Microphysical development of a pulsating cumulus tower: a case study

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SUMMARY

In-cloud microphysical data collected within a 22 minute period during seven consecutive passes at the
−13°C sampling level of a deep (base +22°C) convective cloud provide observational evidence for a
secondary ice production mechanism at work in the Florida environment. The observed microphysical
characteristics of the convective tower, particularly the spatial distribution and habit of the ice phase relative
to the updraught, are consistent with a rim-splintering hypothesis for secondary ice production. It is shown
that the cloud’s updraught structure is critically important in governing the timing of the ice production
by controlling the flux of graupel particles through the critical temperature zone (−3°C to −8°C). The
importance of the cloud’s pulsation growth dynamics on the microphysics is emphasized, particularly as
it relates to rapidly glaciating cumuli.

1. INTRODUCTION

As part of NOAA’s Florida Area Cumulus Experiment (FACE), specially instrumented aircraft have been used to obtain in-cloud microphysical data in order to document the natural conversion of water to ice as well as any microphysical changes which might be induced through massive seeding with silver iodide. When summertime convective towers developing in the South Florida environment are repeatedly penetrated close to their tops near −10°C, the majority of the in-cloud microphysical data collected in unseeded clouds show a sequential development of cloud water, rainwater, graupel, and crystalline ice as the cloud ages. Appreciable quantities of ice in the form of graupel and some ice crystals are often observed in the dissipating stages of the cloud’s development. Sax and Keller (1980) have suggested that this sequence is consistent with the rim-splintering mode of secondary ice production advanced by Hallett and Mossop (1974) and the concepts of Hallet et al. (1978), who hypothesized that proliferation of ice in the form of graupel would be a primary detectable manifestation of an ice multiplication mechanism that relies upon the sweep up of crystals by large drops to produce rapid glaciation.

The rim-splintering hypothesis for secondary ice production advanced by Hallett and Mossop (1974) is based upon the concept that accretion of a population of small and large cloud droplets by graupel particles present within a narrow temperature range (−3°C to −8°C) leads to the formation of crystalline ice which can later serve as centres for new graupel. Implicit in the hypothesis is the importance of the cloud’s updraught structure in governing the timing of the ice production by controlling the flux of graupel particles through the critical temperature zone. In broad sustained rapid updraught regions, even when the cloud particle criteria for secondary ice production are fulfilled, any secondary particles produced and any graupel present will be carried aloft and removed from the generation zone. When this happens, the positive feedback aspect of the multiplication mechanism is broken, at least temporarily, until the updraught weakens and allows the new

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graupel particles to fall back into the generation zone. On the other hand, when the updraught speed is comparable to the fall speeds (up to several metres per second) of the graupel present in the generating zone, secondary ice particles may be produced, grow by vapour diffusion, be captured by water droplets and form new graupel. This process could be successively repeated so long as the moderate to weak updraught is maintained and sufficient cloud water with adequate numbers of large drops is available in the generating zone. As the updraught continues to weaken, of course, any secondary particles produced cease to be carried upwards and, at higher levels, the ice concentration decreases.

Sax et al. (1979) have presented evidence showing the presence of significantly greater quantities of crystalline ice near the $-10^\circ$C sampling level in convective towers previously seeded with AgI pyrotechnics compared to those growing naturally under similar environmental conditions. They interpreted this evidence as a partial verification of the first link in the dynamical seeding hypothesis – the conversion of supercooled water to ice. Until the present study there has been no evidence that concentrations of ice crystals on a scale commensurate with that sometimes observed in seeded clouds (1000 per litre) could be found in the updraught regions of unseeded Florida cumuli.

This paper presents a case study of an unseeded isolated cumulus tower which rapidly produced large numbers of small ice crystals in the active updraught region. In this case, the large numbers of ice crystals are thought to have resulted from pulsating growth of the tower and subsequent secondary ice particle production. The dynamical-microphysical feedback mechanism is similar in principle to that proposed by Mason (1975), who emphasized the need for rapidly glaciating cumuli to have pulsating updraughts.

