

Cumulonimbus Vertical Velocity Events in GATE. Part I: Diameter, Intensity and Mass Flux

MARGARET A. LEMONE AND EDWARD J. ZIPSER

National Center for Atmospheric Research,¹ Boulder, CO 80307

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ABSTRACT

This is the first part of a two-part paper defining the nature of the vertical air motion in and around GATE cumulonimbus clouds. The statistics are from a total of 10^4 km of flight legs, flown on six days in GATE, at altitudes from near the surface to 8100 m. The basic data sets analyzed are time series of vertical velocity at a frequency of 1 Hz. For the purpose of study, convective events are divided into two categories: drafts, requiring only that vertical velocity be continuously positive (negative) for 500 m and exceed an absolute value of 0.5 m s^{-1} for 1 s; and cores, the stronger portions of the stronger drafts, requiring that upward (downward) vertical velocity be continuously greater than an absolute value of 1 m s^{-1} for 500 m. The distributions of average vertical velocity, maximum vertical velocity, diameter and mass flux are given for drafts and cores at five altitude intervals between 150 m and 8 km. In all cases, the distributions are approximately log-normal.

Above cloud base, updrafts tend to be smaller but more intense than downdrafts. Updrafts and downdrafts near cloud base are comparable in size and intensity. Downdraft cores are smaller than updraft cores at all altitudes. They also are weaker, except near cloud base, where updraft and downdraft cores have comparable intensity. In the middle troposphere, only 10% of the updraft cores have mean vertical velocities greater than 5 m s^{-1} , and only 10% have diameters in excess of 2 km.

1. Introduction

This paper and its companion (Zipser and LeMone, 1980) describe the results of a statistical study of convective updrafts and downdrafts, based on aircraft data from cumulonimbus cloud penetrations from six days in the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE), an experiment conducted off the west coast of Africa in the summer of 1974. Frequency distributions of size, intensity and mass flux in convective drafts are presented for a range of altitudes between 150 and 8000 m. The statistics for the stronger portions of the drafts, to be defined as cores, are also examined. Selected statistics from these distributions are examined as functions of height. In Part II, we compare the GATE statistics with those from other regions, and we develop a schematic representation of "typical" GATE convective cores.

We define drafts and cores entirely from time series of vertical velocity measurements. In the moist environment that is characteristic of the GATE area, convective events or even growing cumulus towers are often embedded in cloudy air, debris from previous rising bubbles, outflow from

adjacent towers or independent layer clouds. Further, earlier results by Warner (1970) show that drafts and possibly cores may exist outside of clouds on their downshear side. Consequently, the vertical velocity events cannot be uniquely related to cloud features. Rather our data represent a mixture of growing, mature and dying cells, and turbulence in the vicinity of cells. We are unable to distinguish between these in most instances.

Statistical studies of convective updrafts and downdrafts are needed to provide a more accurate basis for the description of the role of cumulus convection in the transport of mass, momentum, heat and energy. Thus far, the various parametric representations of fluxes by cumulus convection (cf. Ooyama, 1971; Arakawa and Schubert, 1974) have been based on sketchy information. In those, as well as most diagnostic studies, the properties of cumulus and cumulonimbus have had to be assumed, or deduced through one-dimensional models. Greater knowledge of the behavior of the vertical motions within cumulus convection can provide the basis for new formulations and approaches, as well as testing old ones.

2. Previous work

This study fills a gap in the known statistics of convective cloud characteristics, by investigating

¹ The National Center for Atmospheric Research is sponsored by the National Science Foundation.

the cumulonimbus drafts of the oceanic tropics. For studies reporting cumulonimbus draft statistics by direct measurement of internal properties prior to GATE, one must return to the Thunderstorm Project (Byers and Braham, 1949), which involved storms over land in Florida and Ohio, to the summary of cloud penetration data over the USSR by Schmeter (1969), or to Gray's (1965) summary of convective drafts within hurricanes. There have been numerous studies of smaller cumulus clouds, starting with the pioneering trade cumulus observations of Malkus (1955, 1958). Warner (1969, 1970, 1977) provides draft statistics from cumulus up to 4 km in depth. In none of the above studies were the aircraft used equipped with inertial navigation systems. Thus, previous measurements of vertical velocity of a scale larger than a kilometer are victims of large error, and great care must be taken in the processing and analysis to reduce it.

The known relationship between clouds and drafts is illuminating and should be discussed briefly as a background for the statistics shown below. Malkus (1955) and Warner (1970) showed that cumulus clouds in a sheared environment consistently have an updraft on the upshear side. The vertical velocity in the center and downshear parts of the cloud is irregular. Drafts exist outside the visible edge of the cloud on the lee side. Downdrafts occur at most cloud edges throughout the life cycle, probably the result of evaporative cooling.

In some respects, the internal structure of many cumulonimbus clouds is not much more complex than that of smaller cumuli. The idealization of the thunderstorm in terms of its cellular structure dating from the Thunderstorm Project (Byers and Braham, 1949) has held up well, as noted in Lilly's (1979) review of current ideas on storm dynamics, and as documented in detail in Doppler radar studies (see, e.g., Miller, 1975; Strauch and Merrem, 1976). As in smaller cumuli, the strongest updrafts which experience the least entrainment are usually found in the upshear part of the cloud. This is documented both observationally (Heymsfield *et al.*, 1978) and in three-dimensional numerical models (Cotton and Tripoli, 1978; and others). In dying clouds of all sizes, downdraft everywhere replaces the earlier complex up- and downdraft structure.

The acknowledged importance of tropical cumulonimbi together with our lack of specific knowledge of their structure, stimulated considerable observational effort in GATE. The radar-observable characteristics of tropical showers and rain systems have been reported extensively. Houze and Cheng (1977) gave frequency distributions of echo top heights and sizes. An important conclusion of that and other papers (e.g., Leary and Houze, 1979) is that most significant precipitation events are organized into mesoscale systems. Lopez (1976, 1977) has

shown that the distributions of most radar-measured properties (size, duration, height, rain volume) are log-normal. While it is possible to make useful inferences about cloud dynamics and transports from radar parameters (Austin and Houze, 1973), such inferences are necessarily model-dependent. Direct measurements of diameter, vertical velocity and mass flux of convective drafts are required, because they are the fundamental attributes of the processes in which we are interested, and we must not be totally dependent on model results. Some questions, such as the relative frequency of the fabled large, intense, nearly undilute towers, cannot be answered without data, even if model predictions of their properties are perfect.

Direct observations of updrafts and downdrafts for a range of marine convective events were reported by Emmitt (1978). His data base was the unique tethered balloon set from GATE, yielding useful information on the vertical structure and transport in 19 convective events² from near the surface to ~1 km, or about 500 m above cloud base. The aircraft data base in this study covers a larger number of events between 150 and 1000 m altitude, whose statistics will be compared to Emmitt's later. In addition, the results obtained by the same sampling technique will be compared over an altitude range from below cloud base through the middle troposphere.

