U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

HURRICANE MODIFICATION AND CONTROL

April 1971

U.S. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA

U.S. DEPARTMENT OF COMMERCE

HURRICANE MODIFICATION AND CONTROL

TABLE OF CONTENTS

FOREWORD

The issues covered by this study arise from the results achieved by Project STORMFURY, a joint project of the Departments of Defense (Navy, supported by Air Force) and Commerce (NOAA). The purpose of this project is to explore the structure and dynamics of hurricanes and tropical storms, to achieve a better understanding, improve prediction, and examine the possibility of modifying some aspects of these storms. The Project was established by agreement between the Department of Commerce and the Department of the Navy, effective July 30, 1962, following preliminary cloud seeding tests conducted on Hurricane Esther of 1961. In 1963 the Project seeded Hurricane Beulah.

The seeding of Esther and Beulah produced encouraging results, although the sample was too small to produce definite conclusions. However, on August 18 and 20, 1969, the seeding of Hurricane Debbie over a prolonged period was followed by substantial reduction in maximum winds. These wind reductions, as well as other data which have been analyzed thus far, strongly suggest that the results were due to seeding. Further support of this hypothesis was the strong correlation between what actually happened and what computer simulation of the situation predicted would happen. Unfortunately, no opportunities for further experiments arose during the 1970 season.

At the same time that this Issue Study was being undertaken, a parallel decision analysis study was being carried out by Stanford Research Institute (SRI) under contract to NOAA. It was intended that the study provide a complete framework for the economic, social, legal, and statistical factors that would enter into a decision to operationally seed hurricanes. The study is scheduled to be published in May, 1971; however, the principal results and a summary of the study are included in this report.

It is within this framework, then, that this Issue Study is being conducted. The STORMFURY experimental sample is still very small by ordinary statistical standards. But means are becoming available to incorporate physical theory and computer modeling to a greater extent, as will be described in more detail below.

The questions to be answered by the Issue Study are the following:

a. Is the Federal Government technologically ready for operational modification of hurricanes?

b. What are the logistic and budgetary implications for NOAA of operational modification?

c. How should the present STORMFURY effort be improved or expanded?

I. FINDINGS AND CONCLUSIONS

I. Is the Federal Government Technologically Ready for Operational Modification of Hurricanes?

In spite of the apparently highly successful seeding of Hurricane Debbie during August 1969, where marked reductions of the maximum winds followed the seeding experiments, it is not considered that operational status has been achieved for the beginning of the 1971 hurricane season. The STORMFURY Advisory Panel believes that the experimental results to date are sufficiently encouraging to warrant further experimentation, but cautions against premature conclusions that these results provide an adequate scientific basis for the implementation of an operational seeding program. This conclusion is based on the following considerations:

a. The statistical sample is small, and the natural variability of hurricanes is high. The SRI study indicates that even if seeding is effective, the natural variability will cause about a third of the hurricanes to intensity after seeding has been performed.

b. There is concern that in certain cases seeding might cause unwanted change in the direction of movement of the storm.

c. There are several weaknesses in the computer simulation model used as one of the controls for the experiment.

d. There is a general subjective feeling among members of the STORMFURY Advisory Panel that further experimentation should precede operational seeding.

e. Additional experimental seedings, together with improved modeling, must be accompanied by further studies of decision analysis, and social, economic and legal factors.

2. What are the Logistical and Budget Impacts for NOAA of Operational Modification?

The foregoing situation could conceivably change during the course of the 1971 hurricane season if one or more additional experiments showed marked decreases in maximum winds following seeding. This could pave the way for one or two pilot operational seedings later in the season. These could be carried out in a fashion identical to experimental cases. Assuming continuing Navy support, the cost per seeding to NOAA would be approximately $30K in aircraft time, etc., and $15K in seeding expendables. Assets in this amount could be made available.

Once a modification system becomes fully operational, the impacts could vary over a great range, depending upon such matters as the number of seedings per threatening hurricane, the extent of monitoring carried out on operationally seeded storms, the number of storms in a given season, the extent of Navy collaboration, etc. At the very least it would be desirable to increase present NOAA capabilities in aircraft, manpower, etc., by a factor of three to double operational capability and to permit continuation of the present R&D program in addition to the operational effort. This would involve two aircraft, $14 million if purchased, aircraft operation, $2 million annually, and increased funding for R&D, $500,000 annually. An additional $1.8 million annually would be needed for a fourth generation computer to support the R&D program.

3. How Should the Present STORMFURY Effort be Improved or Expanded?

Increased research is required on many fronts to fully establish the feasibility of hurricane modification and to refine the details of control. A 10-year program could be visualized easily. A full discussion is presented in the main body of the report, but some of the more obvious requirements are as follows:

a. Further experimental seeding to define more exactly what is possible in reducing the force of the maximum winds. Is the present level of seeding optimum? Should seeding be carried out continuously? What strategy should be adopted toward storms that remain stationary in a threatening posture off our coast line? How can we redirect storms if this appears a social goal?

b. We must measure in far greater detail the mechanisms and characteristics of unseeded storms, and those that are seeded. Measurements should include supercooled liquid water content at all appropriate levels, the pressure gradients before and at various intervals after seeding. The effect of the seeding on the liquid water must be determined to establish optimum seeding intensities.

c. Computer modeling of hurricanes must be expanded many fold in complexity and realism, to guide the experimental work and to provide a comparison base for actual experiments.

d. Planning should continue for moving STORMFURY to the Western Pacific as early as 1972, to obtain many more additional experiments at an early date.

e. Research should be conducted to advance our knowledge in those areas required for tactical decision making regarding operational seeding of hurricanes, including prediction of changes in hurricane intensity and track.

f. Studies to correlate reduced winds with resulting damage.

g. Studies of the social, economic and legal implications of hurricane modification.

II. BACKGROUND INFORMATION

1. Nature of Hurricanes and Tropical Storms

The hurricane is not the most devastating storm in nature's arsenal, that distinction belongs to the tornado. Nor is the hurricane the biggest storm, since many middle latitude storms are an order of magnitude bigger. But, in combining size and ferocity, the hurricane is without peer. Twice in the last five years we have measured velocities of about 200 mph in hurricanes (Inez, 1966 (1) and Camille, 1969 (2)). Twice in the last five years we have totaled destruction from individual storms of over one billion dollars; in Betsy, 1965 (3) and Camille, 1969 (4).

The hurricane's winds are destructive enough in themselves but, it must be pointed out, these are transitory in nature and such extreme speeds do not persist long over land. Hurricane damage is usually the result of the combined effects of wind and water - both the wind-driven surge which scours the shore, driving all movable items before it as battering rams, and the rainfall which drenches every wind-blown opening.

A tropical storm, on the other hand, is a more peaceful version of tropical "weather". Its winds, by definition, never exceed 75 mph although in size the storm itself may be 2 or 3 times bigger than the hurricane. In consequence, its destructive potential is much less and the storm is ofttimes welcomed for the precipitation it brings despite the minor hardship it imposes. This latter point is also true of the hurricane. Despite the damage (the worst of which is usually confined to the vicinity of the coastal plain), extensive rains which accompany the storm spread hundreds of miles inland and are an important item in the water budgets of those regions normally subject to their incursions.

The hurricane is a closed vortex about which the winds blow counter-clockwise. An area of lowest pressure coincides with the center or eye of the storm about which, only a short distance out, race winds of 74 mph or more. This peculiarity of the wind field which finds the maximum winds so close to the storm center is characteristic of hurricanes. An extreme example of this structure is offered in figure 1 which shows that winds of 170 knots (about 200 mph) in Hurricane Inez (1) occurred less than 10 n.mi. from the storm center where winds must essentially go to zero. Moreover, at a distance of 60 n.mi. the winds were less than 50 knots. This is an amazingly small, tight, strong, circulation.

Many of the workings of a hurricane are schematically illustrated in figure 2. Air in the lower layers (up to about 10 thousand feet) is spiralling in towards the center of low pressure. While moving over the warm tropical ocean, it picks up latent heat in the form of water vapor and it also gains some sensible heat from contact with the ocean. As the air moves in some of it is forced to rise. It does so in rather elongated spiral bands of clouds and, most of all, in the wall cloud which surrounds the eye of the storm and in which is embedded the ring of maximum winds. When the air is forced to ascend, it expands and cools, the water vapor condenses into cloud droplets releasing the latent heat of condensation. With the buoyancy thus provided, the parcels rise freely in the tropical atmosphere - expanding - cooling - releasing more heat, etc., until they reach a level where the temperature of the rising parcels no longer exceeds that of the ambient air and no free buoyancy remains. This altitude varies, but usually is of the order of 40,000 to 50,000 feet or so. As the cloud rises or builds upward the droplets do not automatically freeze as building passes above 0°C (32°F). Instead, they may maintain a supercooled state even to temperatures near -40°C (-40°F). Supercooled tops of cumulonimbus clouds are not unusual in any climate but are quite abundant in hurricanes. Nevertheless, the droplets are ultimately frozen and the cirrus cloud shield that they form allows one to trace the upper level outflow from the storm.

The spiral bands and the wall clouds are regions of heavy precipitation, particularly the latter. A radar 'sees' these elements quite readily and figure 3 presents a slightly idealized sketch of the radar presentation of an actual hurricane. The wall cloud surrounds the eye and contains the heaviest rain and most violent winds in the storm. The spiral bands or feeder bands are also regions of heavy rain of a showery nature. In the rain shield, a more or less continuous collection of precipitating elements, the rain is steadier in nature and somewhat lighter in character.

The inner structure of the hurricane has been fairly well documented in recent years. In figure 4 are presented the temperature anomalies recorded by instrumented aircraft on research flights into Hurricane Hilda (5). Temperatures are as much as 16°C above the annual tropical normal at around the 35,000 ft. level. At low levels (15,000 ft. and below) the anomalous warmth is concentrated in the eyewall and in the eye itself. This concentration of warm, light air is necessary to produce the low pressures recorded in the eye and the rapid rise in pressures (which drive the strong winds) in the immediate environs of the eye.

Now the process and structure we have described have led scientists to speak of the hurricane as a simple, direct heat engine. The air picks up heat and moisture from the ocean, the warm air rises, expands and cools, then finally sinks and contracts at some distance from the storm center. It is a cycle which contains the necessary elements of a heat engine. The actual acceleration of the air parcels is achieved through the conservation of that portion of the absolute angular momentum not extracted by the sea (through surface drag) as the parcels spiral inward to smaller radii.

A quantitative expression of both the necessary and sufficient conditions for hurricane formation is not yet possible. Nevertheless, we have definite precepts as to the gross features which are favorable or unfavorable for genesis. We recognize a need for a pre-existing disturbance, usually it is a disturbance in the subtropical easterlies which reaches its maximum amplitude at altitudes around 10 to 15 thousand feet. Frequently, we can trace these entities over Africa and chart them as they pass off the coast and move westward over the Atlantic. They are accompanied by characteristic cloud patterns which allow them to be tracked by satellite.

From consideration of a variety of factors, such as water surface temperatures, general strength of the easterlies and their horizontal and vertical shears (to 35,000 ft. level), the gross synoptic picture under which the perturbation is moving (6), etc., we can arrive at a qualitative estimate of the likelihood of significant deepening in the next day or so. While these concepts work reasonably well, they are not objective and are not uniformly successful. The fact of the matter is that very few perturbations deepen to become hurricanes despite the relatively frequent occurrence of conditions which appear favorable on this gross scale.

The perturbations or hurricanes move generally on a westerly course carried along by the broad easterly trade winds. Where or whenever the trades are weak they tend to slow down and recurve to the north. If this motion goes to fruition they continue recurving, breaking across the subtropical high pressure ridge, and move northeastward on the periphery of the middle latitude westerlies.

In order to be classified as a hurricane, the (low altitude) closed cyclonic circulation must have winds of 74 mph or more. If the winds are greater than 39 mph and less than 74 mph, it is classed as a tropical storm. This means that nascent hurricanes and senile hurricanes that fail to make the 74 mph criterion are called tropical storms despite the fact that their structure and energetics are those of a hurricane. In addition, however, there is another entity with similar energetics, but different structure which the meteorologist has come to look on as the "true" tropical storm. The differences may be summarized:

Size - The tropical storm is at least 2 or 3 times larger than an average hurricane; i.e., 1,000 n.mi. across vs. 300 to 500 n.mi.

Winds - The winds are not peaked at small radii. The maximum wind may occur 150 n.mi. out from the center of lowest pressure. They are by definition not as strong (less than 74 mph) but the storm may contain as much kinetic energy as a hurricane. Figure 5 is plotted so that areas under the curve are proportional to kinetic energy and show that Hurricane Daisy and Tropical Storm Frieda contained comparable kinetic energies (7). This points up the possibility that the built-up potential energy in the tropics could be dissipated through tropical storms rather than hurricanes, so that modification attempts should be aimed at releasing energy in this manner.

Weather - We have discussed hurricane weather in some detail. The tropical storm has no typical spiral band distribution. Usually, there is an extensive area of bad weather in the region of maximum winds. And, there are a number of bands oriented almost parallel to the low level wind flow that may extend for distances of the order of 50 n.mi. or so. There is, in addition, usually a large area of stratiform cloudiness from which rainfall is less intense and less showery in nature than in the rainbands. This large area of bad weather is usually to the right of the direction of motion and may be centered some distance from the center of low pressure, which, on occasion, may be relatively free of bad weather. The distance from the center, extent of the area, number of bands, etc., are all highly variable. It is a curious coincidence that storms in the tropics seldom if at all have winds stronger than 74 mph without the formation of an eye, eyewall and the development of typical hurricane characteristics - it is a curious coincidence because the 74 mph criterion was laid down long before this fact was established.

Thermal Structure - Just like the hurricane, the tropical storm, when mature, is warm core; i.e., the temperatures aloft are warmer in the center than the surrounding atmosphere. But, the anomalies are much smaller than those found in a hurricane.

Conclusion - It is apparent that the hurricane and "true" tropical storm are distinguishable by characteristic differences in structure. These differences transcend the mere distinction of whether the vortex is associated with winds of 73 mph or less. In general the hurricane is a more concentrated, better organized, smaller disturbance which frequents the same habitat as the tropical storm, frequently has similar antecedents and enjoys a similar energy supply. The hurricane is by far the more destructive but many welcome its rains. The tropical storm is frequently welcomed for the extensive rains which accompany it despite the minor hardships it imposes.

2. Historical Damage to Property and Loss of Life

Damage caused by hurricanes in the United States has been steadily increasing and loss of life due to hurricanes has been steadily decreasing since the beginning of the Twentieth Century. Improvements in the hurricane warning service and the community preparedness programs account for the latter. Expansion of larger cities into areas vulnerable to hurricanes and construction of expensive buildings along coasts ravaged by the storms account for the former. Improved building codes have helped reduce losses in some areas, but the totals for the nation continue to climb. Even with the effect of inflation removed, costs of damages keep increasing at an accelerating rate.

The losses due to hurricanes in the United States summarized by 5-year periods and adjusted for the cost of construction to the 1957-59 base are presented in figure 6. This illustrates how rapid the increase has been in recent decades. Even the adjusted values exceeded $2.4 billion dollars for the period 1965-69. If the actual dollar figure is used, the damages in that period exceeded $3 billion.

The damage figures are tabulated by years in table 1 (8). The variation of loss from year to year is striking. Only by taking longer term averages does it become obvious how rapidly the damages are increasing.

Table 1

Loss of Life and Estimate of Damage From North Atlantic Tropical Cyclones
1915-1969

YEAR	LOSS OF LIFE IN U.S.	ESTIMATED DAMAGE IN U.S. (Millions)	YEAR	LOSS OF LIFE IN U.S.	ESTIMATED DAMAGE IN U.S. (Millions)
1915	550	63.0	1945	7	80.1
1916	107	33.3	1946	0	5.2
1917	5	0.2	1947	53	135.8
1918	34	5.0	1948	3	18.4
1919	287	22.0	1949	4	58.8
1920	2	3.0	1950	19	35.9
1921	5	3.0	1951	0	2.0
1922	0	0	1952	3	2.8
1923	0	Minor	1953	2	6.2
1924	2	Minor	1954	193	755.5
1925	6	Minor	1955	218	984.5
1926	269	106.5	1956	19	26.5
1927	0	0	1957	395	152.1
1928	1836	25.0	1958	2	11.2
1929	3	0.7	1959	23	23.1
1930	0	Minor	1960	65	370.4
1931	0	0	1961	46	331.0
1932	0	0	1962	3	1.1
1933	63	46.7	1963	10	13.0
1934	17	4.8	1964	49	515.2
1935	414	11.5	1965	75	1445.0
1936	9	2.3	1966	54	15.1
1937	0	Minor	1967	18	200.0
1938	600	300.2	1968	9	9.9
1939	3	Minor	1969	255	1420.8
1940	51	4.7			
1941	10	7.7			
1942	8	27.1			
1943	16	16.8			
1944	64	165.0			

Table 2

Losses of Property in the United States from Hurricanes.

