

## Downdrafts as Linkages in Dynamic Cumulus Seeding Effects

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### ABSTRACT

Downdrafts are postulated as a primary linkage between dynamically seeded invigorated cloud towers and those events near and below cloud bases which cause enhanced inflow, new tower growth leading to cloud expansion, and frequent merger with neighboring clouds. Evidence is taken from two series of seeding experiments on relatively isolated cumuli in the tropics and subtropics, and combined with evidence derived from observational material on downdrafts collected since the late 1960's. Because all the events discussed can occur naturally, postulates concerning the effects of the seeding and their detection are proposed. It is suggested how acceleration of the cloud tops invigorated by seeding can lead to enhanced dynamic entrainment, increased evaporation, and hence to more rapidly formed and stronger downdrafts than would be the case without seeding. Supporting model results on natural clouds are cited.

### 1. Introduction

The purpose of this note is to propose one of the previously missing links in the conceptual chain of events following dynamic cumulus seeding. It is postulated that downdrafts are the dominant means of "communication" between the seeded cloud tower(s) and those events near and below cloud base which cause the cloud to grow wider, last longer and frequently merge with a neighboring cloud.

To develop this postulate, material from recent widely different experiments such as GATE<sup>2</sup>, NHRE<sup>3</sup>, FACE<sup>4</sup> (and others) must be combined interactively with some observational results from the early dynamic seeding experiments which may have been underemphasized owing to concentration on numerical models, difficult statistical controls, and problems of accurate rainfall measurement by radar.

The first experimental programs designed to explore dynamic effects of glaciogenic seeding were conducted in the Caribbean in 1963 and 1965 (Simpson *et al.*, 1965, 1967) on relatively isolated cumuli. The main motivation was to test a developing one-dimensional cumulus model. The model calculated that the latent heat released by massive on-top seeding would enhance buoyancy, leading under some conditions to higher cloud tops. The magnitude

of the model-predicted top height difference (seeded versus unseeded) was defined as seedability. In addition to experimental confirmation regarding expected substantial top height increases, these experiments produced some important unexplained results. Surprising the experimenters, 8 of the 20 clouds seeded in 1963 and 1965 grew explosively (Fig. 1) in two stages. Penetrative vertical tower growth (predicted by the model) for 10–15 min was followed by substantial increases in horizontal dimension (outside the scope of the model) for 30 min or more. Thus, the seeding often produced not just a taller tower, but a fatter, longer lived cloud—a modest cumulus congestus often appeared transformed into a spectacular cumulonimbus.

The suggestion that an enlarged longer lasting cloud would rain more led to the transfer of the "single cloud" experiments to south Florida, where their rainfall could be estimated by radar. Rainfall production was crudely simulated in the model and rainfall was added to cloud top as a primary response variable in the 1968 and 1970 randomized experimental series in south Florida (Simpson *et al.*, 1971). Since the days of low seedability were eliminated from these experiments (Woodley, 1970) fewer non-growth cases occurred following seeding; about 13 of the 27 seeded clouds underwent both phases of explosion.

An important result of the Florida program was that the main seed-control difference related to increased rainfall was the larger shower echo area, which characteristically doubled or tripled following seeding, sometimes increasing by a factor of as much as 6 in the explosive cases. Cloud-echo life-

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<sup>2</sup> GATE: GARP Atlantic Tropical Experiment. GARP: Global Atmospheric Research Program.

<sup>3</sup> NHRE: National Hail Research Experiment.

<sup>4</sup> FACE: Florida Area Cumulus Experiment.

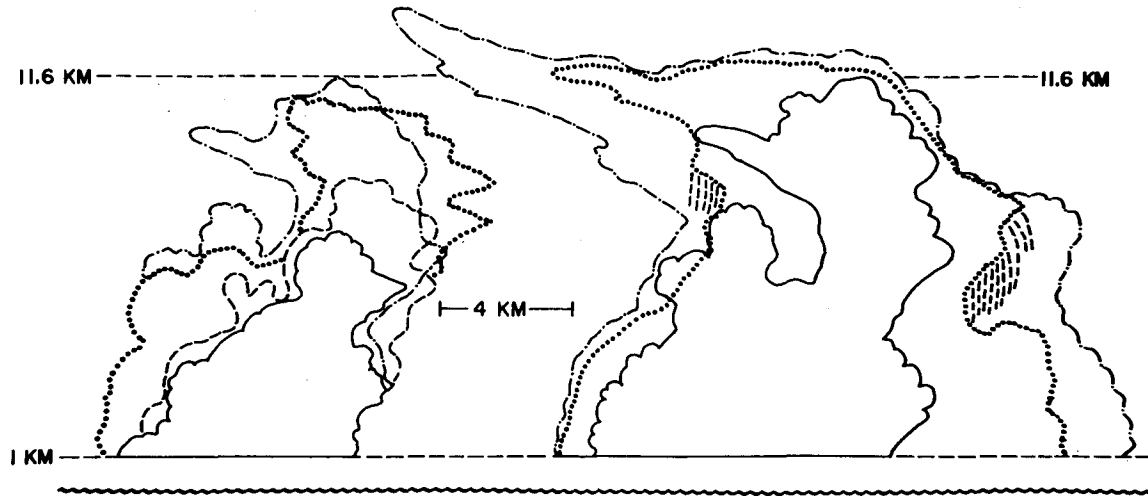


FIG. 1. Two-stage explosion of a seeded tropical cumulus cloud. Phase 1 (left): vertical tower growth. Solid outline is cloud profile when seeded. Second interval, 4 min; others, 5 min. Phase 2 (right): horizontal expansion. First interval, 21 min; second, 4 min. Dashes denote ice crystal showers. (After Simpson *et al.*, 1965).

times were prolonged 50–70%. At that time we had no model, conceptual or numerical, explaining the horizontal expansion of the seeded clouds following seeding—or for a natural cloud undergoing the same evolution. The importance of horizontal explosion was partly recognized in attempts to explain its failure under disturbed conditions (Simpson and Wiggert, 1971). Cloud merger is an important additional component when cloud population and/or area-wide dynamic seeding is undertaken (Simpson and Woodley, 1971).

