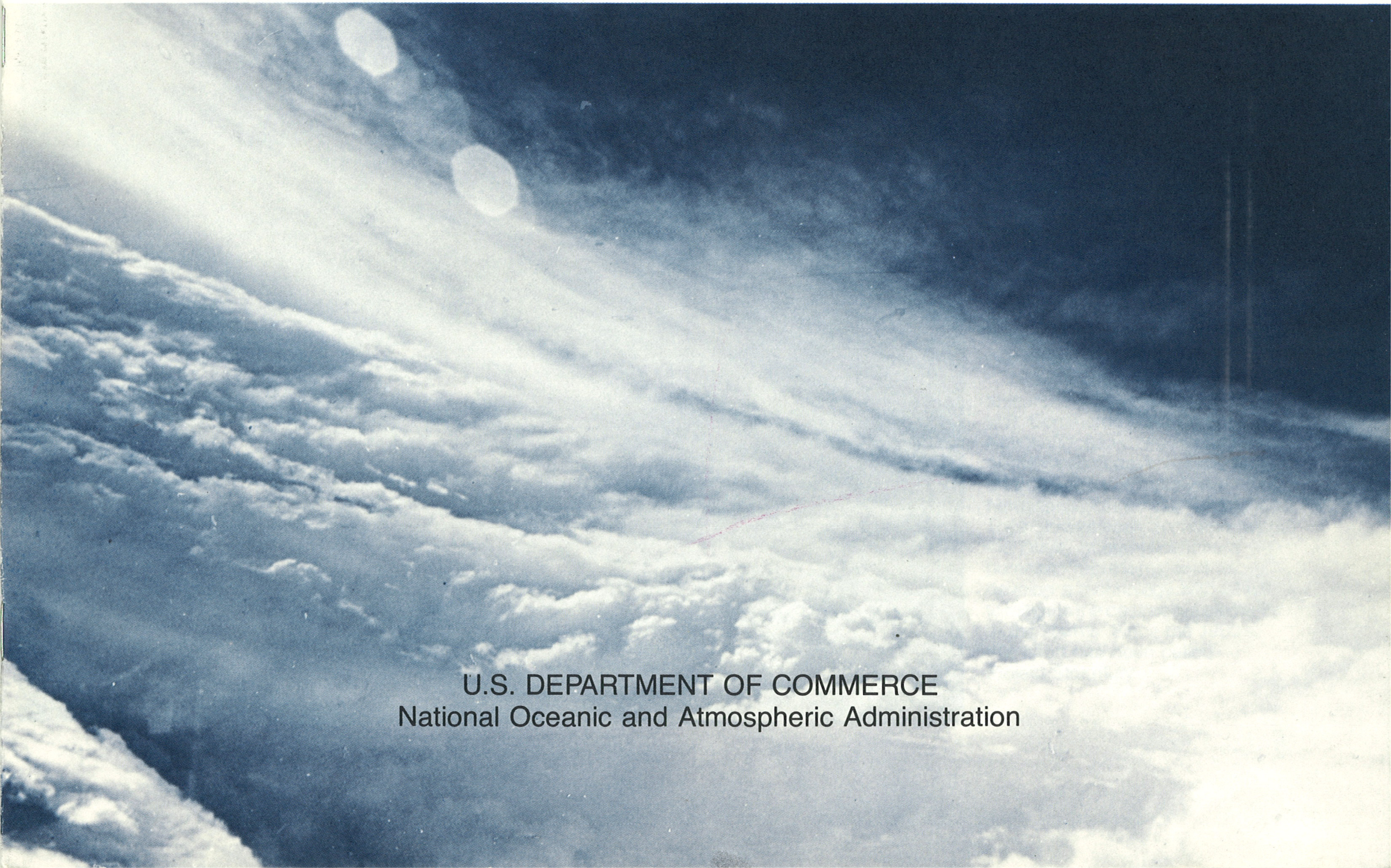
PROJECT STORMFURY



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

CONTENTS

It begins with a disturbance in the tropical atmosphere, a wave of low pressure, a trough, an eddy, and vertical movement of the warm, moist air. Low-level air begins to flow into the disturbed area, where it is raised convectively, releasing large amounts of heat energy as the water vapor stripped off the sea condenses to form water droplets. This energy feeds the initial vertical development, that becomes an efficient chimney in which low-level air is pumped upward, liberating large amounts of heat, and flows away from the storm just below the stratosphere. As the vertical circulation becomes better organized, the horizontal form of the storm becomes the familiar cyclonic spiral—an embryo hurricane.

The young storm is a whirlwind of legendary violence. Hurricane-force winds (winds above 65 knots, or 33 meters per second*) over thousands of square miles. Torrential rains cascade from its spiral bands of dense rainclouds, which ascend in decks of growing cumulus clouds and thunderheads until they reach into the high upper atmosphere. Lightning illuminates the dark world of the rainbands, and waves of turbulence shred the clouds.

At the center of this atmospheric whirlpool is the hurricane's unique feature—the calm eye where there are few clouds and little wind. The storm's worst winds blow in the towering thunderclouds around the eye, the eyewall that is also the hurricane's main conduit for forcing moist air upward, pressing out heat to drive the storm. Most hurricanes develop winds of more than 90 knots (45 meters per second); and severe hurricanes can more than double that.

At maturity a hurricane is eight to ten miles (13 to 16 kilometers) high, with hurricane force winds going out 50 miles (80 kilometers) from the eye, which is usually 10 to 15 miles (16 to 25 kilometers) across. Winds of gale force (23 to 55 knots, or 16 to 28 meters per second) extend out another hundred miles or more on either side of the eye.

When seen from a satellite in space, hurricanes seem strangely compact, as though they could be easily comprehended, easily changed. Nothing could be more misleading.

These great storms rage with energies that are almost incomprehensibly large, and cover tens of thousands of square miles with destructive winds, drowning rains, and swells, waves, and storm surge that can bite away the entire seaward rim of a lowlying coastal city. Hurricanes dominate continent-sized reaches of atmosphere and ocean. They are huge compilations of immensely complicated events, made difficult to study by their interior violence and distance from land.

And yet, scientists believe it may be possible to fly into these storms, seed clouds outside the eyewall, and reduce the hurricane's fierce winds.

There are compelling incentives to mitigate the fury of a hurricane. Even in an age when satellites provide reliable early detection of the storms and the prediction and warning of hurricanes have become extremely sophisticated, the big storms still burden those who live on coastlines where they strike.

Despite all the technology and talent, a cyclone in the Indian Ocean could kill tens of thousands of people in Bangladesh in 1970. In our own hemisphere, hurricane Fifi could kill some 10,000 people when it struck the waist of Central America with flooding rains in 1974. At home there have been fewer storms in recent years; but you can still see the marks of 1969's hurricane Camille along the Mississippi Gulf Coast.

While warnings have greatly reduced the human toll we pay the hurricane, they can do nothing to reduce the destruction of property. In the United States, hurricane-caused damage has grown steadily since 1915. The average annual cost (before Agnes, 1972) of hurricane damage has run around $450 million, with major exceptions: Betsy, in 1965, and Camille, in 1969, each caused more than $1.4 billion damage. Scientists believe only a 10 percent reduction in hurricane winds could reduce this figure by 30 percent or more, saving $50 to $100 million a year. There is also the possibility that storm surge—the hurricane's worst killer—would diminish with the decrease in maximum winds.

For nearly a generation, researchers in what is now the U.S. Commerce Department's National Oceanic and Atmospheric Administration have worked to bring the idea of modifying hurricanes into the realm of science. Their studies seek to comprehend the infinity of complications a hurricane represents, and to develop a technology with which to mitigate the destructive elements of the storms. Since the 1960's, this effort has been called Project Stormfury.

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*One knot equals one nautical mile per hour, 1.15 statute miles per hour, 1.853 kilometers per hour, or .51 meter per second. Multiply meters per second by 3.6 to get kilometers per hour.

STORMFURY PAST

Since the late 1950's, it has seemed feasible to many scientists to try to change the winds in hurricanes through cloud seeding. The first known attempt to do this was made on October 13, 1947, when scientists and aircrews from the General Electric Company, with federal sponsorship, dropped dry ice into thin stratified clouds outside the eyewall of a hurricane drifting east of Jacksonville, Florida.

It was a blind experiment. At that time, the researchers had little detailed knowledge of the structure and dynamics of hurricanes, and lacked the instrumentation to monitor the storm for seeding effects. Visual observations suggested some localized changes had occurred in the thin layered cloud; but it is now well established that one could expect little or no effect on a hurricane from this type of experiment.

The hurricane seeding experiments that evolved into Project Stormfury began in 1961. Project Stormfury was formally established in 1962, when it became a combined Department of Commerce and Department of Defense program, carried out by what is now NOAA and the U.S. Navy. Additional support over the years has come from the National Science Foundation and from the U.S. Air Force, which became an active partner in the late 1960's.

