

Cumulonimbus Vertical Velocity Events in GATE. Part II: Synthesis and Model Core Structure

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(Manuscript received 21 March 1980, in final form 18 July 1980)

ABSTRACT

The properties of convective drafts and cores are presented in Part I. By our definition a convective updraft must have a positive vertical velocity for 0.5 km, and exceed 0.5 m s^{-1} for 1 s; a convective updraft core must exceed 1 m s^{-1} for 0.5 km. Downdrafts and downdraft cores are defined analogously. Here the properties of the drafts and cores are compared to results of previous work. In addition, the implications of the results in Part I are discussed.

GATE cores and drafts are comparable in size and intensity to those measured in hurricanes but weaker than those measured in continental thunderstorms. The lesser intensity seems related to the nearly moist adiabatic GATE sounding. The mass flux by GATE cores is consistent with large-scale requirements. It is fairly evenly distributed over a range of core size and intensity. Updraft core vertical velocity and diameter are positively correlated, primarily the result of a few large strong events.

The vast majority of GATE convective cores are sufficiently weak, with mean vertical velocities $< 3\text{--}5 \text{ m s}^{-1}$, that the time scale for air starting at cloud base to reach the upper troposphere can be in excess of 1 h. The microphysical implications of such long time scales are discussed. They include large fractional rainout from the warm part of the cloud, the presence of ice at relatively warm temperatures, and rapid decrease of radar reflectivity with height above the 0°C level.

Usually the clouds in GATE were part of a larger, organized mesoscale system. The typical distribution of cumulonimbus clouds, cores and drafts in such a system is synthesized by combining our results with other GATE results. A schematic updraft core and downdraft core in the middle troposphere are presented, emphasizing that these entities were rather narrow and weak in GATE clouds.

1. Introduction

In Part I of this two-part study [LeMone and Zipser (1980) hereafter referred to as LZ], we described the data set of aircraft penetrations of GATE cumulonimbus clouds, the six days chosen for detailed study, and the statistical distributions of diameter, vertical velocity and mass flux for convective events. The statistics for drafts were somewhat different from those for cores. For our purposes, the positive vertical velocity events were divided into drafts (vertical velocity $w > 0$ for a horizontal distance $\geq 500 \text{ m}$ and $w > 0.5 \text{ m s}^{-1}$ for 1 s ($\sim 100 \text{ m}$) and cores ($w > 1.0 \text{ m s}^{-1}$ continuously for $\geq 500 \text{ m}$), with definitions of downdrafts and cores analogous.

In Part II, we discuss the representativeness of the data sample, and compare the GATE statistics with those from cumulonimbus in other parts of the world. From the LZ data set we compute core mass flux distribution as a function of core diameter and vertical velocity, the fractional area covered by cores and drafts, and the correlation between

diameter and vertical velocity for cores. Finally, we combine the data set with other observations to describe the typical location of drafts and cores in a GATE convective system, and we present a schematic model of a "typical" GATE convective updraft and downdraft core.

2. Representativeness of the data sample

We have chosen the days in the sample to make the data as representative of GATE as is possible. We assume that the data gathered on a given day are representative of that day. We can support but not "prove" these assertions; however, there are simple tests we can perform to lend some plausibility to them.

In almost all cases, aircraft flight legs were chosen without reference to individual convective towers, as the convective clouds were usually embedded in mesoscale cloud systems in which visibility was quite limited. On two of the six days when isolated convective clouds were clearly visible, an attempt was made to penetrate their most active portions, but since the flight track was set well outside the cloud, these attempts were not always successful. *The result is a data set that resembles a*

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

random sample of mesoscale disturbed areas, which necessarily includes growing, mature and decaying convective clouds. It also includes drafts in the vicinity of those clouds, or persisting in the region after the convection has decayed. This is in sharp contrast to the Thunderstorm Project (Byers and Braham, 1949), where the data sample consists mostly of active convective towers during their growth phase. The GATE sample may be the first to be reported in the literature that investigates convective clouds within disturbances rather than isolated clouds, excepting the study of drafts within hurricanes by Gray (1965).

The particular six days were chosen from among all the GATE flight days in a way that aimed at 1) frequent sampling of disturbed areas, 2) nearly equal sampling opportunities at several altitudes, and 3) a variety of weather types. Only Day 257 met the first two criteria completely. Days 214 and 254 had missions primarily for the purpose of penetrating small cloud systems in which the chances of encountering growing towers were good, although those systems themselves were relatively small. The aircraft flew repeated crossings of cumulonimbus lines on Days 251 and 257 at a number of different altitudes. These lines were good examples of relatively small organized mesoscale convective bands within the intertropical convergence zone. Box patterns were flown on Days 252 and 255 which encountered active portions of significant disturbances several times, although the altitude coverage was not uniform.²

Several authors have described the modulation of the rainfall in GATE by synoptic-scale wave disturbances (Thompson *et al.*, 1979; Frank, 1979). The six days chosen for the current data sample are well distributed over most phases of the waves.

Two rough checks were made to determine whether the mass flux in updraft cores sampled in this study were in agreement with independent estimates. The first compares the mesoscale mass flux computed for a given level with that measured in updraft cores. On Day 257, the upward mass flux in the cumulonimbus line was estimated by analyzing the mesoscale wind field at each

altitude, and integrating the mesoscale mass convergence with height via the two-dimensional mass continuity equation. The mass flux thus computed is $15\,000\text{ kg s}^{-1}\text{ m}^{-1}$ through the 5 km level.³ The aircraft crossed the line from 4800–5500 m seven times, encountering 31 updraft cores in all (Fig. 3, LZ) which had a total mass flux of $89\,000\text{ kg s}^{-1}\text{ m}^{-1}$, or an average of $12\,700\text{ kg s}^{-1}\text{ m}^{-1}$ for each crossing. While there is no reason to expect the mass flux in updraft cores to correspond exactly to the integrated mesoscale mass convergence, it is encouraging that the two independent estimates are not much farther apart. Similar comparisons were made for other levels on that day, with equally encouraging results.

