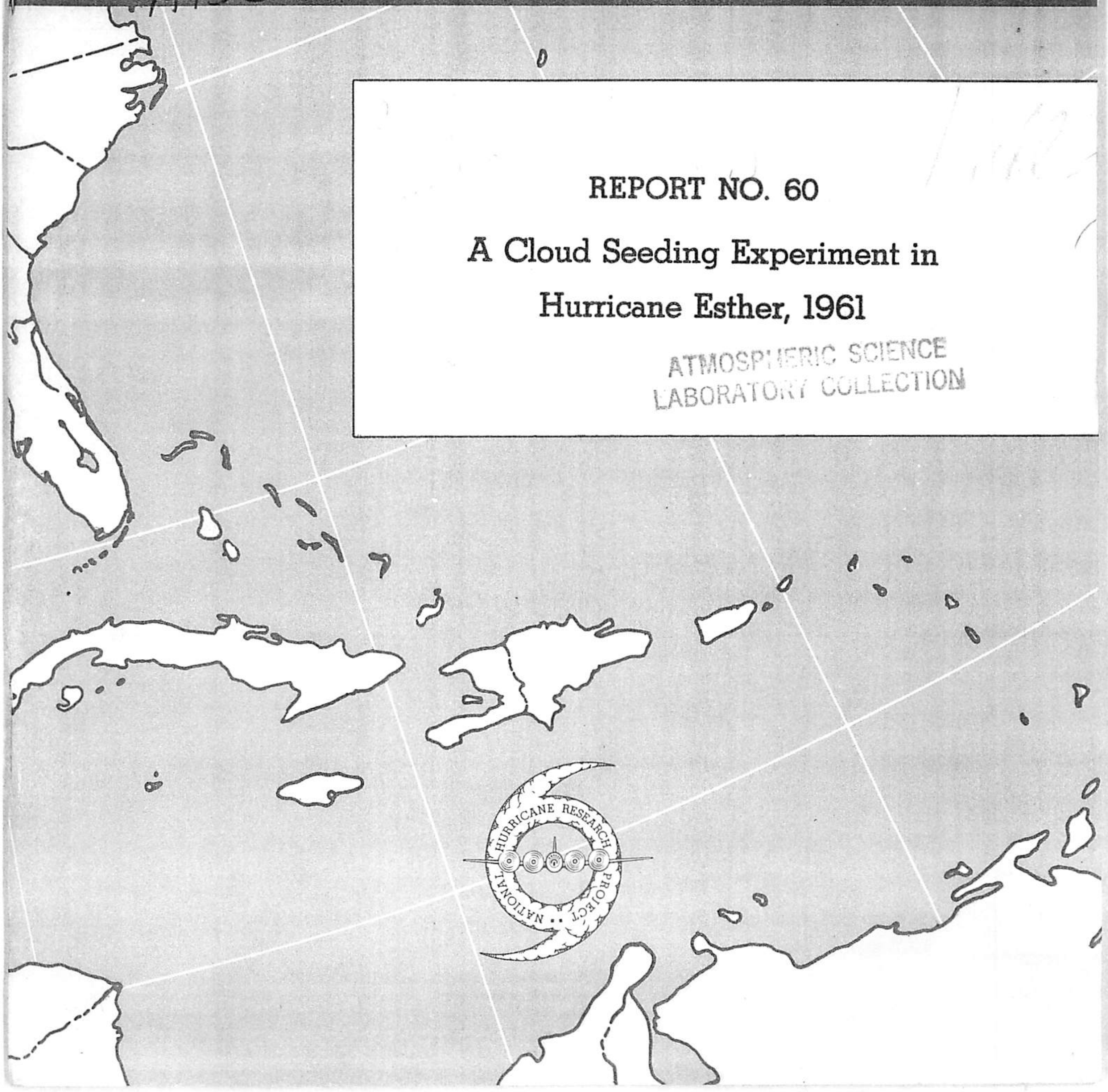
ONAL HURRICANE RESEARCH PROJECT

REPORT NO. 60

A Cloud Seeding Experiment in Hurricane Esther, 1961



U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL HURRICANE RESEARCH PROJECT

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A Cloud Seeding Experiment in Hurricane Esther, 1961

by

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U. S. Weather Bureau, Washington, D. C.

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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FOREWORD

This paper describes a cloud seeding experiment that was made in 1961 during the research operations of the National Hurricane Research Project (NHRP) with special support supplied by the U. S. Navy. Readers who are looking for definite answers to questions about the effects of cloud seeding on the destructive forces of a hurricane will not find them in this paper. Many more experiments and much deeper research are necessary to get answers to these questions.

This paper is nevertheless important for several reasons. Although the experiment it describes is preliminary, it does represent the most comprehensive and concerted scientific experiment in this field up to the present time. It is the prototype for more intensive and more extensive research now provided in the plans of the NHRP which include the collaboration and material assistance of other interested agencies, particularly the Navy and the National Science Foundation.

This research is designed to test hypotheses involving the release of small energy sources which might trigger changes in the structure and mechanism of a hurricane in ways that would modify and reduce its destructive characteristics.

Many inquiries have been received from persons interested in the possibilities of hurricane modification. This paper serves to inform them of the experimentation so far completed. We hope it will strengthen interest for and support of the program and give rise to further ideas and suggestions for the future program.

F. W. Reichelderfer

Chief, U. S. Weather Bureau

CONTENTS

A CLOUD SEEDING EXPERIMENT IN HURRICANE ESTHER, 1961

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ABSTRACT

In September 1961 cloud seeding experiments were conducted in hurricane Esther on two consecutive days. The purpose was to determine whether artificial releases of latent heat of fusion and sublimation could be used to induce circulation instabilities leading to a reduction of maximum wind speeds. Pyrotechnic generators, dropped from aircraft in the tops of clouds, released vertical plumes of silver iodide which were subsequently spread downstream by the hurricane circulation. Results were monitored by research aircraft which maintained continuous radar coverage of a test area and measured changes in kinetic energy before and after seeding.

A marked reduction in reflectivity of 10-cm. radar energy was observed in the test area after the silver iodide was released. Also the kinetic energy diminished. However, the small magnitude of the change and limitations of the analysis restricted the conclusions which can be drawn on the basis of these initial experiments.

1. INTRODUCTION

Most scientific experiments in weather modification have sought means of increasing rainfall or suppressing hail. While a number of investigators have concerned themselves with means of reducing the hazard from severe storms (e.g., Langmuir [4,5], Lopez and Howell [6]), few field experiments have been undertaken, probably for two reasons. First, the amount of energy released by hurricanes or tornado-bearing squall lines is so immense that the work which man, through his own devices, can apply to the atmosphere is insignificant by comparison, unless it can be used to trigger circulation instabilities which cause divergence of momentum or reduce the concentration of kinetic energy. Too little has been known about severe storms to identify their "Achilles heels". Secondly, the same lack of knowledge has tended to expose the experimenter to unacceptable legal liabilities for storm damage which might follow any effort to modify storm intensity.

The first documented effort at weather modification in a hurricane occurred on October 13, 1947, when Project Cirrus conducted a seeding experiment in a small hurricane off the Florida coast (Rex [9]; Mook [8]). In this instance approximately 80 lb. of dry ice were dropped into supercooled clouds, the exact results of which could not be determined because no facilities were available to monitor changes in circulation or cloud structure.

When the National Hurricane Research Project (NHRP) was established in 1956, one of the early findings was that appreciable amounts of liquid water are often present above the freezing level. The feasibility of conducting weather modification experiments was studied by Braham and Neil [2], and the staff of NHRP. In 1958, a silver iodide generator was installed on one of the NHRP research aircraft at West Palm Beach, Fla., and attempts were made to conduct exploratory seeding experiments in hurricanes on two occasions. However, difficulty with the equipment prevented useful results from being obtained.

After five years of experimental research, the findings of NHRP pointed the way to a more complete experiment based upon specific hypotheses from which the results could be evaluated by dynamical analyses. The Weather Bureau and the National Science Foundation agreed on joint sponsorship of a series of these experiments. About the same time, the Naval Ordnance Test Station at China Lake, Calif., developed new pyrotechnic generators for rapidly dispensing large quantities of silver iodide in vertical plumes, using free falling flares launched from aircraft. The Navy offered to supply these new generators to the Weather Bureau for the hurricane seeding experiments and to furnish aircraft to drop the flares. This made it possible to design a more comprehensive and effective experiment. The first two seeding operations were conducted in hurricane Esther on September 16 and 17, 1961. This report will discuss the design of the experiment and present the results of these initial seeding efforts.

2. EXPERIMENT DESIGN

Background. The design of cloud seeding experiments in 1961 was based primarily upon four features of hurricane structure observed on research flights by the National Hurricane Research Project. First, the pressure gradient forces which sustain the strongest winds of the hurricane change very slowly with height through the low and middle troposphere, and therefore are largely a function of temperature distributions in upper layers of the storm. Secondly, the presence of supercooled liquid water is commonplace in hurricanes. As evidenced by aircraft icing, substantial amounts of liquid water exist virtually to the tops of clouds which form the eye wall. Thirdly, the distribution of vorticity in the annulus just beyond the ring of maximum wind is such that small reductions in curvature of the flow can lead to dynamic instability. Finally, evidence from visual and radar observations is that the cirrostratus outflow of the hurricane tends to be fed primarily from a small convective chimney situated near the eye, usually in the right semicircle. In a few instances it has been apparent that most of the mass transported by the lower inflow circulation has escaped upward to the outflow layer through a chimney no larger than 10 by 20 miles (see fig. 1).

The efficiency of the hurricane heat engine is largely dependent upon the difference in temperature between the storm core and the storm environment at the outflow level. And the storm intensity is related to the mass transport from the storm core to the environment at this level. To the extent that the outflow is uniquely fed through a convective chimney near the eye, both the warmth of the upper storm core and the mass transport of the storm must be related to the dynamical and thermodynamical properties of circulations in the chimney. This suggests the hypothesis that weather modification measures in the hurricane might possibly be confined to an area no larger than 200 square miles, less than 1 percent of the surface area ordinarily affected by damaging winds.

The small change in maximum wind speed with height has been discussed by Hawkins [3], and it has been shown that in the region of maximum wind, the pressure gradient tends to be conserved with height. J. Malkus and H. Riehl [7], in studying the means by which the strong pressure gradients of the hurricane are established, concluded that tropical air which enters the hurricane near the surface does not have sufficient heat content to account, by parcel ascent, for the equivalent potential temperatures observed at cloud top levels and which are required if surface pressures are to be lowered enough to sustain hurricane force winds. The enrichment of parcel heat content depends upon transfers of latent and sensible heat from the ocean to the air in the surface layers. Figure 2 illustrates observed differences in parcel ascent temperature at the hurricane periphery and at the point of maximum wind, the additional heat energy having been acquired from the ocean. Curves B and C show the difference in temperature of parcels in which only latent heat of condensation is released and those in which sublimation and freezing of liquid water occurs efficiently above the freezing level (see table 1). If it is assumed the cloud system with its organized outflow is contained beneath a rigid top at 150 mb., and that as much as 1 gm. m.$^{-3}$ of liquid water is present above the freezing level, the change in height of a pressure surface at the freezing level due to release of latent heat of fusion and sublimation could exceed 200 ft. This means that if Nature permits no freezing in clouds, but by seeding, all supercooled clouds are induced to freeze (and the frozen precipitate is removed by the outflow), then hydrostatically the pressure surfaces from sea level to the freezing level could fall by more than 200 ft. It is unlikely that such extreme changes could be produced. However, much smaller (local) changes could alter the balance of forces and reduce the curvature of flow in the annulus just beyond the ring of maximum winds and thus send absolute vorticity values to zero or below.