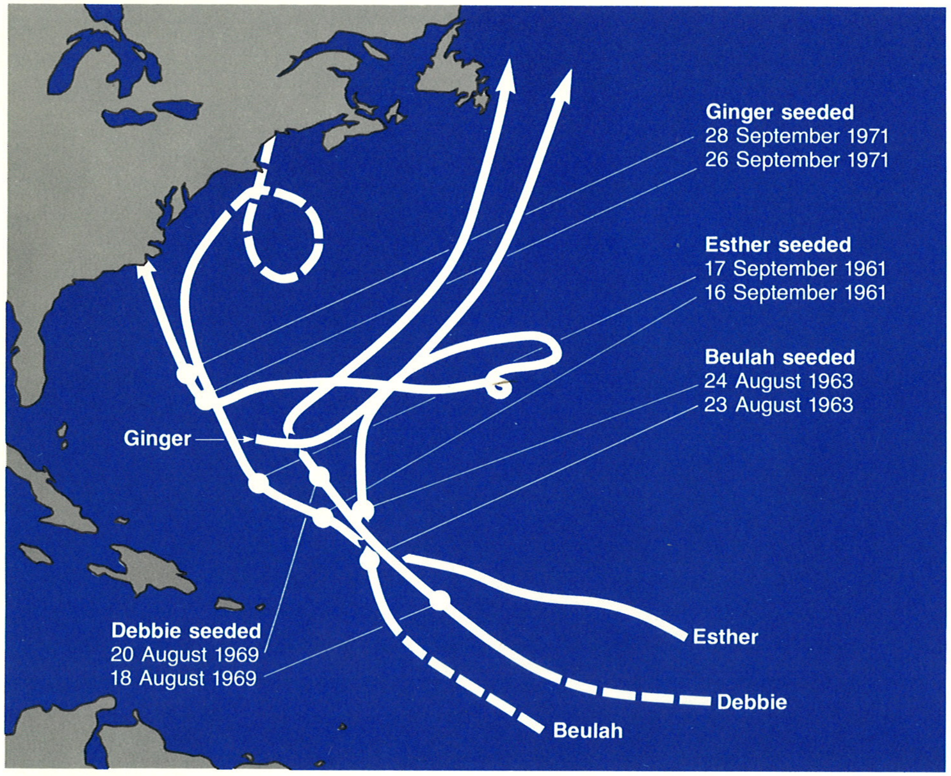
In 1973 the Defense Department decided hurricane modification was not a primary responsibility and discontinued their joint sponsorship of the experiment. Since then, Stormfury has been carried on primarily as a Department of Commerce program.

The seeding hypothesis. Most weather modification experiments that attempt to alter the energetics of cumulus clouds—the "fireboxes" of most severe weather—are concerned with turning liquid water into ice, and liberating its latent heat of fusion into the seeded cloud. Water tends to remain in supercooled liquid state at temperatures far below freezing, unless it has a suitable particle to coalesce around—a nucleus. To freeze supercooled water, an agent introduced into the cloud must either lower temperatures enough for water to freeze spontaneously, or it must provide freezing nuclei. Dry ice, which vaporizes at temperatures above about minus 112 degrees Fahrenheit (minus 80 degrees Celsius), evaporates and reduces local air temperatures enough to cause spontaneous freezing. This was the first seeding agent used in precipitation-modification experiments.

An alternative (and more successful) approach uses silver iodide as the seeding agent. The crystalline structure of silver iodide particles resembles that of ice crystals, and provides an efficient nucleus on which freezing occurs at about 20 degrees Fahrenheit (minus seven degrees Celsius). Silver iodide is the agent used in most modern seeding experiments, deployed in slow-burning, self-consuming, solid-propellant tubes whose exhaust product is a silver-iodide-rich cloud.

The seeding technique employed in Stormfury is called dynamic seeding because it taps into the internal dynamics of cumulus clouds to accomplish the desired result. Developed for use in the cumulus modification experiments conducted by NOAA in Florida, dynamic seeding has produced significant and promising results in improving the rainmaking efficiency of seeded cloud systems.

In that project, towering cumulus clouds are seeded at about the 22,000-feet (6,600-meter) level with pyrotechnics that produce silver-iodide smoke, "persuading" supercooled water in the cloud to freeze, and releasing the water's latent heat into the cloud system. The addition of this heat energy causes the cloud to become more buoyant, develop more fully than it would have naturally, and merge with neighboring clouds. The Florida experiments of recent years have demonstrated that dynamic seeding increases rainfall from the seeded clouds over an area in which seeding has occurred. The technique also intensifies the vertical development of the seeded cloud, which is how dynamic seeding is employed in Stormfury.



Tracks of seeded hurricanes. *Since the early 1960's, Stormfury scientists have seeded four hurricanes: Esther, 1961; Beulah, 1963; Debbie, 1969; and Ginger, 1971. This diagram shows the tracks of those storms, and when and where they were seeded.*

There, the hypothesis went, seeding with silver iodide across the wall clouds of a hurricane would intensify vertical development and change the structure of the storm.

Specifically, it would smooth the characteristically sharp drop in atmospheric pressure across the eyewall. Since this pressure difference drives hurricane winds, smoothing it would reduce maximum winds, and cause the tight spiral of the hurricane to open. This larger circulation, like the extended arms of a spinning ice skater, would slow the spin of the hurricane's winds.

Early experiments. The first storm seeded in this program was hurricane Esther in 1961. On September 16 and 17 clouds near the eyewall were seeded with eight pyrotechnics containing nine pounds (four kilograms) each of silver iodide, which burned from the drop altitude of about 43,000 feet (13,000 meters) down to about 22,000 feet (6,000 meters).

The most striking change observed during subsequent monitoring of the storm was a decrease in radar reflectivity on 10-centimeter radar as against little or no change on three-centimeter radar. This difference could have been caused by a reduction in raindrop size or the replacement of raindrops with ice crystals; however, no cloud physics instrumentation was available on the aircraft to corroborate that possibility, and no significant changes in the appearance of the eyewall were observed. Maximum winds measured by the monitoring aircraft decreased by nine percent at 7,000 feet (2,100 meters) and by fourteen percent at 20,000 feet (6,000 meters). But these changes were well within the range of natural variations in a hurricane. No change was observed on the 17th, when the silver iodide was apparently dropped into a cloud-free zone.

On August 23 and 24, 1963, hurricane Beulah was seeded with pyrotechnics containing about 750 pounds (340 kilograms) of silver iodide. These were dropped in a single seeding run along a flight path outside the eyewall. No changes were observed on the 23rd, when the pyrotechnics were apparently dropped into a cloud-free area. On the 24th, no significant intensity changes in radar reflectivity were discernible, but the pattern of echoes suggested that the original eyewall weakened and a new one became established about 10 nautical miles (16 kilometers) outside the original one in about two hours. At 18,000 feet (5,400 meters), maximum winds shifted outward by about the same amount and decreased by about ten percent in two and a half hours on the right side of the eye, and by about 15 percent over four and a half hours in the left rear quadrant of the storm. Again, the magnitude of these changes was well within the range of natural variations observed in unseeded hurricanes.

The last storm to be seeded by this series of Stormfury experiments was hurricane Ginger on September 26 and 28, 1971. Since this storm did not have a suitable structure for the eyewall modification experiment, clouds were seeded well away from the storm center. Some localized effects were detected, but there seems to have been no effect on the storm. This experiment, like the primitive effort in 1947, is not considered by hurricane researchers as a true test of the Stormfury hypothesis.

Debbie. The set of experiments that appear to have been most successful—and most convincing to skeptical hurricane researchers—was the Project Stormfury seeding of hurricane Debbie on August 18 and 20, 1969. The seeding technique was changed for the Debbie experiments, with five successive seedings carried out at intervals of about two hours. In each seeding, approximately 200 pyrotechnics were dropped, each containing about four-tenths of a pound (.190 kilogram) of silver iodide. Thus, about 80 pounds (36 kilograms) of seeding agent were introduced in each seeding, with a total amount of about 500 pounds (227 kilograms) over a period of eight to ten hours.

On August 18, maximum winds were near 100 knots (50 meters per second) before the seeding began. After five seedings, and by the end of the monitoring period four to six hours after the last seeding, maximum winds had dropped to 70 knots (35 meters per second), a reduction of about 30 percent. There was also clear evidence from radar that the eyewall had expanded to a larger diameter within about an hour after the fourth seeding. Although these changes are still within the range of natural variability, it is rare that an unseeded storm shows such a large decrease in wind speed, followed by a recovery to maximum winds.

Debbie was not seeded on August 19, and regained strength. The storm also developed the rare structure of two concentric eyewall clouds with maximum wind bands about 10 and 20 nautical miles (18 and 36 kilometers) from the storm center. Both eyewalls persisted after the August 20 seeding, but the wind maximum of the inner eyewall nearly disappeared; the outer wind maximum decreased by about 15 percent, to 85 knots (43 meters per second) four to six hours after the final seeding.

Limited opportunities. A key problem in Stormfury has been the dearth of opportunities to test the seeding hypothesis. In an average year, one can expect four to six hurricanes to develop in the Atlantic, Gulf, and Caribbean area. And yet, over a decade Stormfury was able to seed only four storms, and there were six years between Beulah and Debbie.