The second consistency check compares the total mass flux in updraft cores with the cumulus mass flux that would be expected from large-scale considerations. During a typical disturbed period, the vertical velocity in the mid-troposphere on the scale of the 330 km B-scale hexagon, or 10^{11} m^2 , is about $1.5\text{--}2\text{ cm s}^{-1}$ (Thompson *et al.*, 1979; Reeves *et al.*, 1979; Frank, 1979). This is a mass flux of nearly $1.5\text{--}2 \times 10^9\text{ kg s}^{-1}$. Most diagnostic model studies have concluded that mass flux in ascending cumulus towers is greater than the mean mass flux by a factor of 1.5–2 in the mid-troposphere (Nitta, 1977; Ogura and Cho, 1973; Yanai *et al.*, 1973) leading to an estimate over the B-scale area of $2\text{--}4 \times 10^9\text{ kg s}^{-1}$. Assume that each aircraft leg used in this study in the 4300–8100 m altitude range (average leg length 100 km) represents a sample of disturbed conditions that extend in a single band across the 330 km B-scale hexagon. Then we can estimate the mass flux in a disturbed period by multiplying the average mass flux in updraft cores, per flight leg $10^4\text{ kg s}^{-1}\text{ m}^{-1}$ (the product of an average of 4 cores per leg and the mean mass flux per core, $2300\text{ kg s}^{-1}\text{ m}^{-1}$) by 330 km ($3 \times 10^5\text{ m}$), to obtain $3 \times 10^9\text{ kg s}^{-1}$.

The close agreement between the mass flux by cores to estimates from two independent methods suggests (but does not prove) that our sample of convective systems is representative to about a factor of 2. Therefore, our belief is that we have a fair sample. However, we shall demonstrate below that the strongest systems may be underrepresented.

3. Comparison with other data sets

No other data set has been handled in exactly the same way as this one; yet, it is possible to compare the statistics of GATE cumulonimbus with those of other regions.

The closest comparison is to Thunderstorm Project data, which are tabulated by altitude group (Byers and Braham, 1949). The Florida and Ohio

² The most serious sampling defect known to the authors is on Day 255, when the most intense radar echoes of a major squall line were not penetrated, first by chance and then by design, as the strong winds carried off two tethered balloons which posed a potential aircraft hazard near the leading edge. There were penetrations of that strong squall line at 150, 500, 1000 and 1500 m, but not above 1500 m. We chose this day, with all its defects, because no other strong system in GATE was more completely sampled. On Day 252, we computed all statistics for the L-188, which sampled the middle troposphere extensively, but we chose to eliminate those data from the final tabulations, because the angle of attack on that day was measured by a back-up vane which appeared to give suspicious results.

³ This work is part of an extensive case study of the Day 257 cumulonimbus line, which is complete (Zipser *et al.*, 1981).

TABLE 1. Vertical velocity (m s^{-1}) of updraft and downdraft cores compared at 4.5 km altitude from different data sets.

	Thunderstorm Project (Byers and Braham, 1949)	Hurricanes (Gray, 1965)	GATE (This study)
Median updraft core	6.3	3.8	2.9
Strong (10%) updraft core	11.8	6.7	5.0
Median downdraft core	5.8	3.4	1.8
Strong (10%) downdraft core	10.0	5.8	2.9

data were judged to be similar enough to be combined; the resulting data for diameter and vertical velocity were plotted in the same cumulative distribution format (not reproduced) as in Figs. 4a and 4c of LZ. They form about as good a fit to the lognormal distribution as do the GATE data, an interesting fact in itself which has escaped wide notice.

Ostensibly, the Thunderstorm Project drafts are larger than GATE drafts, but allowances must be made for the differences in measurement techniques. Several closely spaced updraft cores would be counted only once by the Thunderstorm Project, which determined the existence of a core, its diameter and its vertical velocity by net vertical displacement of the aircraft, whereas each core would be counted by our 1 s sampling in GATE.

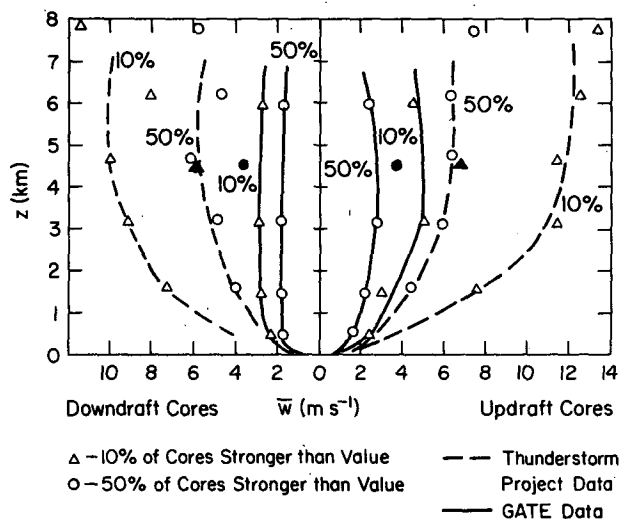


FIG. 1. Mean vertical velocity in updraft and downdraft cores as a function of height, comparing different data sets. The GATE data for strong (10% level) and median (50% level) cores are taken from Fig. 5 of LZ. The Thunderstorm Project Data defined in the same way are adopted from Byers and Braham (1949), Tables 7 and 10. For the 4.5 km level only, data from Gray (1965), Fig. 13, defined similarly, are included (filled symbols).

We believe that the true diameter distributions in the two data sets are very nearly identical.

For vertical velocity, the shapes of the distributions may be similar, but the values are not! *The GATE cumulonimbus cores are much weaker than the corresponding Thunderstorm Project cores.* Fig. 1 compares the two data sets for mean vertical velocity at all heights, and the difference in magnitude is nearly a factor of 3. Remarkably, the variation of updraft strength with height is similar: it increases with height to ~ 3 km, and then remains approximately constant. The Thunderstorm Project downdrafts appear to behave quite differently, irregularly increasing in strength with height to the top of the data set.

Cumulus draft statistics from aircraft in hurricanes were analyzed by Gray (1965), using a technique similar to the one which produced the Thunderstorm Project statistics. His diameter and vertical velocity distributions are also approximately lognormal. His diameter distributions are nearly the same as for the Thunderstorm Project, and by the same reasoning as above, we conclude that the true diameter population in all three data sets is very nearly identical. *The hurricane vertical velocities are much closer to GATE's than to the Thunderstorm Project's* (Table 1, Fig. 1).⁴ Although there is much more that could be said on the subject, this result is consistent with the observation that the mean sounding for the Thunderstorm Project exhibits a rather large amount of conditional instability, while the soundings for disturbed regions in GATE and for the hurricane are more nearly moist adiabatic.

4. Mass flux distribution in cores by diameter and vertical velocity range

The distributions of diameter, vertical velocity and mass flux have been discussed earlier, and are illustrated in Fig. 4 of LZ. But those distributions do not show how the convective mass flux passing through a given altitude range is allocated according to diameter or vertical velocity. This is done in Fig. 2.

