

THE NATIONAL HURRICANE RE

50 Years of Research, Rough Rides, and Name Changes

BY NEAL M. DORST

A history of the National Hurricane Research Project and its progeny organizations relates its origins and early organization, its involvement in hurricane modification, and its present research using cutting edge technology.

FIG. 16. The eye of Hurricane Floyd near its peak intensity 13 Sep 1999. Floyd was a part of the upturn in Atlantic hurricane activity that began in 1995. [Source: Neal Dorst, NOAA.]

Tropical cyclones have plagued coastal communities for millennia, yet mankind knew little about these storms prior to the nineteenth century, when J. Farrar, W. Redfield, and W. Reid established that hurricanes were circulatory rather than straight-line surges of wind (Fleming 1990). It was not until the late nineteenth century that scientists comprehended the differences between tropical and extratropical cyclones (Kutzbach 1979). Prior to the 1930s, they thought tropical cyclones extended less than 6 km in height (Newnham 1922). Many prominent meteorologists, up through 1950, thought that equatorial baroclinic zones initiated tropical cyclones (Bergeron 1954).

These misconceptions were due to a lack of in situ observations. Much of the tropical cyclone's life cycle occurs over the ocean, where few weather observations were made. When tropical cyclones were detected, ships avoided them, depriving scientists of needed data.

SEARCH PROJECT



When mature tropical cyclones made landfall, severe conditions made taking observations difficult, and failures in wind-measuring instruments were common.

Palmén (1948) and Bergeron (1954) attempted to define tropical cyclone structure and thermodynamics using limited information. Their schematics, based on soundings that excluded the central core and on surface observations taken in a Philippine typhoon in the 1930s (Depperman 1939), show an eyewall that slopes outward rapidly with its diameter expanding from 10 km at cloud base to 200 km at cloud top (14-km altitude). The tropopause is depicted inside the eye reaching to within a kilometer of the surface.

Several methods compensated for observational deficiencies. Cline (1926) composited land station observations relative to a moving storm center. In 1944, the first radiosonde was released in the eye of a tropical cyclone (Simpson 2003), and the first ►

radar observations were made as a hurricane passed an experimental naval radar station (Sumner 1944). Simpson (1947) and Arakawa (1950) used the passages of tropical cyclones close to radiosonde stations to collect higher-density soundings and analyze vertical structure. Jordan and Jordan (1954) used radiosonde observations in the vicinity of tropical cyclones to map their outer structure at upper levels.

After J. Duckworth's historic first flight into a hurricane eye in 1943, aircraft observations in the lower portions of tropical cyclones became available. The following year, Major H. Wexler made a flight into the Great Atlantic Hurricane, recording his observations (Wexler 1945). One of the few to follow Wexler in exploiting reconnaissance flights for scientific observations. Robert Simpson of the U.S. Weather Bureau (USWB), participated in U.S. Air Force (USAF) flights in 1947 (Simpson 1954a), 1951 (Simpson 1952), 1953 (Simpson 1954b), and 1954 (Simpson and Starrett 1955), carrying out what he termed "piggyback experiments." Using the time between fix requirements, he had the pilots fly into various parts of the storm to explore its structure and use the limited meteorological instruments to measure temperature and wind at different levels.

Simpson advocated the regular use of reconnaissance to record scientific observations, and urged the USWB to hire researchers to work full time on the "hurricane problem." Restrictive budgets in this era precluded even this modest investment. It also went against ingrained attitudes within USWB, which saw the bureau as being strictly operational and research as being the purview of universities. Its previous major research effort, the Thunderstorm Project (1946–47) had been directed by college professors (Braham 1996).

This remained the case until 1954 when Hurricanes Carol and Edna struck New England within 11 days of each other. There had not been a hurricane landfall



SOME ROUGH RIDES

Although NOAA's Aircraft Operations Center has an exceptional safety record, you cannot make hundreds of hurricane penetrations over the years without a few bad bumps. Throughout this paper you will find some of the more memorable hurricane flights in that regard. [Source: Pete Black, Robert Black, Mark DeMaria, Jim DuGranrut, Paul Flaherty, Howie Friedman, Jeff Hawkins, Greg Holland, David Jorgensen, John Kaplan, Terry Lynch, Frank Merceret, Jim McFadden, John Michie, Jack Parrish, Bob Sheets, and Dave Turner.]

HURRICANE GLADYS: 16 OCTOBER 1968, "40 CHARLIE" As this storm exited the western tip of Cuba, the civilian weather bureau aircraft were tasked by NHC because the reconnaissance pattern fell within Cuban air control. After a run along a rainband to measure cloud drops, they made a final eye fix. Relaxing after the difficult part of the flight, several of the crew unstrapped their seat belts. The plane unexpectedly encountered severe turbulence, and several were injured. One technician was rushed to the hospital on return to Miami, but recovered enough to return to duty.

in this region for a decade. The combined effects of two strikes within a short period were unnerving to a populace unused to such storms. A month later, Hurricane Hazel struck the Carolina coast, its center passing over Washington, D.C., cutting a damage swath all the way to Ontario, Ottawa, Canada, again battering coastal New England (Gentry 1955). The devastating 1954 hurricane season caused over 193 deaths in the United States and over \$756 million in damages, mostly in the northeastern corridor. Adjusting that value not only for inflation but also for increased possessions and greater population density (Pielke and Landsea 1998) would result in damage values totaling \$22.8 billion in 2005. By that reckoning, 1954 would rank as the sixth costliest hurricane season in the twentieth century (Jarrell et al. 2001). Many saw this season as a harbinger of a climate shift that would bring tropical tempests regularly to the northeast (Lissner 1955).

THE FORMATION OF NHRP. During the next legislative session, congressmen from an uneasy New England sponsored bills to increase USWB funding. They allocated \$2.5 million as a first installment on a new weather radar network. By August 1955, days after Hurricane Connie passed Washington, D.C., to the east and as Hurricane Diane loomed, an additional half-million dollar supplemental bill was passed, allowing USWB to modernize its hurricane warning network, including a tropical cyclone

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research effort. Diane's center passed west of the nation's capital, and became the first "billion dollar" hurricane (Dunn et al. 1955). Adjusted for inflation, it would be the "six billion dollar hurricane" today.

To coordinate USWB's tropical cyclone research, Chief Francis Reichelderfer created the National Hurricane Research Project (NHRP), and selected Simpson as its director. After consultation with many world-renowned meteorologists about NHRP's direction, Simpson recruited the following senior staff: Associate Director Noel LaSeur of Florida State University (FSU); hurricane forecaster Robert Cecil Gentry as assistant director; Arthur Johnson as operations manager; Arthur Youmans, based in Washington, D.C., as business manager; Charles Jordan as research and development meteorologist; and Robert Rados as aircraft instrumentation specialist.

Several staff members traveled from Cape Canaveral, Florida, to Puerto Rico to Bermuda, scouting bases and examining aircraft. They finally selected Morrison Air Force Base in West Palm Beach, Florida, for their research operations base (ROB). It had both the support facilities for military aircraft and civilian amenities for scientists, including proximity to the Miami, Florida, hurricane forecast office.

The main data-gathering segment of NHRP was scheduled for 30 months, from April 1956 to October 1958 (NHRP 1956). In addition to a core group of scientists assigned to ROB, NHRP counted on cooperation from several sections of USWB, such as the Office of Meteorological Research (OMR), the Hydrologic Services Division, the Office of Climatology, the Extended Forecast Branch, the Joint Numerical Weather Prediction Unit, and each of the hurricane forecast offices in Miami, San Juan, Puerto Rico, New Orleans, Louisiana, Washington, and Boston, Massachusetts (NHRP 1956). There were also contributions from academic scientists working on grants managed by NHRP. Institutions eventually collaborating included the University of Chicago (UChicago), the Woods Hole Oceanographic

Institute, FSU, the University of Miami (UMiami), New York University, Massachusetts Institute of Technology (MIT), Colorado State University (CSU), University of California, Los Angeles, and the Japanese Meteorological Research Institute. These institutions also supplied priceless support in the form of graduate and undergraduate students who worked at ROB during summer vacation, processing data and participating in research flights. A good number of these students, such as Howie Bluestein, Russell Elsberry, Neil Frank, Joseph Golden, William Gray, Richard Johnson, Arthur Pike, Bill Proenza, Daryl Rubsam, Clark Smith, Russell De Souza, Victor Wiggert, and Edward Zipser, went on to have distinguished careers in meteorology.