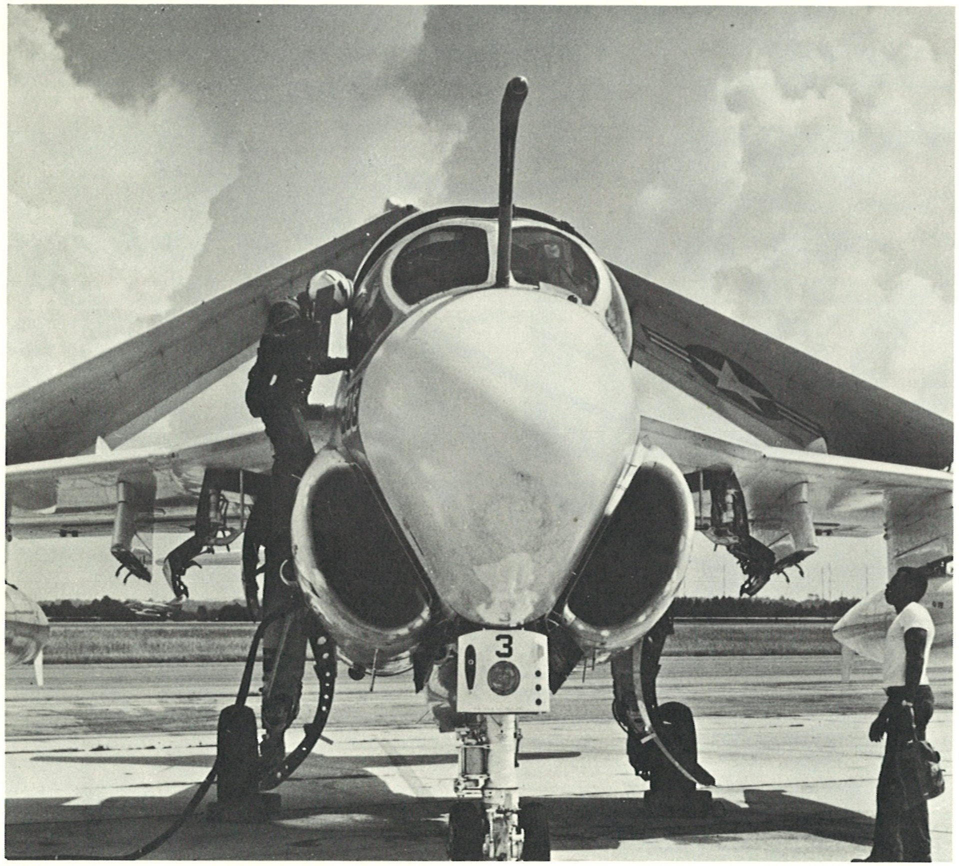
The lack of opportunities came from the safeguards built into the experiment to minimize the possibility that a seeded storm would touch a populated area while the seeding effect—which appears to last only a few hours—persisted. These safeguards reflected public concern that seeding might deflect the storm's path, or increase its intensity, or reduce seasonal rainfall. Although recent research indicates such fears are groundless, they have helped shape the experiment. So has scientific concern that the storms be seeded and monitored

***Stormfury 1969.** For the Debbie seeding in 1969, scientists, and aircrews from the Commerce Department, Navy, and Air Force converged on Puerto Rico. Marine A-6* Intruders *(at right) carried the seeding agent across the eyewall.*

over the neutral environment of the ocean, where anomalous effects from land masses are not a problem.

Thus, to be eligible for seeding under the Stormfury criteria, a hurricane could not have more than a ten percent chance of making landfall within 18 to 24 hours. This constraint put many otherwise eligible storms out of reach.

Back to basics. It became clear after the Ginger seeding that something would have to be done to increase opportunities, and to refine the experiment itself. Hurricane modification could not go very much farther without additional basic research. Also, it was clear that the capabilities of the aircraft and instrumentation taken into the storms would have to be greatly extended. In late 1972, NOAA focused its Stormfury efforts on hurricane research, temporarily suspending the seeding operations of Stormfury. At the same time, it moved to replace the aging piston-powered research aircraft with new, turbine-powered ones, equipped with the best instrumentation available from present-day technology.



Hurricane research from 1973 through 1976 saw Stormfury scientists fly purely research missions into western hemisphere hurricanes. These probes brought back data which they have turned into a greatly improved understanding of hurricanes and their susceptibility to seeding.

Two new aircraft have come on line for hurricane research as well. NOAA's Research Facilities Center, located at Miami International Airport, has received and instrumented two new WP-3D *Orion* aircraft. The four-engined turboprop machines carry instrumentation and state-of-the-art radars that permit scientists to take a closer look at hurricanes than they ever had before. The new aircraft—and a WC-130B also operated by the Miami facility— have the endurance and instrumentation needed to carry out seeding missions of unparalleled duration and precision.

By the hurricane season of 1977, NOAA researchers and their colleagues in other organizations, were ready to test their theories again in the violent laboratory of the hurricane.

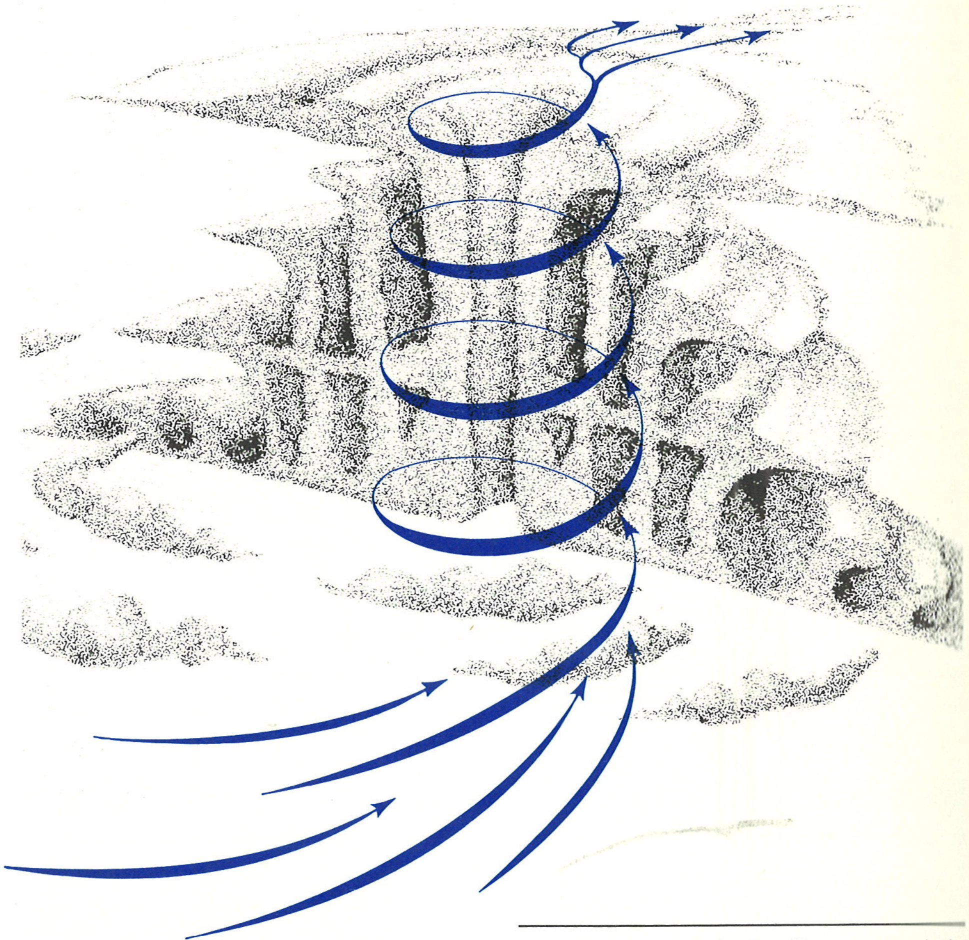
STORMFURY TODAY

The crucial lesson of early Stormfury experimentation was less what seeding could do to a hurricane than that hurricane research and hurricane modification were inextricably linked. As a result, Stormfury has come to identify a continuing program of hurricane research as well as a synonym for seeding them.

The seeding experiment itself resembles the early efforts, although the resemblance is superficial. Now, as then, the seeding experiment is an attempt to evaluate a promising scientific hypothesis; it is not a sudden move into operational seeding of hurricanes, which is a separate and much broader issue than experimental seeding. Today's Stormfury modification experiment rests on a much more extensive body of information than was available to early experimenters. Hurricanes are better understood than they were when a swarm of fighter-bombers, hurricane hunters, and research planes assaulted hurricane Debbie nearly a decade ago.

