Project STORMFURY: A Scientific Chronicle 1962–1983

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Abstract

Between 1962 and 1983, research in hurricane modification centered on an ambitious experimental program, Project STORMFURY. The proposed modification technique involved artificial stimulation of convection outside the eye wall through seeding with silver iodide. The artificially invigorated convection, it was argued, would compete with the convection in the original eye wall, lead to reformation of the eye wall at larger radius, and thus produce a decrease in the maximum wind.

Since a hurricane's destructive potential increases rapidly as its maximum wind becomes stronger, a reduction as small as 10% would have been worthwhile. Modification was attempted in four hurricanes on eight different days. On four of these days, the winds decreased by between 10 and 30%. The lack of response on the other days was interpreted to be the result of faulty execution of the experiment or poorly selected subjects.

These promising results have, however, come into question because recent observations of unmodified hurricanes indicate: 1) that cloud seeding has little prospect of success because hurricanes contain too much natural ice and too little supercooled water, and 2) that the positive results inferred from the seeding experiments in the 1960s probably stemmed from inability to discriminate between the expected effect of human intervention and the natural behavior of hurricanes.

1. Origins before 1962

In 1946, Langmuir (1948) and Schaefer (1946) discovered that introduction of carbon dioxide ice into clouds that contained supercooled water would convert the liquid to ice. Also in 1946, Vonnegut (1949) learned that smoke containing silver iodide had the same effect. The ice crystals formed by seeding quickly aggregated to form snow. The snow flakes fell from the cloud because they were larger than the suspended supercooled water droplets that had existed before. The experimenters claimed that they could either enhance precipitation or dissipate the cloud, depending upon the character of the initial cloud and the amount of seeding agent. The meteorological community had known about supercooled clouds for nearly half a century, but these discoveries allowed them to manipulate the behavior of clouds for the first time.

Despite some initial skepticism about weather modification, several U.S. Government agencies collaborated during the late 1940s in a pioneering weather modification effort, Project Cirrus. Among other notable firsts for Project Cirrus was the first cloud seeding in a hurricane (Langmuir, 1948). Before seeding began on 13 October 1947, the storm tracked toward the northeast over the Atlantic Ocean off the coasts of Georgia and North Florida. After seeding, observers aboard the experimental aircraft noted changes in the visual appearance of the clouds, but they could not demonstrate any other effects on structure or intensity. The one indisputable change—although apparently not the result of seeding (Mook *et al.*, 1957)—was a reversal of track toward the west, which ultimately led to landfall on the coasts of Georgia and South Carolina. Claims by Langmuir (Byers, 1974) that the track had been influenced through human intervention were an embarrassment at the time and left a legacy that had an adverse effect upon political and legal arrangements for later hurricane modification efforts.

The years 1954 and 1955 each brought three major hurricanes to the east coast of the United States. Hurricanes Carol, Edna, Hazel, Connie, Diane, and Ione together destroyed more than six billion dollars in property (adjusted to 1983) and killed nearly 400 U.S. citizens (Hebert and Taylor, 1983; National Oceanic and Atmospheric Administration, 1982). Six hurricane landfalls in two years seemed to call for some sort of governmental action. In the spring of 1955, the U.S. Congress appropriated substantially more money for hurricane research. After the 1955 hurricane season, it mandated that the U.S. Weather Bureau (USWB) establish the National Hurricane Research Project (NHRP), which was to become the National Hurricane Laboratory (NHRL) in 1964 and the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory in 1983. Within a year of its establishment, NHRP was utilizing Air Force aircraft to collect data on hurricanes. Within six years, the Weather Bureau had its own aircraft, and the series of NHRP reports contained nearly 60 titles. These included such topics as: numerical prediction of hurricane motion, storm surge, hurricane rainfall, aircraft instrumentation, hurricane climatology, and detailed studies of aircraft data obtained in the inner cores of a half dozen hurricanes (Simpson, 1980; Gentry, 1980). The mission of NHRP was fourfold: to study the formation of hurricanes; to study their structure and dynamics; *to seek means for hurricane modification*; and to seek means for improvement of forecasts (NHRP, 1956). The third objective was, in time, to provide justification for Project STORMFURY.

In 1961, the working hypothesis was that the area around the eye wall of a hurricane was either inertially unstable or nearly so and that the clouds there contained abundant supercooled water. Seeding near the eye was intended to perturb the surface pressure through additional latent heat release. The perturbation would then trigger the inertial instability and cause outward migration of the eye wall, leading to reduction of the maximum wind through conservation of angular momentum (Simpson *et al.*, 1962). The ideal hurricane for modification under the "STORMFURY Hypothesis" was,

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therefore, fairly intense, with a well-defined eye and a rapid decrease in wind speed with distance outside the eye wall.

The hypothesis was soon tested in the field. On 16 September 1961, a naval aircraft operating with the USWB aircraft dispensed eight canisters of silver iodide in the eye wall of Hurricane Esther. Observations obtained by other aircraft showed that the storm, which had been deepening about 1 mb an hour before seeding, stopped deepening and maintained nearly constant intensity afterward. Radial profiles of kinetic energy showed significant changes and some reduction near the eye wall (Fig. 1a). On 17 September the aircraft returned and seeded again. This time, however, the canisters were observed to fall outside the eye wall, and the storm retained roughly the same intensity that it had after seeding on the previous day. Given the observed weakening on the first day and the misdirected seeding on the second, the experiment was considered a success (Simpson *et al.,* 1962). The encouraging results from Hurricane Esther led to formal establishment of STORMFURY as a joint project of the U.S. Navy and Department of Commerce in 1962.