With one notable exception, it is fair to conclude that the mass flux in our data set is distributed across a range of diameters and vertical velocities

⁴ More recent vertical velocity data in hurricanes is being analyzed by Paul Willis, NHEML/NOAA, with excellent data quality making it possible to define draft structures much as we have done for the GATE data. His preliminary results (personal communication) indicate vertical velocity distributions rather similar to ours. For example, his distributions are also approximately lognormal, and the maximum 1 s vertical velocity in a rather large sample is $\sim 17 \text{ m s}^{-1}$, as in GATE. In contrast, his measurements in cumulonimbus over the Florida peninsula, reported in part by Hallett *et al.* (1978), show much stronger cores, lending credence to the above comparison between the Thunderstorm Project, hurricanes and GATE statistics.

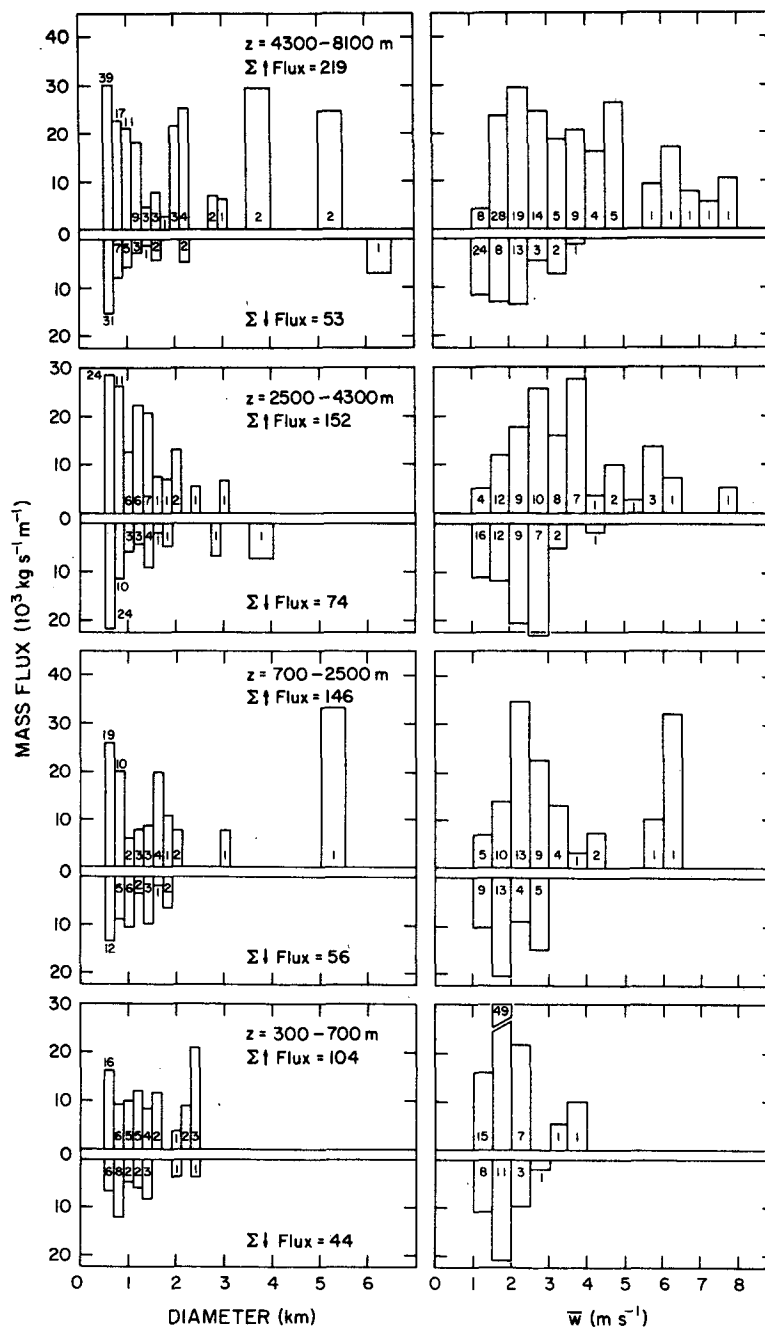


FIG. 2. Mass flux in cores distributed according to core diameter (left) and core mean vertical velocity (right), for each altitude interval. The number of cores in each diameter or vertical velocity class interval is noted within the appropriate bar.

and not unduly dominated by a handful of major events. Typically, the biggest or strongest 20% of the population accounts for 50% of the mass flux. With respect to diameter, a rather small portion of the flux is carried by cores larger than 2 km; with respect to mean vertical velocity, a rather small fraction of the flux is carried by up cores stronger than 5 m s^{-1}

or by downdraft cores stronger than 3 m s^{-1} . Near cloud base, mass flux is nearly uniformly distributed with respect to diameter over the narrow range of observed diameters. It follows that cores which are narrow and weak by almost any standard are not only frequent in GATE, but are important to the vertical transports.

TABLE 2. Fractional length (%) of aircraft legs occupied by drafts and cores.

Altitude range (m)	Drafts		Cores	
	Up	Down	Up	Down
4300–8100	16.9	29.9	4.6	1.8
2500–4300	18.3	30.3	4.8	3.7
700–2500	16.3	25.2	2.1	1.1
300–700	16.6	18.8	1.5	0.8
0–300	15.9	15.7	0.3	0.2

The single exception is in the 700–2500 m range, where a core 5.2 km across with a mean vertical velocity of 6.2 m s^{-1} is responsible for over 20% of the mass flux. This was from a 1500 m pass through the leading edge of the squall line of Day 255. Obviously, our data set is inadequate to decide the true frequency of unusual events such as this as well as their quantitative importance. We have surveyed the vertical velocity data for most days in GATE (including those not analyzed in this paper), and we believe that major events comparable to this one would be encountered occasionally, at most altitudes, but that they would be rare enough not to dominate the mass flux statistics.