![Figure 1. Radiosonde sounding taken 15 August 1978 at 1800 MST from the FACE field site.](image-url)
2. CLOUD ENVIRONMENTAL CONDITIONS

The radiosonde sounding taken 15 August 1978 at 1800 GMT (1400 EDT) from the FACE field site (located near the centre of the FACE target area) is presented in Fig. 1. It shows a strong stable layer over the South Florida peninsula from 5.2 km to 5.5 km. Mid-levels from 2.4 km upwards were very dry with dew-point depressions of 30 °C. A pibal released from the field site at 1930 GMT (1530 EDT) showed easterly winds at all levels up to 3.5 km where the balloon was lost. The 2100 GMT (1700 EDT) satellite photo showed that the only convection over South Florida was a cluster of clouds centred just off the west shore of the Florida peninsula near Naples. This cluster was associated with the west coast sea breeze. The cloud interest in this study was located in the southernmost portion of the cluster but isolated from it. The time history of the Cloud 3 area, obtained from the time-lapse cameras on the NOAA RF42 WP-3D aircraft, shows that the cloud which developed just previous to Cloud 3 and in the same area pinched off in the middle and the cut-off cloud cap drifted to the west. Unfortunately, no earlier penetrations were made in the immediate area of Cloud 3.

The position of Cloud 3 and its movement were determined from the recorded NOAA P-3 aircraft INS positions which correspond to the known cloud penetration times. This cloud was penetrated a total of seven times at the -13 °C sampling level 6.7 km. During the first four penetrations the cloud was in a dissipating state, but by the time of the fifth penetration a new tower was actively growing through the remains of the older cell. Following the seventh pass, the cloud became too large to continue any further penetrations. Pertinent data from each cloud pass are given in Table 1 to simplify relating the pass number to the period of the cloud development.

During pass 3/1 (2111 GMT) the cloud was centred at 25.38°N latitude and 81.38°W

![NOAA P-3 Penetration Sequence Relative to Cloud Position](image)

Figure 2. Penetration sequence relative to Cloud 3 (15 August 1978) as viewed from above. Each of the seven cloud passes is numbered. North is indicated by an arrow.
<table>
<thead>
<tr>
<th>Cloud pass No.</th>
<th>Penetration time (GMT)</th>
<th>Penetration diameter (km)</th>
<th>Vertical velocity (m s⁻¹)</th>
<th>Max JW water (g m⁻³)</th>
<th>Mean JW water (g m⁻³)</th>
<th>Max Splashes (l⁻¹)</th>
<th>Mean Splashes (l⁻¹)</th>
<th>Ice crystals (l⁻¹)</th>
<th>Max (l⁻¹)</th>
<th>Mean (l⁻¹)</th>
<th>Ice crystals (l⁻¹)</th>
<th>Max (l⁻¹)</th>
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Figure 3. Nose camera photograph of Cloud 3 taken at GMT time 2109:17, two minutes prior to pass 3/1. Cloud was pinching off in the middle.

Figure 4. Nose camera photograph of Cloud 3 taken at 2115:45, just a few seconds prior to pass 3/3. On this pass one could easily see through the cloud debris.

Figure 5. Nose camera photograph of Cloud 3 taken at 2123:51, about thirty seconds prior to pass 3/5. The new cloud bubble growing through the old debris completely obscures the view beyond the cloud.

Figure 6. Left side camera photograph of Cloud 3 taken at 2148:03 about fifteen minutes after pass 3/7. Following pass 3/7 the cloud developed lots of pileus and grew to a visually estimated height of over 13.7 km.
longitude (about 22.5 km off the west coast of Florida). For pass 3/7 (2133 GMT) the cloud was centred at 25°39' N latitude and 81°50' W longitude (about 34 km off the west coast of Florida). Throughout the sequence of penetrations the cloud was moving west at approximately 9 m s\(^{-1}\).

Figure 2 shows the penetration sequence relative to the cloud as viewed from above. Figures 3, 4, 5 and 6 are 16 mm time lapse photographs of the cloud and show its progressive stages of development. Figure 3 was taken with the nose camera at GMT time 2109:17, two minutes prior to pass 3/1. Unfortunately, dust on the nose camera window degraded the quality of the photographs. Figure 4 was taken with the nose camera at 2115:45, just a few seconds prior to pass 3/3. Note that on this pass one could easily see through the cloud debris. Figure 5 was taken with the nose camera at 2123:51, about thirty seconds prior to pass 3/5. The new cloud bubble growing through the old debris completely obscures the view beyond the cloud. Figure 6 was taken with the left side camera at 2148:03 about fifteen minutes after pass 3/7 and looks toward the southwest. Following pass 3/7 the cloud developed pileus and grew to a visually estimated height of over 13.5 km. It should be emphasized that no cloud seeding operations whatsoever were conducted in South Florida on this day.