2. Experimentation, 1962-1977

By the early 1960s, cloud seeding had progressed far beyond Langmuir's initial experiments. Although the statistical results of extensive field studies, such as those in Australia (Smith *et al.,* 1963) and Arizona (Battan, 1966), were often ambiguous, the technology for execution and interpretation of seeding experiments improved rapidly. [See Byers (1974) for an informative and colorful account.] Moreover, the entrainment hypothesis (Stommel, 1947; Scorer and Ludlam, 1953; Levine, 1959) and insights from aircraft observations of unmodified cumuli (Malkus, 1952, 1954) led to numerical models of individual convective bubbles (Malkus, 1959). These calculations, originally executed by hand and later on computers, allowed the investigators to simulate the effects of seeding on isolated cumuli. Since conversion of liquid to ice released latent heat of fusion, introduction of seeding agents into the upper parts of cumulus clouds intensified the updrafts by making the air in them more buoyant. The enhanced updraft then drew

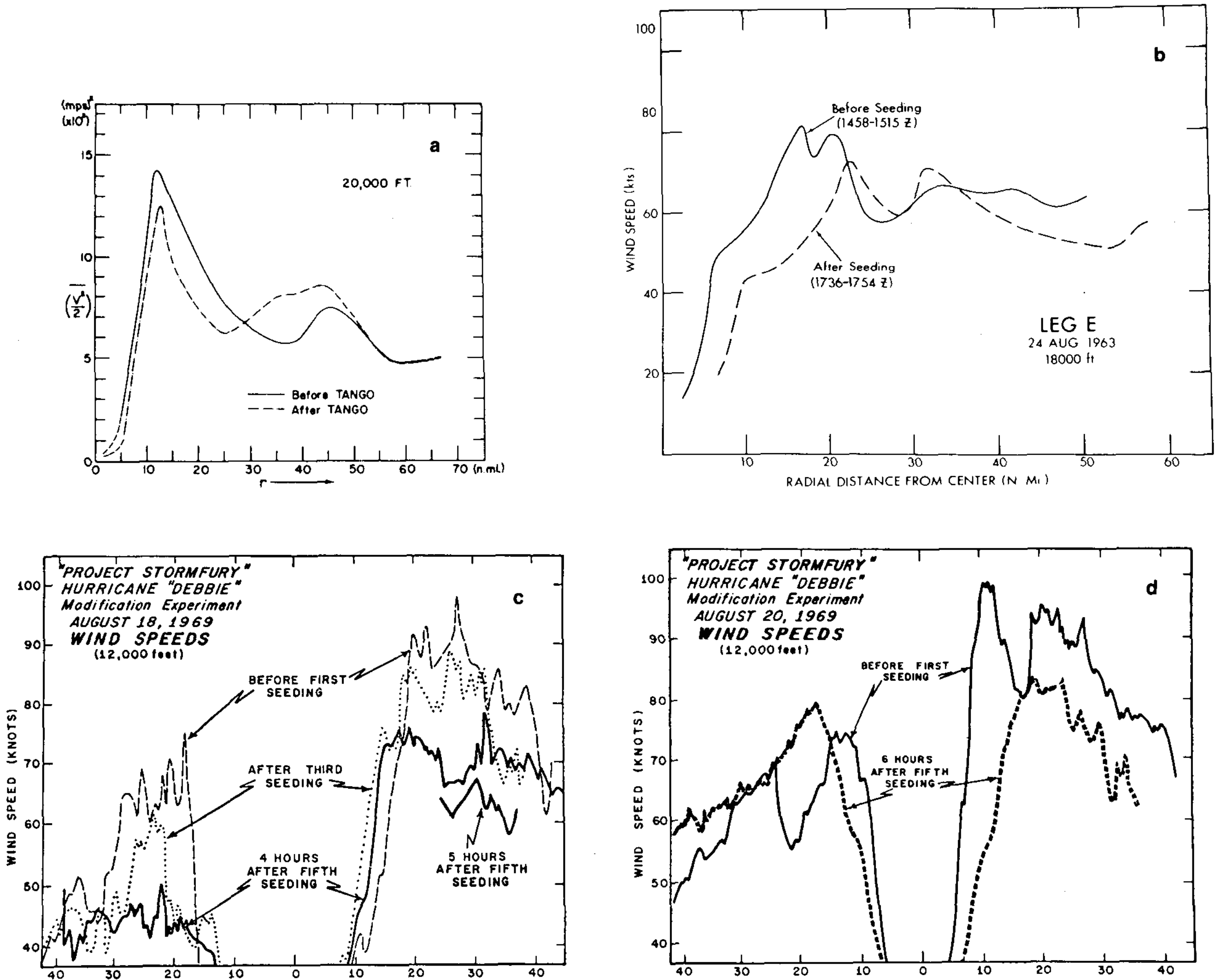


FIG. 1. (a) Radial profiles of wind kinetic energy before and after seeding in Hurricane Esther on 16 September 1961 (Simpson *et al.,* 1963). Radial profiles of wind speed before and after seeding in (b) Hurricane Beulah on 24 August 1963 (Project STORMFURY, 1964), and (c) and (d) Hurricane Debbie on 18 and 20 August 1969 (Project STORMFURY, 1970).

more moisture from low levels and invigorated the cloud still further. All cloud seeding techniques depended upon manipulation of microphysical processes, but seeding to alter the motion of the air was called "dynamic" seeding to distinguish it from "static" seeding, which sought to remove more moisture from the cloud through microphysical changes alone (Malkus and Simpson, 1964b).

Dynamic seeding became the method of choice for modification of convective clouds in hurricanes. Preliminary calculations based upon the sounding observed in Hurricane Daisy of 1958 showed that in hurricanes the conditional instability, and hence the buoyancy of the clouds, was relatively small. Only large convective elements with radii of greater than 3 km could rise from the surface to the tropopause because entrainment diluted momentum and buoyancy at a rate inversely proportional to the radius of the element. Even these relatively undilute "hot towers" were only 1 to 3° warmer than their surroundings (Malkus, 1959). Thus, if seeding could produce temperature rises of a degree or so, it could increase buoyancies and updraft velocities substantially (Malkus and Simpson, 1964a).

The 1962 hurricane season offered no hurricanes suitable for modification. The following summer, between 17 and 20 August 1963, Project STORMFURY conducted a randomized experiment on 11 nonhurricane cumuli. Five of the six treated clouds grew as predicted by the cloud model, and none of the five untreated controls did (Simpson *et al.*, 1965). These experiments did much to enhance the investigators' confidence in the efficacy of dynamic seeding.