3. Strategy for data gathering and analysis³

a. Description of the data

The data used for this study are collected from three aircraft, each equipped with an inertial navigation system and instrumentation to measure speed and attitudes of the aircraft themselves, as well as a host of dynamic, thermodynamic, cloud physics and radiation parameters at a rate of 1 per second. Fig. 1 summarizes the data used for this study. Six days are studied, which represent a range of convective activity and synoptic forcing. A squall line and the rainy air in its wake are represented on Julian Day 255 (12 September 1974). Organized, slowly traveling cumulonimbus lines quite different from the squall line, but probably more representative of bands in the Intertropical Convergence Zone, occur on Days 251 and 257. Day 252 was a day of widespread convection organized into mesoscale "blobs." On all of the above days, multilevel flights were designed to investigate the mesoscale weather system, rather than its constituent clouds. The length of a typical straight and level flight leg was 15–30 min, which

² Emmitt has expanded his data set to about 80 events and reports (personal communication) that the results are similar to those of the 1978 paper.

³ Some parts of this section appeared in a preliminary report on this project given by Zipser and Miller (1978).

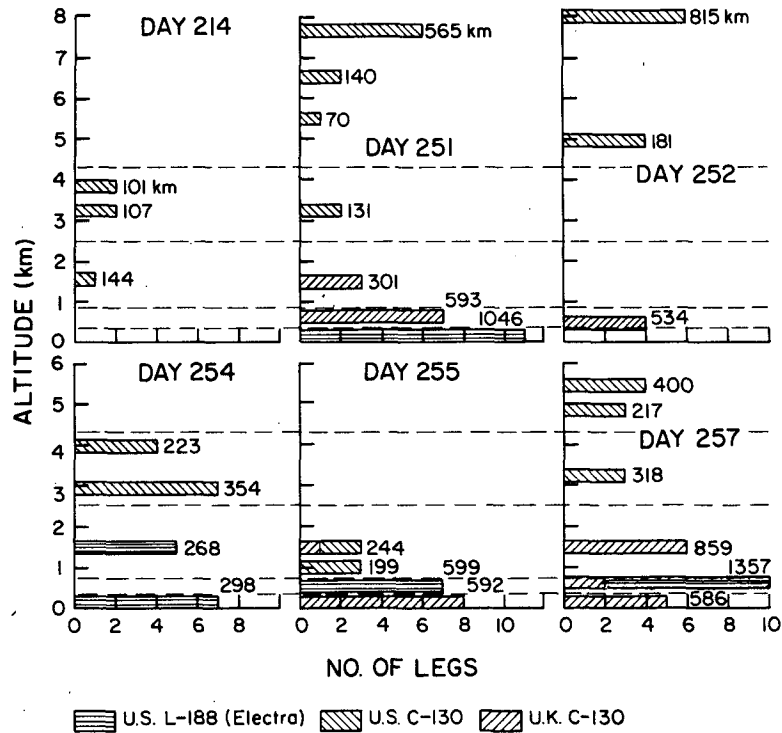


FIG. 1. Summary of aircraft data used in this study. Numbers to the right of bar graphs indicate total length of legs used in kilometers for each day and for each altitude. Dashed lines denote altitude class intervals used in the analysis.

corresponds to 90–180 km at an airspeed of 10 m s^{-1} . On Days 254 and 214, the flight plans were designed to intercept repeatedly the more active parts of relatively isolated cumulus congestus to cumulonimbus cloudiness. The flight legs were correspondingly shorter, ~ 5 min or 30 km. Examination of the flight films for these days suggest that the convective centers were not consistently intercepted, so that the data are more like those of the other days than if all penetrations were “successful.” Hence the same method of analysis can be used for all six days. We assert that these data are a reasonably representative sample of GATE convection. This assertion is supported in Zipser and LeMone (1980).

The different shadings in Fig. 1 are for the three aircraft. These are the U.K. C-130, operated by the U.K. Meteorological Research Flight (MRF), the U.S. C-130 of the National Oceanographic and Atmospheric Administration, and the L-188 (Electra), flown by the U.S. National Center for Atmospheric Research (NCAR). The data for the two U.S. aircraft are available from the U.S. National Processing Center (NPC) for the GATE Aircraft Standard Data Sets, WDC-A (1977). The U.K. data are from the MRF NPC.⁴ In all cases the standard data

sets are composed of 1 s values of flight level meteorological parameters as well as the aircraft navigation and attitude parameters.

b. Processing procedure

The vertical velocity (w) of the air is the vertical wind velocity relative to the aircraft minus the vertical velocity of the aircraft relative to the earth. The methods used to accomplish these measurements have evolved so that relative accuracy near 0.1 m s^{-1} and absolute accuracy of order 1 m s^{-1} is readily attained. This has been facilitated by the incorporation of Inertial Navigation Systems (INS) into research aircraft instrument systems. With an INS the aircraft’s vertical velocity (V_z) is actually measured and recorded if the INS has a full three-axis set of accelerometers. In the GATE aircraft data, however, most of the INS equipped airplanes recorded only the raw vertical accelerations which requires further significant processing before use in the gust equation. Only the NOAA C-130 data system had the capability of Kalman (1960) filtering the raw V_z output from the INS and consequently recorded a usable V_z . The algorithm used in computing w from both the U.K. and NOAA C-130’s was identical and is shown in Eq. (1):

⁴ All data are available from the GATE NPC WDC-A, located at the National Climatic Center, Asheville, NC 28801.

$$w = V_z + U \cos\theta(\tan\alpha \cos R - \tan\beta \sin R - \tan\theta) + L \cos\theta \frac{d\theta}{dt}, \quad (1)$$

where

- V_z aircraft vertical velocity (m s^{-1})
- U true air speed (m s^{-1})
- θ pitch angle
- α attack angle
- R roll angle
- β side slip angle
- L the distance (longitudinal) in meters between the accelerometers and the vanes.
- t time.

Since V_z was not available on the 1 s^{-1} NPC product for the NCAR Electra, Eq. (2) was substituted:

$$w = \frac{dP_A}{dt} + U \cos\theta(\tan\alpha \cos R - \tan\beta \sin R - \tan\theta) + L \cos\theta \frac{d\theta}{dt}, \quad (2)$$

where P_A is the pressure altitude calculated using the GATE mean atmosphere and a running mean value of 5 s used to filter out high-frequency noise. Further, the Electra angle of attack appeared to have an airspeed dependence which had to be compensated for. This attack angle bias is only present on some days and is a linear function of airspeed for all practical purposes. Horizontal velocities are computed in an analogous manner using the equations which appear in Lenschow (1972).