3. DATA COLLECTION EQUIPMENT AND ANALYSIS PROCEDURES

As part of the FACE 78 field program, the NOAA RF42 WP-3D aircraft was utilized in conjunction with two other specially instrumented aircraft to obtain multi-level data bearing on the microphysical evolution of isolated cumuli. However, in the case study (15 August 1978, Cloud 3) presented here, the NOAA P-3 was the only aircraft to penetrate this cloud. The NOAA P-3 aircraft has an inertial navigation system (INS) which accurately gives position, heading and airspeed. The vertical wind measurement system utilizes a vertical accelerometer combined with angle of attack, pitch, and other second order navigation parameters. These parameters are coupled with the static pressure through a feedback loop in the on-board computer. Except when the aircraft is turning, the P-3 vertical wind system should be accurate to within \( \pm 1 \) m s\(^{-1}\), so draught-scale convective updrafts are readily discerned. The three 16 mm time lapse cameras with data chambers are located in the nose and on each side of the aircraft. A de-iced Rosemount temperature sensor, a Johnson–Williams hot-wire liquid water content meter, an ERT (Environmental Research and Technology, Inc.) optical ice particle counter and, most importantly, a DRI (Desert Research Institute) formvar replicator, are other on-board instruments relevant to this study. The ERT ice particle counter is the commercial version of the University of Washington's instrument (Turner and Radke 1973). Its sampling volume at these airspeeds (145 to 160 m s\(^{-1}\)) is about 4 litres per sec. The detection size threshold at these airspeeds was expected to be about 50 \( \mu \)m.

The replicator data were examined frame by frame for the concentration of graupel, vapour grown ice crystals, and cloud drops. The sampling volume of this replicator is about 1 litre per sec at these airspeeds. Since the replicator was operated at 60 frames per sec, the resolution of each frame is about 0.02 s (2.7 m of flight path). Formvar-derived particle concentrations plotted in this study, however, are one second cumulatives, i.e. total count for 60 successive frames of replica. Large ice particles which had no well-defined crystalline habit and/or showed evidence of extensive fragmenting upon impact were regarded as graupel. The degree of riming on the graupel, assessed from the replica, was found to vary greatly and was not a criterion for classification. Crystalline ice in the form of columns or plates was considered only if it was a well-defined, sharp-edged, regular particle distinctly
Figure 7. Plots for cloud pass 3/1 of vertical wind (top scale on ordinate axis), Johnson-Williams (JW) liquid water (middle scale on ordinate axis), and ERT ice particle concentrations (bottom scale on ordinate axis) versus time. Cloud entrance and exit times are indicated by arrows along the abscissa. The zero vertical wind axis is drawn as a horizontal light line which intersects the ordinate axis near its midpoint. Zero for both JW and ice particle concentration from the optical counter is near the bottom of the figure. Aircraft heading (measured clockwise from north) and true airspeed are given along with the air temperature.

separate from graupel impact craters. The minimum size of column crystals detectable with this replicator is about 50 μm (major axis). Since for small sizes it is difficult to distinguish between crystals and cloud droplets, strong conservatism was used in classifying columns. No irregular ice fragments were considered in this analysis. If any doubt existed, the ice was considered as a fragment (resulting from a graupel impact) and was not counted as either a column or a graupel particle. Large liquid drops (splashdrops) were identified by their characteristic splash pattern of radial arms composed of satellite droplets and were presumed to be supercooled at temperatures lower than 0°C.

