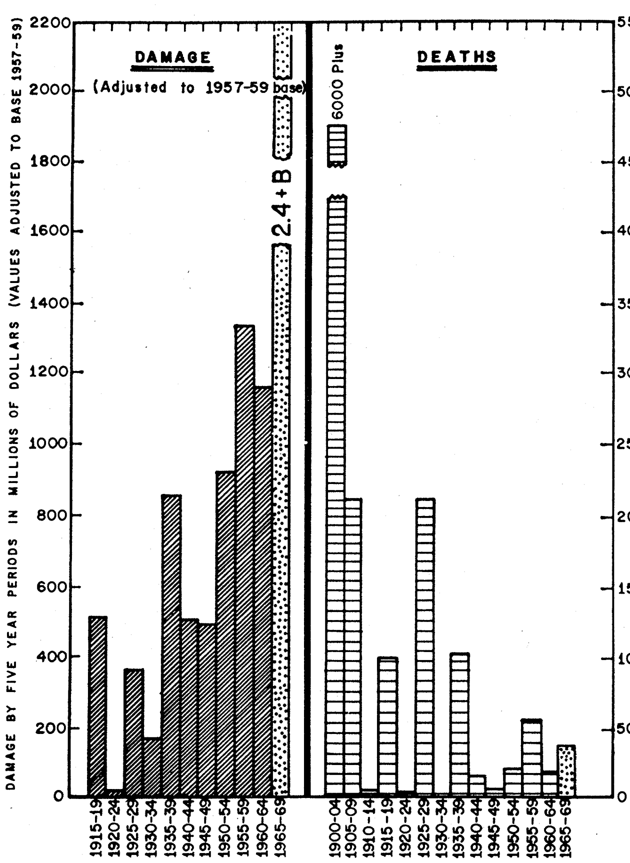
the shock synthesis of organic compounds from mixtures of CH_4, NH_3, and H_2O. A general introduction to shock tube operation can be found in S. H. Bauer, *Science* **141**, 867 (1963).
4. M. O. Dayhoff, E. R. Lippincott, R. V. Eck, *Science* **153**, 628 (1966); *Nat. Aeronaut. Space Admin. Spec. Rep. SP-3040* (1967).
5. R. E. Duff and S. H. Bauer, *J. Chem. Phys.* **36**, 1754 (1962).
6. W. E. Groth and H. von Weyssenhoff, *Planet. Space Sci.* **2**, 79 (1960), and references therein.
7. A. R. Hochstim, *Proc. Nat. Acad. Sci. U.S.* **51**, 200 (1963); *Nature* **197**, 624 (1963).
8. See, for example, E. J. Opik, *Physics of Meteor Flight in the Atmosphere* (Interscience, New York, 1958).
9. See G. S. Hawkins, *Annu. Rev. Astron. Astrophys.* **2**, 149 (1964); P. W. Hodge and F. W. Wright, *Icarus* **10**, 214 (1969).
10. H. R. Hulett [*J. Theor. Biol.* **24**, 56 (1969)], by confusing meteorite with meteoroid and micrometeorite fluxes, reached an erroneous value of 4×10^{-5} cal cm^{-2} year^{-1}.
11. S. L. Miller and H. C. Urey, *Science* **130**, 245 (1959).
12. C. Sagan, *Organic Matter and the Moon* [*Nat. Acad. Sci.–Nat. Res. Counc. Publ. 757* (1961)].
13. Supported in part by NASA grant No. NGR 33-010-101 at the Laboratory for Planetary Studies and by U.S. Air Force Office of Scientific Research contract No. AF49(638)-1448 at the Department of Chemistry.
* Present address: National Aeronautics and Space Administration Ames Research Center, Mountain View, California.
† Present address: Department of Microbiology, Palo Alto Medical Research Foundation, Palo Alto, California.
1 December 1969; revised 2 February 1970 ■