The data are then processed by leg. A leg mean is computed after rejection of data flagged as questionable during previous editing by the GATE NPC. Any points on the remaining data lying farther than 5σ (standard deviation) from the mean are rejected. Since some runs have a number of bad points, computation of σ and re-editing is done three times. Experience showed, even for the most extreme squall passages, that rejection of extreme points did not affect the results appreciably.

c. Definitions of drafts and cores, and analysis technique

The events are divided into two types, illustrated in Fig. 2. To be called a draft, the vertical velocity must be continuously positive (negative) for 500 m and exceed an absolute value of 0.5 m s^{-1} for 1 s. Cores are the stronger portions of the stronger drafts, defined by requiring that upward (downward) vertical velocity be continuously greater than an absolute value of 1 m s^{-1} . The diameter of an event is defined as the product of the duration of the event in seconds and the true airspeed. As we see from

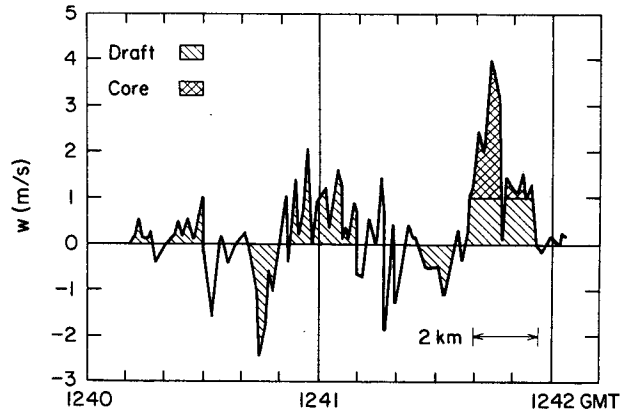


FIG. 2. Time series illustrating definition of drafts and cores, adapted from US C-130 at 5471 m, Day 257. An updraft has to reach 0.5 m s^{-1} and be positive for 0.5 km ($\sim 5 \text{ s}$) or more; a core has to have w of at least 1 m s^{-1} for 0.5 km or more. Downdrafts and downdraft cores are defined in the same way. Note that the draft at the right has two cores.

the figure, all cores are contained in drafts. Further, although the number of drafts is normally greater than the number of cores, the reverse may be true. That is, a single draft may contain several cores.

The definitions, though somewhat arbitrary, were obtained after considerable trial and error, using vertical velocity records for several days. The objective was to try to separate meaningful convective events (cores) from "turbulence" (drafts). Conceptually, cores would be responsible for considerable transport of mass, moisture and momentum. Drafts, on the other hand, would be less well-correlated with excursions of heat, moisture or momentum. Our examination of momentum transport by drafts and cores supports this. The 1 m s^{-1} criterion improves correlation of vertical velocity with other parameters and allows a reasonable sample. Events of smaller horizontal dimension than drafts are not counted as a matter of practicality—there are too many to process in a reasonable amount of time. The treatment is analogous for downdrafts and downdraft cores.

From Section 3b, we do not know the vertical velocity to better than 1 m s^{-1} (absolute). Hence, vertical velocity events are selected after subtracting out the leg mean vertical velocity.⁵ Because of this procedure, a particularly strong positive excursion will force the vertical velocity to remain negative for a minute or more, creating spurious downdrafts several kilometers in diameter. Furthermore, the few very strong events occurring during squall

⁵ An alternative would have been to compute updrafts and downdrafts relative to an environmental velocity. However, the aircraft generally did not fly long enough outside of cloud to define it.

line passage tend to dominate some of the statistics. The effect of these events, and their effect of the uncertain leg mean are discussed below. Large, weak downdrafts also occur in the data of one of the aircraft owing to instrumental problems.

For each flight leg, we now have the wind velocity components u (positive eastward), v (positive northward), and w (positive upward), potential temperature θ and mixing ratio q , and the beginning and ending times for each of the updraft or downdraft cores. Averages of these quantities are then computed relative to the leg average via

$$\bar{b} = \frac{1}{N} \sum_{i=1}^N b_i,$$

where b the quantity measured and N the total number of good data points in the event. Rejection of the extreme points in particularly strong convection was not a significant problem; generally, no more than one or two points were eliminated, and as often as not these were spikes rather than reasonable data. In this study, we deal mainly with the vertical velocity data; clearly, there is potential for future output on momentum fluxes by drafts and cores, and also on thermodynamic fluxes, although the latter must be treated with extreme caution (Lenschow and Pennell, 1974; LeMone, 1980).

4. Results

For each flight day, each aircraft and each altitude, the distributions of draft diameter, mean vertical velocity, maximum vertical velocity and mass flux were tabulated. An example is presented in Fig. 3, and a summary of all the data in Figs. 4a–4d. The mass flux in each draft is given by the product $\rho \bar{w} D$, where ρ is air density, \bar{w} the mean vertical velocity in the draft and D the draft diameter, and is expressed *per unit horizontal distance across the aircraft track*.⁶ To facilitate comparisons between updraft and downdraft statistics, \bar{w} is defined positive downward for downdrafts in all plots. Analogous histograms for cores are superimposed on the histograms for drafts, and analogous cumulative frequency distributions for cores are presented alongside those for drafts.

⁶ An estimate of the total mass flux in a particular draft would be given by $(\pi/4)\rho \bar{w} D^2$, assuming that it is circular. For our main purpose of estimating the frequency distribution of mass flux in drafts and cores, it is appropriate to compute mass flux per unit transverse distance, or $\rho \bar{w} D$. This removes any error associated with arbitrarily assuming the shape of the draft. In the limit, computing the mass flux in this way gives the correct total mass flux over an area if the aircraft flew increasingly fast over an increasingly large number of parallel tracks whose spacing approaches zero.

a. Sample day and altitude: Day 257, 4800–5500 m

The aircraft data set for 14 September 1974 has the most complete coverage of altitudes for which w can be computed, of any day in GATE. The legs through the cumulonimbus lines in the middle troposphere, three at 4800 m and four at 5500 m, have been combined for presentation, because it was obvious that any real differences between those altitudes were dwarfed by the sampling differences. In this case, the 4800 m legs happened to penetrate proportionately more vigorous cumulonimbus cores than did the 5500 m legs.

The sample distributions for the seven legs are fairly typical, and are presented in Fig. 3. There are many more small drafts than large drafts, and there are many more weak drafts than strong drafts. The cumulative frequency distributions of both diameter and vertical velocity are approximately log-normal. The above statements are also true for cores, although the histograms are much more flat.

Updrafts are narrower and stronger than downdrafts. On this particular day, very few downdraft cores were sampled; compared to updraft cores, they tended to be both small and weak. The distributions for mass flux in both drafts and cores show that not only are updrafts/cores generally stronger than downdrafts/cores, but that an appreciable fraction of the updrafts/cores have greater mass flux than the highest observed in downdrafts/cores, respectively.

