U.S. DEPARTMENT OF COMMERCE • Environmental Science Services Administration

the greatest storm on earth . . .

HURRICANE

the greatest storm on earth . . .

HURRICANE

CONTENTS

From a vantage point in space they seem quite small, flat spirals drifting on the sea, gentle eddies in the endless flowing of the planet's atmosphere. But where their drift takes them across shipping lanes and islands and the coasts of continents, their passage is commemorated by property destroyed, prospects diminished, and death.

They are tropical children, the offspring of ocean and atmosphere, powered by heat from the sea, driven by the easterly trades and temperate westerlies, the high planetary winds, and their own fierce energy. In their cloudy arms and around their tranquil core, winds blow with lethal velocity, the ocean develops an inundating surge, and, as they move toward land, tornadoes now and then flutter down from the advancing wall of thunderclouds.

Compared to the great cyclonic storm systems of the temperate zone they are of moderate size, and their worst winds do not approach tornado velocities. Still, their broad spiral base may dominate weather over thousands of square miles, and from the earth's surface into the lower stratosphere. Their winds may reach 200 miles per hour, and their lifespan is measured in days or weeks, not minutes or hours. No other atmospheric disturbance combines duration, size, and violence more destructively.

As they occur in different oceans and hemispheres, they bear names given locally: *baguio* in the Philippines, *cyclone* in the Indian Ocean, *typhoon* in the Pacific. In our hemisphere, the name is *hurricane**—the greatest storm on earth.

* From the Spanish *huracan*, probably derived from the Mayan storm god, *Hunraken;* the Quiche god of thunder and lightning, *hurakan;* and numerous other Caribbean Indian terms for evil spirit, big wind, and the like.

NASA Photo

THE SEASON OF GREAT STORMS

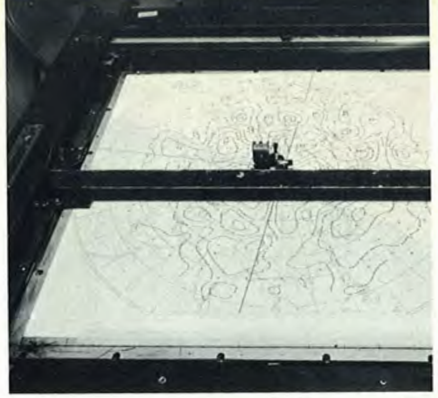
The direct rays of the sun touch the Equator and strike northward toward the Tropic of Cancer, following the annual track of the sun across the earth's surface. In the Southern Hemisphere winter has begun, and it is summer north of the Equator. Behind the sun's passage the sea and air grow warmer; the polar air of winter begins its gradual retreat.

The northward shift of the sun also brings the season of tropical cyclones to the Northern Hemisphere, a season that is ending for the Pacific and Indian Oceans south of the Equator. Along our coasts and those of Asia, it is time to look seaward, to guard against the season's storms. Over the Pacific, the tropical cyclone season is never quite over, but varies in intensity. Every year, conditions east of the Philippines send a score of violent storms howling toward Asia, but it is worst from June through October. Southwest of Mexico, a few Pacific hurricanes will grow during spring and summer, but most will die at sea or perish over the desert or strike the lower California coast as squalls.

Along our Atlantic and Gulf coasts, the nominal hurricane season is from June through November. Early in the season, the Caribbean and Gulf of Mexico are the principal areas of origin; in July and August, this center shifts eastward and by September spreads from the Bahamas southeastward to the Lesser Antilles, and eastward to the Cape Verde islands off the west coast of Africa. After mid-September, principal areas of origin shift back to the western Caribbean and the Gulf of Mexico. If this is an average year, there will be fewer than 10 tropical cyclones, of which about six will develop into hurricanes. These will kill 50 or 100 persons between Texas and Maine and cause property damage of more than $100 million. If it is a worse-than-average year, we will suffer several hundred deaths, and property damage will run to billions of dollars.

At ESSA, the Environmental Science Services Administration, the tempo is increasing. Tornadoes and floods and severe storms are in season elsewhere on the continent; now, to these destructive forces must be added the hazard of the hurricane.

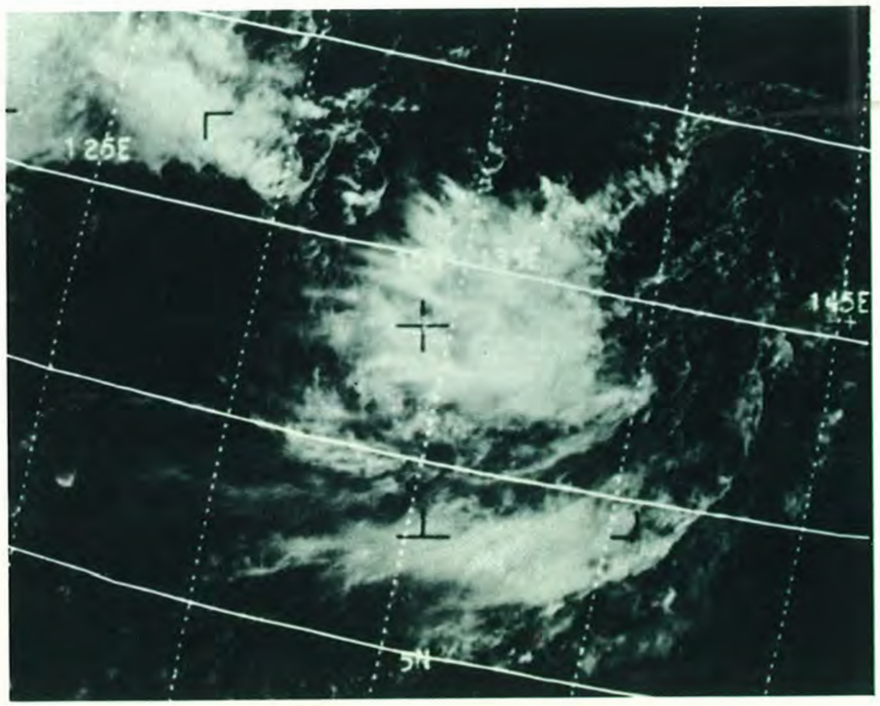
From the National Hurricane Center in Miami, a radar fence reaches westward to Texas, northward to New England, providing ESSA Weather Bureau stations along the coast a 200-mile look into offshore disturbances. In Maryland, the giant computers of

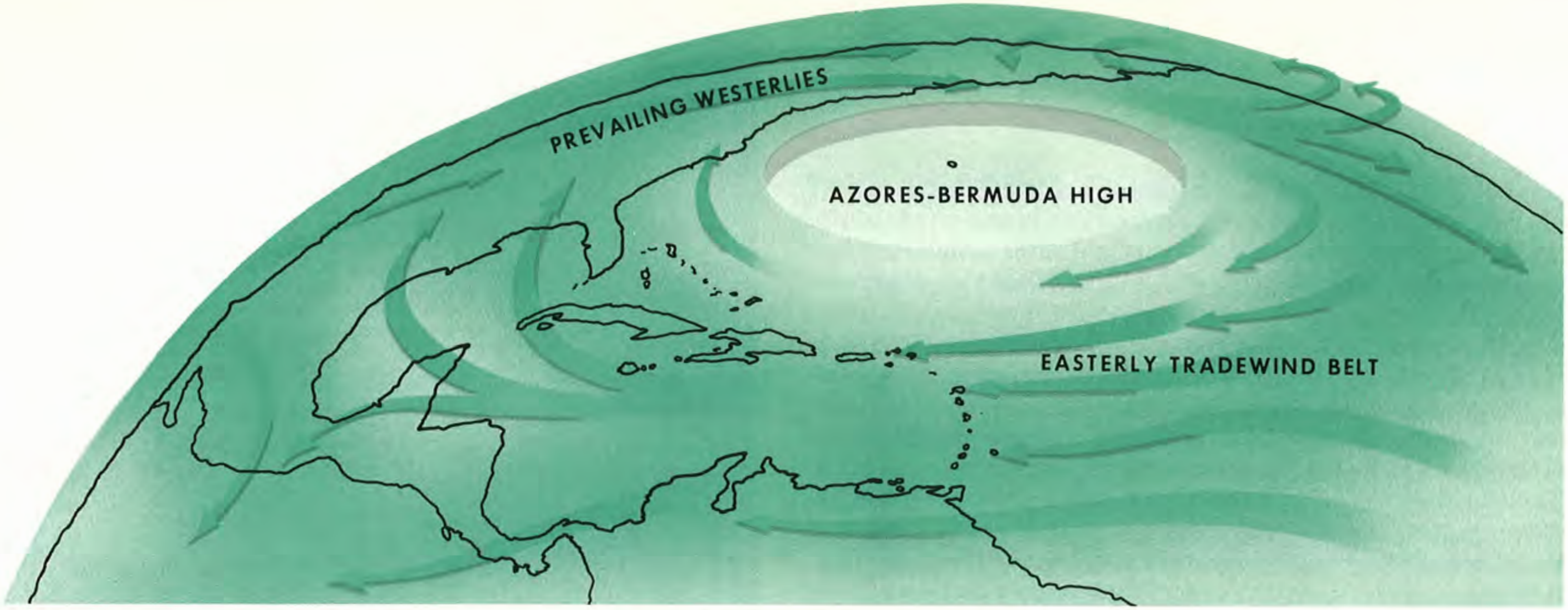


the National Meteorological Center digest the myriad bits of data—atmospheric pressure, temperature, surface winds and winds aloft, humidity—received from weather stations and ships monitoring the atmospheric setting hour to hour, day to day. Cloud photographs from the ESSA (*E*nvironmental *S*urvey *SA*tellite) spacecraft orbiting the earth are received at the National Environmental Satellite Center in Maryland, and studied for the telltale spiral on the warming sea. The crews of U.S. Navy, Air Force, and Coast Guard aircraft over the Gulf of Mexico, Caribbean, and Atlantic watch the sky with special emphasis—waiting for the storm that will bear a lady's name. The machinery of early warning vibrates with new urgency as the season of great storms begins.

The work goes beyond this season's warnings. Scientists from ESSA's Weather Bureau, Institute for Atmospheric Sciences, and Institute for Oceanography muster for another round of experimentation—another season's work in the laboratory of the hurricane and in the sea from which it grows. At the National Hurricane Research Laboratory in Miami, *Project Stormfury* prepares for another attempt to determine whether hurricanes can be modified beneficially. Scientists from the Sea-Air Interaction Laboratory, using research aircraft and the ships of ESSA's Coast and Geodetic Survey, move toward summer experiments in the oceanic breeding grounds of hurricanes. Improved understanding of hurricanes may lead to prediction of their occurrences; prediction is an important step toward control.

U.S. Navy Photo





THE ATMOSPHERIC SETTING

Over the Atlantic, a semipermanent zone of high pressure returns to a surface position centered near Bermuda. This is the subtropical anticyclone between temperate and tropical bands of prevailing winds, and the dominant atmospheric feature over the North Atlantic during summer and early autumn.

North of this Azores-Bermuda high-pressure system, prevailing westerlies of the temperate zone flow eastward in a deep layer from the surface to altitudes of 40,000 feet or more. Near the anticyclone's center, prevailing winds are a mixture of variable and easterly winds. South of the high-pressure system, the surface flow of air is predominantly to the west—the easterly tradewinds. During the warm months, the easterlies may deepen to altitudes of 40,000 feet or more, and cover vast areas over the tropics; or they may break up into small vortices (a whirlpool is a vortex) which drift westward over the Atlantic and Caribbean, and into the Gulf of Mexico.

The characteristic subsidence, or sinking, of air within the anticyclonic system produces the layers which compose the easterly tradewind current. 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 height, cools to the inversion altitude, grows warmer, then begins to cool at greater heights. The warmed air also experiences a decrease in relative humidity because, although its temperature increases, no moisture is added. Beneath the inversion layer, air is swept for hundreds of miles over the surface of the sun-warmed sea, receiving a charge of moisture to a depth of several thousand feet from evaporated ocean water.

Convection in this lower, heated layer and intermittent intrusions of the moist air weaken the inversion, which gradually dissipates as low-level air continues its trajectory above the warm sea. Tropical rainfall is produced by these convective processes, and the heat energy released by condensation is gradually transported to higher levels. At times, this easterly flow is sufficiently disturbed for rain areas to become concentrated—and this concentration may intensify into a storm.

TROUBLERS OF THE TRADES: The Polar Trough

Sometimes, when the Azores-Bermuda high-pressure system is weak and south of its normal position and the easterly trades are shallow (below 15,000 feet), an eastward-drifting trough of low pressure embedded in the temperate westerlies may penetrate the tropics. This occurs most frequently early and late in the hurricane season. If the southern end of the intruding trough becomes quasi-stationary or is trapped in the easterly trades, a hurricane may develop. In other instances, the trough separates and may become another weather-generating disturbance—the easterly wave.

DEFINITIONS OF TERMS

cyclones: Any atmospheric system in which atmospheric pressure diminishes progressively to a minimum value at the center and toward which the winds blow spirally inward from all sides, resulting in a lifting of air and eventually in clouds and precipitation. Cyclones are the Lows of weather maps. Circulation in a cyclone is counterclockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere. The name does not suggest any degree of intensity and is applied to moderate as well as intense storms. Cyclones are divided into tropical and extratropical groups, depending upon characteristics of the surrounding air masses. The hurricane is a tropical cyclone, and is the most ideal vortex in the atmosphere.

anticyclone: An area of high pressure from the center of which air spirals out in all directions, implying sinking air and good weather. ***Cold anticyclones*** are those which move rapidly south or southeastward out of the polar regions and are comparatively shallow or short-lived. ***Warm anticyclones*** like the Azores-Bermuda High are deep systems extending high into the upper atmosphere and are often stationary or quasi-stationary over the oceans. Their influence on atmospheric processes is profound; the Azores-Bermuda anticyclone's oscillations produce changes in continental United States weather and affect the tracks of hurricanes.

convection: Vertical motion produced by thermal or mechanical instability in the atmospheric column. ***Free convection*** is that produced by differences in density of layers within a fluid system, as when dense cold air overlies less dense warm air and overturning of the layers occurs. ***Forced convection*** is more mechanical than thermal, as when inflowing air at low levels forces air upward. The circulation in a tropical cyclone is a combination of free and forced convection.

coriolis force: The apparent force imparted by the earth's rotation that deflects moving objects to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. The coriolis force is proportional to the speed of motion and increases with distance from the Equator.

inversion: In meteorology, a departure from the usual decrease or increase with altitude of the value of an atmospheric property, and, also, the ***layer*** through which this departure occurs. As used here, inversion refers to a departure from the normal cooling of air with increasing height at low and intermediate altitudes; from the base of the inversion, air grows warmer with increasing altitude until the inversion is passed, after which the air cools normally with increasing height.

eddy: A circulation within a fluid mass that has a certain integrity and life history of its own.

trough: In meteorology, an elongated area of relatively low atmospheric pressure, commonly used to distinguish this from the closed circulation of a cyclone; a large trough may include one or more Lows, an upper-air trough may be associated with a lower level Low, and a Low may have one or more distinct troughs radiating from it.

ridge: The opposite of a trough, an elongated area of relatively high atmospheric pressure, commonly used to distinguish this from the closed circulation of an anticyclone; a ridge may include a High, an upper-air ridge may be associated with a surface High, and a High may have one or more distinct ridges radiating from its center.

tropics: The region between the Equator and Tropic of Cancer in the Northern Hemisphere and the Tropic of Capricorn in the Southern Hemisphere. The two Tropics are respectively the northernmost and southernmost positions to receive the perpendicular rays of the sun during the year. Their latitudes (23°27′ north and south) correspond to the inclination of the earth on its axis.

tropical cyclones: The general term for cyclones that originate over the tropical oceans, from tropical disturbance to hurricane or typhoon.

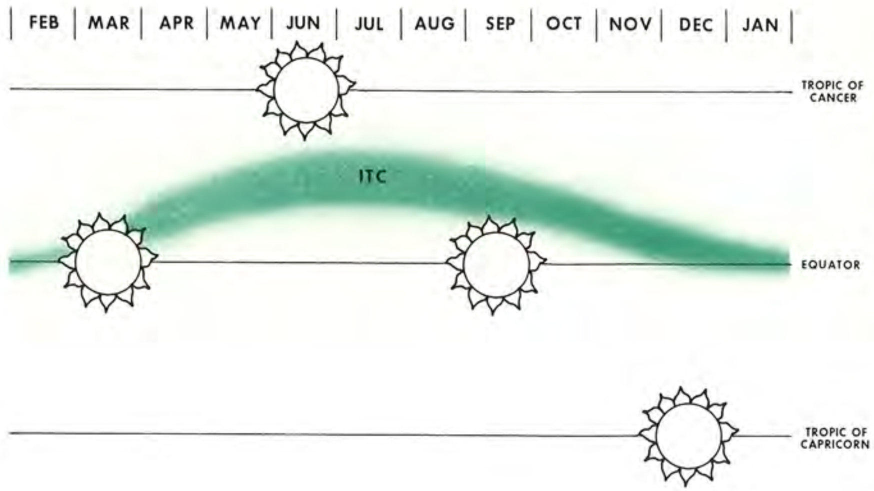
. . . the Easterly Wave

The easterly wave is a westward-moving trough of low pressure embedded in the deep easterly current. It tends to organize low-level circulation into alternate areas of converging and diverging airflow. Where air is diverging, weather is fine. But where convergence occurs, the depth of the moist layer increases, and convection produces heavy cumulus and cumulonimbus clouds which ascend to a maximum height of some 30,000–40,000 feet.

