and Del Genio 1999) suggest that changes in the cloud cover and optical thickness of areally extensive tropical cumulus anvils are a controlling factor for climate sensitivity. Parameterizing the optical properties of these clouds is difficult because of the absence of fundamental physical constraints on the cloud cover and because of the dependence of anvil microphysical characteristics on condensate formation and transport by cloud-scale and mesoscale motions that are not resolved by climate general circulation models (GCMs). The eventual deployment of the Millimeter Cloud Radar at the Tropical Western Pacific (TWP) Atmospheric Radiation Measurement (ARM) sites will permit long-term statistics of cumulus anvil microphysical and radiative properties to be accumulated. For now, though, existing satellite and field program data sets can be used to provide some observational constraints for model development and validation.

We apply the convective cluster identification and tracking algorithm of Machado and Rossow (cf. Machado et al. 1998) to the International Satellite Cloud Climatology Program (ISCCP) DX data set for the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA/COARE) region during its intensive observation period (IOP) during November 1992 through February 1993. This algorithm defines a convective cluster as a contiguous area of pixels with infrared (IR) brightness temperature < 245 K that contains at least one embedded pixel (the convective core) with T_{IR} < 218 K at some time during its life cycle. The effective radius R of clusters is defined as the radius of a circle with the same area. The anvil is defined as all pixels within this region with visible optical thickness τ > 9.38, and the mean anvil optical thickness and cloud top pressure are averaged over this area and over the life cycle to characterize the radiative properties of the cluster. About 9% of the clusters exist only at night and their optical thicknesses cannot be estimated; these are excluded from the analysis. A total of 448 clusters of size R > 100 km are observed during the IOP. Although some large clusters are short-lived, in general, the larger objects have longer lifetimes. Small clusters are distributed randomly in time and are therefore independent of the larger-scale forcing. Larger clusters, however, exhibit a clear preference for the disturbed periods preceding the onset of westerly wind bursts and are definitely suppressed at the times of peak westerly winds.

It might be expected that the largest clusters are also the optically thickest, but the distribution is more complex than this (Figure 1): small clusters span the entire range of optical thickness, while large clusters have intermediate τ. It therefore appears that different physics controls the different cluster radiative properties. One such factor might be convective strength. 85 GHz brightness temperatures from aircraft penetrations of nine of the clusters (cf. McGaughey et al. 1996) show that optically thicker clusters usually have greater brightness temperature depression, indicative of increased scattering by large ice particles and hence stronger vertical motion. The thickest/coldest cluster sampled (February 1, 1993) was associated with extensive lightning discharges and large (30 dBZ) radar reflectivity in the mixed phase region (cf. Petersen et al. 1996), further evidence of strong updrafts, while two of the warmer/thinner clusters sampled occurred during a period of suppressed lightning.