During its first three hurricane seasons, NHRP used three Hurricane Hunter aircraft and crews on temporary loan from USAF to fly research missions. The two WB-50s had a low operational ceiling (see Table 1), but the WB-47 high-altitude jet was able to fly above in the outflow layer. Rados installed better-quality weather instruments on these planes and a punch card system to automatically record data once per second (NHRP 1956).

TABLE 1. Research aircraft used over 50 years.

Aircraft type	Designation	Years of service	Ceiling	Maximum range
WB-50	Gull 46007	1956–58	37,000 ft, 11,300 m	4000 n mi, 7400 km
	Gull 46032	1956–58		
WB-47	Gull 2115	1956–60	40,000 ft, 12,200 m	3500 n mi, 6500 km
DC-6	N6539C "39 Charlie"	1960–75	23,000 ft, 7,000 m	2600 n mi, 4800 km
	N6540C "40 Charlie"	1960–72		
WB-57	N1005	1960–71	43,000 ft, 13,100 m	1900 n mi, 3500 km
B-26	N800W	1961–65	25,000 ft, 7,600 m	1900 n mi 3500 km
C-54	N91282	1965–69	20,000 ft 6,100 m	2700 n mi, 5200 km
C-130	N6541C	1970–81	23,000 ft, 7,000 m	1000 n mi, 2000 km
P-3	N42RF "Kermit"	1976–present	25,000 ft, 7,600 m	3300 n mi, 6100 km
	N43RF "Miss Piggy"	1977–present		
G-IV	N49RF "Gonzo"	1996–present	45,000 ft, 13,700 m	4075 n mi, 7550 km



Fig. 1. Bob Simpson and Cecil Gentry outside the Research Operations Base, West Palm Beach, FL, 1956. [Source: NOAA.]

Project scientists not only designed flight plans and briefed crews on the scientific mission, but also rode along on the WB-50s, in the “bubble” nose with its spectacular view. From there, they could make detailed observations, direct the flight, and make changes “on the fly,” as warranted. This was a critical change from operational flights, and bore fruit in better scientific quality of the information gathered.

NHRP undertook to test a hurricane balloon beacon, designed by USAF’s Geophysical Research Directorate, and participated with the U.S. Navy (USN) in an attempt to photograph tropical cyclones from suborbital rockets (NHRP 1956). The beacon idea was inspired by Simpson’s observations of a “hub cloud” in the eye of Typhoon Marge (Simpson 1952) caused by convergent winds. He reasoned that a constant-altitude balloon, with a radio beacon, released in the eye would keep in the center because of this circulation. It could be tracked remotely, either by aircraft outside the storm or by land stations.

The rocket program used film cameras mounted in the nose cone with a homing signal. The plan was that, when a tropical cyclone approached either Wallops Island, Virginia, or later Cape Canaveral, USN would launch a rocket and photograph the

upper clouds of the hurricane from the edge of space. Falling near the launch site, USN vessels and aircraft would track its signal to recover the film. If all went as planned, meteorologists would have an unprecedented look at the upper structure of tropical cyclones.

NHRP also supported the establishment, manning, and maintenance of additional upper-air stations scattered around the Caribbean Sea (NHRP 1956). These stations provided better synoptic analyses for forecasts and a better understanding of the atmosphere in this poorly sampled region. The stations were eventually turned over to the weather services of the nations where they were located, although USWB continued to supply and support them. This fostered a closer working relationship between these services, and built a better hurricane warning network.

THE RESEARCH OPERATIONS BASE.

Twenty-four scientists were based at NHRP’s ROB in West Palm Beach (Fig. 1). In addition to senior staff, there were analysts and chartists making up the Experimental Analysis Unit, which collected weather reports, including soundings from the new radiosonde network, made detailed, novel maps, and investigated new ways to present the data to assist forecasters. NHRP managers also used these analyses to plan aircraft missions. Additional NHRP scientists (Banner Miller, Paul Moore, Gilbert Clark, and Lester Hubert) were assigned to the Miami and Asheville, North Carolina, offices to research forecast methods and archive operational data. They tried new objective tropical cyclone forecasting techniques, such as Riehl–Haggard method (Riehl and Haggard 1954), and observed how forecasters used information presented to them.

The first research flight for NHRP was into Hurricane Betsy on 13 August 1956 while the storm was over the Turks and Caicos Islands. This and the following mission were minor disasters, with equipment failures and dropped punch card decks



HURRICANE EDITH: 9 SEPTEMBER 1971, “39 CHARLIE”

Edith was approaching the Mosquito Coast of Nicaragua and intensifying on this day. The early eye penetrations went well, but on the last one the eye had shrunk to seven miles in diameter. The turbulence was so severe that the pilots temporarily lost control of the aircraft. By the time they regained control, they had lost 1000 feet (300 m) of altitude.

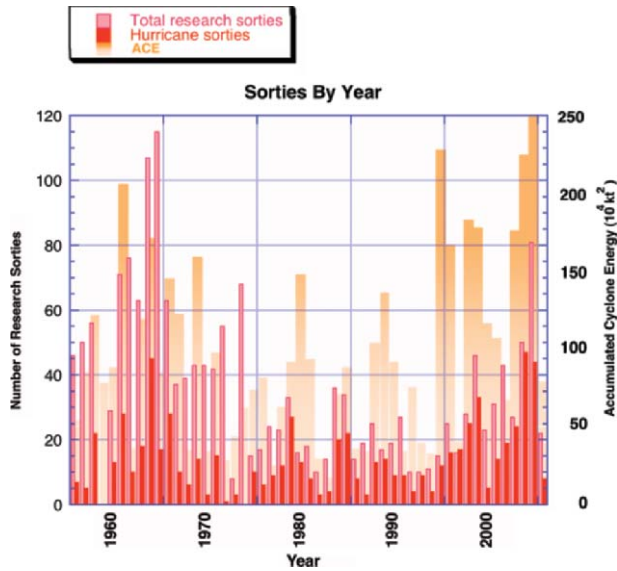


FIG. 2. Research aircraft sorties from which NHRP/NHRL/NHEML/HRD has collected data. Total sorties and sorties in and around hurricanes are plotted along with the yearly accumulated cyclone energy total for the Atlantic for that year.

marring the effort. Subsequent flights that initial year went better. Despite a slow season, NHRP managed to fly 17 sorties into tropical cyclones in 1956 (see Fig. 2), including six into late-season Hurricane Greta throughout its life cycle, including when it was a major hurricane. To showcase this effort, and garner support for continuing NHRP, Simpson convened a review of progress at the ROB in November 1956. This review persuaded USWB to continue NHRP for the next year, notwithstanding an inactive inaugural season (Simpson 1989). It also presaged a biannual effort to review hurricane research, subsequently sponsored by the American Meteorological Society (AMS).

Project scientists' initial efforts were published in the *NHRP Reports*, a series of internally reviewed articles meant to offer a quick distribution of findings. Scientists published more extensive versions of many of these reports in peer-reviewed journals later (see Fig. 3). Among the early reports were ones on a mean tropical atmospheric sounding (Jordan 1957a), dropsonde soundings in the eye (Jordan 1957b), verification of the first numerical weather prediction of tropical cyclone movement (Hubert 1956), and the maximum potential intensity of tropical cyclones based on sea surface temperatures (Miller 1957).

When Hurricane Audrey formed rapidly in June 1957, NHRP only had time for one research flight with the jet before the hurricane devastated Cameron, Louisiana. NHRP gathered time-lapse films from radar sites near landfall as part of its

program to provide cameras and training to coastal weather stations. Simpson decided to collect storm surge and wind damage assessments before clean-up efforts destroyed evidence of the storm's power. He ferried himself, project scientists, and D. L. Harris of OMR, to the disaster area. They gathered detailed measurements of surge heights and damage, starting USWB's efforts to model storm surges (Harris 1958). NHRP continued similarly prompt damage surveys until operational personnel assumed them in 1967 (Simpson 1989).

Because 1957 was another slow season, scientists logged over 400 additional flight hours measuring background trade winds. In September, Jordan left the ROB to teach at FSU, although he continued acting as NHRP's liaison with USN Hurricane Hunters. Harry Hawkins Jr. took over his position (Fig. 4). At the end of the year, Carl Reber replaced Art Johnson as operations manager, and José Colon took over managing the growing data library.

Many *NHRP Reports* were now based on flight data collected the first two years. Miller wrote on the three-dimensional wind structure (Miller 1958a) and steering currents of tropical cyclones (Miller 1958b). Two of NHRP's UChicago contractors, Roscoe Braham and Ernie Neil, wrote of possible tropical cyclone modification experiments using cloud-seeding techniques (Braham and Neil 1958).

