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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

PROJECT STORMFURY - EXPERIMENTS AND OUTLOOK

Helmut K. Weickmann

Atmospheric Physics and Chemistry Laboratory
Boulder, Colorado
December 1978

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INDEX

PAGE

1. INTRODUCTION-- 1

2. SEEDING HYPOTHESIS AND HURRICANE STRUCTURE---------------------- 1

3. LIFE HISTORY OF HURRICANES-------------------------------------- 6

4. THE SEEDING OF HURRICANES--------------------------------------- 14

4.1 The Rationale for the Seeding Hypothesis-------------------- 14

4.1.1 Feedback between Microphysics and Storm Dynamics--- 14

4.2 Seeding Effects--- 18

4.2.1 Dynamic Effects-- 18

4.2.2 Microphysical Effects------------------------------------ 18

5. SEEDING EXPERIMENTS IN HURRICANES------------------------------ 20

5.1 Case Studies-- 20

5.1.1 Esther, 1961--- 20

5.1.2 Beulah, 1963--- 20

5.1.3 Debbie, 1969--- 22

5.1.4 Ginger, 1971--- 22

5.2 Discussion-- 22

5.2.1 Esther--- 22

5.2.2 Beulah--- 23

5.2.3 Debbie--- 23

5.2.4 Ginger--- 24

6. CONCLUSION-- 25

7. OUTLOOK--- 26

LIST OF REFERENCES--- 27

PROJECT STORMFURY - EXPERIMENTS AND OUTLOOK

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1. INTRODUCTION

Subsequently we investigate the evidence of seeding effects following Stormfury experiments. First we investigate the reasonableness of the seeding hypothesis on the background of the structure of a mature hurricane. These hurricanes have features which do not agree with the assumption that a hurricane is a convective storm - such as the widespread occurrence of a bright band in the RAE radar echo. We then discuss the life history of the storm and the seeding experiments; calling attention to the complex feedbacks between microphysics and storm dynamics. In the discussion of the individual seeding cases, we took great pain to quote the correct data for seeding location, seeding level and temperature, as well as seeding amounts and reported observations of seeding effects. The concluding chapter identifies our concern for some of the claims that have been made to suggest a positive seeding effect.

2. SEEDING HYPOTHESIS AND HURRICANE STRUCTURE

Hurricanes are usually considered to be highly convective storms with considerable updrafts pumping much water into the layers above the freezing level. This assumption is not always true. Malkus, et al. (1961), for instance, state that in Hurricane Daisy in 1958, only 1 to 4 percent of the area within 200 nmi from the eye of the hurricane consisted of convective clouds, "hot towers", which penetrated to the top, 1 percent being valid for the developing stage, and 4 percent for the mature stage of the hurricane. This agrees well with the Gentry (1974) statement: "Estimates of the area covered by active cumulus in the 'working part' of a hurricane have usually been around 10%". A hypothesis of hurricane modification was developed by R. Simpson which briefly can be stated as follows: called here, Hypothesis I: "If the supercooled water were frozen through nucleation by silver iodide crystals, the released heat of fusion would produce temperature increases; and therefore, hydrostatically, pressure decreases near the region of strongest pressure gradient. If the central pressure did not concomittantly decrease, a reduction in maximum pressure gradient, and in turn, a reduction in wind speed should be the net result." (Sheets, 1973).

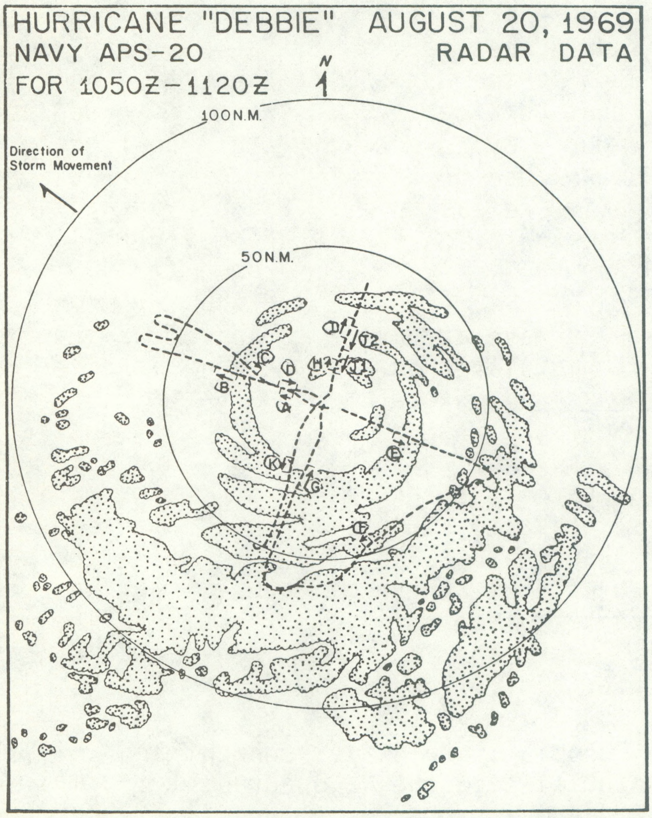
Physical arguments against this hypothesis were brought forward by Rosenthal from numerical experiments, which led him and others associated with Project STORMFURY to propose a different hypothesis II as follows:

"Hypothesis II differs from Hypothesis I in that the latter calls for seeding the eyewall alone whereas the former suggest seeding either from the eyewall outward or entirely outward from the eyewall. While the logistics of these hypotheses differ only slightly, the physical arguments are substantially different. In Hypothesis II, the basic idea is to stimulate convection and ascent at radii greater than that of the eyewall. The region of stimulated convection is intended to compete with the eyewall for the inflowing air at low levels. (Underlining by this author. Note that stimulation of inflow at low levels is required.) If significant portions of the inflow can be diverted upward at the seeded radii, the angular momentum and water vapor supplies to the original eyewall will be reduced. As a consequence, one would expect the original wind maximum to be reduced and the eyewall convection to be diminished". The second seeding hypothesis goes along with the acceptance of the effects of the so-called dynamic seeding, as quoted (Sheets, 1973): "The fact that individual cloud systems can be caused to expand in horizontal coverage and probably merge has been amply (!) demonstrated in Project STORMFURY cloudline seeding operations and by Woodley (1970) and Simpson and Woodley (1971) during experiments conducted over south Florida." In the recent 2nd Scientific WMO Weather Modification Conference in Boulder, these latter claims have received strong criticism. Even the effects of the so-called dynamic seeding of cumulus clouds which is generally accepted, (i.e. the development of cumulus clouds after seeding at the -5 to -10°C level) are far from being understood due to the complex feedback mechanisms between cloud dynamics and cloud microphysics. We will come back to this point later, but it should be mentioned that no microphysical or dynamical data were available above the freezing level for the hurricanes seeded between 1961 and 1969 and that this experiment was simply done on the basis of conjecture: Calculations made by Sheets in 1969 'suggest' that hurricane clouds have 'some seedability' and that the increased buoyancy induced by release of latent heat of fusion in the tops of seeded clouds 'would' cause greater growth of these clouds. As the clouds grow, more water condenses, releasing much greater quantities of latent heat....", namely, heat of condensation (W.N.Hess, Weather Climate Modification, p. 509).

Recently, Barrett, et al, (1976) have attempted to introduce quantitative numbers into the seeding effect as postulated in Hypothesis II and to compare these numbers to the heat of condensation which is released in the hurricane from the base level on upward. Under the most favorable assumptions for the validity of Hypothesis II, seeding will not contribute more than 2 percent to the latent energy of condensation which is released by the storm, or in other words, "the maximum effect of seeding is to supply an amount of energy equal to what the cloud system would provide naturally in 31 seconds in the absence of seeding". Here, we have used a rate of condensation which was based on a cloud base temperature of 22°C, on recent updraft measurements in the wall cloud near the freezing level of 5 m/sec and the assumption, based upon Hypothesis II, of 1 g/kg of liquid water aloft, independent of height within the seeded volume.

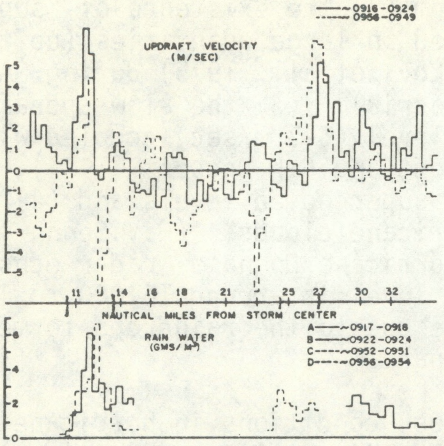
There can be no question that 2 percent is well within the normal variability of hurricane clouds and cumulus clouds, respectively. Furthermore, we can expect that most of the condensed cloud water readily converts into precipitation through collision-coalescence near and below the freezing level, and that, therefore, the released heat of condensation is readily available to drive the hurricane's kinetic energy. The effectiveness of the warm rain process follows not only from (1) the small number of cloud condensation nuclei over the Atlantic Ocean, but also from (2) the existence of "super-large" cloud drops (Diameter >150 μ) observed in large quantities (up to $10^4/m^3$ and more) by the USSR scientists (Borovikov, et al., 1975) during GATE in all types of cumulus clouds (also warm cu mediocris), (3) the slow updraft velocities in the wall cloud near the freezing level (6-7 m/sec) coupled with a high content of precipitation water, (W.D.Scott and C.K.Dossett, 1971), which prevents that much cloud water will reach the supercooled levels and (4) the radar observations of precipitation in hurricane clouds. (H.V.Senn, 1970). Concerning this last point, 78 percent of Hurricane Donna's radar echoes had tops below 20,000 ft. Since the freezing level is around 16,000 to 17,000 ft., it is most likely that these echoes were due to the raindrops formed by the coalescence mechanism in the warm cloud part.

