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ABSTRACT

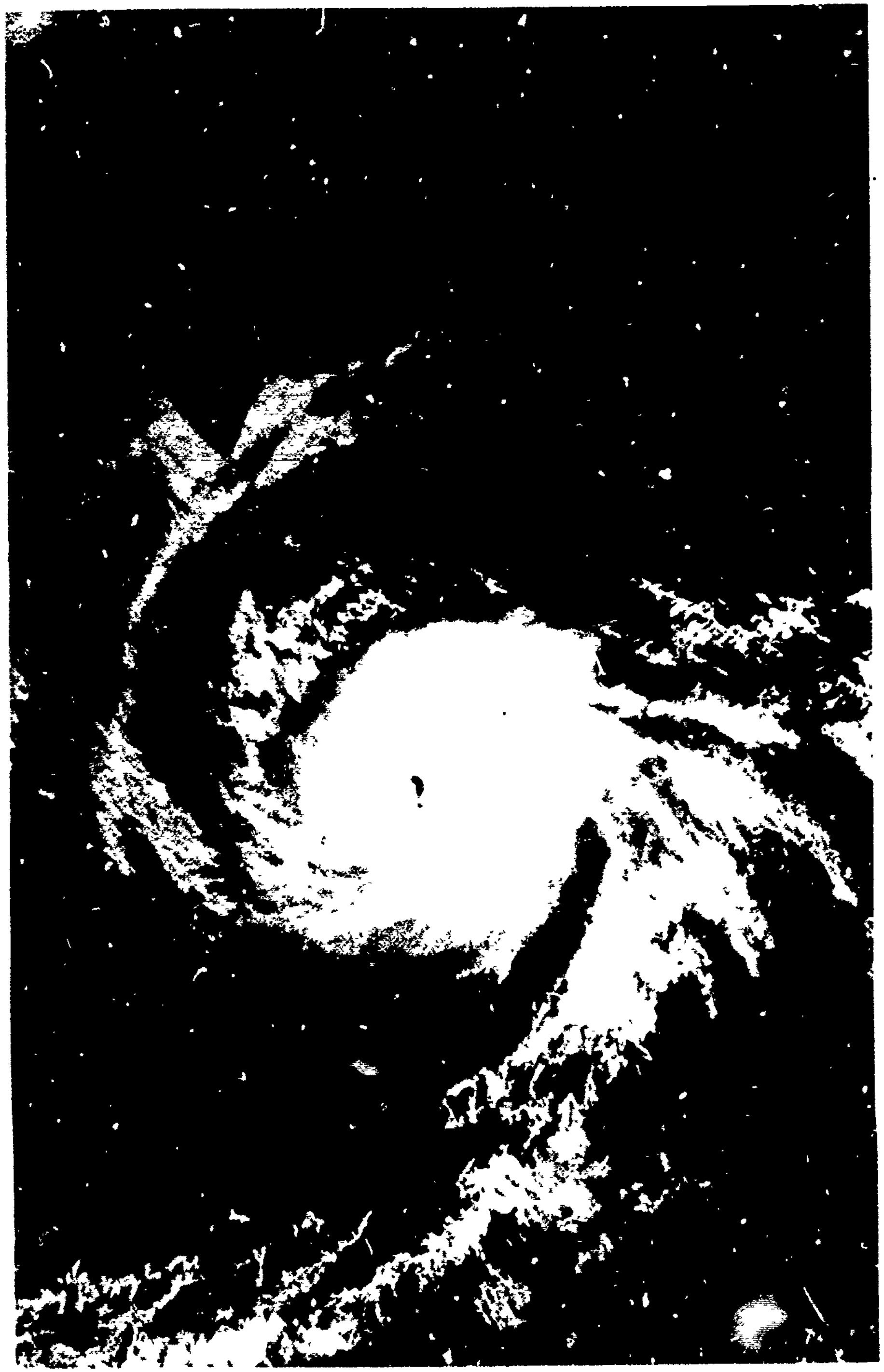
This publication, produced by the National Oceanic and Atmospheric Administration (NOAA), is an illustrated non-technical description of the meteorology of hurricanes and their effects on the land areas they hit. As an information source for students and teachers alike, this publication also describes the damage done in the past by hurricanes, the atmospheric processes behind hurricanes, and the efforts of forecasters and hurricane hunters. A bibliography is also included. (MR)

The greatest storm on earth

the greatest storm on earth

contents

Hurricanes manifest their brute strength in many ways. At left, the land and sea beneath a passing hurricane. At right, a NOAA satellite image of hurricane Ava, the classically organized 1973 storm that is still the most violent hurricane of record for the eastern north Pacific area.



There is nothing like them in the atmosphere. Even seen by sensors on spacecraft thousands of miles above the earth, the uniqueness of these powerful, tightly coiled storms is clear. They are not the largest storm systems in our atmosphere, or the most violent; but they combine those qualities as no other phenomenon does, as if they were designed to be engines of death and destruction.

In our hemisphere, they are called hurricanes, a term which echoes colonial Spanish and Caribbean-Indian words for evil spirits and big winds. The storms are products of the tropical ocean and atmosphere, powered by heat from the sea, steered by the easterly trades and temperate westerlies, and their own fierce energy. Around their tranquil core, winds blow with lethal velocity, the ocean develops an inundating surge, and, as they move ashore, tornadoes may descend from the advancing bands of thunderclouds.

Hurricanes have a single benefit—they are a major source of rain for those continental corners which fall beneath their tracks. Perhaps there are other hidden benefits as well. But the main consequence of the hurricane is tragedy.

In Asia, the price in life paid the hurricane has had Biblical proportions. As late as 1970, cyclone storm tides along the coast of what is now Bangladesh killed hundreds of thousands of persons.

Our hemisphere has not had such spectacular losses, but the toll has still been tragically high. In August 1893, a great storm wave drowned more than a thousand people in Charleston, South Carolina. In October of that same year, nearly two thousand more perished on the Gulf Coast of Louisiana. The Galveston storm of 1900 took more than six thousand lives. More than 1,800 perished along the south shore of Florida's Lake Okeechobee in 1928 when hurricane-driven waters broached an earthen levee. Cuba lost more than two thousand to a storm in 1932. Four hundred died in Florida in an intense hurricane in September 1935—the "Labor Day" hurricane that shares with 1969's Camille the distinction of being the most severe of record.

Floods from 1974's hurricane Fifi caused one of the Western Hemisphere's worst natural disasters in history, with an estimated five thousand persons dead in Honduras, and thousands more in Nicaragua, El Salvador, Guatemala, and Belize.

In the United States, the hurricane death toll has been greatly diminished by timely warnings of approaching storms. But damage to fixed property continues to mount. Camille, in 1969, caused some $1.42 billion in property damage. Floods from Agnes in 1972 cost an estimated $2.1 billion.

That is why such first-order technical accomplishments as early detection and timely warning of approaching hurricanes are not enough for some scientists. For them, there is the persistent goal of somehow disarming the greatest storm on earth.

In the United States, hurricane warning and research are focused in NOAA, the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. And there, as the planet orbits toward the summer solstice, scientists, technicians, pilots, and others brace for another season of great storms.

the season of great storms

Cumulus clouds, the atmosphere's basic weather "factories," and building blocks for hurricanes, climb high into the atmosphere under the energetic influence of the tropical sun.

It is the northern summer. The illusion of a moving sun caused by our planet's year-long orbit brings that star's direct rays northward to the Equator, then toward the Tropic of Cancer. Behind this illusory solar track the sea and air grow warmer, and the polar air of winter beats its seasonal retreat.

This northward shift of the sun brings the season of tropical cyclones to the Northern Hemisphere. Along our coasts and those of Asia it is time to look seaward.

Over the western Pacific, the tropical cyclone season is never quite over, but varies greatly in intensity. Every year, conditions east of the Phillippines send a score of violent storms howling toward Asia; but it is worst from June through October.

