A Parameterization of Warm Clouds for Use in Atmospheric General Circulation Models

K. N. BOWER,* T. W. CHOULARTON,* J. LATHAM,* J. NELSON,** M. B. BAKER,** AND J. JENSEN[@]

*Department of Pure and Applied Physics, UMIST, Manchester, United Kingdom
**Department of Geophysics, University of Washington, Seattle, Washington
[@]Division of Atmospheric Research, CSIRO, Mordialloc, Victoria, Australia

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ABSTRACT

Simple parameterizations of droplet effective radius in stratiform and convective clouds are presented for use in global climate models. Datasets from subtropical marine stratocumulus, continental and maritime convective clouds, and hill cap clouds in middle latitudes and a small amount of data from stratocumulus clouds in middle latitudes have been examined. The results suggest strongly that a simple relationship exists between droplet effective radius and liquid water content in layer clouds with the droplet effective radius proportional to the cube root of the liquid water content. The constant of proportionality is different over oceans and continents. In current global climate models liquid water content is not a predicted variable in convective clouds, and the data strongly suggest that a fixed value of droplet effective radius between 9 and 10 μm should be used for continental clouds more than 500 m deep and 16 μm for maritime cumulus more than 1.5 km deep.

1. Introduction

This paper is concerned with the influence of clouds on climate—more particularly, with research directed toward the need to incorporate certain cloud microphysical characteristics and processes into atmospheric general circulation models (AGCMs) so that they may be used as global climate models to predict future climate by integrating forward in time over many decades. It centers around analysis of data obtained in comprehensive field experiments on ice-free clouds of various types in several geographical locations.

When global climate models are used to simulate the expected climate change produced by increasing concentrations of greenhouse gases, the treatment of clouds, particularly the radiative properties, has proved to be particularly important. Recent improvements to this treatment in the U.K. Meteorological Office model have been introduced by Slingo et al. (1989). The important cloud properties for determining the radiative properties are the liquid water path and the size distribution and phase of the cloud particles.

Mitchell et al. (1990) have reported results from the U.K. Meteorological Office model using an improved cloud scheme developed by Smith (1990). They found that this resulted in a reduction in the equilibrium average global warming, for a doubling of carbon dioxide content, from 5.2 K to 2.7 K. A further modification of the model in which the cloud radiative properties were made to depend on cloud liquid water content resulted in a further reduction in the predicted global warming to 1.9 K.

In these model runs the clouds have been assumed to have a constant droplet effective radius of 10 μm (Slingo 1989). Recently Slingo (1990) performed a sensitivity study on this parameter and showed that reducing the droplet effective radius by approximately 2 μm everywhere would be able to totally offset the warming associated with a doubling of carbon dioxide concentrations.

Bower and Choularton (1992) have suggested simple parameterizations for clouds that are dependent on cloud type. For stratocumulus clouds they suggest a parameterization in which the droplet effective radius is dependent on liquid water content. They also suggest a droplet number concentration that has a different value over oceans and continents. For convective clouds they assume a droplet effective radius independent of liquid water content. The droplet effective radius also assumes a different value over oceans and continents.

In this paper, the microphysical properties of a number of cloud types are presented, forming an extension of the work presented by Bower and Choularton with a more comprehensive dataset. Analyses have been performed of data obtained from aircraft passes through marine stratocumulus clouds in the First ISCCP Regional Experiment (FIRE) (1987, off the coast of California); through summertime continental cumulus clouds in the Cooperative Convection Precipitation Experiment (CCOPE) (Montana 1981) and in New Mex-

Corresponding author address: Dr. T. W. Choularton, Department of Pure and Applied Physics, UMIST, P.O. Box 88, Manchester M60 1QD, United Kingdom.

ico (1987); and through warm maritime cumulus clouds off Hawaii in 1987, together with ground-based measurements within clouds enveloping the UMIST field station site on Great Dun Fell in Cumbria in 1988, 1989, and 1990.

The objective of this study was to provide simple effective radius parameterizations suitable for inclusion in global climate models in their current state of development. In particular, we need to take account of the fact that liquid water content is not a predicted variable for convective clouds in most global climate models. We also aimed to account for the differences between the main cloud types studied in terms of the dominant physical processes controlling the link between the droplet effective radius and cloud liquid water content. A much wider dataset has been examined than in Bower and Choularton, and we aim to refine their parameterizations. Specifically, the data from marine stratocumulus clouds are the same as those used by Bower and Choularton. The data for continental cumulus clouds have been supplemented by case studies from clouds forming over New Mexico in the southern United States. In this paper, data from convective clouds forming over the Pacific have been added. The data from Great Dun Fell have been extended to include a larger dataset including some stratocumulus clouds with a continental influence.

In this paper we emphasize the parameterizations for stratocumulus clouds using data from the FIRE experiment for marine stratocumulus, as these clouds are particularly important in determining the radiative balance of the globe (e.g., see Slingo 1989; Twomey et al. 1984). It is important in climate models to be able to predict the radiative characteristics and spatial extent of these clouds. Recent model results (Baker and Charlson 1990; Albrecht 1989) suggest microphysical parameters might determine cloud cover in some cases. This is due to the regulation of the production of drizzle by the microphysical parameters, which in turn controls the water budget of the cloud. This accentuates the need for accurate prediction of cloud microphysical characteristics. Given the coarse resolution of mesoscale and global circulation models, it is particularly desirable to understand the extent to which these characteristics can be predicted from the large-scale boundary processes.

There have been several comprehensive observational studies of stratocumulus, most notably Brost et al. (1982a,b) and Albrecht et al. (1985), who examined data from clouds off the coast of California, and Roach et al. (1982), Slingo et al. (1982), Nicholls and Leighton (1986), and Turton and Nicholls (1987), who investigated clouds near Great Britain. We do not attempt to reproduce the breadth of these studies but rather to investigate the microphysical factors directly influencing the optical parameters in unbroken stratocumulus. There is, however, a marked lack of data for stratocumulus clouds over land with a marked continental influence.

The instruments used in each of the field experiments are presented in section 2. In section 3 we present the observed relationships between in-cloud thermodynamic, microphysical, and optical parameters, and their variations with height for all the field experiments. We present the relationship between the effective radius $R_{\rm eff}$ (μm) and liquid water content L (g m^{-3}), where

$$R_{\rm eff} \equiv \frac{\int_0^\infty N(r) r^3 dr}{\int_0^\infty N(r) r^2 dr}; \qquad (1)$$

$N(r)dr$ (m^{-3}) is the number of cloud droplets of radii in the interval $(r, r + dr)$. In section 4 we discuss the physical processes that control the behavior of the different cloud types, and finally we present and assess parameterizations of $R_{\rm eff}$, which we hope will be useful in AGCMs.