Hurricane Debbie Modification Experiments, August 1969

Abstract. *Maximum winds in Hurricane Debbie, August 1969, decreased after modification experiments by Project Stormfury. Clouds surrounding the center of Debbie were seeded with silver iodide particles five times at approximately 2-hour intervals on both 18 and 20 August. Before the first seeding on 18 August, the maximum speed of winds at 3600 meters was 182 kilometers per hour, but, 5 hours after the fifth seeding, these winds decreased to 126 kilometers per hour. On 20 August, the corresponding change was from 183 to 156 kilometers per hour. Analyses of the data suggest that the storm was modified.*

Project Stormfury conducted modification experiments on Hurricane Debbie on 18 and 20 August 1969. These experiments were the first performed on hurricanes since 1961 and 1963 (*1*) and the first in which a storm was ever seeded more than once per day. Debbie was seeded five times during 8 hours on each of the 2 days. This report presents preliminary analyses of the data collected in the Hurricane Debbie modification experiments.

R. H. Simpson proposed in 1961 that hurricanes might be modified by introducing freezing nuclei into the massive clouds surrounding the center of a hurricane. At about the same time Pierre St. Amand and his associates at the Navy Weapons Center, China Lake, California, developed pyrotechnic generators, which made it practical to introduce very large quantities of silver iodide into clouds within a few minutes. Groups from the Weather Bureau and the Navy experimented on Hurricane Esther with a single seeding on each of 2 days in September 1961. Project Stormfury was formally organized in 1962 with R. H. Simpson as the first director. In August 1963, the experiment with a single seeding per day was repeated on each of 2 days for Hurricane Beulah. The results of these earlier experiments have been reported by Simpson and Malkus (*1*) and were encouraging but inconclusive. A multiple seeding experiment was designed under the leadership of Joanne Simpson, director of the project for 1965–66. During the years 1965–68 no hurricane occurred in a place suitable for experimentation. Research on hurricanes, both theoretical and experimental, con-



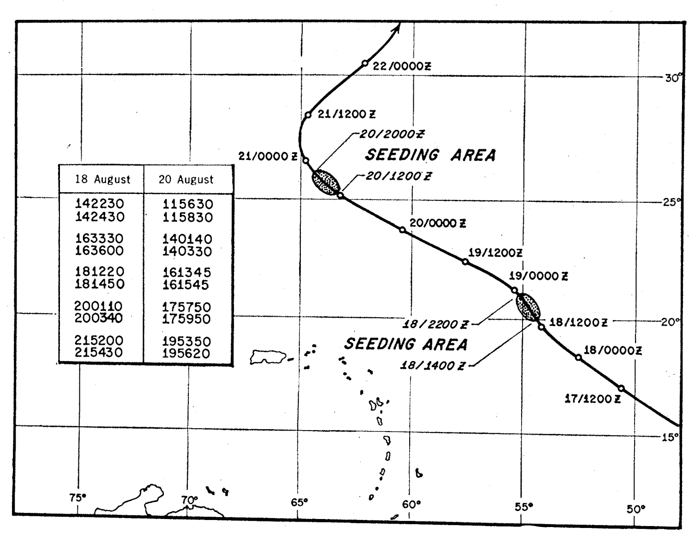
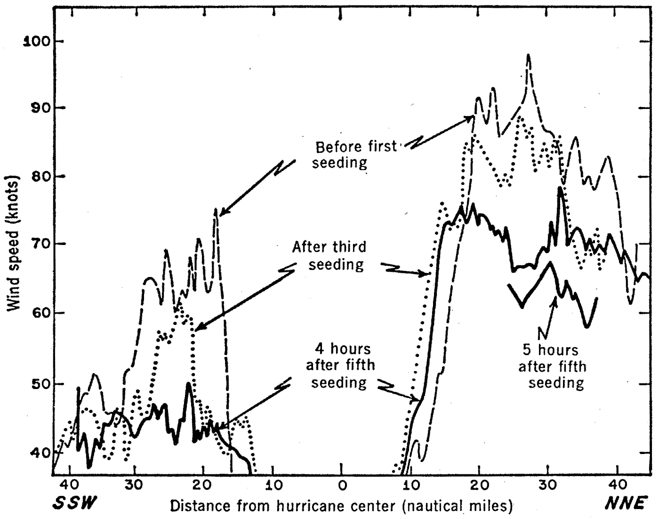