Shower merger in south Florida has been defined in terms of radar echoes joining at the rain rate of  $1 \text{ mm h}^{-1}$  (Simpson *et al.*, 1980). This merger study showed first-order mergers produced an order of magnitude more rain than unmerged echoes, while second-order mergers produced another order of magnitude more, primarily owing to greater size and secondarily to longer duration. On undisturbed days, the merging process was related to model-predicted sea breeze convergence zones on the mesoscale, with suggestion of a positive feedback between cloud interaction and the convergence. Development of realistic merger models is somewhat farther beyond the frontier in modeling than is the horizontal expansion of a single cloud, although aspects of these related processes are suggested in three-dimensional cumulus model results (Miller, 1978; Simpson and Van Helvoirt, 1980).

## 2. Status of conceptual linkages concerning effects of dynamic seeding

At the end of 1978, the conceptual linkages regarding dynamic seeding effects were postulated as summarized in Table 1. Sax *et al.* (1979) have directly verified the first microphysical link and

indirectly the first part of the buoyancy link by comparing aircraft penetrations of seeded and unseeded clouds near the seeding level. Comparing Fig. 1 with Table 1, we recall that one-dimensional models jointly with observations confirm the buoyancy enhancement and increased vertical growth of the seeded towers (Simpson and Wiggert, 1969). The axisymmetric simulation of Koenig and Murray (1976) gives more sophisticated model support of

TABLE 1. Summary of dynamic seeding hypothesis chain.\* Note: Steps 6 and 7, after the line, comprise the extension from single-cloud to area-wide effects.

- 1) Silver iodide is introduced at approximately the  $-10^{\circ}\text{C}$  level in the cumulus clouds, i.e., in a region where there is believed to be a significant amount of supercooled liquid water.
- 2) This seeding results in conversion of water to ice, with resultant release of latent heat of fusion ( $\sim 80 \text{ cal g}^{-1}$ ), producing increased buoyancy. Additional buoyancy is believed to be produced by depositional heating ( $\sim 680 \text{ cal g}^{-1}$ ) associated with the deposition of water vapor directly onto ice crystals, resulting from the fact that the saturation vapor pressure of ice is less than that of water.
- 3) This buoyancy produces an increase in the updraft, which is transferred all the way down to the bottom of the cloud.
- 4) This produces an increase in the inflow of moist air into the bottom of the cloud.
- 5) This increased inflow of moisture eventually results in more rainfall.

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- 6) By appropriate seeding, neighboring clouds can be caused to merge.
- 7) The increased size of the merged cloud systems results in increased total rainfall.

\* I am grateful to Gordon C. Little for this summary of the hypothesis chain postulated by the scientists of the Florida Area Cumulus Experiment, as it appears in NOAA Technical Report ERL-354, WMPO 6 (1976), NOAA, Department of Commerce, Boulder, Colorado.

the upper level buoyancy enhancement, with a slight indication of its extent to the lower part of the cloud. Nevertheless, the weakness in the Table 1 chain begins at the second part of step 3, which mentions "an increase in the updraft, *transferred all the way to the bottom of the cloud*," which is then followed by increased inflow, etc. This paper advocates a more plausible mechanism involving downdrafts, which will now be given observational and logical support.

### 3. The primary data

Airborne still and time-lapse photography was extensively conducted on all experimental clouds in the 1963, 1965, 1968 and 1970 programs. Since the aircraft distance from the cloud was known by radar and precise navigation, scale drawings like Fig. 1 were made by photogrammetry for all experimental clouds, although only a small fraction were published. Some examples appear in papers by Simpson *et al.* (1965, 1967) and Simpson (1967). A major motivation for this immensely laborious task was determination of the "seeded" tower radii at the time of "seeding" (quotes indicate that randomly selected control clouds were penetrated and measured exactly as if seeded), a necessary initial condition for the one-dimensional model (Simpson and Wiggert, 1969, 1971). The scale drawings and films have been reviewed, with some striking similarities appearing in the explosive cases which become clearer when related to cloud information gathered since the late 1960's.

Extensive reexamination of our films emphasizes that rapidly recreasing shower size is a key symptom of the onset of the second phase of explosion. In a common case, with easterly winds decreasing slowly ( $\sim 1 \text{ m s}^{-1} \text{ km}^{-1}$ ) upward through the lower two-thirds of the cloud layer, the horizontal growth shifts from the upshear to the downshear side of the cloud as the second phase of the explosion sets in—right after the tower has stopped growing vertically. Since it was this feature that suggested the role of downdrafts, we now examine evidence concerning downdrafts, including their role in cumulus processes and impacts.

### 4. Relevant evidence on cumulus downdrafts

The major hypothesis of this note is that downdrafts are both the communication mechanisms and inflow enhancers, as will be proposed shortly. Let us first look at evidence regarding downdrafts.

