Project STORMFURY

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Abstract

Project STORMFURY is a project of Commerce and Defense for experimenting at modification of hurricanes. Justification for the work is based on recent discoveries about hurricanes and the high potential benefit to cost ratio of the experiments. Evidence is presented that two approaches for modification should be considered: 1) seeding of clouds, and 2) inhibiting evaporation from the ocean. The scientific aspects and logistic problems of both approaches are reviewed. The Program and goals of Project STORMFURY are discussed.

1. Introduction

Project STORMFURY is a cooperative venture of the Department of Commerce, ESSA, and the Department of Defense, U. S. Navy. Its objective is to determine to what extent man can beneficially alter tropical cyclones including, of course, hurricanes (Gentry and Edelstein, 1968). The Project was formally organized in 1962 after the same groups had attempted modification of hurricane Esther in 1961 with encouraging if inconclusive results. They later conducted modification experiments on hurricane Beulah in 1963 with similar results. Since then, researchers have greatly expanded our knowledge of the structure and energy processes of hurricanes and of the convective processes in tropical clouds. Better instrumentation and techniques for counting freezing nuclei and measuring liquid and solid water content of clouds and other parameters have become available. Theoretical models of the synoptic scale features of a hurricane and of the microscale cumulus convective elements found in hurricanes have been greatly improved. As a result of these developments the emphasis and experimental design have gradually evolved for Project STORMFURY. It seems pertinent, therefore, to summarize the program and the current status of the Project.

In this paper we will list the reasons for having such a project, explain its goals, describe approaches being considered, and outline the research program proposed for the next 2 to 5 years.

Two general considerations justify Project STORMFURY: 1) recent improvements in our understanding of the physical processes fundamental to the maintenance of hurricanes suggest promising avenues of experimentation, and 2) enormous rewards can be derived from

even a slight degree of beneficial modification. The first will be elaborated in later sections; the second may be illustrated by the following rough "cost-benefit" analysis.

Hurricanes caused an average annual damage in the United States of 13 million dollars between 1915 and 1924. By the period 1959 to 1968, this figure had jumped to 295 million dollars. Even after considering the inflated cost of construction in more recent years, a 475% increase in the average annual cost of hurricane damage has occurred in less than 50 years (Gentry, 1966). The current practice of constructing valuable buildings in vulnerable areas indicates that hurricane damage costs will continue to increase. Hurricane Betsy of 1965 alone caused more than 1.4 billion dollars in damage. If the United States continues supporting hurricane modification research at the present rate for the next 10 years and if by that time we modify just one severe hurricane, such as Betsy, sufficiently to reduce its damage by only 10%, the nation will obtain more than 1000% return on its investment. Similarly, if within 10 years we can reduce the damage caused by such a storm by only 1%, the nation will have a 100% return on its investment. The benefits in terms of prevention of human suffering are, of course, incalculable.

At least two fundamentals established in recent years by studies of hurricane structure and maintenance suggest possible avenues for beneficial modification; 1) an internal energy source is necessary if a hurricane is to reach or retain even moderate intensity; this source is the sensible and latent heat transferred from the sea surface to the air inside the storm, and 2) the energy for the entire synoptic-scale hurricane is released by moist convection in highly organized convective scale circulations located primarily in the eyewall and major rain bands. In the first, we find an explanation of the observations that hurricanes form only over warm tropical waters and begin dissipating soon after moving over either cool water or land. Neither of these provides a flux of energy to the atmosphere sufficient to keep the storm at full intensity. In the second, we find a more rational explanation of the low percentage of tropical disturbances that become hurricanes. If a warm sea with its large reservoir of energy were the only requirements, we would have 5 to 10 times as many hurricanes as normally form. During the 1967 and 1968 hurricane

seasons 130 tropical waves were tracked in the Atlantic and adjacent areas where sea surface temperatures were warm enough for hurricane genesis, but only 13 of the areas developed storms of full hurricane intensity (Simpson *et al.*, 1968 and 1969). If, however, there are only a limited number of ways in which the convective and synoptic scales can interact to achieve optimum utilization of the energy flowing upward from the ocean, then it is not surprising that few tropical disturbances intensify and become hurricanes.