Year	Storm	Damage by single storm (millions)	Total damage for year (millions)
1950			35.9
1951			2.0
1952			2.8
1953			6.2
1954)	Carol)	450.0)	)
)	Hazel)	251.6)	755.5)
1955	Diane	800.0	984.5
1956			26.5
1957			152.1
1958			11.2
1959			23.1
1960	Donna	386.5	395.1
1961	Carla	400.0	406.0
1962			1.1
1963			13.0
1965	Dora	250.0	515.2
1965	Betsy	1419.8	1445.0
1966			15.1
1967	Beulah	200.0	200.0
1968			9.9
1969	Camille	1420.8	1420.8
	Totals.....	5578.7	6396.3

If consideration is given to damages from individual storms, it will also be seen that the major damages are due to a relatively few storms. The losses due to these major storms are much greater now than 20 years ago. Table 2 gives the losses for a few of the major storms for the last 20 years and compares that loss to the total loss for all storms for the same 20 years. This shows that 87 percent of the damage has been caused by 9 storms. These were all intense hurricanes. The main point here, however, is that it is becoming progressively much more difficult for a major hurricane to cross the United States coast without doing extensive damage.

3. Theories of Hurricane Modification

Introduction - We have seen in a preceding section that the hurricanes and the tropical storm may both be considered to be simple heat engines. Further, a small but significant portion of the heat necessary to sustain the intensity of the storm itself. Another salient fact is that there exist in the towering cumulonimbi of the wall cloud and the spiral rain bands large quantities of super-cooled water; i.e., cloud droplets which have been borne aloft in the updrafts to well above the freezing level without the droplets turning to ice. This well recognized meteorological condition leads to fairly rapid icing of aircraft flying through such supercooled clouds. And, in the absence of freezing nuclei to "seed" or encourage the growth of ice crystals, significant supercooling may exist for prolonged time periods. Any agent which could trip or 'trigger' the conversion of the droplets to ice crystals would also trigger the release of a significant amount of heat, the latent heat of fusion. Such agents are relatively well known and the logistics and means of dispersing such 'seeds' in meaningful quantities and in the desired locations are well within our resources and state of the art.

We are confronted then with two possibilities. Can we release the latent heat of fusion in such places and quantities that it will have a beneficial or desirable effect on storm characteristics either directly or through initiation of a chain reaction? Alternately, can we in any way modify the surface of the sea over which the hurricane is moving, or about to move, so as to alter the exchange of moisture/heat which we know is picked up by the hurricane and is vital to storm intensity. At the present time these are the two approaches which appear most likely to prove effective. There are other possibilities which appear rather less practical and these will be mentioned later.

Modification through selected release of the latent heat of fusion - The one attack which is currently well within our logistic means is the seeding of supercooled clouds with silver iodide smoke, an effective nucleating agent. A major point of concern immediately arises, namely, will not release of this additional heat just enhance the natural processes and result in further hurricane intensification? It seems quite likely that this would be the result if the seeding were done at the storm center. Instead, the seeding is to be carried out outside of the ring of maximum winds, in outer portions of the wall cloud and in the spiral bands immediately adjacent. In these areas the freezing level is usually 18,000 feet and above so that the silver iodide smoke will be in the neutral or weakly outflowing layer of the storm and will not be carried en masse towards the eye of the storm.

Now our hurricane modelling has shown that if we apply a big enough heating rate at radii just moderately greater than the radius of maximum winds and if we sustain the heating long enough, we can displace the ring of maximum winds outward and with smaller peak values. However, there appears to be an insufficient supply of supercooled droplets at these radii to achieve this effect merely through the conversion of supercooled water to ice. Radar observations indicate that at least in portions of this annular ring outside of the wall cloud there are towering cumulus elements which reach up to the 20 or 25,000 ft. level and contain supercooled water droplets. These tops obviously do not reach up into the strong upper level major outflow region.

These same cloud elements appear to be towering cumuli with definite seeding potential, i.e., if the supercooled water droplets are turned to ice, the added buoyancy from the heat of fusion should stimulate further updraft, more low-level boundary-layer air must rise through the cloud base, more water vapor should be condensed (at greater radii) and the heat of condensation of the moisture thus condensed is available to stimulate greater growth. The cloud grows vertically and may now extend up to the main outflow layer so that air rising at this radius is now removed from the system without penetrating further towards the eye.

Any air which is thus diverted will be air that will not penetrate to the wall cloud. Its moisture has been forced to condense at radii greater than the ring of maximum winds and cannot contribute to the sustenance of the old wall cloud. In fact, a "new wall cloud" should finally form at the greater radius with weaker maximum winds. These are attributable to the fact that the inspiralling parcels achieve a radial balance of forces when the centrifugal and coriolis forces balance the new pressure gradient just being established at the new radius. This new maximum should be smaller than the old maximum which occurred at the inner radius but slightly larger than the winds which prevailed at the new radius under the old regime. In addition any net upper-level warming (which in all probability will be rather slight after the air rises and cools) will tend to make the atmosphere more stable--make it harder for following parcels of air to ascend. Effects of this type which diminish mass circulation through the storm system should weaken it.

There are other seeding agents which could be used, dry ice, liquid nitrogen, etc. The most thoroughly tested is silver iodide smoke. Moreover, there are other areas of the storm where seeding might prove effective. The rain bands are natural targets. Seeding a rain band at a considerable radial distance from the eye wall might amplify local cumulonimbus growth, decrease mass flow in to smaller radii, and could conceivably result in a localized significant area of bad weather somewhat similar to that we frequently find in a tropical storm. Such a result would weaken the tight, well organized structure and may weaken the maximum winds in the wall cloud.

Whether we can materially affect the path of a hurricane seems quite a bit less likely. All evidence clearly shows that the hurricane is, for the most part, advected along through the atmosphere on a deep, broad river of air. The hurricane interacts with and modifies this river in a limited fashion - and it is through this limited "interaction term" that path modification would have to work. Since the heat releases which we are manipulating are relatively small quantities when one considers the total amount of latent heat released, we believe the effect would be small. Further, changes in path could be dependent on asymmetries in the outflow portion of the storm. As yet we have no 3-dimensional mathematical model of the storm which can simulate this interaction. Consequently, we consider possibilities in this area to be uncertain at this time.

Modification through alteration of sea surface characteristics - We have already seen that the addition of moisture and heat to the air spiralling in at low levels plays a vital role in the extreme intensities which a hurricane can develop. Consequently, if we could inhibit this transfer, the storm could not become so intense. It has already been established that evaporation from reservoirs - under low wind conditions - can be inhibited by the use of a monomolecular film (11). The film breaks, is rolled up and deposited ashore in winds much greater than 15 knots. However, other films can be engineered with stronger lateral bonding which can be anchored more securely in the water. Theoretical consideration of this problem is currently underway.

There are many facets which must be weighed in the film engineering. These include:

a. The area to be covered is large, so cost must be reasonable.

b. The film must be readily spreadable, preferably from aircraft.

c. Logistics of quantities involved (weight, etc.) must be within capabilities.

d. The film should be bio-degradable and harmless so that it will break up in a few days and essentially disappear.

e. It should reform rapidly if waves create temporary breaks.

f. Since spray is driven in sheets by the hurricane winds, the film should coat the drops which have the effect of increasing the effective surface area of the water manyfold.

g. Its behavior with hurricane force winds on water must be verified.

Computer simulations have shown (12) that removing the source of latent heat, i.e., the ocean surface, has a very marked effect on hurricane strength. The hurricane immediately begins to weaken and soon becomes just another innocuous storm. Since these modeling results compare so well with our theoretical thinking and budget studies (5), we feel that this is the surest way to weaken a hurricane. What is needed is a monomolecular film with the desired properties and the logistical means of handling it.

There is another possible way to alter sea surface characteristics in a beneficial fashion. The rate at which the hurricane picks up moisture and heat from the surface is a function of the temperature of the sea surface. The warmer the surface is, the more heat and moisture are picked up - other things being equal. The warmest, lightest water is on the top, and, if we neglect salinity and the topmost mixed layer, the water gets colder with increasing depth. If there were some way of stirring the sea to reasonably great depths, the sea-surface temperatures might be reduced by some 5°C or more and thereby diminish the heat and moisture picked up by the storm. No practical means of achieving this result is now known. Documentation now exists showing cold wakes in the rear of some hurricanes suggesting that the hurricane, at least on occasion, achieves this sort of effect itself (13).

Modification by altering the frictional drag offered by the ocean surface - The frictional drag offered by the ocean surface to the air moving over it has two important effects: it helps in the exchange of moisture (in the vapor form) and sensible heat through the formation of waves, bubbles, droplets, etc., and it also causes the air to move in cross-isobar fashion so that one component of the motion is from higher to lower pressure. In a larger sense, of course, friction acts as a brake, a sink, by means of which energy is drained from the atmosphere by the ocean.

Consequently, there is some thinking that, if we could significantly reduce the ocean's drag, we would diminish the waves, spray bubbles, etc., which aid the heat and moisture transfer and diminish the cross-isobar component of flow also. If such an effect were introduced suddenly, the immediate reaction would probably be an increase in wind velocities due to the decrease of friction. However, in time, the less immediate causative factors should exert themselves and the storm should weaken.

Agents to product effects such as these are not altogether unknown. The monomolecular film cited earlier might serve this purpose if the lateral bonding had the right properties. Oil and other impurities have long been known to produce 'slicks' on the sea surface. The most practical program may be that which tries to combine in one monomolecular film the inhibition of evaporation and the ability to produce a slick through the reduction of surface tension. Computer simulation of this problem has been run on the symmetric model and is described under the section on numerical modeling (III-3).

Modification through disturbance of the heat balance - We have seen that the hurricane has its most anomalous warmth in regions of 35 to 40 thousand feet. The question is posed as to what effect further accumulation of heat at these altitudes would have. Would it not make the atmosphere more stable and result in a decrease of the cumulonimbus activity? If so, such a decrease should also weaken the hurricane.

One proposal to achieve these effects envisions the employment of very small, very light, dark colored plastic balls or bubbles. They would be made of one of the well known polymers, presumably created near their release point. They should be placed in upward moving currents of air and, hopefully, should rise to the heights of cirrus outflow and spread laterally. The little spheres should change the albedo of the cirrus layer, darkening the cloud so that more sunlight is absorbed and the temperature raised. Such an experiment could be subjected to computer simulation.

III. PRESENT STATUS OF PROGRAM

1. Current Modification Experiments

Approach - The only modification approach we have used in field experiments on hurricanes is the one in which we seed the clouds just beyond the eyewall of a mature hurricane with silver iodide crystals to stimulate cloud growth. The area in which the silver iodide is deposited is labeled "EYEMOD" in figure 7. An aircraft carrying some 200 silver iodide generators crosses the eye at about 33,000 ft. and enters the wall cloud in or just upwind of the clouds of greatest vertical development. Just after crossing the belt of maximum winds, it starts dropping the generators. They are released on a line extending radially outward from the storm center and are distributed over about 20 miles. Each generator contains 190 grams of silver iodide, and each gram produces 10^{12} or more crystals which are active as freezing nuclei at temperatures found in these hurricane clouds. The compound burns by the time it has fallen to about 18,000 feet, and a curtain of silver iodide is, therefore, introduced into the clouds that is 20 miles long and 15,000 feet high.

The winds of a typical hurricane should sweep the crystals through an annulus around the center with only a weak outward component. Turbulence will further distribute the crystals throughout the annulus except as they are caught in the updrafts and carried out the top of the hurricane or fall in the raindrops to the sea surface.

The current modification experiments call for 5 seedings per day at approximately 2-hour intervals; approximately 1,000 canisters containing nearly 200,000 grams of silver iodide are, therefore, introduced into the hurricane during a period of 8 hours.

Logistics - Project STORMFURY's hurricane EYEMOD experiment involves a number of aircraft flying coordinated patterns over an area of several thousands of square miles, at altitudes between 1,000 and 60,000 feet. One or more instrumented aircraft are in the vicinity of the hurricane from four hours before seeding time through eight hours of seeding to six hours after the final seeding, a total observational monitoring of 18 hours duration.

Aircraft involved in Project STORMFURY include four specially instrumented planes of NOAA's Research Flight Facility (RFF). The two DC-6's, one C-130 and one B-57, all based at Miami, Florida, monitor the experiments by recording numerous meteorological observations from 1,500 feet to 40,000 feet. The RFF is a small team of 47 men and 4 aircraft. The two DC-6's which are generally flown between 1,000 to 20,000 feet are operated by eight-man crews - two pilots, navigator, flight engineer, two meteorologists, and two electronics specialists. Because of tight accomodations, only a pilot and meteorologist-navigator fly the B-57 jet from 35,000 up to 45,000 feet. The C-130 crew consists of two pilots, navigator, flight engineer, meteorologist and two electronics specialists, plus additional personnel as may be needed to operate any special equipment used for specific missions. The C-130 aircraft is flown between 1,000 and 30,000 feet.

The aircraft are crammed with such devices as differential pressure transducers, dropsondes, vortex probes, icing detectors, infrared hygrometers, water content meters, and gust probes. There are three kinds of radar, magnetic tapes for recording digital data, and oscillographs and cameras for visual records. A typical mission produces millions of data bits and thousands of photographs.

The Navy's Hurricane Hunter Squadron (Weather Reconnaissance Squadron FOUR or VW-4) has four WC-121N (Super Constellation Type) and one WP3A (Orion) aircraft based at NAS Jacksonville to provide airborne control of all aircraft in the seeding operation and to measure numerous meteorological parameters. The aircraft have a Doppler radar navigational computer, radar altimeter, meteorological and oceanographic sensing equipment and a data acquisition logging system. The aircraft operate at altitudes of 500 to 1,000 feet during low-level hurricane eye penetrations.

The Navy and Marine Corps' Attack Squadrons (VA-176 and VMA(AW)224) using five A-6A (Intruder) planes (all-weather, two-place, twin-engine jet attack aircraft) drop the silver iodide canisters. This assignment is rotated annually depending on various availability of squadrons.

The Air Weather Service "Hurricane Hunters" (53rd Weather Reconnaissance Squadron), based at Ramey Air Force Base in Puerto Rico, provides WC-130 aircraft for Project STORMFURY. The WC-130 (Hercules) seek out and probe into storms at 1,500 feet, but may climb to 10,000 feet in violent hurricanes. They also make dropsonde measurements, measure high-level winds, take high-level photographs, make radar observations, and measure temperature at flight levels.

High altitude color photography is provided by a squadron of the Air Weather Services 9th Reconnaissance Wing, the 58th Weather Reconnaissance Squadron, based at Kirkland AFB, New Mexico, using a unique long-winged version of the B-57, the four-jet RB-57F.

Additional high-level storm reconnaissance will be provided by a WC-135 of the 55th Weather Reconnaissance Squadron from McClellan AFB, California.

Experimental procedures - The first plane to enter the storm is an Air Force WC-130, crisscrossing and then circling the hurricane at 29,000 feet, to monitor outflow and release dropsondes in the eye and at four points on the perimeter. This flight begins four hours before the first seeding and lasts about six hours. It is repeated after the second seeding.

About two hours before the first seeding, three more aircraft arrive: the RFF B-57 to monitor outflow by flying across and around the hurricane at 37,000 feet for two hours; an RFF DC-6 to fly "X" patterns across the eye, at an altitude of 5,000 feet, for more than four hours; and a Navy WC-121N to circle the storm at 1,000 feet for about eight hours, monitoring inflow. Each of these flights is repeated later during the experiment--the RFF B-57 returning about an hour before the final seeding; another RFF DC-6 arriving just before the third seeding, and the first returning about two hours after the last seeding to monitor the storm. A second Navy WC-121N relieves the first at about the time of the fourth seeding and continues low-level inflow monitoring for another eight hours.

Before seeding begins, two Navy WC-121N aircraft approach the storm at 7,000 and 10,000 feet. These are the command and control aircraft and its alternate. Both remain in or near the storm for more than eight hours. The RFF C-130 will participate as a cloud physics monitor, flying between 22,000 and 25,000 feet for five hours, beginning one hour before the first seeding.