The earliest measured cumulus draft profiles (Malkus, 1954) showed downdrafts of the same general magnitude as the updrafts particularly on their downshear sides. Just above cloud base, these were associated with downward-looking vertical holes through which the sea surface was

visible, suggesting that the cloud has formed by aggregation of smaller elements. Near rising cloud tops, downdrafts bisecting updrafts were harder to explain; we had insufficient confidence in our instrument systems then to recognize their message. However, the dynamics of  $5\text{--}6 \text{ m s}^{-1}$  downdrafts at the downshear edges of trade cumulus updrafts were examined by Malkus (1955) using a quasi-steady-state model with aircraft observations. If saturation were required in the downdraft, above 80% of its air would have to be entrained from the updraft; its downward acceleration and maintenance were explainable by hydrometeor evaporation. Later evidence (e.g., Ruskin, 1967) that many in-cloud downdrafts are 10–20% undersaturated would permit a higher proportion of clear air entrainment.

The crucial role of downdrafts in instigating and maintaining severe continental storms has been long recognized (Ludlam, 1959; Browning, 1964). Recognition of downdraft importance in the tropics was pioneered by Riehl<sup>5</sup> in a continental project, and over the oceans in a classic squall-line case study by Zipser (1969) which anticipated many of the most vital GATE findings, such as the organization of mesoscale downdrafts (Leary and Houze, 1979), the origins of convective-scale downdrafts by evaporation starting at midlevels (Betts, 1978; Betts and Silva Dias, 1979), and the devastating impact of convective-scale downdrafts on the mixed layer, which remains shrunk, stabilized and dried, often for hours, in the wake of active convection (Augstein, 1978). Impacts of these changes (Augstein *et al.*, 1979) will be discussed later.

Fig. 2 is an example of a GATE cloud flux study reported by Emmitt (1978) who has now increased his sample to above 100 clouds<sup>6</sup> in the small-to-medium (2–6 km tops) size categories. The important points to note are that coherent contiguous updrafts and downdrafts commonly extend most or all of the way down to the sea surface, as well as within the cloud. Emmitt found that although most downdrafts were cold and dry relative to their surroundings (as most updrafts were warm and moist) significant fluxes were accomplished by non-buoyant drafts, indicating forcing.

Other University of Virginia GATE analyses (Warner *et al.*, 1979, 1980) have examined the detailed characteristics of moderate gust fronts associated with showering cumuli topping at 4–6 km and miniature gust fronts associated with cumuli which apparently failed to precipitate below their bases. Mesoscale downdrafts in the GATE area, associated with cloud clusters and particularly with fast-moving squall lines, are discussed by Leary and Houze (1979); these almost surely are relevant

<sup>5</sup> Unpublished report of the Colorado State University.

<sup>6</sup> Personal communication.