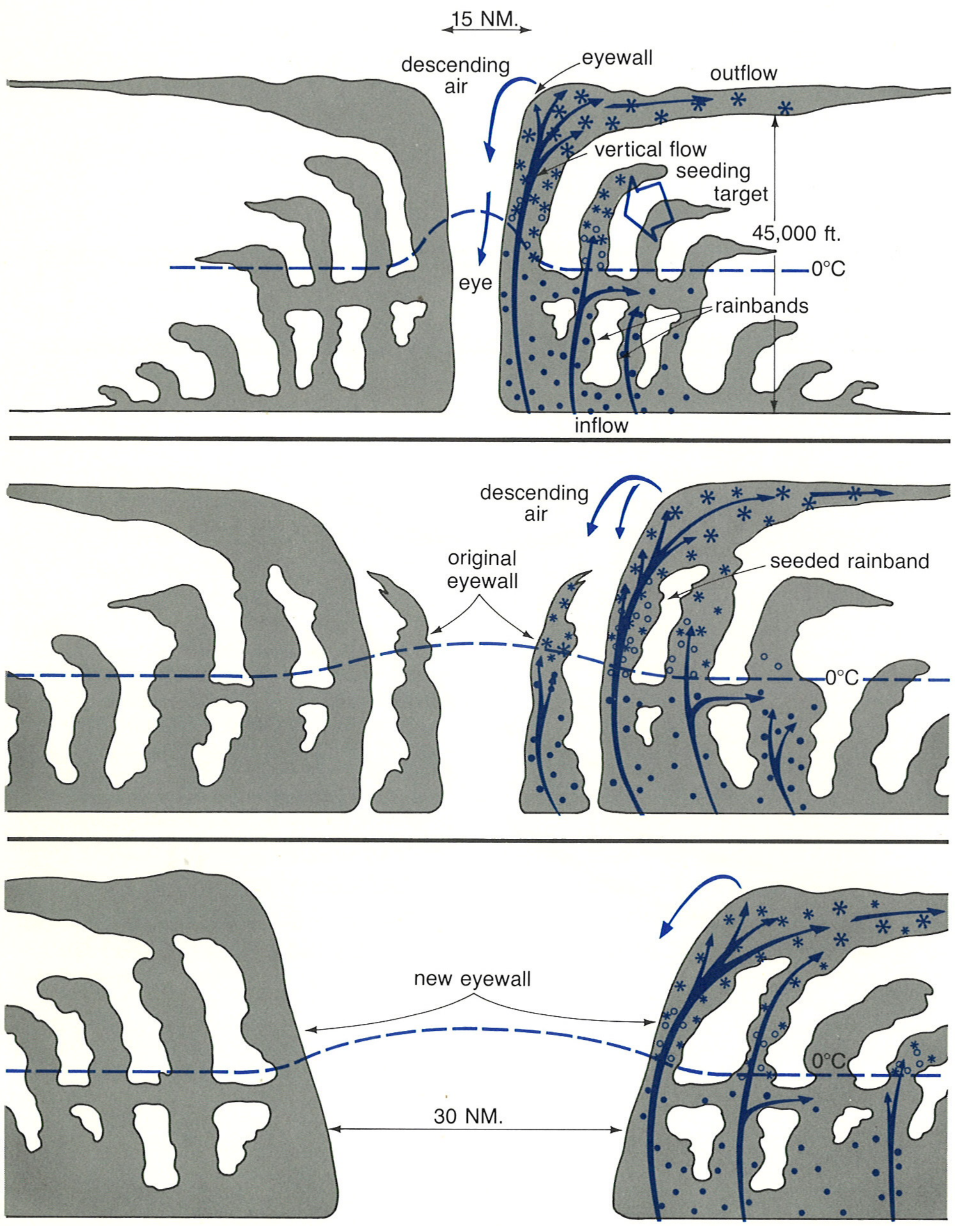
Evolution of a hypothesis. One of the important differences between Stormfury present and Stormfuries past is that scientists have a more complete view of what seeding can be expected to do in a hurricane. Where the early experiments were based on scientific intuitions and experience, the ones proposed today are based on hard data obtained in the years of hurricane research flights.

In the present experiment, the seeding pyrotechnics are dropped between about 27,000 and 30,000 feet (8,000 and 9,000 meters), and burn until they are consumed at about 15,000 feet (4,500 meters) altitude. These altitudes represent the approximate boundaries of available supercooled water in cumulus cloud towers outside the eyewall.



Hurricane structure and dynamics. *Moist air flows into the mature hurricane near the surface, spiralling inward toward the violent maelstrom of wind and water around the calm eye. Vertically developed cloud systems form the eyewall, and are the storm's main conduit for vertical transport of incoming air. As this air is lifted and cooled, its cargo of condensing and freezing water releases large quantities of heat into the storm–this is the energy that drives the hurricane.*

Stormfury hypothesis. *Seeding supercooled water in the immature cumulus cloud towers outside the eyewall induces the water to freeze, liberating its latent heat into the cloud systems. This makes the seeded clouds more buoyant, and enhances their vertical development. As they build up to the hurricane's outflow layer, they replace the original eyewall as the main vertical conduit of the storm. The original eyewall, meanwhile, dissipates, leaving an eye of greater diameter, with reduced maximum winds in the new eyewall.*



● liquid water
* ice
○ supercooled water

Recent research has shown that much of the water in this part of the storm has already frozen, and so is not seedable. But it has also identified something scientists had hoped was present: cloud towers embedded in the storm outside the eyewall in which supercooled water co-exists with ice crystals in sufficient quantities to make dynamic seeding effective.

Seeding would intensify convection (vertical motion) in these embedded towers, causing them to build until they reached the storm's high-altitude outflow layer. The seeded clouds would then become the storm's main vertical conduit, and the original eyewall clouds would dissipate. The effect of building a secondary eyewall outboard of the original is to spread the storm, and therefore cause the maximum winds to diminish.

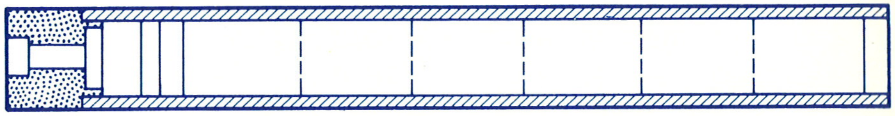
The flight profiles themselves have changed with the advent of new aircraft. Instead of a seeding dash along a radius across the eyewall clouds, Stormfury seeding airplanes stay in the storm, flying a seeding line that is an arc outside and parallel to the eyewall, returning to the eye, then flying the arc again. This permits massive seeding by relatively few airplanes.

Pyrotechnics improved. One of the key ingredients in an experiment like Stormfury is a pyrotechnic seeding device that is reliable and an efficient producer of large numbers of silver iodide ice nuclei. In the past, seeding has been carried out with self-consuming pyrotechnics resembling seven-ounce beer cans, fired from externally mounted racks on the aircraft. For Stormfury, the Naval Weapons Center at China Lake, California, has developed a new seeding apparatus that functions like a kind of Gatling gun.

The new device uses pyrotechnic rounds about the size of a fountain pen, loaded in oblong magazines. When in operation, the seeding apparatus strips a round from the magazine, and drops the round primer-down into a chute in the airplane floor. A firing pin at the bottom of the chute ignites the pyrotechnic as it tumbles clear of the airplane. In a Stormfury seeding sequence, some 8,000 to 10,000 of these pyrotechnic rounds are used, at a rate of up to two per second. The amount of silver iodide is similar to that introduced into hurricane Debbie —about 500 pounds (225 kilograms) per seeding.

Model hurricanes. Given the limited opportunities to explore hurricanes in nature, NOAA's National Hurricane and Experimental Meteorology Laboratory has developed a powerful alternative—the use of advanced numerical models. In these, mathematical equations are used to simulate physical processes in the atmosphere, permitting scientists to study hurricanes with different characteristics, in different atmospheric settings.

Early models from the Miami laboratory were two-dimensional (height versus radius) and treated the storm as symmetrical



Pyrotechnic seeding round. *Cutaway actual-size diagram shows components of pyrotechnic used in Stormfury seeding experiments. The round is dropped from a chute in the belly of the seeding aircraft, and ignites as it falls away from the plane, burning for several thousand feet of fall. It is self-consuming: nothing is left after burning but a vertical column of silver-iodide-enriched smoke.*

about the center. These yield realistic simulations of hurricane development from a weak initial vortex to steady hurricane-like systems. But they do not simulate realistically the interactions between the hurricane and its larger-scale environment, which influence storm intensity and motion. Larger computers have permitted the development of more versatile three-dimensional, time-dependent models that do simulate such effects more realistically.

In general, though, the models compare very well with observations of natural hurricanes with regard to most aspects of hurricane formation, structure, and motion. This ability to simulate natural hurricanes has led the researchers to use the models to test the effects of possible hurricane modification techniques. What the models are simulating is essentially the change in heating rates caused by the addition of heat from dynamically seeded cloud systems, and what the effect of that heating-rate change is likely to be.