The data in Fig. 2 have the potential for comparison with model output. Estimates of the distribution of mass flux as a function of diameter at cloud base can be extracted from spectral diagnostic models (e.g., Ogura and Cho, 1973; Yanai *et al.*, 1973; Nitta, 1977). The cloud base mass flux for each cloud “type” is typically expressed in terms of entrainment rate. Therefore, direct comparison requires an assumed functional relationship between entrainment rate and diameter (usually, entrainment rate is assumed proportional to inverse radius). In regions of significant cumulonimbus convection, the above authors found a bimodal distribution, with mass flux at cloud base concentrated in deep (small entrainment, large diameter) clouds and in shallow (large entrainment, small diameter) clouds. It has been shown by Johnson (1976, 1978) that a spectral model will diagnose greatly reduced mass flux in shallow clouds if the deep clouds include the effects of downdrafts. Our data sample is not large enough to rule out any possibilities, but Fig. 2 does not provide any strong support for a bimodal distribution of mass flux with respect to inverse diameter at cloud base.

5. Fraction of area covered by drafts and cores

For each aircraft leg, we have computed the fraction of leg length occupied by cores and by drafts. The results are summed up over the entire data set by altitude range in Table 2. The fractional leg length

occupied by drafts and cores can be interpreted as fractional area occupied by drafts and cores if we assume that the aircraft legs are randomly chosen with respect to drafts and cores. That is, a hypothetical track parallel to the one actually flown would be equally likely to intersect drafts and/or cores. In the limit, we would obtain the correct fractional area occupied by drafts and/or cores if the aircraft flew increasingly fast over an increasingly large number of parallel tracks whose spacing approached zero.⁵ No assumption about the geometry of cross sections of drafts and/or cores is required.

A more important question than whether fractional leg length is interpretable as fractional area may be, rather, a fraction of *which area*? Aircraft legs averaged 89 km in length (LZ, Table 1). Typically, each end of the leg was in clear air, with the central part of the leg traversing some organized disturbed region which contained all cores and nearly all drafts. The disturbed region may be any shape, but if it was elongated, the aircraft tracks were often chosen such that they crossed its shorter dimension. Therefore, the fractional coverage of line segments in Table 2 may be interpreted as representing fractional coverage of an area, whose short dimension is the aircraft leg length and whose long dimension is the extent of the disturbed region in a direction perpendicular to the aircraft track, typically 100 km or more. Accordingly, it is suggested that the estimates of fractional areal coverage apply to areas of nominal dimensions of 100 km by 100 km.

The results suggest that updrafts occupy 15–18% of the area at most levels, while downdrafts cover 25–30% of the area, (about twice the area of updrafts!) at all levels above clouds base. At or below cloud base, updrafts and downdrafts occupy the same fractional area. Updraft *cores* occupy 1.5% of the area at cloud base, increasing to over 4% coverage in the middle troposphere. Downdraft *cores* occupy about half the area of updraft cores at all levels. These figures confirm the small areal coverage by significant vertical motions.

It is likely that some sampling differences in the data set have influenced the numbers in Table 2. As noted above, both ends of aircraft legs are usually in clear air so a short leg may overestimate the fractional coverage by drafts of a hypothetical 100 km square area. There is some indication that such a positive bias exists in the 2500–4300 m altitude range, where the mean leg length is only 59 km (see LZ, Table 1, for number of legs and mean leg length for each altitude range) and the estimate of fractional area seems high.

⁵ See LZ, Section 4, footnote 4, where the analogous argument is given for mass flux. In Section 2 above, arguments are offered in partial support of the assertion that our sample is random with respect to drafts and cores.

6. Correlation between core diameter and core vertical velocity

Scatter diagrams were made for each day and altitude group, seeking some relationship between diameter and vertical velocity. We succeeded mainly in discovering why they are called scatter diagrams. When data for all days within each altitude group were taken together, the diagram still resembled a shotgun pattern, but with some apparent tendency for large diameter updraft cores to be more intense than smaller cores. Linear correlation coefficients were computed for updraft cores and for downdraft cores in each altitude interval (Table 3). The results vary greatly with altitude; the average correlation of core vertical velocity with core diameter is near 0.4 for updraft cores and about 0.1 for downdraft cores. We place little significance in these numbers. In view of the large scatter, the 0.4 correlation for updraft cores might seem somewhat surprising, but it arises mainly from the existence within each altitude interval of a rather small number of cores which are both large and strong. For example, the addition of a single large (5.5 km) and strong (6.5 m s^{-1}) updraft core to the 58 updraft cores in the 2.5–4.3 km interval would change the actual correlation coefficient of 0.13 (far lower than for the other altitudes) to 0.37 (nearly in line with other altitudes).

7. "Top hat" vs "triangle" profiles; mean and maximum vertical velocity compared

The shape of updrafts and downdrafts is of interest. In particular, a "top hat" profile (constant vertical velocity within a draft or core, discontinuous at each edge) was observed only very rarely. In a core with a top hat profile, the maximum and the mean vertical velocity are equal. A glance at LZ's Figs. 4b, 4c and especially Fig. 5 makes it clear that \bar{w} is much less than w_{\max} for 10% level events as well as for median events. In fact, \bar{w} is typically just over half w_{\max} . That suggests that a better idealization would be a triangular profile, in which the vertical velocity approaches sharply peaked extrema by steady, approximately linear increases and decreases.

We tested this idea for cores, as illustrated in LZ's Fig. 5. A core is everywhere stronger than 1 m s^{-1} , by definition.⁶ Therefore, if cores had triangular vertical velocity profiles, \bar{w} would equal $(w_{\max} + 1)/2$. For both median and strong (10%) cores, up and down, the data fit this approximation very closely indeed. In a statistical sense, then, cores may be modelled by a linear triangular vertical velocity profile. Of course, the core could

TABLE 3. Linear correlation coefficient (r) between mean vertical velocity and diameter for cores.

Altitude interval (m)	Updraft cores		Downdraft cores	
	Number	r	Number	r
4300–8100	97	0.46	50	0.15
2500–4300	58	0.13	47	0.23
700–2500	47	0.51	30	0.05
300–700	45	0.50	23	0.09
0–300	6	0.42	6	0.12

contain more than one triangular peak (e.g., LZ, Fig. 2), but our experience is that one peak generally dominates. Our experience also indicates that smooth profiles such as the Gaussian, while equally consistent with the \bar{w} vs w_{\max} statistics, are hardly ever observed (i.e., the observed profiles tend to resemble sharply peaked ramps).

8. Computability of cloud model results with observed diameters and vertical velocities, and discussion: Why are vertical velocities in GATE cores so low?