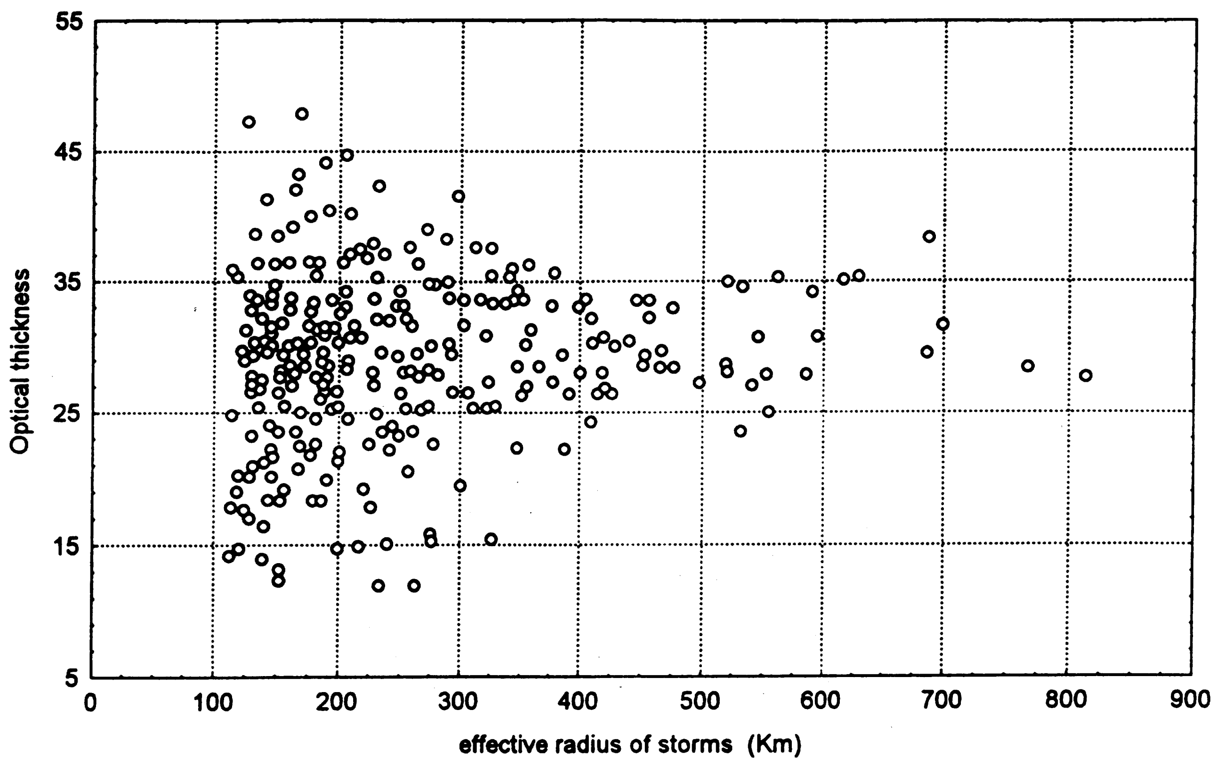

Figure 1. Life cycle mean anvil visible optical thickness vs. cluster size for all convective clusters of size > 100 km during the TOGA/COARE IOP detected with the Machado and Rossow algorithm.

Based on the features of the τ-R distribution, we define three subsets of clusters with similar properties: Large clusters (R > 500 km), small/optically thick clusters (R < 200 km, τ > 36), and small/optically thin clusters (R < 200 km, τ < 21). For all clusters in a given type, we form composites of pre-storm environmental conditions. To do this, we take the dynamic and thermodynamic structure information from the Lin and Johnson (1996) 1° x 1°, 6-hourly objective analysis for the nearest observation time before cluster initiation. This enables us to diagnose the pre-existing large-scale conditions that give rise to a given type of cluster and avoid the ambiguity of the effects of the convection itself on the atmospheric vertical structure. We find that large clusters (Convective Available Potential Energy [CAPE] = 3008 J/kg) have more buoyant rising parcels (defined for undilute pseudo-adiabatic ascent from 1000 mb) than small clusters. Small/thick clusters are marginally more buoyant than small/thin clusters in the upper troposphere but less buoyant in the lower troposphere (CAPE = 2732 and 2642 J/kg for the two cluster types, respectively). R and τ are uncorrelated with sea surface temperature (SST), offering no support for a thermostat-type control of cloud radiative properties. Thus, although updraft strength is positively correlated with buoyancy in a variety of data sets, the thermal structure alone does not seem sufficient to explain the optical thickness variation of small clusters. The relative humidity (RH) field provides a possible clue: large clusters grow into environments with significantly wetter mid-level RH than small clusters, and optically thick clusters occur in wetter mid-level atmospheres than thinner clusters. Thus, differences in entrainment effects on buoyancy in wetter versus drier atmospheres may play a role in the ability of convective updrafts to advect large amounts of condensate upward to produce highly reflective anvils. Small/thick clusters also extend to slightly higher altitudes (mean p = 191 mb) than both large (p = 205 mb) and small/thin (p = 218 mb) clusters, another possible indication of the role of convective strength.

The observed thermodynamic structure differences can be explained as the product of differences in the large-scale dynamics. Large clusters grow into environments with strong large-scale upward motion through the depth of the troposphere (thus plausibly accounting for the steeper lapse rates and higher RH these clusters see). This feature of the data disproves the simplistic notion that upward motion in the tropics only occurs inside convective updrafts. Smaller clusters also occur in rising air, but at much weaker velocities. The thicker clusters experience rising motion comparable to that seen by bigger clusters only at low levels, while the thinner clusters form in environments with almost no low-level uplift but moderate upper-level rising motion. Consistent with this, both large and small/thick clusters are fed by strong low-level moisture convergence, while thin clusters see only weak and shallow moisture convergence.

Numerical simulations consistently suggest the first-order role of wind shear in precipitation development in convective storms (cf. Ferrier et al. 1996). COARE clusters exhibit a distinct preference for zonal propagation. Unfortunately, the propagation direction is at best a weak function of the ambient zonal wind, so shear effects can be included in a climate GCM parameterization only in a probabilistic fashion. Large clusters favor environments with systematic front-to-rear mean flow and shear with height, which helps advect condensate well behind the updraft region and increase anvil area. Small/thick clusters have shear that changes sign with height, such that droplets at mid-levels fall out behind the advancing updraft, limiting autoconversion and optimizing detrainment. Small/thin clusters, however, have a tendency for systematic rear-to-front shear with height, so that droplets fall more often into the path of the advancing updraft, enhancing autoconversion and plausibly reducing detrainment of condensate into a leading anvil.