We have plotted distributions of diameter, mean vertical velocity \bar{w} , maximum vertical velocity magnitude w_{\max} and mass flux for the cores and drafts at all altitudes on all six days. They are not included in this paper, partly because space does not permit it, and partly because the differences between days are less important than the similarities. Compared with the middle troposphere statistics on other days, Day 257 exhibits somewhat weaker drafts and cores. In the mid-troposphere, downdraft cores are particularly weak and infrequent. However, Day 257 was quite typical of other days in the way the draft and core statistics varied with height. Cores were smaller, almost by definition. The 10% level for size was 2.1 km and the median 0.9 km for updraft cores. Downdraft cores were smaller yet, but the sample was too small for meaningful statistics.

b. Combined statistics for all days, summarized by altitude group

Most flight days did not have an adequate data set at enough altitudes for meaningful statistics to be computed. In summarizing the overall data set, a compromise was necessary between vertical resolution and sample size. We were influenced by evi-

DIAMETER, VERTICAL VELOCITY, AND MASS FLUX DISTRIBUTIONS, FOR DAY 257
(14 September 1974), US-C130, 4800-5500 m

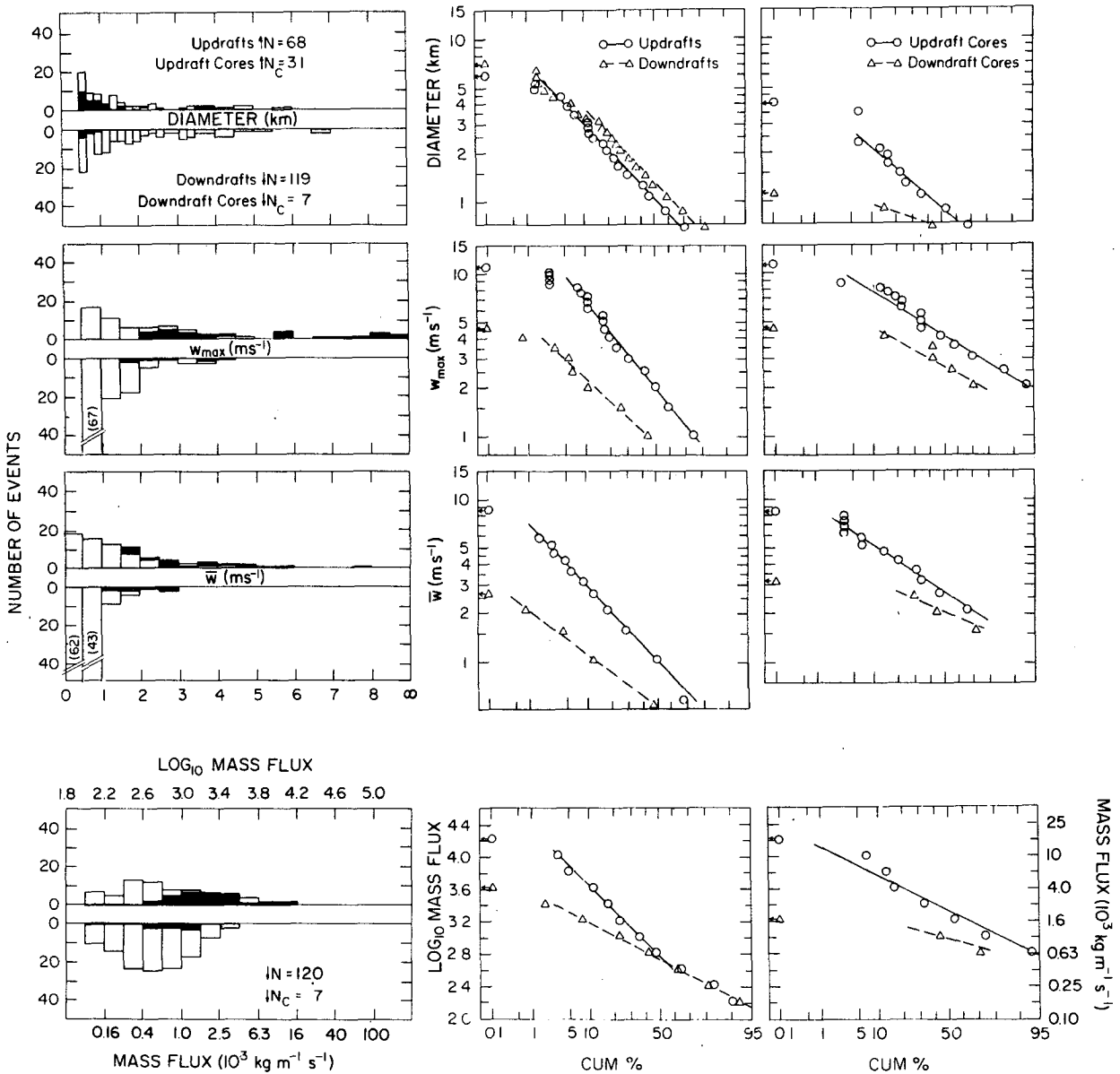


FIG. 3. Diameter, vertical velocity and mass flux distributions for Day 257 (14 September 1974), at 4800-5500 m, from the US C-130. In the left column of the figure, the upward extending bars of the graph are for updrafts, the downward extending bars are for downdrafts. For updraft: (1) \blacksquare bars: total length is total number of drafts; black is number of cores; (2) \square bars: total length is total number of cores; clear, number of drafts. Downdrafts and downdraft cores are coded analogously. Cumulative distributions for drafts are in the middle column; cumulative distributions for cores are in the right column.

dence, presented below, that the variation of the statistics with altitude is relatively small, at least above the lowest kilometer, while corresponding variations from leg to leg and from day to day were quite large. Therefore, we chose to average the data into five rather coarse class intervals of altitude. It was possible to obtain reasonable class intervals

with approximately equal sample size, with respect to total number of legs and with respect to total number of drafts sampled (Table 1, Fig. 1). The results are given in composite figures by diameter (Fig. 4a), w_{max} (Fig. 4b), \bar{w} (Fig. 4c) and mass flux (Fig. 4d). Diameter distributions vary little with altitude, for drafts or cores. As in the example above, the