Hurricane Daisy (1958) provided a trove of data for NHRP scientists. Over a four-day period, scientists

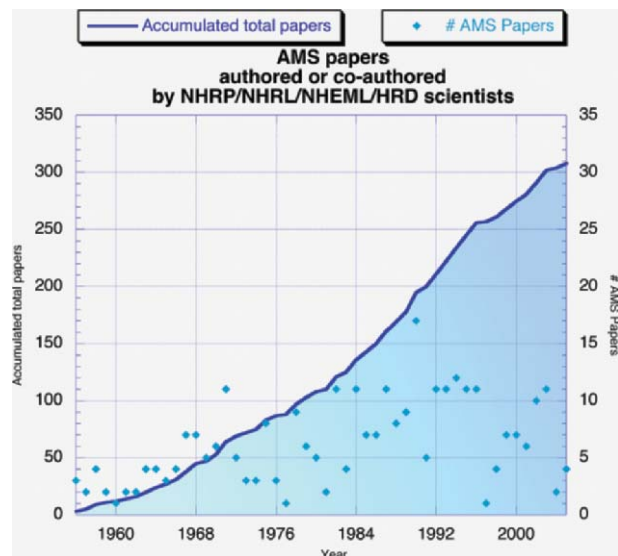


FIG. 3. Number of research papers each year along with cumulative total authored or coauthored by NHRP/NHRL/NHEML/HRD staff published in AMS journals and *Monthly Weather Review*. (Until 1974 *Monthly Weather Review* was a U.S. Government publication.)



Fig. 4. NHRP Deputy Director Harry Hawkins works on one of the DC-6 aircraft in 1963. [Source: Charlie True, NOAA.]

flew eight sorties, including one day when all three aircraft flew into the storm together at different altitudes. Hubert made the first real-time computer track forecasts during Daisy using a model developed on an NHRP grant (Kasahara and Platzman 1963). Daisy was the most-documented hurricane of NHRP's first three years and provided data for a host of studies, including the first detailed picture of tropical cyclone structure (Malkus et al. 1960). Another first occurred in 1958, when NHRP was able to fly one of its aircraft within 1600 feet of the surface, because the USAF waived its 700-mb safety rule for them. This allowed the scientists their first glance at the critical inflow layer of Hurricane Helene.

The active 1958 season proved to be the most scientifically productive of NHRP's first three. To mark this milestone, the AMS sponsored a technical conference on hurricanes in Miami Beach, Florida, that November. Spread over a two-day period, the conference featured eight sessions with many of the 44 papers focused on observations collected by NHRP. The conference ended with a special board of review, chaired by Eric Palmén, which recommended the continuance of NHRP as a vital source of information and focus on tropical cyclone research (Palmén 1958).

NATIONAL HURRICANE CENTRAL.

The conference marked the end of NHRP's initial 30-month period. The board of review's recommendation carried great weight with USWB, which decided to continue the project indefinitely. NHRP's heart was the aircraft program, and for it to continue it was necessary to have ongoing use of highly instrumented aircraft and trained personnel. USAF offered to transfer the WB-50s to the Department

of Commerce, along with a high-altitude WB-57 jet, if the Department of Commerce would assume the maintenance, crewing, and support for the planes. USWB found it would be less expensive to lease commercial aircraft than to maintain military bombers and leased two DC-6s. Because high-altitude jets were harder to come by, the Department of Commerce accepted the USAF's gracious offer of the WB-57. NHRP hired staff with aviation training to operate and maintain the new airframes, including flight meteorologists Frank Christensen, Harlan Davis, Isaac "Wink" Richardson, and Howard Friedman.

With NHRP planning to use civilian aircraft, it was no longer necessary to be at a military base. Simpson had wanted to collocate with the Miami hurricane forecast office from the start, and here was an opportunity to do so. The Miami office had moved from downtown to near the airport the year before, so the new aircraft would be based only blocks away. Simpson saw the combination of research project, main hurricane forecast office, and research aircraft facility as an important locus in tropical cyclone science and coined the term "National Hurricane Central" to describe the three entities. The name was quickly shortened to "National Hurricane Center" ("NHC") (Hawkins et al. 1961). The NHC also included a newly organized research library and offered university-level classes in meteorology taught by center scientists and academic collaborators.

Simpson left NHRP to pursue a doctorate at UChicago, with Gentry succeeding him as director and Hawkins as the deputy director. Both would hold those posts for the next 15 years (Table 2). After Simpson completed his studies, Reichelderfer pro-



HURRICANE GLADYS: 30 SEPTEMBER 1975, "39 CHARLIE"

Gladys, moving east of the Bahamas, had just starting to deepen when NOAA flew a two-plane mission into the storm. The DC-6 had lost its Omega navigation system and so attempted an eye penetration at low levels to use the sea surface to gauge the winds. The eye had contracted down to just a few miles in diameter and the eyewall consisted mainly of one supercell when the plane hit a downdraft and strong tail wind and came within a few knots of airspeed from stalling out. An encounter with a strong updraft and the pilot pointing the nose down despite the 50-foot altitude kept the plane from free fall. The technician who had been injured on the Gladys 1968 flight had the luck to be on this Gladys flight as well.

TABLE 2. Timeline of the hurricane research organization, showing the acronyms it went by, last names of its directors, venues where it was located, airplanes used, names of hurricanes important in their research (seeded storms in bold), major accomplishments of the laboratory, and external experiments to which laboratory personnel contributed. The bottom section is divided into colored 5-year blocks with the last year labeled (except 2005, when we were so busy we ran out of space).

Acronyms	NHRP		NHRL		NHEML		NHRL		AOML/HRD															
Directors	Simpson		Gentry		LaSeur		Rosenthal		Burpee		Willoughby	Marks												
Locations	ROB	Aviation Bldg	U. Miami Computer Center				IRE Bldg.		AOML/Virginia Key															
Aircraft	WB-47		WB-57				G-IV																	
	WB-50		DC-6		C-54		C-130					WP-3 D												
Storms	Greta Audrey Daisy		Donna Carla, Esther		Beulah Cleo Betsy		Inez Beulah Gladys		Debbie Edith, Ginger			Eloise, Gladys Anita		Gloria, Elena Earl Emily Gilbert Hugo		Guillermo, Jimena Andrew		Olivia Marilyn Guillermo Mitch Bret, Floyd		Humberto, Michelle Isidore, Lili Fabian, Isabel Ivan Dennis, Emily Katrina, Ophelia				
Innovations	Flight Data Beacon		Drone NHC-64		NHC-67 SANBAR Cloud physics 2D Model		3D Model		Nested Model		2D 12-layer model Land Radar records 3D 12-layer model SFMR		Eyewall replacement Synoptic flow Sonde editing Alicia		FACE II Non-hydrostatic model Airborne Doppler		Real-time radar		Flight Profiles VICBAR		SHIPS H-Wind Synoptic surveillance Eyewall sondes		R-CLIPER	
Projects	1960		IIOE 1965		BOMEX 1970		GATE 1975		FACE I 1975		1980		preSTORM 1985		GALE EMEX ERICA 1990		TEXMEX TOGA-COARE CEPEX 1995		CAMEX III 2000		CAMEX IV CBLAST IFEX TCSP/RAINEX 2005			

moted him to deputy director of research for severe storms, where he oversaw not only NHRP but also the newly formed National Severe Storms Project.

When NHRP moved to the Miami aviation building on April 1959, it upgraded its computer to a faster, magnetic tape-based version. NHRP also designated an aircraft group, formed of its flight meteorologists and technicians, to work primarily on the planes. As planned, this group was administratively separated to form the Research Flight Facility (RFF) under Reber, in 1961 (Hawkins et al. 1961). As a separate group they could be involved in nonhurricane research during the winter and spring.

After three years' work, NHRP helped produce the *Weather Bureau Forecasting Guide No. 3* (Winston 1959), the first formal, systematic manual to teach new objective hurricane forecast methods. NHRP also produced a storm surge forecasting guide (Harris 1959), furthering their goal to aid forecasters.

Originally scheduled for duty July 1959, the new research aircraft were delayed for a year as the low-bid contractor struggled to install the sophisticated instrumentation. Filling the data gap, NHRP technicians created recording pods for the WB-50s to automatically save flight-level information. Over the next few years, NHRP archived USAF's reconnaissance data, which otherwise would have been lost.

During this hiatus, NHRP concentrated on studying already accumulated data. Two of NHRP's invaluable collaborators, Herbert Riehl and Joanne Malkus, used Hurricane Daisy data to describe the

energetics of a mature tropical cyclone (Riehl and Malkus 1961). NHRP hired two in-house theoreticians to improve interactions with academics—Mikhail Alaka, who studied the hurricane outflow layer, and Stanley Rosenthal, who created a 2D steady-state model of a mature tropical cyclone.

