Photographic and Radar Study of the Stormfury 5 August 1965 Seeded Cloud

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ABSTRACT

In the summer of 1965, a series of tropical cumulus cloud experiments was carried out by Project Stormfury, a joint program of the U. S. Navy and Environmental Science Services Administration. Of twelve clouds seeded with tops colder than −5C, eight grew an average of 10,600 ft following seeding. This is a case study of one of these eight clouds; it was seeded at 25,000 ft (absolute altitude) and grew to about 36,000 ft.

Four instrumented aircraft penetrated the cloud in a stack, at levels from cloud base to about 20,000 ft. A heavily radar equipped "Command" plane controlled the experiment, circling the cloud at a distance of about 25 mi. This paper documents the radar and photographic history of the cloud, mainly as determined from the command aircraft. It is intended to aid in interpretation of the cloud physics measurements provided by the penetrating aircraft, particularly that of the Naval Research Laboratory. The N.R.L. aircraft made repeated traverses through the cloud at 18,000 ft (absolute altitude; 17,000 ft pressure altitude) in the temperature range −3 to −5C. It measured temperature, humidity, and hydrometeor structure, once before and several times after seeding. Conversion from largely water to largely ice was observed in a portion of the cloud together with some interesting temperature increases. This study attempts to relate the seeding effects and internal physical changes to the overall dynamic processes as deduced from radar and photography.

1. Introduction

The 1965 Stormfury cumulus program has been summarized in an earlier article (Simpson *et al.*, 1966). A statistical and numerical analysis of all the 23 cases studied is in progress. Meanwhile, several of the better documented clouds are being treated in detail as case studies. On 5 August, some particularly interesting aircraft penetrations of a seeded cloud were made and are reported on in the accompanying articles by Ruskin (1967) and Averitt and Ruskin (1967). To our knowledge, this is among the first "before and after" physical studies of a seeded tropical cumulus cloud which affords extensive internal and external documentation.

2. Observations

Numerous observations of the 5 August Stormfury seeded cloud and its environment were available, in addition to those made by four penetrating aircraft. The radar and photographic measurements made on the Command Control aircraft will be discussed here, since they are valuable in interpreting the physical sequences from the Naval Research Laboratory (N. R. L.) aircraft, described by Ruskin (1967).

The Command plane (U. S. Navy WC-121N) circled around the cloud in a clockwise path, from the time of cloud selection at 1753 to 1834 GCT, 29 min after the seeding (at 1805 GCT). Still photographs were made in 35 mm Kodachrome and (in black and white) with a wide angle Hasselblad. Both sets were taken at 1-min intervals, at right angles to the fuselage, and accurately timed within seconds.

The radar studies were made by means of APS-20 (10 cm) and APS-45 (3 cm) radars. The radars were operated and photographed under the supervision of Prof. Harry V. Senn of the University of Miami, who also provided essential help in the analysis. The APS-45 was operated mainly in the RHI mode and the scope was photographed manually several times per minute. The APS-20 was photographed automatically on every scan. Thus, we have a continuous record of the aircraft position relative to the chosen cloud and of the cloud's growth in height and size throughout the period. As an additional bonus, the several aircraft were visible on both radar scopes, permitting height calibration of the APS-45 and permitting the tracks of the seeding and monitor aircraft to be determined.

The radar was first used to reconstruct the aircraft patterns relative to the cloud. The cloud echo before seeding consisted of about three cells, lined up approximately east-west. Moving from south to north, the seeding aircraft passed the edge of the echo of the western cell, as seen on the APS-20. Thus, only the western cloud portion could have been seeded. The seeder's notes and the APS-45 showed in fact that he passed centrally through the top of one of the three towers. One and only one of these grew vertically after