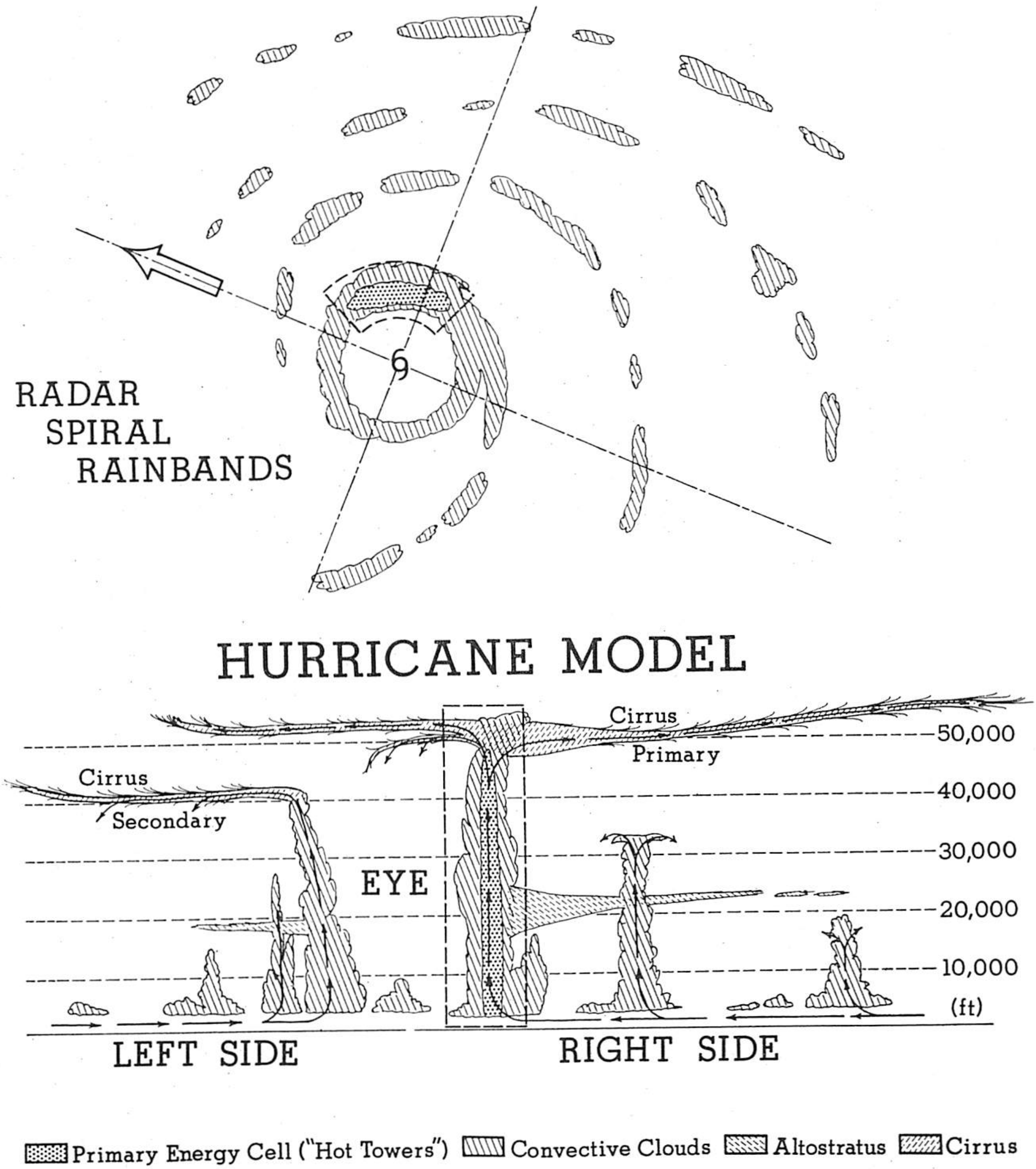


Figure 1. - The hurricane model. The primary energy cell (convective chimney) is located in the area enclosed by the broken line.

PARCEL ASCENT OF SUBCLOUD AIR IN THE HURRICANE

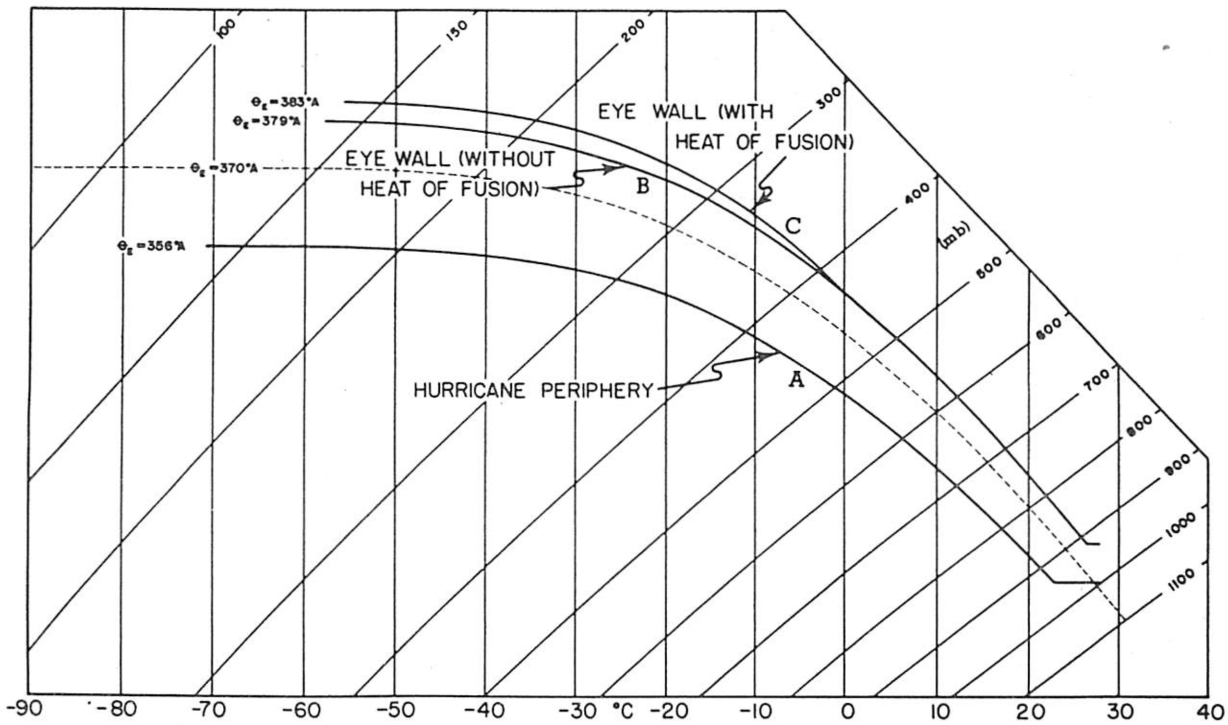


Figure 2. - Curve A illustrates the increase in equivalent potential temperature of air in the subcloud layer due to flux of latent and sensible heat from the ocean. Curves B and C also indicate the difference in temperature of saturated rising parcels which release latent heat of fusion and of those which do not.

Consider the wind profile in Esther, September 16 (fig. 3). The absolute vorticity may be written

$$\zeta_a = f - \frac{\delta c}{\delta n} + \frac{c}{R} \qquad (1)$$

where f is the Coriolis parameter, c the wind speed, n the distance normal to the streamline, positive to the left, and R the radius of streamline curvature. If it is assumed for simplicity that near the ring of maximum winds R = r, the radial distance from the center, and that n lies along a radial then (1) may be rewritten

$$\zeta_a = f + \frac{\delta c}{\delta r} + \frac{c}{R} \qquad (2)$$

Table 1. - The contribution of latent heats of sublimation and fusion during adiabatic expansion of saturated air. The computations show the increments in parcel mean temperature when latent heat of condensation is augmented by heats of sublimation and fusion. It assumes (1) continuous ascent of undiluted sub-cloud air from the freezing level (500 mb.) to cloud tops (150 mb.); (2) initially, all precipitation is liquid, 1 gm. m.$^{-3}$ of liquid water from the lower layers having been distributed uniformly in the layer 500 to 150 mb.; (3) ultimately precipitation (in same amounts) above the freezing level all in the form of ice; (4) cloud tops remain at 150 mb.; (5) all ice crystals continuously removed from the column by the outflow circulation.

Layer (mb.)	$\bar{T}_{m(c)}$ (°C.)	$(\bar{T}_{m(c)}-\bar{T}_a)$ (°C.)	L_s/L_c	$\Delta\bar{T}_{subl.}$ (°C.)	Liq H_2O (gm. cm.$^{-2}$)	L_f cal.gm.$^{-1}$	$\Delta\bar{T}_f$ (°C.)	$\Delta(\delta z)$ (ft.) (subl.+F.)
500-400	-5	4.0	1.12	+0.45	0.16	75	0.7	+25
400-300	-16	10.5	1.12	+1.2	0.20	72	0.8	+56
300-200	-35	11.0	1.10	+1.2	0.26	60	0.9	+83
200-150	-56	11.5	1.10	+1.3	0.15	60	1.1	+55
			Total reduction in height of pressure surface below 500 mb.; 219 ft.					

$\bar{T}_a$ = mean temperature for dry ascent of parcel.

$\bar{T}_{m(c)}$= mean temperature for moist ascent with condensation only.

L_s/L_c= ratio of latent heats of sublimation and condensation.

L_f=latent heat of fusion.

$\Delta(\delta z)$=change in layer thickness.

$\Delta\bar{T}_{subl.}$=increase in layer mean temperature due to heat of sublimation.

$\Delta\bar{T}_f$=increase in layer mean temperature due to heat of fusion.

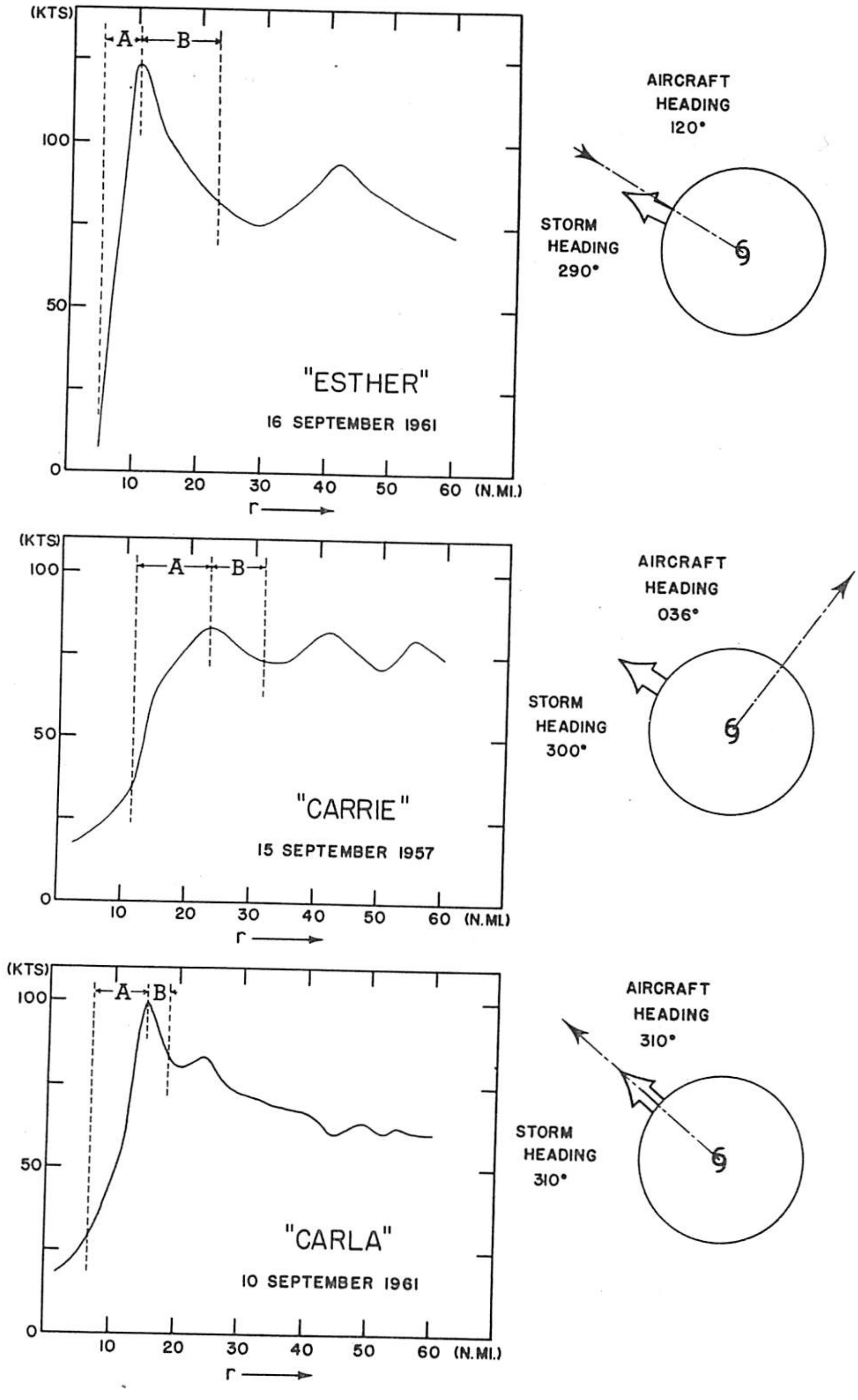


Figure 3. - Radial wind profiles in several hurricanes.