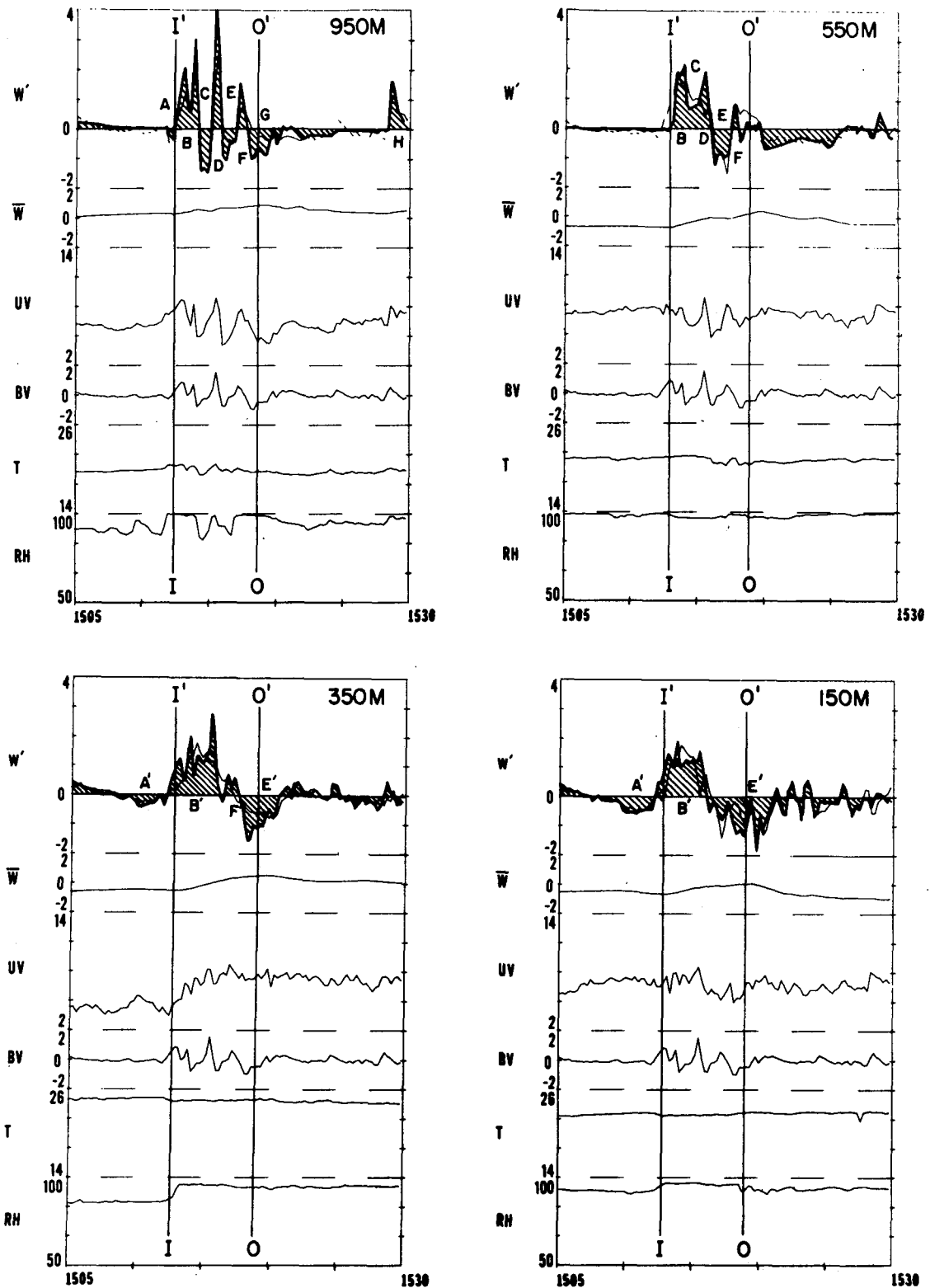


FIG. 2. Profiles from the Boundary Layer Instrument System on shipboard. The cloud base is at about 350 m. The cloud is ~2.5 km in horizontal dimension. The upper curve  $W'$  is the vertical air velocity;  $\bar{W}$  is a running mean,  $UV$  the horizontal air velocity,  $BV$  the balloon velocity,  $T$  temperature ( $^{\circ}C$ );  $RH$  relative humidity (%). Four instrument packages were attached to a tether line of a 72 m<sup>3</sup> balloon (see Emmitt, 1978).

to mergers and area-wide dynamic seeding effects, as will be briefly suggested below.

That contiguous updrafts and downdrafts are commonplace in seedable clouds over Florida is seen by examining the measurements, a few of which are presented by Hallett *et al.* (1978). An example is shown in Fig. 3, where the typical peak downdraft velocities are roughly half those of the updrafts, although some are larger. On the left side, note that the  $6 \text{ m s}^{-1}$  downdraft coincides with the maximum large droplet and natural ice concentrations, as does the maximum liquid water content in precipitation-size particles, which peaks at  $2.4 \text{ g m}^{-3}$ .

The existence of gust fronts associated with south Florida convection is common; they are occasionally sufficiently intense to produce a downburst<sup>7</sup> or a tornado when two gust fronts collide (Holle and Maier, 1980). In a dense mesonet, Ulanski and Garstang (1978) documented surface conditions below 12 thunderstorms; gust fronts were found associated only with moving showers and not with stationary showers. Since the boundary between moving and stationary was chosen as  $3 \text{ m s}^{-1}$  in Florida which has relatively light wind conditions, this result does not necessarily conflict with that of Miller (1978). In his Hampstead England case, a quasi-stationary storm with an intense gust front was moving at  $\sim 4 \text{ m s}^{-1}$  in a strongly sheared windfield. The ability of a gust front to enhance and/or propagate its mother cloud depends on the relative locations, motion vectors and vertical shear profiles (Moncrieff and Miller, 1976; Browning, 1977, Fig. 21; Simpson and Van Helvoirt, 1980).

### 5. The main postulate offered

Fig. 4 and Table 2 are the culmination of this note. The figure postulates the mechanisms by which a seeded cloud may "explode" horizontally, beginning 10–15 min after on-top seeding. Downdrafts are the primary linkages between invigorated updraft and new tower growth. For simplicity, we consider external wind and shear in a plane, in this case easterlies decreasing upward through most of the cloud layer. (The strengthening northeasterlies aloft in the example are indicated by the spreading of the anvil.) An analogous development could be made for westerlies increasing upward. For a wind which turns or changes direction with height, this diagram is probably an oversimplification, as will be discussed in Section 8.

We first stand off from the cloud and contrast differences in the two growth phases. In the first growth phase, the tower grows from  $\sim 6 \text{ km}$  to near  $12 \text{ km}$ . Light showers are observed below cloud

base, mainly on the downshear side. We deduce that the cloud contains mainly upflux, although some downdrafts are clearly present, associated with the showers. Momentum considerations suggest that the cloud is moving leftward slightly faster than the ambient wind in the lower and middle cloud layers (Malkus, 1949) so that it is fed and grows on the upshear side, as observed here and in numerous other studies of growing tropical cumuli.

As mentioned earlier, rapidly increasing shower size symptomizes onset of the second (horizontal) growth phase. The cloud begins to fatten by growth on the downshear side. From this evidence, stronger, more extensive downfluxes are hypothesized, so that lower momentum from aloft causes the cloud now to move leftward more slowly than the ambient air, thereby feeding on the inflow of subcloud moisture-rich air from the right. The gust front as it expands to the right forces the inflow upward, as in severe storm models. Combined convective and conditional instability cause very rapid growth of new towers, whose tops are often observed to receive heavy showers of ice particles. In the early days (Simpson *et al.*, 1965) it was believed that these ice showers were perhaps the main factor in the explosion, shielding the cloud core from entrainment, and perhaps "seeding" the new rising towers as well. The present theory emphasizes dynamic factors in the generation of the new updrafts; the ice showers may play an important secondary interactive role.

The crucial questions relate to how seeding leads to intensified penetrative downdraft(s) following the initial updraft invigoration. The present hypothesis proposes three interacting mechanisms: 1) dynamical invigoration of the vortical internal circulation in the rising tower (Levine, 1959); 2) much increased loading of precipitation particles in downdrafts adjacent to and between updrafts, which continuously augment their negative buoyancy by evaporation (Malkus, 1955) which is enhanced by the increased dynamic entrainment beneath the rising tower; and 3) pressure forces arising from the rapid warming and rise of the seeded tower and also at low levels from the density current aspects of the gust front. Even qualitative specification of pressure forces is beyond the scope of this initial hypothesis formulation; these factors must be investigated by adequate two- and three-dimensional field-of-motion models, as suggested below.