The success of the first weather satellite in 1960 sounded the death knell of the rocket project. There had been one washout with Tropical Storm Becky (1958) and two failed launches in Hurricane Gracie (1959). The only success was a nonhurricane test launch in July 1958. USWB's Chief of Research Wexler used copies of its films to promote the concept of weather satellites. Rockets had been positioned at Cape Canaveral at the start of the 1960 season, but funding vanished. Quietly, USN abandoned the program without ever photographing a hurricane from space.

Oddly, satellites also ended the hurricane beacon program, although it had been far more successful, including the deployments in Hurricanes Helene (1958) and Hannah (1959). USAF command reasoned that if you could watch a tropical cyclone from space, there was no need to put a tracking device into its eye. NHRP's hopes to use the beacon to broadcast useful meteorological information (Hawkins 1960) were dashed.

Under pressure from NHRP, the DC-6s were ready by July 1960, without the magnetic tape recording systems. The WB-57 jet (Fig. 5) would not be ready until later in the season, so NHRP persuaded USAF and USN to supply high-altitude aircraft to cover for it.



FIG. 5. RFF's WB-57 jet was capable of gathering high-altitude data over hurricanes. [Source: Bob Sheets.]

The 1960 Atlantic hurricane season was the last one to occur without satellite coverage, because it fell between the operational periods of Television Infrared Observation Satellite (TIROS) platforms. It was not surprising that by the time Hurricane Donna was discovered, it was already at hurricane strength (Dunn 1961). NHRP flew eight sorties into Donna. The most documented hurricane up to that time, it was tracked by a half-dozen radars, including the newly installed WSR-57 unit at Miami and its prototype in Massachusetts (*Science News Letter* 1960). NHRP staff again carried out damage surveys after the storm had passed, driving down to the Florida Keys to collect photographs and personal accounts, and view the damage from the DC-6 as it flew over inaccessible areas on Florida's southwest coast.

In 1961, Wexler asked NHRP to summarize the achievements of its first five years. Hawkins not only noted the mapping of tropical cyclone structure and defining of storm energetics, but also NHRP's stimulation of the academic community to take up tropical cyclone studies (Hawkins 1962). They supplied copies of their data to scientists worldwide and showed that tropical cyclones were no longer a cipher but could be studied in detail. NHRP had also stimulated USWB to make research a more important part of its activities, carrying out research on severe local storms and fluid dynamics. From 1956 to 1961, USWB's annual research budget increased from \$1.5 to nearly \$6.5 million, from 4.7% of the total budget to 13.2% (Department of Commerce 1957, 1962).

TWEAKING MOTHER NATURE. Enthusiasm for weather modification, sparked by Schaefer's

1946 experiments seeding clouds with dry ice, led USN and General Electric Laboratories to cooperate in Project Cirrus, a series of more ambitious trials (Schaefer 1953). Intending to seed a weak tropical cyclone to prevent strengthening, Project Cirrus leaders failed to find a suitable storm by October 1947. Instead, they seeded a mature tropical cyclone as it moved away from the east coast of Florida. Around the time of seeding, it changed course and eventually came ashore in Savannah, Georgia. Outraged citizens blamed the course change on the seeding experiment, and Project Cirrus attempted no further tropical cyclone experiments. The

public furor made hurricane seeding a touchy subject for a decade. During the NHRP Daisy flights (1958), Braham tested a new cloud-seeding device. Although it was an equipment test rather than a modification experiment, NHRP leaders kept it secret to avoid negative press coverage.

On two of the USN jet flights into Donna, Riehl had ridden in the observer's seat. From his perspective above the cirrostratus deck, he could see a mass of merged cumulonimbus towers associated with the eyewall. From this mass streamed the outflow of the storm. These observations, combined with an aircraft-icing experience in 1947, convincing Simpson that there must be large quantities of super-cooled water in the inner core of tropical cyclones, which could be exploited by seeding (Simpson 1963; Simpson and Simpson 1966).

Simpson learned from Pierre St. Amand that USN was developing a silver iodide delivery system at their China Lake proving grounds (St. Amand and Henderson 1962). The USWB and USN agreed to test the equipment in a tropical cyclone during the 1961 season, and assess the hypothesis that seeding the eyewall would destabilize the inflowing wind, disrupting the circulation.

NHRP carried out its first seeding experiments in Hurricane Esther (1961). The RFF and USN planes observed both changes in the eyewall and a reduction in kinetic wind energy after the first seeding (Simpson et al. 1963). While not definitive, the results were encouraging enough for USWB and USN, along with the National Science Foundation, to formalize their tropical cyclone modification agreement as Project STORMFURY the next year.

Simpson became project director, with Captain Max Eaton (USN) as his able assistant director. Eaton proved priceless in securing the use of Roosevelt Roads Naval Air Station in Puerto Rico, as a forward base of operations.

STORMFURY's next seeding experiment came during Hurricane Beulah (1963). Project scientists had slightly modified their theory since Esther, hypothesizing that seeding the eyewall would cause it to reform at a greater radius and thus reduce the maximum winds resulting from conservation of angular momentum (Project STORMFURY 1964). On the first day, the flares missed their target, but on the second day they seeded the eyewall, and results consistent with the expectations were seen. While encouraged by the results, NHRP scientists realized that they knew too little about natural changes in tropical cyclone structure to be able to claim that the weakening of the wind after seeding was due to their actions.

Over the next six years, project scientists' hopes to carry out further seeding experiments were frustrated by inopportune technical difficulties and by possible target storms such as Betsy (1965) and Faith (1966) passing just outside the restrictive operational area. This area was expanded in 1967 and again in 1968, but still the hurricanes moved outside of it.

During this time, the Environmental Science Services Administration (ESSA) was formed in 1965. In the shakeup, NHRP became the National Hurricane Research Laboratory (NHRL), a change in status reflecting USWB's commitment to making tropical cyclone research a permanent activity. ESSA also began to separate the research branch of USWB from its operational side.

NHRL continued to fly research missions into such storms as Cleo (1964), Betsy (1965), and Inez (1966) in order to understand the natural variability of tropical cyclones that could serve as controls for seeding experiments. The Inez flights, in particular, provided a detailed picture of the structure of a major tropical cyclone (Hawkins and Imbembo 1976).

In 1964, Miller and computer programmer Peter Chase, produced NHC-64, a statistical tropical cyclone track forecast model (Miller and Chase 1966).



HURRICANE ALLEN: 6 AUGUST 1980, N42RF "KERMIT"

As the category-4 hurricane passed between Jamaica and Cuba, the NOAA P-3s began their second day of flights into Allen. "Kermit" approached the eye from the south, and penetrated without any problem. But, the radar showed cells in the north eyewall with extremely high return, as did the rainbands beyond. The lengthy shaking they encountered knocked loose the life raft and convinced one scientist that hurricane research was not his future.

They modified it in 1967 (NHC-67), in time for an eight-year study of numerical computer forecast techniques (Dunn et al. 1968) produced by forecasters and NHRL researchers. NHRL also continued to improve its computer simulations of mature tropical cyclone circulation (Rosenthal and Koss 1968) and to model tropical cyclogenesis (Rosenthal 1964).

NHRL scientists' expertise in tropical meteorology and aircraft observations led them to participate, along with RFF, in several large, multinational weather experiments, starting with the International Indian Ocean Expeditions (IIOE) in 1963 and 1964. Under the Global Atmospheric Research Project (GARP), they carried out research on air-sea interactions over tropical waters in 1969 during the Barbados Oceanographic and Meteorological Experiment (BOMEX) (Holland 1970).

Reber left RFF following participation in the IIOE, and Howard Mason (Fig. 6) became the aircraft center's new director. Both a pilot and engineer, Mason worked to improve the quality of the data coming from the aircraft, creating new instrument suites in house (Fig. 7), establishing a calibration laboratory, and participating in longer deployments as a liaison between scientists and aircraft crews.

NHRL and the hurricane forecast center moved in 1965 to the computer center building on UMiami's Coral Gables campus. The building was constructed specifically to house the hurricane organizations along with the university's computers and environmental sciences department. This not only

BY THE NUMBERS THROUGH 2006

230	Number of named storms into which laboratory research missions have been flown.
334	Number of papers in AMS refereed journals authored or coauthored by laboratory scientists.
1729	Number of laboratory-sponsored research flights.
1772	Number of hurricane eye penetrations made during research flights.
32,270	Number of man-hours laboratory researchers and collaborators have flown.