Immediately after the experiments with isolated cumuli, STORMFURY carried out two modification attempts in Hurricane Beulah. On 23 August 1963, Beulah was not an ideal candidate for modification. She had 40 $\mathrm{m \cdot s^{-1}}$ winds and a poorly formed eye. Furthermore, the seeding material again missed the tall clouds around the eye. Observers aboard the 10 aircraft monitoring the storm reported no significant change. By the next day, the winds had increased to more than 50 $\mathrm{m \cdot s^{-1}}$, and the eye had become distinct. This time the seeding was on target. The aircraft crews reported disintegration of the eye wall, followed by formation of a new eye wall at larger radius. The maximum winds decreased by 20% and moved farther from the center (Fig. 1b). Since these changes were both similar to those reported in Hurricane Esther and consistent with the STORMFURY Hypothesis, Project STORMFURY seemed to have had an auspicious beginning (Simpson and Malkus, 1963, 1964).

For a variety of reasons, four years were to pass before the next modification experiment. In 1964, the aircraft instrumentation was not ready. 1965 saw microphysical observations (Ruskin, 1967; Averitt and Ruskin, 1967) and further experimentation in nonhurricane cumuli (Simpson *et al.*, 1967). Detailed aircraft observations were obtained in Hurricane Betsy, which was too close to land for seeding and made destructive landfalls in both South Florida and Louisiana. A second candidate for seeding, Elena, never came within range of the seeder aircraft. In 1966, STORMFURY went on alert for Hurricane Faith, which recurved before entering the seeding area. Valuable data were collected in Hurricane Inez, but no seeding was done. The Atlantic hurricane seasons of 1967 and 1968 were generally inactive and provided no opportunity for seeding (Project STORMFURY, 1965–1969).

Despite the lack of opportunities for seeding hurricanes, the years 1964–1968 yielded several advances. The investigators considered, but did not try, alternative methods of hurricane modification. These involved restricting heat transfer at the sea surface with monomolecular films, or changing the cloud-top radiation balance with an absorptive medium such as carbon black. Better pyrotechnic seeding devices became available. The seeding of isolated cumuli lead to improved numerical models (Simpson and Wiggert, 1969) and to an experimental precipitation enhancement program (Woodley *et al.*, 1982). Development of numerical hurricane models advanced rapidly (Ooyama, 1969; Rosenthal, 1971) and produced a new seeding hypothesis. The new strategy did not require that the vortex be inertially unstable. Instead, it involved repeated, massive seeding of the first rainband outside the eye wall to stimulate formation of a second outer eye wall that would weaken the original inner eye wall but cutting off its supply of heat and moisture from the boundary-layer inflow. Reformation of the eye at a larger radius, the argument went, would place the most rapidly rotating air farther from the center so that, by conservation of angular momentum, the strongest winds would be weaker than before seeding (Gentry, 1969; Project STORMFURY, 1964–1969; Sheets and LaSeur, 1979).

Finally, Hurricane Debbie provided an opportunity to test the improved modification techniques. On 18 and 20 August 1969, a fleet of 13 aircraft seeded and monitored the storm. Naval aircraft made five seeding runs and dispensed more than a thousand silver-iodide pyrotechnics on each day. Radial profiles of wind speed before and after seeding are shown in Figs. 1c and 1d. The observed changes were consistent with the revised STORMFURY Hypothesis. The winds decreased by 31% and 15% respectively on the two seeding days. Moreover, the decreases occurred at the time expected if they were caused by seeding, and their magnitudes were believed to exceed most of those observed in unmodified hurricanes. Better experimental design worked out in the "inactive" years between 1964 and 1968 seemed to have produced a spectacular double success (Gentry, 1970).

Clearly, replication of the Debbie experiment was in order. Unfortunately, the 1970 hurricane season yielded no suitable subjects. Neither did 1971, but seeding was attempted twice in Hurricane Ginger, a diffuse, late-season storm which, although it was in the experimental area, did not fit the experimental design because it lacked a small, well-defined eye. As might have been expected, seeding had no effect upon Ginger. In 1972, all of the hurricanes were too weak, or too close to land, or out of range. Other difficulties also plagued STORMFURY. In the early 1970s, the Navy ended its support for both STORMFURY and operational reconnaissance in order to pursue goals more closely related to national defense; furthermore, some of the civilian research aircraft were nearing the end of their useful lives after more than a decade of hard use.

The lack of experimental opportunities and the reduction in aircraft resources forced STORMFURY to look toward two new directions: first, to move the project into the Pacific, where two or three times as many subjects were likely to be available for experimentation, and second, to procure two specially built Lockheed WP-3D aircraft similar in design to those that had been proposed for the abolished naval reconnaissance squadrons. These more capable aircraft would observe the consequences of seeding in more detail and establish the chain of cause and effect between seeding and intensity changes. In addition to the new aircraft, the proposed fleet would contain the existing NOAA C-130B, a specially instrumented WC-130H operated by the Air Force, and a Convair 990 operated by NASA. The plan was that, starting in 1976, the five aircraft would operate from Guam in the Western Pacific and establish an operational hurricane modification technology within a few years (Dennis and Gagin, 1977; Sheets and LaSeur, 1979).

For this plan to be realized, STORMFURY had to be viable in five different respects:

> *Political.* Governments had to be willing to accept the risk of a public outcry if a seeded hurricane (or typhoon) devastated a coastal region. This outcry and its legal consequences might arise even if human intervention had no effect at all on the hurricane.
>
> *Operational.* The aircraft, instrumentation, and personnel to do the seeding and to document the result had to be available.
>
> *Microphysical.* Convection in hurricanes had to contain enough supercooled water for seeding to be effective.
>
> *Dynamic.* The hurricane vortex had to be sufficiently labile for human intervention to change its structure.
>
> *Statistical.* The experiment had to be repeatable, and the results had to be distinguishable from natural behavior.

3. Developments since 1977

In the late 1970s, political problems for Project STORMFURY began to multiply. Nearly a decade had passed since the Debbie experiments. The international agreements required to move STORMFURY to the Western Pacific never materialized. Other attempts to move STORMFURY to the eastern Pacific or to Australia also met political resistance.