The observed onset time of expansion of about 15 min after seeding is significant. An object descending at  $6\text{--}9 \text{ m s}^{-1}$  falls  $5.4\text{--}8.1 \text{ km}$  in 15 min. Reviewing Fig. 3, we see  $4\text{--}12 \text{ m s}^{-1}$  downdrafts containing hydrometeors with diameters above  $0.93 \text{ mm}$ . Recall that the terminal velocity of an  $0.93 \text{ mm}$  diameter drop is  $3.7 \text{ m s}^{-1}$ , while a  $2 \text{ mm}$  drop falls

<sup>7</sup> M. Maier, 1979: Informal presentation at the National Severe Storms Conference, Kansas City, 2–5 October.

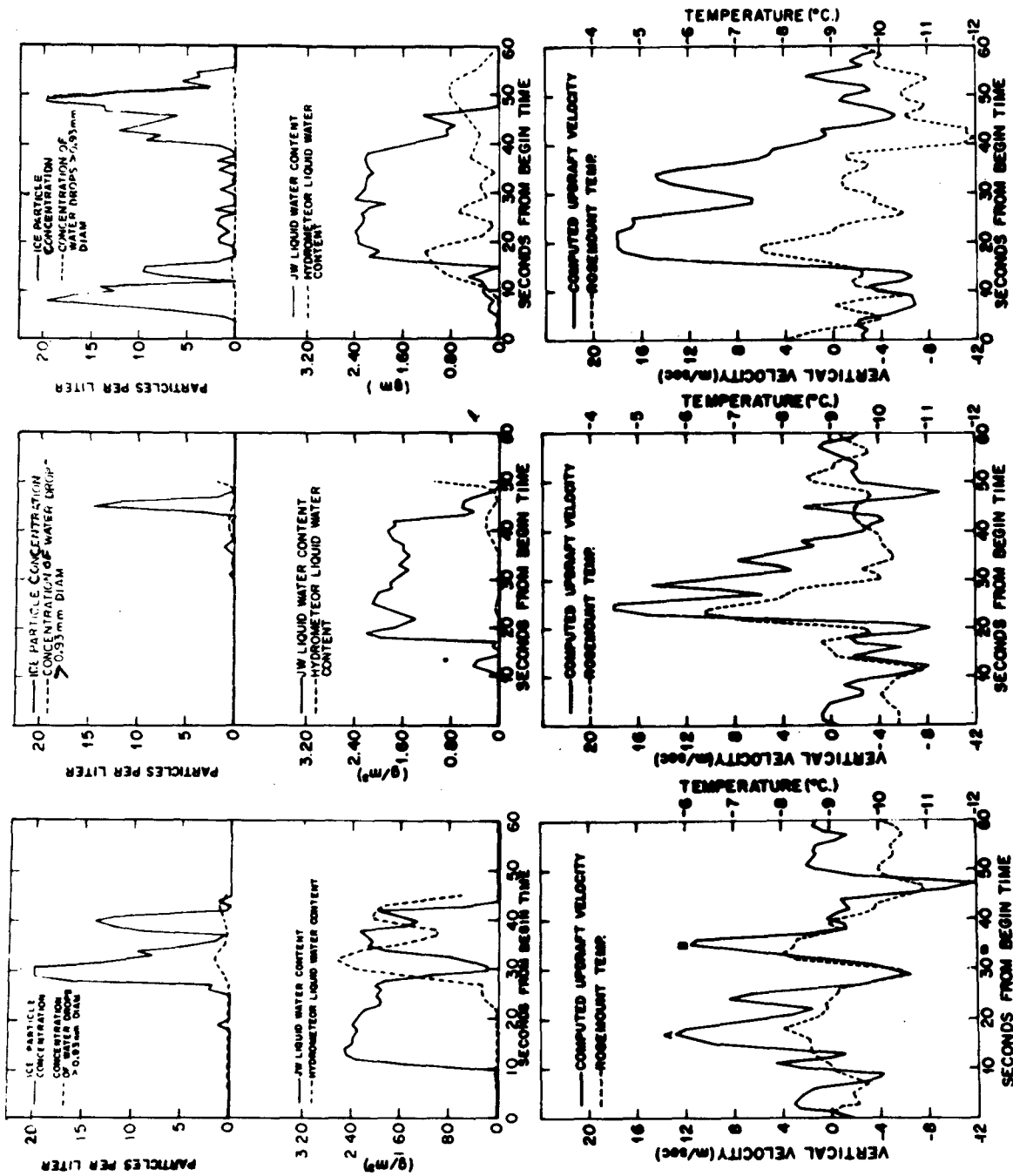


FIG. 3. Measurements from aircraft penetrations of two seedable cloud towers over south Florida on 20 July 1973. Penetrations at the  $-10^{\circ}\text{C}$  ( $\sim 6.1$  km) level. Note particularly the relationships between vertical velocity and concentrations of ice and large water drops (upper graph, solid and dashed lines, respectively). This figure appears in NOAA Tech. Rep. ERL-345, WMPO 6 (1976) by W. L. Woodley and R. I. Sax, NOAA, Department of Commerce, Boulder, Colorado.