FIG. 6. Howard Mason and Joanne Simpson stand in front of an RFF DC-6. [Source: NOAA.]

gave NHRL direct access to better computers, it allowed greater cooperation with the local academic community. NHRL was taking on a new generation of researchers who were familiar with computers, such as Richard Anthes, Peter Black, Toby Carlson, Walter Koss, Muhammad Lateef, Billy Lewis, Robert Sheets, and James Trout. Carlson collaborated with Joseph Prospero (UMiami) in documenting the extent of Saharan dust outbreaks across the Atlantic with implications for tropical cyclone formation (Carlson and Prospero 1972). Sheets would later become director of NHRL's annual field program. Anthes, Koss, and Trout worked with Rosenthal to create a three-dimensional version of his two-dimensional tropical cyclone model (Anthes et al. 1971a). Anthes, during his subsequent career at The Pennsylvania State University (Anthes and Warner 1978) and the National Center for Atmospheric Research (NCAR) (Anthes 1990), continued to develop this model into its present



FIG. 7. Bob Black tends to the FORMVAR instrument, which improved the quality of cloud physics data from the aircraft in the 1960s. [Source: Stan Goldenberg, NOAA.]

incarnation, the fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5).

In 1965, Joanne Malkus Simpson (Fig. 6), who now headed USWB's Experimental Meteorology Branch (EMB), took over the directorship of Project STORMFURY. She ensured that when target tropical cyclones were not available, STORMFURY flew seeding experiments on tropical cumuli, to further understand weather modification. During her directorship, USAF joined STORMFURY with its considerable weather fleet. But, by 1967, she had grown tired of the controversy and publicity demands of STORMFURY and resigned, refocusing on her work at EMB. Gentry, with Hawkins as his alternate director, succeeded her. From this point on, NHRL would be responsible for the civilian management of the project until its end.

ESSA's expanding research wing included, in addition to EMB, a group of oceanographic laboratories under the direction of Harris Stewart, later known as the Atlantic Oceanographic and Meteorological Laboratories (AOML). Both EMB

and AOML moved to Miami in 1967, and construction began on a laboratory building on donated land on Virginia Key, a barrier island across Biscayne Bay from Miami.

Bob Simpson became director of the Miami hurricane forecast center by 1968, claiming the “National Hurricane Center” moniker exclusively for the operational office. In August of the following year, Hurricane Debbie moved into the seeding operational area. STORMFURY scrambled its RFF, USN, and USAF planes to Puerto Rico, carrying out 10 seeding runs over two days (Project STORMFURY 1970). NHRL computer modeling studies (Rosenthal 1970a) led planners to modify their strategy, dropping silver iodide canisters beyond the radius of maximum winds to encourage convection outside the eyewall and reduce winds by spreading the circulation outward. During their Debbie experiments, researchers found a 30% reduction in the winds after the first day, and 15% reduction after the second (Project STORMFURY 1970). But, their investigations in unmodified tropical cyclones, made since 1963, showed reductions of a similar magnitude due to natural fluctuations. Again, they were unable to claim that the changes were solely due to their seeding.

While STORMFURY aircraft were involved with Debbie, Camille, like many Gulf hurricanes, rapidly intensified. Two USN planes, left in Jacksonville, Florida, to cover Gulf reconnaissance requirements, were unable to penetrate the storm at a critical point in its deepening. Many of the aircraft that would back them up were committed to the seeding operations. Simpson persuaded a USAF reconnaissance plane to ferry from California to provide critical information on the storm before its devastating landfall. Later, carrying out a survey of Camille’s damage, Simpson briefed Vice President Agnew, mentioning the poor state of the hurricane reconnaissance fleet that led to this dicey situation. This created a bureaucratic firestorm (Simpson 1989). However, it did spur the acquisition of much-needed new equipment for USN and USAF Hurricane Hunters, and eventually led the Department of Commerce to upgrade the aging DC-6s with new P-3 Orions (Aberson et al. 2006).

Another seeding opportunity presented itself in 1971. Hurricane Ginger followed a wild track far eastward into the Atlantic before looping back. By the time it moved within range of STORMFURY aircraft, Ginger was a minimal hurricane, with a broad, weak wind field, lacking strong convection. This was far from the duplicate of Debbie scientists had hoped for, so instead they seeded its outer rainbands. There was a lack of discernible, objective variations in

radar signature or wind structure due to the seeding (Project STORMFURY 1972).

After the 1972 hurricane season, USN and USAF ended their participation in Project STORMFURY. Two years later the navy disbanded its Hurricane Hunters. RFF, which had acquired a surplus C-130, retired one DC-6 and the WB-57. With its resources more than halved, a great burden fell on Sheets, head of NHRL’s field program and now the STORMFURY director. Silver iodide launchers were built to work on the RFF aircraft, and monitoring plans were modified to use far fewer planes.

THE NOAA SHUFFLE. In 1970, the U.S. Government reorganized its meteorological and oceanographic facilities into the National Oceanic and Atmospheric Administration (NOAA). The operational elements within USWB, including the hurricane warning centers, were formed into the National Weather Service (NWS), while the research elements, including NHRL, RFF, AOML, and EMB, were put under the Environmental Research Laboratories (ERL). As part of the ERL reorganization, the NOAA research facilities in Miami were merged and purged. NHRL and EMB were placed administratively under AOML. While they remained collocated with NHC, they now answered to a different hierarchy and were funded under different budget lines. RFF was adversely affected by a mass reduction in force in 1972 that included firing its director, Mason.

NHRL scientists carried on. Detailed aircraft observations over the years demonstrated that tropical cyclones were not symmetric. Heretofore, computer models had not handled this complexity. The growth of computing power by the early 1970s allowed NHRL’s modeling group to incorporate asymmetries into its three-dimensional model (Anthes et al. 1971b). They also included explicit micro-physical calculations (Rosenthal 1970b) in the two-dimensional model to illustrate the effects of seeding.



HURRICANE EMILY: 22 SEPTEMBER 1987, N42RF “KERMIT” AND N43RF “MISS PIGGY”

Rapidly deepening before encountering Hispaniola, Emily reached its peak strength as both P-3 aircraft encountered very strong updrafts and downdrafts going through the eyewall. Both the turbulence and the continual turning in order to make the 27 combined eye penetrations on this day, made these memorable flights.

Paul Willis was hired to process cloud physics data, and Bob Jones, Michael Moss, and Burt Morris lent additional manpower to the modeling group, creating a nested grid version of the three-dimensional model (Jones 1976).

MIT Professor Fred Sanders' graduate student, Robert Burpee, came to work at NHRL, developing Sander's Barotropic Model (SANBAR), a barotropic track forecast program. He shared an office with Carlson, who interested him in Africa's influence on the tropical Atlantic. Burpee investigated the origins of easterly waves over Africa, tracing their formation to instabilities in the midtropospheric jet south of the Sahara (Burpee 1972).

In the summer of 1974, NHRL eschewed its usual hurricane field program to participate in the GARP Atlantic Tropical Experiment (GATE). Using an international fleet of aircraft, including the RFF DC-6 and C-130, as well as two nested arrays of surface ships off the west coast of Africa, GATE profiled easterly waves. NHRL scientists used GATE results to sketch out wave structure (Burpee 1975; Gamache and Houze 1985), calculate a Z-R relationship for tropical showers (Cunning and Sax 1977), examine cumulus transport (Johnson 1978), and investigate the spatial scales necessary to resolve significant features (Ooyama 1987).

Simpson retired from NHC in 1973, and a former NHRP summer intern, Neil Frank, succeeded him as director. By this time, AOML had completed

construction of its new building on Virginia Key. ERL administrators attempted to move NHRL and the Experimental Meteorology Laboratory (EML; formerly EMB) out to the facility. In his last significant act as director, Gentry thwarted the move to the offshore island, keeping meteorological researchers collocated with NHC.

Gentry retired at the end of 1974 and Noel LaSeur, long assistant director, took leave from FSU to direct NHRL for several years. Joanne Simpson departed EML for the University of Virginia [and later to work for the National Aeronautics and Space Administration (NASA)], leaving no one at either laboratory with the administrative clout to resist consolidation. EML merged with NHRL in 1975, forming the National Hurricane and Experimental Meteorology Laboratory (NHEML). EML personnel (John Cuning, Pat Gannon, Cecilia Griffith, Ron Holle, Raúl Lopez, Bob Sax, Irv Watson, Vic Wiggert, and Bill Woodley) became the Cumulus Group. They continued cloud modification, through the Florida Area Cumulus Experiments (FACE I, FACE II), and brought the total laboratory staffing to its highest level (see Fig. 8).