Taken with hurricane observations made over the years, these numerical simulations are the only source of information on how seeding affects a hurricane. They show that:

- seeding the original eyewall consistently results in increased model hurricane intensity;
- seeding just outside the original eyewall decreases maximum winds by about 10 percent and increases the radius of maximum winds by about 50 percent;
- at the same time, the original model eyewall dissipates, and is replaced by a newly formed model eyewall at the greater radius;
- beyond the radius of new maximum winds there is a small increase in model wind speed, the net effect being an increase in the model storm's total kinetic energy (the energy of rotation);
- an insignificant increase in total storm rainfall in the model is accompanied by an outward displacement of maximum rainfall rates coinciding with the change in radius of maximum winds.
- in simulations with the three-dimensional model, the track of the modeled storm during and for 24 hours after simulated seeding differs from that of an unseeded model storm by less than the diameter of the model storm's eye.

Within the limitations of such model simulations, Stormfury scientists find these results encouraging, for they answer some of the persistent questions—and some of the persistent objections—raised by the experiment. At the same time, they are consistent with the changes observed in the hurricane modification experiments carried out in the 1960's. They are also consistent with the Stormfury hypothesis. Thus, mathematical hurricanes have done much to refine the design of the present Stormfury experiment.

THE EXPERIMENT

When a prospective tropical cyclone circulation becomes apparent during the Stormfury operational period, scientists at the National Hurricane and Experimental Meteorology Laboratory, working with forecasters at NOAA's National Hurricane Center, monitor forecasts for possible candidate storms. An alerting process begins three days (72 hours) before the experiment, with possibilities of cancelled alerts at each decision point. These alerts, which cascade down in 24-hour increments, gradually cause the people and resources needed to conduct Stormfury to converge at the selected base of operations. Primary base of operations for Stormfury operations is San Juan, Puerto Rico, with a secondary base at Miami, Florida. Provisions are also made for recovery of mission aircraft in Bermuda as required.

Eligibility. To be eligible for seeding by Stormfury, a hurricane must be predicted to be within 700 nautical miles (1,100 kilometers) of the operating base for a minimum of 12 hours, and maximum winds in the storm must be at least 65 knots (38 meters per second). Landfall constraints are tighter than before. The predicted track of eligible hurricanes cannot have more than a 10 percent probability of approaching within 50 nautical miles (90 kilometers) of a populated land area for 24 hours after seeding.

Approval for seeding a specific hurricane at a specified time must come from the Associate Administrator of NOAA. Preparations for seeding, and the final decision to seed (based on storm structure and other criteria) are made in the field. Throughout, the Associate Administrator may cancel any previously given seeding authorization before seeding begins.

Stormfury's Project Manager is Director of the Weather Modification Program Office, of NOAA's Environmental Research Laboratories, which controls the two Miami facilities involved. The Director of the National Hurricane and Experimental Meteorology Laboratory is Scientific Director of Stormfury.

The aircraft. Stormfury brings together a uniquely equipped squadron of superbly fitted research aircraft. Three aircraft participate from NOAA's Research Facilities Center in Miami—two WP-3D *Orions,* and the WC-130B.

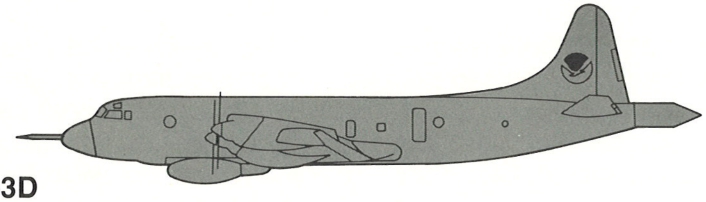
The *Orions* carry what is probably the world's most advanced atmospheric instrumentation, including digitized, video-recorded radar. This high-technology radar gives scientists aboard the airplanes a continuous, three-dimensional look at hurricanes from the inside, permitting them to isolate cells of various intensities. Since the Stormfury seeding concept is built on the ability to identify and seed specific, seedable cloud towers, this radar information is vital.

The new airplanes also carry full arrays of cloud physics instrumentation to measure cloud droplets, liquid water, ice, and a host of other parameters related to the amount and form of water in a hurricane. Because water from the sea carries the heat energy that powers the storm, these are very significant measurements.

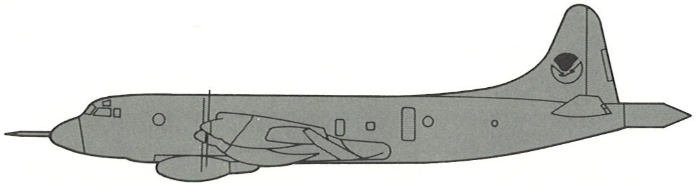
In addition, the *Orions* are equipped with versatile radiation and sea-surface temperature sensors, and expendable instruments to profile the atmosphere between the airplane and the surface and to measure ocean temperatures from the surface to depths of several hundred feet.

The NOAA C-130 carries conventional meteorological instrumentation, and an advanced system called the Airborne Weather Reconnaissance System (AWRS), a computerized data acquisition and display unit developed by the Air Weather Service of the U.S. Air Force.

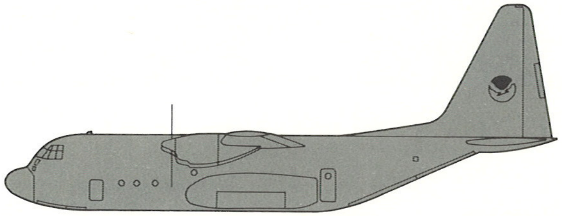
A second WC-130B—the other AWRS airplane—will also participate in Stormfury, operating for NOAA from the Air Force 53d Weather Reconnaissance Squadron at Keesler Air Force Base, Mississippi. This Hurricane Hunter will not engage in seeding,



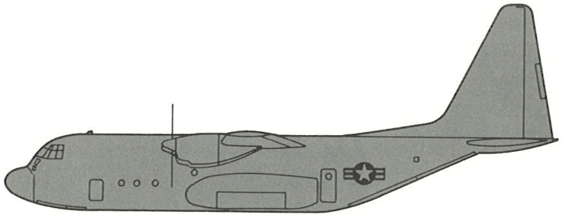
NOAA WP-3D



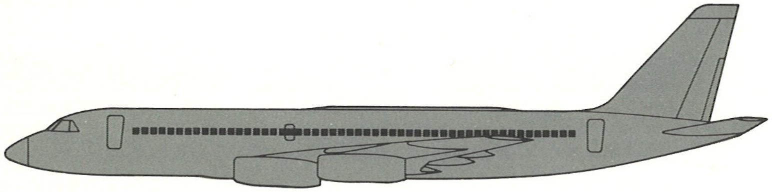
NOAA WP-3D



NOAA WC-130B



Air-Force WC-130B



NASA CV-990

but will perform a monitoring role similar to the hurricane reconnaissance missions routinely provided to NOAA by the Air Force.

The National Aeronautics and Space Administration's Galileo II, a Convair 990 configured for scientific research, provides the high-altitude capability needed in Stormfury. The airplane is operated by NASA's Ames Research Center, Mountain View, California, and has been specially modified with cloud physics instrumentation, radar, and seeding equipment for Stormfury.

To keep the aircraft almost continuously in the hurricane, Stormfury uses backup crews and rapid reprovisionings of returning airplanes at the operations base.

The eyemod experiment. The experiment begins with one of the NOAA P-3's entering the storm between 1,500 and 5,000 feet (460 and 1,500 meters), four hours before the beginning of the first seeding period. The P-3 flies monitoring patterns across and around the edges of the storm for seven hours.

Meanwhile, the faster, higher-flying NASA 990 enters the storm near 40,000 feet (12,000 meters) two hours before the first seeding period, and monitors high-level cloud physics and storm outflow dynamics.

An hour before the first seeding period, the NOAA C-130 enters the storm near 20,000 feet (6,000 meters), flies a monitoring pattern across the storm, and climbs to 27,000 feet (8,100 meters). The 990 descends to 30,000 feet (9,000 meters), and the two aircraft begin the first seeding runs, flying from the eye of the hurricane out into the seeding area, which is an arced band concentric with and just outside the eyewall.