Just before seeding, an RB-57F will begin flying back and forth above the storm, photographing its cloud patterns from 49,000 feet or higher.

For the five seeding runs, scheduled at two-hour intervals, Navy or Marine Corps A-6 seeder aircraft fly across the storm at 33,000 feet.

About an hour after the first seeding, an Air Force WC-135 enters the storm to monitor outflow at 39,000 feet for seven hours, until the time of the fifth and final seeding.

There may be occasions when the eyewall of a storm may be out of the range of the aircraft but the spiral rainbands will be within range. Then, the spiral rain bands will be seeded as indicated in figure 7. Rainbands - curved bands of clouds with heavy precipitation - are normally found at some distance from the storm's eye and may constitute an important link in the chain between relatively simple cumulus convective activity and a mature hurricane. Curtains of silver iodide pyrotechnic canisters will be dropped along a rainband at periodic intervals with monitoring before and after seeding by Project STORMFURY aircraft.

<u>Computer modeling for control</u> - With the advent of a computer simulation model of hurricane development by Dr. Rosenthal of the NOAA National Hurricane Research Laboratory, it is becoming possible to approach the hurricane seeding experiments by conducting simple seeding simulations in the laboratory. As this technique develops over the years, it will contribute more and more to the experimental program and provide important guidance in the conduct and evaluation of field experiments. The current status of this work is described in section III-3.

<u>Precautionary measures</u> - Seeding of hurricanes is restricted for precautionary measures to storms whose probability is small - 10 percent or less - that the hurricane center will come within 50 miles of a populated area during the ensuing 18 hours. There are two primary reasons for the seeding restriction. The

effects of the experiments are expected to disappear in less than 18 hours after seeding, so that a storm will revert to a natural state before striking land. Also, because hurricane structure changes markedly as a storm approaches and passes over land, it is highly desirable to complete the monitoring phase of the data collection (data used to evaluate any changes in structure) before any considerable portion of the storm overlies a land mass.

2. Results of Hurricane Debbie Seeding, 1969

Hurricane Debbie was seeded by the STORMFURY group 5 times in a period of 8 hours on August 18 and again on August 20 (14). No modification attempt was made on August 19 because of aircraft operation safety requirements for crew rest. Several changes occurred in the hurricane during and after the seedings which seem to have been caused by the modification experiment. That is, the changes were of either such a large magnitude, or of such a character that they rarely occur in non-modified storms.

The winds at 12,000 ft. (the level at which the most complete set of measurements were made) decreased following the seedings on both of the experimental days and increased on August 19 when no experiment was conducted (figs. 8 and 9). Beginning about 4 hours after the first seeding the winds started decreasing on each of the experimental days. From then until about 5 or 6 hours after the last seeding, a period of 9 to 10 hours, the winds sometimes increased and sometimes decreased. In the net, however, the maximum wind speeds decreased with the most marked changes observed on August 18.

Before the first seeding on August 18, maximum wind speeds at 12,000 feet were 98 knots. By 5 hours after the fifth seeding, they had decreased to 68 knots, a decrease of 31 percent. On August 20 the maximum wind speed before the first seeding was 99 knots. Within 6 hours after the fifth seeding, the maximum had dropped to 84 knots, a decrease of 15 percent.

Too few data are available to accurately define the natural variability of winds at either 12,000 ft. or sea level. Minimum sea level pressures, however, are available in great quantity for past storms and there is an empirical relationship between the minimum sea level pressure in a hurricane and its maximum winds. Using this relationship, we have computed variability of maximum winds in hurricanes for 6, 12, 18, and 24 hour periods for almost 500 cases. Using these data we can estimate that the decrease of maximum winds of 31 percent and 15 percent were at a ratio that has occurred in past cases of unmodified storms, only 1 time in 160 and 1 time in 10, respectively. Since the relationship between minimum central pressure and maximum winds is not perfect, we probably should not accept these numbers exactly. It certainly seems conservative, however, to say that the decrease in maximum winds on the 18 and 20 August considered as a pair would not have occurred in past cases more often than one time in 40.

Variations in the force of the wind are closely related to variations of the square of the wind speed or the kinetic energy of the air particles. The decreases in maximum winds represent a reduction in kinetic energy in the belt of maximum winds of 52 and 28 percent, respectively on August 18 and 20.

Results of experiments conducted with a theoretical numerical model of a hurricane suggest that the seeding should cause the maximum winds to occur at a greater radius than they were prior to the seeding. This expansion of the annulus of maximum winds did occur on both the 18 and 20 August. By contrast, the radius of maximum winds decreased on August 19, the day with no modification attempt.

The central pressure for Debbie on August 18 following the seedings, increased at a rate greater than has occurred in 91 percent of the cases for non-modified hurricanes. There is a good correlation between the central pressure at sea level in hurricanes and the maximum winds such that rising central pressures are associated with decreasing maximum winds. On August 20 the change in central pressure was small and not much larger than the probable error in the measurements. On August 19 the central pressure decreased.

In most hurricanes the diameter of the eye varies directly with the radius of the maximum winds. Since the experiments with the theoretical model suggest that the seedings should cause an increase in the radius of maximum winds, we investigated changes in the structures of the hurricane and the clouds surrounding it.

Airborne radar photographs of hurricane Debbie, taken on August 18 and 20, 1969, were used to measure the echo free area within the eye at 5 minute intervals beginning one hour before the first seeding and ending one hour after the last seeding on both days. Results for the 18th show a sudden increase in echo free area at seeding time plus one hour and 15 minutes. Increases ranged from 50 percent to three fold.

The results for the 20th were quite different. A double eye structure was present on this day as opposed to a single eye on the 18th. The major portion of the seedings were done on the inner eye. The echo free area within the smaller, seeded eye remains constant throughout the day and the larger eye slowly decreased in area. A study of these radar observations has been prepared for publication by Black.

The most obvious evidence on the 20th suggesting seeding effects, was the rotation rate of the major axis of the elliptical eye. A reduced rate of rotation occurred within 10 minutes after each seeding. This was followed one and one half hours later by a rapid increase in the rotation rate, which continued until the next seeding time. The period of the cycle (the time required for one revolution of the major axis) was about 2 hours. The interval between seedings was also about 2 hours.

Insufficient data regarding natural variability of the hurricane eye are available to calculate probability that the changes in radar structure might have occurred in a non-modified storm. From a limited number of cases, it seems likely that some of the changes observed in Debbie's radar images are relatively rare. The changes in maximum wind speed and other items related to structure of Hurricane Debbie were appreciable following the modification attempts. Study of past storms reveals that the changes come within the range of natural variability. The data are certainly very suggestive, however, that the experiment caused some modification in the storm.

A more exhaustive study (16) of the changes in wind speed profiles in all quadrants of Hurricane Debbie on the 18th and the 20th suggests that at radii in excess of about 75 n.mi. small wind speed increases were observed after the experimental seedings. These changes are compared to those noted in the symmetric model simulation of the experiment (18) and found to agree quite well with the simulation changes except for the excessive decrease in maximum wind noted on the 18th. A possible contributing factor to this decrease was noted in the broad scale synoptic picture but data were far from conclusive in indicating the exact role synoptic events may have played.

Central pressure changes noted in Hurricane Debbie on the 18th were very similar to those of the simulation experiment described in the next section. The experiment on the 20th was further complicated by the "double-eye" structure and comparisons seemed a bit less meaningful. Data did not permit direct comparison of upper level (around 35,000 ft.) temperature profile changes with those of the simulation. What data were available did not disagree with the simulation results. At 12,000 ft. where great quantities of field data were available the temperature profiles over the inner 60 n.mi. of the storm flattened, i.e., the rise in temperatures toward the eye became less pronounced) after the seedings. The simulation indicated little changes were to be expected at this level but this was the sense of the change indicated at higher levels.

3. Numerical Modeling of Hurricanes

Intensive efforts have been underway for several years to develop dynamical-numerical models which will simulate the life cycle of hurricanes. Several scientists at various universities and at the National Hurricane Research Laboratory have developed such models. The one prepared by Dr. S. L. Rosenthal at the latter laboratory has proved useful in testing ideas to be used in the design of the field modification experiments. Despite the fact that tremendous progress has been made in hurricane modeling in the last 5 years, much remains to be done.

A goal of our theoretical investigations of hurricanes is to develop a model which will make it possible to calculate the development, movement, and future state of a hurricane by use of the theoretical equations which govern these factors. The objective is to calculate with a high speed computer the life cycle of a tropical cyclone which results from initial conditions representing either the mean tropical atmosphere or a very weak disturbance similar to those occurring frequently in the tropics during the summer and fall.

Such an achievement, in sufficient realism, will lead to a much fuller understanding of the dynamics and life history of hurricanes, and pave the way for a fully logical and methodical approach to develop modification techniques. It will permit us to test in the laboratory ideas that are suggested for field experimentation. From the calculations made by the computer we can select a period when the simulated storm is in the mature stage and varying little in intensity (over a simulated 12 to 24 hour period). We then rerun the model for this same period with certain changes to simulate the effect of seeding the hurricane. The results of the two calculations can then be compared to see what effect the modification experiment would have on the computerized storm. This comparison is something that we are never able to do in the field experiments because we can never find two storms exactly alike which would permit us to select one as a control and the other as the experimental storm.

The model is developed with a group of equations. The first three are the equations of motion. Others that will usually be used are the equation of continuity and some law related to the conservation of energy. If the set of equations is chosen properly, it is theoretically possible to start with some initial state of the atmosphere and calculate the changes that will occur with time. In actual practice this is quite difficult. The equations are very complicated. They are differential equations and in most cases the group can not be solved simultaneously by presently known analytical procedures. A computer must be used to solve close approximations of these equations. This procedure, however, often provides satisfactory results.

In a hurricane where the gradients of the various parameters such as wind speed, temperature and pressure are so strong, it is necessary to calculate values of the parameters at closely spaced grid points. In our more successful hurricane models the values have been calculated at grid points spaced only 5 to 10 n.mi. apart in the horizontal with the domain covering an area at least 500 n.mi. in diameter. Seven levels have been used in the vertical, but it is quite possible that the ultimate model will have even more levels. Since the computations must be repeated each time step (every minute with the present models) for each grid point on each level, the number of computations becomes very large.

In the theoretical models that have been developed at Miami, calculations are usually started with a weak disturbance. That is, it is assumed that a weak disturbance with maximum winds of 10-20 kts with a closed circulation is already in existence. The wind field for this disturbance is fed into the computer along with the equations governing the model. Rules are provided governing the rate at which energy flows into the system across the lateral boundaries. Most of this energy is in the form of water vapor which is a latent source of heat energy. When air rises in the storm and the water vapor condenses to form water drops, heat is released. In addition, heat and momentum are permitted to be exchanged between the atmosphere and the ocean inside the storm area according to certain laws or conditions defined in the model. From the initial conditions the computer calculates the status of the disturbance/storm every minute. Eventually, when conditions are favorable, the computer will show that a hurricane has developed. The more successful of the models used in Miami simulated development of a hurricane which has maximum wind speeds between 80 and 90 kts. By changing the rate at which energy enters the storm or is dispersed in the storm, one can vary the rate of intensification and the maximum intensity achieved (17).

Section II-1, above, contains a brief description of some of the more prominent structural features and energy processes of hurricanes. It is impossible to successfully simulate all of these features with a dynamical-numerical model at the present time. There are several unsolved scientific problems, and to make the problem tractable, it is necessary to make simplifying assumptions. At the National Hurricane Research Laboratory, we have planned to attack the general problem in three different stages. These are:

a. Development of a circularly symmetric model which provides for little or no interaction with the ambient atmospheric circulations. The circularly symmetric assumption permits use of a 2-dimensional model and therefore greatly reduces the computer requirements.

b. Development of a 3-dimensional model which provides for little or no interaction with ambient atmospheric circulations. No provision is made for forecasting how the hurricane will move.

c. Development of a 3-dimensional model which includes interaction with at least the principal features of the nearby environment and provides for forecasting the movement of the hurricane center.

Progress on the first of these three problems has reached a rather high plateau, and little further improvements in the model are expected until some basic scientific problems are resolved. A highly pragmatic parameterization is used of the transfer of energy and momentum by cumulus clouds. Substantial improvements in this area must await increased understanding of both cumulus convection and its interaction with the larger scales of motion. A similar statement can be made about the energy and momentum transfers between the ocean and the atmosphere and upwards through the first few hundred meters of the atmosphere. Such Projects as BOMEX and the Tropical experiment of GARP may add further understanding to the lower boundary layer processes. Several other groups are studying the dynamics of cumulus clouds. With our present knowledge, the best means of determining whether these processes are parameterized correctly is by evaluating how well the model simulates a hurricane. Some of the models do this very well.

The circularly symmetric model developed by Dr. Rosenthal simulates many features of a hurricane, at least in a sort of mean state, quite well. It can be a very valuable tool for the study of hurricane dynamics, and most of the future work with the model should be for that purpose. And, as mentioned, it can also be used for preliminary testing in a laboratory on a computer of hypotheses suggested for field experiments on hurricane modification. The model now computes energy exchanges in the boundary layer explicitly (rather than by parameterization) using bulk aerodynamic equations. The constant drag coefficient has been replaced with Deacon's empirical relationship. Using this model experiments have been carried out using varied drag coefficients, varied oceanic evaporation, and sensible heat exchange and open and closed lateral boundaries (18).

The basic feature of the STORMFURY hypothesis is the stimulation of tall convection at radii larger than that of the eyewall in the hope of diverting some of the boundary layer inflow, thus reducing the supply of moisture and angular momentum to the eyewall region. In the field experiment, this is to be accomplished by causing relatively short clouds to become tall as described in a previous paragraph. In the model, where all clouds are tall, a conceivable analogue to the field experiments is to increase the concentration of tall clouds at the corresponding radii. Once this point of view has been accepted, the means by which model convection is simulated becomes rather arbitrary.

The addition of a fixed amount of heat as in Rosenthal (19) is only one of many possibilities. Others include arbitrary changes of boundary layer convergence, changes of the humidity patterns, and changes in static stability. Of course, these alterations can also be made in various combinations.

While calculations of this type can still provide helpful information for Project STORMFURY if properly interpreted, clearly literal comparisons between the calculations and the Debbie experiment are unwarranted. Aside from the arbitrary procedures used to simulate seeding, the other questions of parameterization raised earlier in this section must be considered, as must the lack of interaction with other synoptic features.

It is abundatly clear that we must strive to provide more direct numerical tests of the new hypothesis. To achieve this end, it will be essential to include entrainment and some simple representation of the more significant microphysical processes. It may also be necessary to make improvements in the modeling of the interactions between the Cumulonimbus and hurricane scales. This will be a high priority item for the next year.

Work is now under way on step two in the model development process, namely on a three-dimensional model which does not interact with its environment. Anthes, Rosenthal and Trout (20,21) point out that computing economics dictate rather coarse vertical and horizontal resolution for the asymmetric model.

The atmosphere's vertical structure is represented by only 3 layers and horizontal spacing of grid points is 30 km. The radial extent of the computational domain is approximately 435 km. Although the model allows azimuthal variations, the hurricane remains an isolated, stationary vortex on an f-plane similar in fashion to the circularly symmetric models. Like the circularly symmetric models, this model is a theoretical tool with no potential of dealing skillfully with real data.

Despite obvious deficiencies due to the lack of adequate resolution, the model reproduces many of the observed asymmetrical features of the hurricane. Realistic portrayals of spiral rainbands are obtained. The anticyclonic eddies of the upper troposphere are reproduced as are the observed areas of negative absolute vorticity and anomalous winds.

The asymmetric model has been generalized to include an explicit water vapor cycle and has been recoded for a staggered horizontal grid. The latter reduces local truncation error without increasing either the number of grid points or reducing the spacing between them. A number of experiments have been conducted with the revised model and results show great promise. These data are now undergoing careful study.

Despite the realism of the results and despite the increased accuracy obtained through horizontal staggering of variables, the model continues to suffer from a lack of adequate resolution. Improvement of the vertical resolution appears to be economically beyond our reach. There is a possibility, on the other hand, that horizontal resolution, at least in the inner core of the hurricane, may be improved through the use of horizontally variable grids.

4. Decision Analysis Study by SRI

A study contract with Stanford Research Institute (SRI) was initiated March 10, 1970. The objective of the study was to perform a decision analysis of the many factors involved in a decision to operationally seed hurricanes. The Final Report from this study is still undergoing some changes; however, the Summary of the latest version is not expected to change significantly and is given below (edited slightly). There is some redundancy with other sections in this Issue Study; however, the SRI viewpoint is best reflected by printing the Summary in its entirety. The completed final report is to be available in May 1971.