Many authors have discussed the complexities of attempting to compare integrations of cloud models with real data [for a comprehensive review of the subject see Cotton (1975)]. It is well beyond the scope of this paper to go through the major effort that would be required to compare systematically model results with observations for the GATE environment. However, curiosity led us to attempt to reproduce the vertical velocity profiles in Fig. 1 with one-dimensional steady-state cumulus models.⁷ Despite the use of different models, different soundings and different initial conditions, two particular results kept emerging:

1) Some GATE soundings required lifting before realistic clouds were produced; sometimes before any cloud would be produced by the model. (Alternatively, bogus moisture increases near cloud base would improve matters, but not as effectively as lifting the entire lower troposphere by 150–200 m.)

2) When updraft diameters were chosen such that the model cloud-top height was near 12 km, as observed, updraft velocity was overpredicted; when smaller diameters were chosen, so that buoyancy

⁷ We thank Victor Wiggert for running the Simpson-Wiggert (1971) cumulus model with GATE data for several different initial diameters and vertical velocities. We also thank Don Perkey for providing the code for the MESOCU cumulus model (Kreitzberg and Perkey, 1976), and for helping us adapt it to our use. Although the models have fundamental similarities, there are substantial differences between them in a number of details, such as whether the updraft diameter is permitted to change as the vertical velocity changes. Other changes were made by us, such as varying the formulation of drag force.

⁶ Recall that these definitions are for 1 s data.

was reduced through entrainment, and the vertical velocity was reduced to near observed values, model cloud-top height was much too low.

In the particular example of Day 257 where a sounding was verified by a number of aircraft to be representative of air upwind of a convective band, and where the draft statistics are neither unusually weak nor strong, both models were run to produce a 12 km cloud top, as observed. The vertical velocity profile for the two models differed by only $1\text{--}2\text{ m s}^{-1}$ from each other, but both overpredicted vertical velocity by a factor of 2–2.5. If plotted on Fig. 1, the model profiles would lie nearly on top of the 10% curve for the Thunderstorm Project cores, not the GATE cores. Our inability to predict correct vertical velocities and cloud-top heights simultaneously for GATE cumulonimbus clouds recalls the famous challenge to one-dimensional models by Warner (1969) when he was unable to predict correct heights and liquid water contents simultaneously. Cotton and Tripoli (1978) give an illuminating discussion of this matter.

We state these results not to criticize the utility of one-dimensional models for cumulonimbus studies, but only to report our application of a simple, diagnostic tool, much as one might note, in passing, the predicted top height from parcel theory. Naturally, one would expect three-dimensional models to do better.⁸ Nevertheless, the overprediction of vertical velocity is severe enough and persistent enough to consider possible explanations other than model inadequacies (or observational inadequacies).

We believe that part of the explanation lies in the differences between the environment of the actual updraft core and the "environment" as usually defined by a nearby sounding. Above, we noted that most updraft cores were embedded in extensive cloudy regions. Further, recent work Zipser *et al.* (1980) for Day 257 shows that few clouds outside the convective band developed into large cumulonimbus, although we are forced to use the same "environment" sounding to represent the entire area. We *hypothesize* that a portion of the mesoscale cloud system is associated with actual mesoscale ascent between convective cores. In that event, one may envision the following scenario, in which a one-dimensional model using diameters and vertical velocities near those observed would predict a higher cloud top than at present. Mesoscale ascent,

enhanced in most cases along a gust front, initiates a 2 km wide 2 m s^{-1} updraft at cloud base.⁹ Above cloud base, the updraft core rising through a mesoscale ascent area is more buoyant due to local destabilization, and entrains air which is more moist (sometimes actually cloudy and containing residues of previous cores), and which has its origin at a lower level, compared to the distant environment air, so that the buoyancy loss from entrainment of "environment" air is reduced. Finally, the rising updraft core may be advected upward in the mesoscale stream, which may itself have a vertical velocity of 1 m s^{-1} , which is additive. An analogous phenomenon is reported in LeMone and Pennell (1976) in the boundary layer, which leads to small clouds forming only in the upward moving branch of the roll vortex circulation, while elsewhere, the moist buoyant elements are not able to reach the condensation level.

Since over 90% of the updraft cores observed in GATE are much weaker than those predicted by a one-dimensional plume model, this raises the question of whether most GATE cumulonimbus contain coherent updrafts, or whether the vertical transports from the subcloud layer may occur in a less organized, more "turbulent" fashion. We cannot answer this question from our data set directly, but it may be of interest to explore briefly an analogy, admittedly quite far-fetched, between the boundary layer and the GATE troposphere, both of which have near-adiabatic structures because of convective transports (nearly dry and moist adiabatic, respectively).

Conventionally the boundary layer has been treated as turbulent and vertical velocities normalized by a velocity scale $w_* = [gT^{-1}(w'T_v')_0 z_i]^{1/3}$, related to the surface buoyancy flux $(w'T_v')_0$, while studies of cumulus layers have used dynamic or mass transport models. Betts (1976) and Nicholls and LeMone (1980) have shown that the mass transport model which was first applied to cumulus convection also has some validity in the boundary layer. Conversely, we might ask the reverse question: whether the weak median core velocities in GATE, suitably scaled, are comparable to vertical velocities in a turbulent boundary layer.¹⁰ The choice of a suitable scaling velocity is not obvious. However, in the cumulus layer buoyancy is realized through release of latent heat, and we might expect some relationship to exist between mean buoyancy flux and cloud base latent heat or θ_e flux. Approximately, we expect that layer mean $w'\theta_v' \sim \frac{1}{2}w'\theta_{es}'$

⁸ They do. Simpson and van Helvoirt (1980) have reported on a GATE case in which reasonable vertical velocities were predicted with the Schlesinger model. In a preliminary run using the Klemp-Wilhelmson model on the Day 257 case John M. Brown (personal communication) notes that the overprediction of vertical velocity is only ~50% of that of the one-dimensional model.

⁹ It is noteworthy that the observed updraft speeds at cloud base (Fig. 5, LZ) are often *greater* than the 1 m s^{-1} core used to initialize the models.

¹⁰ This analogy was suggested by Alan K. Betts during one of several discussions on the subject matter contained in this paper.

$\sim \frac{1}{2}(\overline{w'\theta_e'})_{CB}$, where θ_v , θ_e , θ_{es} are virtual, equivalent and saturation equivalent potential temperatures, respectively, suffix CB denotes cloud-base flux, and the second overbar a vertical average for the cloud layer.¹¹ As an appropriate scaling velocity, we shall therefore choose

$$w_b = \left[g \frac{(\overline{w'\theta_e'})_{CB}}{\bar{T}_v} z_T \right]^{1/3},$$

where z_T is a typical scale height for GATE cumulonimbus (10 km). Although the analogy with the boundary layer convective velocity scale w_* is rather loose, and the use of $(\overline{w'\theta_e'})_{CB}$ as a representative flux is only approximate, the $\frac{1}{3}$ power is very forgiving! Using Emmitt's tethered balloon data¹² we obtain an estimate of $(\overline{w'\theta_e'})_{CB}$ of 0.27, and of w_b of 4.6 m s^{-1} .