Three hours after the first seeding period begins, the 990 turns for home. As it does, the

Stormfury aircraft instrumentation

	Meteorological Sensors	Temperature	Pressure	Dewpoint	Sideslip	Humidity	Winds	Vertical Wind System	Vertical Wind System (AWRS)	Dropsonde	Omegasonde
NOAA WP-3D[1]		●	●	●	●		●	●			●
NOAA WP-3D[2]		●	●	●	●		●	●			●
NOAA WC-130B		●	●	●			●		●	●	●
USAF WC-130B		●	●	●			●		●	●	
NASA CV-990		●	●		●	*	●	*			

	Cloud Physics Instruments	Cloud Droplet Spectrum	Hydrometeor Size Spectrum	Hydrometeor Size Spectrum (Impactor)	Small Cloud Droplet Spectrum	Cloud Liquid Water	Total Water Content	Total Liquid Water Content	Ice-Water Discriminator	Ice Particle Counter	Cloud Condensation Nuclei	Bulk Water Sampling System	Cloud Particle Replicator	Water Burden (radiometric)
NOAA WP-3D[1]		●	●	●		●	●	●	●		●	●		
NOAA WP-3D[2]		●	●		●	●	●	●		●			●	
NOAA WC-130B			●			●	●	●	●				●	
USAF WC-130B		●					●							
NASA CV-990		*	*				●	●	*					●

	Nuclei	Total dust	Ice Nuclei	Condensation Nuclei	Millipore filter system	Ice nucleus counter
NOAA WP-3D[1]		●	●	●	●	
NOAA WP-3D[2]						
NOAA WC-130B		●	●	●	●	●
USAF WC-130B						
NASA CV-990						

	Radiation	Sea-Surface Temperature	Scanning Radiometer	CO_2 Air Temperature	Microwave Radiometer	Infrared Vertical Temperature Profile	JPL X- and L-Band Imaging Radars
NOAA WP-3D[1]		●		●			
NOAA WP-3D[2]		●		●	●		
NOAA WC-130B		●		●			
USAF WC-130B							
NASA CV-990		*	*	*		*	●

	Radar	Digitized and Videorecorded	C-band belly 360° horizontal scan	X-band tail 360° vertical scan	C-band nose 240° conical scan	X-band nose 220° conical scan	X-band nose 180° pencil scan	X-band beam
NOAA WP-3D[1]			●	●	●			
NOAA WP-3D[2]			●	●	●			
NOAA WC-130B					●			
USAF WC-130B						●		
NASA CV-990							●	*

	Miscellany	Gust Probe	Airborne Expendable Bathythermograph	Flare Seeding (internal)	Photography (nose, side, vertical)	Photography (side, forward)	Photography (forward, horizon-to-horizon)	Laser Altimeter
NOAA WP-3D[1]		●	●	●	●			●
NOAA WP-3D[2]		●	●	●	●			
NOAA WC-130B				●		●		
USAF WC-130B								
NASA CV-990				*			●	

[1] **low level** [2] **high level** * Added by NOAA for Stormfury.

Stormfury aircraft performance data

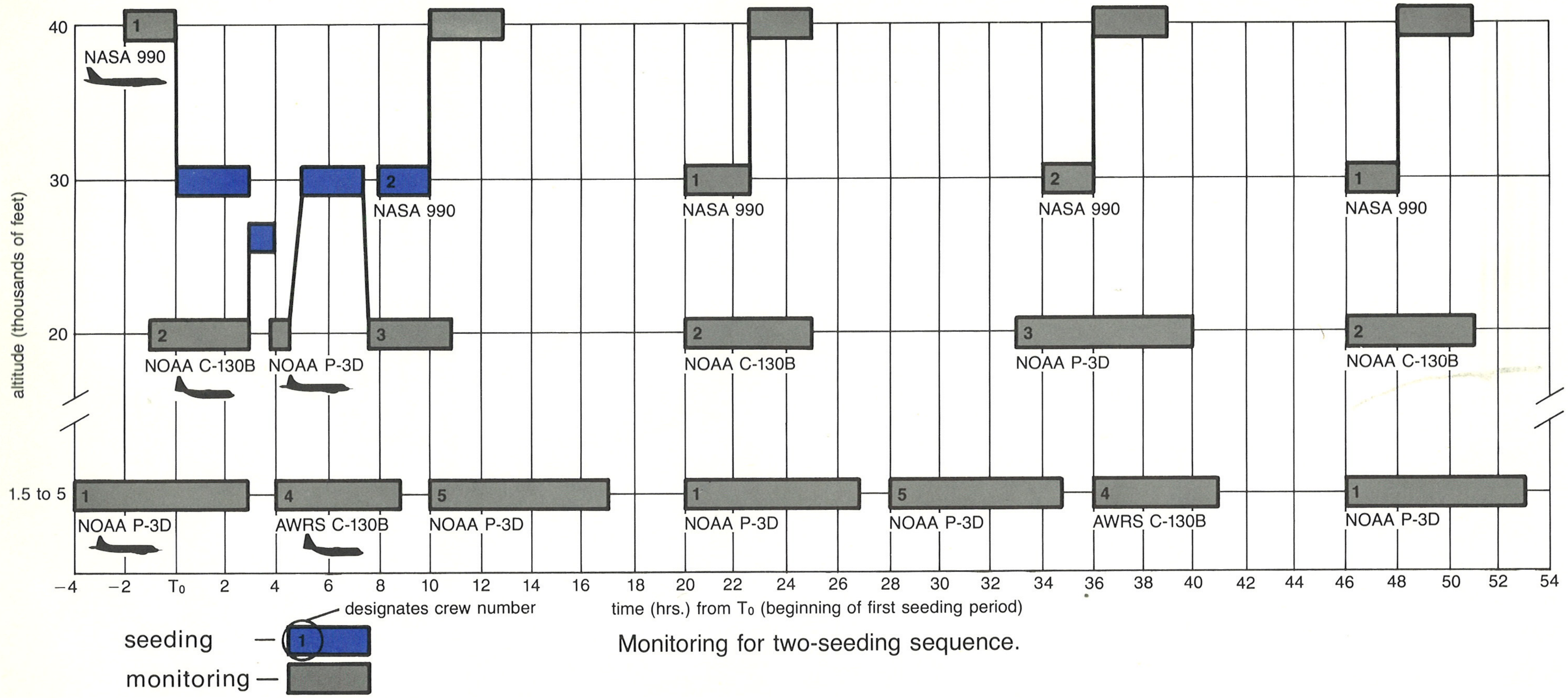
	WC-130B (NOAA & USAF)	WP-3D	CV-990
Production date	1958	1975	1964
Agency acquisition date	1970	1975	1973
Dimensions			
Wing span	132′ 7″	99′ 7″	120′
Length	97′ 9″	111′ 2″	139′ 9″
Engines	4 Allison T-56-A-7	4 Allison T-56-A-14	4 GE CJ-805
Takeoff power, each engine	3,755 hp	4,600 hp	16,100 lb.
Maximum takeoff weight	135,000 lb.	135,000 lb.	253,000 lb.
Normal speed, true, optimum altitude	280 kts.	325 kts.	540 kts. (max. cruise)
Turbulent air speed (severe weather penetration)	180 kts.	220 kts.	
Maximum useable fuel	45,240 lb.	57,800 lb.	105,000 lb.
En route time (hours) at:			
500 feet altitude	6.5	8.5	
10,000 feet	8.0	9.5	
20,000 feet	9.0	10.7	
Maximum range (four-engine cruise) at:			3,350 n.m. with 27,770 lb. payload 180,000 lb. fuel
500 feet	1,700 n.m.	2,250 n.m.	
20,000 feet	2,400 n.m.	3,300 n.m.	
Maximum range (step climb)	2,700 n.m.	3,600 n.m.	

second P-3 arrives on station at 20,000 feet, flies a monitoring pattern through the storm, and climbs to 30,000 feet, replacing the 990 seeder. At the lower levels of the storm the first P-3 returns to base, replaced by the Air Force C-130. The NOAA C-130 also returns to base about five hours after the first seeding period begins.

Eight hours after the first seeding period begins, the second NOAA P-3 descends from seeding altitude to a monitoring altitude of 23,000 feet, where it stays for four more hours. The 990, meanwhile, returns to the storm and resumes seeding at 30,000 feet, then, two hours later, climbs back to 40,000 feet for three hours of high-altitude monitoring.

About 20 hours after beginning the first seeding period the NOAA C-130 takes up its monitoring pattern at about 20,000 feet. The NASA 990 enters the storm at 30,000 feet and monitors for three hours, then climbs to 40,000 feet for monitoring at that level. Low-level monitoring by one of the NOAA P-3's and the Air Force C-130 is nearly continuous.

Additional monitoring is made about ten hours later at the 20,000-, 30,000-, and 40,000-foot levels, with near-continuous monitoring at the low, hurricane-inflow levels. The experiment may last as long as 53 hours after the first seeding period begins.



Monitoring for two-seeding sequence.