In sector A, then, the absolute vorticity is approximately 0.8×10^{-2} sec.$^{-1}$, which is two orders of magnitude larger than is characteristic for extratropical cyclones. In sector B, however, the anticyclonic shear reduces the absolute vorticity to about 8.2×10^{-4} sec.$^{-1}$. It is in this sector that the hurricane may be susceptible to destabilizing influences. Only a small decrease in curvature of the streamline may lead to negative absolute vorticities, that is $(f - \frac{\delta c}{\delta n} + \frac{c}{R}) < 0$. If, for given values of wind speed and wind shear, R_c is defined as the critical radius of curvature at which $\frac{c}{R_c} = \frac{\delta c}{\delta n} - f$ and $\zeta_a = 0$, then the ratio $\frac{R_c}{R}$ in Esther was 1.8; in Carla only 1.2. Hurricanes do not always have striated wind profiles such as those of figure 3. However, it is reasonable to suspect that such striations may characterize certain stages in the development of most hurricanes. In any event there are numerous evidences that circulation imbalances and various kinds of instability tend to develop naturally in hurricanes. Small vortices, apparently of a parasitic nature, have been reported on many occasions (Simpson and Starrett [10]), and the ever changing cloud structures of the eye reflect the frequent injection of cloud debris from the lower troposphere, apparently borne by surges or unbalanced circulations in the lower layers.

Objectives and procedures. The objectives of the 1961 experiments were to use cloud seeding methods in the chimney area with a view to generating negative absolute vorticities and circulation instabilities. The hypothesized results were: (1) a change in radar reflectivity in the seeded area, and (2) a reduction in maximum wind speeds for a short period following the seeding. From the foregoing discussion, the design of the experiment drew upon the following line of reasoning, some of which is necessarily heuristic. If one can identify a chimney area in a hurricane, it comprises the primary connection between the lower inflow and the outflow layer. Temperature gradients in the outflow layer are closely related to surface pressure gradients. The chimney is also a region where deep layers of supercooled clouds are more the rule than the exception. Mean vertical motions should range from 5 to 10 mps here. In much of this region $\frac{\delta c}{\delta r}$ is a generally large negative quantity of about the same magnitude as $\frac{c}{R}$, a positive quantity. By cloud seeding methods, the supercooled water in the chimney can be induced to freeze, release heat of fusion, and permit sublimation to occur efficiently. If the ice crystals are swept up and away in the outflow, and if the storm maintains a rigid top at, say, 150 mb., the height of pressure surfaces below the freezing level should fall.

From this point one may reason further, heuristically, that if the seeding is concentrated in the region of negative $\frac{\delta c}{\delta r}$ values (area B, fig. 3), the net result should be to reduce the slope of pressure surfaces near the point of maximum winds (as in fig. 4). This reduction in pressure forces should provide a component of acceleration toward higher pressure, reducing the cyclonic curvature of the streamline as in figure 5, and thus lowering the value of $\frac{c}{R}$ so that

$$(f + \frac{c}{R} + \frac{\delta c}{\delta r}) \leqslant 0$$

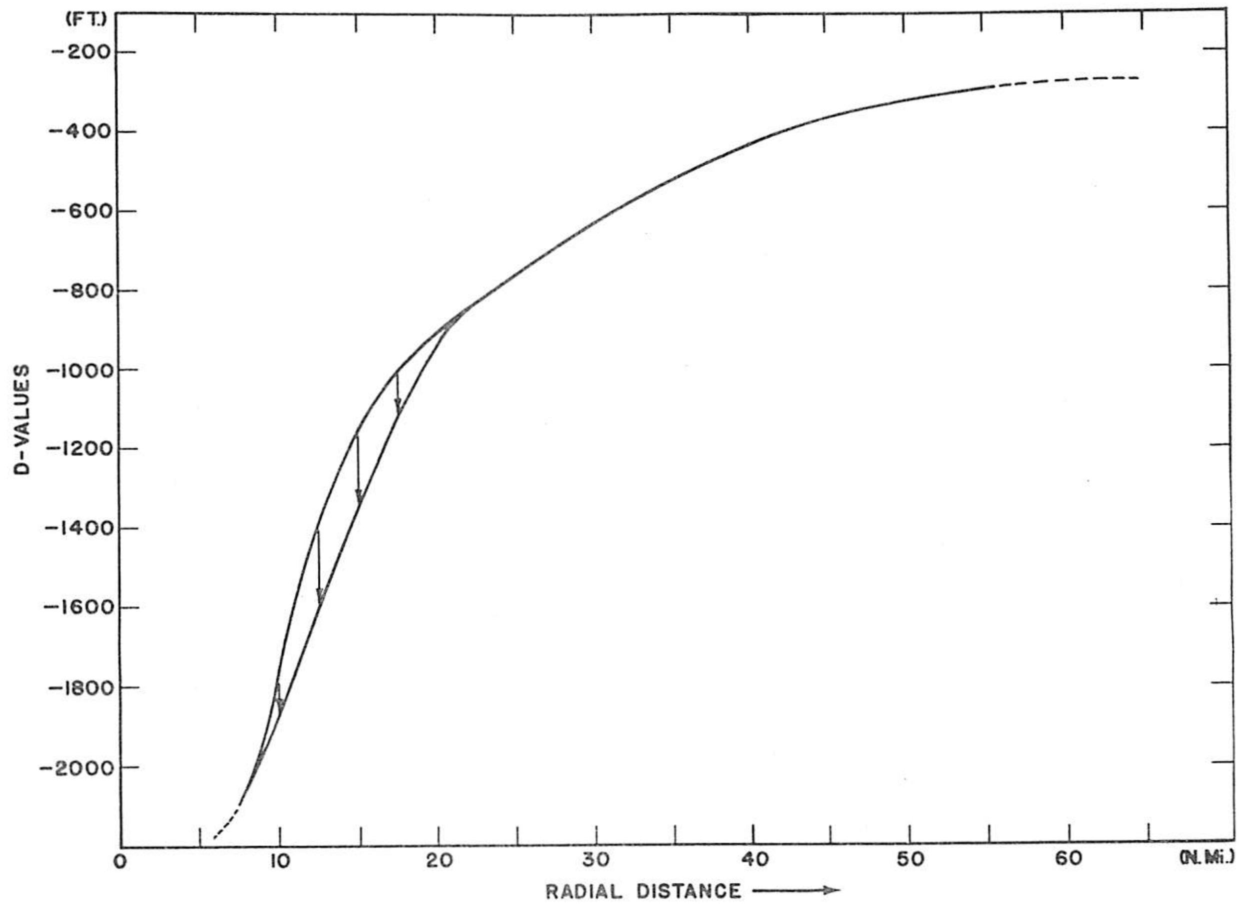


Figure 4. - Anticipated change in slope of pressure surfaces due to seeding.

The air moving horizontally through the instability area probably represents the atmosphere's closest approximation to the ideal vortex upon which perturbation theory is based. Therefore, in the manner of classical dynamic instability, parcels should move outward across contour fields, remaining immune to forces which would restore the balance until the parcels moved beyond the region of instability. If the initial circulation imbalance is sufficiently large, the air will move outward toward higher pressure and upon reaching a region of dynamic stability would begin an inertial oscillation about the eye. The net effect of such a transport outward from the radius of maximum wind is difficult to formulate or treat numerically. However, it is not unreasonable to hypothesize an increase in radius of maximum winds, and in conservation of absolute angular momentum, a reduction of maximum wind speeds. This hypothesis can then be tested experimentally.

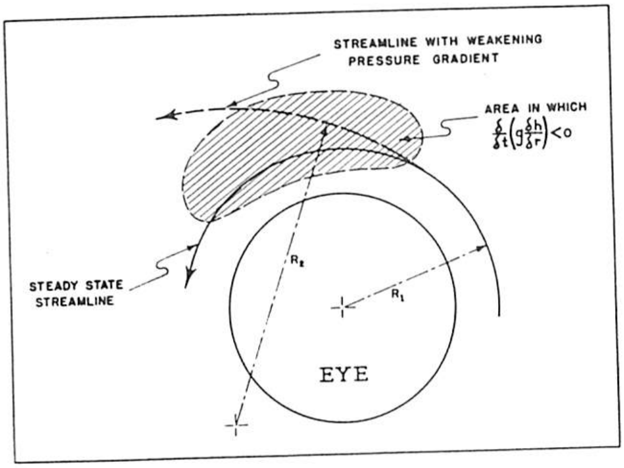


Figure 5. - Decrease of streamline curvature with weakening pressure gradient. The shaded area is a region of diminishing pressure gradient forces.

Navy pyrotechnic silver iodide generators of the kind shown in figure 6 were used in experiments. It was planned to drop the generator canisters from the bomb bay of an A3D flying above 40,000 ft. The generators, falling freely through the chimney area, would then provide a succession of vertical plumes of silver iodide extending through a cloud depth of more than 20,000 ft. These were to be dropped at 5-second intervals along a radial path at the upstream edge of the chimney area. The vertical plumes of silver iodide would then be swept through the chimney area by the storm circulation. Because of large mass transports upward in the chimney area, it was expected that the seeding materials would tend to be swept up and away in the outflow layer before they could infect supercooled clouds downstream from the chimney.

The pyrotechnic generators (St. Amand and Henderson [11]) contained silver iodate with a nitrasol binder. The compound burns at a temperature of 1700°C. and yields silver iodide crystals ranging from 0.5 to 1.0μ in size. Each canister contained approximately 9 lb. of silver iodate with a calculated yield of about 2.4×10^{15} crystals. The 8 canisters were to be distributed over a path 12 km. in length, centered 3 km. radially outward from the maximum wind.

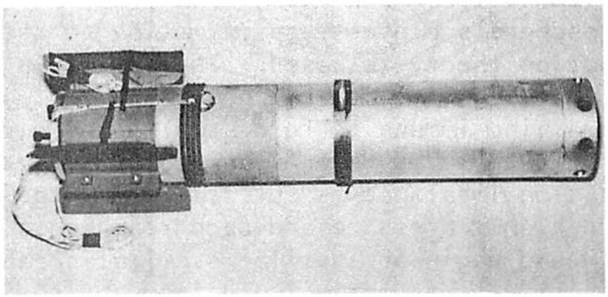


Figure 6. - Navy pyrotechnic silver iodide generator.

It was planned that results of the experiment be evaluated from dynamical analyses of data obtained from the seeded storm sector by research aircraft during a 6-hour period before and after the seeding run, and by analysis of changes in precipitation patterns monitored by radar.