Two WP-3Ds were procured and instrumented as planned. The first was delivered in the fall of 1976 and the second the following summer. The new aircraft proved to be superb observing platforms, faster and more reliable than those used previously. In their initial configuration, they carried three scientific digital radars that were designed for meteorologial investigations and provided both horizontal and vertical depictions of radar reflectivity. The aircraft navigated with modern inertial navigation equipment that was more accurate than the Doppler navigation equipment used previously and permitted better wind determination. *In situ* microphysical measurements were obtained with imaging Knollenberg (1981) probes, which permitted discrimination between liquid water and ice. The Knollenberg data, and indeed nearly all of the data from the WP-3Ds, were easy to process in large volumes because they were in digital form. This development, along with the advent of ground-based minicomputers, enabled the individual scientist to process his own data without the aid of a large technical staff. Thus, as the political fortunes of Project STORMFURY declined, the ability to observe and analyze the energetic core of mature hurricanes increased.

From the beginning, some, both in the larger scientific community and within NHRP, had expressed concern about the undemonstrated aspects of the STORMFURY's physical basis. For example, every year from 1962 to 1972, the STORMFURY Advisory Panel, a group of prominent scientists who met at intervals to review the project's progress, recommended studies of microphysical and statistical feasibility in addition to seeding experiments (Project STORMFURY, 1963-1973). The lack of opportunities for modification experiments and the enhanced capability for making relevant observations provided a chance to address these questions. Observations in Hurricanes Anita of 1977, David and Frederic of 1979, and Allen of 1980 (Jorgensen, 1984a) were of special importance because they substantiated doubts about the physical basis of the STORMFURY Hypotheses and the interpretation of past experimental results. These doubts fell into two general categories: cloud physics and vortex dynamics.

a. Cloud physics

In order for seeding with silver iodide to stimulate growth of cumulus clouds in hurricanes, there has to be an abundance of supercooled water and very little ice in the convective updrafts. If these conditions are met, the added buoyancy caused by release of latent heat of fusion can generate increased vertical motion. Supercooled water can exist if few freezing nuclei are present, and if the updrafts are strong enough to advect liquid water upward through the freezing level more rapidly than it can freeze. Thus, observations both of ice and liquid water concentration of updraft intensity provide a context within which to evaluate the potential for dynamic seeding.

The water contained in precipitation-sized particles can be measured directly with the Knollenberg probes, as described below, but the Johnson-Williams (J-W) instrument provides more reliable measurements of concentration of liquid water in cloud droplets smaller than about 40 microns in diameter. Because this device measures the cooling of a heated wire as a result of evaporation of water droplets that collide with it, the J-W is insensitive to both larger raindrops and ice particles. Another indication of the rain water content is X-band (3-cm wavelength) radar reflectivity, although the proportion of frozen to liquid particles cannot be determined reliably. Mean vertical profiles of cloud water content and radar reflectivity in strong updrafts provide insight into some of the important processes that occur in hurricane clouds.

Jorgensen *et al.* (1985) present a census of 3000 updrafts and 2000 downdrafts observed during 11 aircraft sorties on six different days in Hurricanes Anita, David, Frederic, and Allen. This sample represents altitudes near and below 6 km in intense hurricanes which, except for geographical location, fit the criteria for modification under the STORMFURY Hypothesis. Mean profiles of reflectivity and water content are shown in Fig. 2. The profiles are based upon a composite of maximum values observed in the updraft *cores* in the sample. Updraft cores are defined as regions at least 500 m wide where the updraft velocity exceeds 1 m · s^{-1}. The most striking feature of the observations in Fig. 2 is the rapid decrease of both cloud water content and radar reflectivity above 5 km, the approximate altitude of the 0° isotherm. These vertical profiles are in sharp contrast to data collected in continental thunderstorms, which often reveal radar reflectivities of 50 to 60 dBZ several kilometers above the 0° C isotherm. In continental convection, it is also common for cloud water contents measured by aircraft to exceed 2.5 g · m^{-3} at temperatures as cold as −10°C (Sax and Keller, 1980). These observations show a profound difference in microphysics between mature hurricanes and continental thunderstorms.

Fig. 3 shows the strongest 10% of updraft core velocities in the sample as a function of altitude. For comparison, equivalent data from the GARP Atlantic Tropical Experiment (GATE) (Zipser and LeMone, 1980), continental thunderstorms (from the Thunderstorm Project, Byers and Braham, 1949), and results of earlier hurricane studies by Gray (1965) are also plotted. Fig. 3 clearly indicates weaker updrafts and downdrafts in oceanic convection. The strongest downdraft cores in hurricanes or in GATE were about 3 m · s^{-1}, and the strongest updraft cores were 3–5 m · s^{-1}. The vertical motions in the Thunderstorm Project were over three times larger. More recent aircraft and Doppler radar studies have confirmed these strong vertical motions in mid-latitude convective storms. There is some evidence that isolated convective events in developing tropical storms and weak hurricanes can be more intense than those observed by Jorgensen *et al.* (Gentry *et al.*, 1970; Black, 1983), but the present observations seem to characterize the convection in the lower troposphere of mature hurricanes accurately.

In mature hurricanes, the weak lower-tropospheric updrafts and the relatively large depth from cloud base to the freezing level (4–5 km) mean that times on the order of 1000 s are available for collision coalescence to form precipitation before the updraft reaches the 0° C level. Numerical cloud models indicate that 1000 s is more than enough time for raindrops to grow to millimeter sizes, given a relatively broad, oceanic initial spectrum of condensation nuclei (Mason, 1971). Since radar reflectivity depends on the sixth power of drop diameter, it is not surprising that the largest reflectivities in hurricane clouds occur at low levels, because once drops grow to a few millimeters in diameter, they fall out of all but the very strongest updrafts. Furthermore, both theoretical (Shapiro and Willoughby, 1982) and observational (Jorgensen, 1984b) studies indicate that the updrafts in hurricanes follow surfaces of constant angular momentum. Inasmuch as the slopes of these surfaces from the vertical (i.e., the ratio of the vertical shear to the vorticity) can exceed three to one, precipitation falls out of the inclined updrafts even more readily than the low updraft velocities alone would indicate. The foregoing view is consistent with earlier observations of liquid water concentrations that were a small fraction of the value to be expected from undiluted, adiabatic ascent without fallout (Ackerman, 1963).