(a) DIAMETER DISTRIBUTION BY ALTITUDE INTERVAL - ALL DAYS

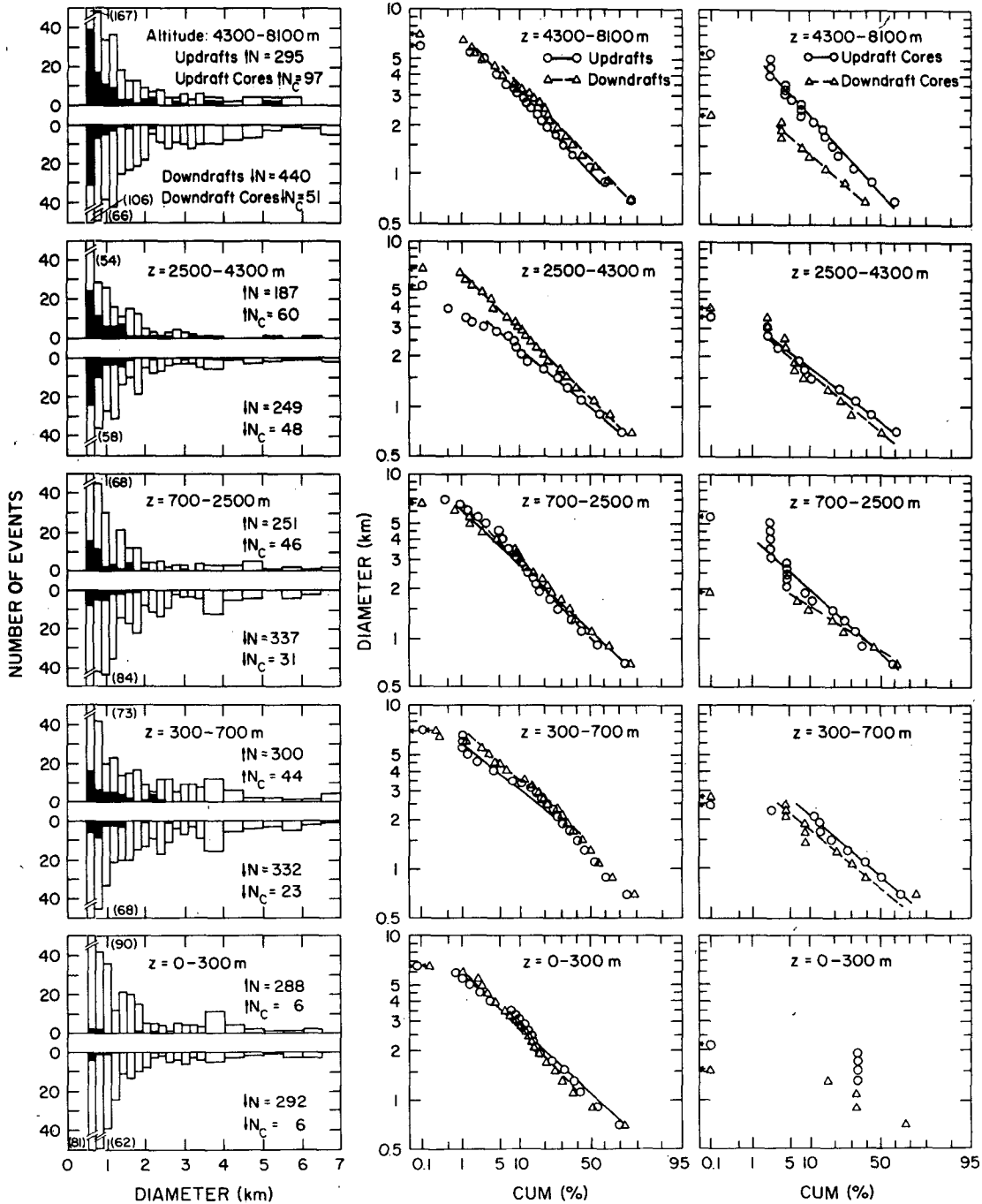


FIG. 4. Combined draft and core statistics, summarized by altitude group. Bar graphs are as in Fig. 3, except that dashed line denotes 1 core, no drafts.

composite data set has many more small than large drafts, the distribution being approximately log-normal.⁷ Updrafts tend to be smaller than down-

drafts except at low levels, where the distributions are nearly indistinguishable. On the other hand, updraft cores tend to be larger than downdraft cores. Most cores are smaller than 2 km across, and cores as large as 4 km in diameter are extremely rare.

The vertical velocity distributions in Figs. 4b and

⁷ Drafts with diameters > 7 km have been eliminated from the data set.

(b) MAXIMUM 1-SECOND VERTICAL VELOCITY (w_{MAX}) DISTRIBUTION BY ALTITUDE INTERVAL - ALL DAYS

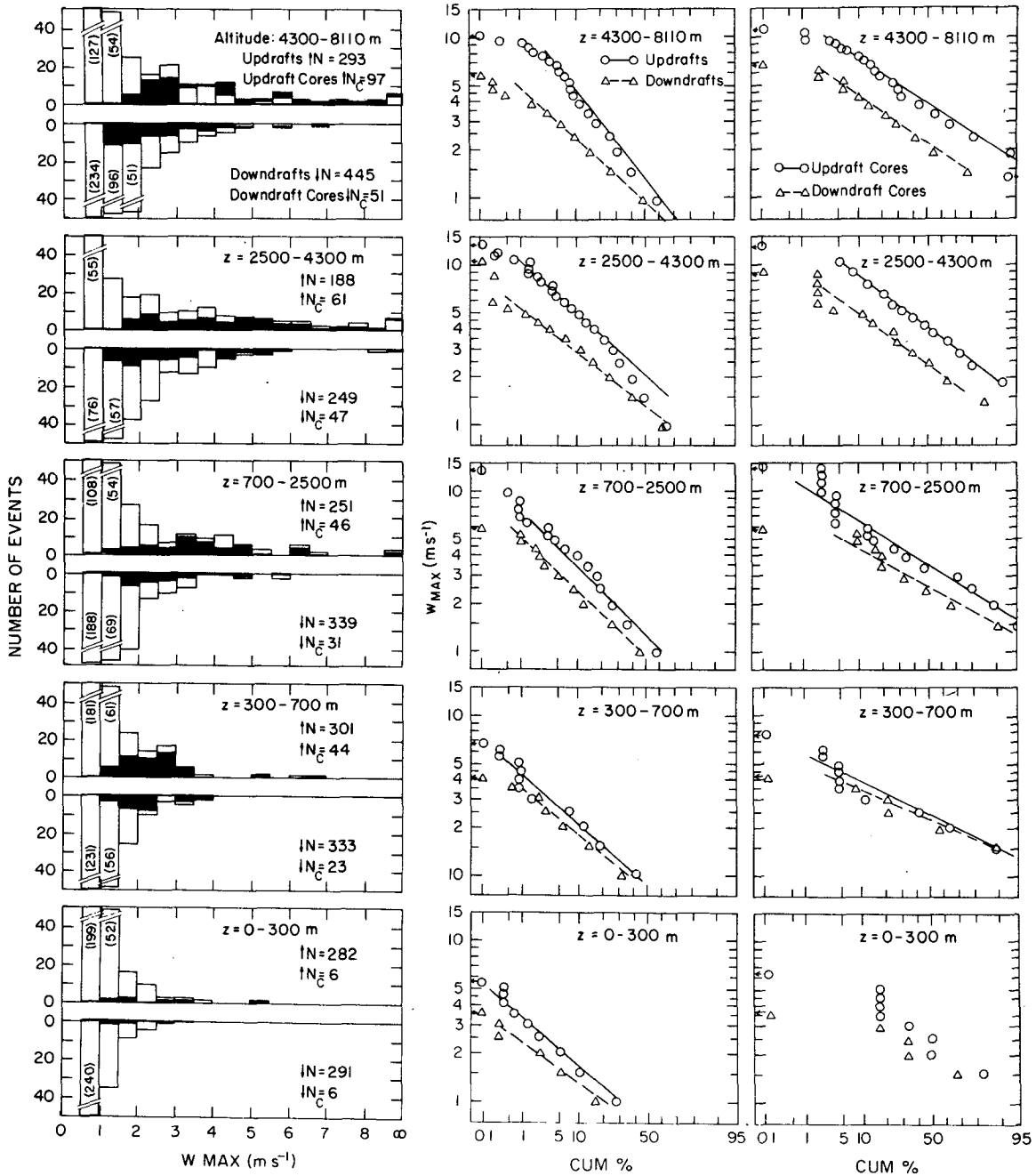


FIG. 4. Continued

4c are more skewed than are the diameter distributions, with a very large number of weak drafts and only a few strong drafts. The \bar{w} curves are similar to those of w_{max} , but show values about half as high. The distribution of cores is flatter, reflecting the elimination of events with smaller vertical velocity. The number of cores and intense drafts is roughly

the same. Some differences are the result of a draft containing more than one core, or a strong vertical velocity event within a draft too narrow ($\geq 1 m s^{-1}$ for $< 500 m$; see Fig. 2) to be counted as a core.