2. Data sources: Instrumentation

a. Montana: Cumulus clouds

These data were obtained from aircraft passes through cumulus clouds by the University of Wyoming King Air research aircraft during the 1981 CCOPE experiment. The instrumentation aboard has been described in detail in previous papers (Hill and Choularton 1985; Blyth and Latham 1985) and is briefly summarized in Table 1. Information on droplet size spectra, droplet number concentration, and cloud liquid water content was provided by a Knollenberg Forward Scattering Spectrometer Probe (FSSP). Details of specific corrections applied to this data are given in Bower and Choularton (1988), as well as information relating to the treatment of the data from the other instruments aboard the King Air aircraft. The clouds studied were ice free, as revealed by data from the optical array probes.

b. New Mexico: Cumulus clouds

The clouds in the New Mexican study were cumulus that formed over the Magdalena Mountains situated in central New Mexico. Multiple penetrations were made chiefly near the cloud tops by the King Air aircraft belonging to the National Center for Atmospheric Research (NCAR) during August 1987. A list of instrumentation typically onboard the King Air, along with their operating characteristics, is given in Research Aviation Facility Bulletin 2. Information on the particles in the cloud was provided by the FSSP, the 1D 260X, 2D-C, and 2D-P probes.

The analysis of data from the 2D probes showed that ice was present in some regions of these clouds. For

TABLE 1. Summary of relevant instrumentation aboard the Wyoming King Air aircraft during CCOPE (after Hill and Choularton 1985).

Parameter	Device	Frequency (Hz)	Resolution (m)	Response (s)
Droplet number N (cm^{-3})	PMS FSSP	10	10	—
Liquid water content L (g m^{-3})	PMS FSSP	10	10	—
Liquid water content L (g m^{-3})	Johnson–Williams	10	—	0.5
High frequency droplet count N_{50}	PMS FSSP	50	~2	—
Droplet spectrum $N(r)$ ($r \sim 1$–19.5 μm)	PMS FSSP	10	10	—
Droplet spectrum $N(r)$ ($r \sim 19$–90 μm)	PMS 1-D	1	100	—
Temperature T (°C)	Reverse flow thermometer	10	—	0.2
Vertical wind velocity W (m s^{-1})	Aircraft dynamic response	10	—	~0.5

the purposes of this study we have considered only regions of ice-free clouds.

c. Hawaii: Maritime cumulus

The Hawaii dataset was gathered using the University of Wyoming King Air using a similar set of instrumentation as that used during the CCOPE project. Due to the large drops in the Hawaiian clouds, we have used a composite spectrum of the FSSP probe and a 1D-C probe (PMS type 260X). Comparisons between observed and calculated liquid water content in many adiabatic parcels revealed a systematic underestimation of the liquid water content. On this basis the FSSP radii were increased by 8%, and a combined spectrum of channels 1–12 from the FSSP and 5–13 from the 1D-C probe was made. This combined spectrum gave a very good comparison between calculated and observed liquid water content in adiabatic cores. The combined drop spectrum covers drops up to 130 micron radius. The 1D-C probe was only sampled at 1 Hz, whereas the FSSP was sampled at 10 Hz. The FSSP spectra were thus averaged to 1 Hz, and all combined drop spectra are thus 1-Hz samples.

Cloudy 1-second samples were selected by requiring that the FSSP 50-Hz total drop count N_T was showing drops in all 50 samples during 1 second. This procedure ensures for practical purposes that 1-sec samples containing macroscopic clear air filaments (holes) are excluded; this procedure is very important since measurements of L/L_{ad} may otherwise be averaged over both cloudy and clear air filaments within a 1-sec sample, whereas spectral characteristics such as $R_{\rm eff}$ are only dependent on the cloudy filaments. These clouds were ice free.

d. Great Dun Fell—Cap clouds

This dataset was gathered using ground-based instrumentation located on the summit of Great Dun Fell. This hill is 850 m high and is located in northern England. A cap cloud forms over this site with winds from the NE and SW directions, so a variety of air masses ranging from very maritime to strongly continental can be studied. A detailed description of the instrumentation used in the measurement of hill cap clouds at the Great Dun Fell field station site may be found in earlier papers (e.g., Choularton et al. 1986).

e. Marine stratocumulus: FIRE

The cloud microphysical data used in this paper were gathered by the U.K. Meteorological Office Hercules

TABLE 2. Relevant parameters measured aboard the MRF Hercules (C-130) aircraft during FIRE. Device description: 1) geometric altitude above surface (1% accuracy) type Honeywell AN/apn 171; 2) see Nichols 1983; 3) static free stream pressure from ports in nose boom, transducer type Rosemount 1301D3BX; 4) open wire Pt resistance in deiced (heated) housing, type Rosemount 102BL102BX; 5) forward looking 4.3-μm radiometer with 3° beamwidth, internal blackbody calibration (see Nichols 1978); 6) Peltier cooled mirror automatic hygrometer EG&G 137; 7) 9.4 GHz open cavity microwave refractometer, continuously referenced to device 6 for stability and calibration; 8) Johnson–Williams hot wire probe; 9) Particle Measuring Systems FSSP.

Parameter	Device	Frequency output (Hz)	Frequency measured (Hz)	Resolution (s)	Range (min–max)
Radar altitude Z (m)	1	1	2	1.0	0–1550
Vertical wind W (m s^{-1})	2	16	—	0.1	−100–100
Static pressure p (mb)	3	16	32	1.0	0–1040
Temperature T (°C)	4	16	32	0.5	−100–100
CO_2 radiation temperature (°C)	5	16	32	0.5	−100–100
Dewpoint temperature T_d (°C)	6	16	4	0.5	−100–40
Specific humidity Q (g kg^{-1})	7	16	32	0.5	0–40
Liquid water content L (g m^{-3})	8	16	4	0.1	−1.0–5.0
Droplet spectrum FSSP $N(r)$	9	1	10	0.1	0–1000