Figure la, b, c, d, reflects these conditions in hurricane "Debbie". Fig. la shows the radar signature of Debbie on August 20 prior to the beginning of seeding. NOAA aircraft penetrated the storm below the freezing level and measured updraft velocity as well as rain water content. Even in the wall cloud echo maximum updrafts did not reach more than 6-7 m/sec while at the same time, considerable amounts of rain water were found in the updrafts indicating an efficient warm coalescence rain mechanism.



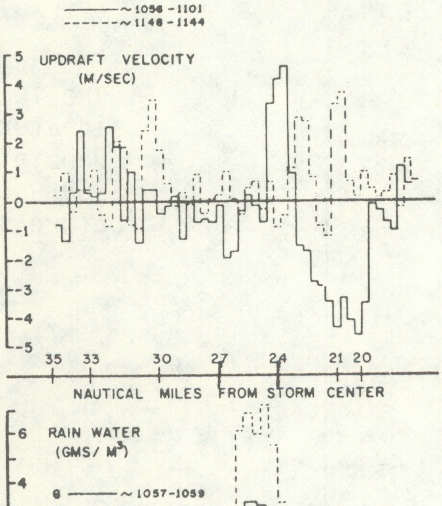
Sampling locations in Hurricane Debbie (690820B1).

Figure la. PPI-Radar signature of Hurricane "Debbie" on August 20, 1969 about one hour before seeding.



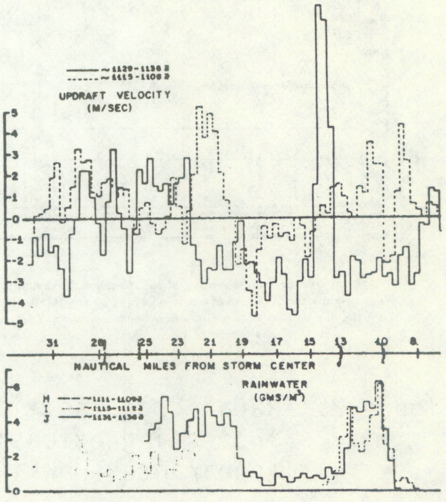
Rainwater and updraft velocities in Hurricane Debbie (690820B1) northwest quadrant.

Figure 1b. Hurricane "Debbie": rainwater content and updraft velocities in the NW quadrant.



Rainwater and updraft velocities in Hurricane Debbie (690820B1) northeast quadrant.

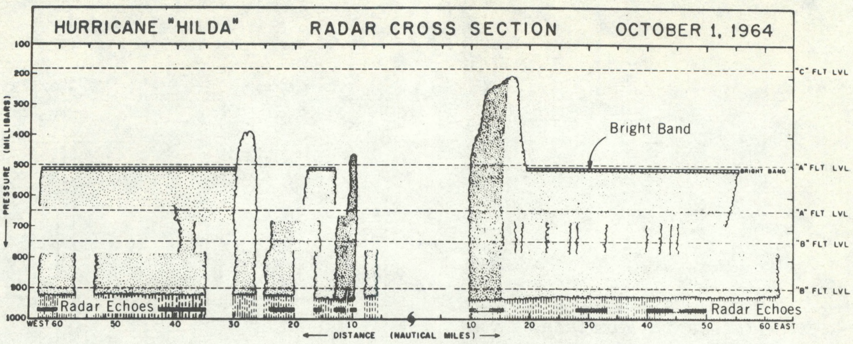
Figure 1c. Hurricane "Debbie": rainwater content and updraft velocities in the NE quadrant.



Rainwater and updraft velocities in Hurricane Debbie (690820B1) southwest quadrant.

Figure 1d. Hurricane "Debbie": rainwater content and updraft velocities in the SW quadrant.

This line of reasoning suggests that one cannot expect much supercooled water to reach the upper hurricane levels where it could be used in a dynamic seeding experiment. The small amount of supercooled water aloft is quickly used up by glaciation and forms cirrostratus or altostratus. This altostratus, which is often invisible for the aircraft 3 cm radar and sometimes also for the land-based 10 cm radar, will cause upon descent of its ice crystals the widespread and well-documented "bright band" in the radar echoes across major parts of the hurricanes such as Hilda (Fig. 2). This "bright band" is the typical radar characteristic of precipitation falling from altostratus, or of light continuous cyclonic precipitation. It forms in the melting level when the snow crystals acquire a wet surface layer which causes them to aggregate intensively and to become large and efficient reflectors of radar frequencies. When the melting is complete, the small size of the droplets and their spatial spreading due to increased fall velocity reduces the echostrength again and the bright band disappears. Atlas et al. (1963) state that the bright band is "characteristic of stratiform precipitation....and is never found in regions of strong convection". The occurrence of a bright band in hurricanes is well known, it is reported in Debbie 1969, Hilda 1964 (Fig. 2), Betsy 1965, and Beulah and Heidi 1967, and we have observed it personally in Inez 1966. The existence of this bright band which occurs also in the clouds in between the rainbands, and the descent of the ice crystals through a very moist (probably above ice saturation) environment, can be a sign of natural glaciation in the upper cloud parts - a phenomenon which we frequently observed in large cirrostratus outflows from cumulonimbus clouds in the Intertropical Convergence Zone during GATE flight missions. This altostratus cloud appears frequently visible as a "blanket" in satellite or astronaut photographs from hurricanes.



—Vertical cross section of radar echoes. Each flight level is stippled where the plane appeared to be in an active 3-cm. radar echo The bright band is indicated where observed by the RDR-1D vertical height-finding radar. The lower, thick lines labeled "radar echoes' are the more stable and well-marked bands composited from the 10-cm. APS-20 film as representative of the band structure over th portion of the period of flight. Darker stippling has been used to represent the major wall cloud and its more active cumulu cter.

Figure 2. Radar cross section through Hurricane Hilda indicating extensive areas of "bright band" appearance (Hawkins and Rubsam 1968).

The formation of the bright band is one of the most powerful arguments against a pronounced convective character of hurricanes. We like to quote here from an analysis of Harry V. Senn in Project STORMFURY, Annual Report, 1970, who has studied the radar signature of numerous hurricanes:

> "If one is looking for precipitation towers on the order of 20,000 to 25,000 ft outside the eyewall of a normal mature hurricane, he should find them in the north and east quadrants. A good RHI radar is a necessity, however, in a brief analysis of such clouds prior to any modification attempts since these quadrants are generally badly messed up by multi-layers of clouds, ample regions of "bright bands" (indicating melting hydrometeoros), etc., which make action purely on the basis of visual observations subject to uncertainty. In fact, some of the above data lead to some rather perplexing questions regarding the seeding hypothesis used in Project STORMFURY. We have found the bright band in most quadrants and ranges of several hurricanes, as indicated in another paper in process. The results above show widespread echoes at heights where one expects glaciation, and certainly high level reconnaissance photos and satellite observations show an abundance of cirrus. However, one is also impressed with the general convective nature most echoes have on the RHI scope, many times in close proximity to the bright band. These observations suggest that echoes exist in all stages of generation and dissipation; but they do little to help answer the questions of whether there is enough mixing of ice nuclei in the wall cloud regions of interest to significantly alter the possible effects of seeding active towers there."