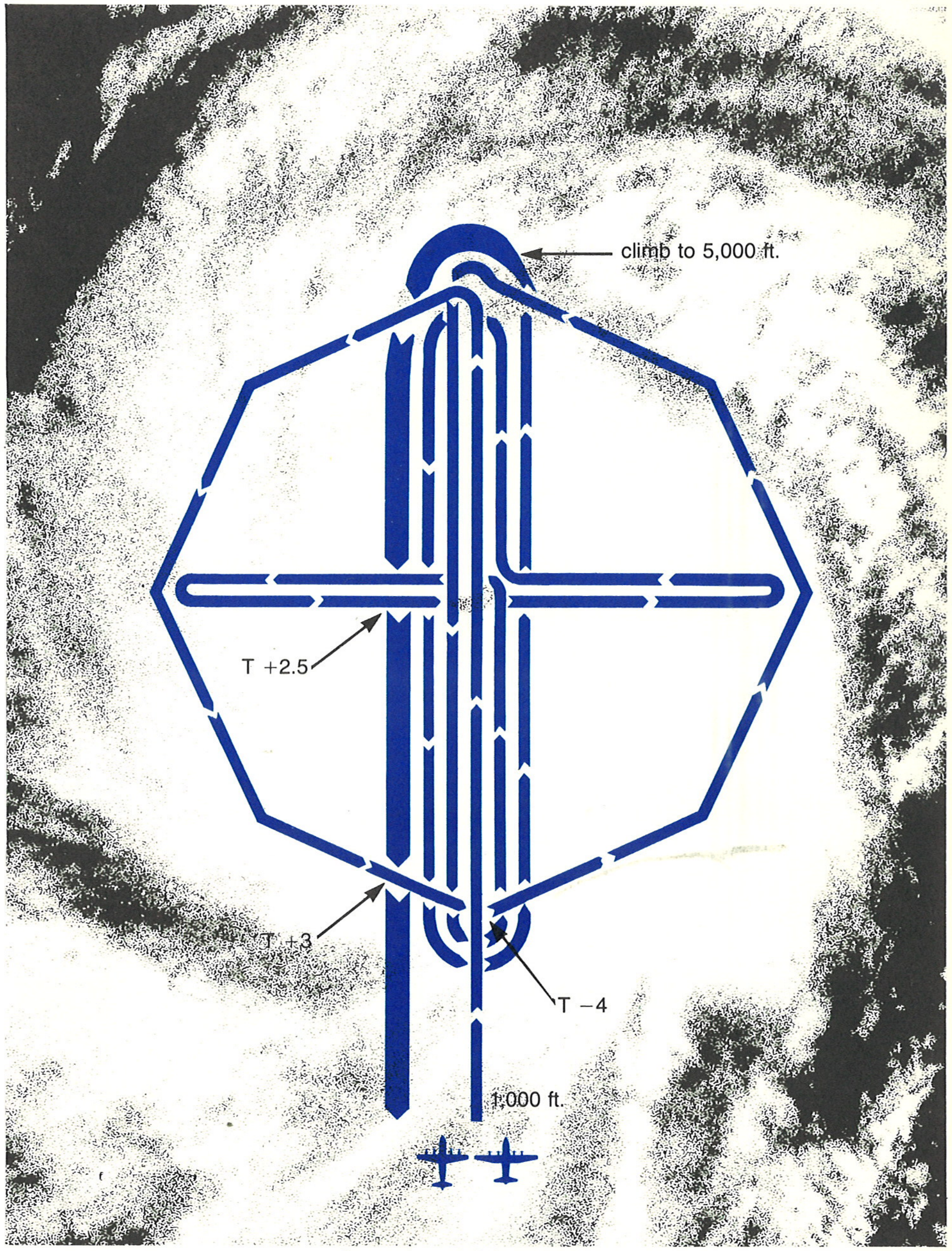
The experiment is not all seeding and monitoring for the effects of seeding. A serious test of the Stormfury hypothesis requires the measurement of certain critical properties of hurricanes. These include:

- how wind, temperature, pressure, and radar echo patterns vary with time in natural and seeded storms;
- how much supercooled water is available, how effectively it converts to ice, and how the resulting nuclei are distributed after seeding;
- how interactions between the hurricane and circulations in the upper atmosphere sustain or inhibit the storms;
- how interactions with the ocean —sea-surface temperature and moisture inflow into the storm, surface wind and wave fields, storm surge, and mixing and upwelling—change between natural and seeded storms.

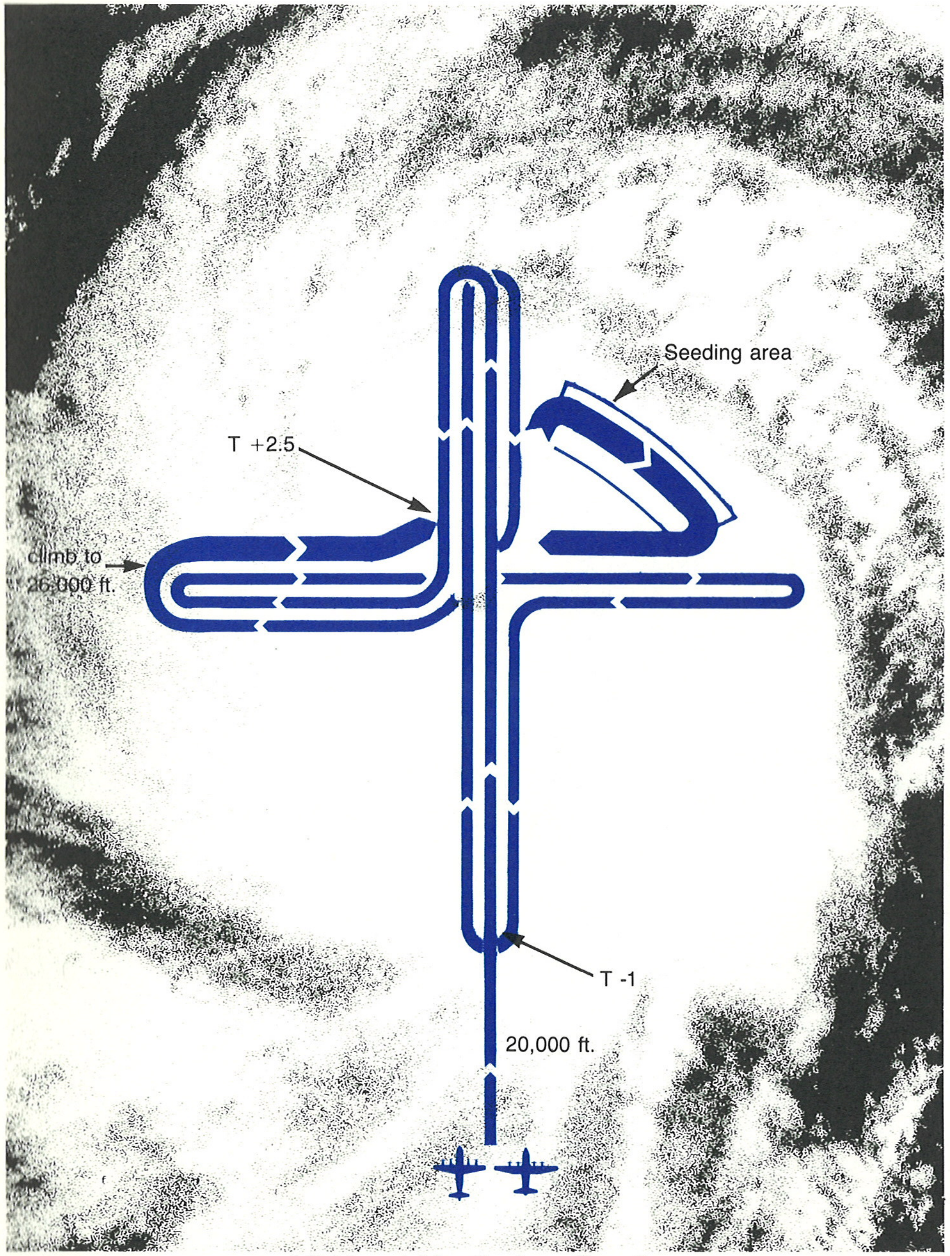
Fallback mission. If a candidate storm is unsuitable for seeding, a fallback long-term monitoring experiment may be conducted. Basically the same as the eye modification experiment without the seeding patterns, this mission permits the aircraft to monitor the storm almost continuously for as long as 60 hours, at three critical levels.

The turboprop P-3's and C-130's monitor two levels. One is 1,500 to 5,000 feet (460 to 1,500 meters), where moist surface air spirals in toward the hurricane center. The other is 20,000 to 24,000 feet (6,000 to 7,300 meters), corresponding to about the five to 23-degree Fahrenheit (minus 5 to minus 15-degree Celsius) levels in developing cloud towers.