Flight tracks. The experiment called for five research aircraft to monitor the changes in circulation and cloud structure over the storm sector which contained the chimney (see fig. 20). These were stationed at 7,000, 10,000, 20,000, 40,000, and 65,000 ft. The last was to provide photographic coverage of changes in cloud structure. Aircraft at 7,000, 20,000, and 40,000 ft. were to measure changes in wind, temperature, and D-value, and that at 10,000 ft. to provide dropsonde observations and maintain long-range radar coverage of precipitation patterns. Figure 10 shows the basic flight tracks used in the experiment.

3. HURRICANE ESTHER

Hurricane Esther was already a mature tropical cyclone when first detected near 15°N., 38°W. In size, intensity, and movement it might be described as a typically mature, severe hurricane. Its lowest central pressure was 927 mb. (see fig. 7), and its maximum winds greater than 130 knots. It moved steadily WNW about 12-14 kt. prior to recurvature; after recurvature, however, a more erratic movement developed as anticyclogenesis set in at higher latitudes and blocked its passage northeastward.

Figure 8 shows the large-scale circulations at the surface and at 500 and 200 mb. a few hours after the seeding operation began on September 16.

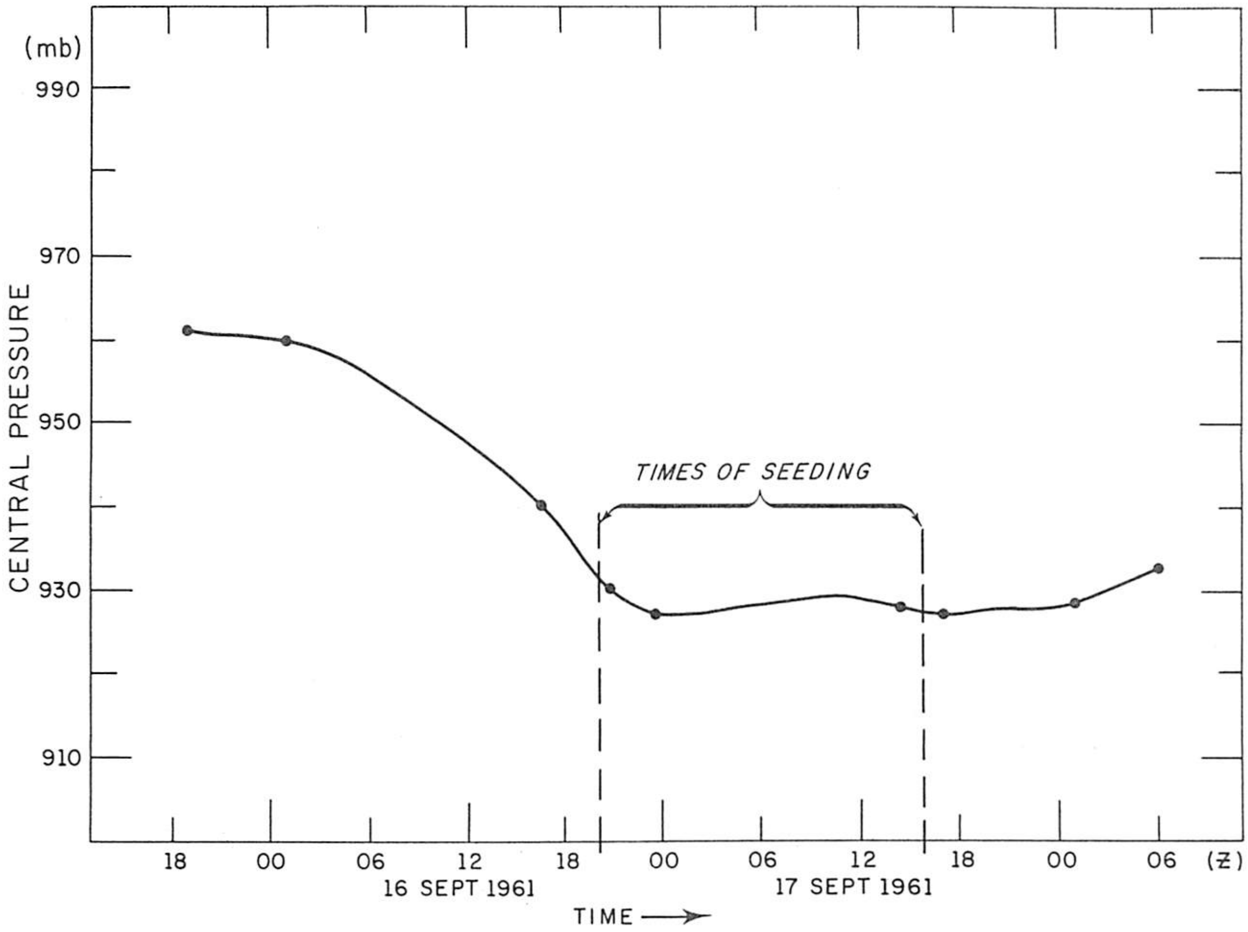


Figure 7. - Central pressure profile of hurricane Esther.

The eye of the storm on both seeding days was relatively small, 14-18 n.mi. in diameter, but was well formed and cloud free above the lower "hub cloud". The freezing level ranged from about 18,500 ft. in the rain area to 20,000 ft. in the eye. The horizontal temperature difference between the immediate environment of the storm and eye was about 15°C. near the freezing level. There were several non-typical features of the storm, including the extensive coverage of altostratus and cirrostratus south of the center and the fact that the spiral rainbands were generally better developed to the south than to the north on both the 16th and 17th, as shown in figure 9.

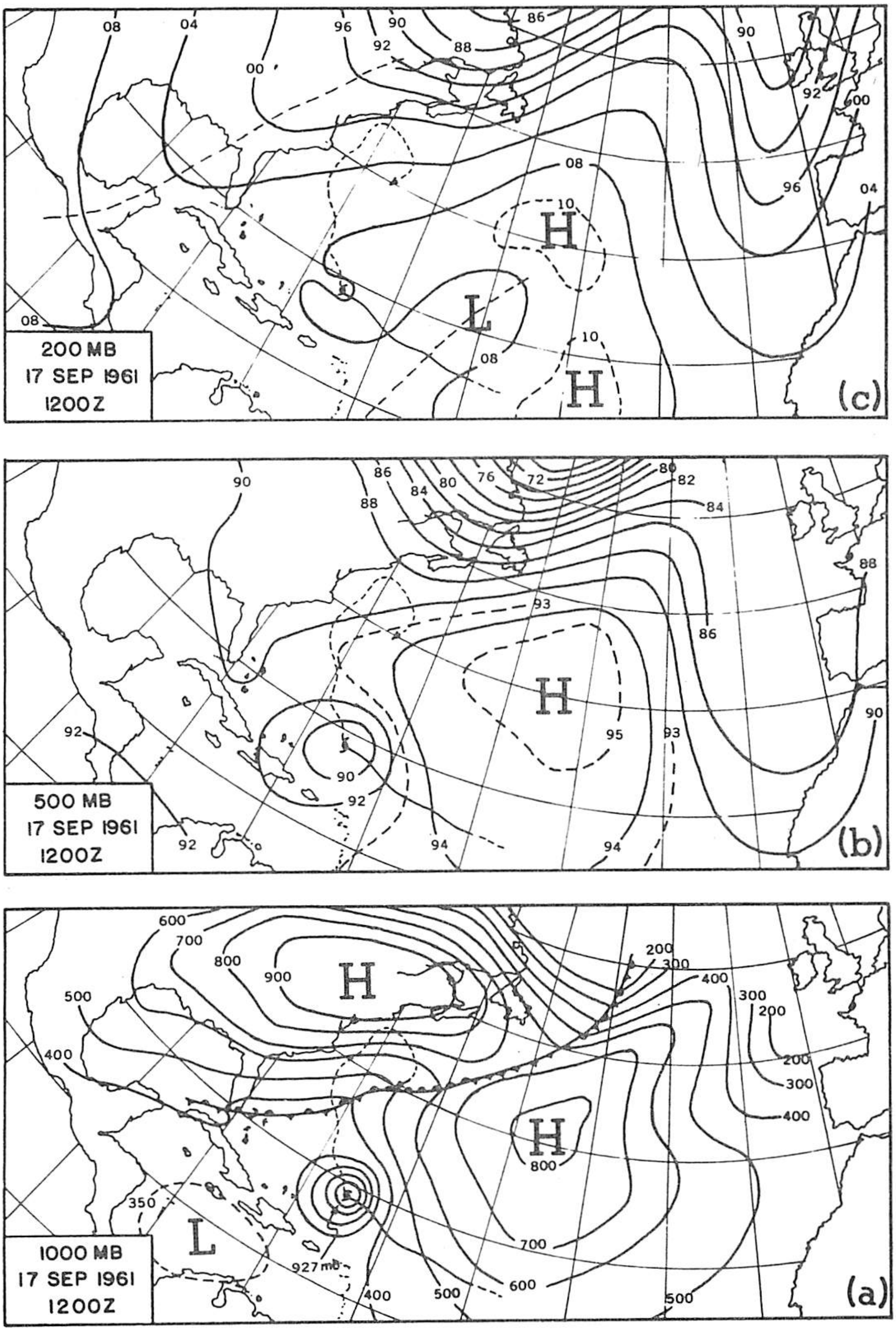


Figure 8. - Surface and upper air conditions, 1200 GMT, Sept. 17, 1961.

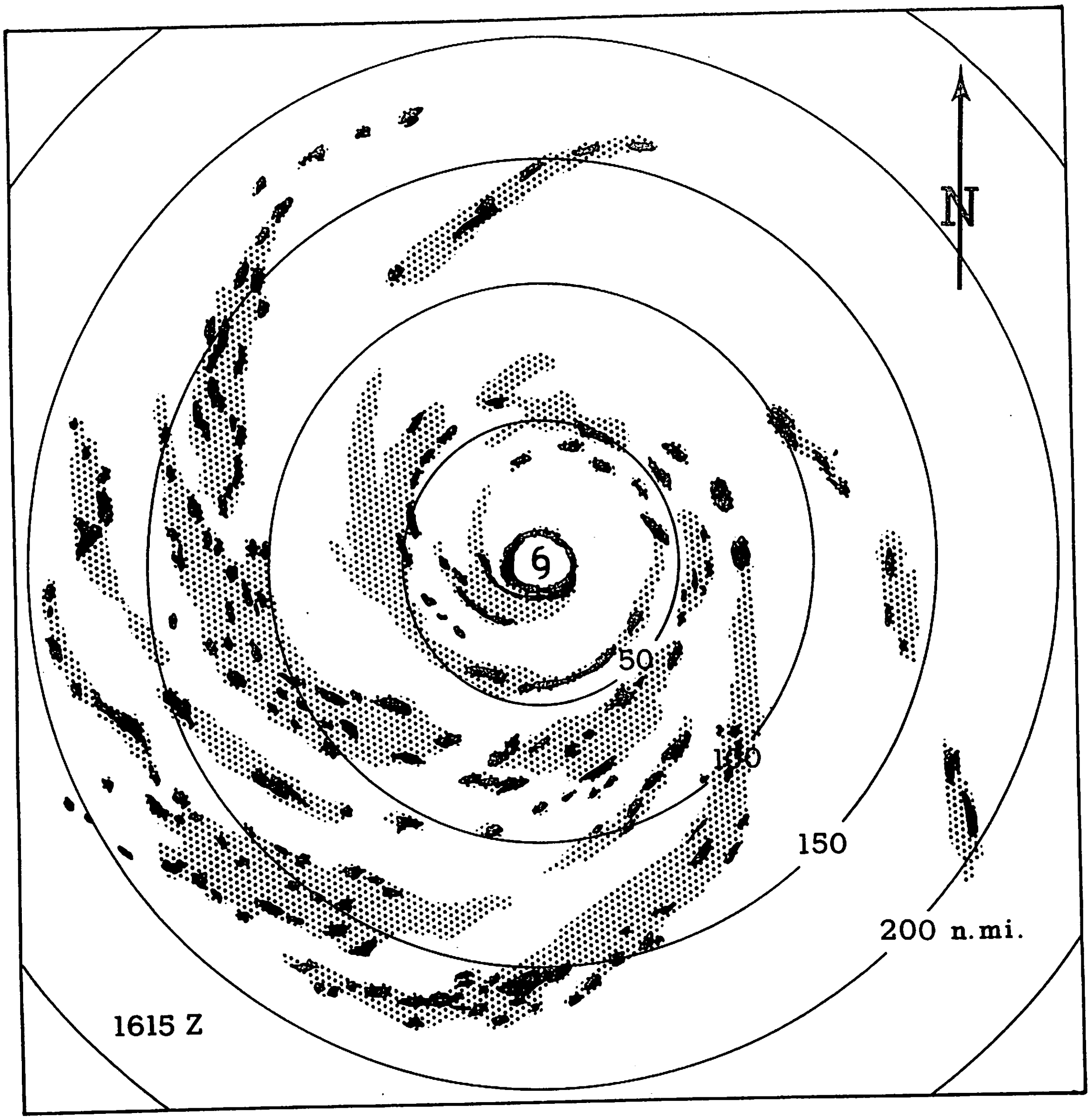


Figure 9. - Radar composite of hurricane Esther, 1615 GMT, Sept. 16, 1961. (WV-30 aircraft, APS-20E, 10-cm. radar)