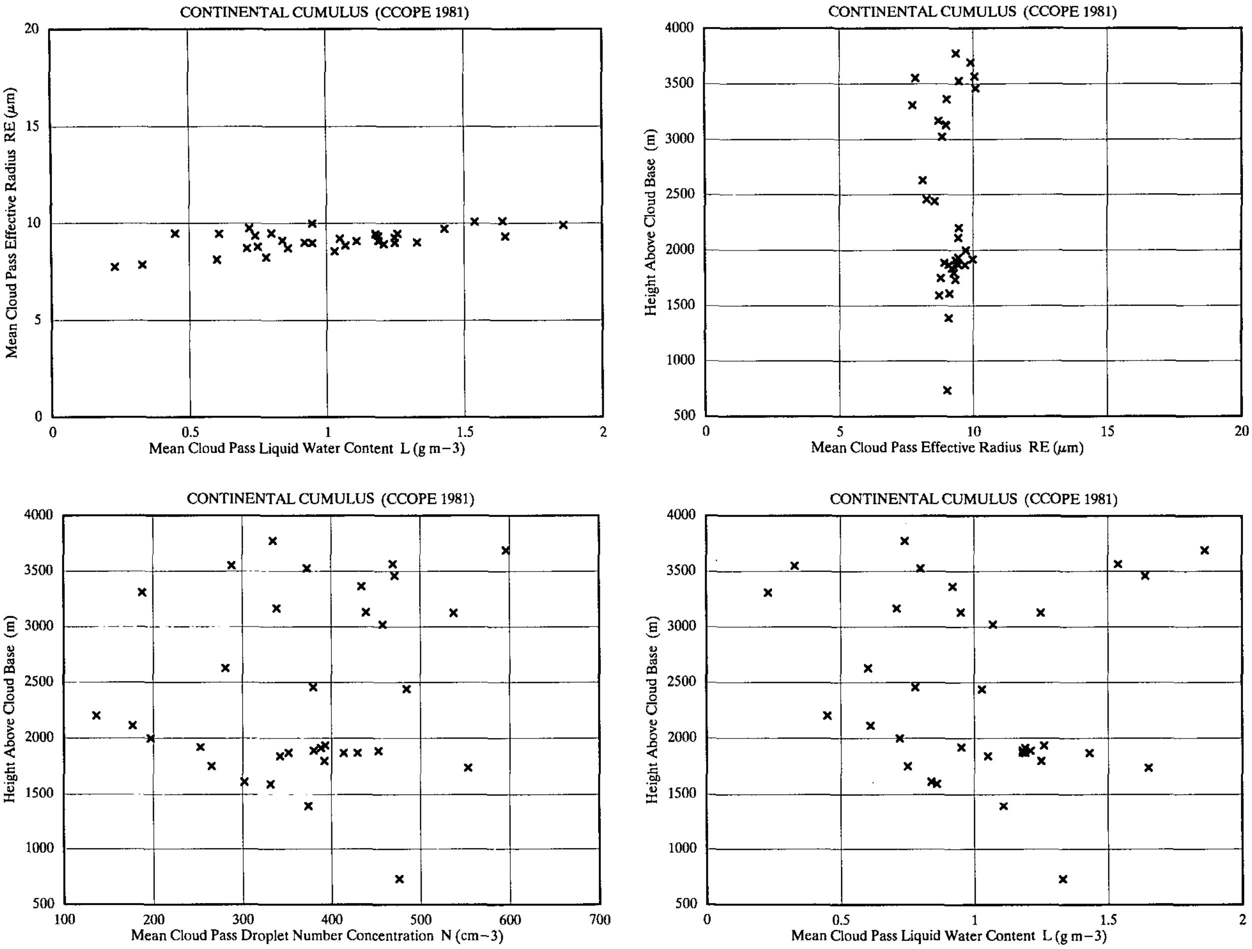


FIG. 1. Parameter plots for continental cumulus clouds CCOPE for (a) mean pass droplet effective radius vs mean pass liquid water content, (b) height above cloud base vs mean pass droplet effective radius, (c) height above cloud base vs droplet number concentration, and (d) height above cloud base vs mean cloud pass liquid water content.

aircraft. This aircraft made passes through marine stratocumulus cloud in the FIRE experiment. Details of the equipment on this aircraft may be found in Nicholls (1978, 1983) and Nicholls et al. (1983). The relevant parameters used in the analysis described in this paper are summarized in Table 2. Details of our treatment of the data may be found in Bower and Choularton (1992).

3. Microphysical and optical characteristics: Effects of entrainment and other processes

In this section, we present and examine in-cloud data from the field experiments cited, and in each case explore the relationships between the measured and derived microphysical and optical characteristics. Priority is given to attempts to identify and quantify the processes that exercise significant influence on these characteristics. Predominant among these is the role of turbulent entrainment—the mixing and incorporation into the cloud of undersaturated environmental air.

It is well known that entrainment, in addition to modifying the temperature and dynamical structure of clouds, can substantially change their liquid water contents L, droplet number concentrations N, and size distributions $n(r)$, with concomitant influences on optical characteristics such as effective radius R_{eff} and liquid water path LWP. In general, entrainment reduces L and broadens $n(r)$, while N can be increased or decreased.

In order to distinguish between the main characteristics of the different cloud types vis-à-vis their optical properties, mean and standard deviation parameters were calculated (including values of R_{eff}, Q, and θ_Q). Time series plots were also generated from the data gathered during horizontal flights through the clouds (and from the summit site measurements in the case of the GDF data). Using these results together with data from the vertical profiles through the same clouds, the main differences between the different cloud types (as discussed below) are seen in the variations of the mean values of the