4. Evolution of in-cloud microstructure at penetration level

Figure 7 shows plots for cloud pass 3/1 of vertical wind (top scale on ordinate axis), Johnson-Williams (JW) liquid water (middle scale on ordinate axis), and ERT ice particle concentration (bottom scale on ordinate axis) as a function of time. Figure 8 shows plots for cloud pass 3/1 also, but of ERT ice particle concentration and formvar replica deduced concentrations of both graupel and vapour-grown ice crystals. In this study only graupel particles having replica crater diameters greater than 300 μm are considered. This corresponds to actual particle diameters greater than about 250 μm. All splashdrops considered had replica crater diameters greater than 300 μm – a size which, from the work of MacCready and Todd (1964), corresponds to an actual drop diameter of about 150 μm. In pass 3/1 all vapour-grown ice crystals detected had diameters greater than 100 μm. In the case of ice
Figure 8. Plots for cloud pass 3/1 of ERT ice particle concentration and formvar replica deduced concentrations of both graupel and vapour grown ice crystals. The ordinate scale is the same for each of these parameters. Regions of downdraught are indicated and divided into two classes: those areas having a vertical wind less than 0 m s\(^{-1}\) and those having less than negative 6 m s\(^{-1}\).

Figure 9. Plots for pass 3/4 of vertical wind, Johnson-Williams (JW) liquid water, and ERT ice particle concentration versus time. Scales and nomenclature are as for Fig. 7.
crystals, replication size and actual size are nearly identical. Also indicated on Fig. 8 are regions of the cloud where the vertical wind (W) is less than 0 m s\(^{-1}\) and less than negative 6 m s\(^{-1}\). In pass 3/1 a downdraught existed at the sampling level over the entire expanse of the cloud. The cloud was in a dissipating state with a cloud top height, deduced from combining nose film photogrammetric measurements with known aircraft altitude, of 12.8 km. The cloud was nearly pinched off in the middle. It contained a moderate amount of ice, nearly all of which was in the form of graupel. The small amount of supercooled water present was in the form of small raindrops. These observations are typical of a dissipating South Florida cumulus cloud. Throughout three subsequent passes the cloud continued to dissipate and was diffuse enough to see through, as is evident from Fig. 4, a nose camera photograph taken just prior to penetration 3/3. By the time of pass 3/4 (Fig. 9), about seven minutes after pass 3/1, the only manifestation of the cloud at the flight level was a pocket of ice debris.

Just prior to pass 3/5 a new cloud bubble grew through the \(-13^\circ C\) flight level in the midst of the dissipating tower previously penetrated four times. Figure 5 is a nose camera photograph of this new bubble taken about 30 seconds before pass 3/5. Figure 10 shows plots for pass 3/5 of vertical wind, JW, and ERT ice particle concentrations. The scales and nomenclature are the same as in similar plots described above. Figure 11 shows plots for pass 3/5 of ERT ice particle concentrations and formvar replica deduced graupel concentrations. Graupel particles having replica crater diameters greater than 1000 \(\mu\)m (actual diameters greater than about 900 \(\mu\)m) were found in concentrations as high as 50 per litre
Figure 11. Plots for pass 3/5 of ERT ice particle concentration and formvar replica deduced graupel concentration. All graupel having replica crater diameters greater than or equal to 300 μm (actual diameters greater than about 250 μm) are plotted on the solid line. A separate curve shows graupel having replica crater diameters greater than 1000 μm (actual diameters greater than about 900 μm).

on this pass. Total graupel concentrations exceeded 250 per litre over a portion of this pass. Note from Fig. 11 that the ERT ice particle counter did not respond very well to the smaller graupel.

Figure 12 shows plots for pass 3/5 of vapour-grown ice crystal concentrations and total graupel concentrations deduced from analysis of the formvar replications. Vapour-grown ice crystals are divided into two classes: those having major axes less than or equal to 100 μm diameter and those with axes greater than 100 μm diameter. Also indicated on Fig. 12 are portions of the pass where the vertical updraught was greater than 4 m s⁻¹. Note that in Fig. 12 the ordinate scale is different from that used in the other figures. The main point to take notice of in Fig. 12 is the presence of many small ice crystals in the active updraught region of the cloud. The concentration of small ice crystals (d ≤ 100 μm) approached 900 per litre. This far exceeds maximum concentrations (typically 50 per litre) previously observed in unseeded South Florida cumuli and even approaches the maximum concentrations (1300 per litre) observed in South Florida clouds seeded with silver iodide, Sax et al. (1979).

Figures 13 and 14 are photographs of formvar replica from pass 3/5. Figure 13, taken
Figure 12. Plots for pass 3/5 of formvar replica deduced vapour grown ice crystal concentrations and total (all $d \geq 300\ \mu m$) graupel concentrations. Ice crystals are divided into two classes; those with $d < 100\ \mu m$ and those with $d > 100\ \mu m$. The region of the cloud with maximum updraught (vertical wind, $W$, greater than or equal to $4\ \text{m s}^{-1}$) is indicated. Note that the ordinate scale is different from that used in the other figures.