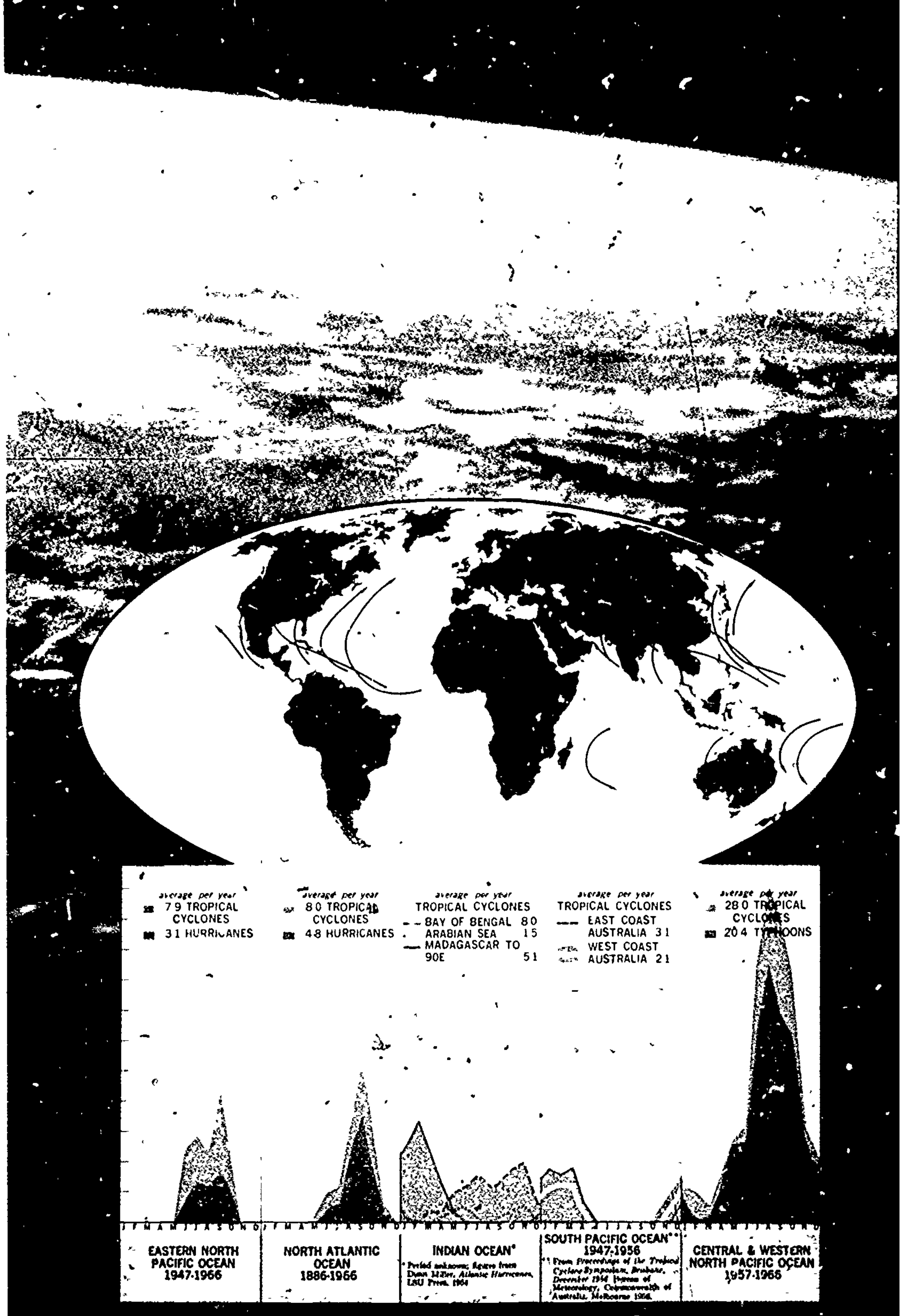
Southwest of Mexico, eastern Pacific hurricanes develop during spring and summer. Most of these will die at sea as they move over colder ocean waters. But there are destructive exceptions when storms curve back toward Mexico.

Along our Atlantic and Gulf coasts, the nominal hurricane season lasts from June through November. Early in this season, the western Caribbean and Gulf of Mexico are the principal areas of origin. In July and August, this center begins an eastward shift; by early September a few storms are being born as far east as the Cape Verde Islands off Africa's west coast. Again after mid-September, most storms begin in the western Caribbean and Gulf of Mexico.

In an average year, more than one hundred disturbances with hurricane potential are observed in the Atlantic, Gulf, and Caribbean; but fewer than ten of these reach the tropical storm stage, and only about six mature into hurricanes. On average, three of these hurricanes strike the United States, where they kill from about 50 to 100 people somewhere between Texas and Maine and cause hundreds of millions of dollars' property damage. In a worse-than-average year, the same storms cause several hundred deaths, and property damage totaling billions of dollars.

For NOAA, the hurricane season means another hazard from the atmosphere, at a time when tornadoes, and floods, and severe storms are playing havoc elsewhere on the continent. Meteorologists with NOAA's National Weather Service monitor the massive flow of data that might contain the early indications of a developing storm somewhere over the warm sea—cloud images from satellites, meteorological data from hundreds of surface stations and balloon probes of the atmosphere, information from hurricane-hunting aircraft.

In NOAA's Environmental Research Laboratories, scientists wait for nature to furnish additional specimens of the great storms to probe, analyze—eventually to modify, if they can be modified with beneficial results.



the atmospheric setting

A tropical sun burns through the nearly cloud-free atmosphere in the area of the so-called Bermuda High. This persistent high-pressure system dominates the North Atlantic atmosphere in summer, and contributes to the sequence of events that sometimes ends with the birth of Atlantic hurricanes.

Over the Atlantic, the budding summer brings other changes as well. A semipermanent zone of high pressure—the familiar "High" of weather maps—returns to a surface position centered near Bermuda and the Azores. This clockwise spiral of descending air, or anticyclone, lies between the temperate and tropical bands of prevailing winds, and, during summer and early autumn, dominates the North Atlantic atmosphere.

North of the high-pressure system, prevailing westerlies flow eastward in a deep layer extending from the surface to altitudes of 40,000 feet (12,000 meters) or more. Near the center of the Bermuda High, winds are variable. But to the south, the surface flow of air is predominantly to the west— the easterly tradewinds. In the northern summer, these easterlies may deepen until they reach from the surface to the stratosphere, and cover vast areas of the tropics; or they may break up into small vortices (a whirlpool is a vortex) which drift westward into the Caribbean or Gulf of Mexico. It is in this tradewind current that most Atlantic hurricanes are born.

The characteristic sinking of air within the anticyclone produces layers in the deep current of the easterly trades. As air sinks to levels of greater atmospheric pressure, it is heated by compression, producing at lower altitudes what is called a temperature inversion—a condition in which air, instead of cooling with altitude, cools only to the inversion altitude, then grows warmer, before it begins to cool again at greater heights. Beneath the inversion layer air sweeps for hundreds of miles over the surface of the sea, receiving a charge of moisture to altitudes of several thousand feet from evaporated ocean water.

Convection, or vertical motion, in this lower, heated layer, and intermittent intrusions of moist air, weaken the inversion, which gradually dissipates as the low-level air continues its trajectory above the warm sea. This vertical penetration of the inversion permits water vapor to be lifted to cooler altitudes, where it condenses into clouds and raindrops. As water vapor condenses, it releases heat energy into the atmosphere. This latent heat energy is gradually transported to higher levels, changing the vertical character to the tradewind belt. Sometimes the easterly flow is sufficiently disturbed by such processes that rain areas become concentrated, and the concentration intensifies into a storm.

The Polar Trough. When the Bermuda High is weak and south of its normal position, and the easterly trades are shallow (below about 15,000 feet, or 4,500 meters), an elongated area of low pressure—a trough—embedded in the temperate westerlies may push southward into the tropics. When the southern end of the intruding trough slows its eastward movement, or is trapped in the easterly trades, a hurricane may develop: or the trough may separate to become another weather-maker—the easterly wave.