Easterly waves may travel thousands of miles with little change of shape. But if the wave is destabilized by excessive convection or by external forces—for example, high-level circulation that tends to organize further the circulation within the wave—it may curl in on itself, vertical circulation may accelerate, and a vortex may develop which, in time, 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.

. . . and Migrants From the Doldrums

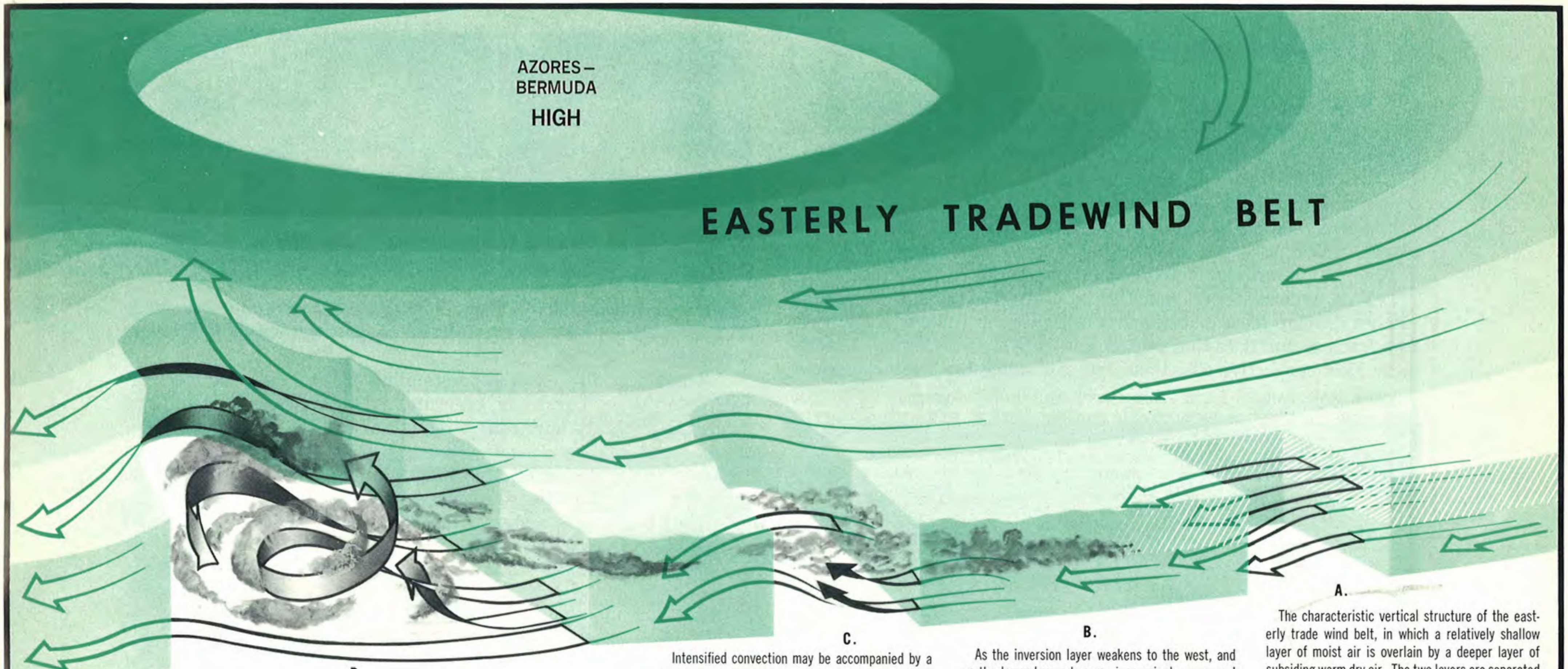
In a highly simplified view of the earth's atmosphere, the alternately eastward- and westward-flowing currents are separated by regions of high or low pressure—that is, subsiding or ascending air. Over the Atlantic, the Azores-Bermuda high-pressure system separates the temperate westerlies and tropical trades. Below the Equator, a similar zone of high pressure has a similar relationship to winds over the tropical and temperate South Atlantic. Where the easterly trades of the two hemispheres converge, in this simplified view, is an equatorial band of low pressure. It is called the equatorial trough or intertropical convergence (ITC) zone or doldrums, but its continuous existence is mainly statistical.



The ITC is more variable than the simple view indicates. Following the sun, it moves from a position near the Equator in February to its northernmost position near 12° north latitude in August. Its day-to-day surface position varies considerably, and, aloft, the ITC may occur as far north as 20°. Sometimes it is so weak as to be nearly undetectable, and almost completely free of significant activity. At other times, it is an intensely active zone 100 miles wide, with cloud tops rising to 40,000 feet and weather aloft as violent as that in the squall lines of the temperate zone. It flows generally in a series of eddies westward, and its intense activity is thought to be associated with the movement of these eddies into the tropics.

While the ITC is near the Equator,* the effect of the earth's rotation is small; but as it moves northward, the influence of the rotating globe—the coriolis force—is great enough to spin a migrating low-pressure system into the tight, violent eddy of a tropical cyclone. Some hurricanes form from vortices which originate in the doldrums, but intensify only after they leave the ITC.

* Hurricanes are virtually nonexistent in the South Atlantic Ocean, probably because the comparatively cold water of this region inhibits their formation. When the sun's direct rays strike their southernmost point along the Tropic of Capricorn, the ITC is still north of the Equator.



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.

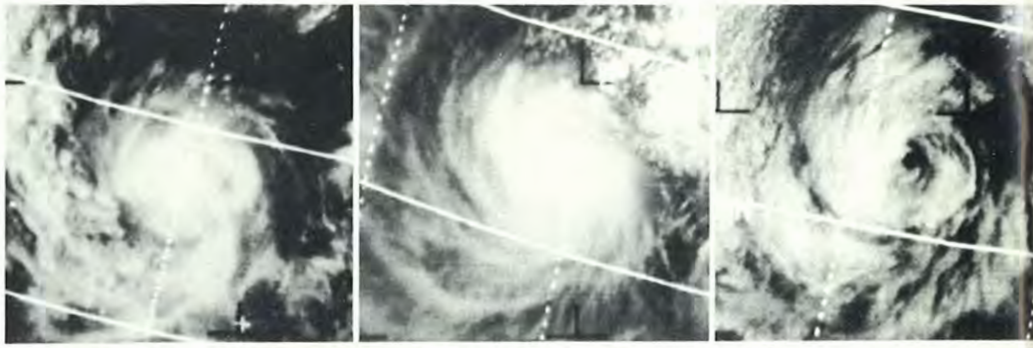
Increased convection, and the pumping action of high altitude winds, may cause the easterly wave to deepen further, becoming strong from the surface to 15,000 feet or more. Atmospheric pressure at the surface drops, an area of low pressure becomes an isolated depression — and the trade winds begin to 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

Hurricane formation was once believed to result from an intensification of the convective forces which produce the cumulonimbus towers of the doldrums, whose light winds have filled our literature with ships becalmed and thirsty sailors. This view of hurricane generation held that surface heating caused warm moist air to ascend convectively to levels where condensation produced cumulonimbus clouds, which, after an inexplicable drop in atmospheric pressure, coalesced and were spun into a cyclonic motion by coriolis force.

This hypothesis left much to be desired. Although some hurricanes develop from disturbances beginning in the doldrums, very few reach maturity in that region. Also, the high incidence of seemingly ideal convective situations does not match the low incidence of



Atlantic hurricanes. Finally, the hypothesis did not explain the drop in atmospheric pressure, so essential to development of hurricane-force winds.

There is still no exact understanding of the triggering mechanism involved in hurricane generation, the balance of conditions needed to generate hurricane circulation, and the relationships between large- and small-scale atmospheric processes. But scientists today, treating the hurricane system as an atmospheric heat engine, present a more comprehensive and convincing view.

They begin with a starter mechanism in which either internal or external forces intensify the initial disturbance—the intruding polar trough, easterly wave, or an eddy from an active ITC—as when diverging flow at upper levels becomes superimposed above the area of convergence in the low-altitude disturbance, setting up a vertical circulation which may be organized into a hurricane.

The initial disturbance becomes a region into which low-level air from the surrounding area begins to flow, accelerating the convection already occurring inside the disturbance. The vertical circulation becomes increasingly well organized as water vapor in the ascending moist layer is condensed (releasing large amounts of heat energy to drive the wind system) and as the system is swept into a counterclockwise cyclonic spiral. But this incipient hurricane would soon fill up because of inflow at lower levels unless the chimney in which converging air surges upward is provided the exhaust mechanism of high-altitude winds.

These pump ascending air out of the cyclonic system into a high-altitude anticyclone, which transports the air well away from the disturbance before sinking occurs. Thus, a large-scale vertical circulation is set up in which low-level air is spiraled up the cyclonic twisting of the disturbance, and, after a trajectory over the sea, returned to lower altitudes some distance from the storm. This

By international agreement, ***tropical cyclone*** is the general term for all cyclonic circulations originating over tropical oceans, classified by form and intensity as follows:

tropical disturbance: rotary circulation slight or absent at surface but sometimes better developed aloft, no closed isobars (lines of equal atmospheric pressure) and no strong winds, a common phenomenon in the tropics.

tropical depression: one or more closed isobars and some rotary circulation at surface, highest wind speed 39 miles per hour (34 knots).

tropical storm: closed isobars, distinct rotary circulation, highest wind speed 39–73 miles per hour (34–63 knots).

hurricane: closed isobars, strong and very pronounced rotary circulation, wind speed of 74 miles per hour (64 knots) or more.

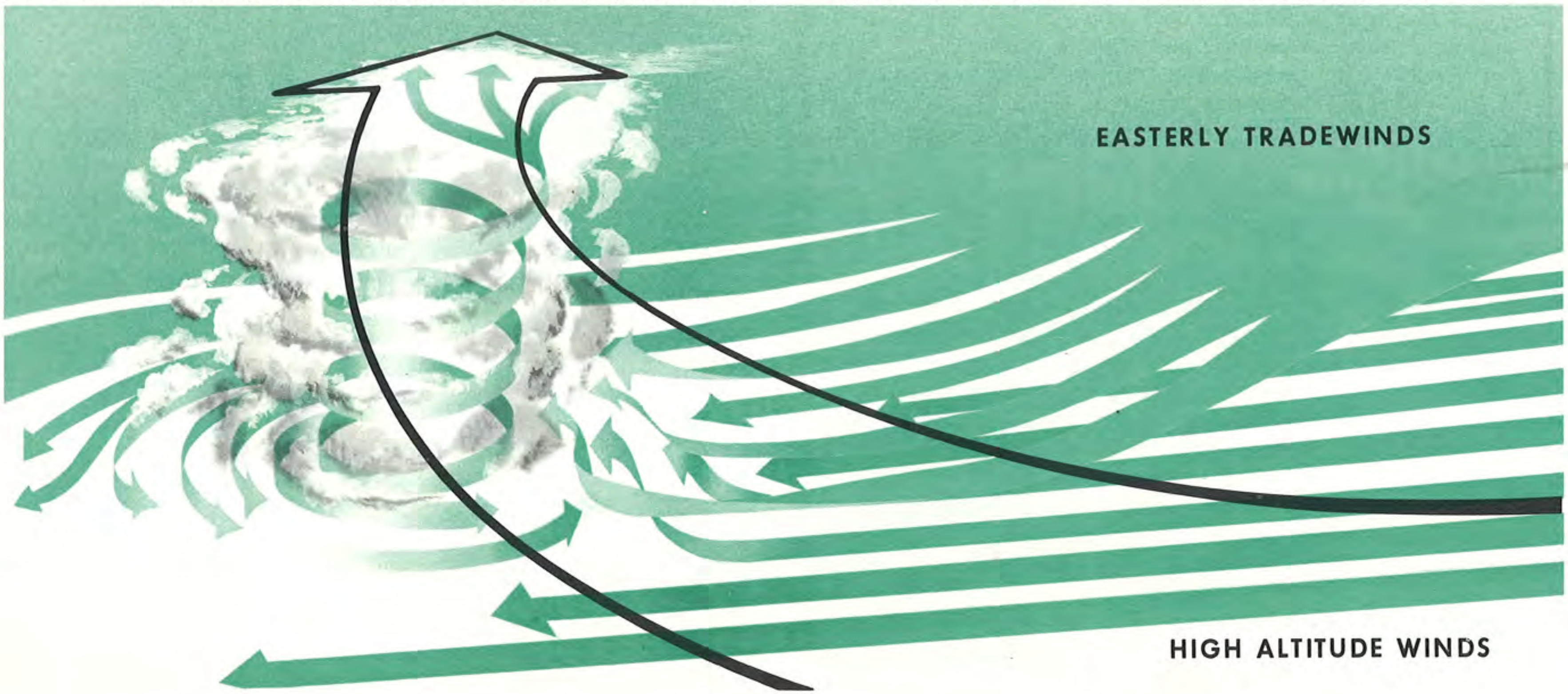
pumping action—and the heat released by the ascending air—may account for the sudden drop of atmospheric pressure at the surface, which produces the steep pressure gradient along which winds reach hurricane proportions.

It is believed that the interaction of low-level and high-altitude wind systems determines the intensity the hurricane will attain. If less air is pumped out than converges at low levels, the system will fill and die out. If more is pumped out than flows in, the circulation will be sustained and will intensify. It is also believed that planetary wind systems, displaced northward, set up an essential large-scale flow which supports the budding storm.

Research has shown that any process which increases the rate of low-level inflow is favorable for hurricane development, provided the inflowing air carries sufficient heat and moisture to fuel the hurricane's power system. It has also been shown that air above the developing disturbance at altitudes between 20,000 and 40,000 feet increases one to three degrees in temperature about 24 hours before the disturbance develops into a hurricane. But it is not known whether low-level inflow and high-level warming *cause* hurricanes. They could very well be measurable symptoms of another effect which actually triggers the storm's increase to hurricane intensity.

The view of hurricanes as atmospheric engines is necessarily a general one. The exact role of each contributor is not completely understood. The engine seems to be both inefficient and unreliable; a myriad of delicate conditions must be satisfied for the atmosphere to produce a hurricane. Their relative infrequency indicates that many a potentially healthy hurricane ends early as a misfiring dud of a disturbance, somewhere over the sea.

As the disturbance becomes better 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 and the pumping action of high-altitude winds thrust it upward into a larger, anticyclonic circulation centered hundreds of miles away—or into some other type of high-altitude wind system. Vertical scale is greatly exaggerated.



267-823 O - 67 - 2

PORTRAIT OF A HURRICANE

Given the cyclonic circulation, the disturbance is distinguished by its form and intensity as it changes from tropical disturbance, to tropical depression, to tropical storm—to hurricane. The early forms are a kind of adolescence. The hurricane, as a young adult taking strength from the warm ocean, is unique in both structure and ferocity.

It stands upon the sea as a whirlwind of awful violence. On average, its great spiral covers an area some 100 miles in diameter with winds greater than 74 miles per hour, and spreads gale-force winds—winds above 40 miles per hour—over a 400-mile-diameter area. Its cyclonic spiral is marked by heavy cloud bands from which torrential rains fall, separated by areas of light rain or no rain at all; these spiral bands ascend in decks of cumulus and cumulonimbus clouds to the convective limit of cloud formation, where condensing water vapor is swept off as ice-crystal wisps of cirrus clouds. Thunderstorm electrical activity is observed in these bands, both as lightning and as tiny electrostatic discharges.

In the lower few thousand feet, air flows in through the cyclone, and is whipped upward through ascending columns of air near the center. The size and intensity decrease with altitude, the cyclonic circulation being gradually replaced above 40,000 feet by an anticyclonic circulation centered hundreds of miles away—the enormous high-altitude pump which is the exhaust system of the hurricane heat 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 around the edge of a whirlpool; and, like those currents, these winds accelerate as they approach the center of the vortex. The outer band has light winds at the rim of the storm, perhaps no more than 30 miles per hour; within 30 miles of the center, winds may have velocities exceeding 150 miles per hour. The inner band is the region of maximum wind velocity, where the storm's worst winds are felt, and where ascending air is chimneyed upward, releasing heat to drive the storm. In most hurricanes, these winds reach 100 miles per hour—and more than 200 miles per hour in the most memorable ones.