3. LIFE HISTORY OF HURRICANES

It is here the place to discuss in more detail the convectivity of hurricanes. Apparently they often develop from tropical storms. It was a fortunate circumstance that during GATE, a small tropical storm formed in the East Atlantic north of the B-scale area on 10 August 1974 (Fig. 3). This storm

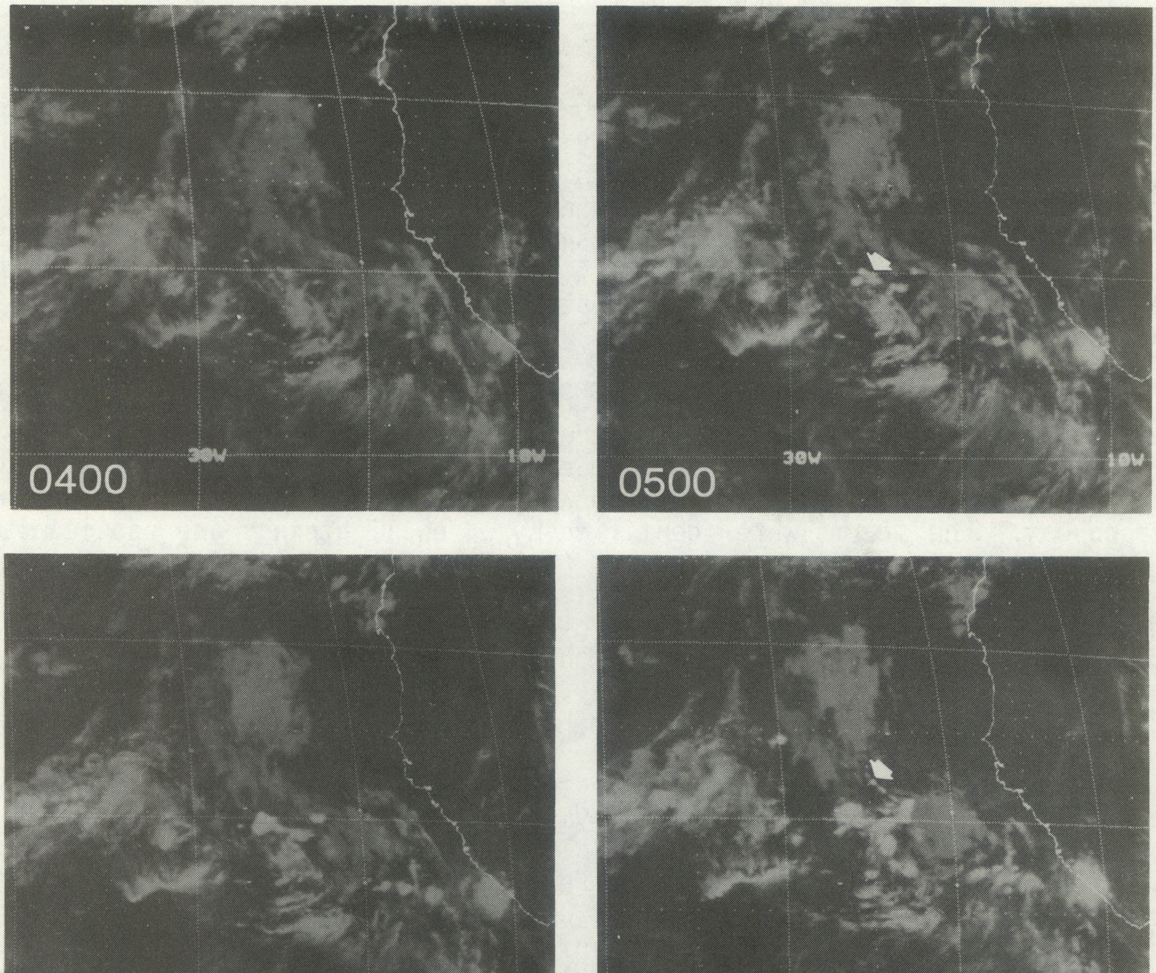


Figure 3. Development of tropical storm ALMA on 10 August 1978. Note the formation of Cb clusters on the 0500 GMT picture which leads, after 17 hours, to a fairly large storm system.

developed originally from about five large cumulonimbus clouds which concluding from the rapid growth of their anvils were quite powerful. The formation of Cb continued and we were able to observe them at 1400 GMT during a flight to the B-scale area. They had already a very extended cirrus anvil but were still actively growing. After 8 hours, they had developed into the small tropical storm Alma, which dissipated after a few days. If this sequence, however, is normal for a "baby hurricane" then it will not only be very difficult to detect at an early stage but it also does not appear that anything beneficial could be modified in this stage by seeding, since the Cb clouds are too powerful.

It appears that the better the hurricane circulation is developed, the less convective it becomes. We had the opportunity to explore on two consecutive days Hurricane Inez, namely, on Sept. 27 and 28, 1966, along the flight path as shown in Figures 4 and 5, and we passed thunderstorms only once on the second day. The storms were identified by a few lightnings and static disturbances in the aircraft intercom system (see Fig. 5, which is from the navigator's log, lightning location determined by author). On the second day, the storm was very well developed with a circular eye and very high wind velocities. As a matter of fact, they were the highest velocities ever recorded up to that date, 164 kts or 190 mph. On this day, the hurricane was repeatedly penetrated at two different levels: at 2,000 ft(Fig. 6) and at 6,000 to 8,000 ft(Fig. 7).

Visual observations of Inez repeatedly emphasize the existence of dense haze which prevents at times surface visibility even from the 2,000 ft flight level and the observation of typical altostratus and cumulonimbus clouds. The data for Figures 6 and 7 are taken directly from the aircraft records of the Doppler navigation system and show as abscissae windspeed in knots, temperature in degrees, and D value in tens of feet. The ordinate is flight distance in 10 km increments, along the straight flight pass through the eye. Note the very smooth curves of the D values and particularly the great symmetry on both sides of the eye (Fig. 6) which does, in no way, indicate the existence of any convective pressure perturbations due to rainbands or cumulonimbus clouds. The windspeed indicated some asymmetry across the eye, while the temperature decreased steadily from about 23°C in the center of the eye to about 19 to 20°C at 25 to 30 km distant from the eye. The same symmetry of the D-value on both sides of the eye appeared also at the 6,000 to 8,000 ft level along a different flight trajectory (Fig.7). The windspeed is again light asymmetric reaching about 150 kts on one side and 132 kts on the other side of the eye, while the temperature decreases again from 17°C in the eye continuously outside of the eye. Interestingly, it shows on both sides a slight increase to 13°C and then a decrease of 11°C. There was a moderate turbulence at best; we realize, of course, that heavy turbulence has also been encountered but we believe that much of it can be due to mountain-wave turbulence behind islands.

Figure 8 shows the cyclonic inflow pattern into the hurricane at 5.8 km altitude, also here, one notes a very persistent pattern uninterrupted by local disturbances from convective clouds. The divergence is high and of the order of that we measured in Colorado thunderstorms. From these data one gains the impression that this powerful hurricane was a very well organized cyclonic storm rather than a convective storm system.

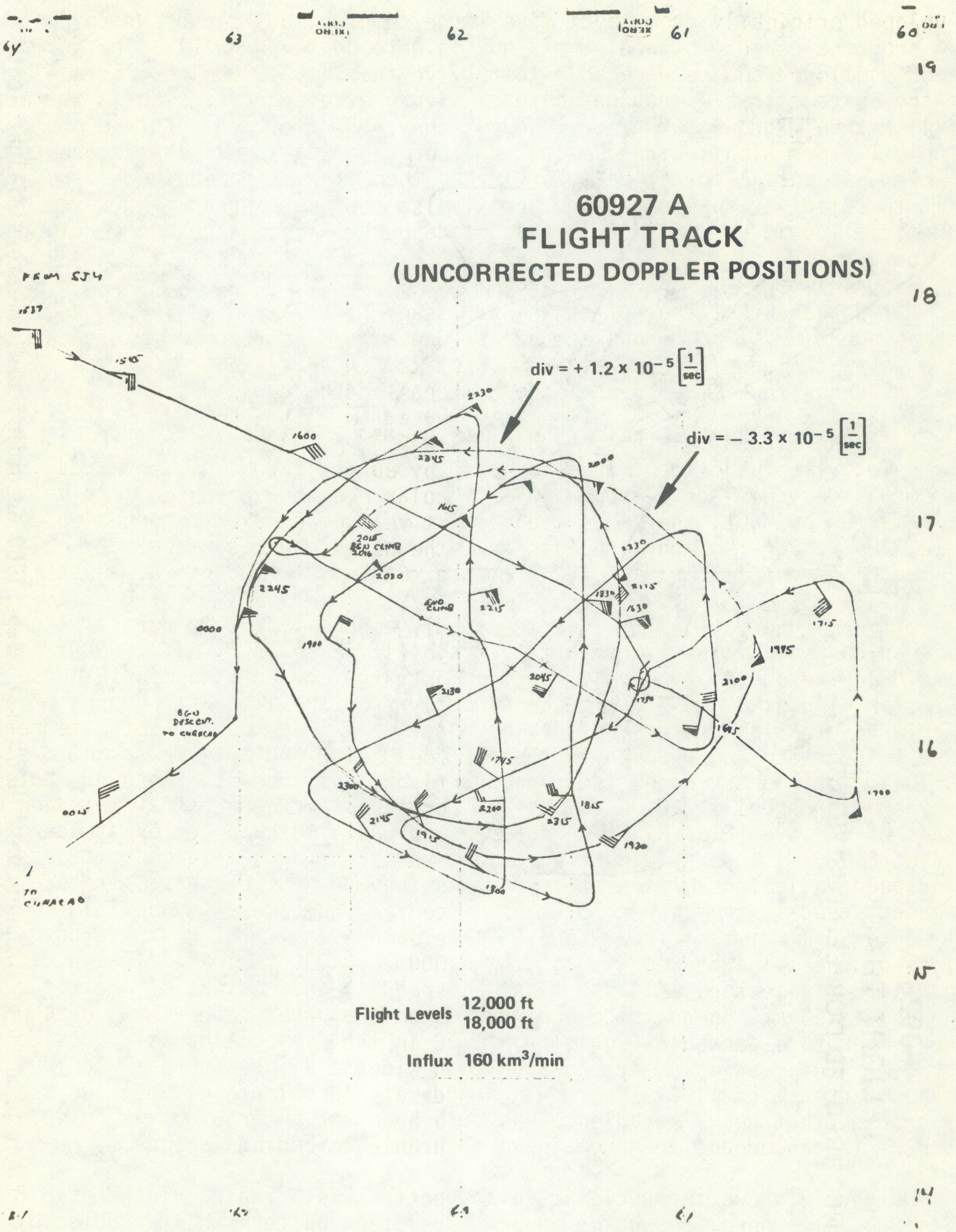


Figure 4. Flight path through Hurricane "Inez" on 27 Sept. 1966, according to Navigator's flight log.