4. THE SEEDING OPERATION

Aircraft staging for the operation was from Puerto Rico. Two DC-6's, a B-57, and a B-26 research aircraft operated from San Juan, while the Navy WV-3 and A3D operated from Roosevelt Roads, about 400 mi. south of the storm center. The WV-3 entered the storm at about 1545 GMT and at 1620 GMT took up its patrol position at 10,000 ft. (fig. 10a). The two DC-6's entered the storm about noon; one at 7,000 ft., the other at 20,000 ft. and completed the circuit of the experiment area (fig. 10a) about one-half hour before seeding began at 2016 GMT (designated TANGO). Both DC-6's repeated their circuit after TANGO. The B-57, flying at 40,000 ft. (fig. 10b) completed the first circuit of its track about 1 hour before TANGO. After refueling, a second circuit was completed about 3 hours after TANGO.

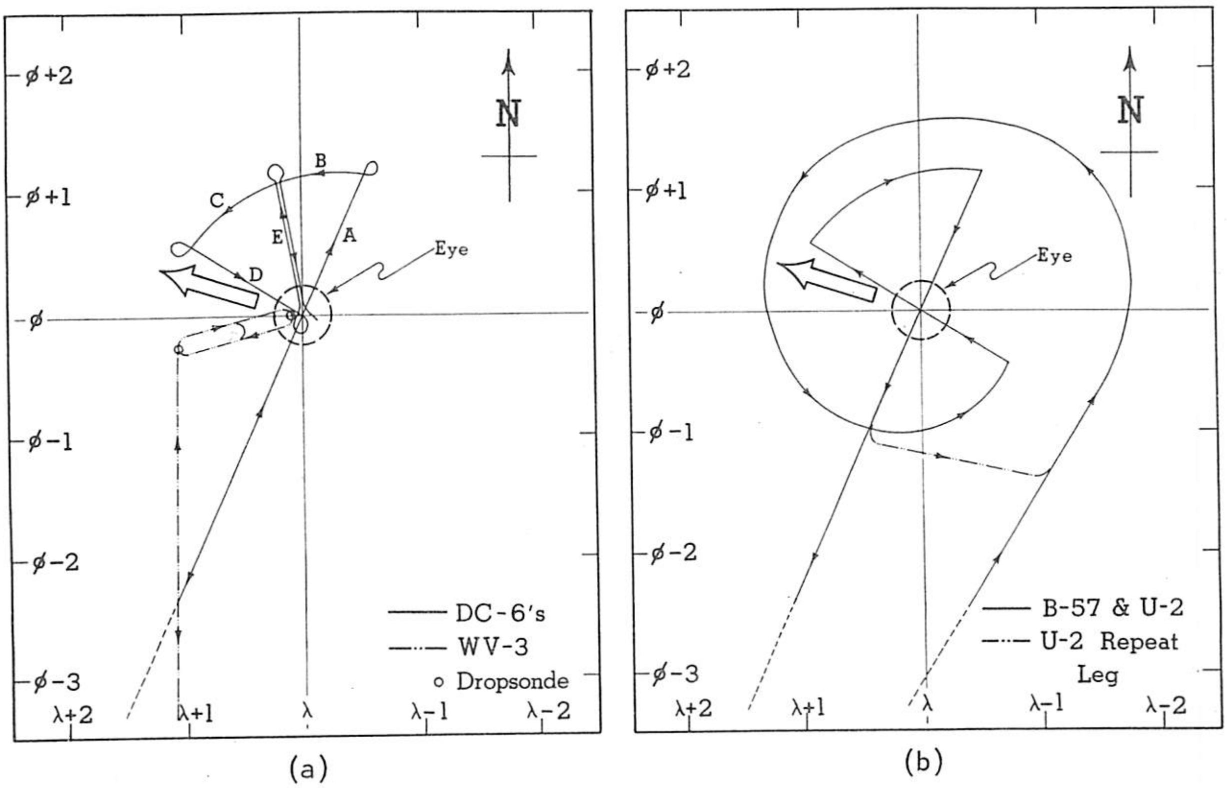


Figure 10. - Basic flight patterns of the research aircraft. Each pattern was completed prior to seeding and repeated shortly afterward.

The A3D approached the storm center at 2010 GMT and, with vectoring assistance from the WV-3, began releasing silver iodide generators at 2016 GMT from an altitude of 43,600 ft. (fig. 11). Eight canisters were released at 1.3-km. intervals, the last being located about 0.5 km. inside the eye wall. The seeding aircraft reported that eight flares ignited and were timed to burn down to about the 22,000-ft. level.

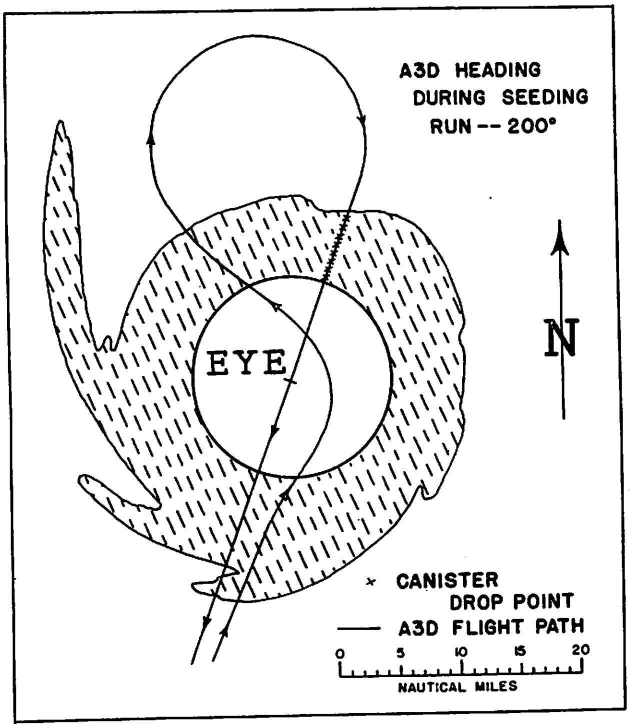


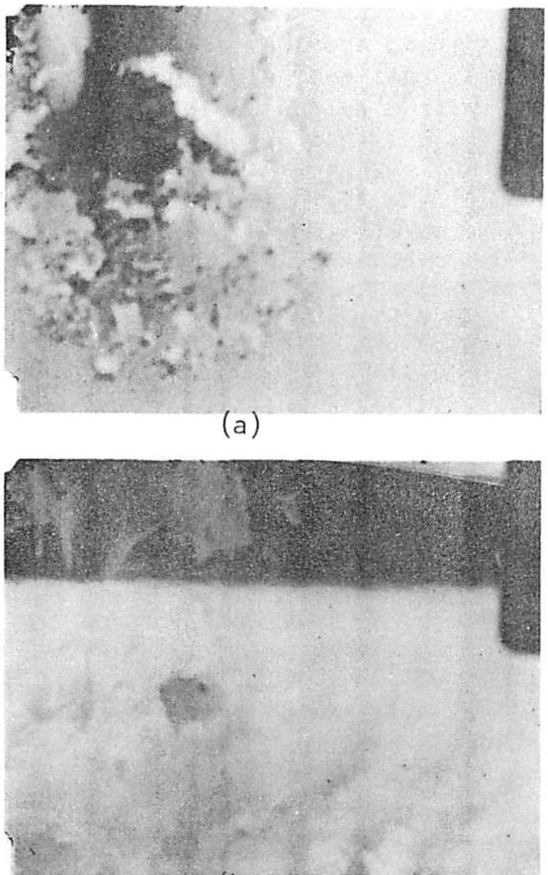
Figure 11. - Flight pattern followed by the A3D on Sept. 16, 1961.

Cloud tops along the seeding track extended above 45,000 ft., icing formed prominently on various parts of the A3D air frame, and turbulence was described as moderate during the seeding run.

The B-57 experienced difficulty with navigation and recording systems and was able to complete only a small portion of its mission in a quantitatively useful manner. However, large accumulations of ice on the optical window of the cloud camera were recorded during flight over the chimney area. Figures 12a and b show comparative frames from this camera, one in the chimney area showing some aspects of the ice structure on the window, the other 40 seconds later in the eye as ice was melting from the window.

The DC-6 stationed at 20,000 ft. encountered heavy icing during transits of leg E prior to seeding, full climb power being required to hold altitude. Difficulty in stabilizing the radar antennas resulted in loss of much radar data from this aircraft. Also, lightning strikes during the first penetration of the chimney after TANGO destroyed the hot wire liquid water sensor. On the other DC-6 and the WV-3 all systems operated effectively.

On September 17 the seeding experiment was repeated almost identically. On this occasion a U-2 photographic aircraft operated at 65,000 ft. (fig. 10b) recording changes in cloud forms during the experiment. Figure 13 shows pictures of the eye made during several U-2 passes before and after seeding. Unfortunately, difficulties were encountered in releasing the silver iodide canisters and most of them fell into the clear air of the eye or northern edge of the eye wall.



(a)

(b)

Figure 12. - Comparative frames from B-57 cloud camera.

At least one was observed from the DC-6 at 20,000 ft. falling inside the eye.

On the 17th the B-57, flying across the chimney area (NE of center) at constant power and attitude, experienced a steady rate-of-climb indication of +2200 f.p.m. approaching the eye, then a rapid reversal to -1800 f.p.m. upon entering the eye. Little evidence of short-period convective drafts was found. However, upon entering the opposite eye wall the rate-of-climb remained near zero and short-period turbulent drafts were prevalent.

On both days the B-26 reconnoitered convective segments of spiral rainbands.