Because of further financial retrenchments, the general services administration moved NHEML and NHC off campus in 1978 to a commercial office building (IRE) in Coral Gables. They continued to share adjoining floors and facilities, and a library. It was a disruptive move, however; some of the archived data were lost, and many longtime employees retired.

The RFF reorganized as the Research Facilities Center (RFC) under Gus Emanuel, and acquired two Orion P-3 aircraft, which became operational in 1976 and 1977. For more information on the impact these new aircraft had on the laboratory's research, and especially on continuation of the STORMFURY experiments, see Abernethy et al. (2006) and Willoughby et al. (1985).

LACK OF "SEED" MONEY. Rosenthal, head of NHEML's Theoretical Studies Group, took over the laboratory when LaSeur returned to teaching in 1977. He completed a 12-layer version of his 2D model that was able to resolve individual convective elements within the hurricane, a large step forward in simulating tropical cyclone dynamics (Rosenthal 1978). In 1980, Jones completed a 3D version of this hydrostatic model (Jones 1980).

Rosenthal began replacing losses, hiring researchers with strong theoretical backgrounds, such as Steve Lord, Lloyd Shapiro, Katsuyuki Ooyama, and Hugh Willoughby. Lord and Willoughby worked with

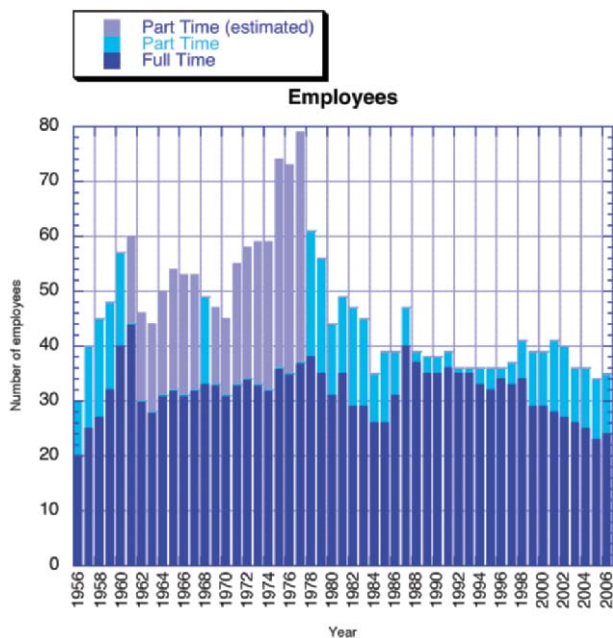


Fig. 8. Number of NHRP/NHRL/NHEML/HRD/AOML employees by year. Part time includes temporary, contract, and summer intern workers.



FIG. 9. Willoughby, Marks, Franklin, Burpee, and Phil Bogert plan a series of missions out of Barbados in 1986. [Source: Neal Dorst, NOAA.]

programmer Jacqueline Piotrowicz to produce a nonhydrostatic 2D hurricane model (Willoughby et al. 1984b). The laboratory also hired observational specialists (Robert Black, David Jorgensen, Mark Powell, and Frank Marks).

The 1970s and 1980s marked a period of relatively low Atlantic tropical cyclone activity, which provided few opportunities for seeding. During 1972, NHRL flew only one hurricane sortie (Fig. 2). NHEML attempted moving STORMFURY to the more active Pacific several times, but political considerations and fear of liability frustrated such plans. With no seeding experiments and many new theoretically oriented staff, NHEML shifted emphasis away from weather modification and toward understanding tropical cyclones in their natural state.

The lower Atlantic tropical cyclone activity did not exclude formation of individual strong, long-lived storms, like Anita (1977), David and Frederic (1979), and Allen (1980). Data gathered from these storms with the new P-3 aircraft (Aberson et al. 2006), flying back-to-back missions (Fig. 9), gave scientists a continuous view over the time scale of days, which led to insights in eyewall (Jorgensen 1984) and rainband dynamics (Willoughby et al. 1984a),

and the formulation of the eyewall replacement cycle theory (Willoughby et al. 1982). This natural transformation mimicked what STORMFURY hoped to initiate, further confusing natural and artificial changes.

Starting with Hurricane Frederic in 1979, NHEML replaced time-lapse film cameras at radar sites with digital recorders, designed to save Weather Surveillance Radar-1957 (WSR-57) analog signals on computer tape (Parrish et al. 1982). Because they had only two units, NHEML staff accompanied the recorders to NWS offices near landfalls (Fig. 10), setup, and operated them as the tropical cyclones passed nearby. This

continued until all coastal stations had digital WSR-1988 (WSR-88s) installed by 1998. Most notable of these deployment adventures (see Table 3) were for Gilbert in 1988 (Black and Willoughby 1992) and Hugo in 1989, where the team barely beat the storm to Charleston, South Carolina. These radar recorders allowed NHEML scientists Powell, Mike Black, and Peter Dodge to carry out studies of landfalling tropical cyclones (Powell et al. 1991). When Texas Tech University, University of Florida, Clemson, and Florida International University (FIU) deployed portable wind towers before landfalls, Dodge and Black coordinated aircraft missions with their locations to maximize data usefulness (Dodge et al. 2004).



FIG. 10. Peter Dodge and Chris Samsury avoid hazard during a land-based radar deployment in Hurricane Emily 1993. [Source: Paul Leighton, NOAA.]

By the early 1980s, public and scientific enthusiasm for weather modification waned and funding declined (Cotton and Pielke 1995). ERL split the Cumulus Group off from NHEML. The laboratory's acronym thankfully shrank back to NHRL, but its staff shrank too, with people transferred to Boulder, Colorado, laboratories. The loss of the Cumulus Group and Sheets' move to NHC in 1980 left very few in NHRL with experience in seeding operations. In 1983, Project STORMFURY officially ended, and with it the allocated funding. In its 21 years, the project had seeded only four tropical cyclones, a paltry number for statistical comparisons. This was partly due to restrictions placed on which storms they could target, and to the lower Atlantic activity. But, NHRL scientists' studies over these years allowed them to write the postmortem on the project (Willoughby et

al. 1985). They found little supercooled water in the hurricane core, no lack of ice to induce freezing, and naturally occurring cycles that would mimic experimentally induced changes.

Other research avenues were now explored. NHRL participated in many multiagency scientific projects (Aberson et al. 2006). Burpee, seeing the effectiveness of dropsondes during GATE, proposed deploying them around hurricanes. Riehl (1955) had recommended that reconnaissance flights sample the steering flow away from the hurricane core, but no one had implemented the idea. With the addition of dropsondes, scientists could now map the three-dimensional structure of the steering flow, and feed that information directly into numerical forecast models. The first of these synoptic flow experiments (Fig. 11) was into Hurricane Debbie (1982) (Burpee et al. 1996).

TABLE 3. Land-based radar deployments.
[Source: Peter Dodge.]

Year	Hurricane	NWS offices where recorders were deployed
1979	David	Miami, FL, West Palm, FL
	Frederic	Mobile, AL, Corpus Christi, TX
1980	Allen	Brownsville, TX
1983	Alicia	Galveston, TX
1984	Diana	Charleston, SC, Wilmington, NC
1985	Danny	Slidell, LA, Lake Charles, LA
	Elena	Pensacola, FL, Apalachicola, FL
1987	Floyd	Key West, FL
1988	Florence	Mobile, AL, Slidell, LA
	Gilbert	Corpus Christi, TX, Brownsville, TX
1989	Hugo	Charleston, SC, Wilmington, NC
1991	Bob	Wilmington, NC, Cape Hatteras, NC
1992	Andrew	Miami, FL, Tampa, FL, Slidell, LA, Lake Charles, LA
1993	Emily	Cape Hatteras, NC

HURRICANE RESEARCH IN A FLOOD ZONE.

Plans were made to move NHC and NHRL from the IRE building to a two-story facility to be constructed for them on the FIU campus, west of Miami. Instead, in 1984, NHRL's consolidation with AOML was completed when ERL moved the meteorologists out of Virginia Key, ending 25 years of collocation with NHC. Like a divorcing couple, NHRL and NHC split up the books in the research library, and the FIU building plan shrank to one story. While ending daily contact with the operational results of their work, the move put the hurricane researchers in closer contact with the oceanographic community, not only at AOML, but also at UMiami's Rosenstiel School for Marine and Atmospheric Sciences, across the street. This association helped with joint studies of air-sea interaction and the ocean's role in tropical cyclone intensity (Black et al. 1988).