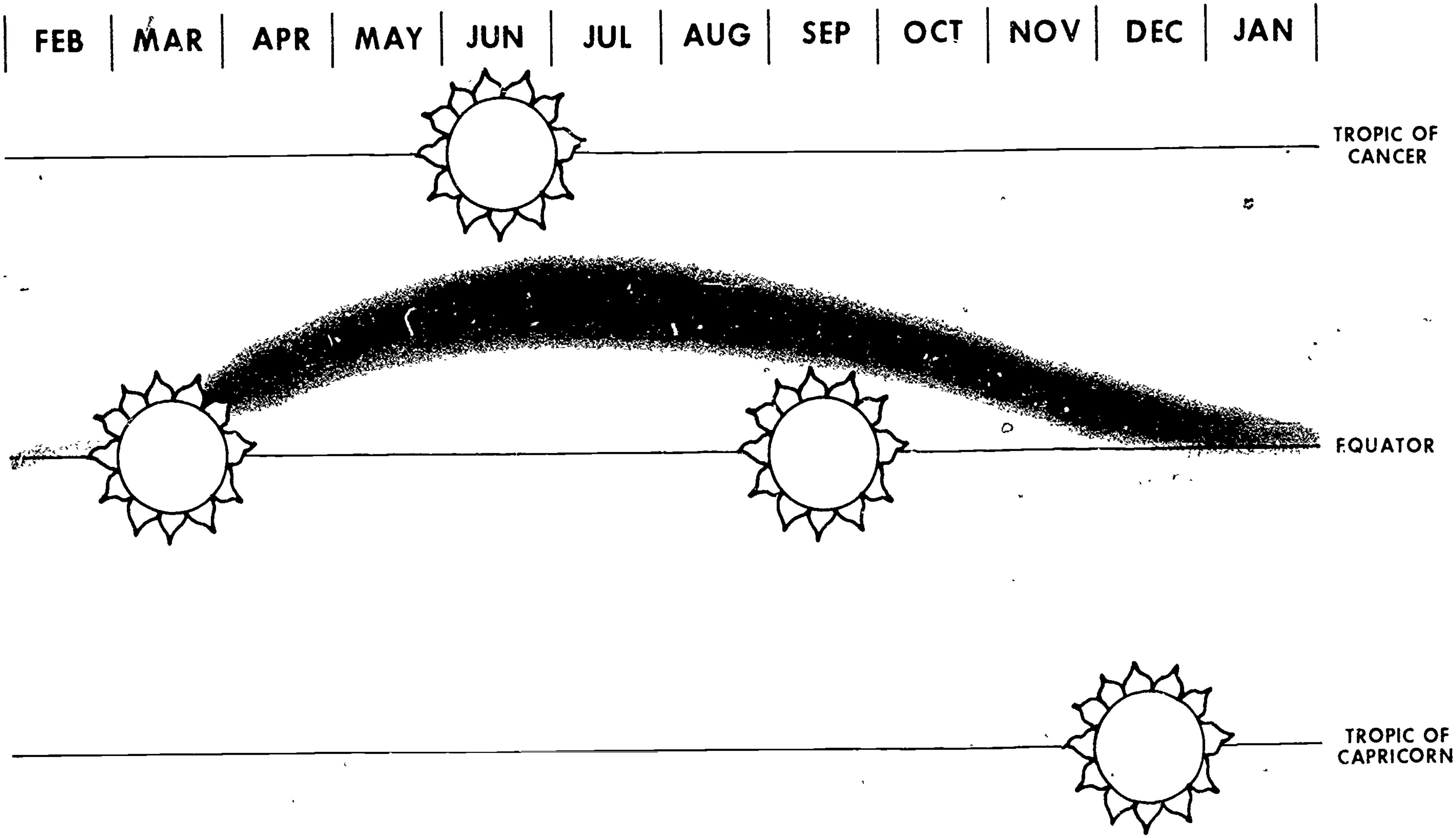
The Easterly Wave. Once embedded in the deep easterly current, this westward-drifting region of low-pressure tends to organize low-level circulation into alternate areas of converging and diverging airflow. Where air is diverging (high pressure), weather is fine. But where convergence occurs (low pressure), the depth of the moist layer increases, and convection produces heavy cumulus and cumulonimbus clouds which build to heights above 30,000 feet (9,000 meters).

Many of the waves in the easterlies have been traced back to western Africa, where they are most evident in the middle and low levels of the atmosphere as they cross Africa's Atlantic coast. These systems may travel thousands of miles with little change in form. But where the waves are destabilized by intense convection or by some external force—for example, high-level winds that promote greater organization of the circulation in the wave—they may curl inward. The vertical circulation accelerates, and a vortex develops that sometimes reaches hurricane intensities.

Easterly waves are present over some part of the Caribbean almost daily from June through September, the months of highest incidence of hurricanes. The waves are also present to a lesser extent in May, October, and November.

Migrants from the Doldrums. The tropical easterly tradewind belt of the Northern Hemisphere has a mirror image in a similar belt of winds south of the Equator. A highly simplified view of the atmosphere would show these tradewind belts separated by an equatorial region of low pressure, popularly called the doldrums—what meteorologists call the Intertropical Convergence Zone, or ITCZ.

The ITCZ varies considerably more than this simple view indicates Sometimes it is so weak as to be



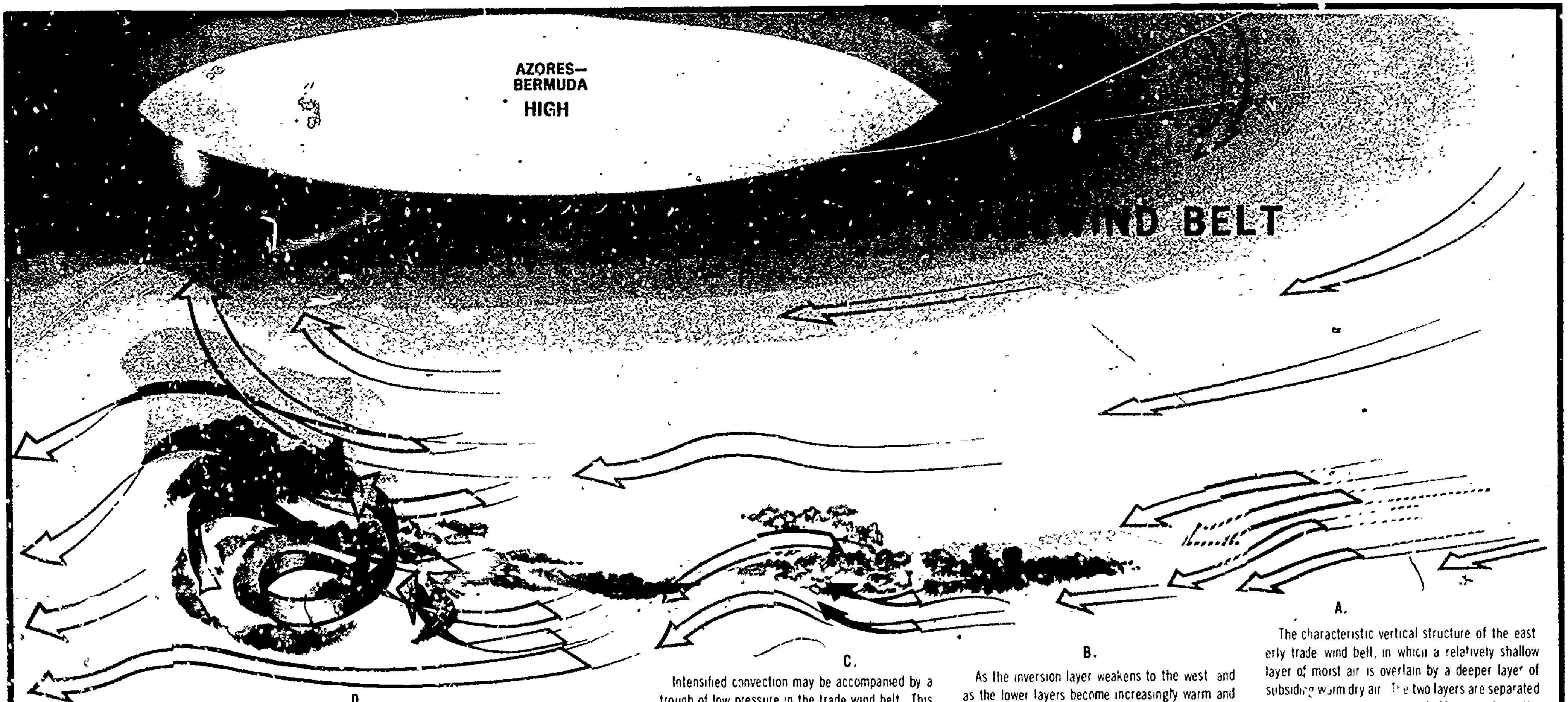
nearly undetectable, and almost completely free of significant weather. At other times it can be an intensely active zone a hundred miles or more wide, with cloud tops rising to the stratosphere and weather, as violent as that in the continental squall lines which sweep our own great plains.