Both of the above findings suggest possible field experiments which may beneficially modify a hurricane. On the basis of the first, we may attempt to reduce the flux of energy from the sea surface to the atmosphere, probably through attempts to inhibit evaporation. On the basis of the second, we may try to modify the release of latent heat in the small portion (1 to 5%) of the total storm occupied by the organized active convective-scale motions in a manner that redistributes heating to produce a weakening of the storm. The logistics and scientific feasibility of both types of field experiments will be discussed.

Can the scientific feasibility of such experiments be investigated by simulating them with the theoretical mathematical models developed within the last few years? Researchers in ESSA and at a number of universities have been developing numerical models to portray the life cycle of tropical cyclones (Ooyama, 1969; Rosenthal, 1969; Yamasaki, 1968; and Kuo, 1965). These models show that hurricanes are sensitive to the sea surface temperature and the heat flux from the ocean to the air (Ooyama, 1969) as well as to the vertical distribution of the latent-heat release (Rosenthal and Koss, 1968; Yamasaki, 1968). Current models are capable, however, of simulating only an axially-symmetric cyclone with rather limited vertical resolution. They parameterize in a relatively simple fashion the effect of air-sea interaction and the transfer of energy by cumulus convection. They cannot predict the effects of storm motion of artificial intervention. More sophisticated models to eliminate many of these restrictions are being formulated.

Even though the developers do not consider that their current models simulate nature sufficiently to be used for evaluating proposed modification experiments, great progress has been made in this field in recent years. Two of the more advanced models have been used to run simple experiments whose results suggest modification attempts for the two approaches mentioned above, that is: 1) reducing the rate of heat transfer from the ocean to the atmosphere, or 2) altering physical processes in convective clouds to effect changes in the interaction between the convection and synoptic scales.

2. Modification of rate of heat transfer from ocean to the atmosphere

The first dynamical-numerical model that simulated many of the features of a hurricane (Ooyama, 1969) indicated that the intensity of the hurricane varied di-

rectly with the rate of transfer of heat from the ocean to the air inside the hurricane. This indication is also given by earlier empirical budget calculations (Palmén and Riehl, 1957) and theoretical and experimental studies (Miller, 1964). They all suggest that hurricane intensity would be substantially reduced if the flux of sensible and/or latent heat from the ocean to the storm circulation could be significantly lowered. In particular, the intensity would be lessened if evaporation from the ocean could be inhibited.

Projects for reducing evaporation from a water surface have been conducted in many water deficient regions of the world. Successful experimenters have used a monomolecular film that can be developed from fatty alcohol compounds. One of the better documented experiments was at Lake Hefner, Oklahoma (Bean and Florey, 1968), where a 58% reduction in evaporation was effected by the monolayer during a 3-day test period. In all known experiments, however, the film has broken when the winds exceeded a critical level, e.g., 25 knots or less. To be effective in modifying a hurricane, the film would need to be used where surface winds greatly exceed 30 knots; thus, development work may be needed to provide more durable films for the ocean surface and to study the effect the film may have on evaporation of droplets or spray.

Use of such monofilms to inhibit evaporation beneath a hurricane introduces large problems in logistics. To spread the film over an area the size of a typical moderately intense hurricane could require more than 50 cargo-type aircraft and chemicals worth about \$500,000.00. If, as is probable, the film blew away from the storm, additional chemicals should be spread for as long as the film was required. This is obviously too great an expense and effort to consider unless the film will be effective in reducing the intensity of the storm significantly. On the other hand, this would be a small price to pay for modifying an intense hurricane poised to devastate a densely populated coast. Results from theoretical models suggest that this approach offers great promise if evaporation from the ocean surface can be sufficiently decreased. We should, therefore, encourage investigations aimed at developing better means for diminishing the evaporation. In addition, we need to learn more about the properties of films that have already been used. We do not know, for example, to what extent the films retain their evaporation inhibitory powers after being broken by high waves. We should conduct feasibility experiments to verify that they will work in salt water (they have been used primarily in fresh water), to determine what rate their effectiveness decreases with increasing wind speed, and to confirm that they have no undesirable side effects. Much of this work can be done in a laboratory. In view of engineering technology, expense and forbidding logistics at this time one cannot justify full scale field experimentation that aims to reduce sea-air fluxes in a hurricane. Vigorous pursuit of these possibilities should be encouraged.