The administrative reconfiguration also forced another name change when AOML was redesignated as a single laboratory. This made ERL's flow chart neater, but reduced AOML's constituent laboratories to divisions. NHRL became AOML's Hurricane Research Division (AOML/HRD), its present sobriquet. RFC, no longer under ERL, gained responsibility of all of NOAA's aircraft and became the Aircraft Operations Center (AOC). Placed under the Office of Marine and Aviation Operations, which operated NOAA's fleet of ships, AOC was commanded by NOAA Corps officers.

USAF, in the early 1990s, disbanded its Pacific typhoon squadrons and transferred its Atlantic hurricane squadron to its reserves. On an upside, their aircraft started receiving onboard computers, which



FIG. 11. Willoughby, Franklin, and Burpee discuss progress of the synoptic flow experiment into Hurricane Earl 1986. [Source: Neal Dorst, NOAA.]

automatically recorded flight-level information. AOML/HRD was back to archiving USAF's data, which it does to this day.

A dramatic El Niño in 1982 and 1983 spurred research into teleconnections between the Pacific phenomenon and Atlantic hurricanes, which renewed interest in tropical cyclone climatology. Shapiro and Stanley Goldenberg established a link between El Niño–Southern Oscillation and Atlantic hurricane activity (Goldenberg and Shapiro 1996). Long-time collaborator Gray's efforts to forecast seasonal tropical cyclone activity (Gray et al. 1992) led his colleague, AOML/HRD scientist Chris Landsea, to collaborate with Goldenberg, the Climate Prediction Center, and NHC, to initiate NOAA's efforts at hurricane seasonal forecasting. Finding serious deficiencies in the Atlantic tropical cyclone database, used in many climatological studies, Landsea also undertook an ongoing, comprehensive reanalysis effort (Landsea et al. 2004).

Despite physical separation from NHC, AOML/HRD's computer programmers—Joseph Griffin, Paul Leighton, William Barry, Nancy Figueroa, and M. Edward Rahn—continued

work on an improvement, the Statistical Hurricane Intensity Forecast (SHIFOR) in 1972 (Jarvinen and Neumann 1979). AOML/HRD scientists Mark DeMaria and John Kaplan began work on an improvement, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria and Kaplan 1994), which became operational in 1995. By 1997, it showed skill over SHIFOR. AOML/HRD scientists, cooperating with the National Meteorological Center, developed a nested-grid barotropic tropical

support for forecasters by helping visualize the flood of information coming to NHC from reconnaissance aircraft. They automated plotting dropsonde data from the synoptic flow experiments. In 1985, radar sweeps from the aircraft (Fig. 12) were sent via satellite to NHC. By 1987, profiles of the flight-level information were being plotted in near-real time. An aircraft computer workstation, operated by AOML/HRD (Fig. 13), allowed radar compositing in 1990 (Griffin et al. 1992).

Hurricane Joan (1988) unexpectedly deepened before striking Nicaragua, underscoring the lack of improve-

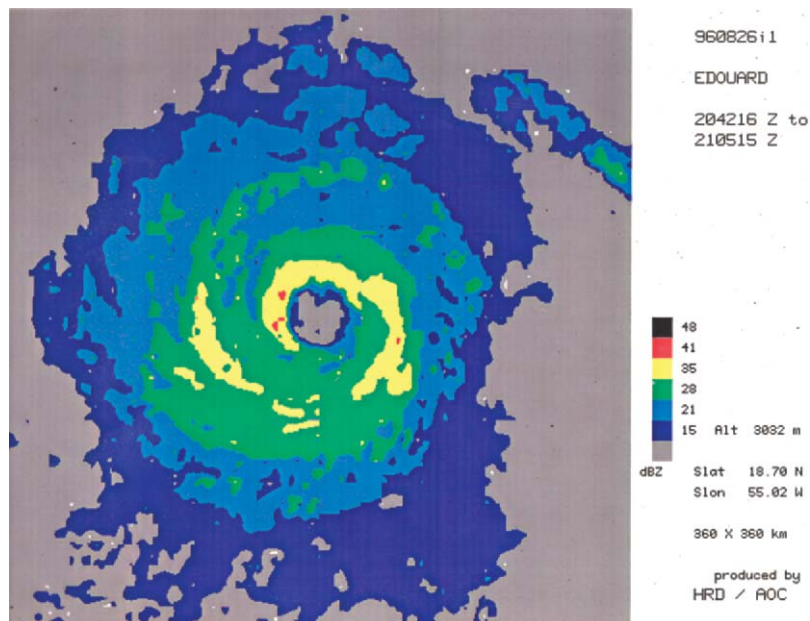


FIG. 12. A Hurricane Edouard real-time radar composite sent to NHC via satellite. [Source: NOAA.]



HURRICANE HUGO: 15 SEPTEMBER 1989, N42RF “KERMIT”

A classic Cape Verde hurricane, Hugo had just moved within operational range of the Leeward Islands by the 15th. Having had few problems with Gabrielle in the same area less than two weeks before, the P-3 went in at 1500 feet. Encountering severe turbulence due to a mesocyclone in the eyewall, a mechanical failure caused one of the engines to shut down. Once again, a life raft broke loose, this time denting the overhead handrail (Fig. 17). The plane had to orbit in the eye, burning fuel, while climbing to a safe altitude. N43RF and a U.S. Air Force plane then escorted the injured “Kermit” back to Barbados. N42RF remained out of commission for the rest of the season.

cyclone track model, Vic Ooyama’s Barotropic Model (VICBAR; DeMaria et al. 1992), which showed skill comparable with other operational models by 1989.

The destructiveness of rapidly deepening tropical cyclones literally struck home in 1992 when Hurricane Andrew chewed a path of ruin through southern Miami–Dade County, Florida. Many laboratory staff had harrowing, even life-threatening, experiences riding out the storm (Fig. 14). The AOML facility on Virginia Key suffered only minor damage, because Andrew’s eyewall passed 10 miles to the south. For a few months, the laboratory served as a staging area for efforts by its people to supply their fellow workers with the water, food, material, and labor needed in rebuilding their homes and lives.

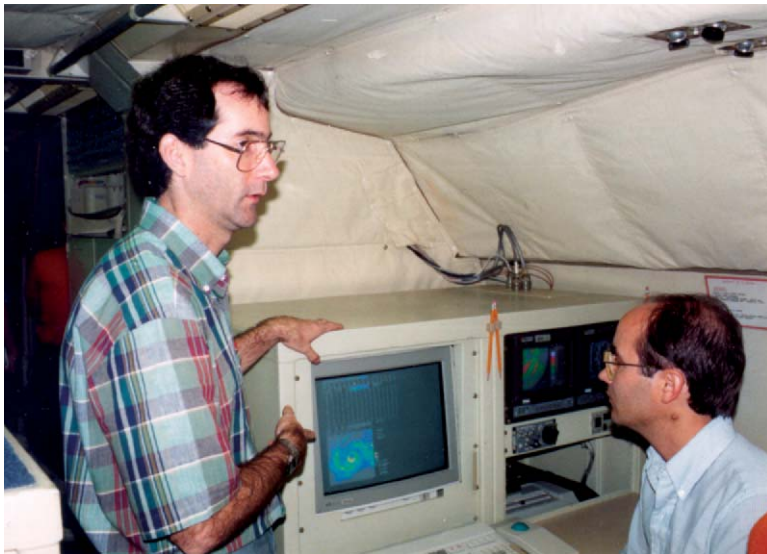


FIG. 13. Joe Griffin (rhs) demonstrates the AOML/HRD workstation to NHC’s Ed Rappaport. The workstation helped to funnel real-time aircraft data to NHC. [Source: Bob Burpee.]

In an effort to better define the wind field of Andrew, Powell and Sam Houston scoured the Miami area for any wind or pressure measurements that the public or other government agencies had taken (Powell et al. 1996; Powell and Houston 1996). Review of the digitized Miami radar revealed a small echo passing through the eye before landfall led to the discovery of a ship that mistakenly blundered through Andrew. AOML/HRD scientists turned into detectives to find the ship and obtain its weather log. This painstaking effort to reconstruct the wind field inspired the creation of AOML/HRD’s Surface Wind Analysis System (H*Wind), a tool to create wind analyses from a variety of sources in an operational environment (Powell et al. 1998). Concern for wind data quality led Powell to work with NWS, the National Climatic Data Center, the National Data Buoy Center, and colleagues Shirley Murillo, Nick Carrasco, and Russell St. Fleur to document the exposures of the Automated Surface Observing System (ASOS) and Coastal-Marine Automated Network (C-MAN) stations (Powell et al. 2004). Andrew also motivated AOM/HRD scientists to address rapid intensification in their SHIPS scheme. By 2000, they had also introduced storm decay within SHIPS (DeMaria et al. 2005).