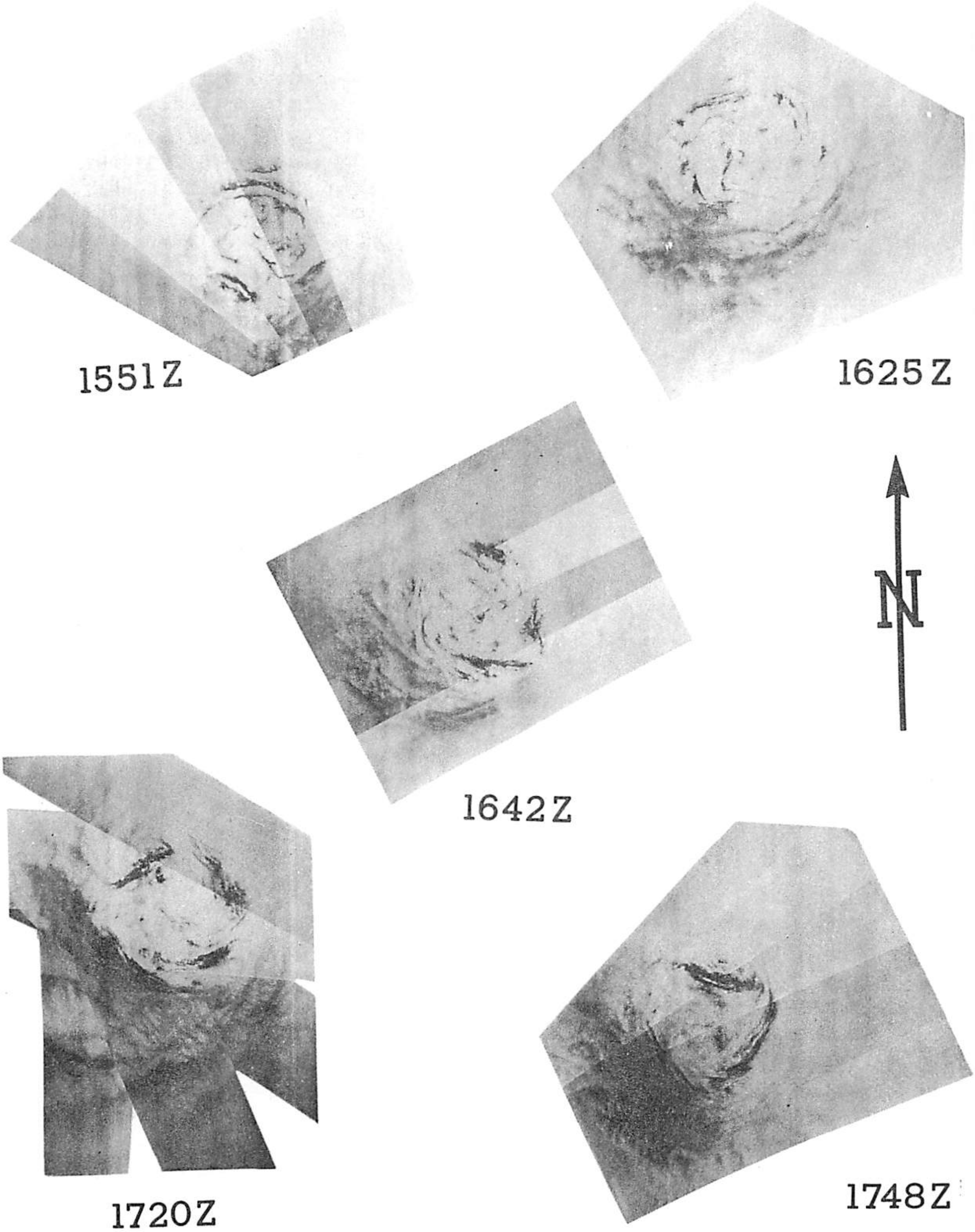


Figure 13. - Composite photos of hurricane Esther made from U-2 aircraft on Sept. 17, 1961. Seeding was begun at 1600 GMT.

5. RESULTS OF THE SEPTEMBER 16 EXPERIMENT

As stated earlier, the experiment was designed to evaluate results by dynamical analyses of data from the storm core and analysis of changes in precipitation echoes observed by radar. Wind direction and speed was measured by an APN-82 doppler radar, D-values by an APR profile recorder. The DC-6's radars included an APS-20E (10 cm.), an RDR-1 (3 cm.), and a WP-101 (5.6 cm.). The WV-3 radars included an APS-20E (10 cm.) and an APS-45 (3-cm. height finder).

Radar observations. The large scale distribution of precipitation in Esther on September 16 is shown in figure 9, a composite from the 10-cm. APS-20E. During the monitoring period no important changes occurred in the spiral rainband structure, or the distribution and intensity of precipitation except near the eye wall.

The RDR-1 radars on the DC-6's were mounted aft of the horizontal stabilizer with antenna rotation in the vertical plane. Figure 14 is a composite showing a vertical cross section of precipitation structure near the eye.

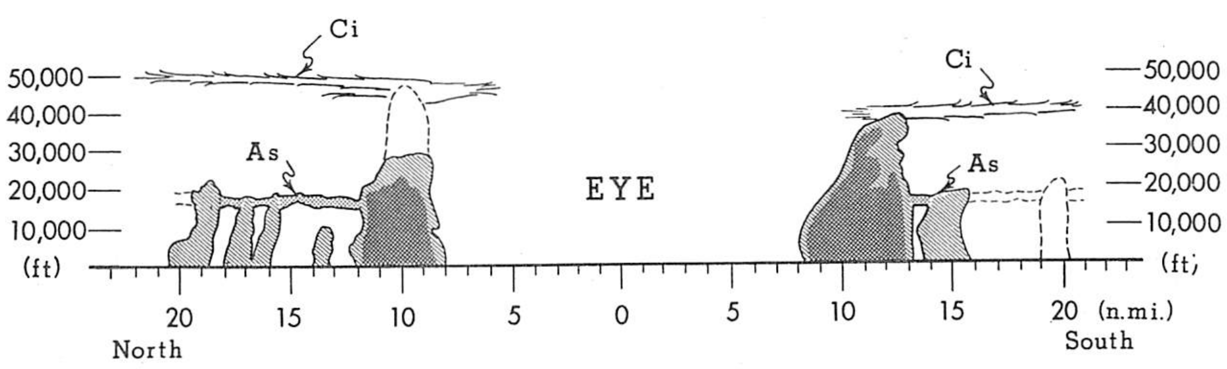


Figure 14. - Cross section radar composite of hurricane Esther, 1945 GMT, Sept. 16, 1961. (DC-6 aircraft, RDR-1, 3-cm. radar)

Before TANGO, all radars showed a continuous PPI return from the eye wall (fig. 15). However, definite changes were noted on all 10-cm. radars beginning less than 20 minutes after the silver iodide flares were ignited. The progress of changes recorded by the APS-20E and comparative PPI pictures from the APS-45 are shown successively in figure 15. At 2036 GMT, the 10-cm. return from the eye wall downstream from the seeding run began to disappear and in the 40 minutes which followed disappeared over a 160° sector. The return from the 3-cm. radar, however, remained continuous. It will be noted that attenuation blocked the receipt of 3-cm. signals from remote sectors of the wall when the plane was not in the eye. By 2120 GMT, 10-cm. reflectivity in the seeded area had been restored.

It is not uncommon for large sectors of an eye wall to break open and rapidly disappear from view, both to radar and to the human eye. In this case, however, no visual change was observed in the eye wall, nor were large changes observed in the 3-cm. echoes. It may not be uncommon for portions of the eye to disappear from 10-cm. radar view and remain visible to 3-cm. radar. However, no cases of this kind have been reported, possibly because there have been few opportunities when both 3- and 10-cm. observations could be recorded simultaneously from the same position. The difference in reflectivity for 3- and 10-cm. radars could have occurred if raindrops were replaced by smaller droplets whose diameters were less than about 300 μ, the critical size for 10-cm. reflectivity; or if the bulk of reflective precipitation were converted from quasi-spherical drops to ice crystals. Three-centimeter radar is able to "see" smaller raindrops and snow which cannot reflect 10-cm. energy. Because of the rapid change in reflectivity after seeding, the latter of the two possibilities is an attractive choice. However, before accepting this explanation it is necessary to consider that while the 10-cm. radar antennas were tilted up at angles varying from 2 to 5 degrees, a significant part of the radar energy was returned from cloud layers several thousand feet below the freezing level.

Circulation and kinetic energy. During the experiment there was continuous monitoring of a 2,000-square-mile pie-shaped sector embracing the convective chimney and the area downstream from the seeding run. By augmenting these data with observations made during the entry and exit track, it was possible to construct analyses showing the approximate distribution of pressure and wind speed over a larger area of the storm. D-value contours for September 16 at 7,000 and 20,000 ft. are shown in figure 16, and isotach analyses are given in figure 17. Difficulty with instrument systems on the B-57 resulted in loss of too much data to permit analyses of this kind at its level.

Little can be deduced concerning kinetic energy changes from such analyses as these because of the amount of extrapolation required, and the lack of synopticity of observations. However, it is interesting to note the radial striation of wind speeds and the fact that maximum winds diminished less than 10 percent between 7,000 and 20,000 ft.

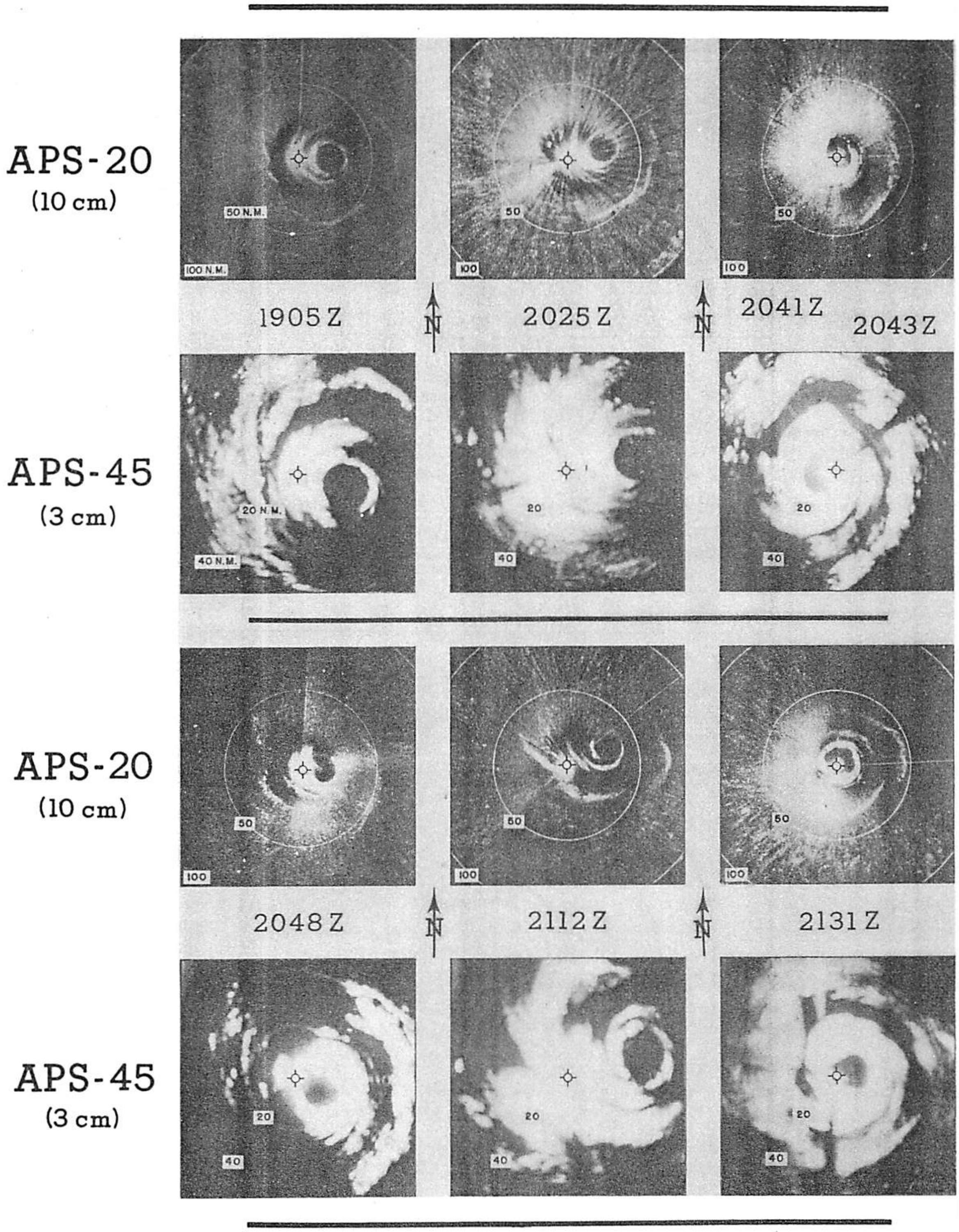


Figure 15. - Series of concurrent radar pictures from 10-cm. and 3-cm. radars before and after seeding on Sept. 16, 1961.