The ITCZ also follows the sun. In February the ITCZ moves from a position near the Equator to its extreme limit near about twelve degrees north latitude in August; however, its day-to-day surface position varies greatly.

This interhemispheric borderland has a flow consisting mainly of eddies (individual currents in a moving fluid) that drift westward, and its intense activity is thought to be associated with the movement of these ed 'es into the tropics.

While the ITCZ is in the southern range of its annual migration (it is never south of the Equator) the effect of the earth's rotation is small; but as it shifts northward, the influence of the rotating globe—the Coriolis force— is great enough to permit a circulation to develop that can evolve into the tight, violent eddy of a tropical cy one.

Hurricanes in Other Oceans. What is true for hurricanes in the North Atlantic is generally true for the hurricanes of the eastern North Pacific, and similar storms like the cyclones of the Indian Ocean, and the western Pacific's typhoon. The storms tend to be born over warm water, spun from disturbances in the equatorial tradewind belts There is little tropical cyclone activity south of the equator, except for the ocean area west of Australia during the southern summer.



A.

The characteristic vertical structure of the easterly trade wind belt, in which a relatively shallow layer of moist air is overlain by a deeper layer of subsiding warm dry air. The two layers are separated by a temperature "inversion." Moisture from the sea evaporates into the lower atmosphere but cannot rise above the inversion. However the moisture charge received by the lower layers contains the latent heat energy that once released by condensation and convection to high levels can drive a tropical disturbance.

B.

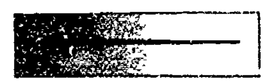
As the inversion layer weakens to the west and as the lower layers become increasingly warm and moist convection intensifies. Clouds form, and begin to rise to greater altitudes.

C.

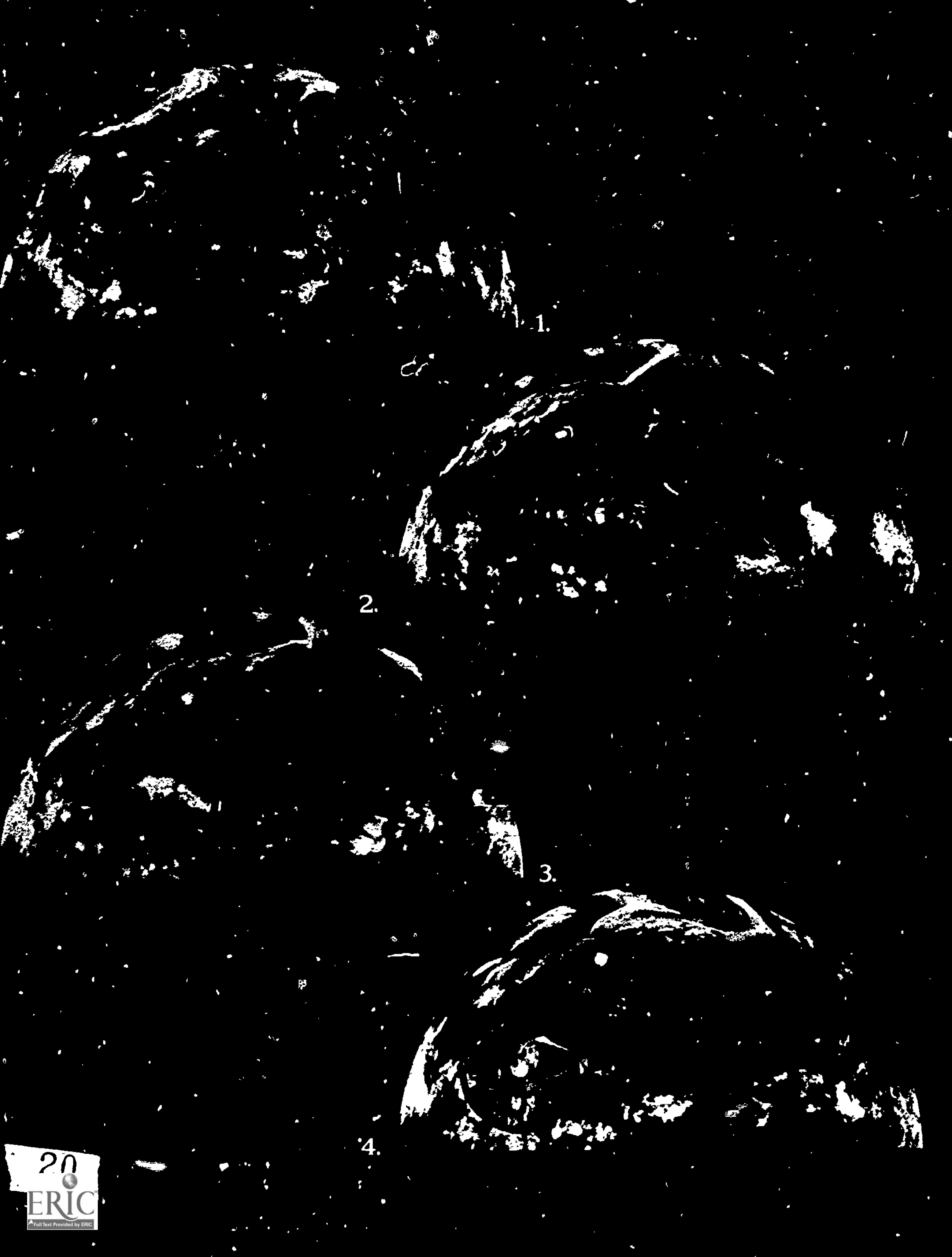
Intensified convection may be accompanied by a trough of low pressure in the trade wind belt. This poorly developed easterly wave is weak at the surface stronger near 15,000 feet weak at high altitude. Thunderstorms may develop behind the wave as the air is raised and shunted northward, ahead of the wave air is subsiding weather is fine. A wave of this intensity may travel for thousands of miles without appreciable change.

D.

Increased convection, and the pumping action of high altitude winds, may cause the easterly wave to deepen further becoming strong from the surface to 15,000 feet or more. Atmospheric pressure at the surface drops an area of low pressure becomes an isolated depression and the trade winds begin to turn in on themselves forming a weak cyclonic circulation about the center of low pressure. This circulation may intensify, pressure may continue to drop the winds spiralling around the center of low pressure may accelerate - the disturbance may become a severe tropical cyclone.



PRESSURE INCREASING



a storm is born

Birth of hurricane Carmen in August 1974 is watched by sensors aboard a Synchronous Meteorological Satellite, in an orbit that keeps it always about 22,000 miles (33,000 kilometers) over the same point on the equator. The embryonic Carmen begins as a poorly organized disturbance in the easterly wave (1), then seems to weaken (2) as the young storm crosses a persistent upper-level trough. But Carmen survives to become a tropical storm headed for the Antilles (3), and a full-scale hurricane (4) that strikes into Yucatan. Colored circles are centered on the storm's approximate center of rotation.

As the disturbance becomes bett. organized and more intense, the familiar shape of the hurricane appears At maturity, the storm is nourished by air converging at lower levels in a great spiral toward the center of low pressure, where convection (vertical motion) and the pumping action of high-altitude winds thrust it upward into a larger, anticyclonic circulation. Vertical scale is greatly exaggerated.

Hurricane formation was once believed to be something like the generation of thunderstorms, where surface heating causes air to rise, water vapor to condense, and thunderclouds to grow. But, in hurricanes, there was an additional element—the inexplicable drop in atmospheric pressure that organized these elements and spun them into a cyclonic spiral.