Figure 13. Photograph of formvar replica from pass 3/5 corresponding to a GMT time of 2124:31. Seven vapour grown ice crystals can be seen.
from a portion of the replica frame corresponding to a GMT time of 2124:31, shows seven vapour-grown ice crystals. Five of these crystals were replicated such that only their basal faces are observable. They appear as hexagons with inscribed six pointed stars. It is difficult to determine if they are really plates, as they appear, or equi-axed columns. The other two crystals in Fig. 13 are shown enlarged in Fig. 14. They are definitely equi-axed columns and the one in the upper part of Fig. 14 shows hollowed prism faces. All seven of these ice crystals have major axis diameters less than 100 μm. In fact, the 100 μm diameter class distinction criteria were chosen for this cloud pass to allow discrimination between these types of crystal, which we believe originated from a secondary ice multiplication process lower in the cloud, and large stellar crystals (not shown), which we believe grew for substantial time periods at or near our flight level.

Figure 15 shows plots for pass 3/6 of vertical wind, JW, and ERT ice particle concentrations. On this pass, a large quantity of cloud water (maximum JW of 4 g m⁻³) was present in the active updraught region of the tower. The maximum updraught had a larger magnitude than in pass 3/5, but only very small ERT ice particle concentrations were associated with it. Corroborative evidence for relatively low ice concentrations in the active updraught of pass 3/6 is presented in Fig. 16 which shows plots of formvar replica deduced ice crystal concentrations and graupel concentrations along with ERT ice particle concentrations. Maximum formvar replica deduced ice crystal concentrations on this pass did not exceed 275 per litre but the ice crystals were larger than the majority of those detected on pass 3/5.
In fact, ice crystals with $d > 100\, \mu m$ were found in about the same concentrations on this pass as ice crystals with $d \leq 100\, \mu m$. Other plots (not shown) show small amounts (approximately 15 per litre) of graupel with $d > 500\, \mu m$. Even though the formvar replica deduced ice crystal concentrations for this pass were less than one-third their values of pass 3/5, maximum ERT ice particle concentrations were greater for pass 3/6 than for any of the other passes. This again indicates, as one might have expected, that the ERT does not respond as well to small ice particles as it does to the larger graupel particles. The major point to notice in Figs. 15 and 16 is that the greater part of the ice on pass 3/6 was located in the downdraught regions, consistent with previous experience, rather than in the updraught region as in pass 3/5.

Figure 17 shows plots for pass 3/7 of vertical wind, JW, and ERT ice particle concentrations. On this pass, there was a moderate amount of cloud water (maximum JW of 0.5 g m$^{-3}$) associated with the maximum vertical wind (8 m s$^{-1}$). The maximum ERT ice particle concentrations, only slightly less for this pass than those of pass 3/6, were again observed on the eastern side of the cloud, Fig. 2. By the time of this pass the cloud had
grown substantially and cloud top was several thousand feet above our flight altitude. Figure 18 shows plots of all graupel ($d > 300 \mu m$) and all ice crystals deduced from formvar replica for pass 3/6. In this pass the major portion of the ice was located on the edge of the updraught and in more stagnant regions. Ice crystal concentrations were reduced significantly compared to pass 3/6. Other plots (not shown) show graupel with $d > 1000 \mu m$ having maximum values of 30 per litre (double that in pass 3/6) although the total concentration of graupel $d \geq 300 \mu m$ was about the same for both passes 3/6 and 3/7. Other plots show more ice crystals with $d > 100 \mu m$ in pass 3/7 than $d \leq 100 \mu m$. This was in contrast with pass 3/6 where these concentrations were about the same, with the concentration of smaller crystals slightly exceeding that of the larger crystals.