There is strong evidence that other factors act as regulators on the storm's intensity. The rate of heat transfer from the ocean to the atmosphere is a function of several items, including wind speed, air temperature, relative humidity and sea temperature. If the air temperature and humidity are relatively high, heat transfer will be slow, but then the air flowing into the storm already contains the sensible and latent heat necessary to fuel an intense hurricane. Once the winds are strong, the sea temperature is the critical parameter related to sea-air heat transfer processes that controls the storm intensity. Fig. 1 relates the maximum intensity of several tropical cyclones to the temperatures of the sea beneath them and shows that both severe and weak tropical cyclones occur when ocean temperatures are relatively high. This suggests that variations in parameters other than the transfer of heat from the ocean to the atmosphere also influence the storm's intensity which leads us to consider our second approach suggested for hurricane modification.

3. Modification of the physical processes in convective clouds

Observations clearly reveal that the physical processes essential for maintaining the hurricane as a coherent weather system occur in concentrated regions of intense cumulus convection in the eyewall and the principal rainbands. Even within the wall cloud, major convective elements are not uniformly distributed and may often be restricted to a single quadrant. They usually occupy less than 5% of the total storm volume and, in some cases, less than 1%. They are located in the wall clouds and principal rainbands, which can be identified easily by radar.

Convective scale processes essential to the energy balance of the hurricane scale are the releases of latent energy associated with phase changes of water substance (i.e., from water vapor to droplets and to ice crystals). Such processes have been modified in individual tropical

cumulus clouds by artificial nucleation (Simpson *et al.*, 1967). We need to learn more about the mechanisms by which energy releases on this small cumulus scale are systematically organized to maintain the larger scale hurricane.

Full scale experiments to modify natural convective processes in hurricanes by cloud seeding with artificial freezing nuclei are indeed logistically feasible. A limited number have already been performed by the STORMFURY group in 1961 and 1963 (Simpson and Malkus, 1964), and recent developments in pyrotechnics makes it even more feasible to do massive seeding of hurricane clouds. Furthermore, reasonable qualitative arguments indicate that modification of the convective scale processes might result in some changes of the temperature field—and possibly of the macrostructure of the hurricane.

Since numerical models of hurricanes are now reproducing many features of the life cycle of tropical cyclones with considerable reliability, we might ask what they say about the chance of modifying a hurricane by altering the convective processes. The developers of these models do not believe they sufficiently simulate nature to give definitive answers to such questions. We are, however, using the 7-level primitive equation model developed by Rosenthal (1969) at the National Hurricane Research Laboratory to get information for improving the design of the field experiments. In experimental seeding of the wall clouds of hurricanes in 1961 and 1963 in the Project STORMFURY group, freezing nuclei were introduced along a line perpendicular to the eye wall from just inside the radius of maximum winds outward for several miles. Later research suggested that better results might be obtained by seeding outside of the radius of maximum winds. Rosenthal's model was used to simulate the seeding experiment on two different circular bands by increasing the heating function at 500 mb and 300 mb by 2C per 30 minutes for 30 minutes. When the maximum winds were 35 km from the center, two bands, 30–50 km and 50–70 km were selected for simulated seeding in experiments run on the computer with

FIG. 1.

FIG. 2. The dotted line represents results from the unmodified model (Rosenthal, 1969); the dashed line gives results of the simulated seeding across the radius of maximum winds; and the solid line gives results of the simulated seeding outside the radius of maximum winds. (Dashed and solid lines based on unpublished work of Stanley L. Rosenthal.)

the model hurricane. One band spanned the radius of maximum winds, the other was outside that radius. The results of the two simulations are compared in Fig. 2. The inference is that the greatest reduction in maximum intensity can be accomplished by seeding outside the radius of maximum winds.