Fig. 1 (left). Trends in losses from hurricanes in the United States summarized by 5-year periods. Damage statistics have been adjusted to the 1957–59 base of the Department of Commerce composite cost index for construction. The adjusted total for 1965–69 exceeded $2.4 billion, which also exceeds the vertical scale of the chart. Fig. 2 (above). Track of Hurricane Debbie, August 1969. Seeding areas on 18 and 20 August are indicated on the track; Z indicates Greenwich Mean Time. The inserted table contains a list of the times of seedings in hours, minutes, and seconds (G.M.T.).



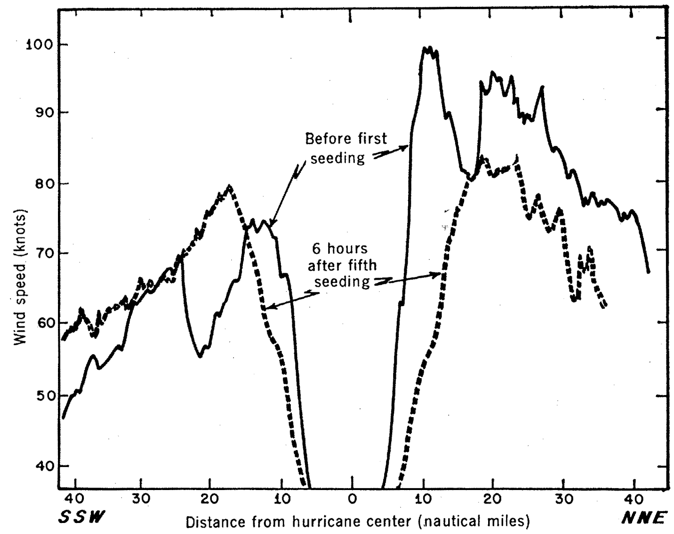


Fig. 3 (left). Changes with time of wind speeds at 3600 m in Hurricane Debbie on 18 August 1969. The winds were measured by aircraft flying across the storm from south-southwest to north-northeast or the reciprocal tract. Profiles are given which show the wind speeds before the first seeding, after the third seeding, and after the fifth seeding (1 knot = 1.852 km/hr; 1 nautical mile = 1.852 km). Fig. 4 (right). Same as Fig. 3, except that the wind speed profiles are for 20 August 1969 and are for the periods before and after the seedings.

tinued, however, with results that produced changes in the original design of the multiseeding experiment. Furthermore, improved pyrotechnic silver iodide generators became available before the 1969 season. The frustration of waiting 4 years without opportunities for experimentation may not, therefore, have been in vain. The succession of apparently minor changes to improve the design of the seeding experiment may have made the difference between success or failure for the Debbie experiments.

Project Stormfury is a joint effort of the Departments of Defense (Navy) and Commerce (Environmental Science Services Administration) in experimental modification of hurricanes (*2*). Two general considerations justify this project: (i) recent improvements in our understanding of the physical processes fundamental to the maintenance of hurricanes suggest promising avenues of experimentation, and (ii) the potential benefit-to-cost ratio of the work is so great.

The second point has been emphasized recently by the accelerated rate of increase in damage caused by hurricanes in the United States. This increase is illustrated in Fig. 1, where damage statistics from 1915 to 1969 are summarized by 5-year periods. The totals have been adjusted for variation in cost of construction to the 1957–59 base. The increase in damages through the years has been extreme, and we must expect the trend to continue because we are building structures that are more and more expensive in areas vulnerable to hurricanes.

By contrast, the costs of the Stormfury experiments and research are relatively low. If during the next 10 years we continue spending at the current annual rate and if at the end of 10 years we are able to modify one hurricane, such as Camille (1969) or Betsy (1965), sufficiently to reduce the damage by 10 percent, the country will obtain a more than tenfold return on its investment.