The climatic importance of different cluster types depends on the radiative impact of each type combined with its frequency of occurrence. Shortwave cloud forcing values are about 50% larger than longwave forcing values for clusters of all size, so net cloud forcing becomes increasingly negative as cluster size increases (Figure 2, panels a through c). (Keep in mind that our definition of anvils excludes associated thinner cirrus whose longwave forcing dominates.) However, small clusters are much more numerous than large clusters. As a result, although larger storms have a greater individual radiative

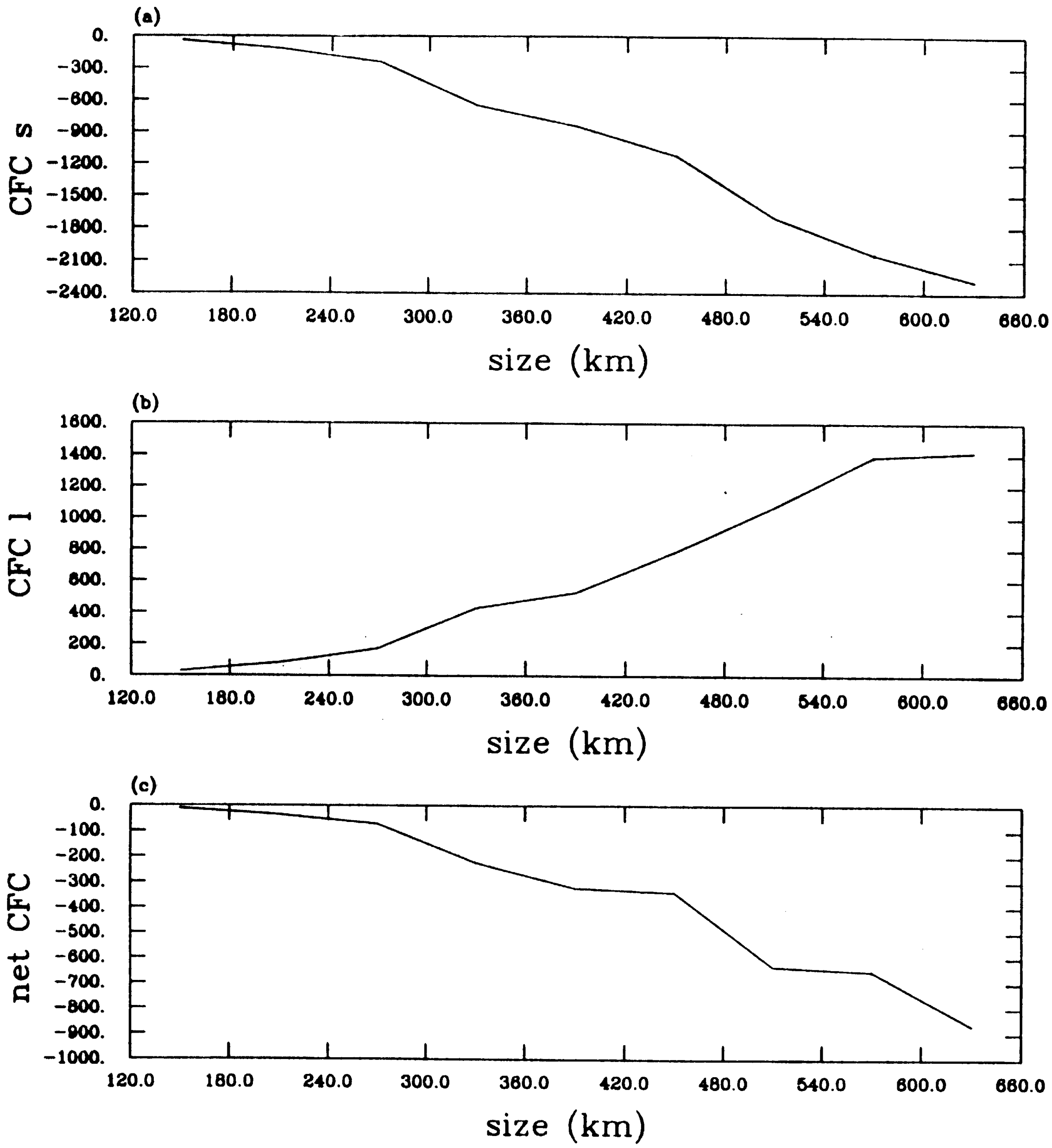

Figure 2. Shortwave (upper), longwave (center), and net (lower) cloud forcing (W/m^2) of individual tropical cloud clusters binned as a function of cluster size.