The results from these experiments (Fig. 2) can be interpreted to mean either that the seeding would cause a temporary reduction in intensity of the storm or that the seeding would cause a change in phase of the quasi-periodic variation of the maximum winds generated by the model. To the extent that the results indicate a change in the storm's intensity, they indicate that it would decrease. The potential benefit of hurricane modification to cost ratio is so great that even the small decrease in intensity suggested by the experimental results in Fig. 2 would be worthwhile. These results can hardly be considered as the final answer. Since neither this model nor those of any of the other investigators are sufficiently advanced to adequately simulate these cloud seeding experiments, a field program is the only method currently available for determining whether modification of the convective processes will result in a quantitatively significant and beneficial change in the hurricane. Recent theoretical work in hurricane modeling has shown sufficient promise to warrant the hope of skillful computer simulation of these field experiments within the next few years. Now the best procedure is to use models for improving the design of field experiments and to use the results from the latter as a feed-back to support further improvement in the models.

Some individual tropical cumulus experiments have already been made, such as modification of cumulus clouds during periods of typical tropical conditions, by J. Simpson and her collaborators, who have also developed a numerical model that predicts how high individual cumulus clouds will grow under natural and seeded conditions (Simpson *et al.*, 1967). Using mean hurricane soundings (Sheets, 1969), we have made computations with the Simpson cumulus model to determine the seedability of hurricane clouds. With reasonable assumptions about cloud bases and diameters, the computations showed that hurricane clouds should grow after seeding just as many of the individual seeded tropical cumulus. The amount of growth in the hurricane clouds that could be attributed to seeding varied directly with the radius, that is, the closer to the center of the hurricane, the less additional growth that should be expected from the seeding.

4. Proposed program for STORMFURY

Earlier hurricane modification experiments (Simpson and Malkus, 1964), and the more recent research suggest that hurricanes may be modified by seeding the clouds with freezing nuclei. Some recent research suggests that more favorable results may be obtained by modifications of original experimental designs. Some people have proposed seeding in a different area of the storm, seeding

the storm at a different stage of development, or seeding rainbands in areas where growth of the clouds might serve to divert some of the energy from the main center.

The first urgent task of STORMFURY and one of its goals is gathering of data from additional tropical cyclones about the structure of cumulus convection to determine how often, to what extent, and under what conditions a valid physical basis exists in tropical cyclones for cloud modification by introduction of freezing nuclei. This task requires more measurements of liquid-water content, cloud drop size distributions, precipitation characteristics, composition (ice and liquid phases), temperature, and vertical motion in the eye wall, in the rainbands, and in the nonprecipitating cloud bands associated with both young and mature disturbances.

In 1968, we recorded the first data collected in a hurricane at a level above 0C isotherm of the drop size distribution and the phase of H₂O. In three passes along a rainband in hurricane Gladys at temperatures of -5C to -8C, the Formvar Replicator data showed that only water drops were present in most of the clouds. This is excellent support for the hurricane seeding modification hypotheses, but measurements are needed from more tropical cyclones. We have some measurements of liquid-water content, but, again, data from more storms are needed to determine frequency and under what conditions that sufficient raw material (supercooled water) is available for seeding. ESSA research aircraft are now equipped to measure many of the desired cloud physics parameters and efforts are continuing to improve instrumentation. In addition we are seeking a cloud physicist to work in the Project to assist in the collection and interpretation of these data.

Second, STORMFURY must determine the physical effects of various kinds of seeding treatments on the clouds associated with tropical weather systems. This includes the complete spectrum of cloud systems; groupings of individual cumulus clouds; cloud bands; cloud structures associated with "disturbances," such as easterly waves; inner and outer rainbands; and the eye wall clouds.

To achieve these first two listed goals, STORMFURY should use every opportunity to seed and observe convective cloud systems over tropical oceans. Disturbances in all stages of development are suitable targets for seeding provided that proper measurements of the cloud structure are made before and after seeding. Aircraft available to the STORMFURY Project are equipped to make such measurements, and every effort is being made to improve instrumentation, observing techniques, and training of personnel to obtain measurements more accurately and dependable. Observations of the variations in nonseeded clouds near those seeded are also of great interest.

Third, STORMFURY must press on with general hurricane research. Efforts to develop improved theoretical models should be accelerated. Efforts to learn more about the structure and energy exchange processes in

hurricanes should be continued by means of well designed observational and analytical programs. Conditions or locations in the storm, if any, where a modified hurricane rainband might cause a hurricane to weaken or to change course must be known.