In the modification experiments, we seek to make the hurricane work against itself. Hurricane clouds contain large quantities of water substance still in the liquid state at temperatures lower than −4°C. At these temperatures the introduction of silver iodide nuclei should cause the water droplets to change to ice crystals and to release the latent heat of fusion, providing a possible mechanism for adding heat to the hurricane. One objective of the Stormfury experiments is to determine in which portion of the hurricane the addition of heat will result in diminished intensity of the storm. One location is presumably at the outer edge of the mass of warm air that occupies the central area of the hurricane. The experiments on Hurricane Debbie were designed to determine if addition of heat in this area would result in diminishing the maximum horizontal temperature gradients in the storm and, eventually, in weakening the maximum winds.

Hurricane Debbie was a mature storm with winds stronger than 185 km/hour on 18 August (Fig. 2). It was about 1200 km east-northeast of Roosevelt Roads, Puerto Rico, the primary operating base of Project Stormfury. This was an extreme range for the experiment, but other conditions were favorable, and the storm was moving west-northwestward on a course that would bring it closer to the base as the day progressed. Thirteen aircraft were available (nine from the Navy, two from ESSA, and two from the Air Force). Fifteen flights were made with these aircraft. Of these flights, five carried the pyrotechnics for seeding the hurricane, and the other ten monitored the storm for changes in structure and intensity, beginning about 6 hours before the first seeding and continuing until 6 hours after the last one.

The Navy seeder aircraft approached the storm from the south-southwest at 10,000 m, penetrated and crossed the eye, and entered the wall cloud on the north-northeast side. Shortly after entering the wall cloud at a spot where past experience suggested that the aircraft would cross the radius of maximum winds as well as the most intense temperature gradients, the crew started dropping the pyrotechnic generators (*3*) that produced the silver iodide. Each aircraft carried 208 of these generators and dropped them along a line leading radially away from the center. Each generator contained slightly more than 120 g of silver iodide, and each gram should produce in excess of 10^{12} freezing nuclei at $-8°C$. There is some evidence that each gram might produce more than 10^{14} nuclei active at temperatures found in hurricane clouds (*4*).

Each seeding run lasted 2 to 3 minutes and covered between 26 and 40 km. The five seeding runs came at intervals of approximately 2 hours on each of the 2 days. The approximate times are given in the inset of Fig. 2.

Many data were collected during ten monitoring flights and some by the five seeder aircraft. We are still analyzing these data, but we can draw tentative conclusions from data processed thus far. A few of the data are shown in Figs. 3 and 4.

The two DC-6 aircraft of ESSA's Research Flight Facility have similar instrumentation that has been cross-calibrated, and they have crews trained in using the same techniques. Data from the two aircraft are as nearly comparable as planning and checking can make them. These aircraft were designed to relieve each other in making repetitive passes across the storm, in order to provide almost continuous coverage of the hurricane by one of them from 3 hours before the first seeding until 5 or 6 hours after the fifth one. This continuous coverage was accomplished with the exception of some time gaps on 18 August, when the storm was at such great range that the first aircraft could not make the round trip to base for refueling during the time that the second aircraft could remain in Debbie. The aircraft flew at 3600 m. In previous mature hurricanes such as Debbie, where we have had measurements at several levels, winds at 3600 m have been about 95 percent as strong as those near the surface (5).

The flight patterns called for each aircraft to make a round trip across the storm from a point about 90 km west-northwest of the hurricane center to 90 km east-southeast of it, or to a point beyond the belt of the strongest winds. Each aircraft then flew similar traverses from the south-southwest quadrant to the north-northeast quadrant until fuel shortage dictated departure from the storm. Since we have more data on the later passes, they are the ones presented in Figs. 3 and 4. In a storm moving toward the west-northwest, the strongest winds are usually found a short distance north-northeast of the center.

Between successive passes on both 18 and 20 August, the winds sometimes increased and sometimes decreased. In the mean, however, the wind speeds dropped from shortly after the second seeding until at least 5 or 6 hours after the fifth seeding. This decrease was most marked on 18 August (Figs. 3 and 4).