Perhaps the most striking result is the rarity of really strong drafts and cores compared to those observed in cumulonimbi over land. *No core in the*

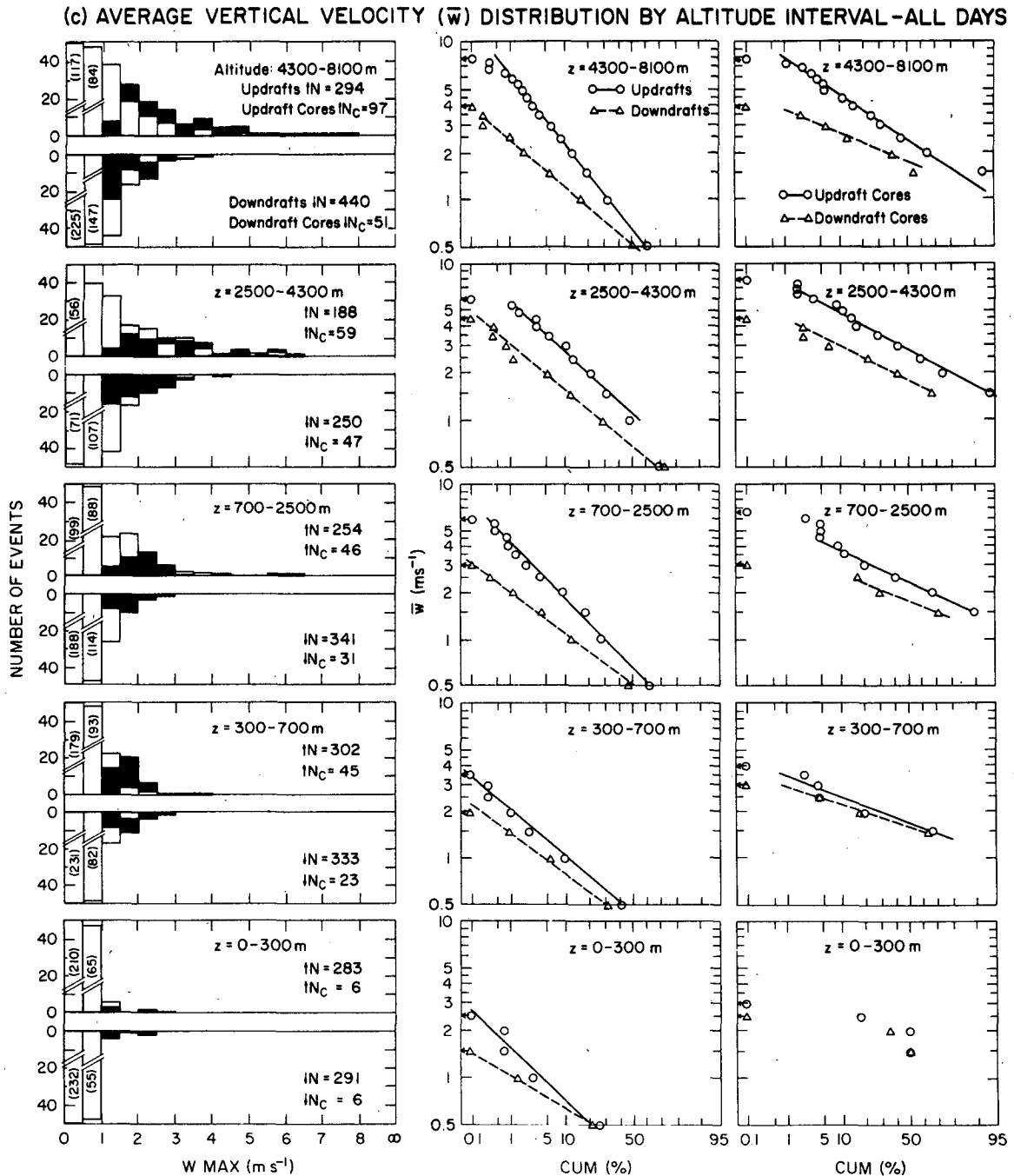


FIG. 4. Continued

entire data sample has a mean vertical velocity as great as 8 m s^{-1} , or a maximum one-second vertical velocity as great as 15 m s^{-1} . In all of GATE, the greatest vertical velocity was measured in a cumulonimbus in the tropical depression of 15 July, and was only slightly stronger than the maximum in the above data set, with \bar{w} of 9 m s^{-1} and w_{max} of

17 m s^{-1} (Zipser and Gautier, 1978).⁸ That case was not included in the current study, because only one penetration of significant cumulonimbus drafts was made during that entire flight.

⁸ We have since noticed that an event encountered near 12°N by the NOAA C-130 while enroute to the GATE B-array on 2 September also had a w_{max} of 17 m s^{-1} .