This theory left much to be desired. Few hurricanes mature in the doldrums, where this kind of activity is usually found, and there are too many seemingly ideal convective situations there and too few hurricanes. And what of the drop in atmospheric pressure?

Even storms as neatly constructed and carefully observed as hurricanes present scientists with an infinitude of unknowns. There is no full understanding of what triggers a hurricane, or how a disturbance in the easterly trades or a disturbance along the ITCZ is transformed into a mature storm.

This is what seems to happen. Some starter mechanism—the intruding polar trough, easterly wave an eddy from an active ITCZ —stimulates an area of vertical air motion. The initial disturbance creates a region into which low-level air from the surrounding area begins to flow, accelerating the convection already occurring inside the disturbance. As water vapor in the ascending moist columns condenses (releasing large amounts of heat energy to drive the wind system), the vertical circulation acquires greater organization; and the horizontal form of the disturbance becomes the familiar cyclonic spiral, in which (in the Northern Hemisphere) the movement of low- and mid-level air is counter-clockwise. Now the storm is an embryo hurricane.

High-altitude winds help the developing hurricane's massive vertical transport exhaust air into the upper reaches of the troposphere, the lower level of the atmosphere where most vertical mixing and weather occur. These winds pump ascending air out of the cyclonic system into the clockwise circulation of a high-altitude anticyclone, carrying air well away from the disturbance before it can sink to the surface again.

Thus, a large-scale vertical circulation is set up in which low-level air spirals up the cyclonic core of the disturbance, and is exhausted at high altitudes. This pumping action—and the heat released by the ascending, water-bearing air—explains the sudden drop in atmospheric pressure at the surface. The drop produces the hurricane's uniquely steep pressure gradient, along whose contours winds are accelerated to hurricane speeds.

It is generally believed that the interaction of low-level and high-altitude wind systems at scales larger than the hurricane's determines the intensity the storm will attain. Scientists also believe planetary wind systems, displaced northward, set up an essential large-scale flow which supports the budding storm, and that the development of hurricanes is often preceded by high-level warming and low-level inflow, in some balance that is not fully understood. There is still much to be learned. For example, researchers have begun to ponder the connection between thunderclouds over the hotplate of Central Africa and disturbances in the easterly tradewind belt, and how these are affected by the massive natural cloud seeding of Saharan dust.

portrait of a hurricane

Given that the hurricane, as an engine, is inefficient and hard to start and sustain, once set in motion, once mature, it is an awesome natural event indeed.

The young storm stands upon the sea as a whirlwind of awful violence. Its hurricane-force winds cover thousands of square miles, and gale force winds—winds of 33 to 55 knots* (16 to 28 meters per second)—over areas ten times larger. Along the contours of its spiral run bands of dense clouds from which torrential rains fall. These spiral rainbands ascend in decks of cumulus and cumulonimbus clouds to the high upper atmosphere, where condensing water vapor is swept off as ice-crystal wisps of cirrus clouds by high-altitude winds. Lightning glows in the rainbands, and this cloudy terrain is whipped by turbulence.

In the lower few thousand feet, air flows in toward the center of the cyclone, and is whirled upward through ascending columns of air near the center. Above 40,000 feet (12,000 meters), this cyclonic pattern is replaced by an anticyclonic circulation—the high-level pump which is the exhaust system of the hurricane engine.

At lower levels, where the hurricane is most intense, winds on the rim of the storm follow a wide pattern, like the slower currents on the rim of a whirlpool; like those currents, these winds accelerate as they approach the central vortex. This inner band is the eyewall, where the storm's worst winds are felt, and where moist air entering at the surface is chimneyed upward, releasing heat to drive the storm. In most hurricanes, these winds exceed 90 knots (50 meters per second)—nearly twice that in extreme cases. Maximum winds run still higher in typhoons.

Hurricane winds are produced, as all winds are, by differences in atmospheric pressure, or density. The pressure gradient—the rate of pressure change with distance—produced in hurricanes is the sharpest in the atmosphere, excepting only the pressure change believed to exist across the narrow funnel of a tornado.

Atmosperic pressure is popularly expressed as the height of a column of mercury that can be supported by the weight of the overlying air at a given time.** In North America, barometric measurements at sea level seldom go below 29 inches of mercury (982 millibars), and in the tropics it is generally close to 30 inches (1,016 millibars) under normal conditions. Hurricanes drop the bottom out of those normal categories. The Labor Day hurricane that struck the Florida Keys in 1935 had a central pressure of only 26.35 inches (892 millibars). And the change is swift: pressure may drop an inch (33 millibars) an hour, with a pressure gradient change of a tenth of an inch (3 millibars) per mile.

At the center of the storm is a unique atmospheric entity, and a persistent metaphor for order in the midst of chaos—the eye of the hurricane. It is encountered suddenly. From the heated tower of maximum winds and thunderclouds, one bursts into the eye, where winds diminish to

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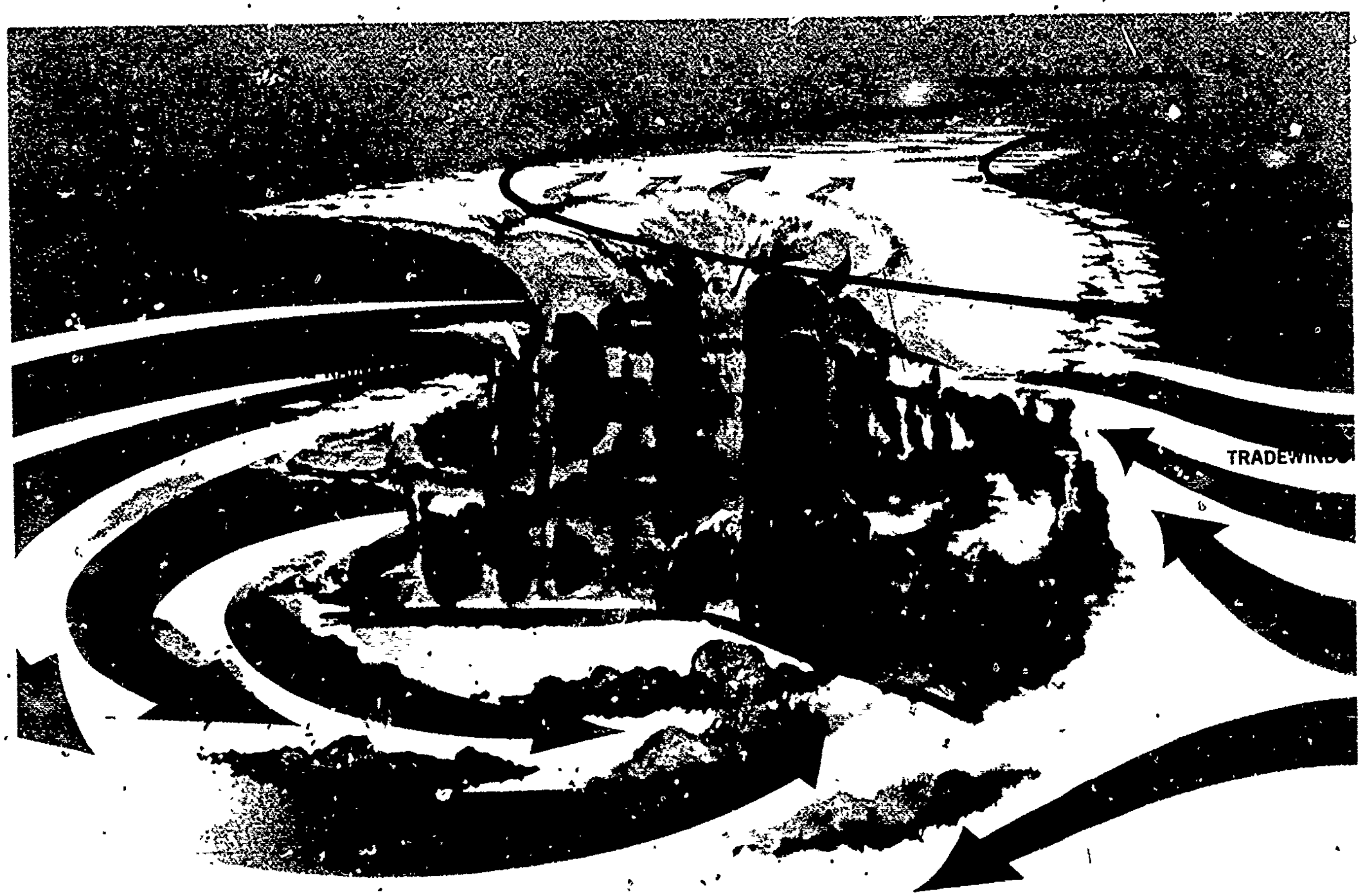
*A knot is one nautical mile per hour, a nautical mile is about 1 15 statute miles