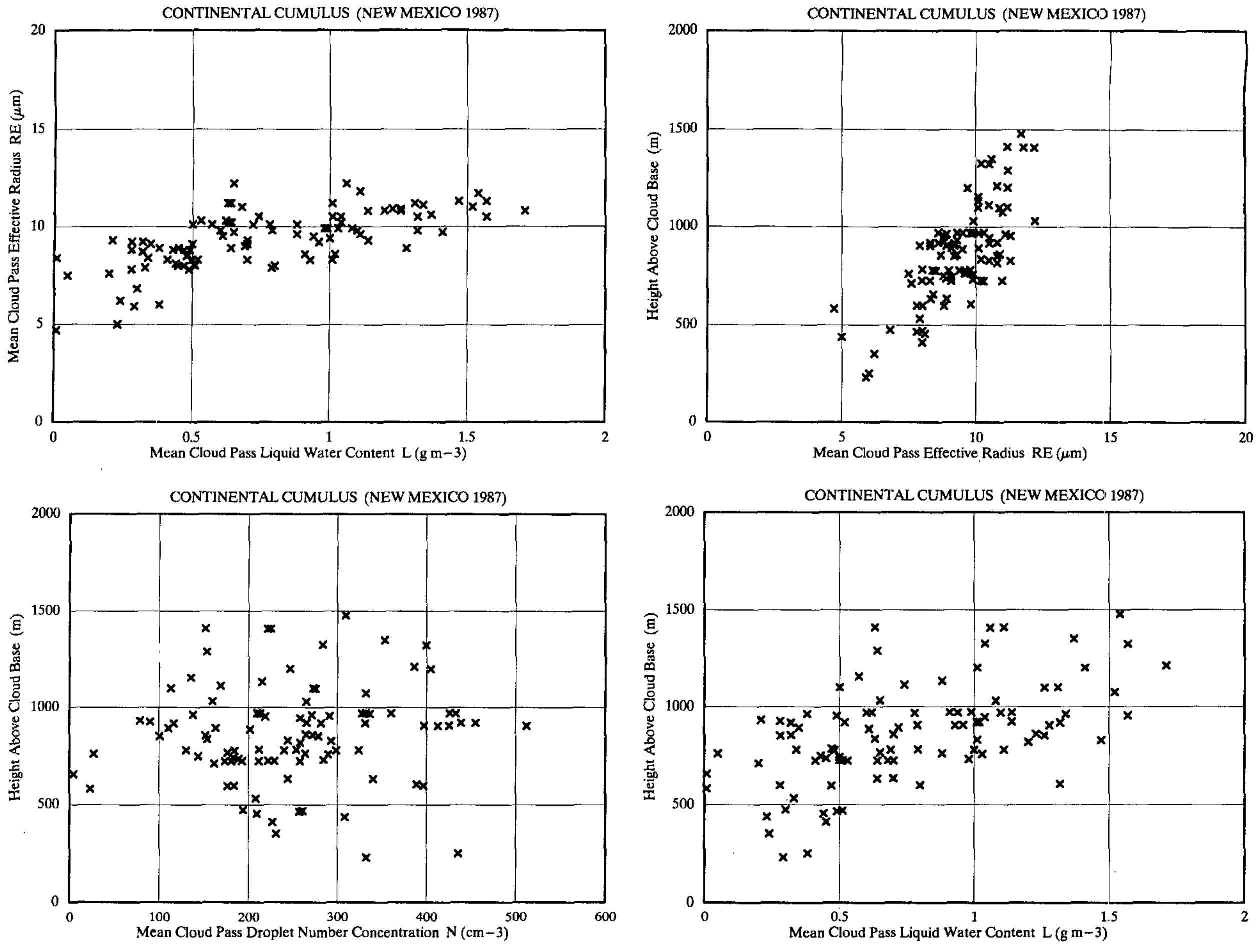


FIG. 2. As in Fig. 1 but for continental cumulus clouds (New Mexico).

droplet number concentration N, cloud liquid water content L, and droplet effective radius R_{eff}.

A summary of the observations of the main parameters through each cloud type will now be given. The data from each of the major experiments are presented in a set of diagrams, each representing one full horizontal path of the aircraft through the cloud (except for the ground-based Great Dun Fell cap cloud data). In this way small-scale variability has been eliminated. For each cloud type we have presented graphs of (a) droplet effective radius against liquid water content, (b) droplet effective radius against height above cloud base, (c) droplet number concentration against height above cloud base, and (d) liquid water content against height above cloud base. These are presented in Fig. 1 for CCOPE data, Fig. 2 for New Mexico cumulus clouds, Fig. 3 for Hawaiian cumulus clouds, and Fig. 4 for marine stratocumulus clouds, and Fig. 5 shows a graph of droplet effective radius against liquid water content for Great Dun Fell cap clouds.

In most cases it is apparent that the cloud liquid water content tends to increase with height above cloud base, particularly low down in the cloud. The exception to this is the CCOPE data, where no data were obtained at heights less than 500 m above cloud base. The convective clouds, which are all strongly affected by entrainment, show considerable scatter in the values of liquid water content. The droplet effective radius increases steadily with liquid water content in the marine stratocumulus and the Great Dun Fell cap clouds, but is almost independent of liquid water content in the continental cumulus clouds. In the case of the maritime cumulus clouds a marked increase in the droplet effective radius with liquid water content is evident in the lowest 1500 m of the cloud with a constant but much larger value (about 16 μm) than observed in any other clouds above this level. The graphs of droplet effective radius against height above cloud base generally show similar trends; the exception is the continental cumulus data from New Mexico when the effects of ice intervene. The regions of cloud with marked ice crystal concentrations (as detected by the 2D probe) have been removed from the graphs and will be discussed in detail in a later paper. The graphs of droplet number concen-

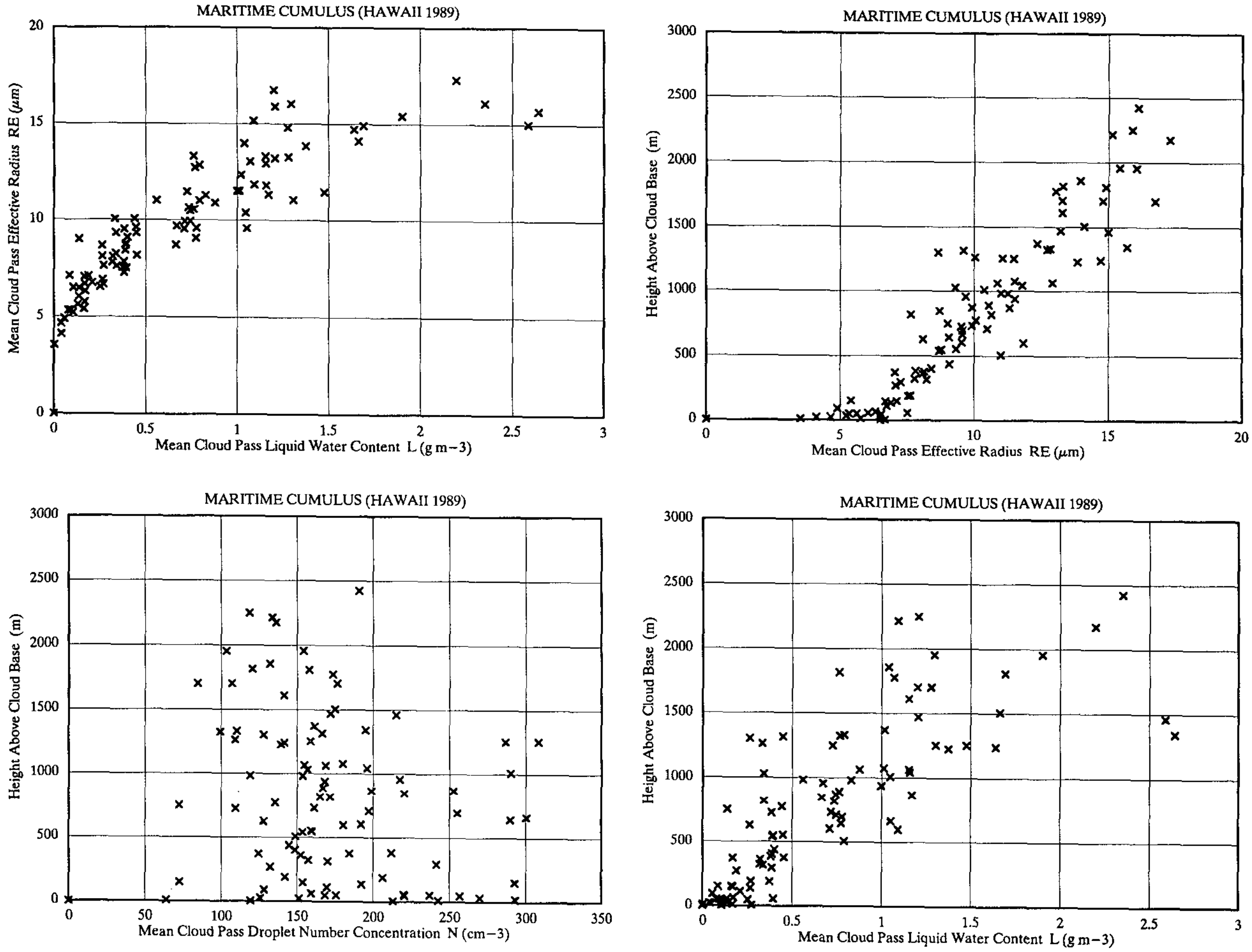


FIG. 3. As in Fig. 1 but for maritime cumulus clouds (Hawaii).