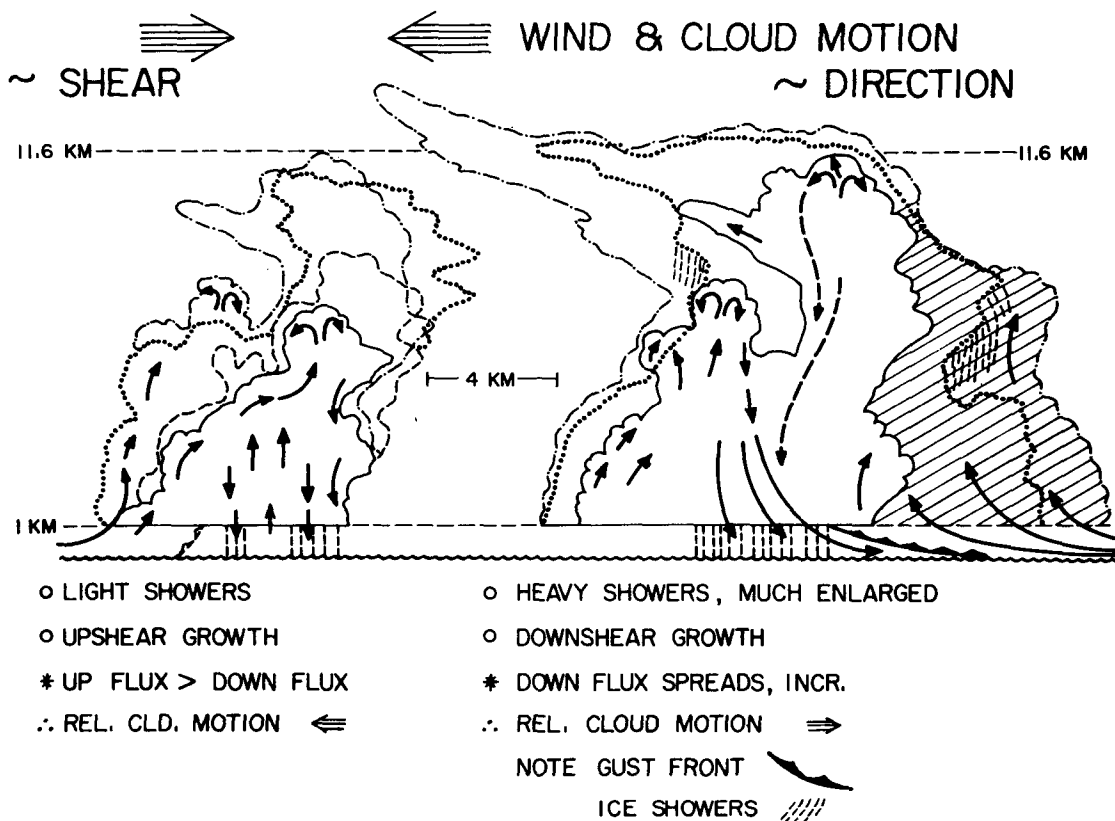


FIG. 4. Diagram illustrating main hypothesis of this note, evolved to explain horizontal explosion of seeded cloud by the downdraft/gust front mechanism. Example cloud is in an environment with easterly winds decreasing upward to an elevation of ~8 km, with northeasterlies increasing above, typical of Caribbean and Florida summers. Drawing to scale. Time intervals as in Fig. 1.

at  $6.5 \text{ m s}^{-1}$ . We are not thinking merely in terms of continuously descending air parcels with hydrometeors falling through them, but also are postulating the downward propagation of negative buoyancy and downdraft intensification by hydrometeor evaporation and probably by pressure forces as well.

The sequence of events in Table 2 is formulated more generally than that in Fig. 4, particularly with regard to locations of downdrafts relative to wind and shear directions. Reasons are explained in Section 8.

If the mechanisms of Table 2 are essentially operative in explosive growth, what conditions might cause them to fail or to work less effectively? We know of one failure situation and suspect two others. The first is the often observed cutoff tower growth mode following seeding (Simpson and Woodley, 1971; Simpson and Dennis, 1974, Fig. 6.14) occurring when a very dry layer is found just above the unseeded cloud tops. After seeding, evaporating virga are seen in the clear air below the still rising cutoff tower, while the lower cloud body dies. On FACE 1 (Woodley *et al.*, 1980) seed days,

the cutoff tower mode was often observed early in the afternoon, followed later by explosive growth in the same cloud group or location. The obvious explanation is diminution of the dry layer by successive towers until a coherent protected path for descending hydrometeors is available.

The other two failure situations are more subtle; their explanation is more speculative. On naturally disturbed rainy days in south Florida, explosive growth was found to be less common or less marked (Simpson *et al.*, 1971; Simpson and Woodley, 1971) than on undisturbed days with isolated showers. Simpson and Wiggert (1971) found the magnitude of the vertical wind shear nearly doubled in the disturbed period of the 1968 experiment. They hypothesized that the resulting cloud slant of  $45^\circ$  or more militated against explosive growth, because the seeding materials falling through the top seeded tower would then have fallen out into clear air without "infecting new towers that are growing quite far" away on the upshear side; they also expected more precipitation export in the anvil relative to downfall through the cloud than in the cases of more vertical development, a factor which

TABLE 2. Modified summary of dynamic seeding hypothesis chain.\*

STAGE I: *Initial growth* (duration 10–15 min)

1) Rapid glaciation of the updraft regions of supercooled convective towers by silver iodide pyrotechnic seeding.

2) Invigoration of the updrafts through the release of latent heats of fusion and deposition, the latter occurring as the cloud air approaches saturation relative to ice.

3) Enhanced tower growth is associated with a pressure fall below cloud, resulting in low-level inflow. At about the same time strengthened dynamic entrainment (Simpson, 1976) into the cloud occurs just below the invigorated rising tower. The increased inflow of drier air increases evaporation of the liquid water falling from the rising seeded tower, which in turn accelerates and strengthens downdraft processes. This combination of events comprises the initial stage of explosive cloud growth.