Figures 19, 20 and 21 show plots for cloud passes 3/1, 3/4, 3/5, 3/6 and 3/7 of formvar replica deduced concentrations per litre of both graupel and splashdrops having crater diameters $> 300 \mu m$. There appears to be a direct relationship between increases and decreases in these two variables from one cloud pass to the next, with the concentrations of graupel exceeding the concentration of splashdrops on all passes. Conservative calculations indicate that in this series of cloud passes at least 0.2 to 0.6 g m$^{-3}$ of supercooled water was
Figure 17. Plots for pass 3/7 of vertical wind, Johnson–Williams (JW) liquid water, and ERT ice particle concentration versus time. Scales and nomenclature are the same as for Fig. 7.

Figure 18. Plots for pass 3/7 of formvar replica deduced concentrations of both graupel and vapour grown ice crystals. All ice crystals, both large and small, are plotted together. Region of maximum updraught (area having vertical wind greater than plus 4 m s⁻¹) is indicated.
Figure 19. Plots for passes 3/1, 3/4, and 3/5 of formvar replica deduced concentrations of both graupel and splashdrops. Splashdrops had replica crater diameters greater than or equal to 300 $\mu$m (actual diameters greater than about 150 $\mu$m). All cloud areas having vertical winds greater than plus 4 m s$^{-1}$ are indicated.

Figure 20. Plots for pass 3/6 of formvar replica deduced concentrations of both graupel and splashdrops. Nomenclature is the same as for Fig. 19 but scales are slightly compressed. The cloud region having vertical winds greater than plus 4 m s$^{-1}$ is indicated.
typically partitioned into splashdrops. Splashdrop concentrations decreased from pass 3/1 to pass 3/4 as the cloud dissipated. There was a maximum of over 150 per litre in pass 3/5, with successive decreases observed from pass 3/5 to 3/6 to 3/7. Graupel concentrations also decreased from pass 3/1 to pass 3/4 as the cloud dissipated. There was a maximum of 300 per litre observed in pass 3/5, with a slight decrease apparent in 3/6. The graupel concentration was essentially unchanged between 3/6 and 3/7.

Following pass 3/7 the cloud continued to grow very rapidly and became sufficiently large that further passes could not have been performed without jeopardizing the safety of both the aircraft and crew.

5. DISCUSSION

The occurrence of abundant numbers of small ice crystals (900 per litre) in pass 3/5 of an unseeded cumulus cloud is interpreted to be direct evidence for a secondary ice multiplication mechanism operative in the Florida atmospheric environment. We suggest that the observations in this study are consistent with the Hallett–Mossop hypothesis for secondary ice production. Graupel particles \( d > 300 \mu m \) ranging in concentration from 50 to 15 per litre (pass 3/1) to 15 per litre (pass 3/4) fell through the flight level \((-13^\circ C\) into the hypothesized generation zone \((-3^\circ C\) to \(-8^\circ C\)\) for a period of at least seven minutes. Splashdroplets \( d > 300 \mu m \) ranging in concentrations from 15 to 10 per litre (pass 3/1) to 10 per litre (pass 3/4) passed downward through the flight level during this same time period. Other studies, Sax and Keller (1980) and Hallet et al. (1978), have shown that large amounts of supercooled cloud water in the form of both small cloud droplets and cloud droplets having diameters greater than 25 \( \mu m \) (conditions necessary for the Hallett–Mossop secondary ice production mechanism to be effective) always exist in the region \(-3^\circ C\) to \(-8^\circ C\) of actively growing South Florida summertime cumuli. Thus, the new bubble (pass 3/5) actively growing upwards through the remains of the dissipating older tower certainly had contained within it the particulate criteria for the Hallett–Mossop ice multiplication mechanism to operate. The 'generation zone' \((-3^\circ C\) to \(-8^\circ C\)\) corresponded to an altitude of between
5·0 km and 6·0 km. Recall that the temperature at the flight sampling level (6·7 km) was 
−13 °C. If one assumes ice splinter particles of negligible size were produced in the generation 
zone and were immediately carried upward with an average velocity of 10 m s⁻¹, 
growing the whole time from the vapour at increasingly colder temperatures, then the 
calculated time interval between splinter production in the generation zone and collection of 
vapour-grown ice crystals on formvar replica at the −13 °C flight level ranges between 
70 and 170 s. Average crystal diameter axial growth rates along both the ‘a’ and ‘c’ axes 
for small vapour-grown ice crystals in a supercooled water cloud over this temperature 
range (−3 °C to −13 °C) are roughly 0·5 μm s⁻¹, Ryan et al. (1976). Using these reasonable 
assumptions, one can calculate that the vapour-grown ice crystals collected at the 6·7 km 
flight level should have had major axis diameters ranging from 35 to 85 μm. This is consis-
tent with the observations of pass 3/5 that the majority (all butstellars) of the ice crystals 
had major axis diameters less than 100 μm. Crystals in pass 3/7 were in general larger than 
those observed earlier because crystals having risen in regions with lower updraughts spent 
more time between the generation zone and the flight level and thus had longer available 
time in which to grow.