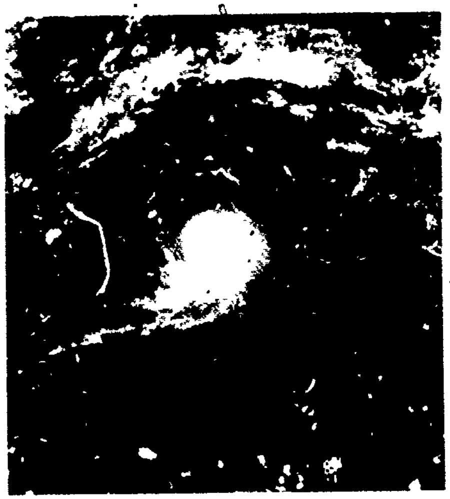
**Weather maps show atmospheric pressure in millibars units equal to a thousandth of a bar. The bar is a unit of pressure equal to 29 53 inches of mercury in the English system, and to one million dynes per square centimeter in the metric system something less than 15 knots (eight meters per second). Penetrating the opposite wall, one is abruptly in the worst of winds again.

A mature hurricane orchestrates more than a million cubic miles of atmosphere. Over the deep ocean, waves generated by hurricane winds can reach heights of 50 feet (15 meters) or more. Under the storm center the ocean surface is drawn upward like water in a giant straw, forming a mound a foot or so higher than the surrounding ocean surface. This mound translates into coastal surges of 20 feet (six meters) or more. Besides this surge, massive swells pulse out through the upper layers of the sea—Pacific surfers often ride the oceanic memory of distant typhoons.

Hurricane Eloise, which struck the Florida panhandle in September 1975, taught scientists something new about the influence of passing hurricanes on the marine environment. Expendable bathythermographs dropped from NOAA research aircraft ahead of, in, and in the wake of the storm showed that the ocean was disturbed to depths of hundreds of feet by a passing hurricane, and "remembered" hurricane passage with internal waves that persisted for weeks after the storm had gone. The same storm also demonstrated that a passing hurricane can be felt deep in the sea-floor sediments.

While a hurricane lives, the transaction of energy within its circulation is immense. The condensation heat energy released by a hurricane in one day can be the equivalent of energy released by fusion of four hundred 20-megaton hydrogen bombs. One day's released energy, converted to electricity, could supply the United States' electrical needs for about six months.



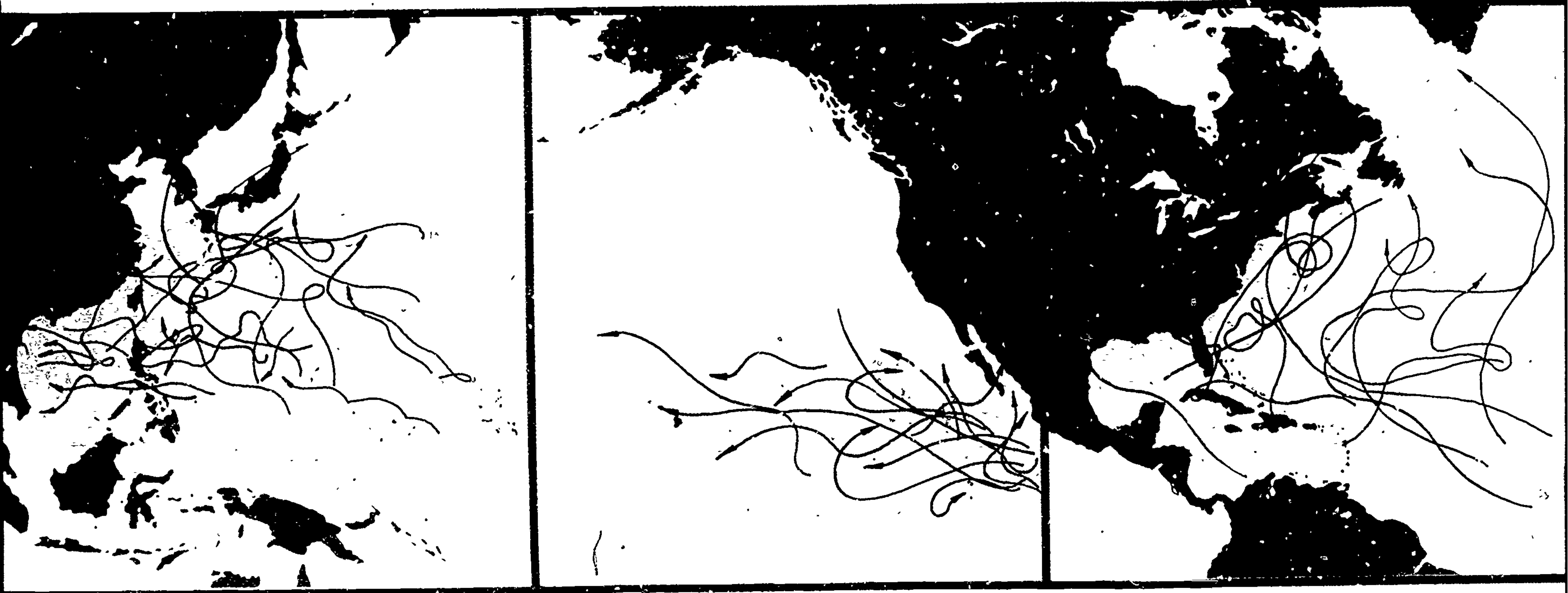


Portrait of a hurricane, as seen by satellite, radar, and illustrator. Cutaway view of storm is greatly exaggerated in vertical dimension; actual hurricanes are less than 50,000 feet (15,000 kilometers) high and may cover a diameter of several hundred miles.

11

the fatal thrust toward land

Hurricane waves besiege a seawall as a storm makes landfall along our Atlantic coast. This thrust toward land is suicidal for the storm, which dies soon after it has extracted its toll in life and property where it comes ashore.



Trends and exceptions in the great storms' thrusts toward land. Shaded areas show general patterns of westward drift and recurvature. Actual storm tracks describe a few of the countless variations possible

From birth, the hurricane lives in an environment that constantly tries to kill it—and ultimately succeeds. The hurricane tends to survive while it is over warm water. But its movement is controlled by the forces which eventually destroy it, forces which drive the storm ashore or over colder water beyond the tropics where it will fill and die. This thrust away from the tropics is the clockwise curve which takes typhoons across the coastlines of Japan and into the Asian mainland, and Atlantic hurricanes into the eastern United States.

Even before a hurricane forms, the embryonic storm has forward motion, generally driven by the easterly flow in which it is embedded. As long as this easterly drift is slow—less than about 20 knots, or 10 meters per second—the young hurricane may intensify. More rapid forward motion generally inhibits intensification in the storm's early stages. Entering the temperate latitudes some storms may move along at better than 50 knots (25 meters per second), but such fast-moving storms soon weaken.

At middle latitudes, the end usually comes swiftly. Colder air penetrates the cyclonic vortex, the warm core cools, and acts as a thermal brake on further intensification. Water below 80 degrees Fahrenheit (27 degrees Celsius) does not contribute much energy to a hurricane. Even though some large hurricanes may travel for days over cold North Atlantic water, all storms are doomed once they leave the warm tropical waters which sustain them. The farther they venture into higher latitudes, the less fuel they receive from the sea; this lack of fuel finally kills the storms.