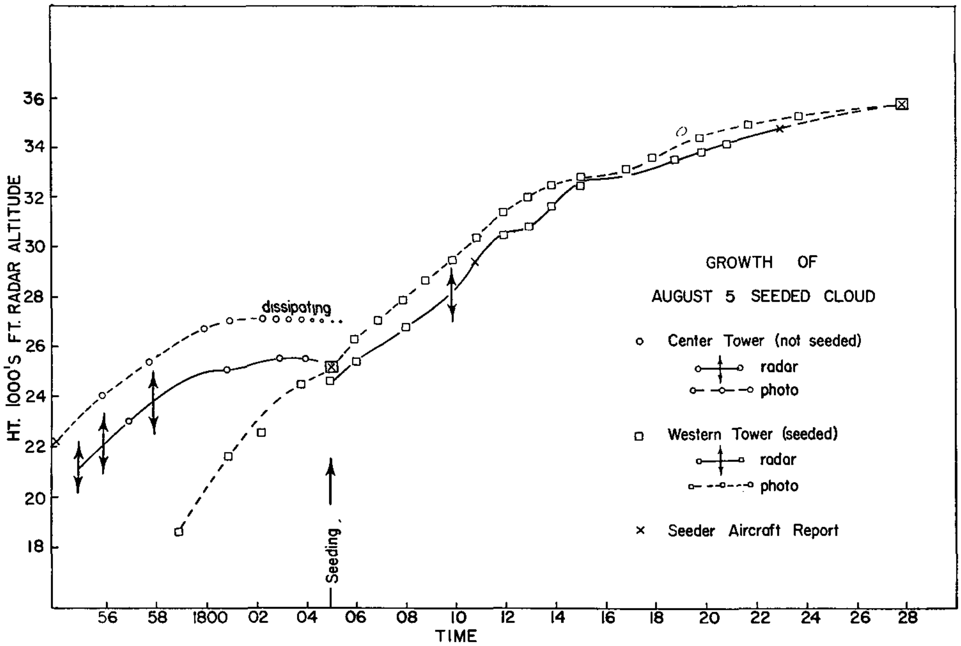

FIG. 1. Vertical growth of seeded cloud, 5 August 1965, as a function of time. Heights have been converted to absolute altitude (1000's ft) above the sea surface. Solid curves are APS-45 measurements. Double-ended arrows appear where latitude in top definition was indicated. Dashed curves are photogrammetric measurements. Seeded aircraft measurements are shown by X's. Circles denote center (older) tower. Boxes denote western (seeded) tower. The photographic measurements were unambiguous regarding which tower was being measured. On the radar, the top of the tallest tower was always selected for measurement.

seeding, but the radar alone (due to horizontal beam width) could not identify which one.

The monitoring "pack" was clearly visible on both radars. The APS-20 (PPI) showed them traversing back and forth on an east-west course; using it we could distinguish for each aircraft those runs which correctly penetrated the seeded western tower. This evidence and that from a nose camera demonstrated that the N.R.L. aircraft succeeded in penetrating the western tower on each of the passes described by Ruskin (1967). The first of the monitoring runs was made about 6 min before the seeding, the remainder being made at 6–8 min intervals beginning 5 min after the seeding.

3. Results

The maximum height of the cloud echo was measured on the APS-45 radar. Since aircraft echoes at known flight altitudes were used to calibrate the radar, the heights should be fairly accurate. Prof. Senn advised that a beam width correction was unnecessary[1] in view of the weakness of the echo intensities, particularly after the cloud became glaciated. After this time, the echo tops were fuzzy and may be underestimated. The general accuracy of the heights was substantiated by the seeder aircraft (an A-3B Skywarrior from the Naval Ordnance Test Station, China Lake, California) which followed the cloud tower upward and recorded its altitude changes with time.

The horizontal distance from the Command plane to the cloud echo was measured independently with APS-20 and APS-45. The APS-20 systematically gave about one nautical mile greater distance. This discrepancy apparently was a function of the radar sets, since it was found also in other days; the difference is, however, within the definition of what we mean by "the tower" or "the echo."

The height-time relationship is shown by the solid line in Fig. 1. It might appear from the radar evidence that the cloud top had reached a maximum and had begun a slight descent by the time of seeding, while subsequently it began to grow rapidly. The photographic study to follow shows that this interpretation, based on radar alone, is probably somewhat misleading.