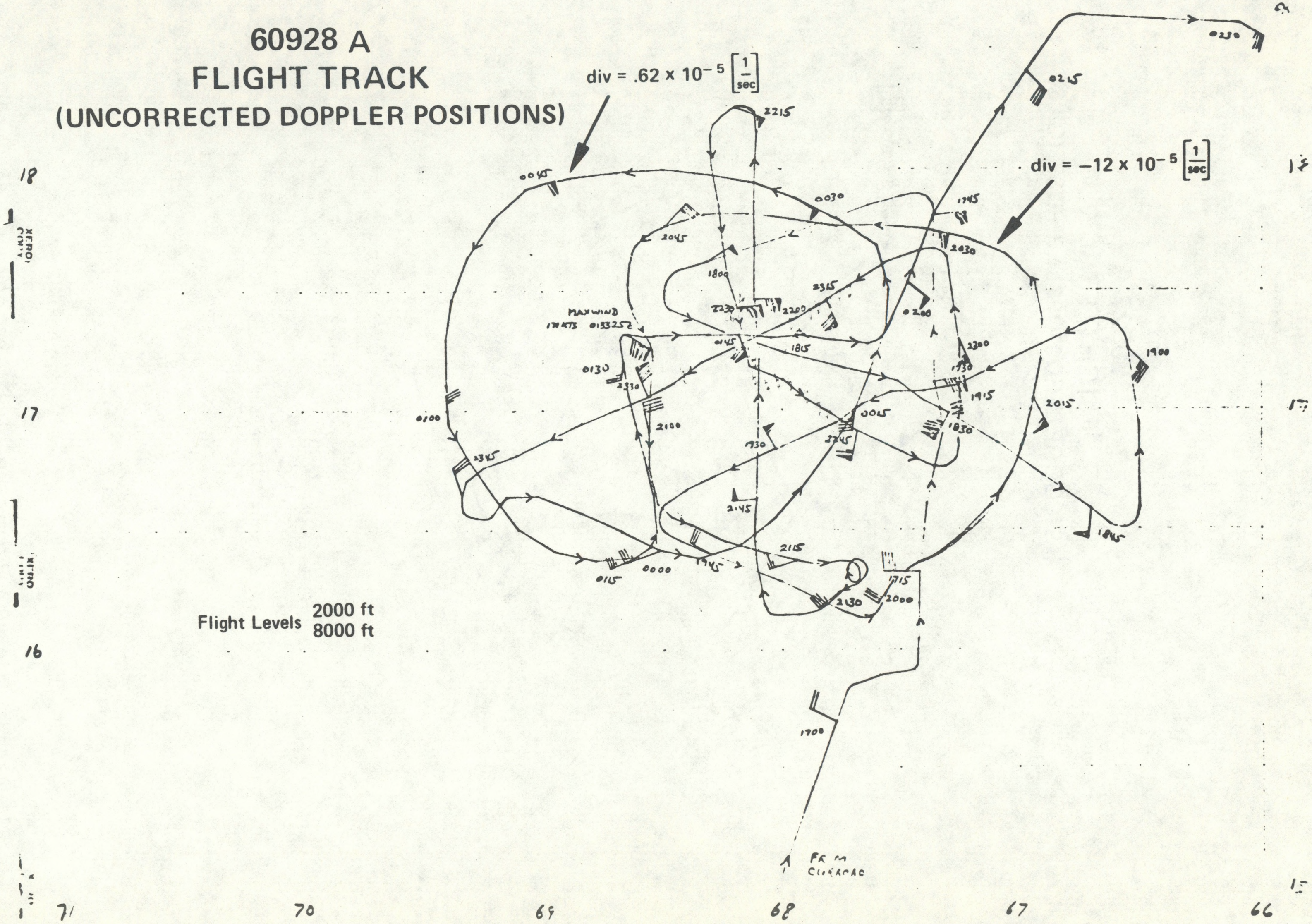
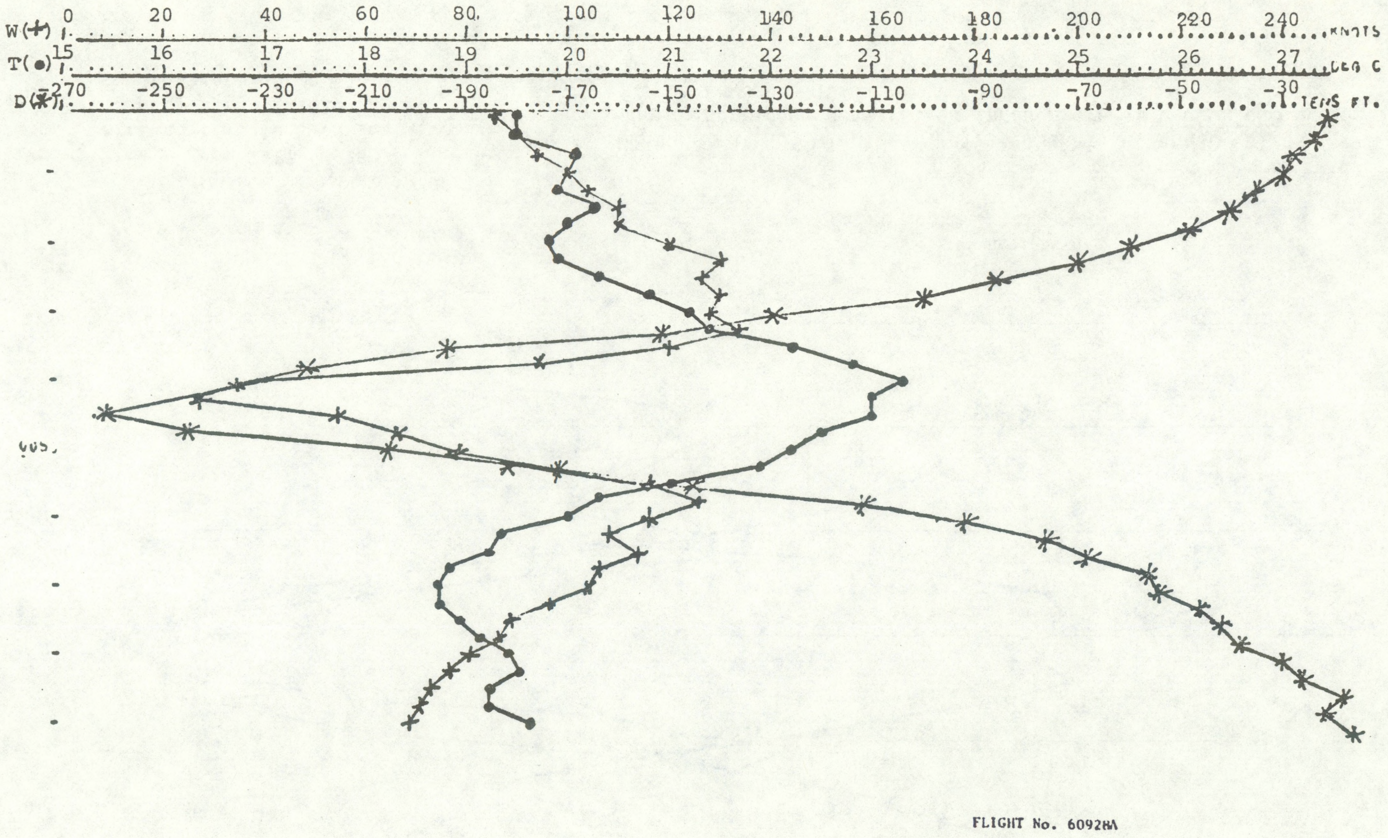
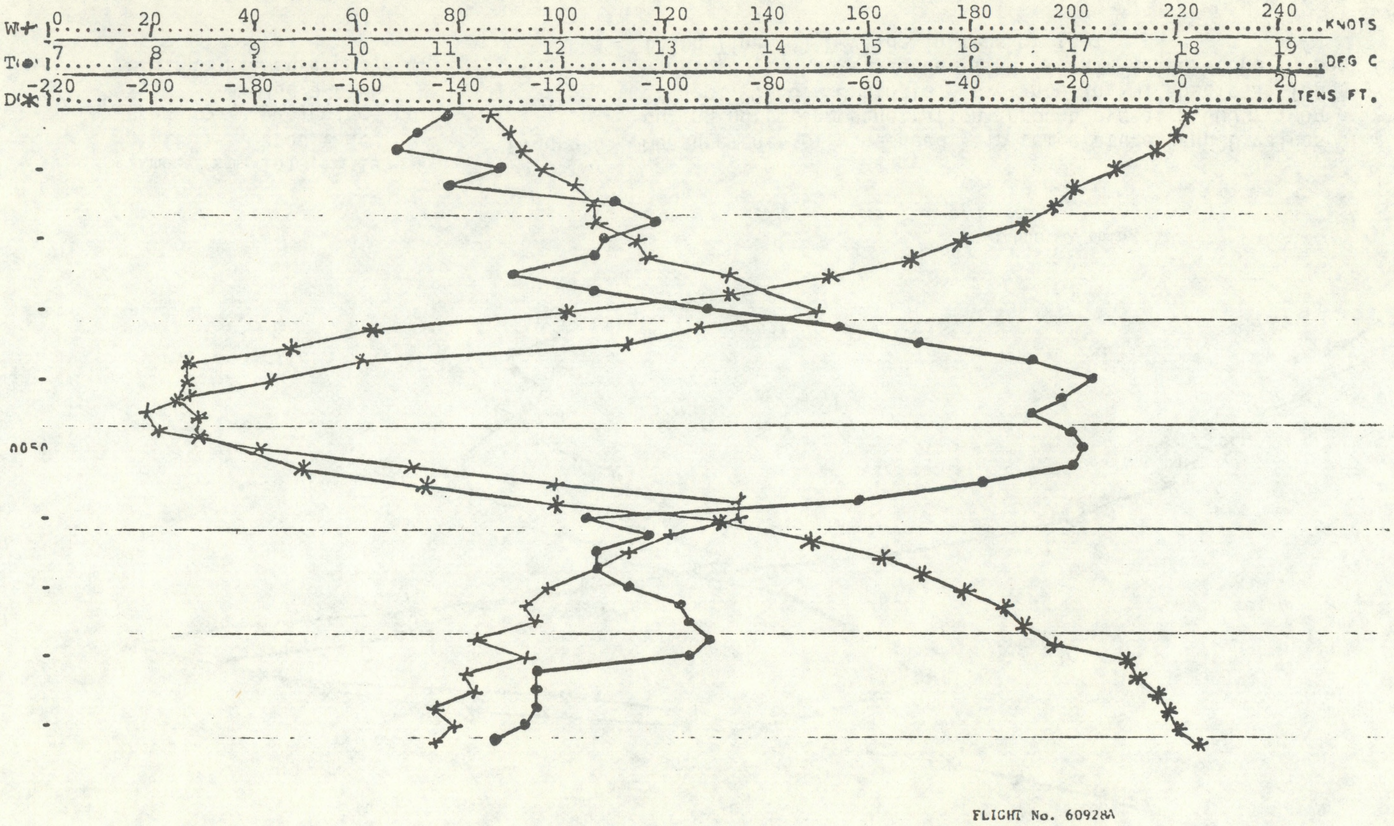