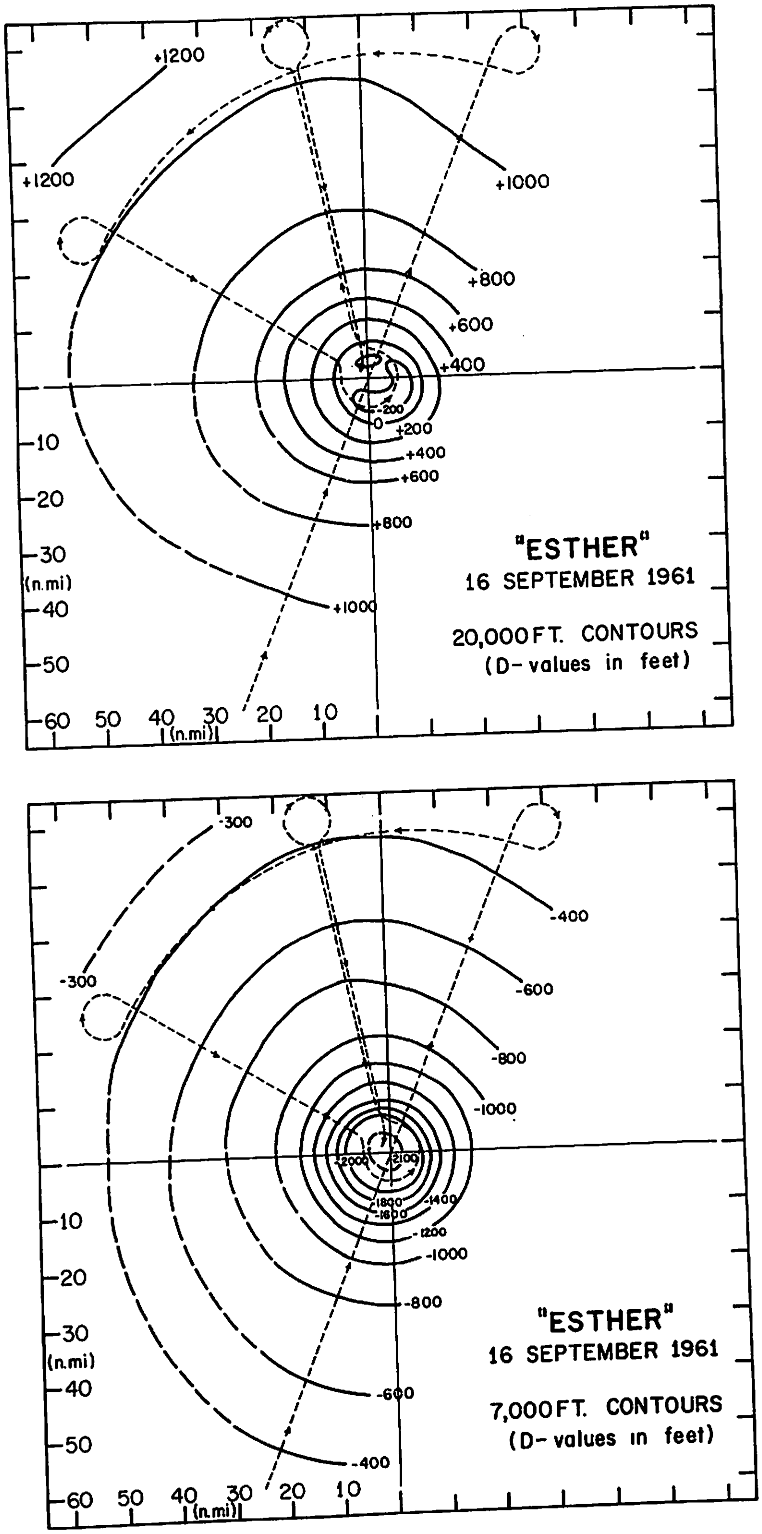


Figure 16. - Hurricane Esther D-value contours.

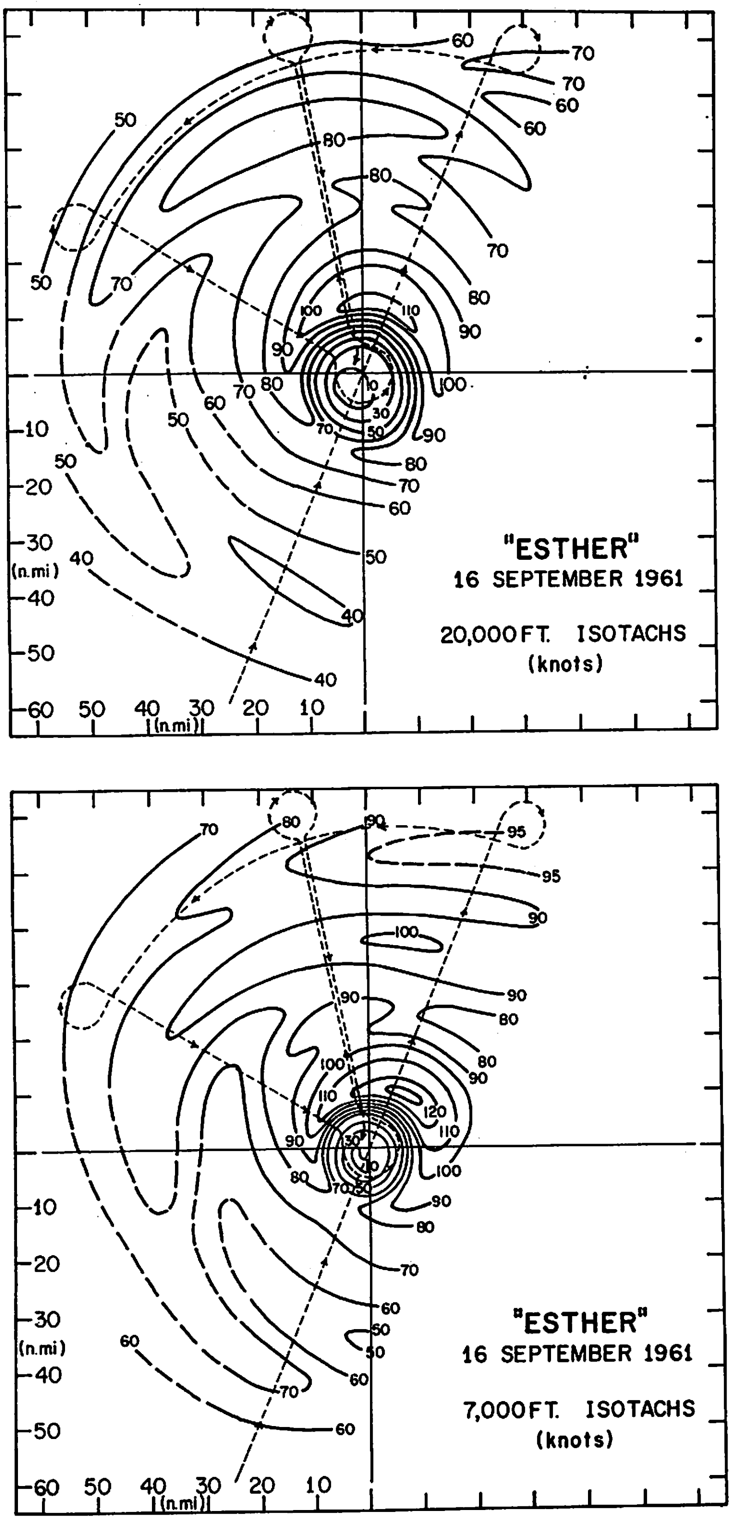


Figure 17. - Wind field around hurricane Esther. Dashed lines show monitoring flight tracks on which data were obtained.

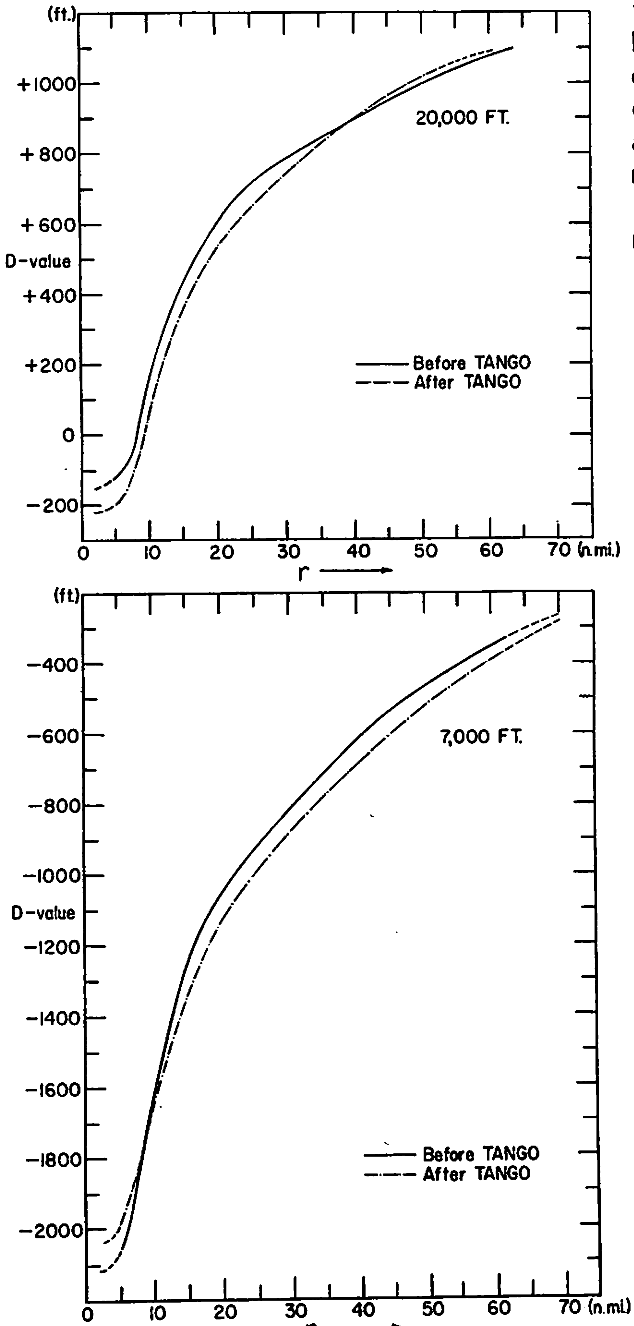


Figure 18. - Mean D-value profiles for hurricane Esther, Sept. 16, 1961, showing change in height and slope of pressure surfaces after seeding.

although the total kinetic energy of the storm apparently diminished with height by more than 30 percent. The only notable difference in geometry or character of circulation before and after seeding was that isotach maxima, in the manner reported by Blumen and LaSeur /1/, tended to move cyclonically with the wind, except those near the eye wall which tended to maintain their azimuth relative to the storm track.