THE CENTER WILL NOT HOLD. In the wake of Andrew, AOC moved to MacDill Air Force Base in Tampa, Florida, ending over 32 years of being in the same city as the hurricane researchers. Although the acquisition of the hangar space improved AOC’s maintenance situation, the move made AOML/HRD’s operations more expensive, and close collaboration on instrumentation and supply became complicated. The storm hastened NHC’s move to its new building on the FIU campus, farther away from Virginia Key. These moves spread Simpson’s vision of a National Hurricane Center across the width of the state.

In 1993, Burpee replaced Rosenthal as division director. The success of Burpee’s synoptic flow flights led Sheets, now director of NHC, to prod NOAA into purchasing a Gulfstream IV (G-IV) high-altitude jet in 1996 (Fig. 15), carrying out operational versions of these missions. With the G-IV came improved dropsondes, relying on GPS navigation and improved humidity sensors. They could now



FIG. 14. Sam Houston, happy he does not own a car, in the NHC parking lot, the morning after Hurricane Andrew 1992. Several AOML/HRD scientists worked at the center during the storm. [Source: Bob Burpee.]

be deployed in clouds and hurricane eyewalls, which AOML/HRD did in Hurricane Guillermo (1997). These data offered insights into the lower wind structure of hurricanes (Franklin et al. 2003). AOML/HRD scientists and programmers, led by James Franklin, developed on-board quality control software for the dropsondes and studied the most efficient targeting of them (Aberson 2003). Sim Aberson has also assessed the change dropsonde data have had on objective forecast accuracy since 1997.

An increase in Atlantic tropical cyclone activity in 1995 (Fig. 16; see title page) motivated AOML/HRD scientist to reexamine climatological records for a reason for the upturn. Their conclusion, reached in collaboration with Gray and AOML colleague Alberto Mestez-Nuñez, was that multidecadal cycles in tropical cyclone activity were linked to the Atlantic Multidecadal Oscillation in sea surface temperatures (Goldenberg et al. 2001). The higher activity since 1995, similar to 1926–69, was linked to the warmer phase of the oscillation. It was unsettling news to a coastal population grown used to lower hurricane activity.

Sheets retired in 1995, and Burpee became the third “Bob” from research

to direct NHC. Willoughby, becoming AOML/HRD’s director, noted hurricane intensity forecasting was lagging hurricane track forecasting. He brought divisional expertise in hurricane dynamics to bear on the problem, using the AMS 78th annual meeting’s special session on tropical cyclone intensity change as a jumping-off point.

AOML/HRD had long been involved with studying the affects of sea temperature on hurricane intensity. Studies of Hurricanes Celia in 1970 (Smith 1975) and Josephine in 1984 (Black et al. 1988), and Tropical Cyclone Kerry in 1979 (Black and Holland 1995) were improved upon as ocean probes became more sophisticated. In 2002, such probes detailed the ocean’s response to Hurricanes Isidore and Lili (Cione and Uhlhorn 2003). They mapped out changes in the Caribbean’s heat content resulting from the storms, more accurately assessing the energy flux.

In 2001, division scientists helped formulate the Joint Hurricane Testbed (JHT; *Federal Register* 2004), a U.S. Weather Research Program grant procedure for transitioning research into operational tools. In addition to H*Wind, dropsonde targeting, and SHIPS refinements, JHT financed John Gamache’s broadcast of real-time Doppler radar information for integration in forecasting models. Marks used JHT to create a statistical scheme predicting rainfall from landfalling hurricanes, Rainfall-Climate and Persistence (R-CLIPER).


After struggling for seven years with stagnant budgets and reduced personnel, Willoughby retired from NOAA to take a faculty position with FIU,



FIG. 15. Barry Damiano and John Kaplan entering the NOAA Gulfstream IV. This high-altitude jet was instrumental in making synoptic flow missions operational. [Source: Neal Dorst, NOAA.]

with Marks replacing him. Despite a background in observational meteorology, Marks sought to reinvolve AOML/HRD in computer modeling, an area neglected since Shapiro and Ooyama had left. Robert Rogers stepped up to fill this gap, cooperating with NHC and the Environmental Modeling Center (EMC) in developing a Hurricane Weather and Research Forecast model, which will use real-time, detailed reconnaissance data to forecast intensity. To further this, AOML/HRD initiated the Intensity Forecasting Experiment (IFEX) in cooperation with NHC and EMC (Rogers et al. 2006).

RFF experimented with operating drone aircraft from their DC-6s back in 1962. However, drone use in a tropical cyclone was not realized until 44 years later, when AOML/HRD scientists Joe Cione and Eric Uhlhorn collaborated with Greg Holland (NCAR), NASA, and the Aerosonde Corporation to fly an



HURRICANE ISABEL: 14 SEPTEMBER 2003, N43RF “MISS PIGGY” During a CBLAST experiment on this day, the P-3 flew to within 200 feet (50 m) of the surface in hurricane force winds, through a boundary layer full of sea spray. This led to a salt buildup inside the turboprop engines, causing the no. 3 engine to shoot out a 30 foot flame as its compressor failed. The crew flew back to St. Croix, uncertain if the other engines would not do the same. After this flight, AOC enacted new protocols for low-level flights.

aerosonde into Hurricane Ophelia in 2005. Having proved its feasibility, the next step is to measure critical energy fluxes near the air-sea boundary.

AOML/HRD’s Jason Dunion renewed interest in the effects of the dry Saharan air layer (SAL) on tropical cyclogenesis, with the development, in collaboration with Chris Velden and colleagues at the University of Wisconsin, of new satellite products that defined areas of SAL (Dunion and Velden 2004). These studies offer another possible factor in seasonal hurricane forecasting, as well as changes in intensity.

The 2005 hurricane season, especially Hurricane Katrina, sparked a divisive public debate over what factor anthropogenic global warming played in that disastrous season. AOML/HRD scientists engaged in that debate, citing their earlier study (Goldenberg et al. 2001) as evidence that many naturally occurring climatological cycles have a stronger influence on yearly hurricane activity than smaller, longer-term trends (Pielke et al. 2005).

ARE WE THERE YET? Nope. When the NHRP was extended in 1959, it was with the realization that 30 months was not enough time to unlock all the secrets of the hurricane. It turns out that 50 years is not enough time, either. Much has been learned, but work continues in many promising areas.

Hurricane intensity forecasting is still a work in progress. The influence of SAL and shear on hurricane dynamics promises fruitful studies. The full extent of the air-sea interactions has yet to be quantified, as does the change of the surface wind field when the hurricane comes ashore. The factors influencing the climate trends need to be better understood.

In the last 50 years, scientific understanding of tropical cyclones has increased tremendously, primarily due to the direct observations made by the National Hurricane Research Project and its various



FIG. 17. N42RF’s cabin after a run-in with Hurricane Hugo 1989. The life raft in the foreground was dislodged 10 feet from its berth. Al Goldstein nervously checks an engine’s status out the window. [Source: James McFadden, NOAA.]

WEB SITES

NHRP/NHRL/NHEML/HRD history:
www.aoml.noaa.gov/hrd/hrd_sub/beginning.html
Joint Hurricane Testbed:
www.nhc.noaa.gov/jht/index.shtml
Dropsonde assessments:
www.aoml.noaa.gov/hrd/assessment/index.html
Flight data archives:
www.aoml.noaa.gov/hrd/data_sub/hurr.html
H*Wind analyses:
www.aoml.noaa.gov/hrd/data_sub/wind.html
NHRP/NHRL/NHEML/HRD data rescue project:
www.aoml.noaa.gov/hrd/project2007/rescue.html

incarnations, and by the collaboration of its scientists with researchers worldwide. By demonstrating that the “hurricane problem” was not intractable, NHRP stimulated the academic community to engage in tropical cyclone studies, and supplied them with the hard data needed. As the first permanent research organization within USWB, it sparked a change in attitude that the bureau needed to move beyond operations to improve forecasting. Following its initial success, U.S. Government funding of weather research dramatically increased and became a significant part of NOAA’s budget.

For 50 years these federal hurricane researchers have led the way in designing airborne experiments, in the use of new technologies to study tropical cyclones, in attempting weather modification, and in carrying out theoretical and computer studies of storm dynamics, all the while, flying into the heart of hurricanes, examining the phenomena first hand.

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