STAGE II: *Enhanced downdrafts and secondary growth* (duration 30–50 min)

4) Enhanced downdrafts below the invigorated seeded tower as the precipitation and the evaporatively cooled air entrained into the tower moves downward. This results in convergence at the interface between the downdraft and the ambient flow, in the growth of secondary towers (which in turn might be seeded) and in the expansion of the cloud system. This is the second stage of explosive cloud growth.

In the example in Fig. 4, the second stage of explosion involves gust front forcing of new growth and major explosion on the downshear flank. Location of main expansion/new tower growth may differ depending on the wind profile (see text).

STAGE III: *Interaction with neighboring clouds*

5) Seeding of secondary towers in the parent cloud results in their growth, followed by expansion and intensification of the downdraft area which then moves outward to interact with outflows from neighboring clouds (which also might have been seeded). With the ambient conditions of Fig. 4, carefully timed seeding might encourage merger by capitalizing on the tendency of two cumulonimbus in different life cycle stages to approach each other (see text).

6) Accelerated/increased merging, together with larger merged systems, increases the mesoscale convergence, resulting in new cloud growth available for seeding.

STAGE IV: *Increased area rainfall*

7) Augmented and more efficient processing of the available moisture from the larger, more organized seeded cloud systems results in increased rainfall.

8) Increased rainfall over the entire target (assuming the absence of compensatory rainfall decreases in the unseeded portions of the target).

\* Evolved in collaboration with FACE colleagues, particularly Stage I, step 3, introduced mainly from unpublished Doppler radar data analyses by John Cunning.

would inhibit penetrative downdraft development. We propose two additional reasons for the weaker explosion on generally rainy days: 1) a near-saturated environment would mean weaker or less well-developed gust fronts and 2) GATE results confirm earlier evidence that the lower boundary layer is more stable and drier in the wakes of rain-producing systems, and on disturbed days in general (Augstein, 1978; Augstein *et al.*, 1979). In

south Florida, the third failure situation may be on so-called stationary echo days when clouds were found to respond differently to dynamic seeding both singly (Biondini, 1976) and area-wide (Simpson *et al.*, 1973). In the sample of Ulanski and Garstang (1978) stationary Florida showers did not show evidence of gust fronts; moreover, they had smaller echo areas and shorter lifetimes than the moving showers of the same sample.

In a shearing wind field, the relative cloud motion should change between phase 1 and phase 2, with the cloud system slowing down in the example shown. A cloud in a westerly wind field increasing upward would speed up as it enters phase 2. It is possible, in this framework, that a stationary cloud in a field of weak wind and weak shear might be unable to develop a sharp gust front and thereby possess diminished potential for horizontal explosion, although this requires much further investigation.

## 6. Merger processes

In Fig. 4, suppose that the two outlines are exchanged from left to right (i.e., an older seeded cloud is undergoing downshear expansion on the left) while a more recently seeded neighbor on the right is in the tower growth stage, expanding on the upshear side. The clouds are both propagating and moving toward each other. Note that the inflow arrows in the figure are motions *relative* to the cloud, so there is not divergence between them, but probably convergence when their gust fronts begin to collide or interact. Examination of mergers by eye and photography shows that about 15–45 min before the high towers or shower echoes merge, a “bridge” of low towers forms between the interacting cloud systems (Simpson *et al.*, 1980). When mesoscale organization of many clouds occurs in Florida, usually later in the day, the merger process becomes more complex, involving later generation clouds and probably mesoscale downdrafts as found in the GATE area by Leary and Houze (1979). Pielke (1974) and Pielke and Mahrer (1978) have shown that their modeled sea-breeze convergence is the primary convection-forcing factor on undisturbed days in south Florida. Mergers of the showers also occur predominantly in the modeled sea-breeze convergence zones. Positive feedback from the type of downdrafts discussed here to the intensity of the convergence zones has been proposed by Fritsch and Chappell (1980).

## 7. Relevance to covariates and predictors for identification of dynamic seeding effects

The natural variability in cumulus processes and products (e.g. rain, hail, lightning, etc.) is so large that it is essential to find measurables which predict or correlate with the untreated response



variables, unless a very long, expensive sample size is feasible (Tukey *et al.*, 1978).

In the early stages of data analyses from the Florida Area Cumulus Experiment, natural rain distributions were found to differ significantly depending upon whether shower echoes "marched" or were stationary. More significant rainfall predictor equations could apparently be developed within echo motion category than for the unstratified control data set (Biondini *et al.*, 1977). Furthermore, evidence also suggested that the dynamic seeding effects differed with echo motion category in both the single-cloud and area-wide experiments (Biondini, 1976). However, at the urging of statisticians, attempts to objectify the stratification by 1) more rigid echo motion versus no echo motion selection criteria and 2) use of mean vector wind speed in place of echo motion appear to have decreased both the significance of the stratification with regard to rain distribution and of the cited predictor equations within stratifications. Woodley *et al.* (1980) subsequently developed significant predictor equations without wind speed or echo motion stratification, by adding additional predictor variables. However, the foregoing material on the role of downdrafts suggests that 1) cloud motion relative to some framework may indeed be crucial in the basic physics/dynamics of both natural cumulus processes and of their responses to seeding; 2) the linkages discussed here must be better understood and verified to identify those motion variables that are important; and 3) the crucial motion variables may not be simple objective measurables such as a mean vector wind calculated from a rawinsonde near the target. For example, wind derivatives such as vertical shear and horizontal convergence may be involved.

## 8. Supporting work and recommendations

### a. Models

Field-of-motion models using the primitive equations are essential to identify the important pressure effects, and perhaps also those of gravity waves, well beyond the scope of the present heuristic note.