If these weak updrafts extend into the upper troposphere, they may also be responsible for the rapid decrease of cloud water and reflectivity above the freezing level. Not only are

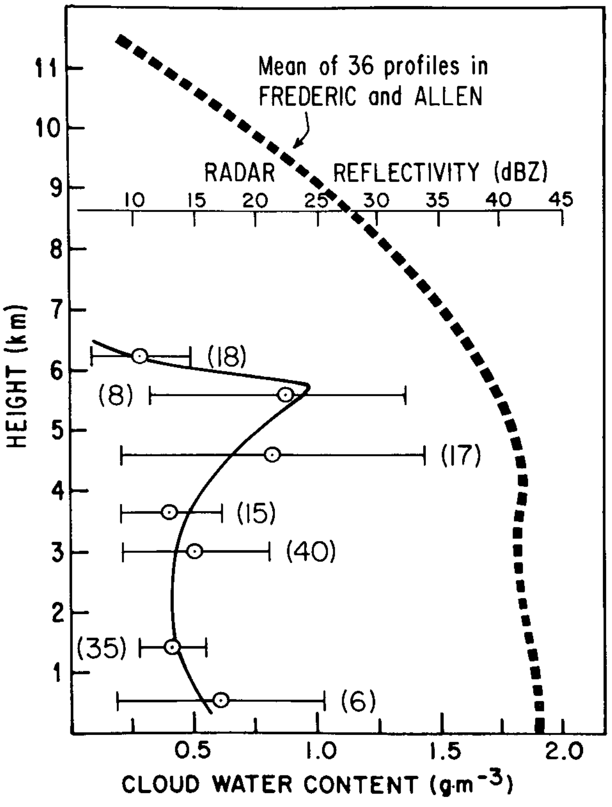


FIG. 2. Mean variation with height of maximum cloud water content measured in updraft cores by the Johnson–Williams instrument (solid line) and of radar reflectivity (dashed line) in Hurricanes Anita, David, Frederic, and Allen. The numbers in parentheses indicate the number of passes upon which the maximum cloud water content is based, and the bars show standard deviation of cloud water content. The radar reflectivity profile is a composite of 36 profiles from the vertically scanning X-band radar in Hurricanes Frederic and Allen (Jorgensen *et al.*, 1985).

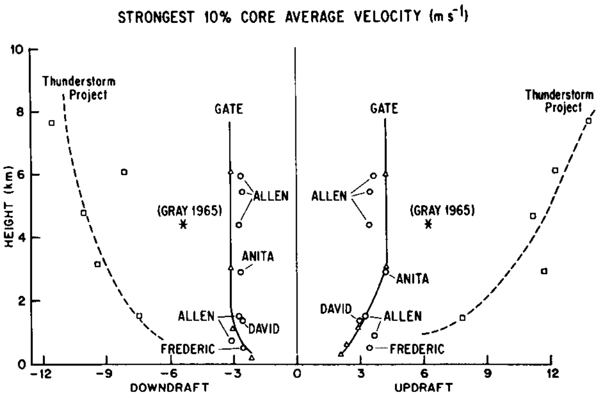


FIG. 3. Average vertical velocity in the strongest 10% of updraft and downdraft cores as a function of height. Values in GATE are indicated by triangles, those in the Thunderstorm Project by squares, and those in hurricanes by circles with the storm name. The hurricane observations made by Gray (1965) are also included for comparison. (Jorgensen *et al.*, 1985, adapted from Zipser and LeMone, 1980).

few large raindrops brought up to the freezing level in the updrafts, but it takes a long time for air to ascend from the freezing level to the tropopause. Even without internal recirculation of ice crystals within the updrafts, this time interval is ample for conversion of supercooled water to ice, given any ice nuclei at all (Jorgensen *et al.,* 1985). The rapid reduction of radar reflectivity above the freezing level may, therefore, be explained by freezing as well as by fallout, because the radar reflectivity of ice particles is an order of magnitude less than that of similar-sized water drops.

Why are updrafts in mature hurricanes so weak? A comparison between the soundings in hurricanes and in continental thunderstorms reveals substantially different stability. The inner cores of mature hurricanes are much more stable because of the well-documented warm anomaly aloft (e.g., Hawkins and Imbembo, 1976). Additionally, the strong surface heating, the dry middle troposphere, and the cold air advection aloft that often characterize mid-latitude thunderstorms are absent in mature hurricanes. Indeed, the convective available potential energy in thunderstorms is nearly four times larger than in hurricanes (Jorgensen *et al.,* 1985).

In addition to the foregoing observations of updraft speed and liquid water content, direct, *in situ* observations with the Knollenberg probes can determine the potential of clouds in hurricanes for modification. In quantitative terms, the limiting values for effective dynamic seeding were more than 1 $gm \cdot m^{-3}$ of liquid water (Malkus and Simpson, 1964b) coexisting with fewer than one ice particle per liter at −10° C (Mason, 1971). If the liquid water content were below the critical value, insufficient latent heat would be available; if the ice concentration were above the critical value, natural ice processes would dominate seeding, which is designed to produce only 10 artificial ice particles per liter.

The WP-3D aircraft can attain the −10° C level only near the end of a mission when they have used most of their fuel. Nevertheless, observations at lower altitudes (i.e., higher temperatures) indicate less liquid water and, significantly, more ice than the critical values. It is unlikely that more liquid water or fewer ice particles would be present at −10° C. Although both operational constraints and the difficulty of keeping instrumentation functional for six to eight hours in severe hurricane conditions have limited the amount and quality of observations, Black and Hallet (1984) have analyzed 17 hours of data at temperatures below 0° in Hurricanes Allen of 1980, Ella of 1978, and Irene of 1981. This sample may be too small to be definitive, but the results from all three storms are consistent with one another and with the observations of updraft strength, liquid water content, and radar reflectivity.