Figure 5. Flight path through Hurricane "INEZ" on 28 Sept 1966 according to Navigators' flight log. Lightning occurrence is marked with an arrow.



Time: From 1913 to 1929
Altitude: 2000 feet
Pressure: Beginning and
end 940 mb.
Minimum Pressure: 876 mb.

Figure 6. Measurements of windspeed, air temperature, and D values during hurricane penetration through eye at 2,000 ft. on 28 Sept. 1966. Ordinate: distance in Km; abscissa: Top (+) windspeed in knots, second line (•) air temperature in Deg. C, third line (*) D value in tens of feet.



Time: From 2317 to 2333
Altitude: 8000-6000 feet
Pressure practically
constant at 750 mb.

Figure 7. Measurements of windspeed, air temperature, and D values during hurricane penetration through eye at 6,000 to 8,000 ft. on 28 Sept. 1966.

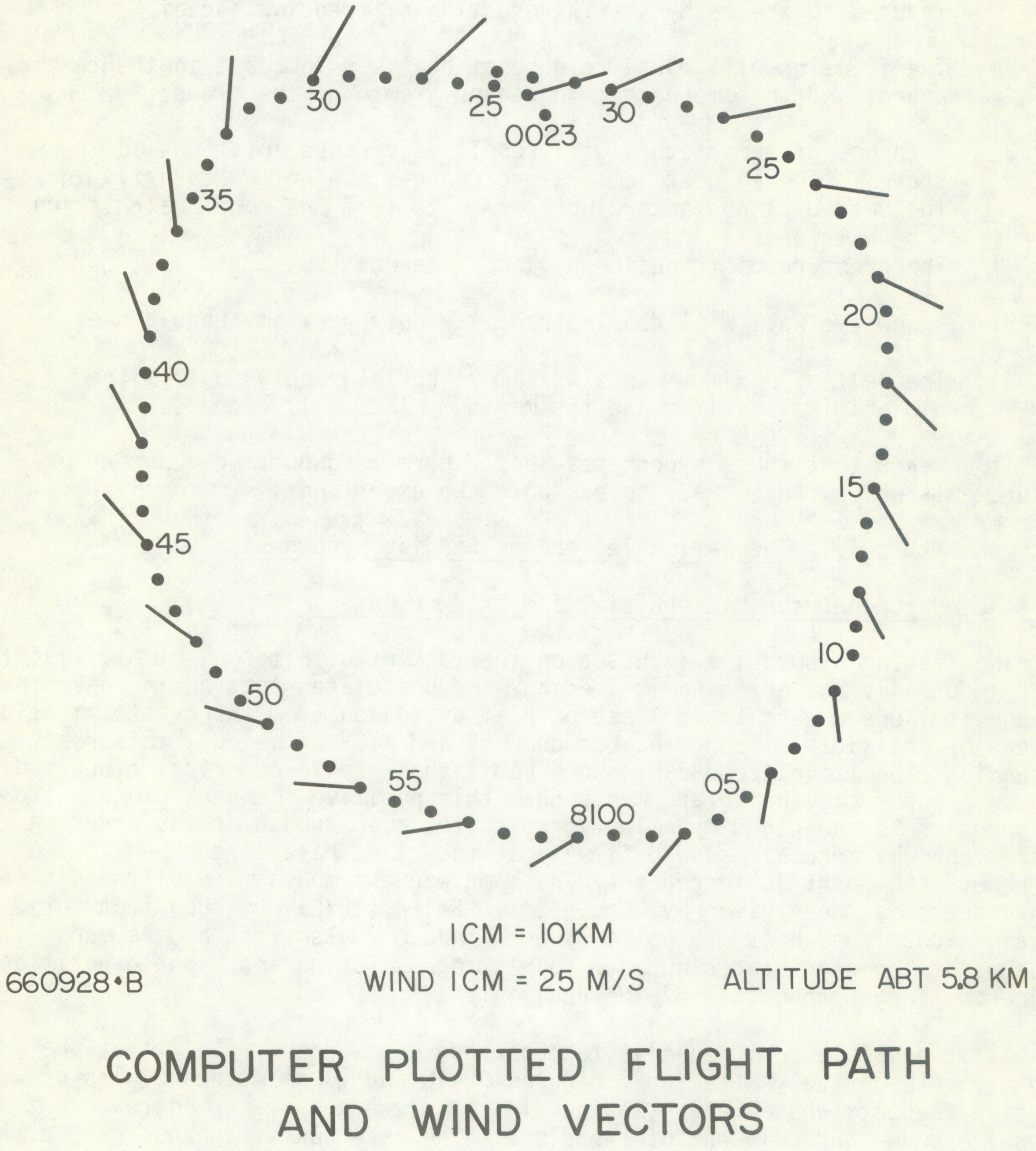


Figure 8. Cyclonic inflow pattern into hurricane at 5.8 km flight level.

4. THE SEEDING OF HURRICANES

The following hypotheses are the basis of the present STORMFURY experiment:

"1) There is supercooled water in the hurricane's clouds which can be induced to freeze by the introduction of freezing nuclei.

2) The freezing will cause release of heat, an increase in the temperature, and in some cases, increased growth of the clouds.

3) A change of temperature will result at various locations in the storm. (The largest temperature changes are not necessarily in the seeded clouds according to results from the model calculations.)

4) The pressure distribution will be altered.

5) A new eye wall will develop radially outward from the old one.

6) The belt of maximum winds will move radially outward from the old original maximum and the maximum winds will decrease."

It appears that these hypotheses should permit conducting a number of measurements which can be made to evaluate the experiment.

4.1 The Rationale for the Seeding Hypothesis

4.1.1 Feedback between Microphysics and Storm Dynamics

The seeding hypothesis is based on the work of J. Simpson, et al. (1965), which is usually called "dynamic seeding" and postulates that an increase in buoyancy follows due to the release of heat of fusion from the crystallization process by artificial ice nuclei between -5° and -10°C. We call this reaction to seeding "positive feedback". Combined with a simple numerical cloud model, Simpson brought convincing arguments that this positive feedback process from microphysics to the cloud dynamics is possible, even though it was never made quite clear why more air should flow in at the cloud base if the buoyancy of the upper cloud part is increased. The complete thermodynamics of the glaciation process has been given by Chappell and Smith (1975) who show that for certain cloud types heat may not only be gained but also lost as the vapor pressure of the glaciated cloud due to heating by fusion and vapor deposition may become larger than that of the environment.