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

Atmospheric pressure is 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, and in the Tropics it is generally close to 30 inches under normal conditions. Around a hurricane, however, pressure drops with increasing sharpness from a few points below 30 inches on the periphery to pressures of the order of 28 inches near the center. The lowest barometric reading of record for the United States is the 26.35 inches obtained during a hurricane at Lower Matecumbe Key in September 1935. Pressure has been observed to drop more than an inch per hour, with a pressure gradient amounting to a change of 0.11 inch per mile.

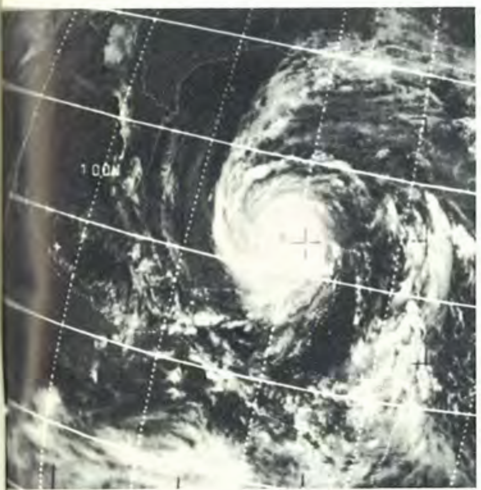
Weather maps show atmospheric pressure in millibars, units equal to 1/1000 *bar*. The *bar* is a unit of pressure equal to 29.53 inches of mercury, in the English system; and to 1 million dynes per square centimeter in the centimeter-gram-second (metric) system. Use of the millibar notation permits worldwide compatibility of meteorological data.

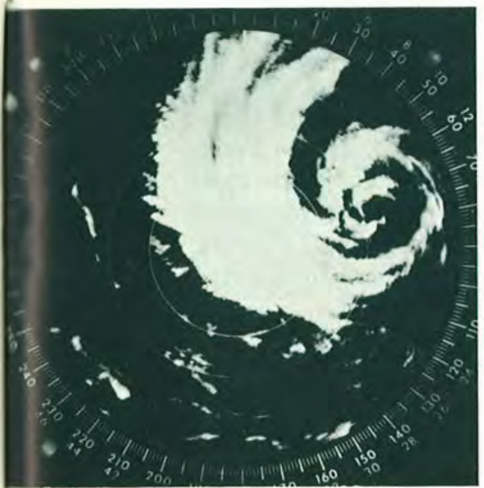
In the hurricane, winds flow toward the low pressure in the warm, comparatively calm core. There, converging air is whirled upward by convection, the mechanical thrusting of other converging air, and the pumping action of high-altitude circulations. This spiral is marked by the thick cloud walls curling inward toward the storm center, releasing heavy precipitation and enormous quantities of heat energy. At the center, surrounded by a band in which this strong vertical circulation is greatest, is the core—the eye of the hurricane.

The eye, like the spiral rainbands, is unique to the hurricane; no other atmospheric phenomenon has this calm core. On the average, eye diameter is about 14 miles, although diameters of 25 miles are not unusual. From the heated tower of maximum winds and cumulonimbus clouds, winds diminish rapidly to something less than 15 miles per hour in the eye; at the opposite wall, winds increase again, but come from the opposite direction because of the cyclonic circulation of the storm. To primitive man, this transformation of storm into comparative calm, and calm into violence from another quarter must have seemed an excessive whim of arbitrary gods. Still, it *is* spectacular. The eye's abrupt existence in the midst of opaque rainsqualls and hurricane winds, the intermittent bursts of blue sky and sunlight through light clouds in the core of the cyclone, the relatively calm sea beneath, the galleried cumulus and cumulonimbus clouds—these make lyricists of all who see them.

That is how an average hurricane is structured. But every hurricane is individual, and the more or less orderly circulation described here omits the extreme variability and instability within the storm system. Pressure and temperature gradients fluctuate wildly across the storm as the hurricane maintains its erratic life in the face of forces which will ultimately destroy it. If it is an August storm, its average life expectancy is 12 days; if a July or November storm, it lives an average of 8.

While a hurricane lives, the transaction of energy within its circulation is immense. If a hurricane is taken to be a heat engine, the efficiency with which it converts thermal to mechanical energy is quite low, near 3 percent. Nevertheless, the condensation heat energy released by a hurricane in one day often is the equivalent of that released by fusion of 400 20-megaton hydrogen bombs. Put in more comprehensible terms, one day's released energy, converted to electricity, would supply the United States' electrical needs for more than six months. There is no satisfactory way of scaling down a hurricane; it is immense to us, like the ocean and atmosphere themselves.





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 high and may cover a diameter of several hundred miles.

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 variation

THE THRUST TOWARD LAND

Once generated, a hurricane tends to survive while it is over warm water, for it is the temperature difference between air and water that drives and sustains the storm system. But the forces which control its movement are destructive; they drive the storm ashore or over the colder water beyond the tropics where it will fill and die, or be resurrected as a storm of another type. This thrust away from the tropics is the clockwise curve which takes typhoons of the tropical Pacific across the coastlines of Japan and northern Asia, and the hurricanes of the tropical North Atlantic, Caribbean, and Gulf of Mexico across the eastern United States.

Even before a hurricane forms, the embryonic storm has forward motion, driven by the easterly flow in which it is embedded. While this easterly drift is small—less than 20 miles per hour—intensification is favored; greater movement generally inhibits intensification during the early stages. When the hurricane matures, greater forward motion is frequently accompanied by intensification. The intensification which often follows acceleration is usually shortlived. At temperate latitudes, a few hurricanes reach forward speeds of 60 miles per hour.

Forecasting the direction this steering current will take the hurricane is complicated by several factors. The hurricane winds mask the basic current over a large area, both horizontally and vertically. Also, the steering mechanism is incompletely understood. It is not known, for example, what fraction of the storm's forward motion comes from its own internal energy and what portion is applied by the basic current, which is ordinarily the dominant force.

The tracks of hurricanes are as individual as the storms themselves. No two tracks are precisely superimposed, and only the most general trends can be established. A hurricane drifting westward past Cuba may seem poised to recurve north and east across Florida, only to dither, then spin off through the Gulf of Mexico—to Yucatan or New Orleans or Brownsville. Or a hurricane may follow a course from birth to death whose only consistency is an erratic, aimless looping across the tropics. Although most hurricanes ultimately recurve, there have been numerous exceptions. Hurricane Inez of September 1966, which doubled back instead of recurving and finally died in central Mexico, is a case in point.

DEATH OF A GIANT

From generation, a hurricane is acted upon by those forces which finally destroy it. At middle altitudes, air flows through the cyclonic vortex, cooling the warm core and acting as a thermal brake on storm intensity. Friction between the storm and ocean is only slightly inhibiting. It is possible that, without frictional effects, there would not be enough low-level inflow to keep the storm fueled with moist, warm air. Over land, frictional effects are greater and contribute to filling and dissipating the storm—although it is the loss of energy from the sea, not friction, which finally kills a hurricane.

Hurricane intensity is unquestionably linked to the warmth of ocean waters in its path. The storms do not form over water much below 80° Fahrenheit (F.), and decreases in water temperature have a direct influence on the rate at which the hurricane decays. Off California, small hurricanes deteriorate rapidly once they reach the cold eastern Pacific waters; larger hurricanes in the Atlantic may travel for longer periods over cold North Atlantic water, the rate of decay also being a function of storm size and intensity.

Over land, a hurricane decays rapidly. Without its heat source, and with the added effects of frictional drag, the circulation is rapidly destroyed. Hurricane rains, however, may continue even after the winds are much depleted. It has been estimated that hurricane rainfall—with or without destructive winds—accounts for nearly a fourth of the southeastern United States' annual precipitation.

Many hurricanes are transformed into extratropical cyclones at higher latitudes, or combine with existing temperate-zone disturbances. In these cases, the storm circulation expands over a large area and becomes a major atmospheric feature. Storms moving up the Atlantic coast of the United States are often in the throes of this transformation as they strike into New England. In such instances, external forces sometimes intensify the hurricanes enough to overcome the dissipating effects of friction and reduced supply of heat from the sea.

When the hurricane moves inland, loss of heat energy from the sea — and, to a lesser degree, increased friction at the surface — cause the cyclone to "unravel"; the storm spreads, fills up, and begins to die.

BRINGERS OF DESTRUCTION

Hurricanes are the unstable, unreliable creatures of a moment in our planet's natural history. But the destruction they bring to islands and continental coastlines in their paths is legend. Most of the death and damage is brought by wind, flood-producing rains, and, most lethal of all, the storm surge.

Normal atmospheric pressure at sea level is approximately 2,000 pounds per square foot. As winds increase, pressure against objects is added at a disproportionate rate. Pressure mounts with the *square* of wind velocity, and over a tenfold increase in wind speed, added pressure increases 100-fold. For example, a 25-mile-per-hour wind increases atmospheric pressure by about 2 pounds per square foot; a wind of 200 miles per hour increases atmospheric pressure by about 220 pounds per square foot. For some structures, the added force is sufficient to cause failure.

Hurricane winds may also produce an inverse effect, as when atmospheric pressure outside a closed structure is reduced enough to cause normal pressure inside to flow outward explosively. Tall structures like radio towers, fretted by gusting hurricane-force winds, may be made to oscillate until structural failure occurs. Although wind is the least destructive and least lethal of the hurricane's battery of destructive elements, wind-driven barrages of debris can be quite dangerous, and in areas less developed than the United States, hurricane winds cause great damage and fatality.

Floods produced by hurricane rainfall are more destructive than the winds. The typical hurricane brings 6 to 12 inches of rainfall to the area it crosses, and the resulting floods have caused great damage and loss of life, particularly in mountainous areas. Hurricane Diane of 1955 caused little damage as it moved onto the continent; but, long after its hurricane winds subsided, it brought floods to Pennsylvania, New York, and New England—floods that killed 200 persons and cost an estimated $700 million in damage. In the West Indies and Central America, hurricane-triggered floods have killed thousands.

The hurricane's worst killer comes from the sea. Over the deep ocean, waves generated by hurricane-force winds may reach heights of 50 feet or more; beneath the storm center, the ocean surface is drawn upward (like water in a giant straw) a foot or so above normal by reduced atmospheric pressure. The hurricane's presence may be detected well in advance of its arrival on land by sea swells emanating from the storm.

As the storm crosses the Continental Shelf and moves coastward, mean water level may increase 15 feet or more. Behind the storm center, offshore hurricane-force winds may cause a decrease in mean water level, setting up a strong current. The advancing storm surge is superimposed on normal astronomical tides, and, in turn, wind waves are superimposed on the surge; 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 above mean sea level, the danger from storm surges is great.

Surge heights along flat coasts can bring catastrophe. When the surge is forced up a narrow channel, like a river bed, the surge may appear as a wall of water—what is incorrectly called a "tidal wave."

Wave and current action associated with the surge also causes extensive damage. Water weighs some 1,700 pounds per cubic yard; extended pounding by giant 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 weaken coastal structures. Many buildings withstand hurricane winds until, their foundations undermined by erosion, they are weakened and fail. Waves and currents severely erode beaches and highways, and, in confined harbors, damage to shipping may be extreme. 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.

The greatest loss of life associated with hurricanes is caused by flooding due to the storm surge. History is filled with such catastrophes.

In Asia, the price in life has been tragically high. In 1737, storm surges killed 300,000 near Calcutta, and another 50,000 in 1864. In 1876, 100,000 were killed by a storm surge in Backergunge, India. In 1881, 30,000 persons in Haifung, China, were killed by drowning and the famine following the flood.

Our hemisphere has had its share of storm-surge deaths. In August 1893, a great storm wave drowned between 1,000 and 2,000 persons in Charleston, S.C.; in October of that same year, a storm surge drowned 1,800 along the Gulf coast. More than 6,000 persons perished in Galveston in 1900, and, in 1928, some 2,000 persons drowned in Florida when a hurricane caused Lake Okeechobee to overflow. A storm surge in November 1932 killed 2,500 in Cuba,

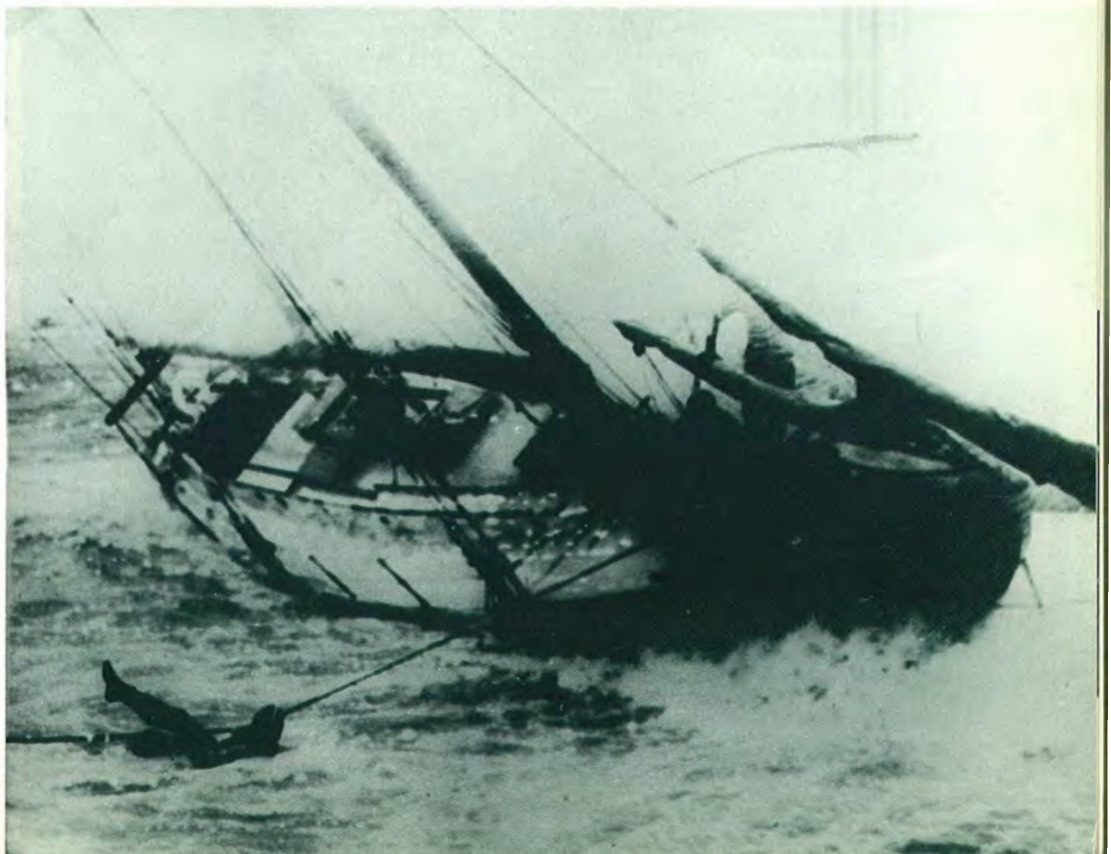
American Red Cross Photo

and 400 were killed in Florida by the intense hurricane of September 2, 1935. The September 21, 1938, hurricane killed 600 in New England. About 380 persons drowned when Hurricane Audrey struck Louisiana in June 1957.

Over the years, the toll in life has diminished encouragingly. In the United States, reduction in hurricane deaths has been the effect of timely warning for the people along the Nation's coasts.

But, given the increased population and development of areas affected by hurricanes, damage to fixed property continues to mount. Betsy, in 1965, caused some $1.4 billion in property damage, and it is expected that this trend will continue until the destructive storms can not only be predicted, but neutralized as well.

American Red Cross Photo



American Red Cross Photos

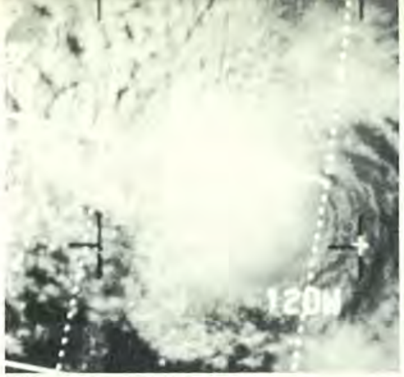
THE WORK OF TIMELY WARNING

Detection of hurricanes and timely warning against them has been the task of the Weather Bureau for nearly a century—since the Signal Corps issued a hurricane warning for the coast between Cape May, N.J., and New London, Conn., in 1873. The success of this operation is reflected in the steady decrease in hurricane deaths at a time when population in hurricane-effected areas has doubled and tripled. The present hurricane warning system, headquartered at ESSA's National Hurricane Center in Miami, Fla., is a smoothly operating warning establishment, supported by the experience and dedication of its personnel and the broad new technology that has become an integral feature in America's weather service.