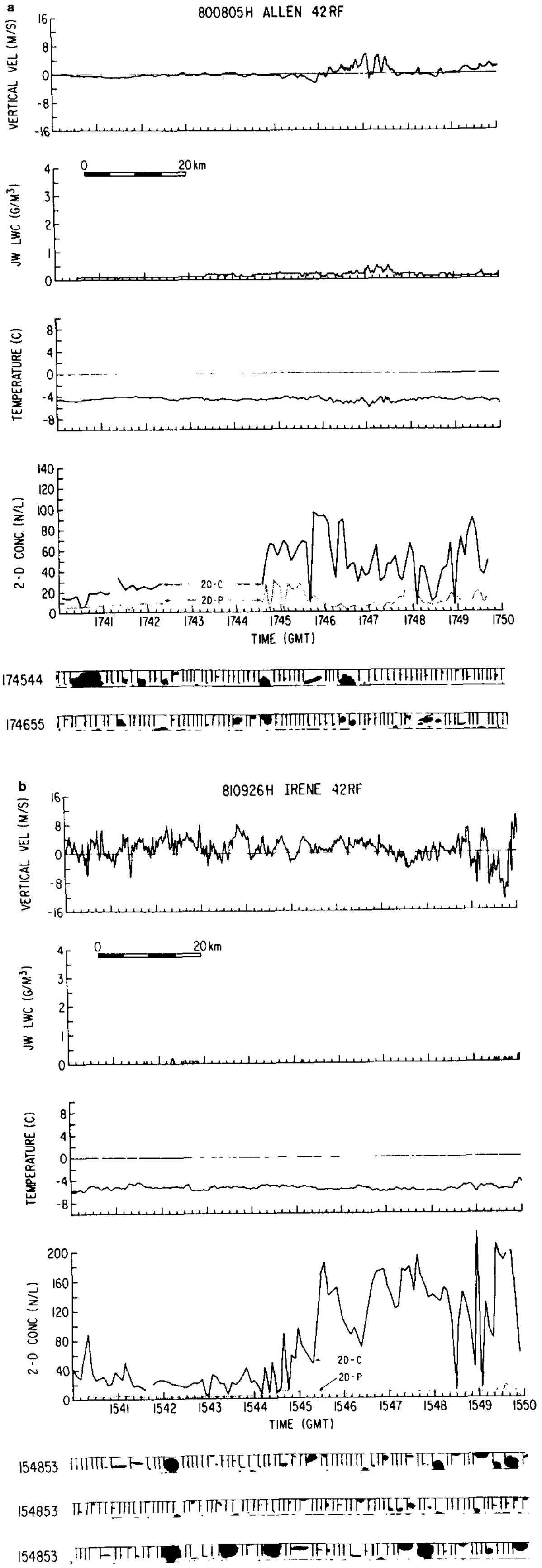
The principal rainband (as defined by Willoughby *et al.,* 1984b) of Hurricane Allen on 5 August 1980 at the −5° C level is typical of the observations outside the eye wall. Fig. 4a shows profiles across the rainband of vertical velocity, liquid cloud water content as measured by the J-W instrument, temperature, and particle concentrations as measured by the Knollenberg probes. The peak updrafts are fairly strong for a hurricane, 4 to 6 $m \cdot s^{-1}$, but the liquid water content remains below 0.5 $g \cdot m^{-3}$. In this case and throughout the storm, liquid water is confined to the updrafts; the downdrafts and stratiform areas are completely glaciated. At the bottom of Fig. 4a appear typical precipitation images observed with the Knollenberg probes in downdrafts (174544 GMT) and updrafts (174655 GMT). Each image has a time bar along its left side and represents a field of view 1.6 mm wide. The images may fall into three classes: streaks due to precipitation striking the probes themselves, irregularly shaped ice particles, and spherical particles which may be either graupel pellets or raindrops. In both updrafts and downdrafts, the unambiguous ice particles are much more common than spherical hydrometeors. Indeed, the ice particle concentration in the band is typically 40–50 per liter, several times that expected to result from seeding at a temperature 5° colder. The foregoing is typical of the regions outside the eye wall in the other two storms. For example, Fig. 4b illustrates a traverse along the principal rainband of Hurricane Irene of 1981 at −5° C, where abundant frozen precipitation and virtually no liquid water occur. Thus, the predominance of natural ice over liquid water dictates that cloud seeding in the outer rainbands—such as required by the STORMFURY Hypothesis—would be ineffective.

On the other hand, liquid water concentrations as high as several $g \cdot m^{-3}$ are present in the eye wall and in a few other locations where strong updrafts occur at temperatures near 0° C (Fig. 4c). Ice particle concentrations are typically 1 per liter in the updrafts and 10 to 100 per liter in the environment or adjacent downdrafts. The ice particles outside the updrafts are typically columns, needles, and graupel pellets which apparently form through the ice multiplication process of Mossup (1976) at an altitude somewhat above that where they are observed. Although the low ice concentration in the updrafts—at temperatures 5–10° C warmer than that where silver iodide would be an effective seeding agent—means that the updrafts themselves might be marginally seedable, they are unlikely to remain so at −10° C if they entrain much environmental air, with its high concentration of natural ice.

In the convective regions of these mature hurricanes, the measured rapid decrease in cloud water content above the 0° C isotherm indicates that the precipitation is largely frozen. Radar reflectivity also decreases rapidly above the 0° isotherm, indicating an absence of both large, supercooled raindrops and wet hailstones. Finally, the Knollenberg probes observe low concentrations of supercooled water associated with abundant natural ice particles in concentrations that approach or exceed those that could be produced by seeding. The decreases of both cloud water and radar reflectivity and the increase in natural ice are consistent with the observed weak updraft velocities, which, in turn, result from the small convective instability of the inner core. Thus, despite the relatively small sample of *in situ* measurements and the lack of definitive observations at the crucial −10° C level, both direct microphysical measurements and indirect inference from cloud dynamics indicate that seeding with silver iodide is unlikely to be effective in hurricanes.