Is it possible that negative feedback processes occur, i.e., that the buoyancy is negatively affected? Figures 9, 10 and 11 show the results of negative feedback where heavy seeding did not cause a buoyancy increase but intensive snow- and rain-out of the cloud. The case was a vigorous cumulus congestus cloud system shown in Fig. 9 against the horizon which developed as a rear feeder into a small thunderstorm. We penetrated the newly formed feeder cloud with the NOAA C-130 aircraft from North to South at about 22,000 feet, temperature below -20°C, and measured width and strength of the updraft. The width was about 5 km and the updraft velocity estimated from the aircraft

Figure 9. View of rear feeder storm in Colorado. West is at the right side, East is on the left side. Penetration and seeding was made on the western-most cloud development.

Figure 10. Start of precipitation falling out about 10 to 15 minutes after seeding.

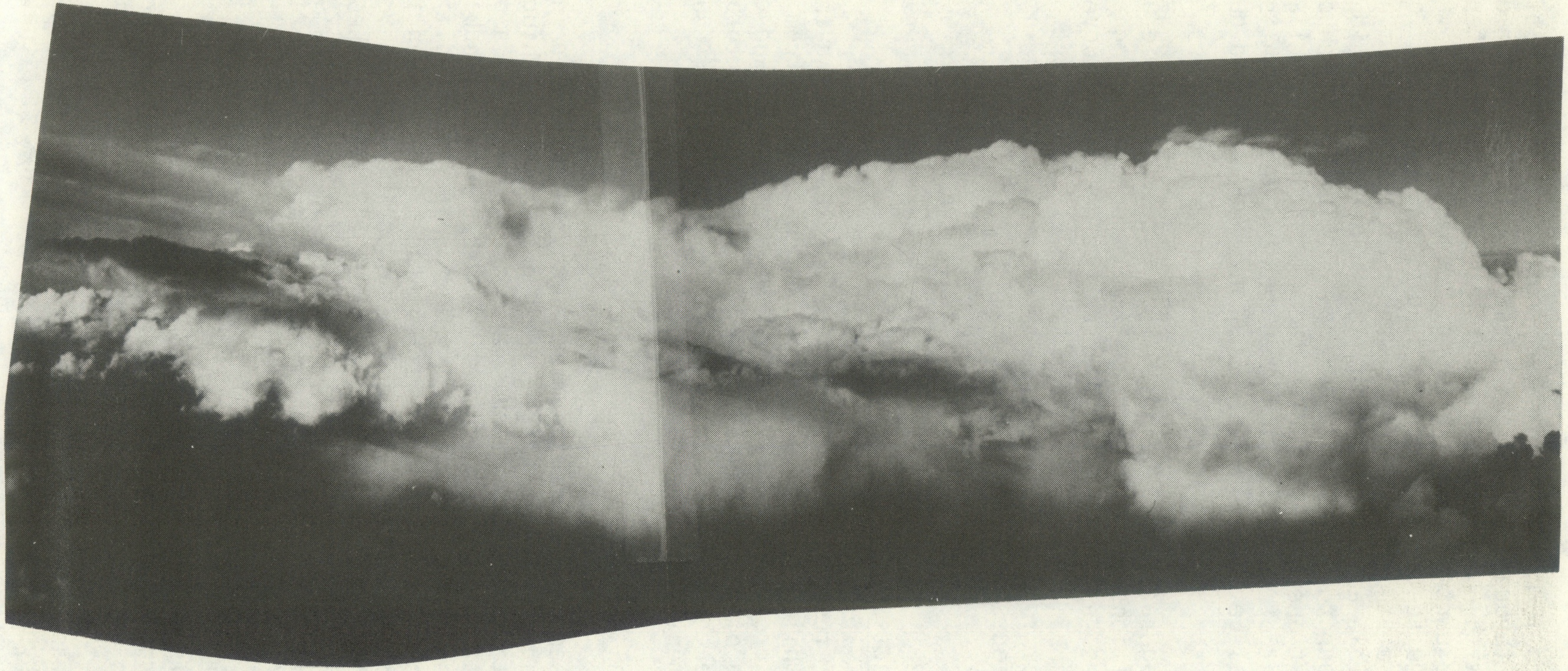


Figure 11. Large precipitation curtain discharged from seeded storm, cloud in foreground is newly formed feeder cloud.

variometer was 10 to 15 m/sec. There was some light precipitation in the cloud as we passed through. After the first penetration, we made a 180° turn and began to seed with AgI pyrotechnic cartridges as we re-entered the updraft. Every 5 seconds one cartridge was released up to a total of 15. They fell through about 12,000 feet releasing 100 g AgI each, or a total of 1500 g AgI. Much to our surprise, the cloud did not develop but after 10 minutes, precipitation became visible at the base (Fig. 10). The precipitation extended within less than 1/2 hour to a very sizable shower (Fig. 11) which dissolved the cloud while the next one was forming on the western end. Similar observations of rapid development of precipitation when seeding was accomplished within the temperature interval between -10° and -20°C has been observed during the Great Lakes Project.

The interesting fact shall be noted that Hurricane Debbie was seeded under similar conditions with respect to temperature range and release frequency of the flares, as the cumulonimbus calvus described above.

We propose that following this type of seeding arranged into well separated drops, two effects became dominant:

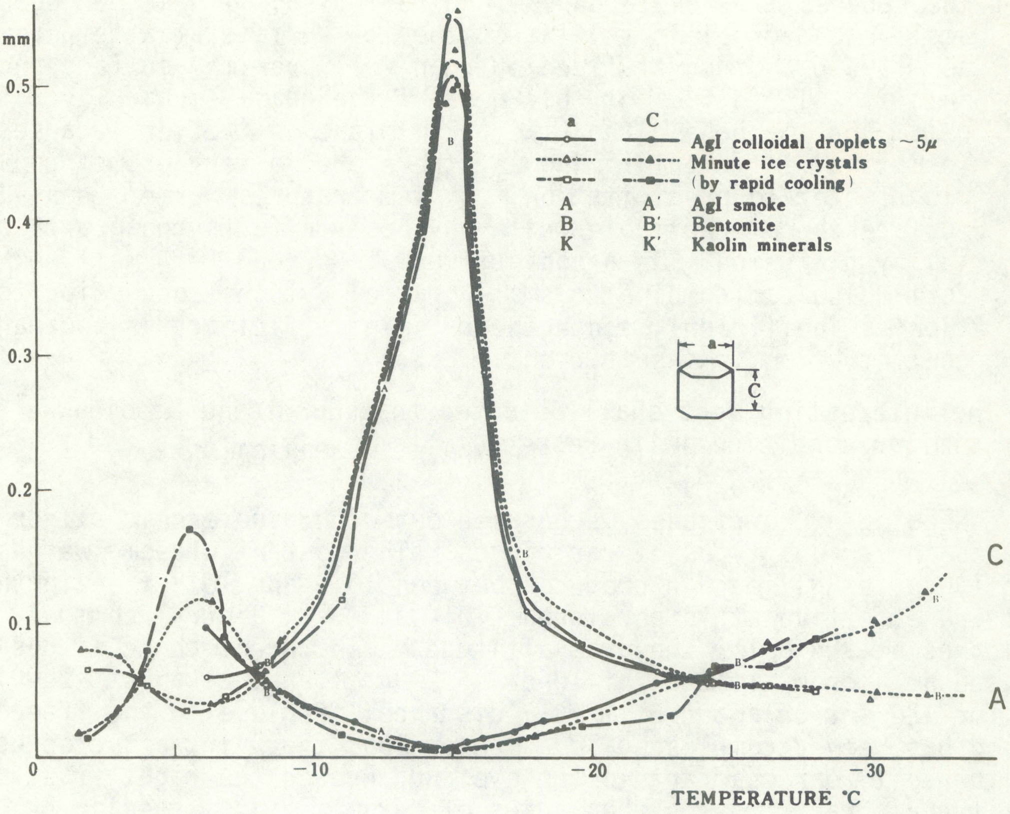
4.2 Seeding Effects

4.2.1 Dynamic Effects.

Heat of fusion and condensation is released along the trail of the flare, while cooling in the environment follows from the evaporation of the droplets. Consequently, we create warm and cold columns next to each other. This may cause internal eddies, turbulence, and horizontal exchange which all work against the updraft and support the development of precipitation.