It should be noted that while SRI has done an excellent job of analyzing the available data and of structuring the various factors that enter a decision to operationally seed hurricanes, their conclusions are based on a relatively small amount of data. Particular areas requiring more data, more analysis, or more experimentation include, 1) the effect of seeding on the maximum winds and on the track of the hurricane, and 2) the relationship between maximum wind velocity and the total expected damage from storm surges and winds.

SUMMARY (from SRI Draft Report "Decision Analysis of Hurricane Modification")

1.1 Major Findings and Recommendations

Operational Seeding

Finding: Meteorological theory and field experiments suggest that seeding may reduce the maximum winds of a hurricane by about 15%. Data on past hurricanes shows that such a wind reduction may be expected to cut property damage in half. While the effectiveness of hurricane modification is uncertain, current meteorological and economic information indicates that seeding would be beneficial: With seeding, the probability that hurricane damage will exceed any given level is lower.

Recommendation: The present policy prohibiting the seeding of any hurricane threatening a coastal area should be rescinded. We recommend that seeding should be considered on an emergency basis at this time if a severe hurricane threatens the coast of the United States.

Legal Basis for Seeding

Finding: The modification of hurricanes entails a substantial government responsibility. At the present time no firm legal basis for operational seeding appears to exist.

Recommendation: An agency should be established with clear legal authority to carry out operational seeding.

Further Analysis

Finding: The decision to seed a particular hurricane will be taken shortly before the hurricane is predicted to strike the coast. This difficult decision should take into account many factors, including the specific characteristics of the hurricane and its projected path.

Recommendation: Decision procedures supported by further analysis should be developed to aid the hurricane modification agency in determining whether to seed each threatening hurricane.

Experimentation

Finding: Resolving meteorological uncertainty on the effect of modification has an expected value of over $20 million per year. The expected value of an additional field experiment of the type conducted on Hurricane Debbie in 1969 is over $10 million for a single hurricane season.

Recommendation: Research and field experiments should be conducted on a greatly expanded scale to provide a more refined basis for operational seeding decisions.

1.2 Present Information Concerning the Effects of Hurricane Modification

The possibility of modifying hurricanes by introducing freezing nuclei into the clouds surrounding the eye of a hurricane was proposed by R. H. Simpson in 1961. The hypothesis that such seeding will reduce the intensity of maximum winds has been reinforced by a small number of field experiments carried out by Project STORMFURY over the last several years and by theoretical studies conducted by Dr. Stanley L. Rosenthal using a computerized model of hurricane dynamics.

These results are encouraging but not conclusive. Meteorologists presently believe that seeding having no effect on maximum sustained winds is as probable as seeding causing a substantial reduction in maximum sustained winds. There is no basis in meteorological theory or past experimental results for believing that properly conducted seeding will make a storm worse. It is difficult to make a case for assigning a probability larger than 2% to the possibility that seeding causes hurricanes to become more intense.

While it is unlikely that seeding will cause a hurricane to be worse, it is conceivable that the storm will become worse following seeding because of the erratic natural behavior of hurricanes. Hurricanes are notoriously variable and unpredictable. Natural forces may cause the hurricane to intensify or diminish by an amount larger than the effect of the seeding. On the basis of present meteorological knowledge about the effects of seeding and the variability of hurricanes, the following probabilities are assigned for the change in maximum winds between initiation of seeding and arrival at the coast a predicted twelve hours thereafter.

Probability of Changes in Maximum Wind over a Twelve-Hour Period for Modified and Natural Hurricanes

Wind Change	Probability of Wind Change for a Seeded Hurricane	Probability of Wind Change for an Unseeded Hurricane
Increase of 25% or More	.04	.05
Increase of 10% to 25%	.14	.21
Increase of 0% to 10%	.18	.24
Reduction of 6% to 10%	.21	.24
Reduction of 10% to 25%	.26	.21
Reduction of 25% or More	.17	.05

There is a probability of 0.36 that a seeded hurricane would intensify, and a probability of 0.18 that the hurricane would intensify by a significant amount, ten per cent or more. Such intensification may be expected as a result of the natural variability in hurricane winds, and it is important to note that the corresponding probabilities for an unseeded hurricane are even higher (0.50 and 0.26). This result is in fact a general one: For any level of maximum wind, the probability that this level will be exceeded if the hurricane is seeded is less than the probability that the level will be exceeded if the hurricane is not seeded.

Even if the present hypothesis that seeding is expected to cause a 15% wind reduction were confirmed by additional field experiments such as those conducted on Hurricane Debbie, 29% probability would be assigned to intensification of at least 10% after seeding a particular hurricane. Advancements in hurricane meteorology may reduce this figure below 9%, but it is doubtful that in the foreseeable future meteorologists can guarantee that the effect of seeding will always predominate over natural forces acting to intensify the storm.

Other aspects of hurricane behavior are also uncertain. While meteorologists believe that seeding will not have a significant effect on the path of the hurricane, its rainfall distribution or on large scale weather patterns, few of them feel confident about these assumptions in view of the limited information available. It would be virtually impossible at present to prove that some erratic feature of a seeded hurricane (e.g., a sudden change of course) was not related to the seeding.

1.3 Expected Benefits of Hurricane Modification

Although the risks of intensification or of erratic behavior such as a change in course are significant, they must be compared with the substantial expected reduction in property damage that can be computed from the probabilities in the table in Section 1.2. Although an accurate assessment is nearly impossible to make, the available data on property damage in past hurricanes indicates that a 15% reduction in maximum winds will reduce the property damage by roughly 50%. On this basis the probabilities of this table imply that the expected damage from a seeded hurricane is 19% less than for an unmodified storm. For a single hurricane such as Betsy (1965) or Camille (1969) this figure represents an expected saving in property damage of over 200 million dollars.

1.4 Expansion of Hurricane Modification Research

The present annual budget for Project STORMFURY is $750,000, an amount that is much smaller than the value of resolving the uncertainty on the effect of seeding for a single hurricane of moderate size. At the present time the "STORMFURY" hypothesis that seeding causes a substantial reduction in the maximum sustained wind of a tropical hurricane is given a probability of nearly one-half. If the hypothesis proves to be true, the potential annual savings in property damage in the United States may be as high as 200 million dollars a year. Considering this enormous potential benefit to the people of the eastern and Gulf coast states, the present level of support for hurricane modification research is surprisingly small.

A single field experiment may resolve much of the uncertainty on the effect of seeding. There is a probability of 0.33 that a repetition of the two seeding experiments conducted on Hurricane Debbie in 1969 would largely confirm the "STORMFURY" hypothesis that seeding causes a substantial reduction in maximum winds. The probability of a strongly negative result is 0.075, and a probability of 0.595 is given to an inconclusive result that would neither confirm or deny the "STORMFURY" hypothesis.

A high priority should be given to repeating this field experiment as soon as possible. The expected value of the experiment is approximately 4.7% of the property damage caused by storms that might be operationally seeded; the figure is even higher if it is assumed that operational seeding will not be permitted until another successful field experiment is obtained. Even if it is assumed that half of the hurricanes striking the U.S. coast would not be seeded operationally because of tactical considerations, the expected annual property damage from seedable hurricanes would be 220 million dollars a year. The value of an additional field experiment is then at least ten million dollars, for a single hurricane season. The discounted value of the experiment for future seasons (discounting at 7%) is at least 150 million dollars.

Opportunities for experimental seeding occur at irregular intervals. Although only one experimental opportunity has occurred in the period from 1966 through 1970, it is estimated that an average of one hurricane per year will occur that could be seeded experimentally with the present capabilities of Project STORMFURY. If an expanded capability could be developed giving an average of two experimental opportunities a year, the expected benefit would be equal to the value of the field experiment for half of a hurricane season, or five million dollars. The development of an expanded experimental capability therefore seems highly desirable. One possibility for achieving this expanded capability would be a program of seeding hurricanes in the Pacific Ocean.

The economic values of hurricane modification are much larger than the costs of the present program, and the usual economic cost-benefit comparisons give extremely positive answers. Even greater benefits may accrue to successful hurricane modification than the values in property damage would be accompanied by a corresponding decrease in the deaths and suffering caused by hurricanes. Further, the benefits are not limited to the United States, but would be shared by the many other nations of the world that are menaced by hurricanes and typhoons.

1.5 The Need for New Legislation to Authorize Operational Seeding

The government has a responsibility for a modified hurricane that is not present when the hurricane is considered a natural disaster. This responsibility coupled with the possibility that the storm will intensify or change direction from natural causes must be balanced against the expected benefit from seeding when establishing hurricane modification policy. Nearly all of the government hurricane meteorologists we have questioned have said they would seed a hurricane threatening their homes and families -- if they could be freed from professional liability.

In the decision to seed a hurricane threatening the U.S. coast, the crucial element is the tradeoff between mitigating property damage and accepting some responsibility for a destructive and unpredictable natural phenomenon. While this tradeoff is difficult to assess, it is clear that if responsibility is not given an extremely high value relative to property damage, then the present policy against seeding hurricanes that are threatening U.S. coastal areas should be reconsidered. For example, if the cost of this responsibility is judged to be equivalent to an increase of 25% in property damage when the storm intensifies and an increase of 10% otherwise, the lowest total expected cost is still achieved by seeding and accepting the responsibility. Such a high negative value to government responsibility is difficult to justify for a hurricane such as Camille (1969). We believe that at this time seeding should be considered on an emergency basis if a severe hurricane threatens the coast of the United States.

The present legal basis for operational seeding is confused and uncertain. In decisions where government action is associated with danger to the public it is highly desirable that the decision should be made with as broad a participation as possible on the part of the public. It is therefore recommended that legislation be submitted to Congress that would establish an expanded hurricane modification program with authority to seed operationally. This legislation should define the extent to which hurricane modification activities will be protected by sovereign immunity and define the basis under which the government can be held responsible for damage caused by seeded hurricanes.

The actual decision to seed a particular hurricane should be made at a high level of authority, with the assistance of meteorological experts. In this tactical decision many factors should be included that have not been included in the analysis of this report:

- possible changes in the hurricane track
- precipitation effects
- changes in the size of the hurricane
- the intensity of the hurricane
- synoptic environment and other factors that influence the predicted behavior of the hurricane.

These factors should be carefully considered before a decision is taken to seed a particular hurricane. These tactical factors could be formally included in a decision analysis that is an expansion of the analysis presented in this report.

(End of SRI Summary)

IV. OPERATIONAL CONSIDERATIONS

1. Operational Procedures and Implications

Technologically, the operational seeding of hurricanes to reduce maximum winds would be based on the latest research findings, and would resemble the experimental mode quite closely. An important difference would be that of careful timing of the seeding operations to minimize the adverse effects of the hurricane at the time the eye of the storm neared or passed over the coast line. Seeding would also be carried out at a somewhat earlier stage to reduce the extent of the storm surge or tide produced by the hurricane's winds while it was still at sea. The need for more exact timing of the seeding would require an increase in the frequency of fixes of the storm's position, and thus the number of reconnaissance flights. This increased flight activity would have to be borne by the Departments of Defense and Commerce. This will mean, so far as Commerce is concerned, at least a doubling of flight crews and seeding operations for the NOAA Research Flight Facility. Furthermore, since a continuation of the present R&D effort must accompany the early years of operational activities, an additional increase in RFF capability must be provided to permit both R&D and operational seeding to take place simultaneously when two or more hurricanes were present. An example of this requirement occurred in 1969 when both Camille and Debbie were coexistent, with Camille approaching the Gulf Coast at the same time that experiments were being readied for Debbie. The initiation of the operational mode will also have a strong impact on the Department of Defense effort, and could readily result in the need for the establishment of a new squadron of hurricane hunters and seeders dedicated to operational seeding.

The main impact of routine operational seeding can be anticipated in the socio-economic-legal field. Thus far there have been substantially no objections voiced to the R&D effort, primarily because it is limited to storms well out to sea, with no apparent implication for coastal areas. However, quite a different situation will prevail under an operational mode. The full extent of the problems that may be encountered and the actions required by the Federal Government prior to seeding have not been fully investigated. Many of these aspects were considered by SRI (see III-4). At the moment it appears that prior approval at very high levels of Federal, State and local governments would be required. Many of these problems would be of less concern if through further R&D the precise effects of seeding could be predicted. This is not possible at present.

NOAA is currently conducting cloud seeding in Central and Southern Florida in an attempt to relieve the severe drought situation. This work is in response to a request by the Governor of the State. Since, if the project is successful, some disbenefits might occur to certain agricultural interests, some valuable social and legal precedents might evolve. Further, NOAA is planning to undertake a major investigation of the social, economic and legal aspects of all phases of weather modification efforts.

The SRI study did recommend that, since a hurricane could intensify or change course after it is seeded, the hurricane modification program should be debated publicly and authorized by Congressional legislation. The recommended legislation should define the extent to which hurricane modification activities will be protected by sovereign immunity and define the basis under which the government can be held responsible for damage caused by seeding hurricanes. Initial action to seek such legislation is being taken under the auspices of ICAS.

The foregoing has presented only a generalized picture of the operational mode of hurricane modification as visualized today. It is based only on an estimate of possible operational activity and efforts as foreseen at present. Full-scale operations would be preceded by pilot operations and these would provide guidance in the establishment of the full operational configuration.

2. Budgetary Aspects

The costs of Project STORMFURY to NOAA vary from year to year because of the varying degree of research and flight activity which depend upon storm occurrences. During Fiscal Year 1970 costs were approximately $350 thousand. As mentioned in the preceding section it will be necessary to double our present RFF activity in support of the operational seeding. This will involve an annual cost of around $1 million. At the same time we will wish to increase our aircraft facilities and provide additional crew and flight operations to take care of simultaneous R&D. This will involve capital cost of around $14 million for two aircraft, additional operations of around $1 million and R&D of up to $1 million per year. As will be discussed the R&D will also require a fourth-generation computer facility at $1.8 million annually. Total increases are then $14 million capital expense, plus $4.3 million annually.

Regarding costs one fact does stand out, however; the saving in lives and property from one successful modification of a hurricane such as Camille would completely outweigh any probable cost of an operational endeavor.

The decision analysis study by SRI concluded that the uncertainty regarding modification should be reduced by a greatly expanded program of meteorological experimentation. A meteorological field experiment will give an expected savings of at least $10 million in property damage during a single hurricane season, at least 20 times the cost of the present type of field experiments.

3. STORMFURY Operational Criteria

It would be desirable to establish in advance the criteria to be used in determining when the experimental results of hurricane seeding were of such a positive nature as to warrant the conclusion that there was a high probability that the effects were real, and that practical application was justified by the high economic and social benefits anticipated. However there is no universal rule by which such a decision can be made.

Strictly objective criteria are difficult to establish. The decisions relating to operational seeding of hurricanes are concerned with three partially incommensurate "currencies": (1) the public dollar, (2) the Government dollar, and (3) public confidence in, and support for, a Government program of hurricane modification. The basic decision implicitly involves making a tradeoff between the above three currencies. While the SRI study is favorable toward operational seeding, it does not explicitly analyze or introduce these tradeoffs. The SRI study introduced the idea of "Government responsibility" costs and indicated these were significant; however, no detailed analysis of these are available.

In many areas of research, standard statistical design and tests are available to assist in reaching such a decision. The Salk Vaccine test is an example of an ambiguous test of this nature. However, in the case of hurricane modification, we are faced by limited knowledge of the natural variance of the significant parameters against which to weigh the significance of alterations following seeding trials. Further, there exists at present a very limited number of seeding experiments, and this limitation will probably continue for a considerable time into the future. It is estimated that application of a randomized test of the seeding hypothesis would require between 50 and 100 cases, which would take many years to achieve.

As in the analysis of the seeding experiments on Hurricane Debbie, the primary parameters for testing correspondence of experimental results with those predicted by the hypothesis include:

a. Increase in height of clouds seeded outside the eyewall area;

b. Decrease in strength of maximum winds following seeding;

c. Decrease in pressure gradient in the inner portions of the storm;

d. Increase in diameter of the storm's eye.

As mentioned, however, the evaluation of the significance of observed changes and the establishment of specific criteria for decisions regarding the extent of technological results achieved will be limited due to lack of knowledge of the natural variability of these parameters in unseeded storms.