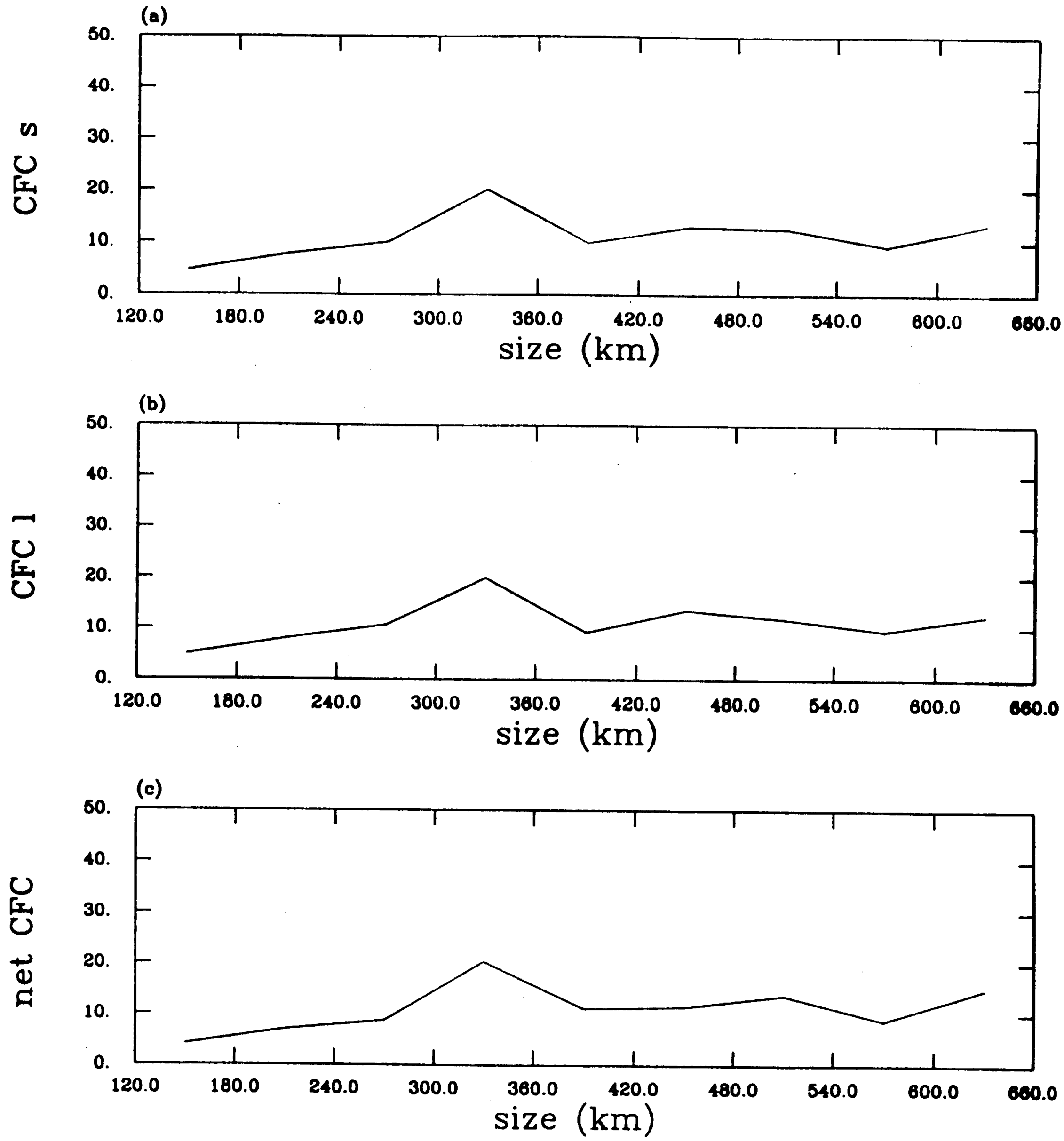

Figure 2 (contd). Percent contribution of clusters in each size category to the time mean shortwave (upper), longwave (center), and net (lower) cloud forcing.

impact, collectively storms of all sizes contribute about equally to the time mean cloud forcing of the tropical west Pacific. This does not necessarily mean that they will contribute equally to cloud feedback in a climate change, however, since the environmental conditions that favor each type may not change in the same way.

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