It has not always been so. Until the end of World War II, meteorologists lacked both the techniques and the equipment to conduct even an adequate hurricane warning operation. The development of improved detection apparatus and forecasting techniques made such a system possible. The devastating hurricane season of 1954 reminded residents of the Atlantic and Gulf coasts from Brownsville to Providence how vulnerable they were to these great storms—and made a hurricane warning system mandatory. The capability and the impetus led, in 1955, to the warning system operating today, and to its attendant research effort.

The hurricane information issued by the National Hurricane Center requires that meteorologists detect and monitor hurricanes from initial disturbance to formation to intensification, and forecast the hurricane's future path. Technology has provided the means of early detection and constant tracking. Although more objective methods are under development, forecasting still depends partly on the educated intuition of experienced meteorologists.

U.S. Air Force Photo



U. S. Coast Guard Photo

Initial Detection

The flow of weather data through the National Hurricane Center is constant. Weather stations in the United States and through the Indies provide data on surface conditions and conditions aloft at frequent intervals. From the National Meteorological Center near Washington, D.C., weather data from ships, aircraft, and weather stations are assembled and plotted by men and computers for the Northern Hemisphere, and transmitted as facsimile maps to weather stations in this country and overseas. Photographs of cloud cover transmitted by orbiting ESSA spacecraft are received at the National Environmental Satellite Center at Suitland, Md., computer-modified by the addition of geographic coordinates and landforms, and relayed in facsimile to weather stations. In addition, Automatic Picture Transmission (APT) receivers at Miami pick up eight or nine ESSA photographs a day, when the satellite is within its 2,000-mile transmission range. The Miami facility also receives APT photos relayed from Puerto Rico. Between the two APT receivers and information from Maryland, the Center has photographic coverage of most of the tropical North Atlantic, Caribbean, and Gulf of Mexico.

The forecasters at Miami are not studying this rich flow of data for small changes in local weather. Their search is for the instability in an easterly wave, a trough shoving northward from the ITC, a polar trough drifting on the easterly trades—atmospheric processes which appear on weather maps and satellite photographs only when the inference is made by a practiced eye. It is a ferreting out of small clues, an assembling of related weather data, and the judicious application of long experience. And it is work that goes on around the clock, around the calendar; the beginning of the hurricane season only raises the stakes.

They watch for a change from tropical cumulus to the solid altostratus and cirrostratus of highly organized convective systems; for steady rainfall instead of tropical showers; subnormal atmospheric pressure; intensification of the wind field in the easterly trades; a westerly component within the tradewind system; certain suspect changes in upper air patterns.

This watchfulness is the routine part of natural hazards warnings, whether the prospectively destructive event is a tornado, a seismic sea wave, a seasonal flood—or a hurricane. At the National Hurricane Center, the emphasis shifts slightly when the initial area of suspicion is detected; then, while routine work continues, part of the forecasters' intuition and interest focuses on the hint of a tropical cyclone somewhere over the warm sea.

The incipient disturbance is monitored by the flow of hemispheric weather data from the National Meteorological Center, local data from stations south of the Miami facility, reports from ships crossing the area of suspicion, satellite photographs, and hurricane reconnaissance flights deployed by the U.S. Navy and Air Force. These are the long-range eyes of the hurricane warning service; a radar fence from Brownsville to Boston, and from Miami to the Lesser Antilles, will pick up the disturbance—the tropical cyclone, if the disturbance has matured—when it moves landward.

267-823 O - 67 - 3

The Hurricane Hunters

No one had deliberately flown an airplane into a hurricane before the afternoon of July 27, 1943, when Army Air Corps Maj. Joseph P. Duckworth flew a single-engined AT–6 into a hurricane off Galveston. He made the trip twice that day, the first time taking navigator Lt. Ralph O'Hair, the second, taking weather officer Lt. William Jones-Burdick. There have been Hurricane Hunters ever since.

Weather reconnaissance now is performed jointly by the Hurricane Hunter squadrons of the U.S. Navy and Air Force. Between them, they cover an ocean area of some 1,500,000 square miles. This interservice reconnaissance is linked to the National Hurricane Center by the Chief, Aerial Reconnaissance Coordination, Atlantic Hurricanes (CARCAH)—an Air Force or Navy officer who distributes hurricane warnings to military installations, and who coordinates military reconnaissance flights with the information needs of the Center.

Hurricane reconnaissance began in May 1944, when a unit of the Army Air Corps' Air Weather Service was commissioned to track tropical storms. Today, the 53d Weather Reconnaissance Squadron carries out the Air Force Hurricane Hunter mission, flying weather-modified WC–130 *Hercules* and WB–47 *Stratojet* aircraft around, above, and through tropical cyclones. The WB–47 flies high-level reconnaissance; the WC–130 carries out low-level penetrations, then climbs to altitudes between 10,000 and 30,000 feet for penetrations.

The Navy Hurricane Hunters are Weather Reconnaissance Squadron Four—VW–4 in service parlance. VW–4 is the seventh naval aircraft squadron to fly the hurricane circuit, a mission it took up in 1953. In 1958, Navy Hurricane Hunters received the WC–121N aircraft, *Super Constellations* modified to sweep 200,000 square miles with one revolution of their big radar antenna, and instrumented to do the meteorological sampling of several aircraft. These rugged 70-ton aircraft operate at altitudes as low as 500–1,000 feet and perform both routine weather reconnaissance and the more dramatic low-level penetration of fully developed storms. The Navy Hurricane Hunters also participate with ESSA in *Project Stormfury,* an experiment in hurricane modification.

Both exploratory and special reconnaissance missions are flown by the military Hurricane Hunters. Exploratory flights may detect a disturbance which ultimately blossoms into a hurricane. Special patrols are made in response to the suspicions of meteorologists at the National Hurricane Center.

The airborne laboratories of ESSA's Research Flight Facility fly hurricane reconnaissance and penetration missions in addition to their research and *Project Stormfury* duties. These civilian hurricane hunters, in an average year, will also spend some time hunting typhoons and thunderstorms, tracing atmospheric electricity and hail formation, and helping scientists assemble the knowledge man will need to modify weather beneficially.

Hurricane hunting has always been a dangerous business, and men and aircraft have on rare occasion been swept to their deaths in the high winds of typhoons and hurricanes. Since 1944, when aerial reconnaissance became a permanent part of the hurricane warning service, hurricane hunting has also been an increasingly technical business. The aircraft used today carry a variety of sensors and detectors, the new instruments of meteorology.

U.S. Navy Photos

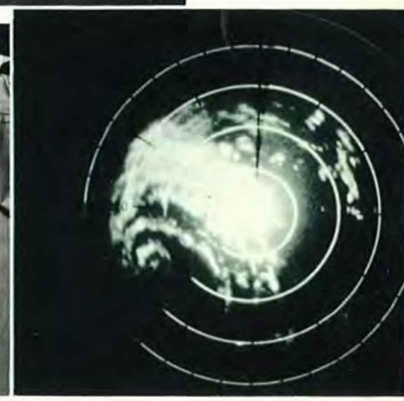
Observations of wind, pressure, and other weather elements are made by aircraft personnel flying to and from the area of suspicion, and, when developing and mature storms are encountered, during penetration. From this reconnaissance, forecasters on the ground receive data on strongest wind speed, lowest pressure at the center, radius of hurricane-force winds, distribution of gale-force winds, and the position of various weather processes—what amounts to several meteorological profiles of the tropical cyclone. Reconnaissance also provides at least two fixes per day on the storm's center position, from which direction and speed of forward motion are obtained.

One of the most useful instruments aboard Hurricane Hunter aircraft—and the central feature of the Weather Bureau warning fence along the Gulf and Atlantic coasts—is radar (from *RA*dio *D*etection *A*nd *R*anging), a World War II development which gave the first clear delineation of the hurricane's spiral structure. The radar apparatus emits a pulsed radio beam that is reflected back to a radar receiver by water droplets in the rain bands around the storm center; this "echo" is converted to a visual display. The orientation of spiral bands is such that they can be used to locate the hurricane center quite accurately, even though the "precipitation center" of the radar display may not always coincide with the low-pressure center of the storm. When aircraft penetration is not feasible, the storm is positioned by radar.

When additional center fixes are needed, the Hurricane Hunters fly at night. Some of these night flights penetrate the dangerous winds; some stay at the edge of the storm and track the storm's path by radar.

Aerial reconnaissance of suspicious disturbances is an invaluable aid in positioning and tracking the developing storm—and in determining whether meteorological clues point to a storm at all. Often, the Hurricane Hunter flight finds the suspected area to be storm free. Sometimes an area must be reconnoitered over a period of days before the anticipated development occurs. Most disturbances remain weak and finally dissipate without reaching hurricane intensity.

It is when aerial reconnaissance confirms the development of a disturbance into a tropical storm that the hurricane emergency begins. The aircraft stay with the disturbance while it develops, and feed the storm's position, intensity, extent, and structure to the National Hurricane Center, where the hurricane warning apparatus moves into action.



U. S. Navy Photos

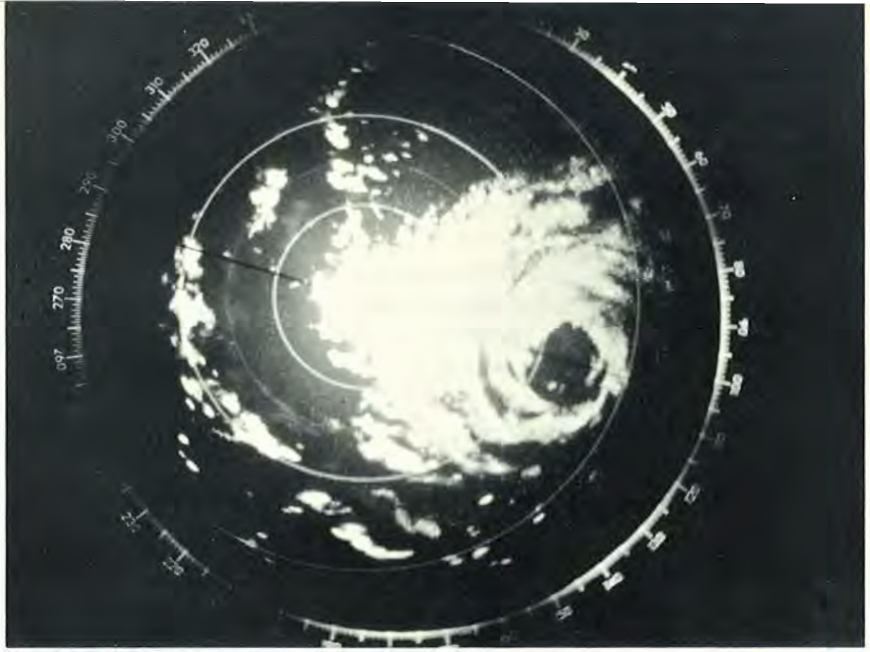
The Hurricane Warning Service

Until the emergency begins, the National Hurricane Center is the visible portion of the Hurricane Warning Service. Then, like lightning behind a tree, the warning cycle illuminates the structure of the entire system. The National Hurricane Center is still the focus of action and still controls the total warning apparatus; it also acts as the National Hurricane Information Center, coordinating the flow of bulletins and advisories to the public. Local warning responsibility is dispersed, however, among the Miami center and four other ESSA Weather Bureau offices—at New Orleans, Washington, Boston, and San Juan. These Hurricane Warning Offices have assigned areas of responsibility—New Orleans covering the Gulf of Mexico west of 85° West Longitude; Washington, between the latitudes of 35° and 40° North and west of 65° West; Boston, above 40° North and west of 65° West; San Juan, the eastern Caribbean and Atlantic south of 20° North and between 55° and 75° West. The National Hurricane Center at Miami has warning responsibility for the area west of 35° West and for all unassigned areas, and forecast responsibility for all Atlantic and Gulf coastal areas.

This broadening of authority is a way of concentrating local expertise, and a means of ensuring that warnings for each area are directed where they will do the most good. For example, the meteorologist in charge (MIC) at San Juan has extensive hurricane experience, and his advisories can focus that experience on the warning needs of his sector. The same is true of the Miami, New Orleans, Washington, and Boston hurricane forecasters.

The Hurricane Warning Offices and National Hurricane Center are linked by normal Weather Bureau communications and by a special Hurricane Teletypewriter Circuit—the coastal portion of the Weather Bureau's RAWARC (*RA*dar report and *WAR*ning *C*oordination) system that focuses on hurricane warning activities from June 1 through November 30, the nominal hurricane season.

These communications systems, and those of the Office of Civil Defense, Federal Aviation Administration, and the Armed Forces, tie hurricane forecasters to local governments, law enforcement agencies, and other emergency forces (like the Coast Guard and Red Cross), and, through newspapers and radio and television stations, to the general public. As the emergency develops, the flow of information will be from the Hurricane Warning Offices outward



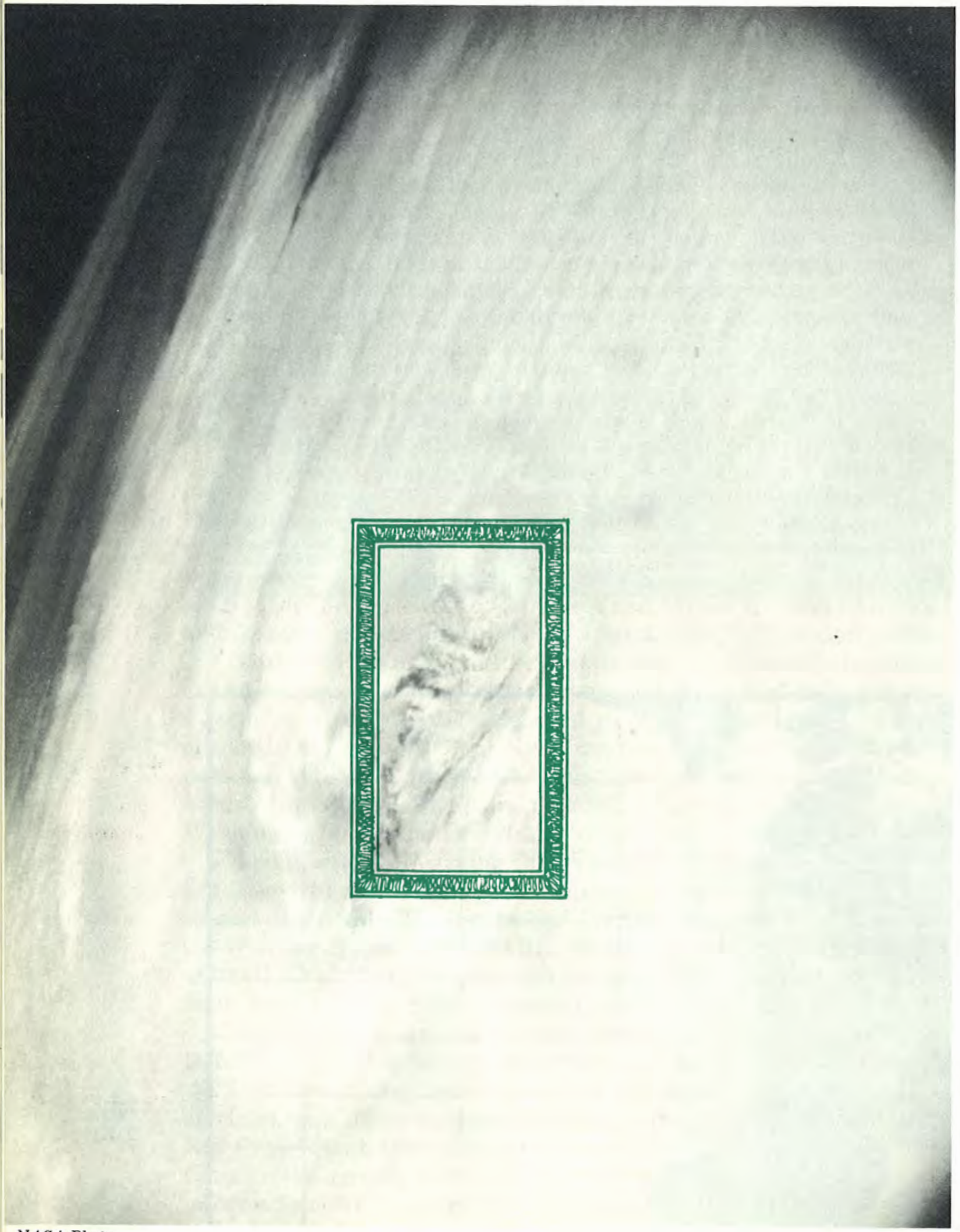
along these rapid-communication networks, with the Miami headquarters coordinating all local efforts.

The flow is not one way. Along the coastline from Brownsville, Tex., to Portland, Me. a double fence of observers contributes its information to other data received at the Miami center. Part of this fence is the line of radar-equipped, first-order Weather Bureau offices. Part is the network of volunteer observers, called CHURN (*C*ooperative *HU*rricane *R*eporting *N*etwork)—Coast Guard stations and private and public citizens who operate wind-measuring equipment and provide local information on tides and storm surges. Each CHURN outpost is linked to the nearest Weather Bureau office, which links it in turn to the National Hurricane Center in Miami.