4.2.2 Microphysical Effects

After seeding, a great number of crystals develop in the water cloud leading to local glaciation and humidities reaching from ice saturation to water saturation. Inside a water cloud a profound difference exists between ice crystal growth and growth habits for temperatures above and below -10°C. For the special conditions of ice crystals growing at water saturation, the growth perpendicular to the main axis and secondary axis has been experimentally investigated by Yamashita (1974), Ryan, Wishart and Shaw (1976), and theoretically, by Lacmann and Stranski (1972). The conditions for the growth of crystal surfaces along the main (c) and secondary (a) axis are shown by Fig. 12 (Yamashita). This figure agrees very well with the data obtained by Wishart, et al (1976). The temperature of -10°C is a convenient threshold: at warmer temperatures than -10°C, less and less crystals form due to a lack of freezing nuclei and the forms are prismatic, while at colder temperatures, plates and dendrites form whose C-axis growth is practically zero, while it is optimum perpendicular to the A-axis. According to Ono (1970), at -15°C, the rate of growth per mass is greater by about a factor of 100 when compared with that of a crystal at -10°C in spite of the fact that the vapor pressure



RATE OF GROWTH OF A AND C AXES OF ICE CRYSTALS AT WATER SATURATION (A. YAMASHITA 1974)

Figure 12. Rate of growth of A- and C-axes of ice crystals at water saturation. (A. Yamashita, 1974).

difference between water and ice at these two temperatures is about the same. The reason for this important abnormality is, presumably, a quasi-liquid layer which covers prism and base planes at -10^{o}C and prevents the crystal from taking full advantage of the vapor pressure difference between ice and water (cloud droplets); at -15^{o}C, the prism planes only are wetted, while the surface of the base plane is quasi-liquid and does not grow because two-dimensional nuclei apparently do not form in a quasi-liquid layer and the condensing molecules simply follow the diffusion field of the vapor. This favors the prism planes. It is not the place here to discuss in depth these new important insights into crystal growth but theoretical and experimental research indicates that the crystal surface begins to deteriorate in the temperature range -17^{o} to -25^{o}C to a quasi-liquid type of surface based upon the observation that two ice spheres upon contact will hang together by cohesion. There is no crystallization as it has been observed that the spheres may rotate on one another, also, it has been observed that small cloud droplets falling on the ice surface at a temperature as low as -19^oC do not crystallize but can roll over the surface and evaporate into it. The different thickness of the quasi-liquid layer for the prism and the base plane (the prism plane is "wetter") causes dendrite formation, efficient riming and therefore, a very prompt conversion of cloud water to precipitation. At temperatures warmer than -10^oC, both surfaces become wettable which obviously affects the growth of the crystal by diffusion. In a convective water cloud few small wet prisms form which can combine to small graupel but the conversion to precipitation is inefficient, since their riming efficiency is poor and their concentration is insufficient.

5. SEEDING EXPERIMENTS IN HURRICANES

Seeding of hurricanes is carried out with pyrotechnic silver iodide (AgI) mixtures in various types of cartridges. The content of some weighs 290 g of which 190 g is AgI, each g produces between 10^{12} and 10^{14} freezing nuclei "that are effective at temperatures (10^{12} at -8^oC, Gentry) commonly found in hurricanes at and below the drop altitude". The pyrotechnic is designed to be released at a drop altitude of 10 or 11 km (temperature about -25^oC) and to burn for 120 sec or about 6 km fall distance, or close to the freezing level. Seeding has been accomplished in a manner that the "aircraft crosses the storms from the left rear quadrant to the eye and through the right front quadrant. After the aircraft crosses the radius of maximum winds, seeding drops are started and last for 30 to 40 km. During the course of this run, approximately 200 of the pyrotechnics are dropped (or one per each 150 or 200 m), producing a curtain of silver iodide crystals 25 to 40 km long and 6 km deep. The crystals (freezing nuclei) are transported in a circular path by the winds blowing around the storm center. Considerable turbulence and strong horizontal shear exist in this layer so that in about 2 hours the silver iodide should be distributed in an annulus around the hurricane center with the inner edge near the center of the eye wall extending gradually outward for about 30 km. At the present time, it is not known what percentage of the silver iodide crystals blow out through the top of the hurricane or fall out at the bottom in raindrops. The remainder, however, should be fairly evenly distributed around the storm within 3 hours".

5.1 <u>Case Studies</u>:

Seeding experiments in hurricanes. Summary (see also Table 1):

5.1.1 ESTHER, 1961	Single seeding on each of 2 days (ref. R.H.Simpson, et al 1963). 8 AgI generators, type "Cyclop", from 43,600 ft, 4 miles thick layer to 0^oC level. 1 Cyclop ∿ 130 lbs, ∿ 70 lbs AgI, 60 lbs propellent.
5.1.2 BEULAH, 1963	Single seeding on each of 2 days (ref. R.H.Simpson, 1964). 750 kg AgI each day, from 35,000 ft, 20 miles radially; measured IN at 18,000 ft, before and after seeding.

TABLE 1

HURRICANE	SEEDING	SEEDING LOCATION	RESULTS
"ESTHER 16 Sept 1961	43,600 ft to 22,000 ft, 8 Flares at 1.3 km Intervals 280 kg Agl Total	NNE Sector Wall Cloud	Disappearance of 10 cm Radar Echo
"BEULAH" 24 Aug 1963	35,000 ft 375 kg Agl in 50 "Canisters" 14.58-15.15z	32 km Path into Wall Cloud	Ice nuclei Measurements Before and After Seeding at 18,000 ft. Increase by one order of Magnitude. Windspeed Reduced 17% 2 Hr 21 Min After Seeding at 15,000 Ft (17.36 - 17.54z)
"DEBBIE" 18 Aug 1969	"Eye Mod" Experiment 10,000m 208 Cartridges at 190 g Agl 5 Seedings about 2 Hrs Intervals 39.5 kg Agl at Each Seeding Run Total 197.6 kg/Day. First Seeding Began 142230, Last Seeding Ended 215430.	26-40 km Wall Cloud Radially	5 Hours after Last Seeding Windspeed at 3600 m Has Dropped 31% (182 km/Hr to 126 km/Hr).
20 Aug 1969	Same Experiment First Seeding Began 115630, Last Seeding Ended 195620.	26-40 km Wall Cloud, Radially	6 Hours After·Last Seeding Windspeed Has Dropped 15% (183 to 156 km/Hr).
"GINGER" 26 Sept 1971 Winds 69-63 kts About 75 km from Center	Rainband Experiment Seeding Level 22,000 Ft - 12"C. Two seeding into the Clouds. First Seeding 150 to 200 km South of Eye 1701-1751z 31 Pyrotechnic Devices at 160 g Agl, Total of 4.99 kg	150-280 km South of Eye	No Cloud Growth. Area "Was Probably Overseeded".
	Second Seeding 1900-1913z, 15 Flares 22,000 Ft Seeding Level	200-280 km South of Eye	No Results. Very Low Water Contents 1-2 g/m^3
28 Sept 1971	Three Groups of Seedings, Each With About 200 Pyrotechnic Devices, 22,000 Seeding Level, No Special Cloud Selection, Every 5 seconds One Flare Was Released. Within 3 ½ Hours More than 600 Flares were Released on this day.	110-185 km North of Center	No Cloud Growth. Authors believe they Overseeded!

TABLE 1. Compilation of seeding information for STORMFURY experiments on four hurricanes.

5.1.3 DEBBIE, 1969 Multiple seedings ("eye mod" experiment) on each of 2 days (R.C.Gentry, 1970).

5.1.4 GINGER, 1971 Multiple seedings (rain sector experiment) on each of 2 days (H.F.Hawkins, et al, 1971).

Since information on most seeding experiments of hurricanes is difficult to come by and scattered in numerous reports, memoranda and publications, we have endeavored to collect it and have summarized the data in Table 1.

5.2 DISCUSSION:

5.2.1 ESTHER

Hurricane type: Typically mature, severe hurricane, maximum winds >130 kts. Eye 14 - 18 nm Ø. 0^0 level 18,500 in rain area, 20,000 feet in eye.

Seeding Experiment:

16 Sept. 1961 Drop of AgI generators begins 2016 GMT from 43,600 ft. Eight canisters were released at 1.3 km intervals, the last being located about 15 km inside eyewall. Eight flares ignited and were timed to burn down to about the 22,000 ft. level. Cloud tops along seeding track extended above 45,000 ft. Icing occurred on the A3D air frame, turbulence moderate during seeding run. DC-6 at 20,000 ft., encountered heavy icing, also lightning strikes.

17 Sept. 1961 Seeding experiment repeated almost identically. Unfortunately, most AgI canisters fell into clear air of the eye on northern edge of eyewall. On this day, B-57 flying across the chimney area (NE of center) experienced a steady rate of climb indication of +2200 fpm, -1800 fpm upon entering the eye. Little evidence of short period convective drafts was found. On opposite eyewall, rate of climb remained near zero and short period turbulent drafts were prevalent.

Results Sept. 16, 1961

Within 1 hour after seeding began, the 10-cm echo disappeared over a section of 160^0 downstream from the seeding area .3 cm radar echo and visual appearance did not change. Maximum winds decreased 9 percent at 7,000 ft; 14 percent at 20,000 ft.

Aggregation of evidence tends to support certain tentative conclusions. These are:

1) A large amount of supercooled liquid water was converted to ice;

2) The release of latent heat from (1) may have led to certain imbalances and instabilities;

3) The total kinetic energy over the test area was reduced and the maximum windspeeds diminished.