Fig. 3 shows median velocities for boundary-layer plumes (scaled by w_*) compared with median updraft core velocities for GATE (scaled by w_b). The good correspondence suggests that this crude analogy may deserve further study; that for some purposes it may be useful to visualize the weak GATE cumulonimbus motions as a kind of turbulent field.

A comparison with midlatitude thunderstorms also emphasizes the relative weakness of GATE cumulonimbus cores. For this purpose, we use a scaling velocity which is straightforward to obtain: that vertical velocity which would be realized if all convective available potential energy (CAPE) in a sounding were converted to kinetic energy, i.e., $w_{CAPE} = [2(\text{CAPE})]^{1/2}$, where

$$\text{CAPE} = \int_{\text{cloud base}}^{\text{cloud top}} g \left(\frac{T_{vp} - T_{ve}}{T_{ve}} \right) dz,$$

where the subscripts p and e refer to parcel and environment, respectively.

For GATE, we computed CAPE for hundreds of soundings, and chose a value of $1500 \text{ J kg}^{-1} = 1500 \text{ m}^2 \text{ s}^{-2}$ as being representative of soundings just ahead of convective systems. For the Thunderstorm Project, we computed the CAPE to be $3000 \text{ m}^2 \text{ s}^{-2}$ from the sounding published in Byers and Braham (1949) which is essentially a mean proximity sounding (Braham, personal communication). For the northeast Colorado hailstorm of 22 July 1976, the (proximity) sounding for Sterling was used (Charles

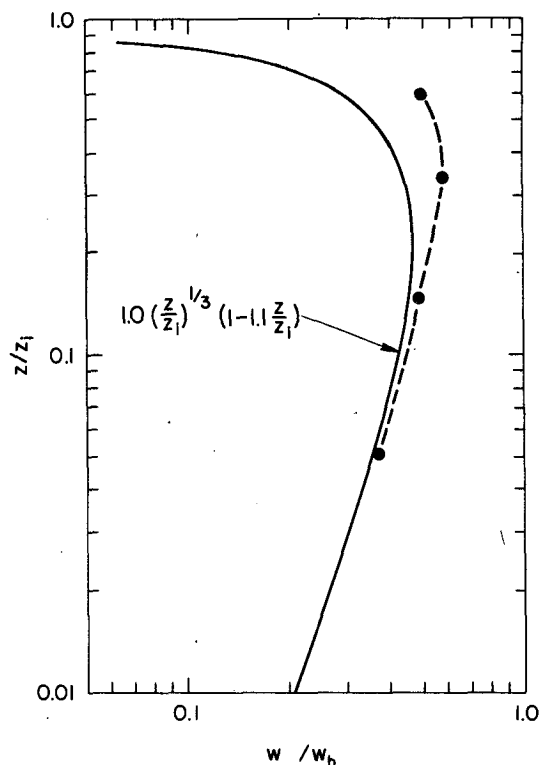


FIG. 3. Comparison between vertical velocity in median GATE cumulonimbus cores (solid circles, dashed curve) and in thermals in the AMTEX boundary layer. The solid curve represents the equation by Lenschow *et al.* (1980). Normalization is by w_b , a characteristic velocity. See text for definitions of w_b for thermals and GATE cumulonimbus cores.

G. Wade, NCAR, personal communication). The boundary-layer plumes were treated in the same manner, in spite of the gross differences in scale, with the data taken from Lenschow and Stephens (1980) and Lenschow (personal communication). Fortunately, the main point can be made without relying upon great accuracy in determination of CAPE. In Table 4, GATE cumulonimbus cores are compared with both boundary layer plumes and with midlatitude convective storms. Note that the GATE core velocities are the weakest compared to their (theoretically) available potential buoyant energy.

9. Implications of weak cumulonimbus updraft cores for cloud microphysics and radar reflectivity profiles

Low vertical velocities in updraft cores imply long time scales for cloud microphysical processes to act within the GATE cumulonimbus clouds. Consider the time scale for updraft air to reach the 0°C level (4.5 km) from cloud base (0.5 km). For an unusually vigorous updraft core, with $\bar{w} = 4 \text{ m s}^{-1}$ over the entire interval, it requires fully 10^3 s ,

¹¹ Betts (personal communication) and the authors have discussed this approximation extensively, and while we can find some empirical evidence to support it, we are unable to offer any physical argument in justification at this time.

¹² Report of the U.S. GATE Central Program Workshop, National Science Foundation and National Center for Atmospheric Research, 1977. 515 pp. Obtainable from Publications Office, NCAR, P.O. Box 3000, Boulder, Colorado 80307.

TABLE 4. Comparison of vertical velocities and selected scaling parameters for GATE cores with those from AMTEX plumes and from midlatitude convective events.

	GATE updraft cores (10%)	AMTEX** plumes (Lenschow and Stephens, 1980)	Thunderstorm Project updraft cores (10%) (Byers and Braham, 1949)	Hailstorm updraft core*
convective layer depth = z_i (km)	12	1.3	13	14
CAPE (J kg^{-1}) = ($\text{m}^2 \text{s}^{-2}$)	1500	19	3000	2100
$w_{\text{CAPE}} = [2(\text{CAPE})]^{1/2}$ (m s^{-1})	55	6	77	65
\bar{w} observed (at altitudes where \bar{w} is max)	5	0.9	13	16
\bar{w}/w_{CAPE}	0.09	0.15	0.17	0.24
$z_{\bar{w}_{\text{max}}}/z_i$	0.35	0.25	0.60	0.56

* Data from NE Colorado storm of 22 July 1976, courtesy Harold W. Frank, NCAR. For consistency with GATE cores \bar{w} is taken as half of the maximum w observed by triple Doppler radar, which is in close agreement with the maximum w observed by the penetration (T-28) aircraft. Preliminary analyses of this case appear in papers presented by Wade and Foote; Kelly, Frank, Foote and Wade; and Heymsfield, Musil and Foote; all in *Preprints, 18th Conference on Radar Meteorology*, Atlanta, Amer. Meteor. Soc.