tration against height show very little overall trend; however, there is considerable scatter in the graphs for the cumulus clouds and almost constant values for the marine stratocumulus through the main body of the cloud. There is more scatter in the data for the stratocumulus clouds very near cloud top. The values of the minute averaged droplet number concentration observed in the Great Dun Fell cap clouds vary from 200 to 500 cm^{-3} for the data presented in the diagrams. These represent maritime air masses that have been modified by a continental influence, which varies from day to day depending on the air trajectory to the site. Short-term variability in the droplet number concentration is introduced by the effects of entrainment; however, this is not as marked as in the convective clouds. When a strong continental influence is present the droplet number concentration is around 600 cm^{-3}. The properties of the cloud are otherwise very similar to those discussed above.

These data will be used to prepare our suggested parameterizations described in section 5. The physical processes responsible for these differences have been discussed elsewhere.

The convective clouds are strongly influenced by the entrainment of dry air from outside their boundaries and their microphysical properties are controlled by a nonhomogeneous mixing process as described by Baker and Latham (1979, 1982). The effects of this mixing on the CCOPE data have been described in detail by, for example, Bower and Choularton (1988), Hill and Choularton (1985), and Blyth and Latham (1985), and in the New Mexico data by Blyth and Latham (1991). The effects of mixing in the hill clouds are generally much less than in the convective clouds; for example, see Choularton et al. (1986).

The marine stratocumulus clouds are discussed in detail by Bower and Choularton (1992). The height of cloud base in the stratocumulus cloud is determined by a combination of the moisture flux from the sea surface competing with a drying influence from air entrained from above the capping inversion. In these clouds, however, the cloud top entrainment instability criterion was

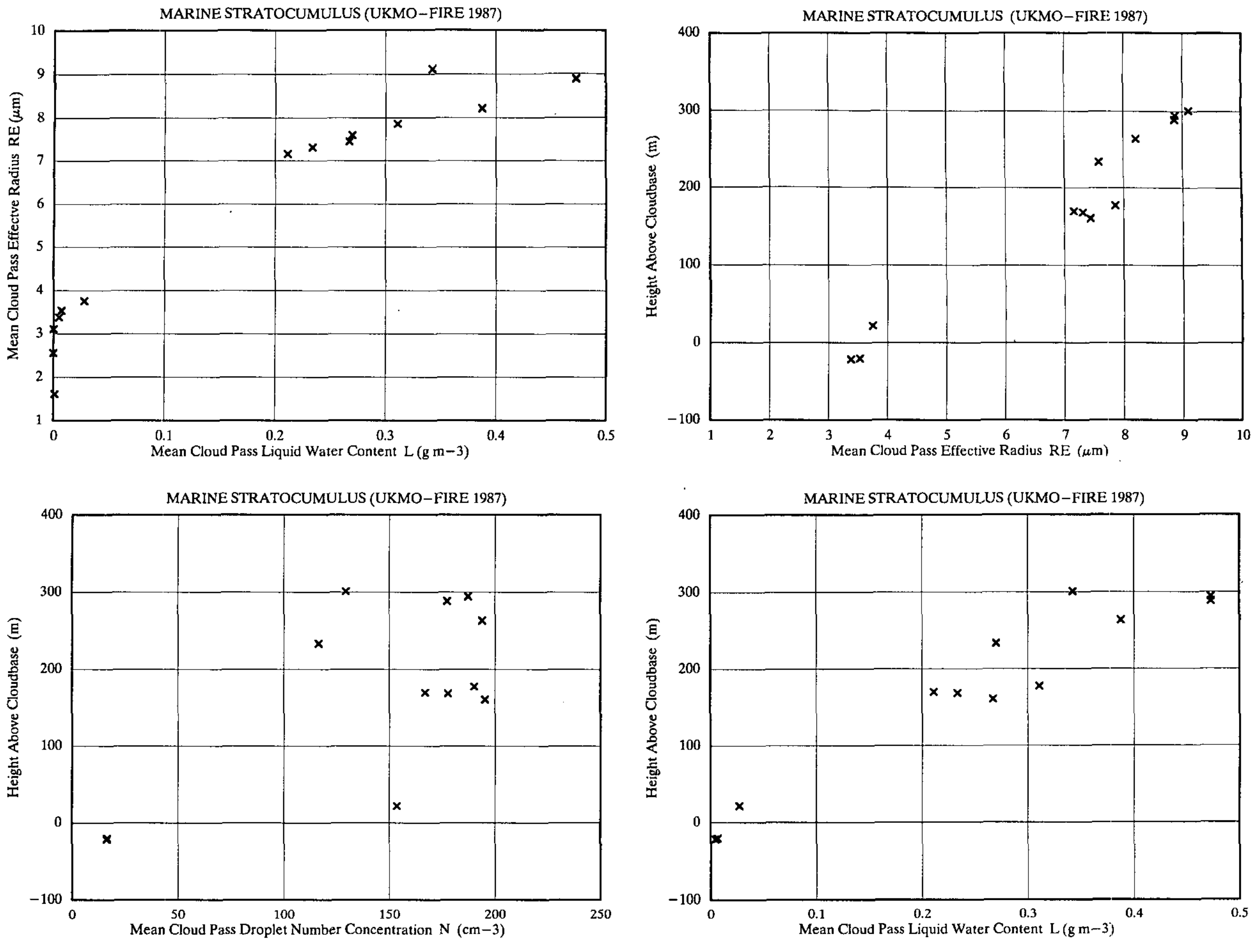


FIG. 4. As in Fig. 1 but for maritime stratocumulus clouds.

not satisfied, and the direct effects of entrainment on the cloud microphysics were confined to the upper parts of the cloud. Throughout the body of the cloud, the liquid water content was essentially adiabatic as determined from the observed cloud base height and cloud base temperature. Although observed droplet spectra were somewhat broader than adiabatic predictions (due to the effects of radiative cooling) the droplet effective radius increased with height, as the liquid water content increased with height above cloud base with an almost constant droplet number concentration. The exception to this is in the region directly affected by entrainment near to the cloud top where the effective radius was suppressed and the liquid water content became subadiabatic. These results are essentially the same as those found by other investigators; examples include the observational study of Nicholls and Leighton (1986) and the modeling study of Turton and Nicholls (1987).