Hurricanes are creatures of the sea as much as of the atmosphere. Weather Bureau offices from Brownsville to Boston supplement their radar and meteorological intelligence with telemetered information from ESSA's network of tide gages. These Coast and Geodetic Survey stations measure the gradual rise and fall of sea level caused by the astronomic tide. Under normal conditions, the tidal record, or marigram, is a gentle, continuous oscillation; the swells which precede hurricanes, storm surges during the final approach and passage of the hurricane, and wave action caused by hurricane winds are of a shorter period and appear as radical discontinuities in the tidal record. Weather Bureau offices at a score of coastal locations can thus monitor changes in local water level—an important element in forecasting the arrival and destructive potential of storm surges and hurricane-driven waves.

Because Atlantic hurricanes pose the greatest threat to the United States, emphasis here is placed on the Atlantic hurricane warning apparatus. But ESSA's Weather Bureau is also quite active in the Pacific, where the incidence of tropical cyclones is some three times what it is in the Atlantic. At Hurricane Warning Offices in San Francisco and Honolulu, the same watch is kept for the same destructive storms, and warning is given to ships and coastlines in their path.

The easterly trades work in our favor in the Pacific, and only very rarely does a tropical cyclone of hurricane intensity strike a western coastline in our hemisphere. The work of ESSA along the Pacific is best known to aviators and mariners, whose craft are saved periodically by the timely warning of the great storms. In fact, more tropical cyclone advisories are issued from Honolulu and San Francisco than from Miami. When a Pacific hurricane turns toward California, when a typhoon threatens Hawaii, the warning will go out in advisories like those used along our eastern coasts—and the message will be as critical to preserving life and property.



NASA Photo

Who is That Lady? The Naming of Hurricanes

The National Hurricane Center flexes the warning service when a tropical disturbance is detected and confirmed by aerial reconnaissance. These initial messages are in the form of bulletins, which alert the system that a suspicious area is under surveillance. Bulletins are also picked up by news media, where the word goes out that ESSA is watching a disturbance for future developments over the Atlantic, Gulf, or Caribbean. If the disturbance intensifies into a tropical cyclone, it is given a lady's name—and gender, for, almost unconsciously, forecasters and news media begin to call the storm "she."

The early Caribbean practice of naming hurricanes for the saint on whose day they occurred was never used in this country, but our substitute was a cumbersome latitude-longitude identification. The advent of high-speed communications, together with the confusion which arose when more than one tropical cyclone was in progress in the same area, forced a change. For a time, tropical cyclones were designated by letters of the alphabet (*e.g.*, A–1943,), and by the World War II phonetic alphabet (Able, Baker, Charlie); and it has been suggested that the storms be named from the International Civil Aviation Organization's phonetic system (Alpha, Bravo, Cocoa), the letters of the Greek alphabet (Alpha, Beta, Gamma), the names of animals (Antelope, Bear, Coyote), and descriptive adjectives (Annoying, Blustery, Churning). It has also been suggested that the storms carry the names of well-known personalities, places, and things, and the names of mythological figures.

It appears that the feminization of tropical cyclones began during World War II, when weathermen plotting the movement of storms across vast theaters of operations identified them alphabetically, using the names of girls. George R. Stewart's novel, *Storm* (Random House, 1941), may have been the first published account of this practice. Whatever the origin, the use of ladies' names for tropical cyclones has been persistent. Even though some alternative recommendations have had merit, the practice continues, and has been official Weather Bureau policy since 1953.

The Weather Bureau, in 1960, prepared a quasi-permanent list of four sets of tropical cyclone names in alphabetical order. Names beginning with Q, U, X, Y, and Z were not included because of their scarcity. A separate set of names is used each year, beginning with the first name in each set. Although each set is used again every four years, names used for major hurricanes—like 1965's Betsy—are retired for at least ten years and another name is substituted.

Typhoons and Pacific hurricanes have also been feminized. In the eastern North Pacific, the alphabetical listing of names is prepared in sets of four, and designations are cycled from year to year. In the central and western North Pacific, the practice differs because of the high incidence of tropical cyclones. The four sets prepared for typhoons originating there are not cycled annually, instead, all names are used consecutively, regardless of the year—for example, if the 1968 typhoon season ended with Phyllis, then 1969 would begin with typhoon Rita, both from the same set of names.

CENTRAL AND WESTERN NORTH PACIFIC:

Agnes, Bess, Carmen, Della, Elaine, Faye, Gloria, Hester, Irma, Judy, Kit, Lola, Mamie, Nina, Ora, Phyllis, Rita, Susan, Tess, Viola, Winnie.

Alice, Betty, Cora, Doris, Elsie, Flossie, Grace, Helen, Ida, June, Kathy, Lorna, Marie, Nancy, Olga, Pamela, Ruby, Sally, Tilda, Violet, Wilda.

Anita, Billie, Clara, Dot, Ellen, Fran, Georgia, Hope, Iris, Joan, Kate, Louise, Marge, Nora, Opal, Patsy, Ruth, Sarah, Thelma, Vera, Wanda.

Amy, Babe, Carla, Dinah, Emma, Freda, Gilda, Harriet, Ivy, Jean, Kim, Lucy, Mary, Nadine, Olive, Polly, Rose, Shirley, Trix, Virginia, Wendy.

EASTERN NORTH PACIFIC:

1967—Agatha, Bridget, Carlotta, Denise, Eleanor, Francene, Georgette, Hilary, Ilsa, Jewel, Katrina, Lily, Monica, Nanette, Olivia, Priscilla, Ramona, Sharon, Terry, Veronica, Winifred

1968—Annette, Bonny, Celeste, Diana, Estelle, Fernanda, Gwen, Hyacinth, Iva, Joanne, Kathleen, Liza, Madeline, Naomi, Orla, Pauline, Rebecca, Simone, Tara, Valerie, Willa

1969—Ava, Bernice, Claudia, Doreen, Emily, Florence, Glenda, Hazel, Irah, Jennifer, Katherine, Lilian, Mona, Natalie, Odessa, Prudence, Roslyn, Sylvia, Tillie, Victoria, Wallie

1970—Adele, Blanca, Connie, Dolores, Eileen, Francesca, Gretchen, Helga, Ione, Joyce, Kirsten, Lorraine, Maggie, Norman, Orlene, Patricia, Rosalie, Selma, Toni, Vivian, Winona

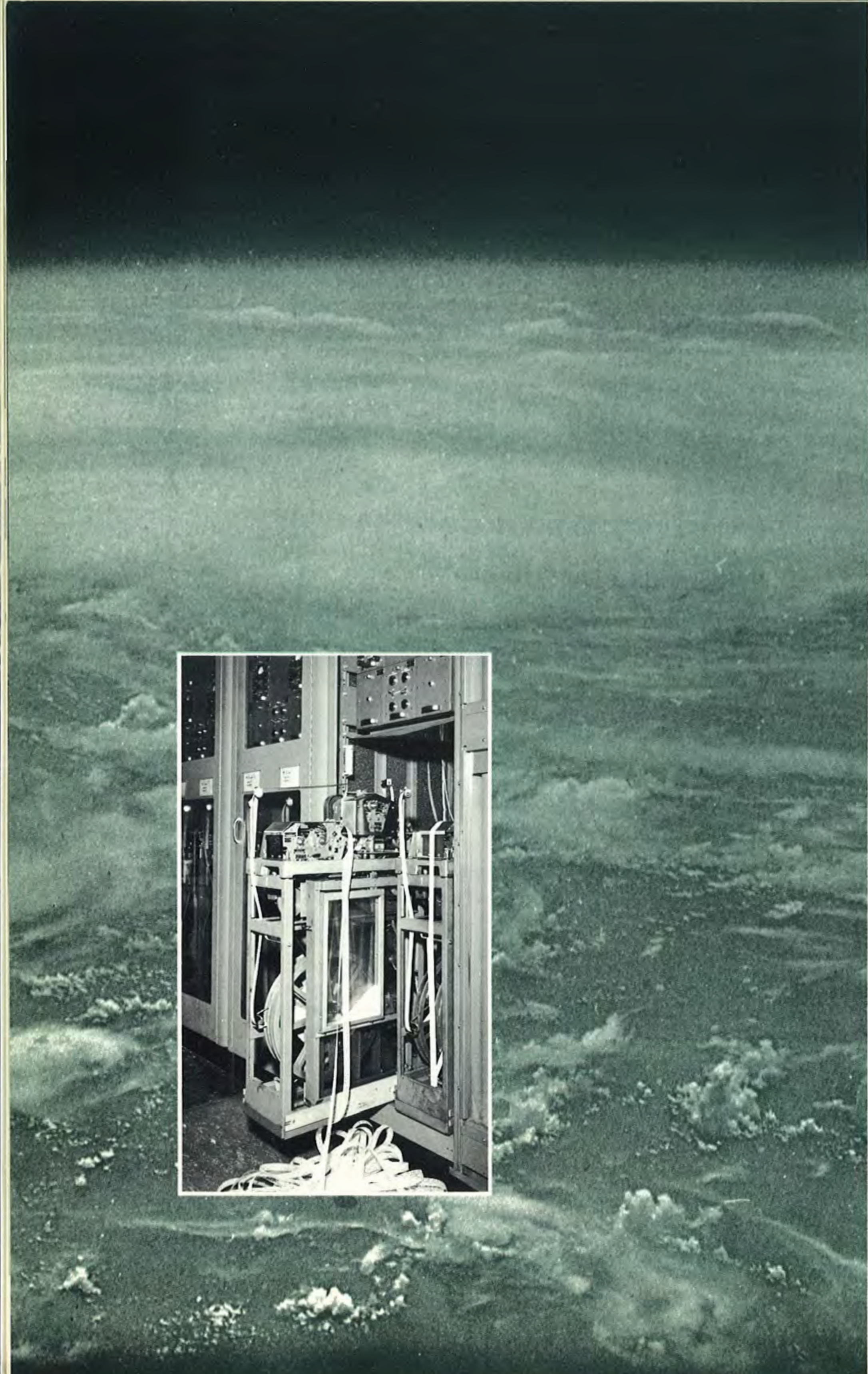
ATLANTIC, CARIBBEAN, AND GULF OF MEXICO

1967—Arlene, Beulah, Chloe, Doria, Edith, Fern, Ginger, Heidi, Irene, Janice, Kristy, Laura, Margo, Nona, Orchid, Portia, Rachel, Sandra, Terese, Verna, Wallis

1968—Abby, Brenda, Candy, Dolly, Edna, Frances, Gladys, Hannah, Ingrid, Janet, Katy, Lila, Molly, Nita, Odette, Paula, Roxie, Stella, Trudy, Vesta, Wesley

1969—Anna, Blanche, Carol, Debbie, Eve, Francelia, Gerda, Holly, Inga, Jenny, Kara, Laurie, Martha, Netty, Orva, Peggy, Rhoda, Sadie, Tanya, Virgy, Wenda

1970—Alma, Becky, Celia, Dorothy, Ella, Felice, Greta, Hallie, Inez, Judith, Kendra, Lois, Marsha, Noreen, Orpha, Patty, Rena, Sherry, Thora, Vicky, Wilna



Tropical Cyclone Advisories and Bulletins

The storm is named as a preliminary to a cycle of tropical cyclone advisories—messages issued by the Hurricane Warning Service at 6-hour intervals describing the storm, its position and anticipated movement, and its prospective threat. Advisories are numbered consecutively for each storm, and issued simultaneously by all Hurricane Warning Offices and the National Hurricane Center in Miami. As a general rule, advisories are prepared for this simultaneous release by the Hurricane Warning Office in whose area the storm is progressing, or may progress during the next 12 hours.

Advisories are not issued arbitrarily, but result from closely coordinated experience. Before the first advisory goes out, the National Hurricane Center confers with weathermen at the National Meteorological Center, Suitland, Md. This preliminary conference provides the hurricane forecaster with the best computer estimates of the storm's future progress: the probabilities of the disturbance gaining hurricane intensity, the probabilities of its taking this or that course, and the statistical necessity for issuing a tropical cyclone advisory.

When the National Hurricane Center issues the initial advisory, the hurricane warning system comes to full alert status. The emergency begins, its progress marked by the changing content of the advisories and bulletins which follow; for these messages are evolutionary, like the storm they monitor, and their emphasis shifts from the tropical cyclone to the storm's potential destructiveness as it moves landward.

The decisions hurricane forecasters must reach at various points in the emergency are difficult ones. They must apply their intuition, experience, and the array of new technology at their disposal to determining where the storm is, where it is going, whether it will intensify to hurricane strength, and what its destructive effects will be.

Initial forecasts cover a period 24 hours into the future. In the tropics, the storms drift slowly, at some 12–15 miles per hour; but this can mean more than 300 miles of travel for the 24-hour forecast period, over a path influenced by a myriad of forces. As the storm moves landward, as its winds increase to hurricane strength,

NASA Photo

and as its recurvature into the temperate zone accelerates its forward speed, forecasting of future position and intensity becomes increasingly complicated—and increasingly an art.

The National Hurricane Research Laboratory and National Hurricane Center in Miami have jointly experimented with improved forecasting techniques—for example, the use of computers for numerical prediction and studies of steering forces—and have realized some 10 percent improvement over recent years. Present methods of forecasting hurricane motion make judicious use of climatological data, extrapolation of the storm's past motion, evaluations of the basic current in which the storm is embedded, and the changes this current is expected to undergo in response to planetary wave patterns. The average 24-hour forecast error in hurricane position is about 120 miles; the average error in predicted path is less than 10 degrees. The accelerations and decelerations which characterize a hurricane's passage, and the large fluctuations in intensity, are at present even more difficult to predict. Hurricane forecasting remains the province of experienced individuals and their partly subjective, partly objective, estimates of present and future conditions.

The 12- and 24-hour forecasts included in tropical cyclone advisories are developed out of the close coordination of experienced hurricane forecasters. Telephone conferences between forecasters at Miami and the Hurricane Warning Offices, ESSA units in Washington, and military meteorologists provide a pool of forecast intelligence which is distilled into the 12-, 24-, and 48-hour prognoses of hurricane progress. A 72-hour outlook is also prepared as a guide to forecasters, although it is not sufficiently accurate to be used as a public tool.

Because hurricanes are influenced by many unpredictable—and some unknown—forces, hurricane forecasts have inherent error. To compensate for erratic storm behavior, the Hurricane Warning Service must "overwarn" to some extent. This means that when a high probability exists that a hurricane will strike a general area within a given interval of time, the threatened area is warned. Sometimes, the entire area covered by a hurricane warning is not touched by the storm. Judicious overwarning is a way of ensuring that sudden accelerations or deviations of the hurricane will not catch people unawares. As with automobile insurance, it is easier to absorb the economic loss of precautionary measures than the destruction of an accident.

What the public should remember—and what it frequently forgets—is that in the business of hurricane warning, there are no false alarms. The threat is real, and probable, before a warning is issued.

Precautionary measures during a hurricane emergency cost much time and money. A city of Miami's size spends hundreds of thousands of dollars preparing for a destructive tropical cyclone. As an aid to guiding preparation for these storms, ESSA's hurricane advisories are phrased to suggest ascending and descending degrees of urgency, like a newspaper story.

All advisories have certain information in common. They begin with a headline, which summarizes the message, and describe the tropical cyclone's location, direction of movement, intensity, and size. They also provide forecasts of storm position over the ensuing 24 hours, and give the time and source of the next advisory. But as the warning sequence develops, advisory information begins to concentrate on coastal and inland effects. While the storm is at sea, advisories are issued at 6-hour intervals, at 0400, 1000, 1600, and 2200 Greenwich Civil Time (GCT, GMT, or Z). As the tropical cyclone threatens land, these are supplemented by special bulletins issued as conditions demand.

Early advisories generally pertain to a storm at sea that is not threatening land. These messages are straightforwardly descriptive and predictive. In this initial phase, ships are alerted to avoid the disturbance, with the result that meteorological measurements in the storm and precise location of its center are obtained entirely by reconnaissance aircraft.

As the tropical cyclone moves within range of the coast, advisories focus on possible dangers to specific areas. These messages are written by the cognizant Hurricane Warning Office, and released simultaneously throughout the warning system. A *hurricane watch* announcement is included in these advisories that specifies the area which might be threatened. A hurricane watch is not a hurricane warning, but a first alert for emergency forces and the general public in *prospectively* threatened areas. A hurricane watch is announced when a hurricane poses a significant but uncertain threat to a coastal area, or, when a tropical storm threatening the watch area has at least a 50–50 chance of intensifying into a hurricane. Small-craft warnings are issued as part of an advisory containing a hurricane watch.

When a tropical cyclone is expected to pass near the coast (its hurricane-force winds remaining at sea), advisories contain whole gale or gale warnings as well as the hurricane watch announcement. Local warning information and recommended emergency procedures are also added to the message, which still includes small-craft warnings. At this point, the hurricane is close enough for peripheral tornadoes and flooding to be an added hazard. Weather Bureau River

Forecast Centers near the affected area, and the National Severe Storms Forecast Center at Kansas City, Mo., join the National Hurricane Center in assessing these new destructive possibilities.