(d) MASS FLUX DISTRIBUTION BY ALTITUDE INTERVALS - ALL DAYS

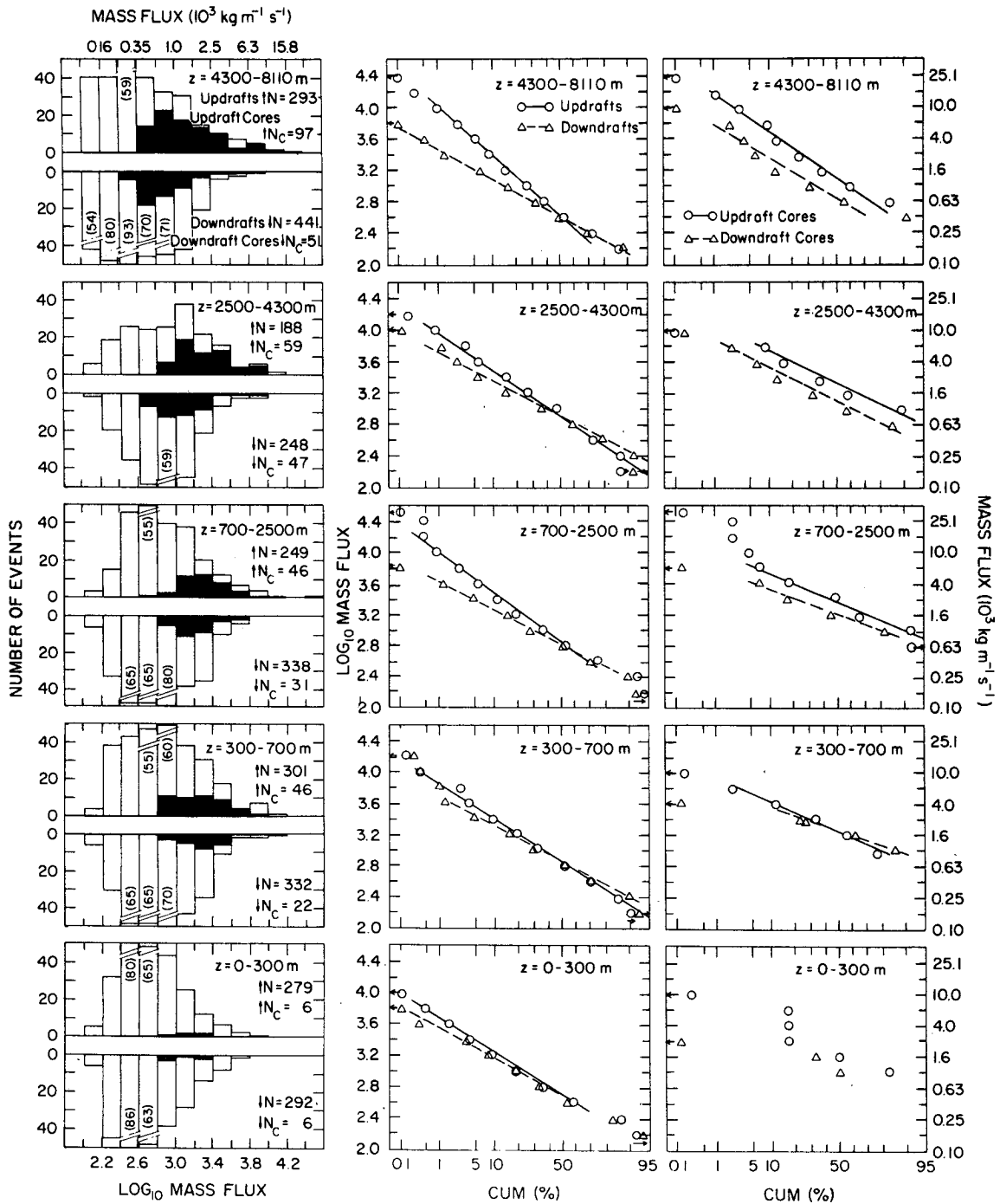


FIG. 4. Continued

The mass flux distributions (Fig. 4d) required a more compressed logarithmic scale than used for either diameter or vertical velocity, as mass flux varies from $100 \text{ kg s}^{-1} \text{ m}^{-1}$ in the most insignificant

drafts to $33\,000 \text{ kg s}^{-1} \text{ m}^{-1}$ in the updraft at the leading edge of the 12 September squall line during a pass at 1500 m altitude. For reference, recall that an aircraft passing through the center of a minimal core

TABLE 1. Number of legs by Julian Day and altitude range. Total leg length (km) follows number of legs.

Altitude range (m)	Julian Day						Total	Average leg length (km)
	214	251	252	254	255	257		
4300–8100	0 (0)	9 (775)	10 (996)	0 (0)	0 (0)	7 (617)	26 (2388)	92
2500–4300	4 (207)	2 (131)	0 (0)	12 (577)	0 (0)	3 (318)	21 (1233)	59
400–2500	1 (144)	3 (301)	0 (0)	5 (268)	6 (443)	6 (859)	21 (2015)	96
300–700	0 (0)	7 (593)	4 (534)	0 (0)	7 (599)	10 (1357)	28 (3083)	110
0–300	0 (0)	11 (1046)	0 (0)	7 (298)	8 (592)	5 (586)	31 (2522)	81
Total	5 (351)	32 (2846)	14 (1530)	24 (1143)	21 (1634)	32 (3737)	127 (11241)	89

with \bar{w} of 1 m s^{-1} and a diameter of 10^3 m senses a transport of $10^3 \text{ kg s}^{-1} \text{ m}^{-1}$ through an altitude where the density is 1 kg m^{-3} ($\sim 2 \text{ km}$).

c. Mid-tropospheric and cloud base distributions compared

For the stronger drafts, and for cores, a rather marked mass flux variation with height was observed in Fig. 4d for updrafts but not for downdrafts. At low altitudes, there was little difference between the strength of updrafts and downdrafts. However, by the middle troposphere, the stronger updrafts and updraft cores had considerably greater mass flux than did the corresponding downdrafts and downdraft cores. This is reflected in the steepening of the slope of the updraft curves and near-constancy of the slope of the downdraft curves. For the flight legs between 4300 and 8100 m altitude, updraft cores had about twice the mass flux of downdraft cores.

The histograms in Fig. 4d not only show this asymmetry between updraft and downdraft core strength, but also serve as a reminder that there were twice as many updraft cores as downdraft cores. The total mass flux in the mid-tropospheric updraft cores was actually four times that in downdraft cores. (Recall, the abscissa is logarithmic!) In contrast, the mass flux statistics of updrafts and downdrafts near cloud base are nearly identical even though there were twice as many updraft cores as downdraft cores. It should be noted here that our results near cloud base are in excellent agreement with Emmitt's (1978) draft statistics based on tethered balloon data. He also finds twice as many updraft as downdraft events at cloud base, and a rather small difference between updrafts and downdraft events with respect to both size and diameter.

d. Diameter, vertical velocity and mass flux in cores as functions of height

While careful inspection of Fig. 4 gives rough indications of variability with height, it is desirable to inspect these variations more precisely. For the population of updraft and downdraft cores, values of each parameter were extracted at the 50% level

(median) and at the 10% level (only 10% of cores are more intense). This was done for each altitude interval, and plotted at frequency-weighted mean altitudes (see Table 1) of 0.5, 1.5, 3.2 and 6.0 km. The 0–300 m altitude interval had only a few cores and was not used. The result is given in Fig. 5.

Core diameters are quite small, and change little with height. Median core diameters are everywhere less than 1 km. The 10% level of updraft core diameters is $\sim 2 \text{ km}$ near cloud base and in mid-troposphere, and somewhat less in between.

Vertical velocities in updraft cores increase with height through the lowest 3 km only. Downdraft cores become stronger with height only to 1.5 km. Again, we note that all statistics for w_{max} could be well approximated by multiplying the like statistic for \bar{w} by 1.6–2.0. Even for strong (10%) updrafts, the change with height is rather modest, from \bar{w} of 2.5 m s^{-1} near cloud base to only 4–5 m s^{-1} in mid-troposphere.

The mass flux in strong (10%) updraft cores is only slightly greater in the mid-troposphere than near cloud base, while median updrafts have less mass flux higher up than near cloud base. Mass flux in both median and 10% downdrafts is greater near cloud base than at any higher level. This is consistent with Fig. 4d, which shows that distributions for updraft cores are much different (stronger) than for downdraft cores in the mid-troposphere, while the distributions are nearly identical at cloud base.