4. Discussion: Parameterizations

In this paper we have studied the microphysical properties of subtropical marine stratocumulus and continental and maritime cumulus. To illustrate the main physical processes controlling the relationship between the droplet effective radius, the cloud liquid water content, and the height above cloud base, individual clouds have been studied in some detail. The results are summarized in Figs. 6a–d, which show combined plots for examples of all the clouds studied of droplet effective radius against liquid water content, droplet number concentration against liquid water content, droplet effective radius against height above cloud base, and liquid water content against height above cloud base, respectively. The results presented are typical of the types of cloud described. A few points from the nocturnal stratocumulus data of Caughey and Kitchen (1984) and the small cumulus cloud data of Kitchen and Caughey (1981) have been added. It can be seen that for the same range of liquid water content, number concentrations in the GDF data (200–500 cm^{-3}) are higher than in the FIRE stratocumulus data, but that effective radii are lower and are around 5–7 μm on average. The larger number concentrations may be explained by an increase in the continental component of the basically

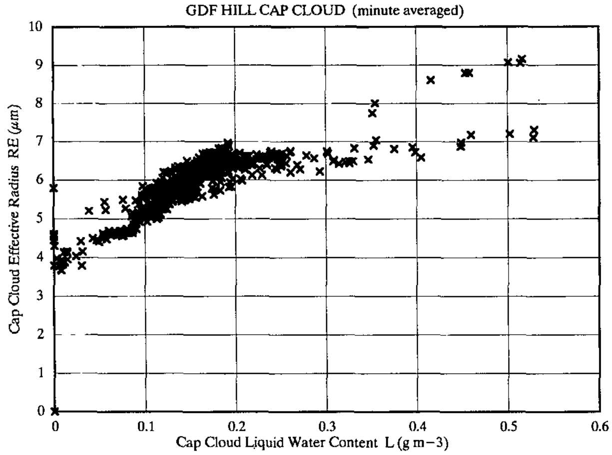


FIG. 5. Minute-averaged droplet effective radius against liquid water content for clouds enveloping Great Dun Fell.

maritime CCN in the air arriving at Great Dun Fell. In addition, the GDF data are only 1-minute averaged rather than pass averaged and consequently show more variation. The results presented are for modified maritime air masses, and number concentrations of up to 600 cm^{-3} have been observed.

In both hill cap cloud data and marine stratocumulus data, mean effective radius increases with L, but appears to be fixed in the case of the CCOPE cumulus data. The majority of points in the New Mexican continental cumulus dataset also tend to have a fixed value of R_{eff}, but the scatter of these two parameters is much greater than for the CCOPE data. The points with highest values of R_{eff} tend to occur at the lowest measured temperatures, so it is conceivable that such data are contaminated by the ice phase. Data containing measurable quantities of ice as detected by the 2D probes have been removed. The data points from the small cumulus cloud observed by Kitchen and Caughey fit into the proportional relationship of the marine stratocumulus data, probably due to the adiabatic nature of the cloud in this early stage of its development. The few points derived from the nocturnal stratocumulus data also fit this relationship. The data from the marine cumulus show somewhat different behavior with much larger droplet sizes, approaching 16 μm. This is characteristic of the much smaller number of droplets activated over the oceans (typically 150–200 cm^{-3} in this case). The droplet effective radius also exhibits a much stronger height dependence than the continental cumulus clouds reported. In contrast, mean droplet number concentrations for all the convective cloud types appear to increase with increasing values of mean liquid water content L, although in general for a particular cloud type there is a greater spread in this data than there is in the effective radius plot. The hill cap cloud and the marine stratocumulus show very little relationship between droplet number concentration and liquid water content due to the lack of nonhomogeneous mixing through the depth of these clouds.

A model of the entrainment process has illustrated the importance of this process in controlling the droplet effective radius in strongly entraining convective clouds (Bower and Choularton 1993). Its role, however, was only of marginal importance in the other cloud types studied.

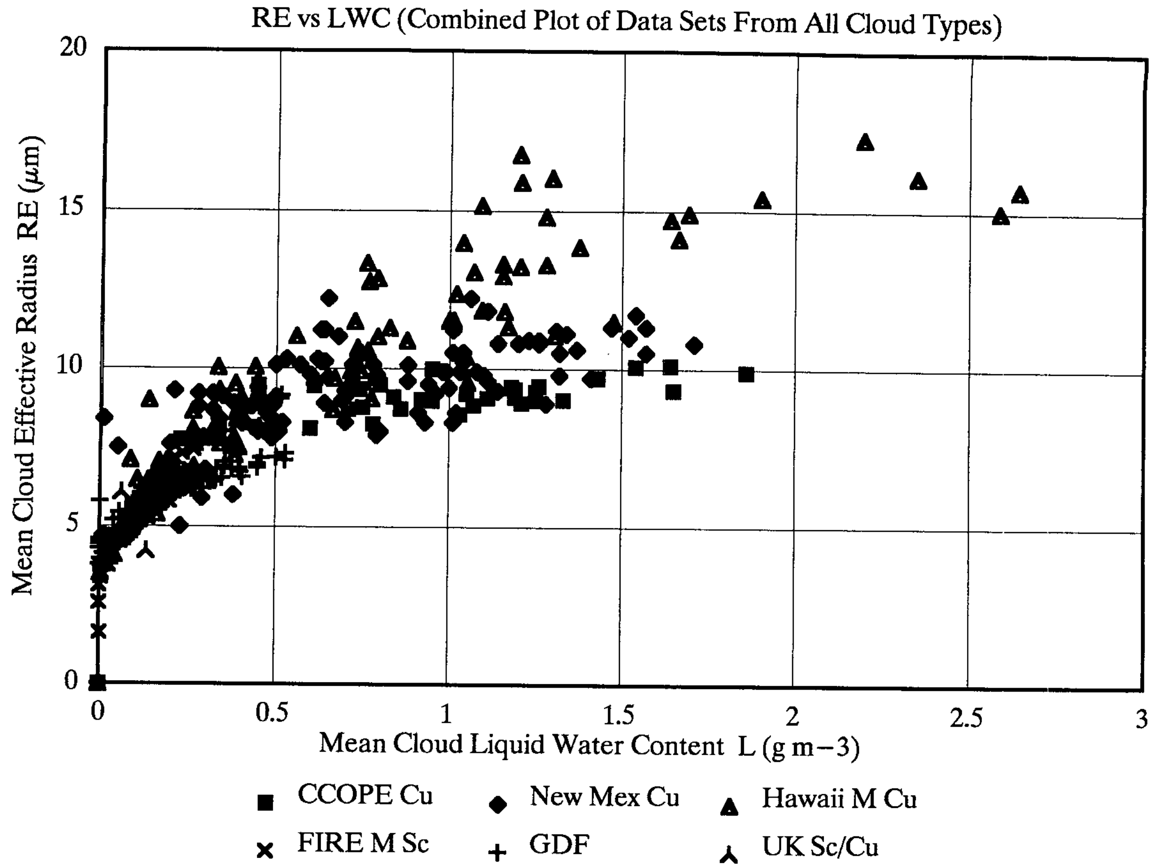
The behavior of layer clouds when the cloud top entrainment instability criterion is satisfied needs further investigation, particularly when this leads to the breakup of the cloud deck (Siems et al. 1990). In addition, the effects of the ice phase, both in modifying the cloud microphysics and in increasing the precipitation efficiency of the cloud, need to be considered, particularly for convective and deep layer clouds forming in association with frontal systems.