A *hurricane warning* becomes part of advisories when a hurricane is expected to strike the coast within the next 24 hours. Warnings supersede the hurricane watch for a given area; however, additional watch announcements may be made for areas along the projected path of the hurricane.

The issuance of a hurricane warning crystallizes the forecasting problem, for the warning must be given sufficiently in advance for precautions to be taken in threatened areas—and it must be dependable. The requirement for dependability on the one hand and timeliness on the other can rarely be satisfied without some compromise. Most warnings give 12 to 16 hours' advance notice, and some—because of erratic storm path or behavior—cannot dependably give more than 6 hours' warning.

Advisories containing hurricane warnings include an assessment of flood danger in coastal and inland areas, small-craft warnings, gale warnings for the storm's periphery, estimated storm effects, and recommended emergency procedures. Tornado watches from the National Severe Storms Forecast Center may also be included.

As the hurricane moves inland, it begins to fill and die; its winds diminish and its spiral form expands. Advisories continue at this point, but their emphasis shifts to the danger of flooding, particularly in mountainous regions. These messages assess storm effects over the land, and include gale and small-craft warnings. Tornado watches are also included.

Tropical cyclone advisories are interspersed with tropical cyclone bulletins—information released as often as necessary to keep the public adequately informed. When a tropical cyclone is well at sea, bulletins are not normally issued. But when a tropical cyclone poses a threat to a populated coast over the ensuing 48 hours, interim bulletins inform the public of any significant changes. Most bulletins are prepared by Hurricane Warning Offices, and contain information for specific regions.

Advisories are discontinued when a tropical cyclone moves far enough inland to lose its hurricane characteristics. But as long as the disturbance retains its identity and threatens life and property, bulletins on the storm are issued at regular intervals.

The hurricane emergency may develop over a period of days or hours, and the violent storm may live for weeks, following an erratic, self-destructive path from the warm waters south of Cancer to polar ice floes. While the storm lives it will be tracked, and timely warning will go out to those living in its path.

small-craft warning: When a hurricane moves within a few hundred miles of the coast, advisories warn small-craft operators to take precautions and not to venture into the open ocean.

gale warning: When winds of 38–55 miles per hour (33–48 knots) are expected, a gale warning is added to the advisory message.

storm warning: When winds of 55–74 miles per hour (48–64 knots) are expected, a storm warning is added to the advisory message.

Gale and storm warnings describe the coastal area affected by the warning, the time during which the warning will apply, and the expected intensity of the disturbance. ***When storm warnings are part of a tropical cyclone advisory, they may change to a hurricane warning if the storm continues along the coast.***

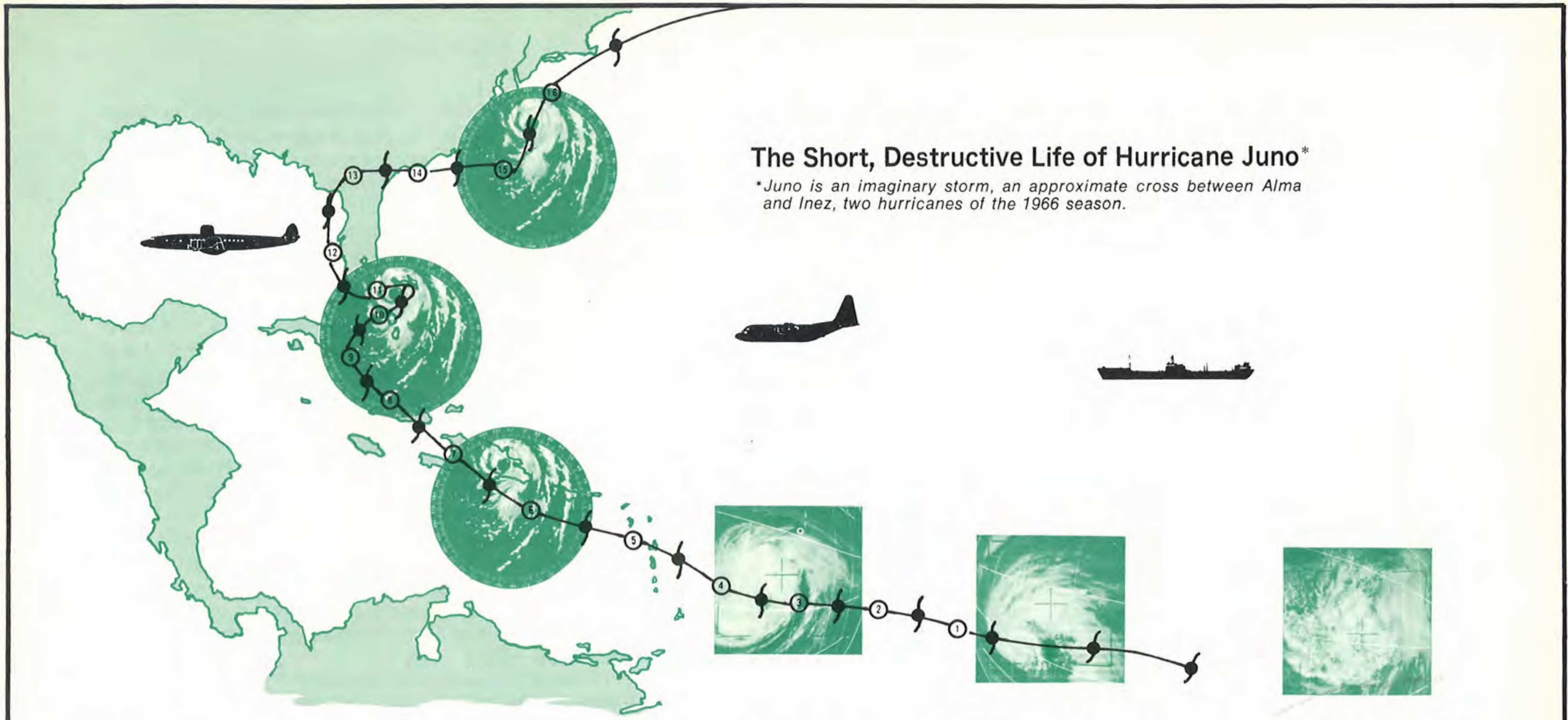
hurricane watch: If the hurricane continues its advance and threatens coastal and inland regions, a hurricane watch is added to the advisory, covering a specified area and duration. A hurricane watch means that hurricane conditions are a real possibility; it does ***not*** mean they are imminent. When a hurricane watch is issued, everyone in the area covered by the watch should listen for further advisories and be prepared to act quickly if hurricane warnings are issued.

hurricane warning: When hurricane conditions are expected within 24 hours, a hurricane warning is added to the advisory. Hurricane warnings identify coastal areas where winds of at least 74 miles per hour are expected to occur. A warning may also describe coastal areas where dangerously high water or exceptionally high waves are forecast, even though winds may be less than hurricane force.

When the hurricane warning is issued, all precautions should be taken immediately. Hurricane warnings are seldom issued more than 24 hours in advance. If the hurricane's path is unusual or erratic, the warnings may be issued only a few hours before the beginning of hurricane conditions. Precautionary actions should begin as soon as a hurricane warning is announced.

The Short, Destructive Life of Hurricane Juno*

**Juno is an imaginary storm, an approximate cross between Alma and Inez, two hurricanes of the 1966 season.*



Day 1:
Satellite photographs show a suspicious disturbance developing into a tropical depression. Hurricane Hunter reconnaissance verifies that a developing storm exists.

Day 2:
Depression deepens into tropical storm, with winds of 45 mph near center, gale winds over area 250 by 80 miles; the storm is moving west-northwest at 14 mph, and does not threaten land. First ESSA advisory issued for "Tropical Storm Juno." Other advisories will follow at six-hour intervals until Juno dies out. Later in day, satellite photographs, ship reports, and reconnaissance aircraft indicate Juno is growing more intense. A small-craft caution note is added to advisories.

Day 3:
Juno continues 14-mph drift to west and west-northwest. Hurricane Hunters report winds near 70 mph in center; further intensification is expected. By afternoon, Juno has become a hurricane. Before the day ends, Juno's winds reach 80 mph near the storm center. Hurricane warnings are issued for the Leeward Islands. Small craft cautionary messages become small-craft warnings.

Day 4:
Hurricane warnings continue for Leeward Islands. Gale warnings are added covering areas for several hundred miles around Juno's eye. Hurricane Hunters report winds of 95 mph at center. Small-craft warnings are joined by warnings of high storm tides on the Islands' coasts. The wind already has begun to rise at St. Kitts.

Day 5:
Juno hits Leewards' shortly after midnight, and appears poised to strike at the Virgin Islands and Puerto Rico. A new hurricane watch is issued for the Virgin Islands and Puerto Rico. Gale warnings are added for the Dominican Republic's southeastern coast.

Day 6:
Juno keeps south of her forecast position, missing the Virgin Islands and Puerto Rico. It is a blessing, for Juno is a monster: winds around the storm center have reached 140 mph; gale-force winds cover tens of thousands of square miles. Hurricane warnings are replaced by gale warnings for Puerto Rico and the Virgin Islands, but extended to cover the Dominican Republic. A hurricane watch is issued for Haiti.

Day 7:
Before daylight, Juno smashes into the southern coast of the Dominican Republic, whirling its destructive way across Hispaniola. As Juno moves back out to sea, flood warnings for Haiti and the Dominican Republic are added to ESSA hurricane advisories. Cubans in Oriente Province are urged to take precautionary measures before Juno reaches their coast. Hurricane warnings for Hispaniola are lowered.

Day 8:
The storm strikes into Cuba's coast, slowing over the central mountains, and curving northward.

Day 9:
Juno is centered over the island for nearly 40 hours before moving to sea, starved for energy; as the storm loops northward the advisories are once more for a tropical storm. Hurricane Hunter flights report winds have dropped to 50 mph. Gale and small-craft warnings cover the western Bahamas.

Day 10:
As Juno limps northward, it appears the weakened storm is recurving. Gale warnings continue for most areas in the storm's path, and small-craft warnings are up in the Florida keys and western Bahamas. Juno is in range of land-based radars and is being tracked by Hurricane Hunters. The spiral structure has become less striclty organized, and no distinct eye is visible on the radar screens. But Juno is only resting.

Day 11:
The storm intensifies, its winds rising to 85 mph. Advisories become hurricane messages. Hurricane watches and gale warnings are up for the southeastern Florida coast and the Keys. Juno continues to the northeast, then doubles back to the south of Florida across the Keys. Hurricane watches and warnings are issued for areas ahead of Juno's sudden westward sweep.

Day 12:
Juno, with winds now at 100 mph, accelerates along a track paralleling Florida's Gulf coast. Hurricane watches and warnings precede her, by dusk covering the Mississippi, Alabama, and Florida Gulf coasts.

Day 13:
The hurricane recurves, striking across the Florida panhandle into southern Georgia. Juno causes $16 million property damage in her brief passage across the southeastern United States — not a devastating storm as hurricane damage is reckoned. There are no deaths.

Day 14:
A much weakened Juno regains the ocean early in the morning, and continues a northward drift. Flood warnings are issued for Georgia, and gale warnings are issued in advance of Juno's northward track; the hurricane has become a tropical storm once more, and shows signs of dissipating.

Day 15:
Juno, a dwindling disturbance, drifts seaward. This day, and the several days that follow, will see the storm diminish and merge with the weather of the temperate North Atlantic.

COMMUNITY ACTION–an Imaginary Town

Like a song that exists only if it is heard, ESSA's hurricane advisories have no life of their own. Their only purpose is to help communities help themselves save lives and property from the onslaught of destructive storms. That they achieve this purpose is demonstrated by the year-by-year reduction in hurricane deaths.

Many communities on the Atlantic and Gulf coasts have taken steps to use their advisories effectively; but some have not, and others have waited for an expensive lesson in disaster before taking corrective steps. To encourage more widespread community preparedness, ESSA's Weather Bureau invented a vulnerable town, and made it a model of hurricane preparedness.

Homeport is a town of 25,000 laid out along a rather flat, straight Atlantic beach, on land rising from about 3 to about 30 feet above mean sea level. The business district begins about 500 feet inland from the beach. Across a mile-wide channel, Homeport Beach faces the city, and is connected to it by a two-lane causeway about 4 feet above mean high water. Homeport Beach is the residential section of Homeport, and the homes are mostly small one-story wooden buildings of light construction. The city is well-managed and policed, with adequate fire protection and public transportation. Red Cross and Civil Defense are well-organized and active. Some fishing craft operate out of its beach piers, and there is a marina in a lake just north of town with a canal to the sea. WHPT/WHPT–FM is Homeport's radio station. A nearby inland community, Metropolis, operates the television station closest to Homeport.

Homeport is an old city, but progressive. One of the more pleasant communities in Achilles County.

Homeport has been fortunate with regard to hurricanes. The major hurricane disasters of recent years have missed the little beach city. But towns like Homeport have not had that town's luck. Along the Atlantic coast, the hurricane of September 18–20, 1926, caused an estimated $100 million property damage, and made some 15,700 families homeless. The hurricane of September 15–17, 1928, killed some 1,836 and injured 1,870 more, and caused property damage of $25 million. Hurricane Carol in August 1954 devastated New England, causing property losses estimated at more than $400 million. And Betsy, 1965, killed 75 and set the U.S. record for property loss—$1.4 billion, more than the San Francisco Earthquake and Chicago Fire combined. A slight change in path, a slight diminution of Homeport's excellent luck, could have brought great damage and loss to this small city.

Despite the attitude of some of its citizens, Homeport has taken steps to be prepared for the day its luck changes for the worse. Its citizens have *anticipated* disaster, not waited for its lessons, for they know hurricane winds and storm surge and flooding rains could raze the houses of Homeport Beach, and drown the business district. They want to be able to recover quickly once their town is stricken.

The citizens of Homeport have set up a hurricane preparedness committee, a permanent body consisting of civic leaders, the local Civil Defense director, law enforcement and disaster relief personnel, representatives of city utilities and news media, and representatives from the State and Federal Governments. Their first step was to assess potential hurricane dangers, particularly storm tides, and then to earmark those areas of Homeport to which these dangers most applied. They have set up an emergency operating center, where auxiliary power and telephone communications ensure the city will not be cut off from the outside world by a hurricane. Working with the Red Cross, the committee has designated stout buildings as shelters, shelters have been arranged with inland towns near Homeport, and the City Engineer has prepared maps which show areas to be evacuated for several magnitudes of storm tide. The old city water supply plant is now supplemented by a secondary plant on higher ground; an 8-foot rise in mean sea level will contaminate the old plant, but the new unit will supply cooking and drinking water until the old plant is repaired.

Homeport takes preparedness seriously. The hurricane preparedness committee meets every May, and each month from June through November the equipment and procedures are checked. Assignments have been made to law enforcement and fire protection personnel, to aircraft and boat operators, to everyone concerned with getting Homeport through a natural disaster. And the citizens of Homeport are educated to help take care of themselves.

This does not mean that Homeport will not be damaged when a hurricane finally strikes that coast; it is neither possible nor desirable to move the beach town inland, and storm tides and winds will do great damage. But what can be moved will have been moved before the hurricane strikes, what can be saved will have been saved, and there should be no loss of life. Homeport is ready for its hurricane.

So are many communities along the Gulf and Atlantic coasts, and in the Caribbean.

What about your town? *

---

* Officials of coastal communities may get a free copy of ESSA's Homeport story, *A Model Hurricane Plan for a Coastal Community*, from:

Emergency Warnings Branch, W113
Weather Analysis and Prediction Division
ESSA Weather Bureau
Silver Spring, Md. 20910

INDIVIDUAL ACTION

And what about you? How well equipped are you to make the most of ESSA's early warning? These safety rules will help you save your life, and the lives of others.

1. **Enter each hurricane season prepared.** Every June through November, recheck your supply of boards, tools, batteries, nonperishable foods, and the other equipment you will need when a hurricane strikes your town.

2. **When you hear the first tropical cyclone advisory,** listen for future messages; this will prepare you for a hurricane emergency well in advance of the issuance of watches and warnings.

3. **When your area is covered by a hurricane watch,** continue normal activities, but stay tuned to radio or television for all ESSA Weather Bureau advisories. Remember: a hurricane watch means possible danger within 24 hours; if the danger materializes, a hurricane warning will be issued. Meanwhile, keep alert. Ignore rumors.

4. **When your area receives a hurricane warning:**

   Keep calm until the emergency has ended.

   Plan your time before the storm arrives and avoid the last-minute hurry which might leave you marooned, or unprepared.

   Leave low-lying areas that may be swept by high tides or storm waves.

   Moor your boat securely before the storm arrives, or evacuate it to a designated safe area. When your boat is moored, leave it, and don't return once the wind and waves are up.