Figs. 2–7 are selected from the long photographic series to illustrate the visual history of the cloud near the seeding time. The seeded tower is clearly recognizable at the western (right hand) edge of the cloud. It is shown by the arrow. The 35-mm slides were projected in sequence, adjusting the projector distance so that 1 inch on the screen always equalled 1 km on the cloud, as described for a similar 1963 study (Simpson *et al.*,

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[1] See a discussion of beam width effects by A. E. Bent, P. M. Austin and M. L. Stone in a report entitled "Beam width and pulse length in radar weather detection." Tech. Rept. No. 12, Dept. of Meteorology, Mass. Inst. of Technology, Aug. 1950.

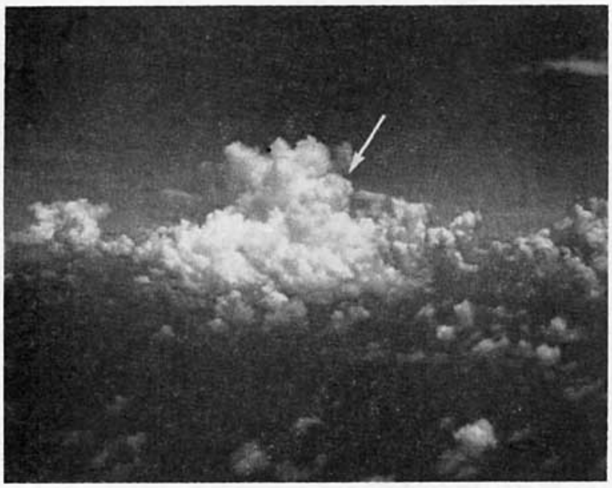

FIG. 2. First in series of Hasselblad photographs of seeded cloud on 5 August 1965, at 1801 GCT, 4 min before seeding. The photographs were all made by Claude Ronne from the Command Control aircraft. Arrows point to seeded (western) tower.

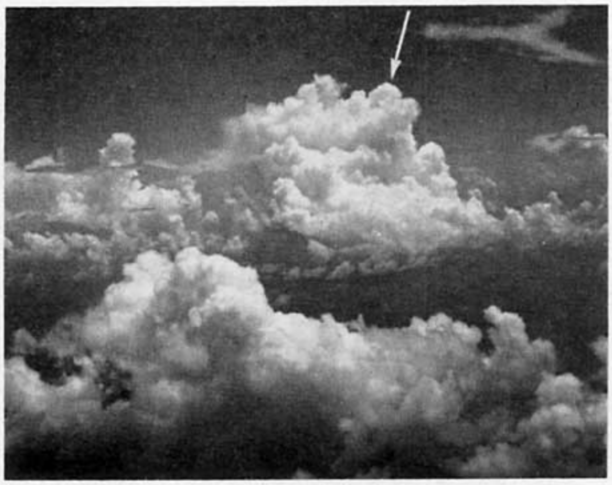

FIG. 5. Same cloud at 1806:14 GCT.

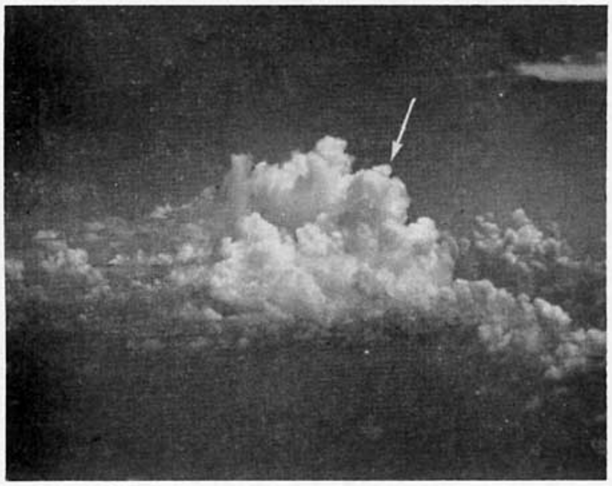

FIG. 3. Same cloud at 1803:32 GCT.