Before the first seeding on 18 August, maximum speeds at 3600 m were 182 km/hour. By 5 hours after the fifth seeding, they had decreased to 126 km/hour, a decrease of 31 percent. On 20 August the maximum wind speed before the first seeding was 183 km/hour. Within 6 hours after the final seeding, the maximum had dropped to 156 km/hour, a decrease of 15 percent.

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. These decreases in maximum winds represent a reduction in kinetic energy in the belt of maximum winds of 52 and 28 percent, respectively, on 18 and 20 August.

That Hurricane Debbie decreased in intensity following multiple seedings on 18 and 20 August is well established. What we do not know is whether the decrease was caused by the seeding or by natural changes in the hurricanes.

From analyses of past storms we can, however, make some comments about the probability that the changes observed might have occurred naturally. The rate of rise in central pressure in Debbie that accompanied the reduction in wind speed on 18 August has occurred in only 9 percent of 502 periods of similar length for other tropical cyclones that we have studied. Our measurements of winds in previous hurricanes are less complete than are our measurements of the pressure changes, but it is believed that the rate of decrease in wind speeds on 18 August is also a relatively rare event.

Although the rate of decrease in wind speeds on 20 August was smaller than on 18 August, it occurs in less than one-half of the hurricane days. Furthermore, on each of the days, the reduction in wind speed occurred at a time when it could have been caused by the seeding experiment.

We are still studying satellite pictures taken by the ATS-111 satellite; radar pictures taken aboard the project aircraft; and measurements of the pressure, temperature, and liquid water taken by the project aircraft. When all these data are finally processed and analyzed, perhaps we will be able to say with greater certainty whether or not the artificial seeding caused the observed reduction of hurricane intensity.

Some support for the idea that the modification experiment could have caused the reduction in wind speed is given by a theoretical model of a hurricane. Rosenthal (*6*), Ooyama (*7*), and others have been developing numerical-dynamical models to simulate the life history of hurricanes. Although these models are far from perfect, they do simulate many features of hurricanes. We have tried to simulate the Stormfury modification experiment on Hurricane Debbie with Rosenthal's model of a hurricane. With reasonable assumptions about the amount of liquid water existing at subfreezing temperatures, we have been able to achieve a 15 percent reduction in maximum winds with a simulated seeding experiment.

Since the 1969 experiments suggest strongly that modification was accomplished, such experiments must be repeated on one additional storm, or more, as soon as practical to seek further confirmation. We must also continue to search for clues from the data still to be analyzed and from results of our theoretical investigations in order to better identify probable cause and effect relationships and to improve the design of our seeding experiments.

R. Cecil Gentry
National Hurricane Research Laboratory, Environmental Science Services Administration, Miami, Florida 33124

References and Notes

1. R. H. Simpson and J. S. Malkus, *Sci. Amer.* **211**, 27 (December 1964).
2. R. C. Gentry, *Bull. Amer. Meteorol. Soc.* **50**, 404 (1969).
3. The pyrotechnic generators were developed by the Navy Weapons Center, China Lake, California, under the leadership of Pierre St. Amand. The massive seedings which introduced more than 10^{17} active freezing nuclei into the hurricane clouds within 10 minutes were not possible until Dr. St. Amand's team developed the pyrotechnic generators.
4. S. D. Elliott, Jr., R. Steele, W. D. Mallinger, *Project Stormfury Annual Report 1968* (U.S. Department of the Navy and U.S. Department of Commerce, 1969), appendix B, pp. 1–11.
5. H. F. Hawkins, *National Hurricane Research Project Report 55* (U.S. Weather Bureau, Washington, D.C., 1962).
6. S. L. Rosenthal, *ESSA Technical Memorandum ERLTM-NHRL 88* (Environmental Science Services Administration, Washington, D.C., 1970).
7. K. Ooyama, *J. Atmos. Sci.* **26**, 3 (1969).
8. The results reported represent the work of a large team, to whom I express appreciation and thanks. They include the Navy, Air Force, and ESSA crews, the members of the National Hurricane Research Laboratory and of other agencies who assisted in the research, and the Stormfury Advisory Panel.

12 January 1970