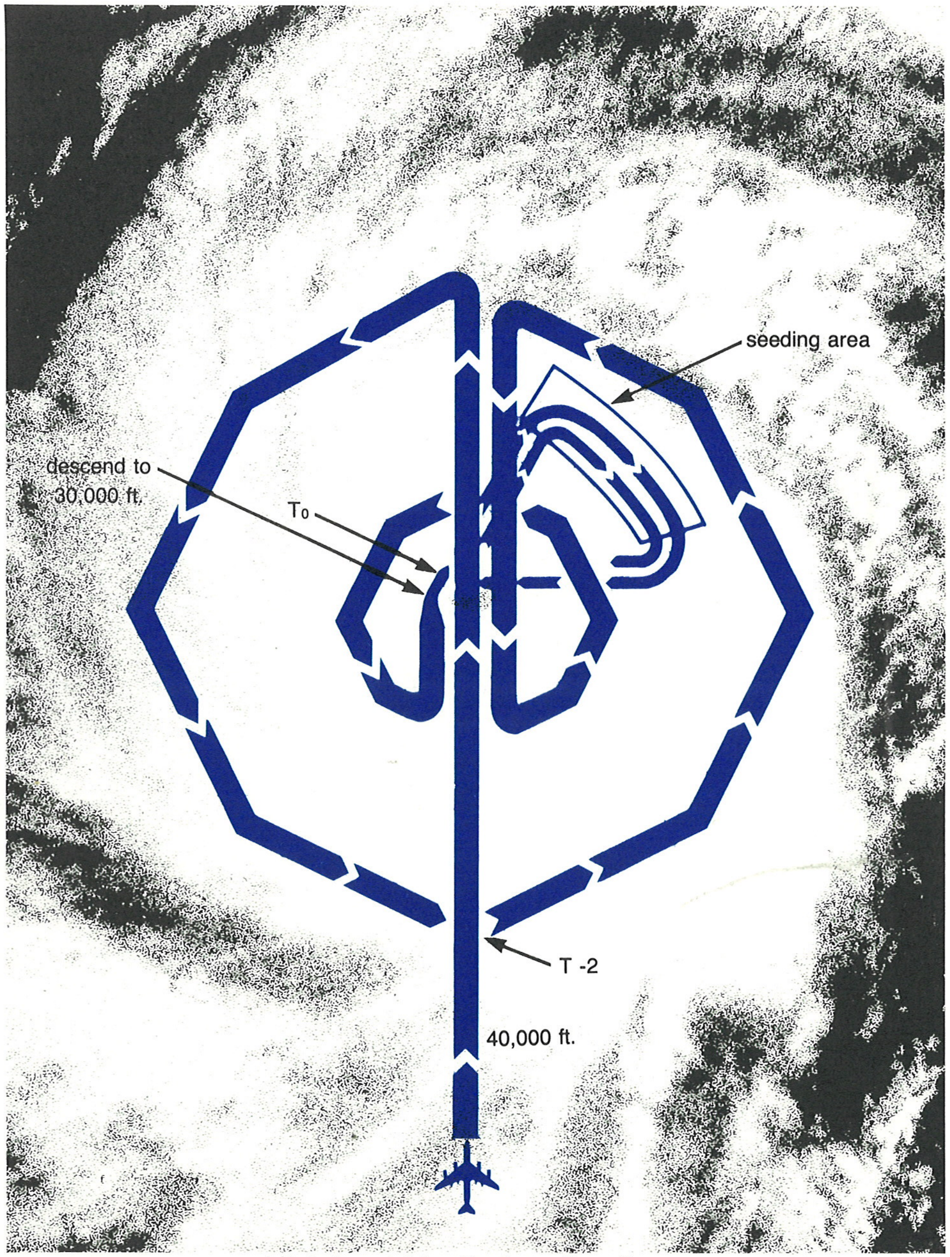
The higher-flying pure-jet 990 flies the 30,000 to 40,000-foot (9,000-to-12,000-meter) level, where the thermal engine of the hurricane exhausts enormous quantities of air and ice into the upper levels of the atmosphere.



Low-level Monitoring
1,000-5,000 ft.
(WP3-D, WC-130B)



Mid-level Monitoring; Seeding
20,000-26,000 ft.
(WP3-D, WC-130B)



High-level Monitoring; Seeding
30,000-40,000 ft.
(CV-990)

THE UNSOLVED PROBLEM

One of the major difficulties in getting Stormfury ready for resumption in the 1970's has been the search for more opportunities for seeding experiments. Stormfury scientists need a sample of at least ten successful hurricane-seeding experiments to evaluate their hypothesis. In the past, a decade's work produced only four opportunities; ten storms could take a generation.

But alternatives are being actively explored.

Stormfury 1977-1978 has working grounds in an area of the Western Atlantic northeast of the Bahamas and Antilles and south of Bermuda.

It may be that in future seasons the project will evolve into *Stormfury-Americas,* in which the United States and Mexico would collaborate in the experimental seeding of storms in the Atlantic-Caribbean area and in the eastern North Pacific. These Pacific storms have the advantage that they tend to curve out into the empty ocean, and so they would furnish more eligible hurricanes than the Atlantic.

Still another possibility under exploration by the nations concerned is that Stormfury would work hurricanes in the Western Atlantic during the northern hurricane season (June 1 through October 31), then move to Australia and collaborate with that government in seeding storms experimentally during the southern hurricane season, which coincides with the northern winter.

The most ambitious possibility is *Stormfury Pacific,* in which the project would move to the Western North Pacific, where the incidence of typhoons (the larger hurricanes of that region) is better than three times that of Atlantic hurricanes, and where the opportunities for seeding experiments, even with Stormfury constraints, would increase sixfold.

By mid-1977, much diplomacy and planning still separated a Stormfury seeding mission from the hurricanes of other regions. The probability was that the working grounds for Project Stormfury would continue to be the Western Atlantic northeast of the Bahamas, and that opportunities to test the Stormfury hypothesis would be as rare as they were in the 1960's.

Possible Stormfury areas. *In 1977 and 1978, Stormfury will work storms in western Atlantic area north of the Bahamas. Other possibilities under study include Atlantic-Caribbean area and eastern Pacific, typhoon areas of western Pacific, and South Pacific near Australia.*

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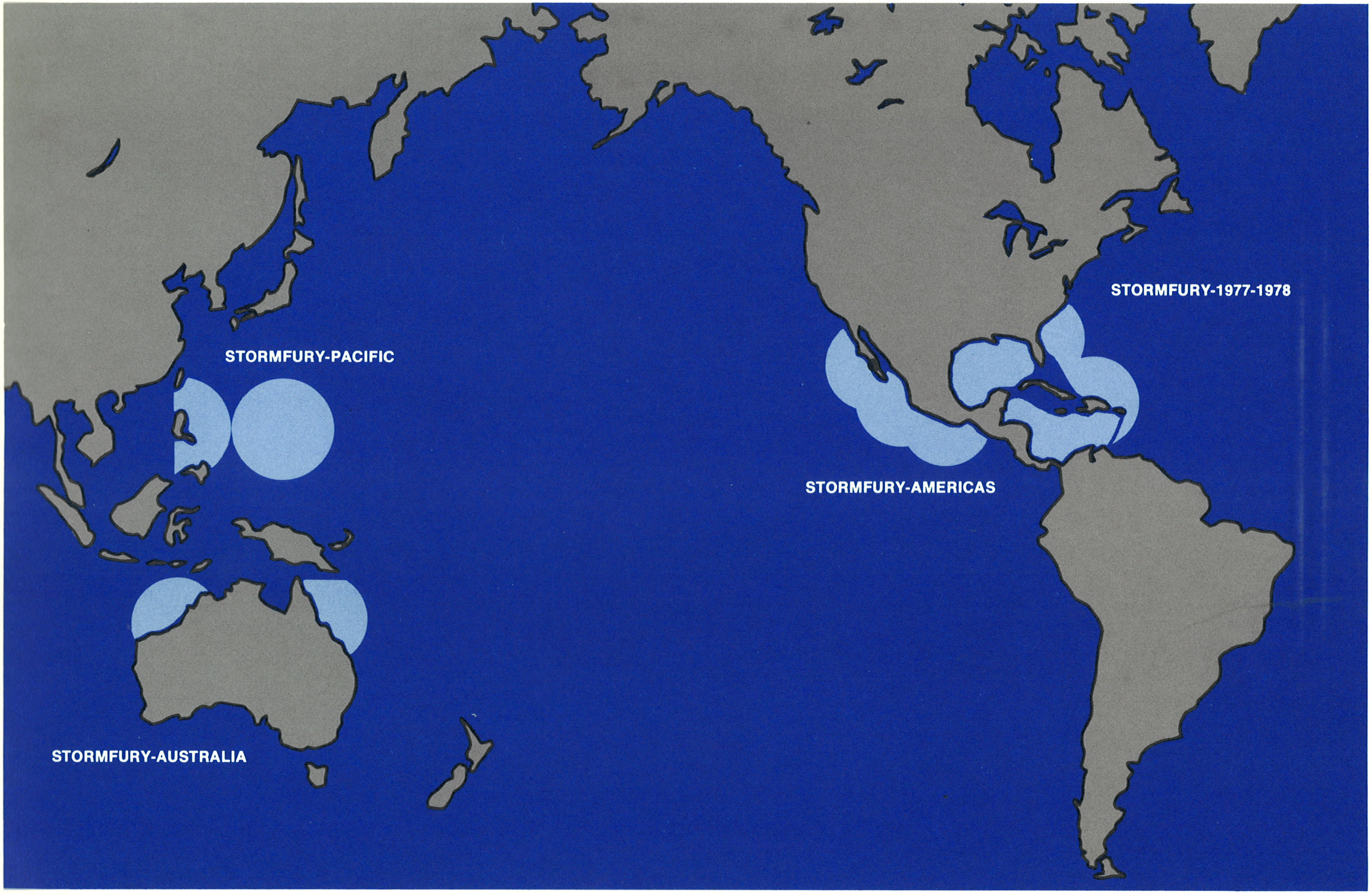
STORMFURY-PACIFIC
STORMFURY-1977-1978
STORMFURY-AMERICAS
STORMFURY-AUSTRALIA

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
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