It is important to keep in mind that the height variations depicted in Fig. 5 are comparisons of statistics obtained from different altitude ranges and do not necessarily represent variations with height following given sets of cores rising from the surface. For example, it is entirely possible that some median cores at cloud base never reach the middle troposphere at all, and that median cores in the middle troposphere become organized into identifiable entities somewhere above cloud base.

e. Effects of uncertain mean vertical velocity on results and conclusions

Our analysis technique subtracts out the averaged mean leg vertical velocities before counting

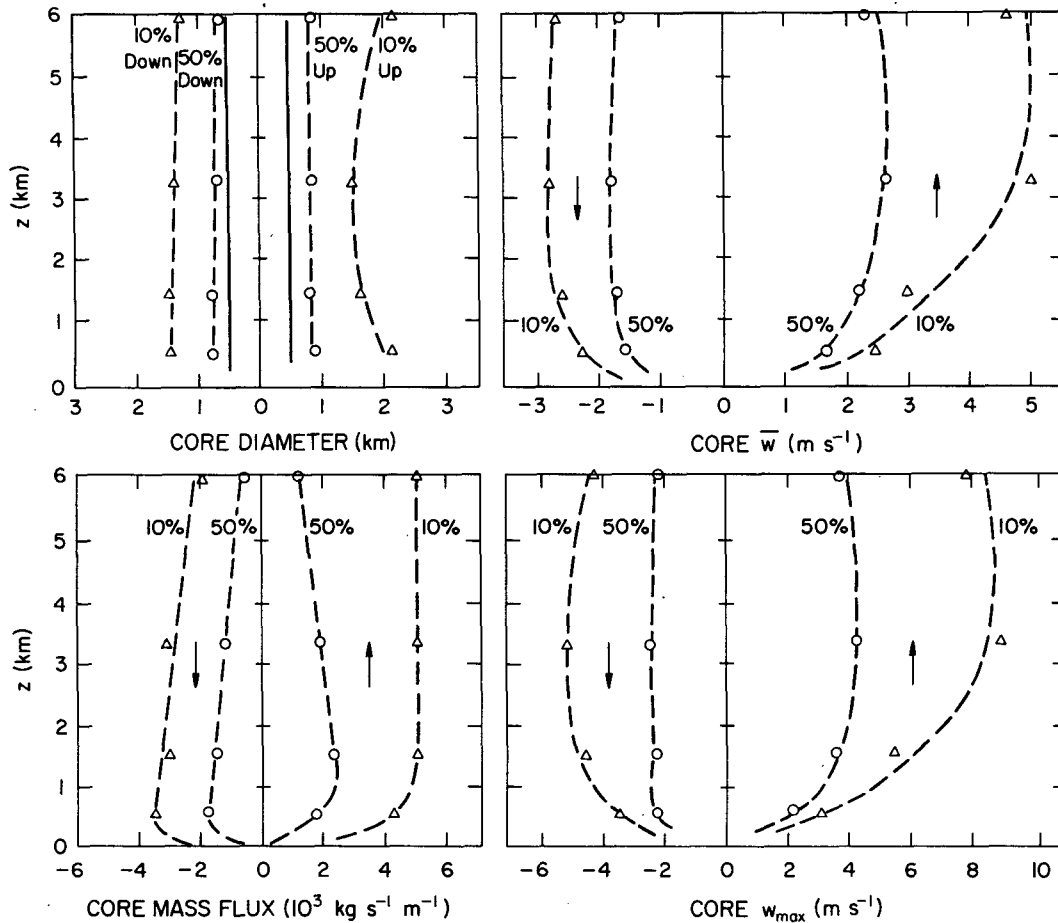


FIG. 5. Variation with altitude of median (50%) and 10% level (stronger than 90% of the population) updraft and downdraft cores, with respect to core diameter, mean vertical velocity of cores, maximum 1 s vertical velocity within core, and core mass flux.

drafts and cores. An estimate of the error thus introduced can be made by considering the effect of a single major event. Suppose that a large, strong updraft with $\bar{w} = 5 \text{ m s}^{-1}$ is intercepted by the aircraft over a 2 km distance. The contribution to the leg-averaged \bar{w} is 5 m s^{-1} multiplied by the fraction of the leg occupied by the event (2% of a 100 km leg), or 0.1 m s^{-1} . Most events are weaker than that, so it seems fair to estimate that this "zero offset" error is the order of 0.1 m s^{-1} . It is likely to be most significant in the mid-troposphere, where the strongest drafts occur.

The most serious consequence of the zero offset error is to create artificial "downdrafts" of large diameter for flight legs dominated by strong updrafts. The reason is simply that the vertical velocity trace, before or after a *true* downdraft, may be near-constant at a *true* value of zero. But due to the 0.1 m s^{-1} offset, the computed vertical velocity is -0.1 m s^{-1} until the next updraft is intercepted. A large and strong downdraft would have the analogous effect of creating artificially large updrafts; however, such cases are rare.

The most important error introduced by the zero offset is an artificial increase in the frequency of downdrafts of large diameter. To a certain extent, these were spotted and removed from the data set but, undoubtedly, some were not, and that was the principal reason for the arbitrary truncation of all diameter distributions at 7 km.

Two other sources of introduced error remain. First, updraft speeds are underestimated by precisely the value of the zero offset, on the order of 0.1 m s^{-1} . Second, the diameter of updrafts may be slightly underestimated. (Similarly, downdrafts are overestimated in both size and speed.)

The above offset means that the bar graphs for updraft and core vertical velocity distributions are too far to the left by $\sim 0.10 \text{ m s}^{-1}$, and the downdraft and core w distributions too far to the right by the same amount, if we assume the events are similar in shape.

The effect of the offset on size distribution is more difficult to assess, since it depends directly on the shape of the drafts and cores. The offset will tend to exaggerate the size difference between updrafts and

downdrafts, artificially increasing the size of downdrafts and decreasing the updraft diameter. We attempted to eliminate this effect in the course of the analysis.

We examined the impact of vertical velocity error on mass flux distribution directly. In the "worst case," vertical velocity offsets altered the mass flux of significant individual events by 10%. This is certainly tolerable in view of the sampling errors.

An important final point is that this class of error is far more important for drafts than for cores. The cores are generally steep-sided, so the effect on diameter should be insignificant, and vertical velocity errors of order 0.1 m s^{-1} are hardly significant for cores.

5. Summary and conclusions

We have analyzed a unique set of data based on numerous aircraft penetrations of cumulonimbus clouds over the tropical eastern Atlantic. Probably for the first time, this set makes it possible to describe statistics of convective drafts in ordinary disturbed weather over a tropical ocean from direct measurements of in-cloud properties over a wide range of altitudes. We summarized the properties of two kinds of events: drafts, requiring only that vertical velocity be continuously positive (negative) for 500 m and exceed an absolute value of 0.5 m s^{-1} for 1 s; and cores, the stronger portions of the stronger drafts, requiring that upward (downward) vertical velocity be continuously greater than an absolute value of 1 m s^{-1} for 500 m. For six days of GATE in which cloud penetrations were made at more than one level, statistics of cores and drafts have been presented, with the following results:

1) Their diameter, average vertical velocity, maximum vertical velocity magnitude and mass flux are approximately log-normally distributed within each altitude group.

2) Above cloud base, downdrafts are somewhat larger than updrafts, and considerably weaker than updrafts. Near and below cloud base, downdrafts are nearly the same size as updrafts, and only slightly weaker.

3) Downdraft cores tend to be smaller than updraft cores at all altitudes, and are about two-thirds as frequent.

4) Vertical velocity and mass flux in downdraft cores are less than those in updraft cores, except near cloud base where updraft and downdraft cores are about equally strong.

5) In the middle troposphere, only 10% of the GATE updraft cores have diameters in excess of 2 km, and only 10% of updraft cores have mean vertical velocity as great as 5 m s^{-1} .

In Part II (Zipser and LeMone, 1980), further aspects of these results are presented, their representativeness is evaluated, comparison is made with other data sets, and a synthesis of these findings leading to construction of model GATE convective cores is given.

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