It is important to delineate the conditions favorable and unfavorable for gust fronts, and the relationship of gust front formation both to penetrative downdrafts and to ambient conditions. Encouraging results have been found by Klemp and Wilhelmson (1978) in early trials of their model in a shearing wind field. The model updraft is cut in two by a precipitation-formed downdraft, which forms a gust front.

To seek criteria for gust front intensity and behavior in natural clouds, experiments varying ambient wind profiles and moisture conditions were undertaken with a minor modification of Schlesin-

ger's (1978) model applied to a GATE data set (Simpson and Van Helvoirt, 1980) to simulate two classes of clouds, namely, congestus (tops 5–7 km) and cumulonimbus (tops 11–14 km). Briefly, relevant results were as follows:

- 1) Comparisons of the model congestus and cumulonimbus showed the role of the stronger dynamic entrainment coupled with higher water content in creating a stronger downdraft with gust front in the cumulonimbus. In the model, the latter cloud was produced by a larger, slightly greater initial perturbation, showing the essential role of the stronger, higher updraft preceding the enhanced downdraft (Table 2, Stage 1, step 3).

- 2) The model clouds underwent changes in their relative motion with age substantially as outlined.

- 3) The mature model cloud replicated broadly the major aspects of the right-hand cloud in Fig. 4, *viz.*, the main downdraft was upshear of the updraft, which fed on its downshear side.

- 4) Conditions favorable for initiation of new towers occurred as in Fig. 4 on the upwind side where gust front and inflow collided.

- 5) Pressure forces may work against or overcome initial momentum in the drafts, so that the downdraft also spreads upshear at the surface, most extensively in that direction when the low-level wind blows upshear, as in the shallow GATE monsoon.

- 6) The intensity of downdraft and gust front varies with the magnitude of the mid-tropospheric minimum in equivalent potential temperature, which apparently has an optimum value.

Model and observational tests should be conducted interactively, without and later with simulated or actual seeding.

Three-dimensional model applications to Florida (and other environments) are urgently needed to better understand the role of downdrafts in natural and subsequently seeded clouds. In direct relevance to dynamic seeding, these model studies are needed to clarify potential covariates for natural cloud behavior, such as shower echo motion, and to identify other predictors or covariates on a sound physical basis.

Considerable model development (Cotton, 1975) is needed to simulate both the ice phase and convergent forcing, while simulated seeding experiments on three-dimensional model clouds incorporating these advances may require a new generation of models. Already, however, the models of Chen and Orville (1980) (two-dimensional) and Cotton and Tripoli<sup>8</sup> (three-dimensional) can impose varying degrees of environmental convergent forcing. Conver-

<sup>8</sup> The early development of this model has been reported by Cotton and Tripoli (1978). Since then liquid cloud microphysics and variable external convergence have been incorporated in a paper to be submitted to *J. Appl. Meteor.*

gence interacts significantly with the size and downdraft processes in modeled natural clouds; the interaction of seeding effects with convergent forcing will be of immense importance to model and measure.

#### b. Observations

Data sets from multi-Doppler radars already exist to begin observational examination of the downdraft hypothesis. Multi-Doppler networks are examining unseeded storms in the network of the National Severe Storms Laboratory (NSSL) in Oklahoma and in the National Center for Atmospheric Research (NCAR) area in Colorado. The tri-Doppler network of Lhermitte in south Florida has obtained data on both seeded and unseeded clouds in a 2500 km<sup>2</sup> area within the FACE target.<sup>9</sup>

As the next step, a dynamic single cloud seeding program is recommended, in the context of a well-documented dynamic and thermodynamic meso-scale measurement program to advance understanding of cloud-environment interaction. This objective requires a tri-Doppler radar system to view the experimental area. Instrumented aircraft penetrations of the same clouds, as conducted by Sax and collaborators are essential, as is a dense surface network of wind systems, temperatures and humidity sensors and raingages. Some method of profiling the subcloud layer by combined sondes (Emmitt, 1978) and remote sensors should be planned. Since adequate understanding of cloud interactions will be unlikely without velocity measurements in the precipitation-free cloud surroundings, it would be an immense addition to employ a pulsed Doppler lidar system as proposed by Bilbro and Vaughn (1978). With the target area limited to about 2500 km<sup>2</sup>, it might appear that a long experiment would be required to obtain a randomly selected sample of 50–100 clouds. However, in Florida it should be possible to locate a target of this size away from tomato fields and the heaviest air traffic, so that the annual seeding season would extend throughout the five months between 15 April–15 September. If extrapolation from the 1968 and 1970 single-cloud experiments is valid, each season's sample could comprise roughly twice the cases (of the total previous two years) in about one-fourth the previous area, so that again two seasons experimentation should provide an adequate sample. If the expense of S-band multi-Dopplers could be met, the available area could be enlarged, reducing the time required for the necessary data sample.

<sup>9</sup> Analysis of these data appear in the AMS *Preprint Volume for the Conference on Weather Modification*, Banff, Canada, October 1979. Results are incorporated in Table 2. Information provided courtesy of J. Cunning and W. L. Woodley.

### 9. Concluding remarks

Several types of evidence have been synthesized to suggest that the cumulus-scale downdraft is a crucial element in the chain of events comprising explosive growth of convective clouds, both natural and seeded, to large cumulonimbus. It has been postulated how dynamic seeding may initiate or accelerate these events, via downdraft augmentation following the initial buoyancy and upward growth enhancement.

The reasoning presented here, although incomplete, suggests specific modeling and observational steps for verification. The knowledge of cloud processes and interactions obtained from these efforts would, moreover, advance short-term forecasting, hydrology and severe storm research, as well as build the necessary foundation vital for dynamic seeding.

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