b. Vortex evolution

The STORMFURY Hypothesis depended upon a relation between expansion of the eye and reduction of the maximum wind. Some empirical evidence existed to support such a relation (e.g., Shea and Gray, 1974), and its validity seemed to follow from the principle of conservation of angular momen-



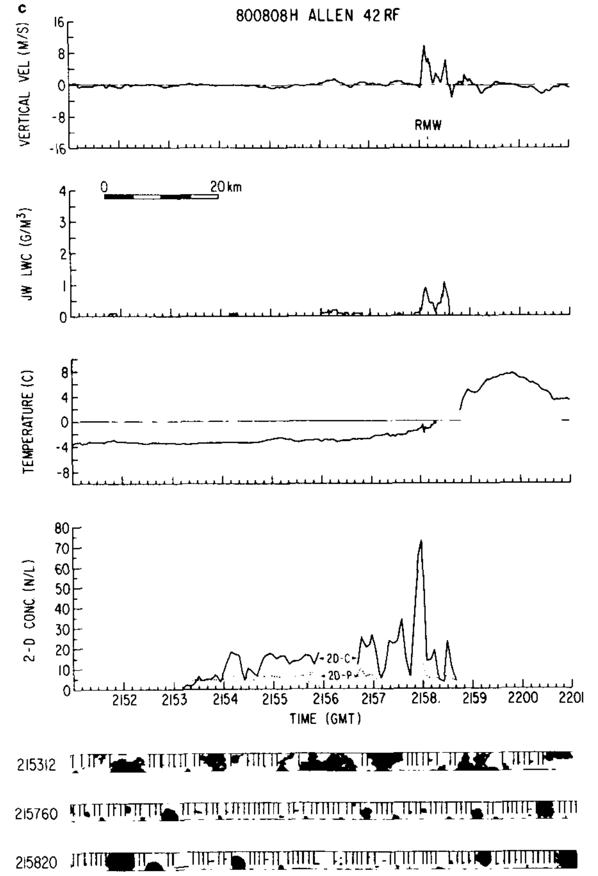


FIG. 4. Aircraft observations of vertical velocity, liquid water content, temperature, particle concentrations, and precipitation images in: (a) a radial pass through the principal band of Hurricane Allen on 5 August 1980; (b) a traverse along the principal rainband of Hurricane Irene on 26 September 1981; and (c) a radial pass through the eye wall of Hurricane Allen on 8 August 1980.

tum. Indeed, the four apparently successful modification attempts showed a correlation between weakening of the maximum wind and expansion of the eye (Fig. 1). If this sequence of events were indeed rare in unmodified hurricanes, the results provided strong support for the STORMFURY Hypothesis; if it were common, the results might well have occurred by chance and the hypothesis had little observational support.

The evolution of Hurricanes David and Allen provides evidence in favor of the latter interpretation (Willoughby *et al.*, 1982). In both cases, outer wind maxima associated with a ring of convective clouds surround the eye. Fig. 5a illustrates the appearance of Hurricane David on radar on 30 August 1979 and Fig. 5b the corresponding distributions and tendencies of the tangential wind and 50 kPa height. The wind is increasing at and inside the wind maximum in the outer eye wall; it is decreasing at the inner eye wall. Therefore, the outer eye wall is intensifying and contracting as the inner eye wall is weakening. Both the sequence of events and the storms' appearance on radar are very similar to observations of Hurricanes Beulah, Esther, and Debbie (Simpson *et al.*, 1962; Hawkins, 1971; Black *et al.*, 1972). In both David and Allen, the transformation is associated with dramatic rises in central pressure. Fig. 6 shows the cyclic variations of eye radius