We postulate that maximum graupel (d > 300 μm) concentrations were high (300 
per litre) in pass 3/5 and remained high (150 per litre) in passes 3/6 and 3/7 because 
ice splinters were being continuously captured by supercooled droplets in the manner 
predicted by Hallett et al. (1978), who showed that the probability of a splinter being caught 
by a supercooled drop is roughly independent of the size of the drop in the range 0·1 to 
1·0 mm. Splinters are considered here as either ‘splinters’ produced directly in the ice 
multiplication process which then grow by deposition from the vapour or the result of 
vapour growth on droplets subsequent to their nucleation by ‘splinters’ (in which case the 
frozen droplets may be thought of as second generation ‘splinters’).

With an updraught velocity of 10 m s⁻¹, the parcel of newly rising cloud containing 
the entrained graupel and splashdrops from above together with a supply of large cloud 
droplets generated from below will pass through the hypothesized −3 °C to −8 °C secondary 
ice production zone in about 100 s. Hallett et al. (1978), using reasonable assumptions 
regarding the time constants for splinter production and splinter removal (through collection), 
have shown that the ratio of splinters to initial graupel should be between a factor of 
10 and 100 after that elapsed time. The observation of roughly a factor of 20 increase 
between the initial graupel concentration in pass 3/1 and the ice crystal concentration found 
in pass 3/5 is consistent with those analytical calculations. We should point out that other 
mechanisms of secondary ice production associated with freezing of large drops and with 
riming have been advanced quantitatively, e.g. Chisnell and Latham (1976), and need to be 
assessed in the light of the observations presented here.

The prolific number of ice crystals observed in the active updraught region of pass 3/5 
contrasts markedly with observations in pass 3/6. In pass 3/6 considerably fewer crystals 
were observed, most of which were located in stagnant regions, with the strong updraught 
area nearly ice free. Pass 3/6 is representative of conditions typically observed in growing 
convective clouds in Florida. Notice how critical timing is in the sampling process when one 
wishes to characterize a rapidly changing system. In this case less than five minutes elapsed 
between passes 3/5 and 3/6, but if pass 3/5 had been missed, large numbers of ice crystals 
in the active updraught would not have been observed. As an aside, it should be noted that 
if only observations from the optical ice particle counter were available, it would have 
appeared that there were more ice particles in pass 3/6 than in pass 3/5.

The importance of cloud pulsation growth dynamics on the microphysics cannot be 
overemphasized. In this case the dissipating cloud provided a large flux of graupel through-
out the hypothesized generation zone of the new cloud bubble. If ice multiplication pro-
ceeded according to the Hallett-Mossop hypothesis, it is reasonable to assume that following the initial production of prolific numbers of splinters, the strong updraught velocity carried the majority of the secondary particles and the graupel aloft and away from the generation zone. The positive feedback aspect of the multiplication mechanism would be repressed until the updraught again weakened or graupel particles grew sufficiently large to allow them to fall back into the generation zone.

It is certainly possible that the timely natural production of ice particles and subsequent freezing of supercooled water in the cloud examined in this study contributed significantly to its explosive growth. In view of the dry environmental atmospheric conditions prevalent and the abundant number of ice crystals which were produced in the active updraught of this cloud it is doubtful that intentional massive seeding with silver iodide pyrotechnics in the cloud updraught at the time of pass 3/5 could have contributed much more to the explosive growth which occurred naturally. Although the self-seeding mechanism in this cloud appeared to be very effective, the set of circumstances observed here was very special and, from observations collected in FACE throughout the years, the presence of large quantities of ice in active updraught regions is a rare event in terms of the total number of clouds. Nevertheless, pulsation growth is, in itself, not an unusual event and, as shown in this study, can be responsible for a highly efficient manifestation of secondary ice production in convective clouds growing in the South Florida environment.

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