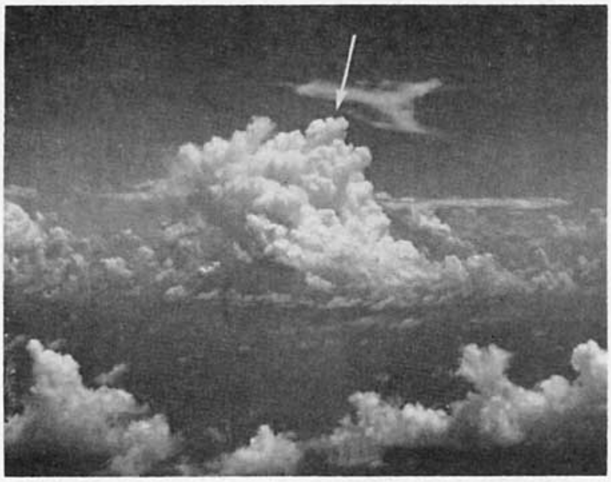

FIG. 6. Same cloud at 1808 GCT.

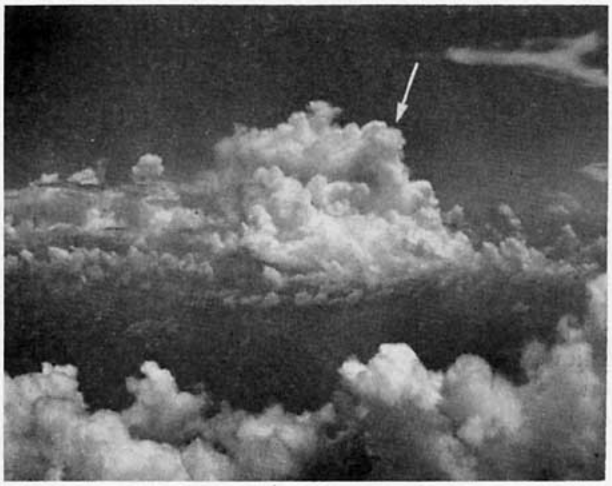

FIG. 4. Same cloud at 1805:15 GCT, 15 sec after seeding.

FIG. 7. Same cloud at 1810:10 GCT, simultaneous with the second N.R.L. monitoring pass.

1965). When distance, times, and cloud base heights are known as accurately as they are here, dimensions can be found correctly to better than ±1000 ft. The dashed line with squares in Fig. 1 shows the measured *top* height of the seeded tower, as followed visually on the photographs. The dashed line with circles shows the top height of the central (older) tower, which could not be measured quite so accurately since the input parameters were not so firmly established early in the control aircraft's pursuit of the cloud.

The photographic study, however, is essential in understanding the sequence of events and in reinterpreting the radar (compare Figs. 3 and 4). The middle tower of the cloud was probably dominating the radar picture up to 1805 GCT (seeding time) at which time Fig. 4 shows it was starting to evaporate and that the western (seeded) tower was catching up. The photographs make clear that from shortly after 1805 GCT, the seeded tower becomes the dominant, tallest tower of the cloud, greatly exceeding the top heights achieved by any clouds in the area.

The visual cloud tops systematically exceed that of the radar echo, by about 1000 ft during the most accurate period of measurement. This discrepancy could be due in part to uncertainty in detecting the cloud base on the photographs (the base height was accurately measured as 1800 ft by a monitor aircraft at that level), or the difference is most likely a real difference between visual and radar clouds. It is not attributable to cloud slope, since the actual horizontal distance to the tower top itself was used in the radar distance determination.

Three instantaneous profiles and a composite tracing of the cloud from the slides help in interpreting the N.R.L. cloud physics data. These diagrams appear in Figs. 8–11. All important measurements were checked from the Hasselblad prints, applying the standard photogrammetric techniques adapted by Ronne.[2] Fig. 8 shows the cloud at the time of the first monitoring run (about 1759–1800 GCT). The N.R.L. aircraft's track through the cloud is shown; we see that he passed through the top of the growing "west cell," which was later seeded. The measured 1.25 km horizontal extent agrees with the "west cell" dimension for this run in Ruskin's Fig. 5, as does the distance spent in the remainder of the cloud to the eastward. Below, at 10,000 ft, a DC-6 aircraft experienced a warm core just beneath this western cell, suggesting a coherent updraft. The eastern portions of the cloud top are considerably older than the western portions. The former are 25,000–26,000 ft in top height, with top temperatures of approximately −20C.