In view of the limitations on experimental cases expected over the ensuing years, it will be important to extract the maximum amount of information from each experiment. One approach will be to monitor closely each of the steps in the physical process of modification specified by the hypothesis as leading to the final result - the decrease in maximum winds. Beginning with the 1971 hurricane season a C-130 aircraft belonging to the Research Flight Facility, will make possible measurements within the active supercooled layers of the storm, roughly between 20 and 30 thousand feet. Measurements will include:

a. Concentration and volume of supercooled cloud water;
b. Conversion of such layers into ice crystal clouds following the seeding;
c. Changes in the temperature structure of the storm.

Again, the interpretation of observed changes will be hampered by the uncertainties concerning the natural variability of cloud conditions. The new STORMFURY hypothesis is subject to radar verification. With proper radar surveillance the presence of seedable towers can be documented, their transformations after seeding can be noted and any significant expansion of the eyewall should become obvious from the radar data.

Additional criteria will be furnished by the development of more advanced and realistic computer models of the hurricane, and comparison of experimental results with predictions derived from such models. Of particular importance will be determinations of correspondence regarding:

a. Decreases in wind intensity;
b. Changes in direction of motion of the storms, if any.

The ultimate determination as regards scientific or technological results will be the general agreement of the scientific community that a specified probability of verified desired results has been achieved, and that the probability of unwanted results (increase in winds, change in direction of storm, etc.) is acceptably small.

Although it will be desirable to establish the full effects of hurricane seeding to a high degree of probability before converting to an operational mode, the possibility of extremely large economic and social benefits from the reduction in hurricane winds will be an important factor in deciding at what stage in the experiments to begin operations. Thus much reliance will be placed on the utilization of modern decision theory in combining incomplete experimental results and the associated uncertainties regarding successful modification with the vast benefits which could be realized if modification were possible. The application of decision theory to the problem of hurricane modification and the establishment of a rationale for decision making has been undertaken by the Stanford Research Institute for NOAA, and the results are summarized in III-4, above.

An important input to the making of practical decisions regarding operational status will be the extent of the benefits that can accrue, say, from a given percentage decrease in maximum winds as the result of seeding. Definitive data on this point are lacking at present. However, the Stanford Research Institute group has looked into this question and assembled at least a limited body of information. Full investigation of the matter will require a more extensive study than has been possible for Stanford.

4. Technological and Operational Competence

As described under III-1, an elaborate system has been developed for conducting STORMFURY experiments, involving close collaboration between Navy, Air Force, and NOAA flight operations. The seeding technology, using pyrotechnic devices, developed by the Naval Weapons Center at China Lake, California, has undergone progressive improvement over the years, and now represents what is believed to be one of the most efficient pyrotechnic generators of silver iodide seeding smoke particles in existence. Means have been developed for dispensing some 200 of these pyrotechnic canisters over a short period to seed the narrow sector of the hurricane lying just outside the ring of maximum winds.

5. Operational Status for 1971 Season

In spite of the apparently highly successful seeding of Hurricane Debbie during August 1969, where marked reductions of the maximum winds followed the seeding experiment, it is not considered that operational status has been achieved for the beginning of the 1971 hurricane season. No experiments were possible during the 1970 season. Thus the STORMFURY Advisory Panel believes that the experimental results to date are sufficiently discouraging to warrant further experimentation but cau tions against premature conclusions that these results provide an adequate scientific basis for the implementation of an operational seeding program. This conclusion is based on the following considerations:

a. The statistical sample remains small. Three hurricanes have been seeded thus far. In 1961 preliminary tests were conducted on Hurricane Esther The seeded portion of the eye wall faded from the radarscope, indicating either a change in liquid water to ice crystals or the replacement of large droplets by much smaller ones. In 1963 the project seeded Hurricane Beulah. Soon after seeding, the central pressure of the eye rose and the area of maximum winds moved away from the storm center. In August 1969, a much more prolonged experiment was conducted on Hurricane Debbie, with substantial decreases in maximum winds occurring following the seedings. Although these changes were in the direction called for by the seeding hypothesis, lack of sufficient knowledge of the natural variability of hurricanes precludes definite conclusions from being drawn as to the reality of the results being due to the seeding.

b. On the other hand, the SRI group concluded that the present evidence was sufficient to justify the seeding in an emergency of a hurricane approaching the U. S. coast, provided certain tactical considerations were fulfilled. The latter related to the predicted behavior of the storm, its intensity, and the probablé effects of seeding on precipitation. They also recommended that the present voluntarily adopted restrictions against seeding hurricanes nearing landfall be dropped, and that social acceptance of the program be sought. Their recommentation regarding the need for legislative backing has been mentioned above. See III-4 for further discussion.

c. There is concern that in certain cases seeding may cause an unwanted change in the direction of movement of the storm. This possibility has not been adequately investigated.

d. There are weaknesses in the computer simulation model used as one of the controls for the experiment. These are discussed elsewhere in this study, but include such matters as assumptions of symmetry in the model (where actual hurricanes are often quite asymmetrical, leading to marked varied interactions with the storm's environment); the assumptions and simplifications entering into the model regarding such important factors as sea-air interaction and the convective process; and the lack of consideration given to the cloud physics aspects of the seeded portion of the storm.

e. There is a general subjective feeling among the members of the STORMFURY Advisory Panel that further experimentation should precede operational seeding.

6. International Aspects

A. Introduction - It has become established policy, before conducting experiments that may meet with objections from foreign governments, to obtain assurance from the Department of State that there will be no valid objections raised by the affected governments. This requires transmittal of the project plans to the State Department representatives abroad who in turn notify the various governments.

B. Operational Seeding - Discussion of the International aspects of operational hurricane seeding will involve three separate situations:

(1) Seeding only those hurricanes which are moving into the U. S. mainland, and have almost zero possibility of affecting Cuba or Mexico;

(2) Seeding, in addition to (1), storms moving into Puerto Rico or the Virgin Islands;

(3) Seeding, in addition to (2), all hurricanes which threaten inhabited areas in the western North Atlantic, in order to extend the benefits of hurricane modification to foreign as well as domestic areas.

It is assumed that the established procedure to obtain approval for experiments will be followed also in the case of proposed operations.

In the first example, where the mainland of the U. S. only is intended to be involved, there will probably be no objections from any nearby foreign government. However, it should be remembered that hurricanes have on occasion entered the U. S. only to move later into a foreign country. For example, Beulah (1967) entered the U. S. Gulf Coast but moved up the Rio Grande Valley and crossed into Mexico.

Extension of seeding for the protection of Puerto Rico and the Virgin Islands would almost certainly require the specific approval of the neighboring governments, in view of their close proximity. The Department of State would be requested to negotiate special authorizations in this case.

Further extension of the program to the seeding of all hurricanes threatening populated areas, domestic and foreign, would require the prior general approval of the governments involved, followed by specific requests for seeding on each occasion of a threatening hurricane. Groundwork for such a program could probably be laid through the Region IV Association of the WMO.

C. <u>The Need for Further R&D</u> - Thus far no government has objected to our experiments under Project STORMFURY. If objections were raised in the future, it is not clear at what point our plans, either for experiments or operations, would be altered or dropped. As mentioned above, it seems highly unlikely that serious objection would be raised to U. S. mainland seeding. However, if operations are substantially expanded it is possible that at some point objections would be raised. The best way to avoid this will be to be able to demonstrate very convincingly that the seeding has only the desired effect and that there is a minimal chance of unwanted side effects. This will require an extensive body of further experimental work, so that it will be of the utmost importance to continue and intensify the experimental aspects of Project STORMFURY, even though operations are also conducted.

7. Legal Aspects

The legal aspects of weather modification include a broad spectrum of questions, including: the rights of underlying property owners to clouds and potential precipitation over their land; possible trespass by the prospective modifier; question of nuisance when a modifier casts chemicals or other substances over property of another; and the proprietary interest of a land holder generally in the airspace over his property. The principal facet of weather modification activities of interest to the legal profession, continues to be the questions relating to potential liability in connection with modification activities, particularly excessive rainfall.

Though there are no Federal claims or liability statutes pertaining particularly to weather modification activities, a number of Federal claims statutes might, under appropriate circumstances, be relied upon if litigation or settlement were considered appropriate in a given case.

It may be anticipated that in the event of substantial losses, the Federal Tort Claims Act (28 USC 1346b), would most probably be the statutory vehicle through which compensation would be sought.

An essential requirement of that Act is a finding that the sovereign immunity of the Government has been waived with respect to the particular activity. Among other things, the Act specifically excepts "discretionary functions." While that exception has been limited in a number of cases, nonetheless, in a suit for recovery of damages arising out of the Texas City disaster, for example, it was held that the activities being carried out did not fall within the waiver of sovereign immunity provisions of the Federal Tort Claims Act.

That Act also requires that the plaintiff establish causation between the acts of the Government representative and the damage sustained. In a number of the reported cases, suits were dismissed for failure to establish this essential ingredient. However, as the state-of-the-art increases, it may be anticipated that expert testimony would be available to establish such chain of causation.

Another requirement of the Federal Tort Claims Act is that negligence be shown by the plaintiff. Here another factual determination would be required establishing that the project was carried out without due regard for the persons and property of others, and in a careless and negilgent manner.

While much has been written on the liability aspects of weather modification, no unequivocal statement can be made with respect to the Government liability for damages which might possibly arise from engaging in such experiments. The existing body of case law on the subject tends to support the conclusion that the United States would not be pecuniarily liable for damages resulting from weather modification activities conducted pursuant to the existing statutory authorization.

8. Alternatives to Operational Modification

A. Improved Forecasts - Improved forecasts of where a hurricane will strike a coastal area would reduce the expense of unnecessary preparations performed in places not affected by hurricane force winds. However, it would not reduce the damage where the hurricane force winds strike. It is a matter of record that even with excellent warnings, villages and resort areas have been virtually destroyed by the more severe hurricanes. Modification of these severe hurricanes could at least reduce some of the damage. The average annual damage from hurricanes in the United States is about $400 million. The value would be $200 million if one were to consider only a single hurricane. There are, on the average, about three hurricanes every two years that move onshore or close enough to produce hurricane conditions over a significant area.

In the case of minimal or moderate storms, a good forecast can help to minimize the losses. A poor forecast issued too late, or when too few people are warned, or when too many are over-warned, can add to costs. In an article entitled, "Economic Aspects of Hurricanes," Sugg (22) stated that the cost of unnecessary warnings (protection, evacuations, and special interests) could amount to nearly $7 million for an average hurricane season. In fairness to the hurricane warning service, it should be mentioned that the warning service saves in excess of $32 million while spending or causing to be spent $7 million during an average season.

The history of hurricane forecasting shows that there has been improvement in forecasts from virtually no warning during the first and second decades of this century to the current 24-hour displacement error of the center locations of the storms of about 100 nautical miles. It is considered that there is considerable potential for improving the accuracy of prediction of hurricane motion through the development of more advanced mathematical models and improved analyses of tropical conditions through the use of satellite data. The immediate goal is to reduce displacement error to the order of 75 miles over the next several years. Our hope for the future is to achieve maximum benefits through a combination of improved forecasting and significant moderation.

B. <u>Revised Construction Practices by Public</u> - While striving to modify hurricanes and to improve forecasting, emphasis should be placed on encouraging better building codes patterned after those in Dade County, Florida. More counties and states vulnerable to hurricanes should adopt these proven building codes.

V. FUTURE DIRECTIONS

1. Improvements in Program Generally

The apparent success of the 1969 experiments on Hurricane Debbie has brought new urgency to the work and increased pressure for additional experiments. The decision analysis study by SRI concluded that the uncertainty regarding modification should be reduced by a greatly expanded program of meteorological experimentation, as has been mentioned. More experiments are urgently needed and the possibility of moving the program to the Western Pacific will be discussed below. Further, because of the low number of opportunities under any conditions, we must choose advisedly between repeating the identical experiment and making modifications to the experiment in the light of additional experience and knowledge.

One of our major objectives at present is to ferret out change which the seeding should, as indicated by theory, computer models, or inductive reasoning, introduce into the storm. We must then plan to observe the occurrence or non-occurrence of any such changes during the seeding experiment. If enough of these detailed effects can be proposed and documented in actual experiment, very few experiments will be necessary to prove or disprove the basic hypothesis and its implications. However, certain changes appear advisable even if experiments nearly identical to those conducted on Hurricane Debbie are run. These include:

a. A longer period of monitoring both before and after seedings in order to document fluctuations in particular storms and their gradual return to "nature's own."

b. The monitoring should be conducted at about 5,000 ft. or lower to ensure that any beneficial effects are reflected at fairly low levels where the effects are desired.

c. We should fully exploit the newly acquired C-130 aircraft to obtain the cloud physics documentation of conditions around the 25,000 ft. (-15°C level) as to: the amounts of supercooled droplets, their phase change to ice after the seeding, and the accompanying temperature or temperature gradient changes.

We should also consider making changes in the experiment which we might expect to enhance the likelihood of producing the desired effects or adding to our knowledge. These at present include:

a. Seed for 18 hours instead of 8.

b. If and when the ring of maximum winds moves out, then move the seeding out with it.

c. Seed every hour with half the current number of pyrotechnic devices.

d. Seed a rainband significantly removed from the eyewall or do a sector seed at a fairly large radius (i.e., seed at 45° sector from radius 50 to radius 75 n.mi.). (See figure 7.)

e. Seed both sides of the storm, each side with half the current number of pyrotechnics.

f. Seed with the DC-6's using silver iodide burners and seed as often as the C-130 monitor at 25,000 feet suggests the presence of enough supercooled water to warrant it.

g. Can we overseed and what is the result? Use two or three times as many pyrotechnic devices and try to determine the difference in effect from that of normal seeding.

h. Can and should we time our seeding with "natural pulsations" of the eye? We could try seeding as the innermost band or wall-cloud is collapsing and try seeding the outer portion of the succeeding band.

i. Expand the seeding--do not confine it to the "outer wall cloud;" seed every promising area outside of the wall as well as the outer wall itself.

j. Seed at higher altitudes and compare effects (if data show presence of adequate supercooled water).

As discussed under Section II-3 (Theories of Hurricane Modification), other possible approaches to hurricane moderation have been proposed. Among these are the use of thin films spread in the path of the hurricane to reduce evaporation and frictional drag, and the release of tiny dark plastic bubbles into the updraft to discolor the cirrus shield and disturb the radiation balance of the storm area. Attention is being given to both of these proposals and it is expected that the engineering problems will receive specific attention over the next several years.

2. Moving STORMFURY to the Pacific

Consideration for a number of years has been given to the desirability of moving Project STORMFURY experimentation to the Western Pacific, where the number of typhoos greatly exceeds the number of hurricanes in the North Atlantic. The importance of such a move has been emphasized by the almost total lack of hurricanes eligible for seeding under STORMFURY criteria during previous seasons--far less than could be expected climatologically. Since its establishment in 1962, the Project has seeded only two hurricanes. Further relaxation of the seeding eligibility rules would add little to increasing the research average opportunity of two eligible hurricanes per year. Such further reductions in the eligibility limitations would be just one step away from operational seeding where storms might be continuously seeded as they approach a land area. Until more is known about artificial modification of hurricanes, we cannot hope to monitor the changes induced by the experiments against a background which includes landfall natural storm modification effects.

Studies have been completed which show that, if operations could be conducted from both Guam and Okinawa, opportunities for seeding in the Western Pacific would be, on the average, much greater than in the Atlantic region. An average of at least six opportunities could be anticipated during only a three-month operation period in the late summer. Field experimentation could be accelerated by at least a factor of three. It was for this reason that a move to the Pacific was endorsed by the 12th Annual Interagency Conference on Weather Modification, the STORMFURY Advisory Panel, and by the SRI study.

At present extensive planning is under way for a move to the Pacific as early as the summer of 1972, with operations taking place during August, September and October. A final decision will depend upon the availability of funds, facilities and bases, and on the favorable response of the interested nations in the area. The World Meteorological Organization and the U. N. Commission on Asia and the Far East will be kept informed of the proposed experimental program, and the cooperation of interested nations will be solicited. It is presently estimated that the additional cost to NOAA will be of the order of $1.7 million per season. This funding is scheduled to come from the increases requested in the 1972 and 1973 budget requests.

3. Improved Numerical Modeling

At the present time, the biggest unsolved problem we have in the hurricane modification project is the evaluation of results. This is due to the fact that changes in experimental hurricanes are rarely larger than the changes which sometimes occur in non-modified storms. So long as this is true, it is very difficult to identify the portion of the changes caused by the modification experiment and those that occurred naturally. If a theoretical model could predict that changes would occur in one sequence or of a certain magnitude in a modified storm, but occur in a different sequence or of a different magnitude in a non-modified storm, we would have a tool invaluable for evaluating the results. Its indications could be used when deciding which data should be collected in the field experiments.