** AMTEX data, Lenschow, personal communication.

2×10^3 s for median updraft cores. It should be no problem at all for GATE clouds, starting with a maritime droplet spectrum, to undergo droplet coalescence for a sufficiently long time to develop a full precipitation drop size spectrum (Mason, 1971, p. 154; Pruppacher and Klett, 1978, pp. 535–541).

The time scale for a vigorous GATE core to ascend from the 0°C level to the -20°C level is not much less than it took to ascend from $+20^\circ\text{C}$ to 0°C , or about 10^3 s, as there is every indication that the $\bar{w}(z)$ curve has a very flat maximum, which is probably not far from the 0°C level. Even without the introduction of ice crystals from adjacent or older cloud towers, and without consideration of internal circulation within updraft cores, 10^3 s may be ample time for considerable conversion of supercooled water to ice, given any ice nuclei at all.

Yet a third implication of the low updraft speeds for microphysical processes is that millimeter-sized raindrops, once formed, have terminal fall-speeds greater than the mean updraft speeds of virtually all observed cores, and greater than maximum updraft speeds for all but the strongest 10% of observed cores. Therefore, the weaker 90% or so of GATE cores do not advect many large raindrops (≥ 1 mm diameter) upward through the 0°C level or through any other level.

In a typical GATE cumulonimbus, therefore, the predominance of weak updrafts implies an inability to form either hail or significant liquid water concentrations in the form of large raindrops above the 5–6 km level, where the temperature would be colder than -5 to -10°C , because much rain would fall out of the ascending air below the freezing level, and there would be ample time for most of the remaining liquid water to be converted to ice above that level. If that is true, the radar reflectivity in most GATE cumulonimbus should decrease rapidly above the freezing level, because of the sixth

power dependence on drop diameter, and because the reflectivity of snow is much less than that of rain.

With the exception of some strong squall line cores (Houze, 1977) which may well have updrafts as strong or stronger than the maximum measured during aircraft encounters, the GATE radar observations are completely consistent with these deductions. Leary and Houze (1979) show a number of examples of radar cross sections in which reflectivity has a characteristic profile of a flat maximum below the 0°C level with a rapid decrease in reflectivity in height above that level. In a number of weaker cases (such as the 14 September case under study by the authors), the reflectivity drops sharply from 45 dBZ below the 0°C level to below 25 dBZ by the -10°C level, even though the “active” cumulonimbus tower are observed to extend to the -55°C level.

In marked contrast, mid-latitude cumulonimbus often have high reflectivities extending to much higher levels, then decreasing much more slowly with height. Konrad (1978) reported on a larger number of rain cells near the mid-Atlantic coast, and summarized extensive literature on reflectivity characteristics of cells from many locations, and the drop-off in reflectivity with height for many GATE cells is more rapid than for any of Konrad’s profiles. Caracena *et al.* (1979) point out that the low-echo-centroid (LEC) of the Big Thompson (Colorado) storm was one of the characteristics that differentiated it from the typical severe thunderstorms of the Great Plains, typified by high reflectivities extending to great heights. In their view, the Big Thompson storm was dominated by warm rain processes, and was more like tropical thunderstorms. The typical GATE cumulonimbus cell has a lower echo centroid than any of the profiles in the literature, consistent with our findings here that their vertical velocities may well be the weakest.

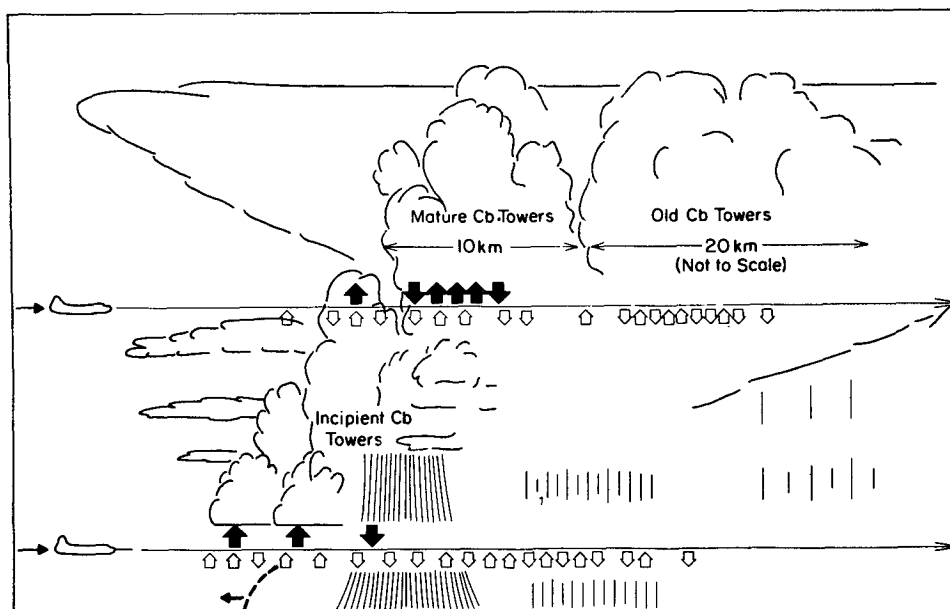


FIG. 4. Schematic of "typical" aircraft passes through a convective band, showing location of drafts and cores near cloud base and in the middle troposphere. There are wide variations from day to day and from one pass to the next on any given day. An average leg is 90 km in length, half of which would be involved with clouds and precipitation and which would contain most of the drafts and cores.

10. Synthesis: Model GATE convective drafts and cores

The distribution of clouds, cores and drafts in a typical convective system is illustrated by the schematic in Fig. 4. The drafts, cores and clouds are part of a larger, organized mesoscale system. Typically on an average (90 km) leg, one or two active cumulonimbus were intercepted, with the larger fraction of the leg flown through decaying towers and extended precipitation. Both ends of the leg were in clear air. The numbers of drafts (clear arrows) and draft cores (solid arrows) are from Table 1 and Fig. 4 of LZ. Note that the number of drafts is about the same at cloud base as higher up, while the number of cores per leg is greater for the higher altitude intervals than for cloud base.

The placement of cores and drafts in the figure is based in part on work in progress on Day 257. Cores are located only in close association with active convective clouds, although not necessarily within cloud boundaries. Drafts are more numerous, occurring in or near older, as well as developing clouds. Near cloud base, the situation is most ordered, with updraft cores near the gust front, and downdraft cores in heavy rain areas. The largest number of drafts not containing cores are found in the rear of the system, under dying towers and the mesoscale precipitation usually associated with the mesoscale downdraft (Houze, 1977; Zipser, 1977). It is

probable that a large number of the drafts at all levels are the decaying turbulent motions which were generated in more convective regions.