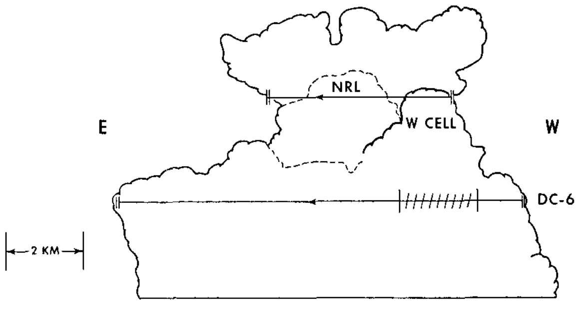

FIG. 8. Pre-seeding profile of 5 August 1965 seeded cloud. Profile made at time of first monitoring run at 1759 GCT. Constructed to scale from projection of 35-mm slide made from Command Control aircraft, looking due south, plane of picture east-west. N. R. L. aircraft's west to east traverse through cloud is shown, double vertical lines indicating entrance and exit. "W cell" is western cell, later seeded, measured as 1.25 km across on both this construction and N. R. L. record [see Ruskin (1967)]. A vertically stacked "pack" of four monitoring aircraft penetrated this cloud. A DC-6 at 10,000 ft (pressure altitude) measured a "warm core" beneath the west cell, its extent denoted by the hatching. The DC-6 traverse is delineated between the lower double vertical lines.

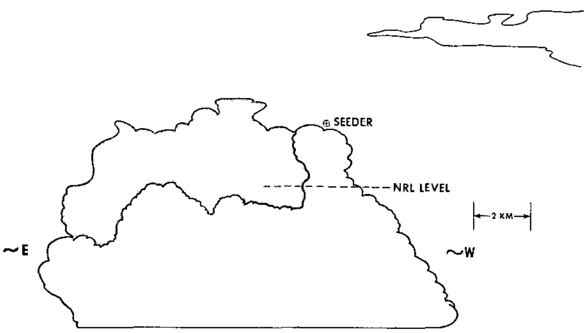

FIG. 9. Profile of 5 August 1965 cloud at seeding time 1805 GCT made from Command Control aircraft photograph looking 20 deg west of south. Sixteen pyrotechnic silver iodide generators (Alecto units) were dropped into the western tower from seeder aircraft flying toward north (into the diagram, as indicated by the encircled X) just above tower top. Scale diagram reconstructed from 35-mm slide in same manner as Fig. 8.

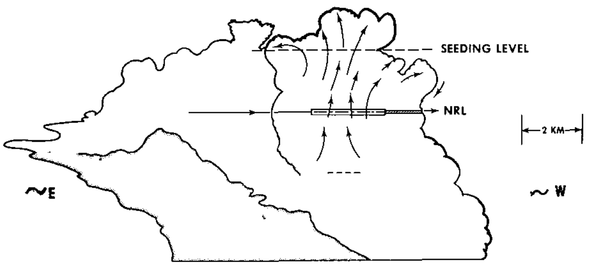

FIG. 10. Post-seeding profile of 5 August 1965 cloud. Profile made at time of second monitoring run at 1810 GCT made from Command Control aircraft photograph looking approximately southwest. Constructed to scale in same manner as Figs. 8 and 9. N.R.L. aircraft's east-west traverse through cloud is shown, double vertical lines indicating entrance and exit. Darkened portion is western 1.25 km. Thickened white portion is central region where about 2C warming, relative to previous run, was observed.

Fig. 9 shows the cloud profile at seeding time, with the seeder's passage across the western tower top entered schematically; he crossed about 6500 ft above the N.R.

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[2] Ronne, C., On a method of cloud measurement from aircraft motion picture films. Woods Hole Oceanogr. Inst. Ref. No. 59-29. Unpublished manuscript.