Sufficient information was available from the monitored sector to examine changes in the pressure surfaces and to obtain quantitative estimates of variations in kinetic energy. The mean D-value profiles (fig. 18) show the decrease in height and slope of the pressure surfaces for both the 7,000 and 20,000 ft.-levels. In figure 19, $\frac{V^2}{2}$ values have been averaged for legs A, D, and E of the experimental sector for periods before and after TANGO, and for both 7,000 and 20,000-ft. levels. From these mean profiles it would appear there was little change in total kinetic energy in this area. However, near the eye, the kinetic energy dropped by 14 percent at 20,000 ft. and 5 percent at 7,000 ft., while compensating increases occurred at greater radial distances. The mean maximum wind was located at a slightly greater distance from the eye after seeding. The maximum wind speeds recorded in the experimental sector were 9 percent lower at 7,000 ft. and 14 percent lower at 20,000 ft. after seeding. The small increase in radius of maximum wind in the test area suggests that any change in maximum wind speeds may have been due solely to changes in pressure gradient or other transient instabilities in circulation. However, in the absence

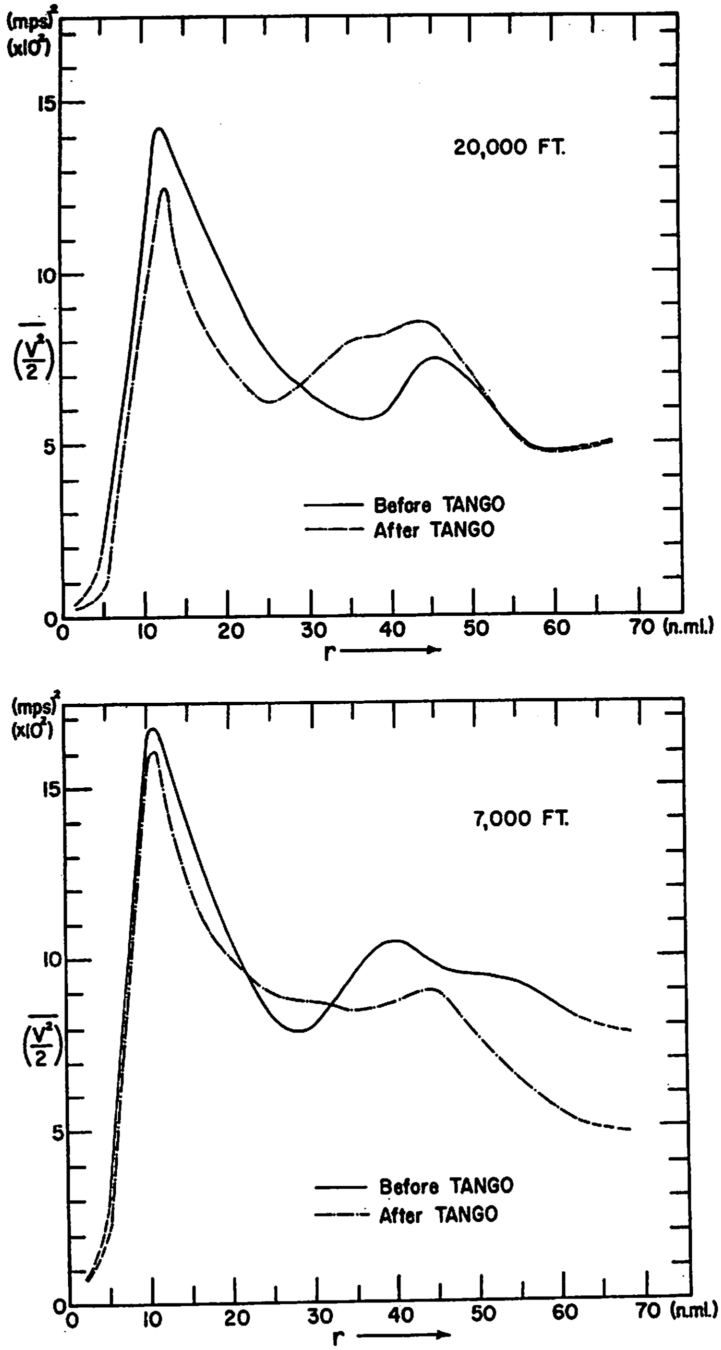


Figure 19. - Mean kinetic energy profiles in hurricane Esther, Sept. 16, 1961.

of adequate information from other sections of the storm, conclusions cannot be reliably reached. Most of the observed trends must be regarded as approximations which are rather severely limited due to probable errors in measurement and of analysis. However, the trends in the test area conform with results predicted by the hypotheses, and with the acquisition of three or more test cases, a more objective interpretation can be made, and perhaps some useful conclusion can be drawn from such observed trends.

Changes which occurred in the experimental sector after seeding were reflected in the kinetic energy of circulation expressed by

$$K = A \int_{p_o}^{p} \frac{V^2}{2} \frac{\delta p}{g} \qquad (3)$$

where A is the test sector area and V is the observed wind speed. A hurricane model comprised of three cylindric layers, X, Y, and Z (fig. 20), representing the inflow, a small-divergent middle layer, and the outflow, was designed for these computations. As indicated previously, the limitations of data require that the analysis be restricted to sector A (fig. 20). Furthermore, B-57 data were inadequate to analyze the outflow layer. For the purpose of integration it is necessary to assume that the circulation at 7,000 ft. was a representative mean for layer X, and that at 20,000 ft. for layer Y. The results of these computations before and after seeding, separated in time by about three hours, are presented in table 2. After seeding, a net kinetic energy reduction of nine percent was observed, with a 13 percent reduction in the lower inflow layer.

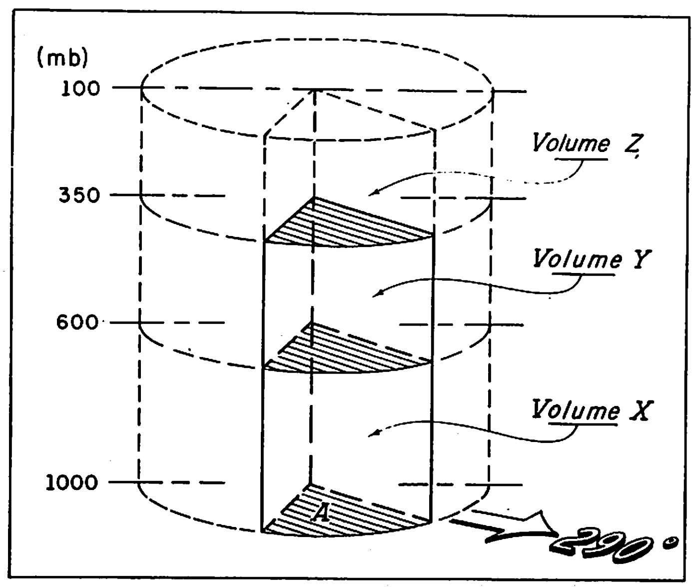


Figure 20. - Schematic diagram of hurricane considered to be in 3 cylindrical layers representing the inflow (X), a small-divergence middle layer (Y), and the outflow (Z).

Table 2. - Kinetic energy of circulation in the experimental sector before and after seeding (10^{13}kj.), Sept. 16, 1961.

Layer	Before	After	% Change
Y	1.38	1.38	0
X	2.74	2.38	-13
X+Y	4.12	3.76	-9

Changes in the production of kinetic energy due to pressure forces on the tangential and radial components of motion were computed for the 3-hour period which straddled the time of seeding. For volumes X and Y the changes were in the direction predicted by the hypothesis. However, the magnitude was comparable to changes which have appeared to occur over short intervals in some sectors of unseeded storms.

None of the analyses or computations which have been attempted have provided unassailable evidence for experimental conclusions. However, 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 circulation imbalances or instabilities,
(3) the total kinetic energy over the test area was reduced and the maximum wind speeds diminished.

There is no experience from which one can estimate the probability that all these changes could have come from natural causes. In previous hurricane research flights, the flight plans have been designed to collect data along a clover-leaf track at several different levels rather than to measure changes with time. Therefore, the best (and perhaps only) means of assessing the validity of the hypotheses and reaching final conclusions concerning experimental results is through the repeatability of these results in succeeding experiments.

6. RESULTS OF THE SEPTEMBER 17 EXPERIMENT

As indicated earlier, the silver iodide canisters were not dropped according to plan on September 17. Apparently all the silver iodide was released in sector A (fig. 3) or in the clear air of the eye. If released in Sector A, the effect, if any, should have been to steepen the slope of pressure surfaces in the eye wall. If released in the eye, entrainment of silver iodide into the eye wall would have tended to proceed slowly, as borne out by the trajectory of constant pressure balloons released in the eye during earlier experiments, balloons which remained in the eye for more than 24 hours. In either event the seeding should not have led to circulation instabilities of the kind which this experiment sought to investigate. The results, analyzed in the same manner as those of the 16th, follow.

Neither 3-cm. nor 10-cm. radar showed any significant change in precipitation patterns or form. Figure 21 compares the 10-cm. radar return just before TANGO with that one hour after TANGO.

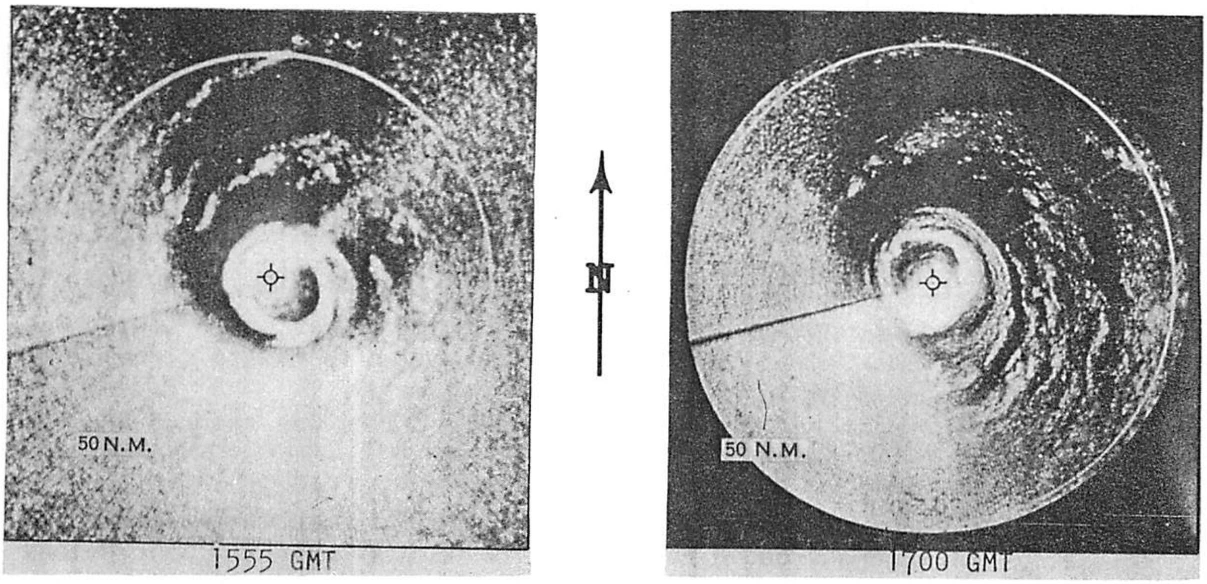


Figure 21. - Radar return just before seeding of hurricane Esther on Sept. 17, 1961, and 1 hour after seeding. (APS-20, 10-cm. radar)

The composite photographs of the eye on September 17 as viewed from a U-2 aircraft from about 65,000 ft. (fig. 13) indicate the conservative character of the eye and eye wall during the period before and after the seeding.

7. SUMMARY AND CONCLUSIONS

The initial experiments have provided interesting but by no means conclusive results. The change in reflectivity of 10-cm. radar energy is difficult to explain unless it was due to the rapid transformation of supercooled liquid water to ice. However, a portion of the radar energy was reflected from the clouds below the freezing level where such a transformation could not have occurred.

On the 16th there was evidence that kinetic energy may have been diffused outward after the seeding, and maximum winds reduced by about 10 percent for a 2-hour period. These changes could have occurred from natural fluctuations in structure and intensity of the hurricane. However, after several additional experiments it should be possible to determine whether the results from the experiment of September 16 are repeatable and the tentative conclusions justified. If so, it should be feasible to extend the scope of the experiment to determine whether destructive winds in the hurricane can be reduced progressively by successive injections of silver iodide.

ACKNOWLEDGMENTS

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