A successful model can also be invaluable in giving a preliminary test to new ideas for modification. It is very desirable to run the preliminary tests with the model on a computer. This makes it unnecessary to wait for nature to produce a hurricane, or to risk lives of those flying into the storm; and it is much cheaper than the field experiments.

A conference was held in Miami, March 13, and 14, 1970, to discuss what improvements should be made in the models of hurricanes.

The group was very complimentary of the model that has been developed at the National Hurricane Research Laboratory, but did offer several suggestions as to what should be done in the future. These suggestions were primarily directed at removing restrictive assumptions made in the current model. They recommended that models be developed which would provide for more of the asymmetries that occur in hurricanes and that would simulate interaction between the hurricane and its environment. They also recommended that research be continued to develop better physical interpretations of the various parameterizations used in the current models. Progress has been made along the suggested lines and is reflected in the previous discussion of the current state of hurricane modeling (III-3).

The relatively successful hurricane models now in use all assume circular symmetry. This permits reducing the model to two dimensions and greatly reduces the computer time requirements. If one takes a quick glance at hurricane charts, one may be impressed with the symmetries. Closer examination reveals, however, that there are many asymmetries in the circulations, and that some of them can be very important. When a storm is moving, for example, the winds will be stronger on the right side of an observer in the center of the storm facing in the direction of the movement. If movement of the storm is to be either simulated or forecasted, therefore, asymmetries must be provided for. In real storms the inflow at low levels is usually stronger in one quadrant than in the others. This may be very important because it affects which of the circulations around the hurricane has the most influence on its development. The nature of the interactions with the surrounding circulations, furthermore, may determine whether the hurricane intensifies or dissipates. So long as the hurricane is modeled without regard to its environment, one gets, at best, only a mean state of the hurricane development. However, the isolated asymmetric model is now at hand.

As mentioned in Section III-3, significant progress has already been made in the numerical simulation of hurricanes and the present model simulates many of the stages, phases and processes which we know from observations characterize the hurricane. The research is progressing in three steps: (a) development of a circularly symmetric model which provides for little or no interaction with the ambient environment, (b) development of a 3-dimensional model which again provides for little or no interaction, and makes no provision for hurricane movement, and (c) development of a 3-dimensional model which includes interaction with at least the principal features of the nearby environment and provides for prediction of hurricane movement.

At present work is moving forward on stage (b) above. Although our research is ultimately aimed at stage (c), we feel that it is desirable to proceed through stage (b) as a preliminary step. One reason for this is that we do not presently have computer time available to work on stage (c). Computer time for the second phase is roughly 10 to 50 times as much as that required for the first phase. Development of the final phase will require 10 to 50 times as much capability as the second phase. Each phase also adds an additional set of complexities and problems that must be solved. Each succeeding phase builds on the successes achieved under the preceding stage.

In efforts to economize on computer time, we have investigated variable grids. In a hurricane, a storm in which wind speeds, pressures and temperatures all vary rapidly in short distances, it is necessary to make computations at grid points much more closely spaced than would be true when modeling for a middle latitude storm. Well away from the hurricane center, however, the values of the parameters do not change so rapidly with distance and grid points do not need to be so densely spaced. This suggests having a grid with variable spacing. Research is underway on this sub-problem. Dr. R. A. Anthes has developed one variable grid, tested it, and prepared a report for publication. A second grid has been developed and compared with the first for efficiency and accuracy.

Better physical understanding is needed for some of the processes simulated by the hurricane models. Energy and momentum are transferred between the ocean and the atmosphere, and they are transferred upward through the atmosphere by motions on the scale of cumulus clouds. In addition, energy is converted from one form to another in the clouds. Many of these and other processes are poorly understood, and all of them are so detailed that they cannot be entirely represented in a hurricane model. At the present time, simple pragmatic parameterizations are used to represent some of these. The best means of judging whether they are good is to see if the model produces something that looks like a hurricane. The answer is yet, many features of a hurricane are reproduced remarkably well by the circularly symmetric models. We still do not know, however, whether the processes are parameterized correctly. Two different parameterizations may be in error with the errors cancelling each other. This could cause trouble in trying to simulate modification experiments in the model, if our simulation affects only one of the parameters. Further progress in removing these restrictive assumptions will have to await results of further basic research.

Prime emphasis will be placed on the development of the 3-dimensional models. In addition, however, the present symmetric model will be exploited to the utmost. The research will include:

a. Development of a more sophisticated cloud representation to be used with the 7-level symmetrical model.

b. Use of this new cloud representation to simulate the experiments.

c. Simulation of the seedings with the asymmetric model.

d. Possible use of a variable mesh for the asymmetric model for more economical computing.

e. Removal of the stationary, isolated vortex assumptions in the asymmetric model to permit interaction with a moving environment.

In addition, it will be interesting to see if the simulated hurricane has a natural reaction time and, if so, whether it can be exploited by timing the seeding to produce instabilities, or in other words to try periodic seeding at various periods.

The computer simulation work represents an extremely important phase of hurricane modification research, and as outlined in the foregoing discussion will have a high priority in the future research effort of NOAA. However, major progress can be expected only if adequate computer capability is provided. At present it is necessary to share time on an operational computer at the Suitland facility, and conflicts with operational use of this facility are a major stumbling block to progress. Work at the National Hurricane Research Laboratory is now reaching the point where one full shift of a CD-6600 or equivalent could be used, and it is recommended that support of this nature be provided at the earliest opportunity.

4. Studies to Support "Tactical" Decision

The decision-analysis study by Stanford Research Institute (SRI) refers to "strategic" decisions, i.e., whether there are any circumstances under which operational seeding should be permitted, and "tactical" decisions, i.e., the specific situations under which operational seeding should be performed. SRI indicates that the tactical decision to seed operationally in specific situations deserves additional study with particular emphasis on (1) possible changes in the track, size, intensity, and precipitation pattern of the hurricane resulting from seeding, and (2) the synoptic environment and other factors that influence the predicted behavior of the hurricane.

The SRI conclusion implies that on rare occasions operational seeding could be justified at the present time for those hurricanes that present a severe threat; this would include very large and very intense hurricanes that are headed directly toward a large metropolitan area.

To justify operational seeding of hurricanes in other than the most extreme cases, it is also necessary, to study in more detail the expected benefits or reduction in total damage. This would include the damage from storm surges, winds, and flooding. The study should also include the effects of population density and industrial development along the track of a hurricane.

Storm surges cause a substantial part of the total hurricane damage. As a result studies relating storm surge to coastal features and hurricane characteristics are of special importance. Such studies are now being carried out by the National Weather Service. Because seeding increases the total energy of the hurricane and also changes the distribution of energy within the hurricane, there is a possiblity that seeding could increase the storm surge. Present studies indicate that for a long straight coastline the storm surge will decrease as the maximum winds decrease. However, for certain coastline configurations the studies indicate that the storm surge will increase as a result of a decrease in the maximum winds. Continued studies along these lines will be required to support a tactical decision on whether to seed a particular hurricane headed toward a particular coastal area. Before a particular hurricane is seeded fairly accurate predictions of the storm surge along the coastal areas should be available for both, the seeded and the unseeded hurricane.

After studies such as the above have been completed, there will still remain some uncertainty regarding the effects of seeding and regarding the government liability. This will be true even in the case of extremely threatening hurricanes. Executive judgment will still be necessary to attempt to balance the expected savings to the public and the risk of losing some support for the program in the event that a seeding operation did not appear to reduce the damage or that seeding appeared to intensify the hurricane.

References

1. Hawkins, H. F. and D. T. Rubsam, "Hurricane Inez - A Classic 'Micro-Hurricane'" Mariners Weather Log, vol. 11, No. 5, Sept. 1967, pp. 157-160.

2. "Hurricane Camille, August 14-22, 1969 - Preliminary Report", ESSA, Weather Bureau, Dept. of Commerce, Sept. 1969, 58 pp.

3. Sugg, A. L., "The Hurricane Season of 1965", Monthly Weather Review, vol. 94, No. 3, March 1966, pp. 183-191.

4. Simpson, R. H., A. L. Sugg and Staff, "The Atlantic Hurricane Season of 1969", Monthly Weather Review, vol. 98, No. 4, April 1970.

5. Hawkins, H. F. and D. T. Rubsam, "Hurricane Hilda, 1964, II Structure and Budgets of the Hurricane on October 1, 1964", Monthly Weather Review, vol. 96, No. 9, Sept. 1968, pp. 617-636.

6. Gray, W. M., "Global View of the Origin of Tropical Disturbances, and storms", Monthly Weather Review, vol. 96, No. 9, October 1968, pp. 669-700.

7. Riehl, H. and R. C. Gentry, "Analysis of Tropical Storm Frieda, 1957, Preliminary Report", National Hurricane Research Project Report No. 17, U.S. Department of Commerce, June 1958.

8. Gentry, R. C., "Nature and Scope of Hurricane Damage", Hurricane Symposium, Publ. No. 1, American Society for Oceanography, 1967.

9. Simpson, R. H., Mr.R. Ahrens and R. D. Decker, "A Cloud Seeding Experiment in Hurricane Esther, 1961", National Hurricane Research Project Report No. 60, U. S. Department of Commerce, April 1963, pp. 1-30.

10. Rosenthal, S. L., Manuscript currently in preparation describing results of computer calculated hurricane seeding simulation experiments on a model hurricane, to be published in the Monthly Weather Review.

11. Bean, B. R. and Q. L. Florey, "A Field Study of the Effectiveness of Fatty Alcohol Mixtures as Evaporation Reducing Monomolecular Films", Water Resources Research, 4, 1968, pp. 206-208.

12. Ooyama, K., "Numerical Simulation of the Life Cycle of Tropical Cyclones", Journal of Atmospheric Sciences, vol. 26, January 1969, pp. 3-40.

13. Leipper, D. F., "Observed Ocean Conditions and Hurricane Hilda, 1964", Journal of Atmospheric Sciences, vol. 24, No. 2, March 1967, pp. 182-186.

14. Gentry, R. C., "Hurricane Debbie Modification Experiments, August 1969", Science, vol. 168, April 24, 1970, pp. 473-475.

15. Black, P. G., H. V. Senn, and C. L. Courtright, 1971: Some Airborne Radar Observations of Precipitation Tilt, Bright Band Distribution and Eye Configuration Changes During the 1969 Multiple Seeding Experiments in Hurricane Debbie. Submitted for publication in the Monthly Weather Review.

16. Hawkins, H. F., "Comparison of Results of the Hurricane Debbie (1969) Modification Experiments with Those from Rosenthal's Numerical Model Simulation Experiments, "Monthly Weather Review, 1971 (to be published).

17. Rosenthal, S. L., "A Survey of Experimental Results Obtained from a Numerical Model Designed to Simulate Tropical Cyclone Development. ERLTM-NHRL Technical Memorandum No. 88, NOAA, U. S. Dept. of Commerce, NHRL, Miami, Fla., 1970, 78 pp.

18. Rosenthal, S. L., "The Response of a Tropical Cyclone Model to Variations in Boundary Layer Parameters, Initial Conditions, Lateral Boundary Conditions and Domain Size". Accepted for publication in the Monthly Weather Review, 1970.

19. Rosenthal, S. L., "A Circularly Symmetric, Primitive Equation Model of Tropical Cyclones and Its Response to Artificial Enhancement of the Convective Heating Functions". Accepted for Publication in the Monthly Weather Review, 1970.

20. Anthes, R. A., S. L. Rosenthal and J. W. Trout, "Preliminary Results from an Asymmetric Model of the Tropical Cyclone. Accepted for publication in the Monthly Weather Review, 1970.

21. Anthes, R. A., J. W. Trout and S. L. Rosenthal, "Comparisons of Tropical Cyclone Simulations with and without the Assumption of Circular Symmetry". Accepted for publication in the Monthly Weather Review, 1970.

22. Sugg. Arnold L., "Economic Aspects of Hurricanes," Monthly Weather Review, vol. 95, No. 3, March 1967, pp. 143-146.

Illustrations

Figure 1. Wind speeds recorded by airborne Doppler in a very strong, small hurricane. Note winds of 170 knots less than 10 miles from the center of the vortex which is denoted by the hurricane symbol.

Figure 2. Low-level air spirals in towards the wall cloud of the hurricane picking up moisture and heat from the sea surface. It rises, condensing in the cloud towers of the spiral bands and the wall cloud and is borne out in the cirrus shield.

Figure 3. A partially idealized sketch (of a radar picture) of Hurricane Betsy, 1965, when it was closest to Miami. The features shown are actively precipitating elements which outline the backbone of the hurricane's structure.

Figure 4. Temperature departures from normal within 8 n.mi. of Hurricane Hilda. Temperatures were 16°C warmer than normal at the 35,000 foot level over the eye of the storm.

Figure 5. Profiles of wind speed against radius comparing a hurricane with a tropical storm. Solid curve is tropical storm Frieda (September 23, 1957). Dashed curve is a hypothetical hurricane wind profile which fits well the circles which denote observed winds in Hurricane Daisy (August 26, 1958). The areas beneath the two curves; i.e., the total kinetic energies of the two storms, are about equal.

Figure 6. Trends of losses from hurricanes in the United States.

Figure 7. Project STORMFURY planned experiments. (EYEMOD, RAINSECTOR, RAINBAND)

Figure 8. Profile of wind speeds across Hurricane Debbie before, during, and after seeding, August 18, 1969.

Figure 9. Profile of wind speeds across Hurricane Debbie before and after seeding, August 20, 1969.

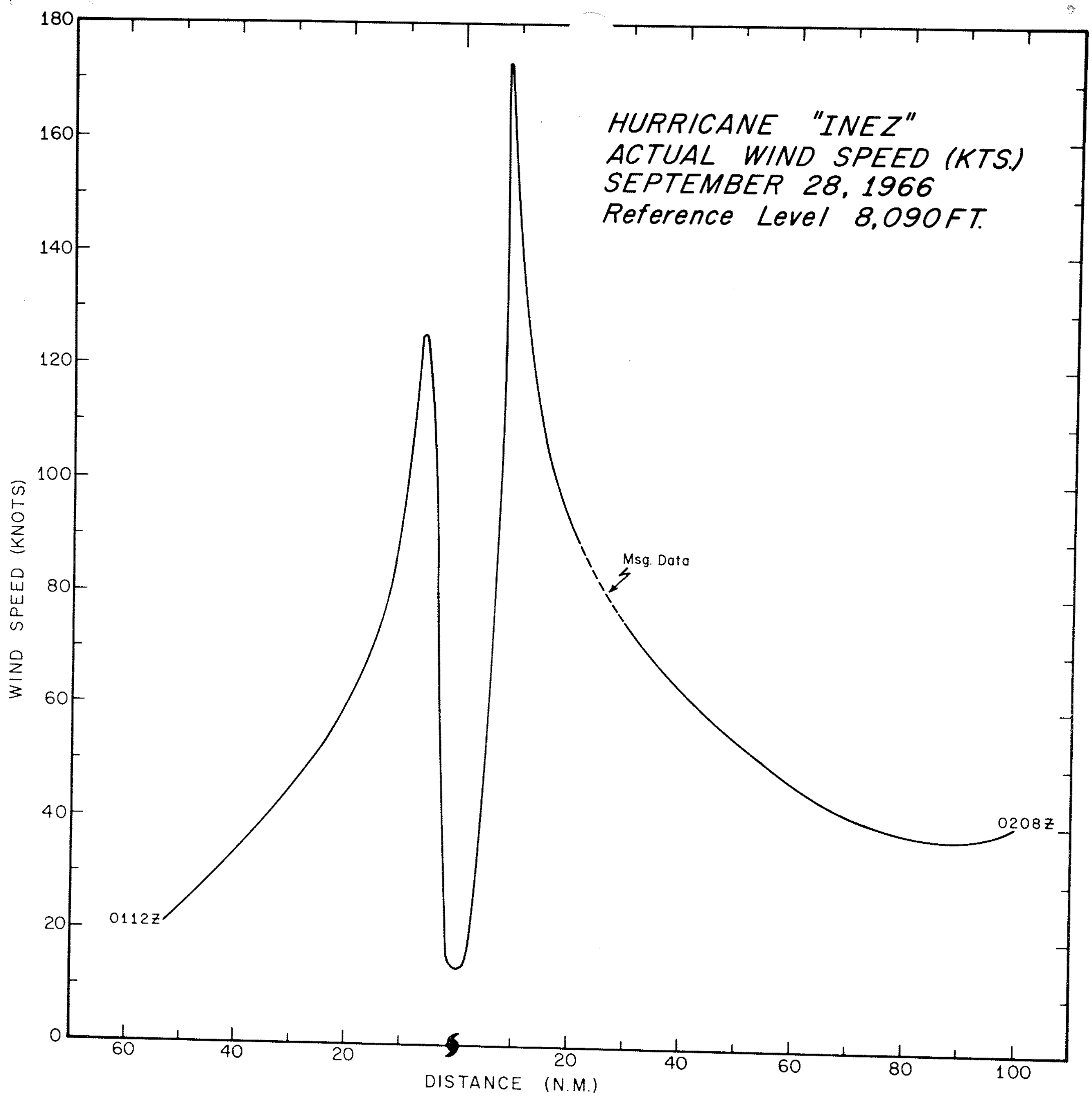
HURRICANE "INEZ"
ACTUAL WIND SPEED (KTS.)
SEPTEMBER 28, 1966
Reference Level 8,090 FT.
Msg. Data
0112Z
0208Z
WIND SPEED (KNOTS)
DISTANCE (N.M.)
180
160
140
120
100
80
60
40
20
0
60
40
20
20
40
60
80
100

Figure 1.