Despite these shortcomings, the work presented in this paper does suggest some simple parameterizations of the effective radius that may be relatively easy to combine with the cloud water scheme of Smith (1990). This parameterization is similar to that proposed by Bower and Choularton but has been modified using the increased dataset available to us. It is suggested that the clouds should be divided between continental and maritime to reflect their location, and should also be divided between convective (strongly entraining) and layer clouds (weakly entraining). For convective clouds over a continent, Fig. 6 suggests a fixed value of R_{eff} of between 9 and 10 μm for clouds with a vertical depth greater than about 500 m. The lower droplet number concentrations present over the oceans suggest that a value of $R_{eff} = 16$ μm would be more appropriate in this instance, but only for heights more than 1.5 km above cloud base. At lower levels the layer cloud parameterization should be used. It should be emphasised that these parameterizations for convective clouds are only approximate. All clouds show some tendency for droplet effective radius to increase with height (Blyth and Latham 1991). In addition, the results are complicated by the presence of the ice phase. However, the convective schemes of general circulation models are generally not able to predict liquid water content, and it is suggested that these approximations are a good first step in improving the parameterization of the variable in global climate models.

For layer clouds the data suggest that the effects of entrainment of dry air are much smaller. Hence it is probably appropriate to assume that the droplets grow adiabatically with height above cloud base. The effective radius is thus calculated from the formula

$$R_{eff} = 100 \times [\mathrm{LWC} \times 3/(4\pi \times N)]^{1/3}, \quad (2)$$

where LWC is the liquid water content (in g m^{-3}) predicted from the liquid water scheme and N is a fixed estimate of the droplet number concentration taken as 150 cm^{-3} over the oceans and 600 cm^{-3} over the continents. The latter figure for continental clouds was es-



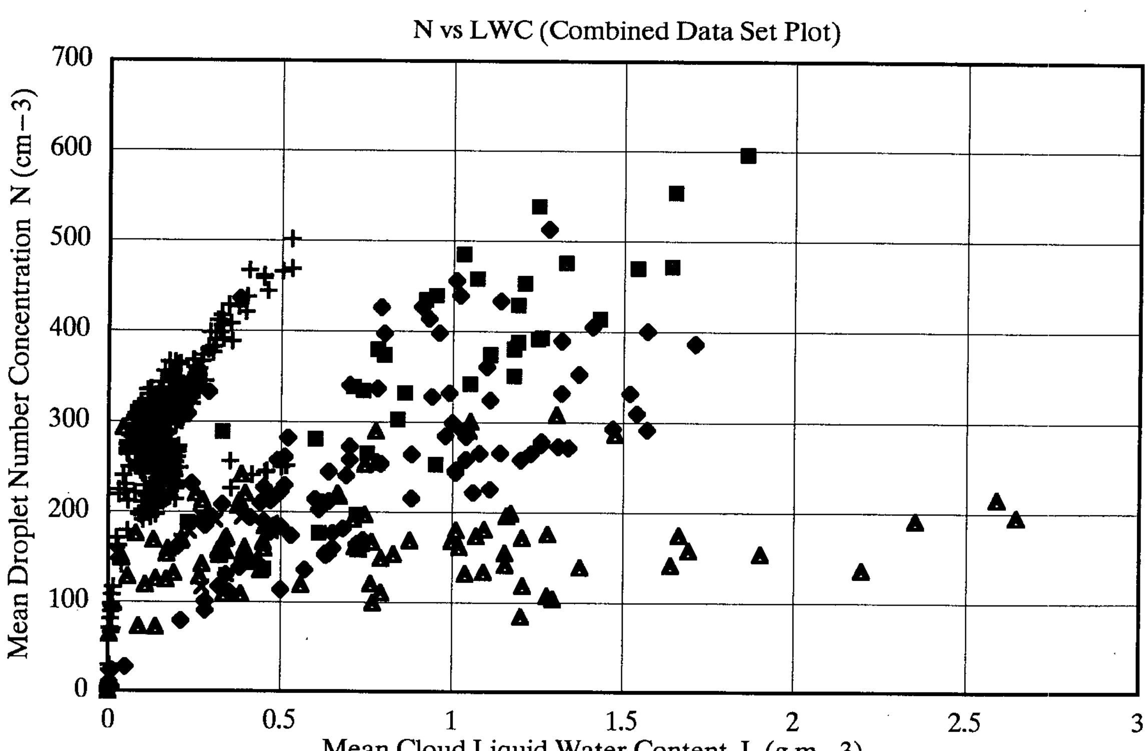
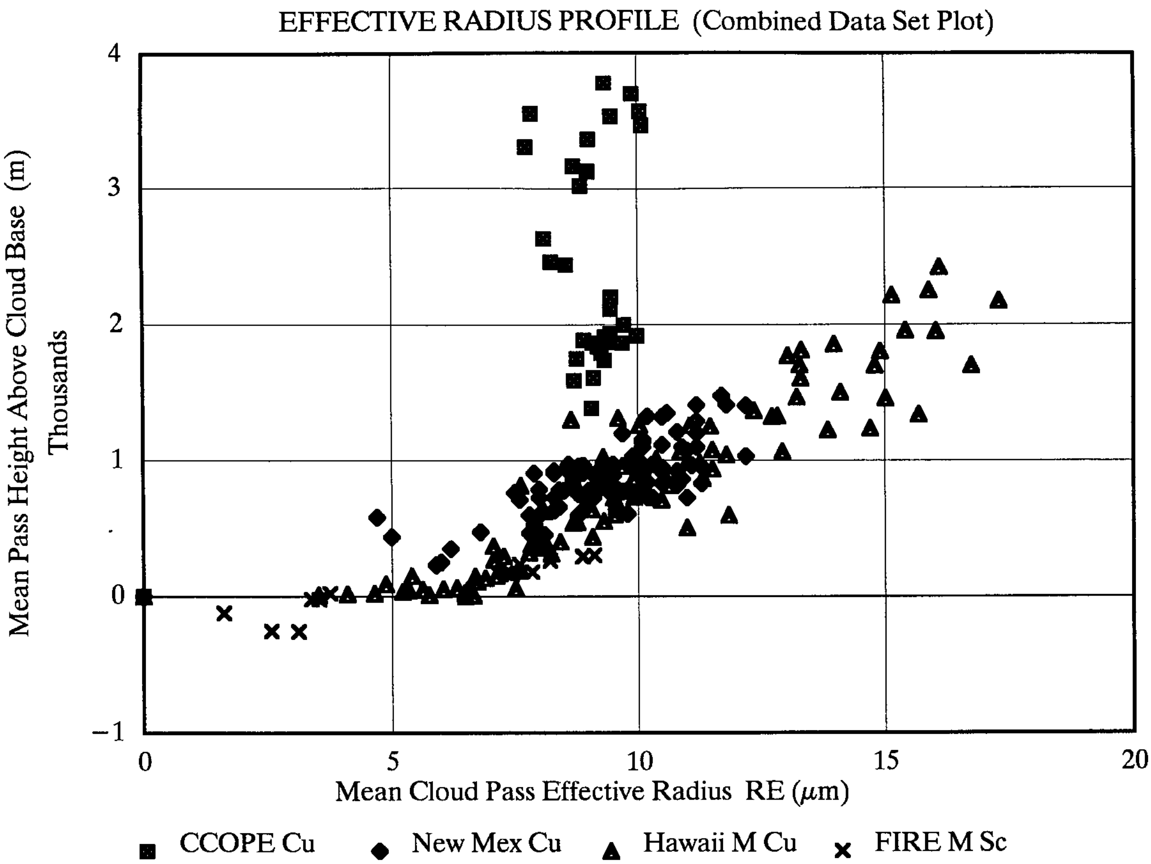