   Board up windows or protect them with storm shutters or tape. Danger to small windows is mainly from wind-driven debris. Larger windows may be broken by wind pressure.

Secure outdoor objects that might be blown away or uprooted. Garbage cans, garden tools, toys, signs, porch furniture, and a number of other harmless items become missiles of destruction in hurricane winds. Anchor them or store them inside before the storm strikes.

Store drinking water in clean bathtubs, jugs, bottles, and cooking utensils; your town's water supply may be contaminated by flooding or damaged by hurricane floods.

Check your battery-powered equipment. Your radio may be your only link with the world outside the hurricane, and emergency cooking facilities, lights, and flashlights will be essential if utilities are interrupted.

Keep your car fueled. Service stations may be inoperable for several days after the storm strikes, due to flooding or interrupted electrical power.

Stay at home, if it is sturdy and on high ground. If it is not, move to a designated shelter, and stay there until the storm is over.

Remain indoors during the hurricane. Travel is extremely dangerous when winds and tides are whipping through your area.

Monitor the storm's position through ESSA Weather Bureau advisories.

Avoid the eye of the hurricane. If the calm storm center passes directly overhead, there will be a lull in the wind lasting from a few minutes to half an hour or more. Stay in a safe place unless emergency repairs are absolutely necessary. But remember, at the other side of the eye, the winds rise very rapidly to hurricane force, and come from the opposite direction.

5. **When the hurricane has passed:**

Avoid loose or dangling wires, and report them immediately to your power company or the nearest law enforcement officer.

Seek necessary medical care at Red Cross disaster stations or hospitals.

Stay out of disaster areas. Unless you are qualified to help, your presence might hamper first-aid and rescue work.

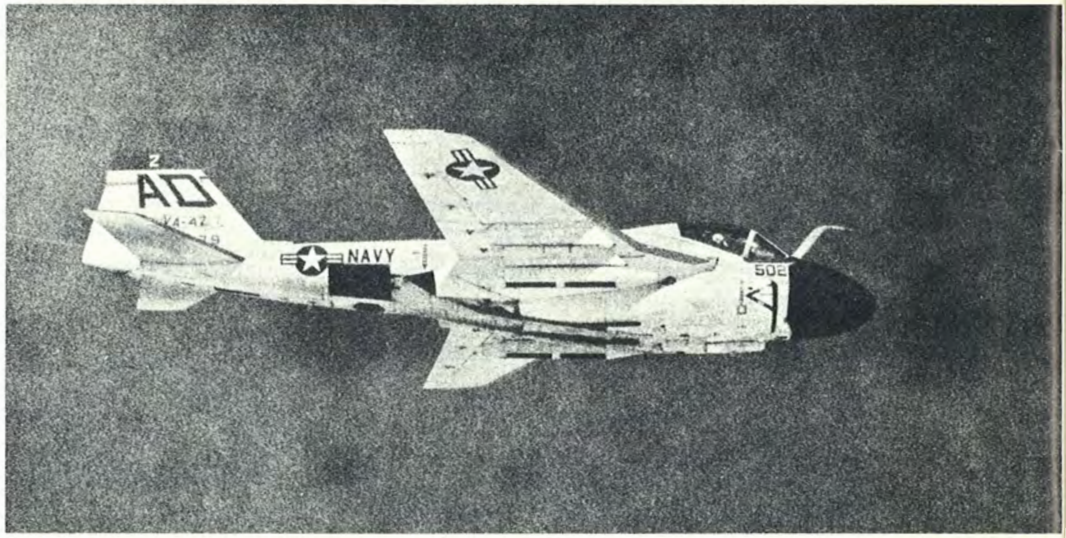
Drive carefully along debris-filled streets. Roads may be undermined and may collapse under the weight of a car. Slides along cuts are also a hazard.

Report broken sewer or water mains to the water department.

Prevent fires. Lowered water pressure may make firefighting difficult.

Check refrigerated food for spoilage if power has been off during the storm.

Remember that hurricanes moving inland can cause severe flooding. Stay away from river banks and streams. ESSA Weather Bureau advisories will keep you informed on river flood stages.



TOMORROW—AND BEYOND

At present ESSA detects and tracks hurricanes, and attempts to predict their future course. This information is translated into warnings for affected areas. The system works, but environmental scientists in ESSA are searching for something better. Part of this search involves programs which study the structure and dynamics of the hurricane, the processes which control its forward motion, and the atmospheric conditions in which the storm is born. Part of the search is for the products of a new technology—radars that reach out more than 200 miles from coastal Weather Bureau stations, computers whose electronic minds and memories can digest the data needed to predict the occurrence and path of a hurricane, earth-orbiting satellites and automated deep-sea buoys that track the storm from birth to death with great precision.

ESSA is expanding its natural hazards warnings communications and detection networks, refining the technology and procedures to protect every American against the natural hazards which threaten him. ESSA is also broadening the public awareness of the dangers of natural hazards—this booklet, and booklets like it, are part of this educational effort.

But no matter how effective the warning against hurricanes, no matter how precise the tracking and accurate the prediction, the great storms will continue to rack up increasing dollar costs along our coasts. As coastal communities expand and coalesce, the investment threatened by a hurricane increases almost geometrically. A storm like Betsy in 1965 could produce an estimated $1.4 billion in damage, despite timely warning. Another Betsy 10 years hence could easily top that record by striking the thickly settled coast of the 1970's and 1980's.

Research into the physics of hurricanes—the causes of their generation and the forces which drive them forward—may provide a partial answer to the cost of these great storms. Experiments that seek to modify hurricanes by reducing their destructive potential may provide another.

Sea-Air Interaction

The interaction of ocean and atmosphere characterizes almost every phase of the complex process we call weather. The two fluid systems, one of water and one of air, are inextricably linked in the heat engine of sea and air. Climate over the continents and distribution of solar energy over the earth's surface are largely functions of sea-air interaction. In its general features, the hydrologic cycle is an atmospheric bridge from ocean to land; the ocean as well as the atmosphere creates such long-term effects as drought and seasonal flooding. Thus, an understanding of either the sea or atmosphere involves an understanding of the interactions between them. Nowhere is this more dramatically exhibited than in hurricane research, for there the price is high, the threat, immediate.

ESSA is actively investigating air-sea interaction through its Institute for Oceanography's Sea-Air Interaction Laboratory (SAIL) and through other elements within ESSA. Perhaps the most dramatic air-sea interaction program is one planned for an investigation of the total environmental system in the tropical Atlantic. This continuing series of interagency investigations will use earth-orbiting satellites, research ships and aircraft, instrumented balloons and sounding rockets, and remote island and buoy stations to sample the full range of marine and atmospheric processes.

Through ambitious studies of this kind, science can establish the exchange of energy and matter between the two fluid systems, at various scales. The experimental results will influence the way in which all weather is predicted—but its most immediate effect will be on improved hurricane prediction—a first step toward mitigating the hurricane's destructive effects.

Project Stormfury

The unavoidable cost of hurricanes is part of the practical impetus behind ESSA's exploration toward goals more elusive than prediction—the modification and neutralization of hurricanes. *Project Stormfury* is such an attempt, born of practical necessity and driven by the quest for knowledge that drives most ventures into the unknown.

Project Stormfury is an interagency program conducted jointly by ESSA and the U.S. Navy, and developed from studies performed since 1956 by the National Hurricane Research Laboratory. *Stormfury* has the objectives of exploring the structure and dynamics of tropical cyclones, developing knowledge needed for improved prediction, and investigating the possibility of modifying some destructive aspects of these great storms. It is a laboratory program with a difference: the laboratory is the atmosphere and the violent interior of the hurricane itself.

For several years, *Project Stormfury* has conducted cloud-seeding experiments on hurricanes and tropical cumulus clouds outside of hurricanes. These experiments are based on a chain theory which predicts what should happen to the storm as the consequence of seeding. Theoretically, seeding alters the cloud structure in such a way that the balance of wind-controlling forces near the eye is upset. Injection of silver iodide particles into the eye wall upstream of the hot towers—the thermal chimneys of the hurricane—should transform supercooled water droplets to ice crystals, releasing heat energy into the storm system near the warm core. The effect of this additional heat should reduce atmospheric pressure adjacent to the low-pressure center of the storm, and reduce the difference in pressure across the eyewall—the steep pressure gradient which produces winds of hurricane force. This smoothing of the pressure gradient should cause the hurricane winds near the center to diminish, and, like a spinning ice-skater putting out his arms to slow his motion, the storm should expand its spiral bands and lose some portion of its fury.

It is a kind of atmospheric judo. Man cannot muster anything approaching the energy of a hurricane, and so has no hope of overcoming the storm by force. The *Stormfury* hypothesis attempts to use the giant's own energy and size against it, setting in motion a chain of reactions within the storm that finally reduces its intensity. To date, *Project Stormfury's* experiments have sought to test and refine this theory.

Science does not yet know precisely what seeding will do to a hurricane or how much supercooled water exists in the eyewall at altitudes between 20,000 and 40,000 feet. Instruments to measure water content have only recently been adapted for use on the rugged aircraft needed to carry them into the turbulence and icing conditions of the hurricane at those altitudes, and are not yet part of *Project Stormfury*.

There are problems besides those of equipment. Hurricanes are by nature highly variable—their "noise level" tends to mask small-scale changes produced by seeding. As yet, there is no satisfactory numerical model of a hurricane that permits a computer to sort out the natural and man-generated processes in the storm.

Finally, *Stormfury* experiments through 1966 were restricted to an Atlantic area from which no hurricane on record had ever struck a highly populated coastal area within 36 hours. This reduced the available sample to an average of less than one storm per year—with some years providing no sample at all.

The *Project Stormfury* Advisory Panel, composed of five distinguished meteorologists, has recommended that the guidelines for selecting storms for experimentation be changed. Concluding that neither past nor future *Stormfury* experiments pose any threat to life and property greater than the risks inherent in a hurricane, the Panel recommended that storms be considered for experimentation when they were forecast to remain away from land for at least 24 hours. This would give *Stormfury* time to collect data needed for an evaluation of experimental effects before the hurricane circulation was materially changed by land influences.

Only two hurricanes have been treated in the *Stormfury* "laboratory," Esther in September 1961 and Beulah in August 1963. In addition, numerous cumulus seeding experiments have been conducted. Although the sample is quite small, *Stormfury* seeding has produced interesting effects. The seeded portion of Esther's eyewall faded from the radarscope which detects water droplets, indicating either a change of liquid water to ice crystals or the replacement of large droplets by much smaller ones. Beulah 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 also have produced those effects.

U.S. Navy Photos

Seeding experiments on cumulus clouds have produced significant accelerations of cloud growth. In experiments conducted near Puerto Rico by the U.S. Navy and ESSA, heavy silver iodide seeding apparently caused large maritime cumulus clouds to grow thousands of feet higher than similar, unseeded clouds nearby. Such experiments are fundamental to successful modification of the hurricane's convective processes—and to man's eventual modification of precipitation.

Thus far, *Stormfury* has not brought hurricane modification even within real theoretical grasp, but enough of the *Stormfury* hypothesis has been supported that the program continues.

Before the hurricane season begins, *Project Stormfury* personnel and aircraft muster at Roosevelt Roads Naval Air Station, P.R. This group includes atmospheric physicists and meteorologists from ESSA's Institute for Atmospheric Sciences, and flight crews from ESSA's Research Flight Facility and the Navy Hurricane Hunter Squadron. Additional Navy equipment and personnel arrive from the Naval Ordnance Test Station, China Lake, Calif. It is a large project, involving nearly 300 persons and 16 aircraft.

Aircraft used in *Project Stormfury* vary from season to season. In recent years, four instrument-crammed ESSA aircraft from the Research Flight Facility—two DC–6's, one DC–4, and one WB–57—have been joined by Navy Hurricane Hunter WC–121N *Super Constellations*, Air Force Hurricane Hunter WC–130 *Hercules* and WB–47 *Stratojet* aircraft, and, at one time, U–2 aircraft. *Project Stormfury* has used two types of Navy aircraft for seeding: RA–3B *Skywarriors* from China Lake and Heavy Photo Reconnaissance Squadron 62, and A6–A *Intruders* from Attack Squadron 35.

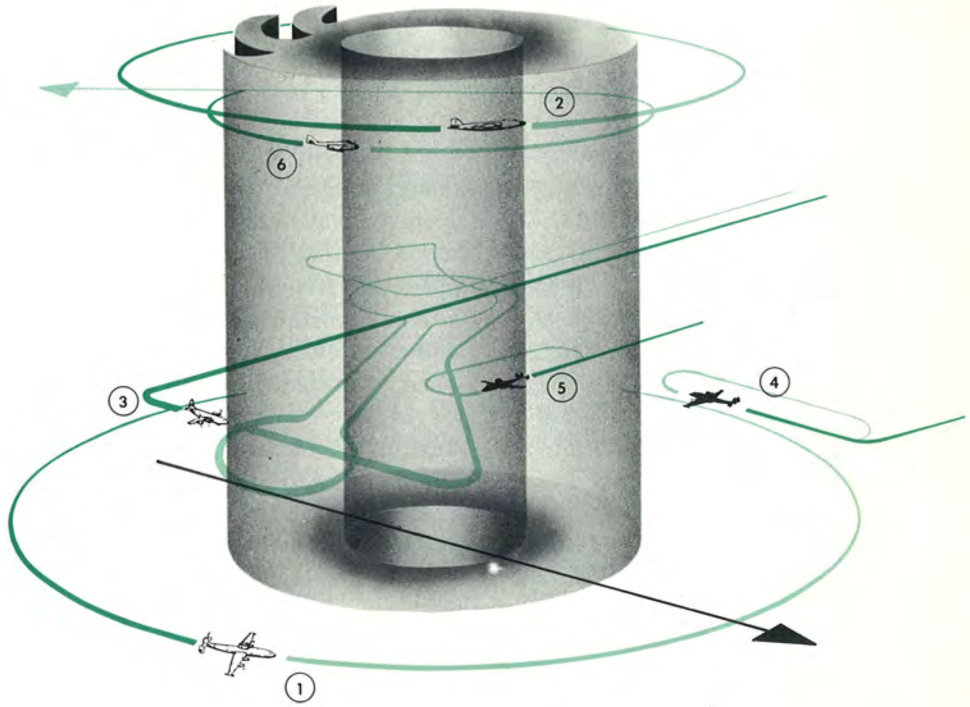
Stormfury aircraft and personnel are at a constant 72-hour alert status through the hurricane season. When a mature hurricane drifts into their assigned experimental area, they move to meet it. Several types of experiments are designed into each *Stormfury* season, and include rainband and cumulus seeding experiments. But the most ambitious and complex experiment is the seeding of the hurricane eyewall. As the experiment begins, the Federal Aviation Administration and Navy reserve the airspace in the test area, advising commercial and military flights to stay clear of the *Stormfury* experiment.

The WC–121N is the command control aircraft. Present versions of this Hurricane Hunter airplane have been modified with the addition of a variety of new environmental sensors, improved Doppler radars (radars which use the Doppler frequency shift to

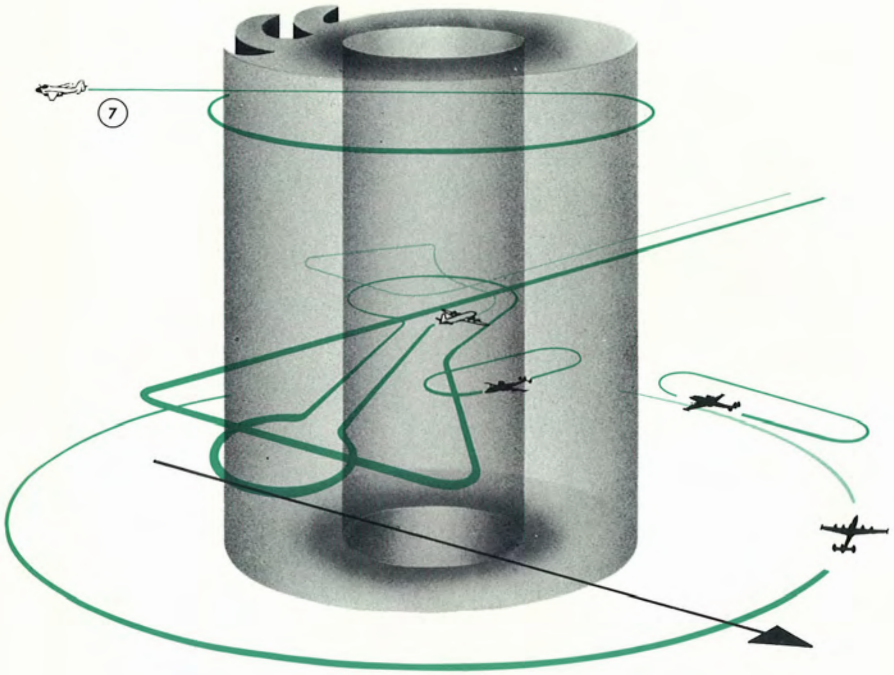
Project Stormfury's eyewall experiment involves a number of aircraft over an area of several thousand square miles, at altitudes between 1,000 and 50,000 feet; one or more aircraft are in the vicinity of the hurricane from four hours before seeding (T, or "Tango," for zero time) to 12 hours after seeding (Tango plus 12). This diagram shows the approximate sequence and traffic pattern in and near the storm.