Over land, hurricanes break up rapidly. Cut off from their oceanic source of energy, and with the added effects of frictional drag, their circulation rapidly weakens and becomes more disorganized. Torrential hurricane rains, however, may continue even after the winds are much diminished. In the southeastern United States, about a fourth of the annual rainfall comes from dissipating hurricanes, and the Asian mainland and Japan suffer typhoons to get water from the sky.

Hurricanes are often resurrected into extratropical cyclones at higher latitudes, or combine with existing temperate-zone disturbances. Many storms moving up our Atlantic coast are in the throes of this transformation when they strike New England, and large continental Lows are often invigorated by the remnants of storms born over the tropical sea.

destruction in a hurricane

Wind and water do the hurricane's destructive work. The mighty storm tide and powerful, debris-laden winds create such scenes of havoc as these.

Hurricanes are the unstable, unreliable creatures of a moment in our planet's natural history. But their brief life ashore can leave scars that never quite heal. In the mid-1970's, the hand of 1969's Camille could still be seen along the Mississippi Gulf Coast. Most of a hurricane's destructive work is done by the general rise in the height of the sea called storm surge, wind, and flood-producing rains.

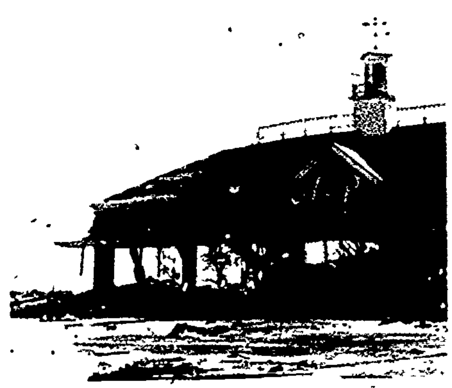
Hurricane winds can be the least destructive of these, although there are important exceptions like 1971's Celia, whose high winds did most of the storm's destructive work. These winds are a force to be reckoned with by coastal communities deciding how strong their structures should be. For example, normal atmospheric pressure at sea level is about two thousand pounds per square foot (19,000 kilograms per square meter). As winds increase, pressure against objects is added at a disproportionate rate. Pressure mounts with the square of wind velocity, so that a tenfold increase in wind speed increases pressure one-hundred-fold. Thus, 20-knot (12 meter-per-second) wind increases atmospheric pressure by about two pounds per square foot (10 kilograms per square meter); a wind of 200 knots (110 meters per second) increases atmospheric pressure by more than 225 pounds per square foot (1,100 kilograms per square meter). For some structures, this added force is enough to cause failure. Tall structures like radio towers can be worried to destruction by gusting hurricane-force winds. Winds also carry a barrage of debris that can be quite dangerous.

All the wind damage does not necessarily come from the hurricane. As the storm moves shoreward, interactions with other weather systems can produce tornadoes, which work around the fringes of the hurricane. Although hurricane-spawned tornadoes are not the most violent form of these whirlwinds, they have added to the toll we pay the hurricane.

Floods from hurricane rainfall are quite destructive. A typical hurricane brings 6 to 12 inches (150 to 300 millimeters) of rainfall to the area it crosses, and some have brought much more. The resulting floods have caused great damage and loss of life, especially in mountainous areas, where heavy rains mean flash floods. The most widespread flooding in United States history (through 1976) was caused by the remnants of hurricane Agnes in 1972. Rains from the dying hurricane brought disastrous floods to the entire Atlantic tier of states, causing 118 deaths and some $2.1 billion in property damage.

The hurricane's worst killer comes from the sea, in the form of storm surge, which claims nine of every ten victims in a hurricane.

As the storm crosses the continental shelf and moves close to the coast, mean water level may increase 15 feet (5 meters) or more. The advancing storm surge combines with the normal astronomical tide to create the hurricane storm tide. In addition, wind waves five 10 feet high are superimposed on the storm tide. This buildup of water level can cause severe flooding in coastal areas, particularly when the storm surge coincides with normal high tides. Because much of the United States' densely populated coastline along the Atlantic and Gulf coasts lies less than 10 feet (3 meters) above mean sea level, the danger from storm surges is great.



Wave and current action associated with the surge also causes extensive damage. Water weighs some 1,700 pounds per cubic yard (1,000 kilograms per cubic meter); extended pounding by frequent waves can demolish any structures not specifically designed to withstand such forces.

Currents set up along the coast by the gradient in storm surge heights and wind combine with the waves to severely erode beaches and coastal highways. Many buildings withstand hurricane winds until, their foundations unde[illegible]ined by erosion. they are weakene[illegible] and fail. Storm tides, waves, and currents in confined harbors severely damage ships, marinas, and pleasure boats. In estuarine and bayou areas, intrusions of salt water endanger the public health—and create bizarre effects like the salt-crazed snakes fleeing Louisiana's flooded bayous.

forecasters and hunters

Stalking a storm (shown in the satellite photograph), rough riding meteorologists may fly right to the hurricane's eye for detailed information.

The day is past when a hurricane could develop to maturity far out to sea and go unreported until its thrust toward land. Earth-orbiting satellites operated by NOAA keep the earth's atmosphere under virtually continuous surveillance, night and day. Long before a storm has evolved even to the point of ruffling the easterly wave, scientists at NOAA's National Hurricane Center* (a National Weather Service Forecast Office) in Miami, Florida, have begun to watch the disturbance. In the satellite data coming in from polar-orbiting and geostationary spacecraft, and in reports from ships and aircraft, they look for subtle clues that mark the development of hurricanes—cumulus clouds covered by the cirrostratus deck of a highly organized convective system; showers that become steady rains; dropping atmospheric pressure; intensification of the tradewinds, or a westerly wind component there.

Then, if this hint of a disturbance blooms into a tropical storm, a time-honored convention is applied: it receives a name. This practice began in the 1940's, when wartime weathermen plotted the movement of storms—informally named for wives and sweethearts—across vast theaters of operations. It has been Weather Service policy since 1953. The system uses an alphabetical series of names—Anita, Babe, Clara...—that changes each year, and is different for the North Atlantic and the Eastern North Pacific. Typhoons also receive names in alphabetical order, but because they occur throughout the year, these storms are named consecutively without regard to the year—that is, a calendar year of typhoon activity could begin with typhoon Wanda.

The first hurricane warning in the United States was flashed in 1873, when the Signal Corps warned against a storm approaching the coast between Cape May, New Jersey, and New London, Connecticut. Today, naming a storm is a signal which brings a considerably more elaborate warning system to readiness. Long distance communications lines and preparedness plans are flexed.

As an Atlantic hurricane drifts closer to land, it comes under surveillance by weather reconnaissance aircraft of the U.S. Air Force, the famous "Hurricane Hunters," who bump through the turbulent interiors of the storms to obtain precise fixes on the position of the eye, and measure winds and pressure fields. Despite the advent of satellites, the aircraft probes are the most detailed information hurricane forecasters receive. The hurricanes are also probed by "flying laboratories" from NOAA's Research Facilities Center in Miami. Finally, the approaching storm comes within range of a radar network stretching from Brownsville to Boston, and from Miami to the Lesser Antilles.

Through the lifetime of the hurricane, advisories from the National Hurricane Center and other warning offices give the storm's position and what the forecasters in Miami expect the storm to do. As the hurricane drifts to within a day or two of its predicted landfall, these advisories begin to carry hurricane watch and warning messages, telling people when and where the hurricane is expected to strike, and what its effects are likely to be. Not until the storm has decayed over land and its cloudy elements and great cargo of moisture have blended with other brands of weather, does the hurricane emergency end.

This system works well. The death toll in the United States from hurricanes has dropped steadily as NOAA's hurricane tracking and warning apparatus has matured. Although the accuracy of hurricane forecasts has improved over the years any significant improvements must come from quantum jumps in scientific understanding.

The forecasters also know that science will never provide a full solution to the problems of hurricane safety. The rapid development of America's coastal areas has placed millions of people with little or no hurricane experience in the path of these lethal storms. For this vulnerable coastal population, the answer must be community preparedness and public education in the hope that education and planning before the fact will save lives and lessen the impact of the hurricane.