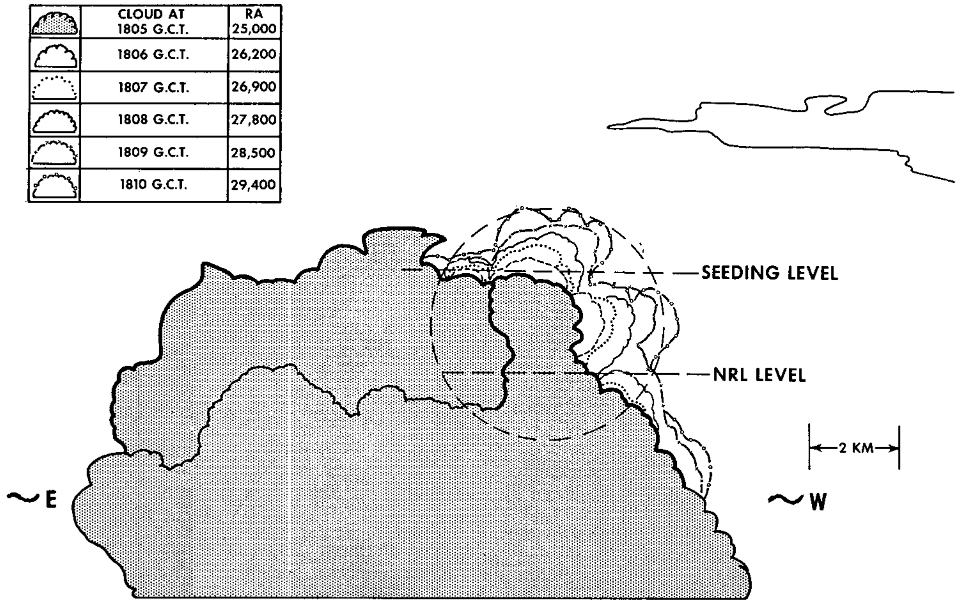

FIG. 11. Composite after-seeding profile of 5 August 1965 cloud. Growth outline shown at 1-min intervals from 1805 to 1810 GCT. Dashed circle with 5 km diameter roughly denotes portion of cloud "activated" following seeding. These dimensions are comparable to those of vortical circulations computed after 5 min following heat input in such numerical model studies as that by Murray and Anderson (see footnote 3).

L. flight level. The tower top temperature was about −18C at seeding. Fig. 10 shows the cloud outline at the time of the first monitoring run after seeding (1810–1811 GCT). The seeded tower top has now reached about 29,400 ft which is somewhat above the height achieved by any previous towers. The N.R.L. traverse through the cloud is shown, divided into an eastern, central, and western portion. As Ruskin (1967) has shown, the eastern portion had warmed little, the central part had warmed about 2C, and the western part had warmed about 1.5C since the previous (pre-seeding) monitoring pass.

On Fig. 10, the vertical motion field has been reconstructed qualitatively from time-lapse movies and sequence projection of the 35-mm slides. For present purposes, the main point is the rather strong updrafts inferred in the central portion and the weak or nonexistent updrafts in the western edge of the N.R.L. traverse. This general draft configuration is supported by model studies (Murray and Anderson, 1965)[3] and actual draft measurements in somewhat smaller tropical cumulus clouds.[4] It is also confirmed by Fig. 11, a composite series of outline tracings of the cloud each minute from 1805-1810 GCT. The central portion of the tower outline moves rapidly upward, while the western portion moves mainly outward, without any marked rising or sinking evident.

The warming of the western (1.25 km) segment is readily accounted for by local freezing. The total liquid plus solid H_2O content at N.R.L. level remained nearly constant between 1759 and 1810 GCT, indicating a quasi-steady condition in this parameter. Releasing the latent heat of fusion from the 2.4 gm m^{-3} liquid water (measured by Ruskin on the "before seeding" pass) would warm the cloud air by about 1.2C. In addition, vapor sublimation in going from saturation relative to water to saturation relative to ice would contribute another 0.5C.

The slightly greater warming in the central portion, which showed *less* ice in the second pass, is easily accounted for by the postulated ascent. It is important to recall that all but the western part of the previous N.R.L. pass went through inactive cloud. Let us assume that the temperature lapse rate in the inactive cloud exceeded moist adiabatic by the conservative figure of 17 per cent (Malkus, 1958). If then, for illustration, the air in this vicinity rose at an average rate of 7 m sec^{-1} in the 5-min interval between seeding and 1810 GCT, the air sensed by N.R.L. in the central portion of its 1810 traverse would have been 2.1 km lower at seeding time. If, at that level, this air was indistinguishable in buoyancy from its environment, a 2C rise in temperature (relative to the inactive cloud sensed by N.R.L. at 1759 GCT) would be experienced.[5]

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[3] Murray, F. W., and C. E. Anderson, 1965: Numerical simulation of the evolution of cumulus towers. Douglas Report SM-49230. Douglas Missile and Space Systems Division, Douglas Aircraft Co., Santa Monica.