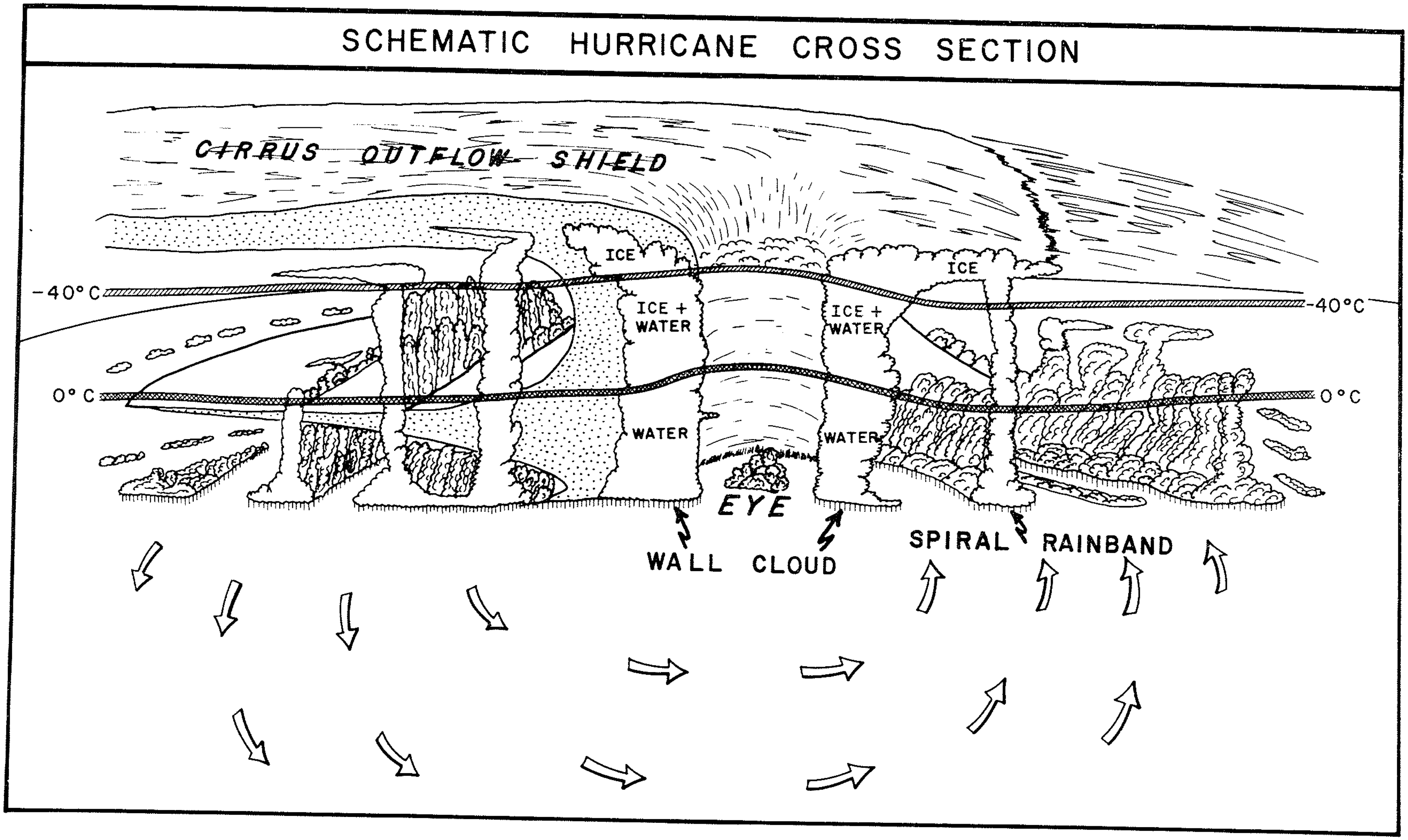
SCHEMATIC HURRICANE CROSS SECTION
CIRRUS OUTFLOW SHIELD
ICE
ICE + WATER
WATER
ICE
ICE + WATER
WATER
ICE
-40°C
0°C
-40°C
0°C
EYE
WALL CLOUD
SPIRAL RAINBAND

Figure 2.

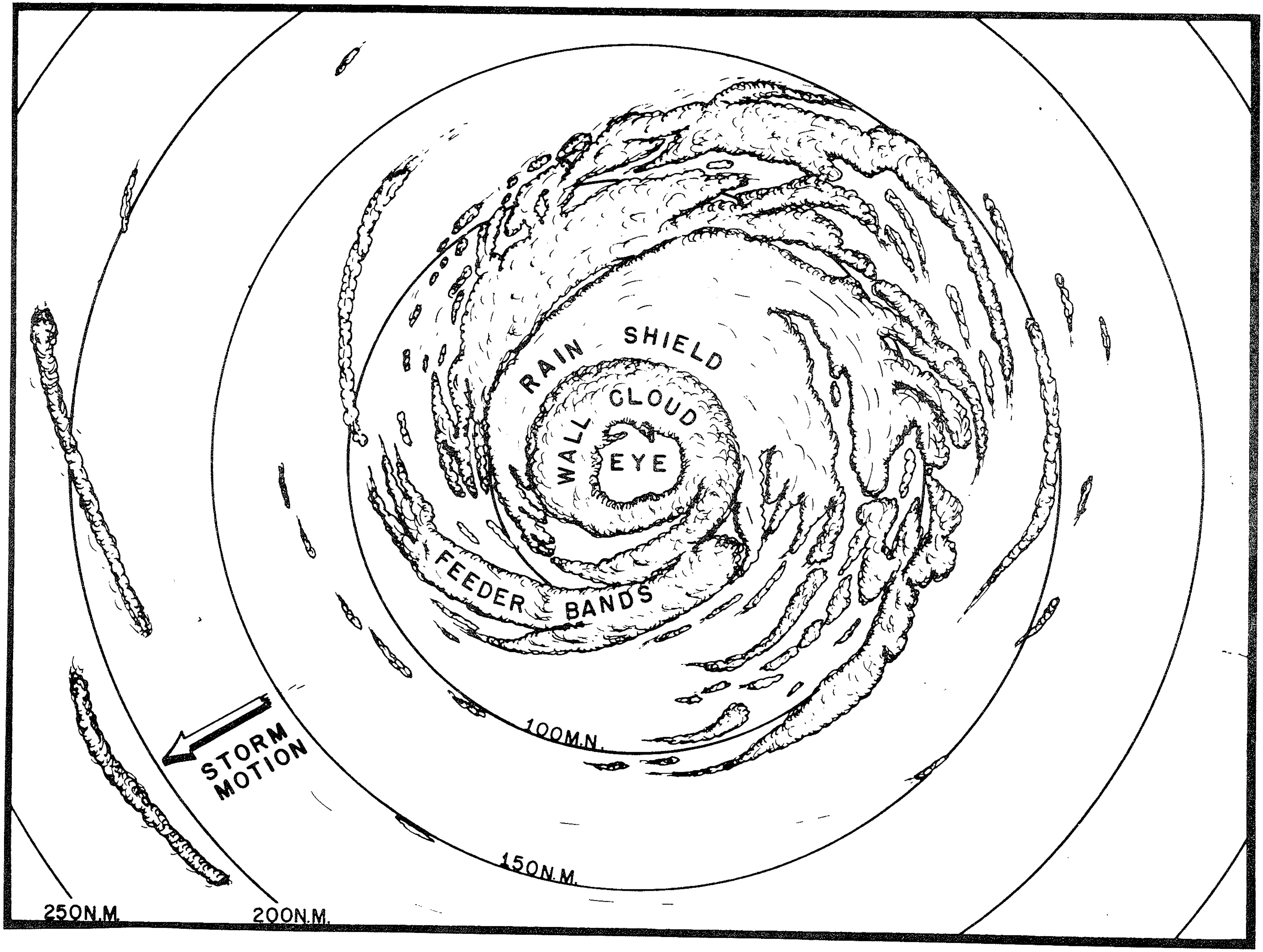
RAIN SHIELD
CLOUD
WALL
EYE
FEEDER BANDS
STORM MOTION
100M.N.
150N.M.
200N.M.
250N.M.

Figure 3.

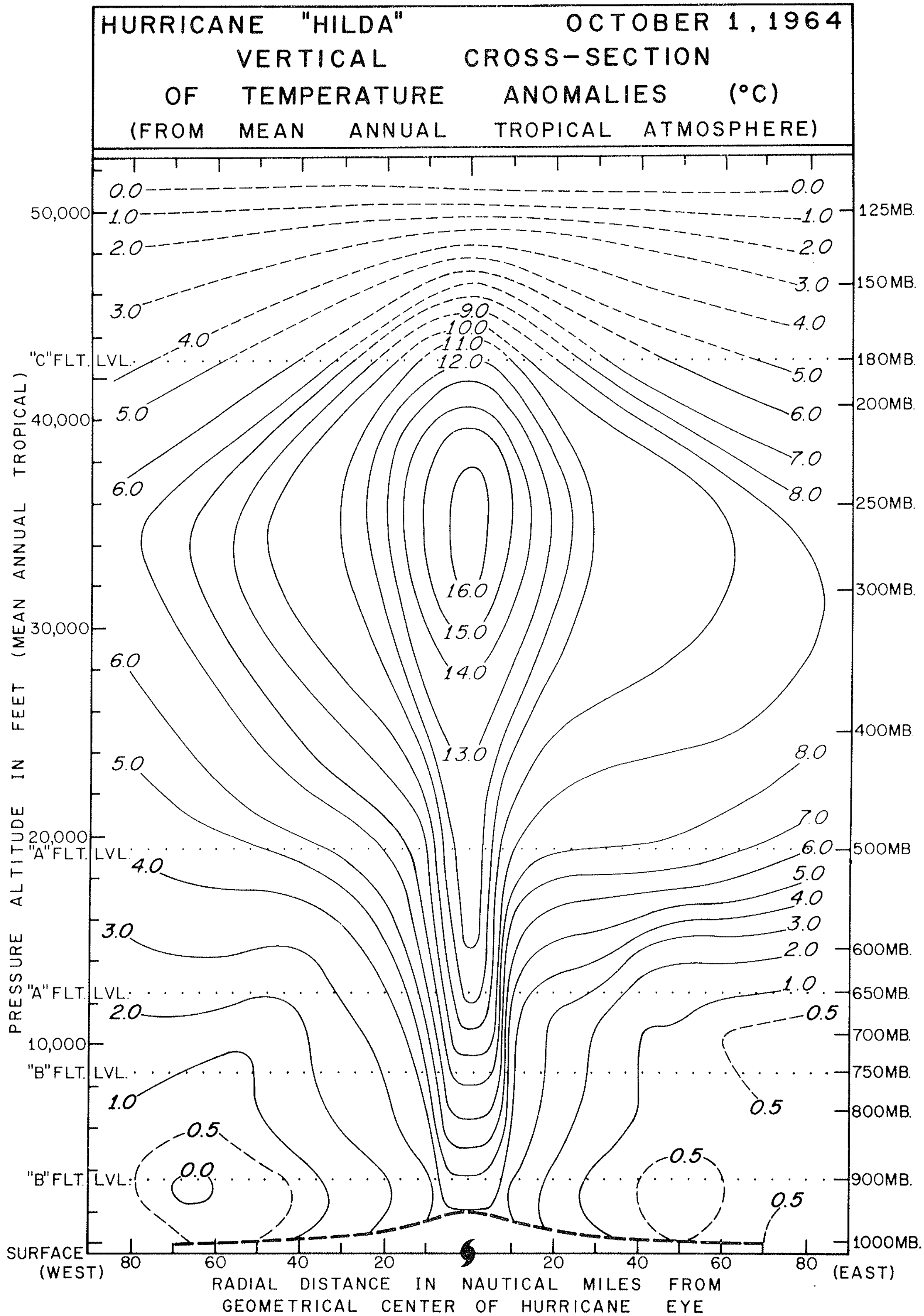
HURRICANE "HILDA" OCTOBER 1, 1964
VERTICAL CROSS-SECTION
OF TEMPERATURE ANOMALIES (°C)
(FROM MEAN ANNUAL TROPICAL ATMOSPHERE)
PRESSURE ALTITUDE IN FEET (MEAN ANNUAL TROPICAL)
50,000
40,000
30,000
20,000
10,000
SURFACE
"C" FLT. LVL.
"A" FLT. LVL.
"A" FLT. LVL.
"B" FLT. LVL.
"B" FLT. LVL.
125MB.
150MB.
180MB.
200MB.
250MB.
300MB.
400MB.
500MB
600MB.
650MB.
700MB.
750MB.
800MB.
900MB.
1000MB.
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
0.5
(WEST) 80 60 40 20 20 40 60 80 (EAST)
RADIAL DISTANCE IN NAUTICAL MILES FROM
GEOMETRICAL CENTER OF HURRICANE EYE

Figure 4.

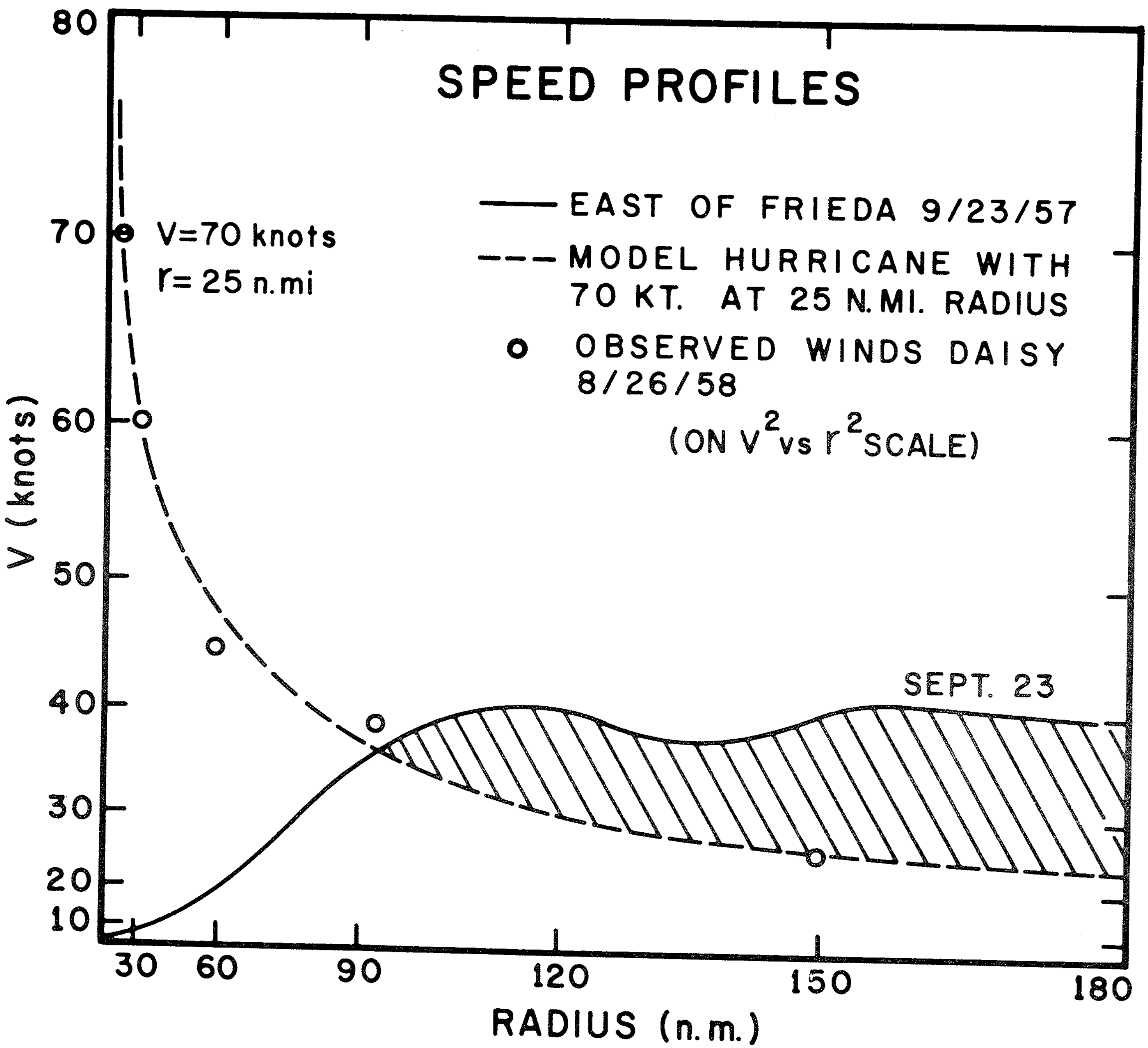
SPEED PROFILES
EAST OF FRIEDA 9/23/57
MODEL HURRICANE WITH 70 KT. AT 25 N.MI. RADIUS
OBSERVED WINDS DAISY 8/26/58
(ON V^2 vs r^2 SCALE)
V=70 knots
r= 25 n.mi
SEPT. 23
V (knots)
RADIUS (n.m.)
80
70
60
50
40
30
20
10
30
60
90
120
150
180

Figure 5.