*More tropical cyclone advisories are issued by NOAA's Hurricane Warning Offices in Honolulu and San Francisco than by Miami. These Weather Service Offices keep the same kind of watch for the same destructive storms, and warning is given to ships and coastlines in their path. But, because the Pacific tradewinds carry most storms away from land, this warning work is perhaps best known to aviators and mariners.

stormfury

NOAA's WP-3D Orion flies a hurricane mission during Project Stormfury, an effort to determine whether man can modify hurricanes through cloud seeding with beneficial results.

No human effort to change the atmosphere has quite the dimensions of Project Stormfury, NOAA's experimental attempt to mitigate the winds of hurricanes. As a scientific achievement, learning to modify hurricanes would rate very high. As a complex, carefully executed field experiment in the atmosphere, it has few equals.

Stormfury is an effort to learn enough about hurricanes to be able to say whether they can be altered through cloud seeding, with beneficial results. The experiment developed from studies performed since 1956 by what is now NOAA's National Hurricane and Experimental Meteorology Laboratory, in Miami. Basically a kind of atmospheric judo, it pits scientists and aircraft and cloud-seeding techniques against the giant forces of a hurricane. The object is to use the giant's own energy against it, setting in motion reactions within the storm that finally reduce its intensity.

The rationale for Stormfury is that by reducing hurricane winds—and, so, greatly reducing the force of the winds on structures—damage in areas struck by the big storms could be significantly diminished. Also, because waves and storm surge are closely coupled to wind fields in a hurricane, reduction of winds presumably would also moderate these more destructive elements. In those terms, Stormfury is an experimental investment which scientists expect to pay for itself many times over, if what is called the Stormfury hypothesis is correct.

This hypothesis has evolved as scientists have obtained a better understanding of the storms. Initially, the object was to seed clouds just outside the ring of maximum winds in the outer portions of the eyewall and adjacent spiral bands causing supercooled water—water cooled below freezing but still in liquid form—to freeze, releasing large quantities of heat energy into the clouds near the eye. This large release of latent heat of fusion outside the ring of maximum winds, the hypothesis went, would flatten the pressure gradient, causing the hurricane to spread into a storm system of lesser intensity.

Today, the Stormfury hypothesis has been refined by measurements brought back by new airborne sensors, and analysis in the Miami laboratory. The present seeding strategy is to seed clouds outside the eyewall, in an effort to redistribute the mass flow of the storm. Here, seeding still converts supercooled water to ice, triggering the release of enormous quantities of energy into the storm outside the eyewall. But the effect is to cause immature clouds there to develop, condensing more water vapor at greater distances from the eye, the heat of condensation released by this effect is also available to stimulate cloud growth. Thus, these outer clouds grow at the expense of the eyewall, the storm's chimney system. In effect, Stormfury would create a secondary eyewall which would replace the initial one, effectively spreading the storm center. This would flatten the pressure gradient across the eye, and turn a severe hurricane into a moderate one. The effects of seeding, Stormfury researchers believe, would persist from six to twelve hours, after which the hurricane—other things remaining equal—would regain its original intensity.

Stormfury has been chronically short on experimental opportunities, however. Public concern that seeding might cause a storm to change its track, or increase intensity after seeding, or reduce seasonal rainfall from hurricanes, or simply "go against nature," has partly shaped the experiment; but recent research and past observations indicate such fears are groundless. Scientific concern that the hurricane be handled objectively—that is, seeded and monitored over the neutral environment of the ocean—has also been a powerful shaping force. These factors led to stringent rules which prohibit seeding when the storm has more than a ten percent chance of making landfall within 24 hours—constraints which have put many storms out of reach.

From 1961 through 1971, Stormfury, then a joint Department of Commerce-Department of Defense experiment, was able to "treat" only four storms. Esther in 1961, Beulah in 1963, Debbie in 1969, and Ginger in 1971.

Although this sample is quite small, seeding appears to have produced some interesting effects. The seeded portion of Esther's eyewall faded from the radarscope (which "sees" water droplets), indicating either a change of liquid water to ice crystals or the replacement of large droplets by much smaller ones. Beulah also appeared to respond to seeding. The central pressure of the eye rose soon after injection of silver iodide particles and the area of maximum winds moved away from the storm center, however, natural oscillations within the hurricane could have produced effects of this magnitude.

Hurricane Debbie was the first storm subjected to multiple seedings (August 18 and 20, 1969), receiving massive charges of silver iodide at two-hour intervals, five times each day. Appreciable changes in maximum wind speed—a 30-percent reduction on the 18th, 15 percent on the 20th—and other parameters related to the structure of Debbie occurred after seeding. Analyses of past storms indicated the rate of decrease in wind speed observed on August 18 would be very rare in an unseeded hurricane; and windspeed decreases on August 20 could be expected to occur naturally in fewer than one tenth of a sample of unmodified storms. The fact that the storm's wind diminished on both seeding days suggests the modification experiments were effective.

Results obtained from hurricane Ginger, seeded on September 26 and 28, 1971, were ambiguous. The silver iodide seeding agent was dispersed into the rainsector bands near the eyewall, rather than just outside the eyewall, and some cloud changes appeared to be related to the seeding. But Ginger was too poorly organized for scientists to separate seeding effects from the storm's natural noise level.

Late in 1972, the decision was made to concentrate on hurricane research, temporarily suspending the seeding operations in Stormfury. This interim period would also be used to replace the aging piston powered aircraft used to carry NOAA's scientists and instrumentation into hurricanes with new, turbine-powered ones equipped with the best instrumentation available through present-day technology.

NOAA's C-130, still a key participant in hurricane research and Project Stormfury, is one of two such aircraft carrying an Air Force-developed Airborne Weather Reconnaissance System (AWRS), a computerized set of instruments and data analyzers controlled from the panel shown at lower left. At lower right, a scientist launches a bathythermograph, to probe the cold wake some hurricanes leave behind them in the sea.

Thus, the hurricane seasons from 1973 through 1976 saw Stormfury scientists fly purely research missions into western hemisphere hurricanes. These long, bumpy missions, and new generations of airborne instruments, brought back data which researchers have turned into a significantly better understanding of hurricanes and their susceptibility to seeding.

Throughout, the emphasis has been on learning the dynamic context of the entire hurricane system, from the microphysical processes that control the giant storm, to the immense circulations and interactions of the hurricane itself. These probes confirmed that hurricanes have the right combination of liquid water and developing (but still immature) cloud towers to make seeding feasible, and that hurricane winds from the surface to altitude were about what scientists had believed. They also confirmed that revised flight patterns through the hurricane, redesigned to keep the aircraft in rainbands just outside the region of greatest winds for extended periods of time, could be flown safely. Parallel research led to development of significantly improved mathematical models of the big storms.

Meanwhile, NOAA's Miami-based Research Facilities Center has been revitalized with the addition of two new Lockheed WP-3D Orion aircraft, built to NOAA's special requirements. The Orions and their instrumentation systems are the most advanced airborne platforms for environmental research in the world, and represent a major step in man's ability to look at the internal dynamics of hurricanes. NOAA's C-130 also carries an advanced airborne weather instrumentation system.

Stormfury-Americas. The weather-modification side of Stormfury has been revived in Stormfury-Americas, which schedules seeding of selected western hemisphere hurricanes late in the decade of the 1970's.

The principal operational difference between Stormfury-Americas and its predecessor missions is that it is in many ways a simpler experiment. The missions are flown with similarly stringent conditions—that is, storms with more than a ten-percent chance of coming within 50 miles (80 kilometers) of landfall within 24 hours of seeding are not eligible for seeding. It employs the three NOAA aircraft, an additional WC-130 on loan to NOAA from the Air Force, and the National Aeronautics and Space Administration's **Galileo II**, a high-flying, heavily instrumented Convair 990. In the storm, advanced instrumentation systems aboard these aircraft permit scientists to seed where it will have the greatest effect, and then monitor that area to detect seeding-connected changes.

Stormfury-Americas is a new Stormfury, guided by deeper knowledge of the hurricane, and backed by greater sophistication of computer models, instruments, aircraft, and other equipment. It will be through such projects that humanity discovers whether science and technology can be used to tame hurricanes, the greatest storms on earth.

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