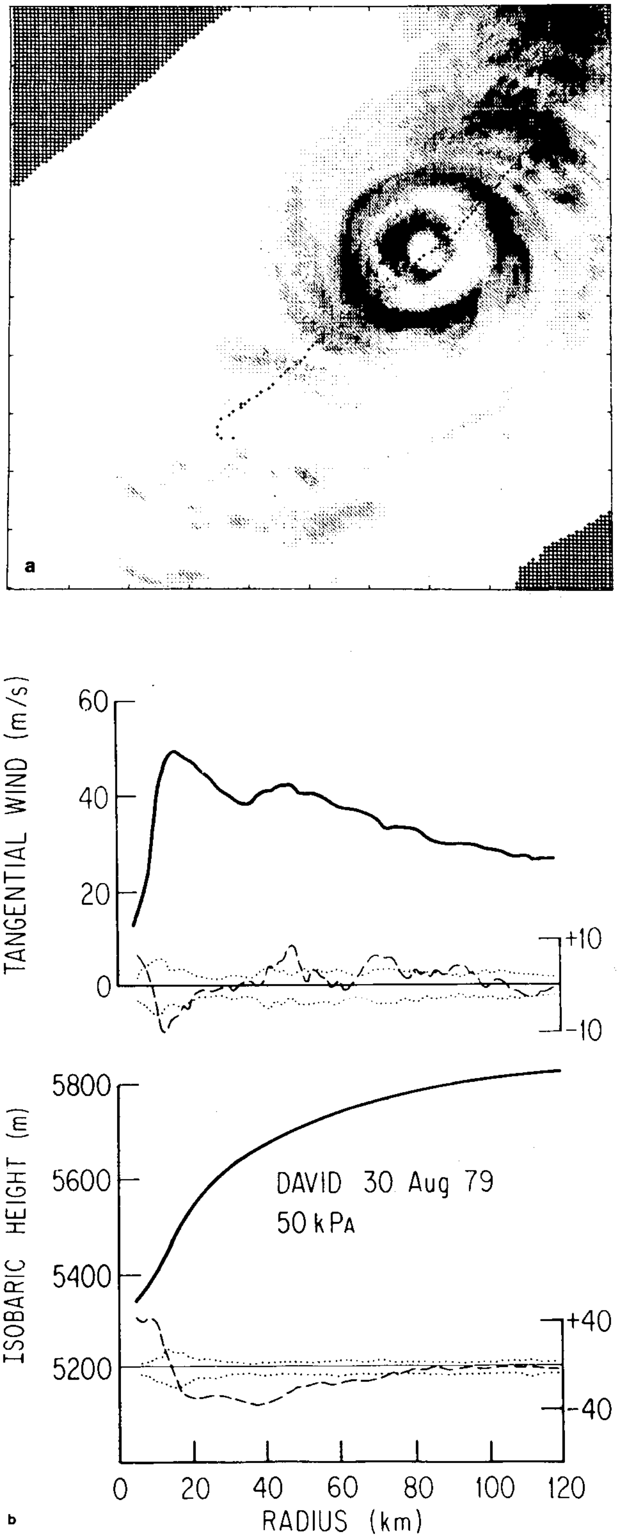


FIG. 5. (a) Composite of radar reflectivity in Hurricane David between 1045 and 1130 GMT on 30 August 1979. Plus signs indicate the aircraft track, and the frame represents an area 300 km square. (b) Radial profiles of tangential wind component and height of the 50 kPa surface in Hurricane David at 0925 GMT on 30 August 1979. The solid curves denote the quantities themselves, the dashed curves the change in six hours, and the dotted curves the standard error of measurement remaining after the linear change with time is accounted for (Willoughby *et al.*, 1982).

and central pressure in the latter storm. Examination of reconnaissance observations from the western Pacific reveals additional cases of cyclic pressure changes correlated with concentric eye walls. Furthermore, a review of the literature shows that similar events have been described before (Fortner, 1958; Jordan and Schatzle, 1961; Jordan, 1966; Hoose and Colon, 1970; Holliday, 1977).

All concentric eyes have similar dynamics regardless of their horizontal extent, unless they are very large (Shapiro and Willoughby, 1982). Thus, a hurricane with an outer convective ring can be considered as two hurricanes with the smaller one within the eye of the larger. Shapiro and Willoughby present a simple, diagnostic model of a gradient-balance vortex in which convective rings propagate inward as a result of convective heat release. In this model, the pressure falls rapidly on the inner side of the ring and less rapidly on the outer side. The pressure gradient and wind just inside the ring strengthen, causing inward propagation. In more elaborate, prognostic modeling studies (Willoughby *et al.*, 1984a), the inner ring dissipates as the outer ring contracts because the descent forced by the outer ring dries and warms the air around the inner. This produces an unfavorable environment for convection, reduces the latent heating in the inner ring, and leads to its dissipation.

Reference to Fig. 1 shows that outer wind maxima were present before seeding began in Esther on 16 September 1961, in Beulah on 24 August 1963, and in Debbie on 20 August 1969. Moreover, these hurricanes' evolutions and appearances on radar closely resembled those of David and Allen. It is, however, more difficult to relate the events in Debbie on 18 August 1969 to the convective-ring scenario. Thus, in retrospect, it seems probable that outer eye walls formed by chance in three of the four "successful" experiments and that the changes in the hurricane's intensity were the result of natural evolution rather than a consequence of seeding.

The observational studies that contributed to understanding of unmodified hurricanes involved budget or composite analyses under the steady-state assumption and did not address the question of temporal changes (Colon and staff, 1961; Riehl and Malkus, 1961; LaSeur and Hawkins, 1963; Colon, 1964; Hawkins and Rubsam; 1967; Gray and Shea, 1974; Shea and Gray, 1974; Hawkins and Imbembo, 1976). In contrast, Project STORMFURY evaluated modification experiments by examination of sequences of radial profiles (see Fig. 1) and comparison between the timing of the ob-

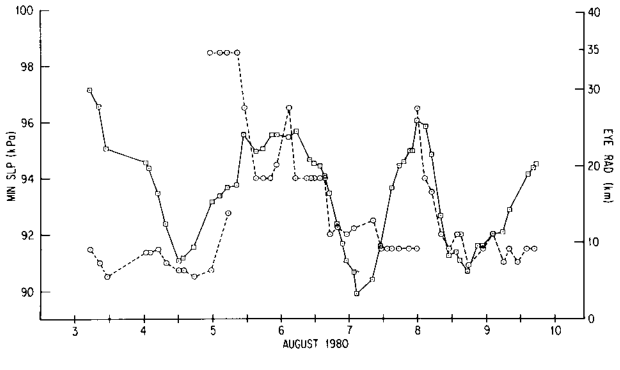


FIG. 6. Evolution of the central pressure (solid curve) and eye radius (dashed curve) of Hurricane Allen. Numerals denoting the date are plotted at 1200 GMT each day (Willoughby *et al.*, 1982).

served changes and that expected to result from seeding (e.g., Knight and Brier, 1978). Given the frequency with which concentric eye walls accompanied by intensity changes have been observed since 1977, it seems probable that similar phenomena occurred in some of the earlier unmodified storms as well as, apparently, in three of the modified ones. This contention is supported by the contemporary reports of concentric eye walls. Had Project STORMFURY devoted more attention to temporal changes in unseeded storms (as in Sheets, 1970, 1972; or Knight, 1978), the difficulty that the concentric eye phenomenon poses for statistical control of hurricane modification experiments might have been appreciated much sooner.

4. Conclusions

The goal of human control of hurricanes was captivating and seemed to be physically attainable in the beginning. As Project STORMFURY pursued that goal, it provided resources and an institutional setting for many worthwhile investigations—particularly in instrument development, cumulus dynamics, numerical modeling, and observational studies of unmodified hurricanes. STORMFURY also motivated the acquisition of the WP-3D aircraft, which have, STORMFURY aside, proven their worth to atmospheric science in general as well as to hurricane research.

STORMFURY itself, however, had two fatal flaws: it was neither microphysically nor statistically feasible. Observational evidence indicates that seeding in hurricanes would be ineffective because they contain too little supercooled water and too much natural ice. Moreover, the expected results of seeding are often indistinguishable from naturally occurring intensity changes. By mid-1983, none (or perhaps only one: dynamic feasibility) of the five conditions for development of an operational hurricane amelioration strategy could be met, and Project STORMFURY ended. Its lasting legacies are the instrumented aircraft and two decades of productive research. Of the four original objectives for hurricane research set down in 1955 at the establishment of NHRP, three—understanding formation, understanding structure and dynamics, and improvement of forecasts—remain areas of active investigation.

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