Critique:

We believe that the disappearance of the 10 cm radar pattern downwind from the seeding area might have been a true seeding effect due to glaciation or snow out. Note that the seeding level was 43,600 feet where the temperature must have been below -25^{o}C. If supercooled water would have been present in the seeded area, it would have quickly converted to ice thus affecting negatively the 10 cm radar echo. This may have caused either one of two effects:

1) Agreement with the hypothesis #1, it released heat of fusion and decreased the air density, equalizing the surface pressure gradient.

2) It converted the supercooled clouds to precipitation which may have caused widespread downdrafts.

Both effects could have weakened the hurricane as it implicitly is suggested in the third conclusion above.

5.2.2 BEULAH

On August 23, 1963, the seeding agent was dropped outside of seedable clouds, while on the second day (August 24, 1963) the results were inconclusive.

5.2.3 DEBBIE

Hurricane type: Typically mature, severe hurricane.

Seeding times:

18 August 1969								20 August 1969						
Hr.	Min.	Sec.	-	Hr.	Min.	Sec.	← GMT →	Hr.	Min.	Sec.	-	Hr.	Min.	Sec.
14	22	30	-	14	24	30		11	56	30	-	11	58	30
16	33	30	-	16	36	00		14	01	40	-	14	03	30
18	12	20	-	18	14	50		16	13	45	-	16	15	45
20	01	10	-	20	03	40		17	57	50	-	17	59	50
21	52	00	-	21	54	30		19	53	50	-	19	56	20

Seeding by Navy aircraft approach from SSW at 10,000 m penetrated wall cloud and crossed eye, began seeding after entering wall cloud on NNE side. Each aircraft carried 208 AgI cartridges and dropped them along a line leading radially away from the center. Each cartridge contained slightly more than 120 g of AgI, each g to produce $>10^{12}$ nuclei at -8°C. Evidence indicates that each g produces 10^{14} at the low seeding temperatures used in hurricane clouds. The two DC-6's covered the seeding operation from 3 hours before the first seeding until 5 to 6 hours after the last one by alternating their flight schedule to produce continuous coverage. The aircraft flew at 3600 m. Wind speed maximum was 182 km/h before 1st seeding on 18 Aug 1969 and 126 km/h, 5 hours after seeding on 18 Aug 1969.

On 20 Aug 1969, corresponding change of wind speed was from 183 to 156 km/h.

Results:

Hurricane Debbie was seeded five times within 8 hours on August 18, and again on August 20, 1969. The maximum winds measured and recorded by highly instrumented aircraft flying at 3600 m decreased from 50 mps before the first seeding on August 18 to 35 mps 5 hours after the fifth seeding, a 30 percent reduction in 13 hours. The maximum winds, which had meanwhile returned to the original levels, decreased on August 20 from 51 mps before the first seeding to 43 mps within 6 hours after the fifth seeding, or by about 15 percent in 13 hours. These results were so encouraging that a greatly expanded research program was planned.

Critique:

It is physically inconceivable that the seeding effect of this experiment should come as long as 5 hours after the last seeding, and after seeding had progressed for 8 hours prior to that.

5.2.4 HURRICANE GINGER (Hawkins, et al, 1971)

Hurricane Ginger was seeded on 26 September and 28 September 1971. When compared to Debbie, it was less intensive with a broadly sprawling eye formation with wind up to 65 kts between 30 to 40 nm distant from the center. It was, therefore, concluded that Ginger was not a suitable object for wall-cloud seeding ("eye mod") and it was decided to conduct a rain sector experiment.

26 September. The tops of most storm clouds in the region selected of the southern sector, 80 to 150 nm away from the center, were at 23,000 ft. The seeder aircraft flew at 22,000 ft. where the temperature was about -12°C. Thirty one pyrotechnic devices (each producing 160 g of AgI) were used during the first seeding, 17.01 - 17.17 and 17.34 - 17.54. The devices were placed into updrafts showing "some evidence of the presence of liquid water". The updrafts were rather weak and the liquid water content "moderate or less". No startling cloud growth followed. It is stated that "it was the opinion of those aboard that, in view of the state of the rainband encountered, the area had probably been overseeded". Since the concept was to stimulate the clouds to greater growth, only underseeding could cause ineffectiveness, due to insufficient release of heat of fusion while overseeding should definitely release all heat of fusion available and cause cloud growth. It must, therefore, be a different reason why the experiment did not work. Another

experiment was carried out between 19.00 GMT and 19.13 GMT using 15 flares. The echoes were 5 to 15 nm apart and the cells contained only mild to moderate updrafts. The liquid water content at 5,000 ft was small, about 1 gm/m^3 on the average with 2 gm/m^3 maximum; it appeared still smaller above the freezing level. The seedability of the clouds was calculated from vertical soundings with dropsondes, the result of these computations supported some growth would occur, but in practice, it did not.

A similar experiment was carried out on September 28 in the NNE quadrant of the hurricane in a much more extensive effort as 600 flares were dropped within 3½ hours. Only a "brightening of the radar echoes was noted temporarily", but "direct evidence that any significant cumulonimbus activity was stimulated by the seeding is totally lacking." The authors came to the following cryptic conclusions about this experiment:

> "We are forced to the tentative conclusion that Hurricane Ginger was a sprawling old storm that (on Sept. 28) was filling and losing strength. It did not provide the environment necessary for any vigorous growth, and under these conditions, the areas were undoubtedly overseeded to such an extent that significant growth was highly unlikely."

Again, we find the erroneous conclusion about the "overseeding" effect. It has become customary in weather modification experiments which do not produce what the experimenter likes to achieve, to blame it on "overseeding". Nothing could be more wrong in this hurricane case than to invoke the overseeding spectre. Just the opposite is true: overseeding would effectively release all heat of fusion available to stimulate buoyancy while it is underseeding which could adversely affect the development of buoyancy. In this case, neither overseeding nor underseeding is to blame, there was simply no effect!

6. CONCLUSION

With the exception of "Ginger" all hurricanes were seeded at temperatures below -20°C. For this reason, it cannot be assumed with certainty that a dynamic effect was caused. It is possible that precipitation loading of the clouds occurred, leading to cloud dissipation and downdrafts. Since it is possible, however, that most of the precipitable water furnished by the updraft rains out due to the warm rain process and that the cyclonic character of the mature storm is characterized by altostratus aloft rather than by convective clouds, (only 10% of the clouds are convective according to Gentry), we doubt that much will happen to the storm at all.

We believe that only in one case has a true effect of seeding been observed, namely, in Hurricane Esther. This hurricane was sufficiently close to land that it was surveilled by a land-based 10-cm radar set. The disappearance of the 10-cm radar echo one hour after seeding at 20.36 GMT and downstream of the seeding path is exactly what one can expect if seeding increases the number of ice crystals and eliminates liquid water. No new cloud formation was indicated due to the unchanged radar return from the 3-cm radar and the visual appearance of the clouds. The 10-cm radar return appeared again at about 21.20 GMT. This time span is reasonable for letting the crystals fall out and the clouds reform. It is stated that the maximum wind decreased 9% at 7,000 ft and 14% at 20,000 ft for 2 hours after seeding.

Most often quoted as suggestion that seeding according to Hypothesis II works and diminishes the windspeed is the experiment conducted with Hurricane Debbie. The winds diminished 5 hours after seeding ended and seeding extended over more than a 7-hour period. It is hard to understand the significance of the 5 hours. What is the magic that makes the wind decrease 12½ hours after seeding began and not after 5 hours, nor 10, nor 15? It appears that 5 hours after the last seeding, all previous seeding effects including the last one should have subsided due to rain-out or blow-out at the cloud tops of the seeding material. It strongly suggests that accidentally 12 hours after the seeding began, the winds subsided.

There is strong evidence that mature hurricanes are well organized deep cyclonic storms with a small amount of convective clouds interspersed. Radar bright bands are present throughout the storm, relatively small updraft velocities are measured, large cirrus outflows makes it unlikely that sizeable amounts of liquid water are lifted far beyond the freezing level. The feedback mechanisms between cloud microphysics and cloud dynamics is by no means so well established that a hurricane modification concept could be based upon it. While the feedback mechanism may be positive at seeding temperatures above -10^{o}C (increased buoyancy), it is most likely negative (decreased buoyancy and rainout with cloud dissipation) at seeding temperatures colder than -10^{o}C. Seeding temperatures in hurricanes are from -25^{o} to -5^{o}C due to the release level of AgI cartridges at 33,000 ft.

We conclude our considerations here with an important question: The seeding of Debbie was accomplished in a way that negative feedback and additional rainout was possible if supercooled water was available. In such a case, would the effect on the hurricane be positive, negative, or neutral?

7. OUTLOOK

It is absolutely necessary on the basis of what was said above, to study much more thoroughly than has been possible so far, the effect of seeding in all types of clouds and under various temperature conditions. Most important for Project STORMFURY is the study of cloud micro- and mesophysics above the freezing level, particularly the liquid water content and type and number of convective clouds. With this information it may be possible to develop a valid seeding hypothesis.

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