Fig. 5 shows a schematic updraft core and down-

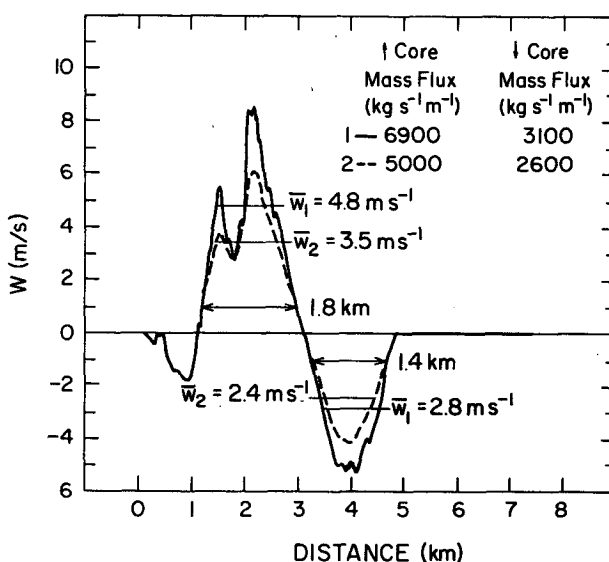


FIG. 5. Schematic vertical velocity profile through 10% level GATE updraft and downdraft cores (stronger than 90% of the population). Case 1 (solid) represents hypothetical cores at the 10% level for both diameter and vertical velocity, which is stronger than the 10% levels with respect to mass flux. Case 2 (dashed) represents the 10% level for mass flux and diameter, with vertical velocity adjusted downward for numerical consistency.

draft core in the middle troposphere. From Fig. 4, one should interpret these cores as belonging to a mature cumulonimbus within an organized mesoscale system, probably in close proximity to other cores within the same cloud. The solid curve represents cores at the 10% level for diameter and for vertical velocity. Because any given core at the 10% level for diameter is not likely to be at the 10% level for vertical velocity, the mass flux carried by the solid curve core is *not* at the 10% level for mass flux itself. The dashed curve is added to show the reduction in vertical velocity required if the 10% core with respect to mass flux were to also be at the 10% level for diameter.

We believe that either curve is a fair representation of a "typical" strong convective core, as sampled by GATE aircraft between 2.5 and 8 km altitude, where the variation of the properties of cores with height tends to be small. *The picture that emerges is of rather narrow and weak entities, with \bar{w} in updraft cores in the 3–5 m s⁻¹ range, and \bar{w} in the 2–3 m s⁻¹ range for downdraft cores.* Median cores are much weaker, but we emphasize the 10% level cores because they are much more likely to be representative of convective currents which are involved in mass transport through large vertical displacements.

We have elected not to dwell on the structure of the drafts (as opposed to cores) in this summary by presenting any schematic model, although it would be elementary to do so from the statistics in Fig. 4 of LZ. All cores are contained within drafts, so the strongest drafts already have their strongest features included within the core statistics, in a sense. The "typical" strong draft *not* containing a core would be larger (especially for downdrafts), considerably weaker, and have considerably less mass flux than a core. But the real reason for avoiding detailed discussion of such is that they most often are not primary convective drafts at all, and it is probably misleading to consider them as agents of significant mass flux in the vertical *through deep layers*. Rather, they are frequently manifestations of decaying turbulence in the wake of strong convection, or the dying stages of primary convective drafts, or motions auxiliary to primary convective drafts, such as adjacent strong subsidence regions. While we believe that much useful information could be extracted from our statistics of these weaker drafts, a study of decaying turbulence should not rely solely upon this kind of event analysis, but should include such techniques as spectral analysis.

11. Summary and conclusions

1) Compared to Thunderstorm Project statistics, GATE cores peak at somewhat lower altitudes, are

about the same size, and are a factor of 2.5–3 weaker. Compared to hurricane cloud statistics, GATE cores are about the same size and intensity.

2) Total mass flux in updraft cores is in approximate agreement with large-scale requirements. Together with other consistency checks, this suggests that the data sample is representative of GATE conditions.

3) Mass flux in both updraft and downdraft cores is distributed over a wide range of diameters and vertical velocities.

4) Fractional area covered by updraft cores on the 100 km scale is 1.5% at cloud base, increasing to over 4% coverage in the middle troposphere. Downdraft cores occupy about half the area of updraft cores at all levels. Drafts occupy a much greater area, 15–18% for updrafts, 25–30% for downdrafts.

5) Vertical velocity and diameter are positively correlated, although rather weakly for updraft cores and insignificantly different from zero correlation for downdraft cores.

6) Vertical velocity profiles through drafts and cores resemble "triangles" more than "top hats".

7) If one-dimensional steady-state cloud models are applied to GATE soundings cloud diameters chosen to represent the correct cloud-top height result in overprediction of vertical velocity. Alternatively, if smaller diameters are chosen so that the model gives realistic vertical velocities, cloud-top heights are greatly underpredicted.

8) A crude analogy can be drawn between the vertical velocity profile of GATE cumulonimbus clouds and that of thermals in the AMTEX boundary layer, further emphasizing the weakness of the GATE clouds in a nearly moist-adiabatic environment.

9) For the 90% of GATE convective cores with mean vertical velocities less than 3–5 m s⁻¹, the time scales for convection are quite large, perhaps in excess of 1 h for air starting at cloud base to reach cloud top. Such time scales are consistent with a large rainout from the warm part of the cloud, the presence of ice at relatively warm temperatures, and rapid decrease of radar reflectivity with height above the 0°C level.

10) The drafts, cores and clouds in GATE are typically part of a larger, organized mesoscale system. Cores are found only in close association with active convective clouds, while a large number of drafts are the decaying turbulent motions which were generated in more convective regions.

Acknowledgments. For the aircraft data set used in this study we are indebted to Alan H. Miller and all those acknowledged in LZ. William Faulkner and Greg Woods ably performed the lengthy data processing needed for this paper. Patricia Waukau helped

with data manipulations and did an excellent job typing the manuscript. Donald Perkey and Victor Wiggert generously assisted in running their cumulus models and discussing their meaning. We had useful discussion with John M. Brown. We are especially grateful to Alan Betts for stimulating discussions and for a critical manuscript review.

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