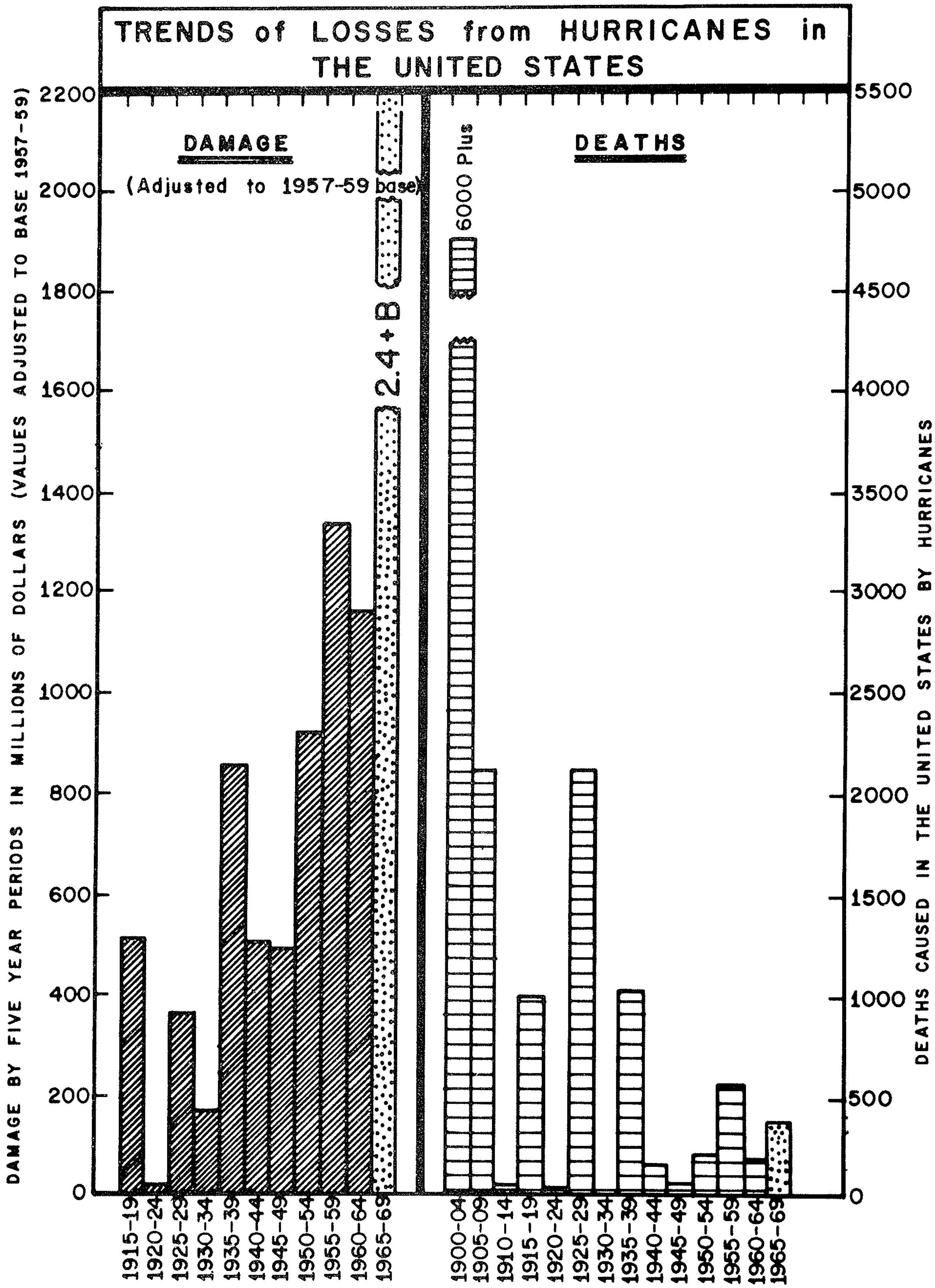
TRENDS of LOSSES from HURRICANES in THE UNITED STATES
DAMAGE
(Adjusted to 1957-59 base)
2.4+B
DEATHS
6000 Plus
DAMAGE BY FIVE YEAR PERIODS IN MILLIONS OF DOLLARS (VALUES ADJUSTED TO BASE 1957-59)
DEATHS CAUSED IN THE UNITED STATES BY HURRICANES
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
1915-19
1920-24
1925-29
1930-34
1935-39
1940-44
1945-49
1950-54
1955-59
1960-64
1965-69
1900-04
1905-09
1910-14
1915-19
1920-24
1925-29
1930-34
1935-39
1940-44
1945-49
1950-54
1955-59
1960-64
1965-69

Figure 6.

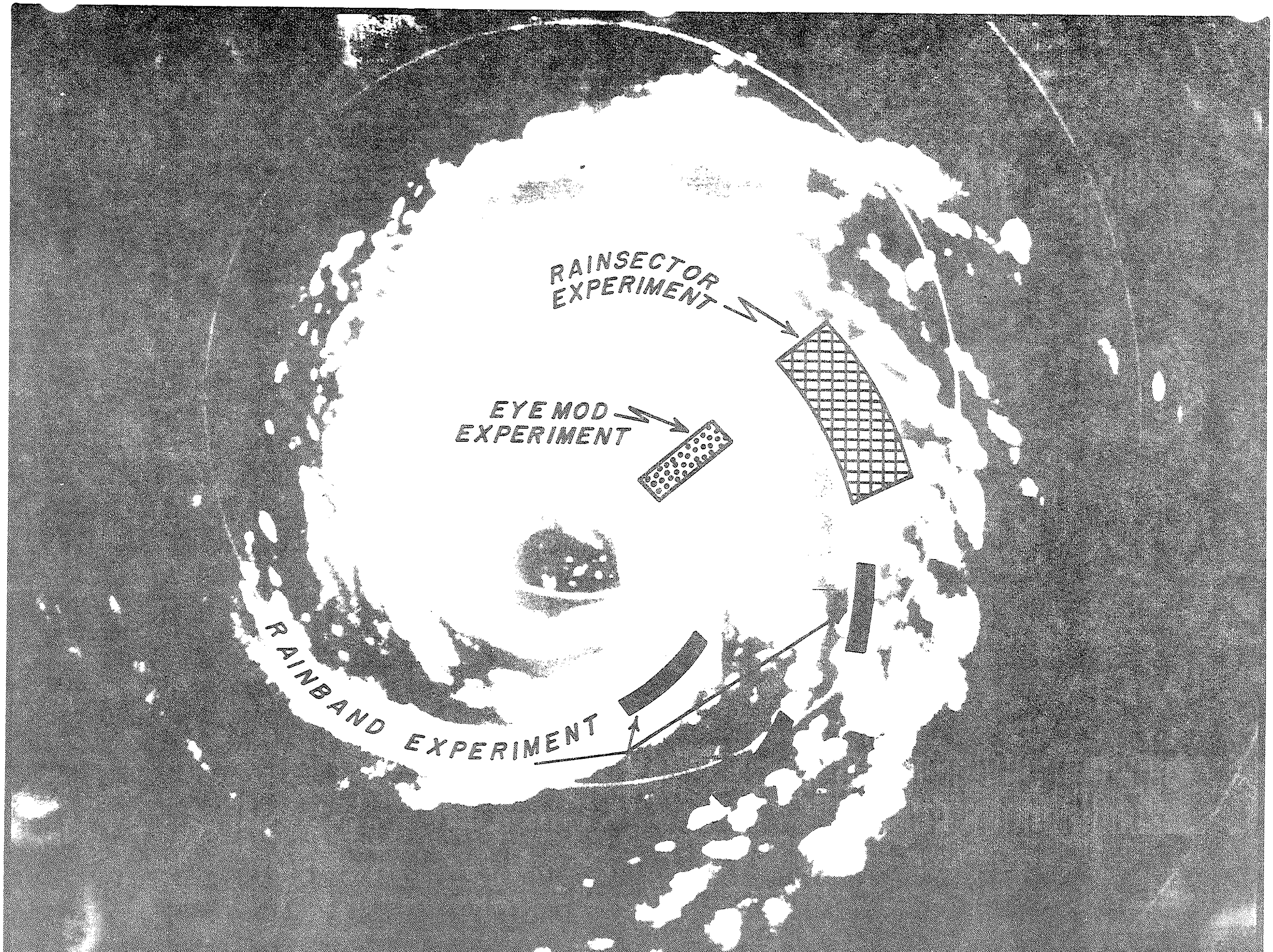
RAINSECTOR EXPERIMENT
EYE MOD EXPERIMENT
RAINBAND EXPERIMENT

Figure 7.

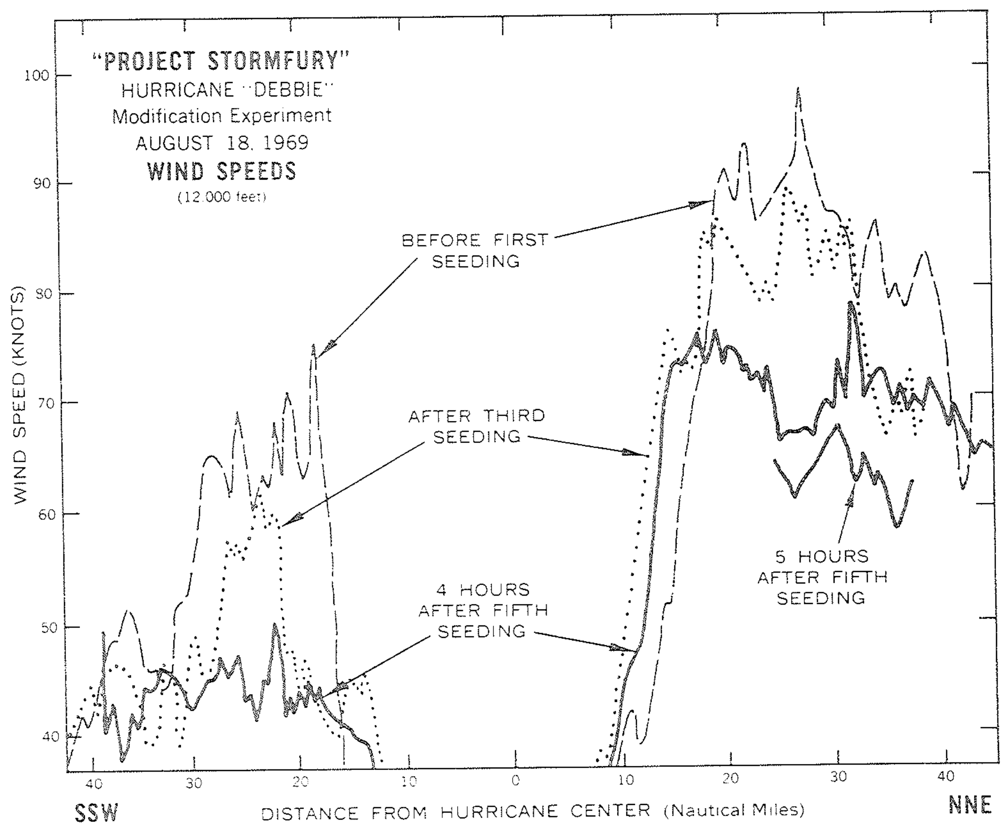
"PROJECT STORMFURY"
HURRICANE "DEBBIE"
Modification Experiment
AUGUST 18, 1969
WIND SPEEDS
(12,000 feet)
WIND SPEED (KNOTS)
100
90
80
70
60
50
40
BEFORE FIRST SEEDING
AFTER THIRD SEEDING
4 HOURS AFTER FIFTH SEEDING
5 HOURS AFTER FIFTH SEEDING
40
30
20
10
0
10
20
30
40
SSW
DISTANCE FROM HURRICANE CENTER (Nautical Miles)
NNE

Figure 8.

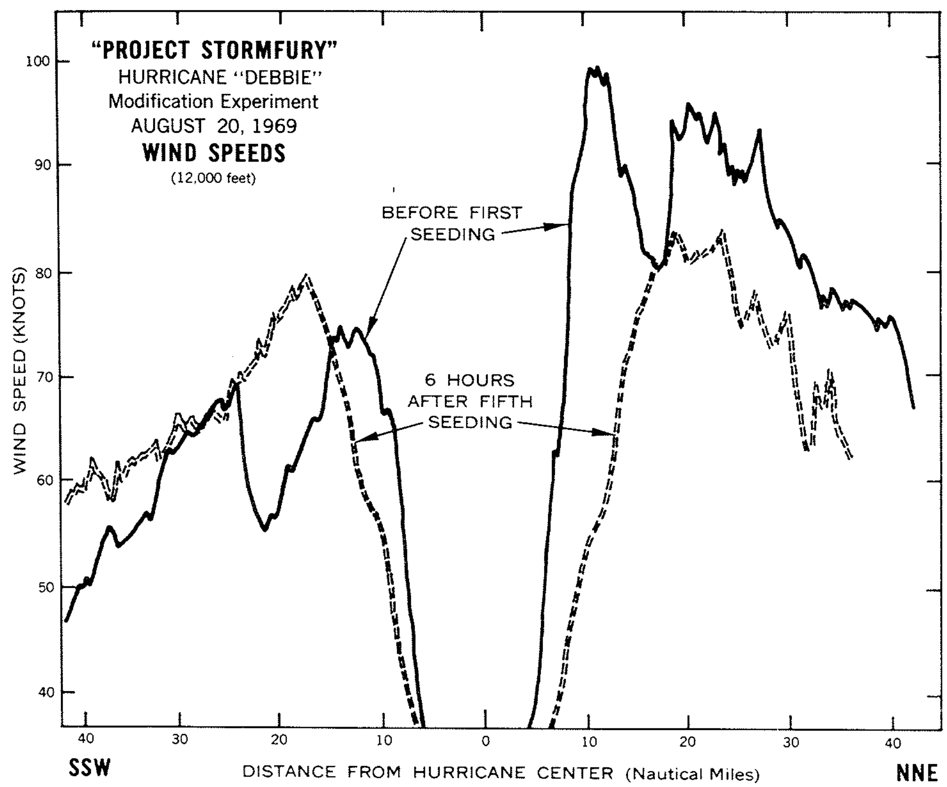
"PROJECT STORMFURY"
HURRICANE "DEBBIE"
Modification Experiment
AUGUST 20, 1969
WIND SPEEDS
(12,000 feet)
BEFORE FIRST SEEDING
6 HOURS AFTER FIFTH SEEDING
WIND SPEED (KNOTS)
100
90
80
70
60
50
40
40
30
20
10
0
10
20
30
40
SSW
DISTANCE FROM HURRICANE CENTER (Nautical Miles)
NNE

Figure 9.