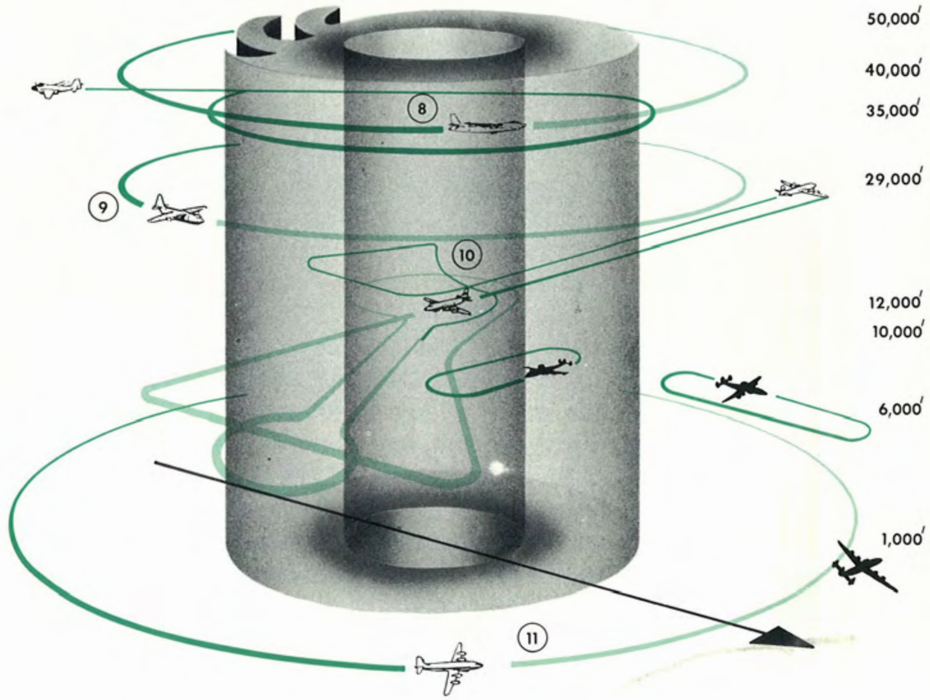
The Navy WC-121 low-level inflow monitor (1) takes position 75-100 miles from the hurricane's center and 1,000 feet high at Tango minus 4. At Tango minus 3, ESSA's WB-57 (2) makes high level outflow measurements near 40,000 feet, staying 75-100 miles from the storm center. At the same time, an ESSA DC-6 (3) begins its first penetration of the storm at 12,000 feet, gathering weather information at this intermediate level. About 75 miles from the center, the Command Control WC-121 (4) takes up an elongated flight path at 6,000 feet. Another WC-121 (5) circles in and out of the hurricane at 10,000 feet; this radar and dropsonde aircraft measures characteristics of the storm upstream of the area to be seeded. The seeding aircraft, a Navy A-6A *Intruder* (6), moves into a pattern 50 miles from the center at 35,000 feet. At Tango, the *Intruder* breaks its circular holding pattern and rams through the hurricane-force winds, dropping 80 *Alecto* canisters (7) along the path on the far side of the eye. Seeding is repeated at two-hour intervals — at Tango plus two, four, six, and eight hours.

As the experiment progresses, an Air Force WB-47 (8) arrives to monitor high-level outflow near 40,000 feet and a C-130 cloud physics monitor (9) moves into a circular pattern at 29,000 feet, 75-100 miles from the storm center. The ESSA DC-6 which made the first penetration leaves the area, while another (10) begins its penetration. The low-level monitor heads for home as an ESSA DC-4 (11) moves into position. Another WC-121 will replace it after this four-hour patrol. At Tango plus 9, all but three aircraft return to base. Another WC-121 replaces the DC-4 as low-level inflow monitor, another ESSA DC-6 flies the penetration pattern at 12,000 feet, and ESSA's WB-57 returns to monitor outflow at high altitudes.

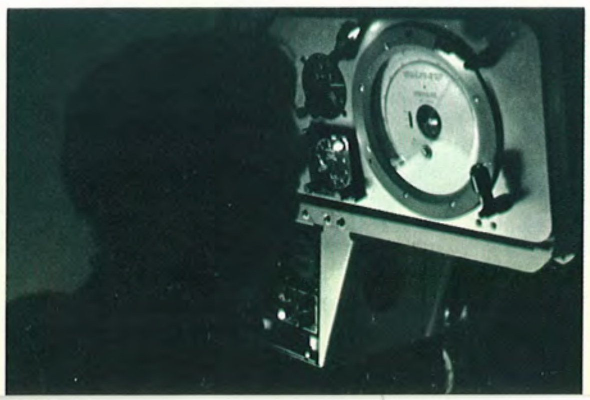


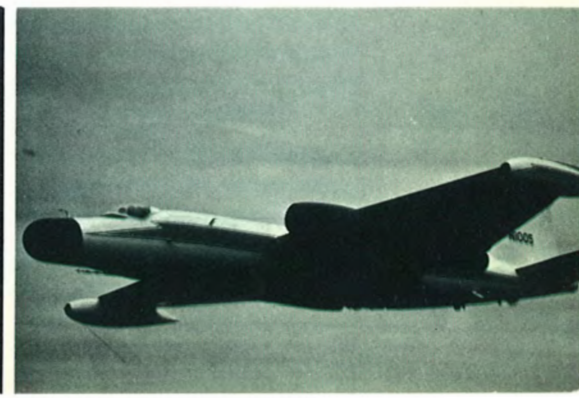
U. S. Navy Photos





U.S. Navy Photos





portray relative motion of reflected particles), navigational computers, and radar altimeters. In the eyewall experiment, the command WC–121 stays outside the storm at about 6,000 feet and monitors *Stormfury* aircraft operating in and near the hurricane. At a given moment, the WC–121 might be monitoring as many as 12 aircraft, between 1,000 and 42,000 feet. The command WC–121 also takes meteorological measurements.

The seeding is made at altitudes of at least 35,000 feet by A6–A *Intruder* all-weather attack jets, which are equipped for massive seeding operations. Seeding is accomplished by launching *Alectos*—small pyrotechnic canisters whose exhaust products form a stream of silver iodide particles—into the eyewall upstream of the hot chimneys. In the eyewall experiment, 80 *Alectos* are dropped on each of five seeding runs, made at 2-hour intervals. The twin-engine jet seeders also provide meteorological data.

The ESSA DC–6's and DC–4 and additional Navy WC–121's alternately monitor inflow at low-to-intermediate altitudes (1,000–12,000 feet) within the storm, one operating at midlevel and three alternating on low-level passes. One of the WC–121's launches dropsondes, instrument packages dropped from aircraft that send meteorological readings back to an airborne receiver. The ESSA WB–57 and the Air Force WB–47 measure high-level outflow from the hurricane. Air Force WC–130's operating near 30,000 feet make radar and cloud physics measurements. Above the storm—at altitudes near 60,000 feet—Air Force aircraft provide photographic coverage and measure wind and temperature.

The 8-hour experiment—and, through 1966, conditions prevented this massive eyewall seeding—is only a beginning. The digital and photographic records gathered by *Stormfury* aircraft are analyzed for the following season, and the one after. Year by year, the project evolves in response to the addition of knowledge, and raises its chances of success.

To describe *Project Stormfury* simply as an operation, though, is to miss its importance as a symbol. It is an extension of man's persistent effort to shape the world around him, to make it more accommodating and hospitable to his kind; there is a mythological sweep to the notion of tiny man taming giant hurricanes.

If *Stormfury* is successful, it will provide the human counterthrust to the advance of destruction from the tropical sea. But while that weapon is being forged, ESSA keeps its watch on the warm ocean beneath the advancing sun, and when the great cloud spirals grow, gives timely warnings.

U. S. Navy Photo

U. S. GOVERNMENT PRINTING OFFICE : 1967 O - 267-823

American Red Cross Photo

HURRICANE BIBLIOGRAPHY

The technical basis of this booklet, and some of the language, come from several primary sources: *Atlantic Hurricanes,* by Gordon E. Dunn and Banner I. Miller (Louisiana State University Press, 2d edition, 400 pp., Baton Rouge, 1964); *Florida Hurricanes,* by Gordon E. Dunn, and staff, in press, 1967; *Hurricane Modification Experiments,* by Dr. Joanne Simpson, presented at the meeting of the American Society for Oceanography, October 11, 1966; *Nature and Scope of Hurricane Damage,* by R. Cecil Gentry, in press, 1967. The reader is referred to those sources for a fuller and more technical discussion of hurricanes, their destructive effects, and their modification. Additional sources are listed below.

American Meteorological Society, "Statement on Hurricanes," *Bulletin of the AMS,* vol. 40, No. 7, July 1959.

Cry, George W., "Tropical Cyclones of the North Atlantic Ocean: Tracks and Frequencies of Hurricanes and Tropical Storms, 1871–1963," *Technical Paper* No. 55, U.S. Weather Bureau, Washington, D.C., 1965, 148 pp., Price 70 cents.*

Fletcher, Robert D., Smith, James R., and Bundgaard, Robert C., "Superior Photographic Reconnaissance of Tropical Cyclones," *Weatherwise,* vol. 14, No. 3, June 1961.

Gentry, R. C., "Review of Recent Hurricane Research," *Weatherwise,* vol. 13, No. 5, October 1960, pp. 206–209.

Haggard, W. H., "Where Hurricanes Begin," *Weatherwise,* vol. 12, No. 6, August 1959, pp. 145–150.

Hamlin, T. F., "When You Get Caught; Things That Will Help in Squall or Hurricane," *Yachting,* vol. 98, October 1955, pp. 50–51.

Harding, Edwin T. and Kotsch, Wm. J., *Heavy Weather Guide,* U.S. Naval Institute, Annapolis, 1965, 210 pp. Illustrations, Price $6.00.

Hardy, Albert V., and Carney, Charles B., "North Carolina Hurricanes," U.S. Department of Commerce Weather Bureau, November 1962, Price $0.20.*

Harris, D. Lee, "Characteristics of the Hurricane Storm Surge," *Technical Paper* No. 48, U.S. Weather Bureau, Washington, D.C., 1963, Price $0.70.*

Hartley, William, "Miami's Hurricane-Proof Building Code, *Coronet,* vol. 47, March 1960, pp. 166–170.

House and Garden, "How to Protect Your Home and Garden Against Hurricane Damage," vol. 106, November 1954, pp. 214–216.

Hubert, L. F., "Tropical Cloudiness, Severe Storms, and Convective Cells," *Proceedings of the International Meteorological Satellite Workshop, November 13–22, 1961,* National Aeronautics and Space Administration and U.S. Weather Bureau, Price $1.75.*

Ludlum, D. M., *Early American Hurricanes, 1492–1870,* American Meteorological Society, Boston, 1963, 198 pp. Price $5.00.

Riehl, Herbert, "On the Origin and Possible Modification of Hurricanes," *Science,* vol. 141, No. 3585, September 13, 1963, pp. 1001–1010.

Rosendal, Hans E., "Eastern North Pacific Tropical Cyclones, 1947–1963," on back of Pilot Chart of the North Pacific Ocean, April 1964, published by U.S. Navy Oceanographic Office, Navy Department, Washington, D.C., Price $0.30.

Simpson, Robert H. and Malkus, Joanne S., "Modification Experiments on Tropical Cumulus Clouds," *Science,* vol. 145, No. 3632, August 7, 1964, pp. 541–548.

Simpson, R. H. and Malkus, Joanne S., "Experiments in Hurricane Modification," *Scientific American,* vol. 211, December 1964, pp. 27–37.

Tannehill, I. R., *Hurricane Hunters,* Dodd, New York, 1955, Price $3.00.

Treadwell, Mattie E., "Hurricane Carla" (A post-storm study of warning, evacuation, reception and shelter, reentry, and rehabilitation in a major hurricane), Office of Civil Defense, Region 5, Denton, Texas, 1961, Price $0.55.*

U.S. Weather Bureau, "Summary of North Atlantic and North Pacific Tropical Cyclones," *Climatological Data, National Summary,* Annual 1965 and other years, Price $0.20.*

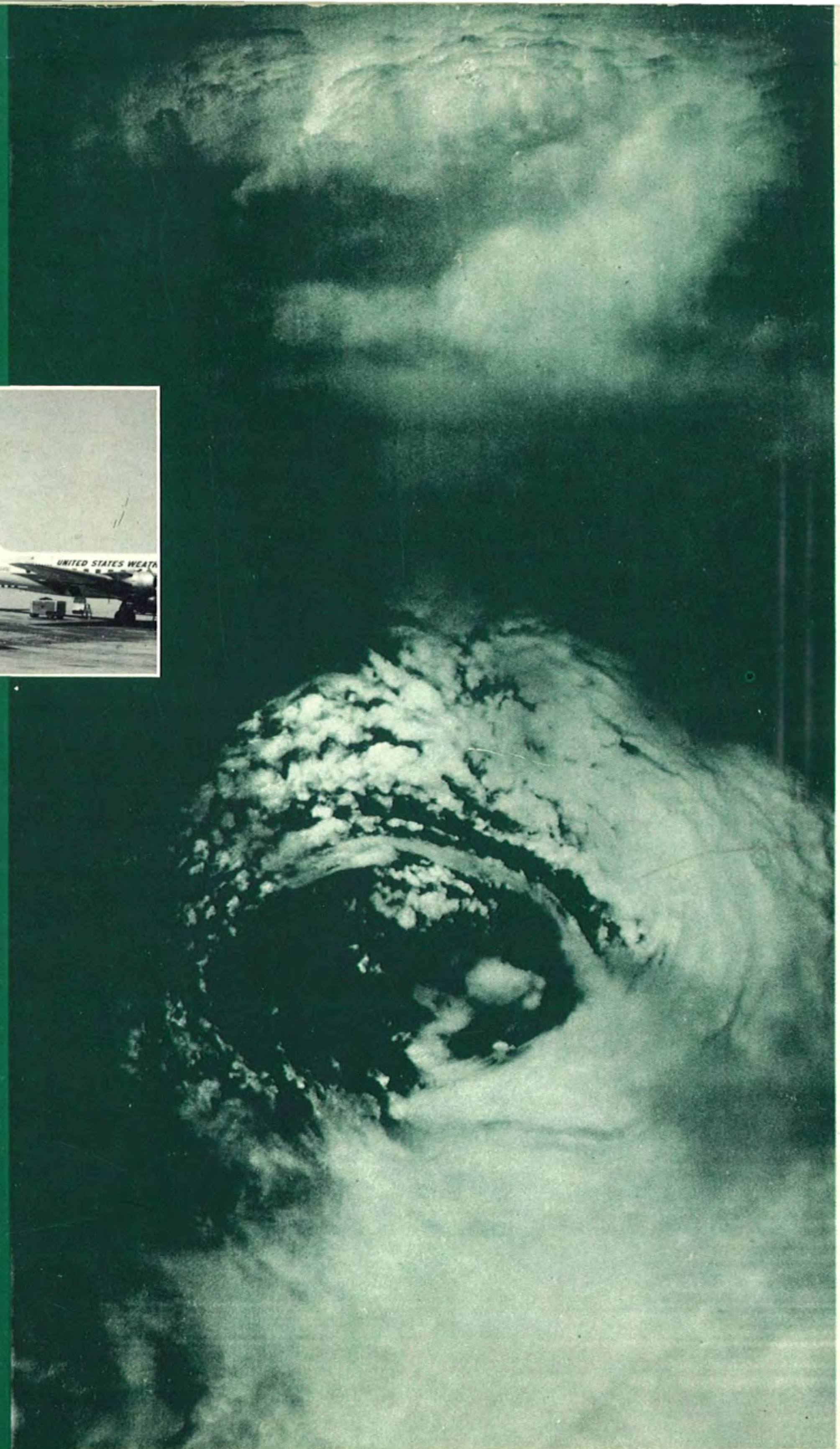
Weatherwise, Almanac Issue, February 1966 and other years. Includes article on hurricanes of the previous year by a recognized authority.

Weatherwise, "Hurricane DONNA" (three articles on the storm and its effects in Florida, North Carolina and the Northeast, respectively), vol. 13, October 1960, pp. 210–217.

Additional references to hurricanes may be found in the *Monthly Weather Review* published by the U.S. Weather Bureau and in *Readers' Guide to Periodical Literature.*

*For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, at the prices shown.

U. S. Air Force Photo



U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
essa

1967

ESSA/PI 670005

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 – Price 45 cents