FIG. 6. (a) Variation in mean pass values of droplet effective radius with mean pass liquid water content for all datasets [includes small Cu and nocturnal Sc data of Kitchen and Caughey (1981) and Caughey and Kitchen (1984)]. (b) Combined dataset plot showing the



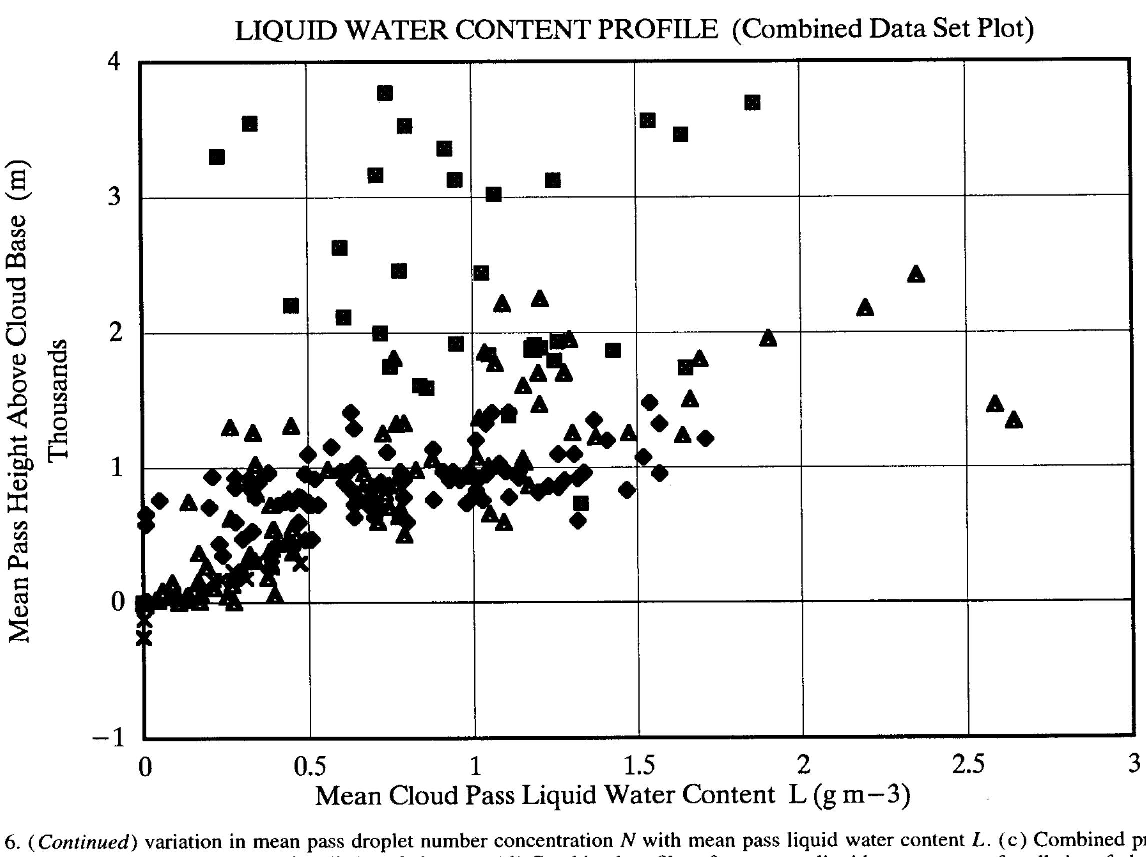


FIG. 6. (*Continued*) variation in mean pass droplet number concentration N with mean pass liquid water content L. (c) Combined profiles of mean pass droplet effective radius for all aircraft datasets. (d) Combined profiles of mean pass liquid water content for all aircraft datasets.

timated from stratocumulus clouds enveloping Great Dun Fell when the airstream over the site was of continental origin. It is suggested that this scheme should also be used for shallow convection (<500 m in depth over the continents and 1500 m in depth over the oceans), as the randomizing effect of entrainment, which leads to the almost constant value of effective radius for a wide range of heights above cloud base in deep convective clouds, will be dominated by the rapid growth of droplets with increasing height above cloud base in this region. The effects of entrainment, together with large variations in updraft speed (which controls the number of droplets activated), will, however, result in more widely scattered values of effective radius than in stratiform clouds.

Comparing these parameterizations with those obtained in Bower and Choularton (1992), the suggested parameterization for layer clouds is unchanged, but we have extended the range of applicability of this parameterization to marine cumulus. The constant effective radius parameterization for deep convective clouds is largely unchanged. The extended dataset, however, suggests that the scatter in effective radii encountered may be larger than suggested, particularly if the ice phase is initiated.

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