A difficulty in interpreting results of a hurricane modification experiment is the lack of suitable controls. This problem is accentuated by the large natural variability of hurricanes and the few opportunities we have for experimenting with mature hurricanes. If the changes wrought in a hurricane by a seeding experiment were of the magnitude indicated in Fig. 2, the Project aircraft could measure those changes, but there would still be the question whether they were due to the action of the artificial freezing nuclei?

In research flights of recent years, we have developed measuring techniques and ways of grouping the data that help to filter the natural variations associated with the microscale features of the hurricane, making it easier to identify trends in hurricane intensity in a shorter time. The Project aircraft are now equipped to measure changes in the structure and size of the clouds; to record changes in temperature, pressure and winds in and near the seeded clouds; and to record the changes in phase of the water substance and the amounts of liquid and total water content. Efforts to improve these latter measurements and to add recordings of the vertical wind components continue. By designing flight patterns to obtain measurements both before and after the seeding, it should be possible to determine if changes in parameters occur in the right sequence and at approximately the right time intervals to have been caused by the seeding. In addition, measurements can be made of changes in the hurricane on synoptic and convective scales to determine if these changes are in accordance with indications from the various theoretical models.

The field program planned for the 1969 and successive hurricane seasons is based not only on the foregoing considerations but also on available resources. The plans call for: 1) seeding of the clouds around a hurricane eye wall five times during a period of 8 hours, 2) seeding of hurricane rainbands, 3) seeding of cloud lines in the tropics not associated with hurricanes or tropical storms, 4) intensification of efforts to collect data discussed in earlier paragraphs, 5) feasibility or laboratory experiments on the use of monofilms to reduce evaporation from the sea surface, and 6) increased research on models to simulate hurricanes and to predict their behavior.

It is hoped there will be opportunities to repeat each of the three seeding experiments more than once. The objectives of the first experiment are to determine whether: 1) cumuli in the major convective regions of hurricanes will react to seeding in as predictable a manner as individual cumuli, 2) the reaction of the macrostructure will be significant and along the lines suggested by qualitative reasoning and by simple experiments performed on the computer with the numerical

models, 3) responses to single seedings are periodic and in phase with repetitive seedings, and 4) responses to repetitive seeding are accumulative. To get help in the evaluation of the experimental results, sufficient measurements will be made of conditions in the seeded clouds to determine if changes in phase of water substance, temperature, pressure and wind occur in the proper sequence to have been caused by the seeding.

The objectives of the second and third experiments are to determine: 1) under what conditions the life cycle of cumulus convection cloud systems can be altered by man, 2) whether the reaction to seeding of larger systems of cumuli is similar to that found in individual cumuli, 3) to what extent models of individual clouds can be used for predicting the reaction of a cloud system to seeding, and 4) what effect changes in modified clouds have on nearby clouds in the same line or band, and on clouds in adjacent lines or bands. When possible, controls (clouds, cloud lines or rainbands) will be observed simultaneously with the seeded clouds and statistical techniques will be used in evaluating results when appropriate and feasible.

It should be emphasized, however, that Project STORMFURY is not a controlled experiment entirely amenable to statistical evaluation. The low frequency of occurrence of hurricanes as experimental targets precludes the accumulation of a large body of test data in a short time and application of statistical methods for testing of the complete hypothesis. The Project is still exploratory, and is aimed at a better physical understanding of the dynamics of hurricanes, in addition to eventual modification of a storm. The theoretically possible potential benefits are so great compared to the experimental costs that the artificial modification of tropical cyclones is a justifiable scientific pursuit and could be of great importance for mankind.

Acknowledgments. This report has been reviewed and approved by the Advisory Committee to Project STORMFURY: Dr. Noel E. LaSeur (Chairman), Dr. Edward N. Lorenz, Dr. James E. McDonald, Dr. Daniel F. Rex, and Dr. Jerome Spar. The members of the Committee have also made many suggestions as to its format and context. In addition, the following contributed significantly to preparation of this report: Dr. Stanley L. Rosenthal, Harry F. Hawkins, William D. Mallinger, and Max Edelstein. Jack Tracy collected the data for Fig. 1.

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