[4] Levine, J., 1965: Trade wind cumulus observations from aircraft and their interpretation. Part of Ph.D dissertation on file, Dept. of Meteorology, Mass. Inst. of Tech.

[5] Assuming moist adiabatic ascent. An entrainment calculation with saturated surroundings gives updraft temperatures (after a 2.1-km ascent) little short of those of a moist adiabatic parcel, under the conditions postulated to prevail within this cloud.

With an initial buoyancy excess of the rising air, the temperature increase would be larger. Clearly, an initially steeper lapse rate in the inactive cloud would permit a slower updraft (higher altitude of the air at seeding time) to give the same observed warming. The details of lapse rate or of updraft size, depth, and magnitude are not critical, nor can they be resolved further with this aircraft spacing. What is important is that in the central portion of the N.R.L. 1810 GCT run, the warming relative to the previous pass is easily and logically explainable dynamically. Furthermore, this magitude and vertical extent of updraft below the heat input region is consistent with the dimensions of the roughly circular vortical circulations which evolve from rest after 5 min in the model experiments of Murray and Anderson (1965, *loc. cit.*).

The warming of the *western* edge of the tower, on the other hand, cannot logically be explained by the motion field. It is, in fact, evident that the observed icing there occurred *in situ* rather than being imported from above by sinking. In a super (moist) adabatic lapse condition, sinking would have led to a relative cooling between the two N.R.L. traverses. Further evidence exists to confirm this point. If the rising tower glaciated naturally at the time when its top achieved 25,000 to 26,000 ft, there is little reason to expect that it would have provided any more ice at the N.R.L. level than the amount found there on the pre-seeding run, which was 1–10 per cent of the H_2O in hydrometeor form. If the rising tower became 100 per cent iced as its top reached 27,000–29,000 ft, which levels it achieved between 1807–1810 GCT, descent rates exceeding 15–20 m sec^{-1} would have been necessary to convey the crystals to the N.R.L. level by the 1810 pass. Firstly, those speeds of descent are physically unrealistic, and secondly, if any significant sinking were experienced by the cloud air, it would have led to about 2C cooling rather than 2C warming at the western edge of the tower.

In conclusion, these computations support the inference by Ruskin (1967) that the freezing observed at the edge of the cloud occurred *in situ* and that, in all likelihood, it was due to the silver iodide seeding. The frequency, however, of 100 per cent natural freezing in tropical clouds at −3C to −5C will be investigated further. The causal relationship, if any, between the seeding, freezing, and subsequent cloud growth remains to be studied by comparison between numerical model studies in progress and all the observations, of this cloud and the 22 others studied during the 1965 field program (summarized by Simpson *et al.*, 1966). Pending completion of the calculations for all cloud cases, we should mention the following two points: Firstly, the numerical model [essentially that described by Simpson *et al.* (1965)] shows that an unseeded tower in the size range and environment of this one should not have grown much, if any, above 25,000–26,000 ft, while a seeded one should have grown about 10,000 ft higher. Secondly, no other oceanic cloud was observed to reach more than about 27,000 ft in this area nor were any higher ones visible from it during the 6-hr period of this exercise.

Acknowledgments. The writer is grateful to her colleagues Claude Ronne and Harry Senn who lent their expertise both on the flights and on data analysis. She is grateful for many stimulating discussions with Mr. Robert Ruskin, whose fine cloud physics and instrumental work has provided the meat of this particular phase of the cloud study.

Most especially, the officers and men of the Navy's VW-4 Squadron deserve a large portion of the credit for these results. This article is dedicated to the Commanding Officer, Commander Walter Reese, U. S. N., and the crew of MH-5, the Command and Control aircraft on the mission described herein. Fittingly enough, Commander Reese selected this particular cloud for study.

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