adjacent bottoms and not on the reef. These results illustrate the importance of nonresident food resources in determining the trophic structure of reef communities.

The number of mid-water organisms attracted at night appeared relatively constant, presumably because the lights drew from an approximately constant volume of water. If the supply of attracted organisms remained constant, the standing crop of residents would eventually be limited by a shortage of food. This apparently did not happen during the 44-day period, because the total number of residents and three of the four most abundant species were still increasing at the end of the project. The fourth species, vermilion rockfish, was obviously limited by something other than availability of foods; they reached a peak density early in the project and maintained it even though there apparently was interchange with canyon populations. By the end of the project the estimated biomass of prey attracted each night was about 2.8 percent of the standing crop of residents. This figure is close to daily food requirements that have been reported for fishes at similar temperatures (*14*). Even though our estimates of visiting prey are probably minimal, this figure suggests that the observed rate of increase in standing crop would not have continued much longer.

Seasonal and other long-term changes in the fauna would be expected. The species initially attracted to *Sealab II* were already present nearby in the canyon or along its edges. Undoubtedly other species would eventually wander in from more remote areas or appear as juveniles metamorphosing from planktonic larvae. Such new species could interact with those already present as prey, predators, or competitors. The disappearance of croakers after the sea lions arrived shows that the presence of even a single new species can drastically alter the density and trophic structure of the attracted fauna. It would be interesting to determine whether such marked changes would continue to occur as new species appeared, or whether, as predicted by theories of community diversity (*15*), the changes would become less violent as the diversity of the resident fauna increased. It would also be interesting to determine whether lighted reefs, because they appear to be more immediately effective in concentrating fishes, would also yield a greater sustainable harvest of commercial or sport fishes than unlighted reefs.

References and Notes

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Characteristics of Hurricanes

Analyses and calculations made from measurements by aircraft result in a fairly complete description.

Banner I. Miller

Fully mature tropical cyclones, called hurricanes in the Atlantic and typhoons in the western Pacific, are large rotating storms of extraordinary violence. They are born over the warm waters of all the tropical oceans except the South Atlantic (*1*). Although hurricanes are neither the largest nor the most intense atmospheric storms—they cannot match the concentrated fury of tornados or compare in size with the winter storms of the middle latitudes—their considerable size and great intensity make them the most dangerous and destructive of all storms.

A hurricane is more destructive than any other natural disaster: damage in the United States exceeded $1 billion in 1954 (*2*) and approached $2 billion the following year; in 1965 hurricane Betsy alone caused property damage of about $1.5 billion in Florida and the Gulf states (*3*). The greatest damage and loss of life arise from storm surges that inundate low-lying coastal areas with wind-driven sea water in which all floating objects act as gigantic battering rams, from flooding caused by the heavy rains, and from winds that frequently exceed 240 kilometers per hour.

The great economic impact of hurricanes amply justifies efforts to study them; moreover, scientists find them a challenging subject for investigation. Observation of hurricanes, however, has not been easy. Before World War

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II most of our knowledge was based on observations from ships at sea, by observatories located on small islands, or by a network of meteorological stations after a hurricane had moved inland. Surface winds, pressures, and rainfall were measured reasonably well, but, in the vertical, hurricane information consisted of limited inferences drawn from surface data and observations of the approaching storm clouds.

On 27 July 1943, Colonel J. P. Duckworth (*1*) made the first planned flight into a hurricane, penetrating its eye as it moved inland from the Texas coast just north of Galveston. Routine hurricane-reconnaissance flights by the Air Force and the Navy have since contributed significantly to detailed knowledge of the structure and energetic processes of hurricanes, chiefly because of the development of aircraft capable of flying safely into the core of the storm. Specially instrumented aircraft operated by the Research Flight Facility of the Environmental Science Services Administration (ESSA) have flown about 400 missions (more than 3200 hours) into hurricanes and tropical storms, at altitudes ranging from a few hundred meters above the ocean to more than 12,000 meters. Aircraft (U-2 and similar planes) have flown over hurricanes at altitudes greater than 18,000 meters. Measurements of winds, temperatures, and pressures obtained by these research flights have resulted in a fairly complete three-dimensional description of hurricanes.

Until radar, adapted for observation of weather, revealed the spiral nature of the hurricane rainbands (Fig. 1), no one had been led, by either theoretical considerations or the examination of

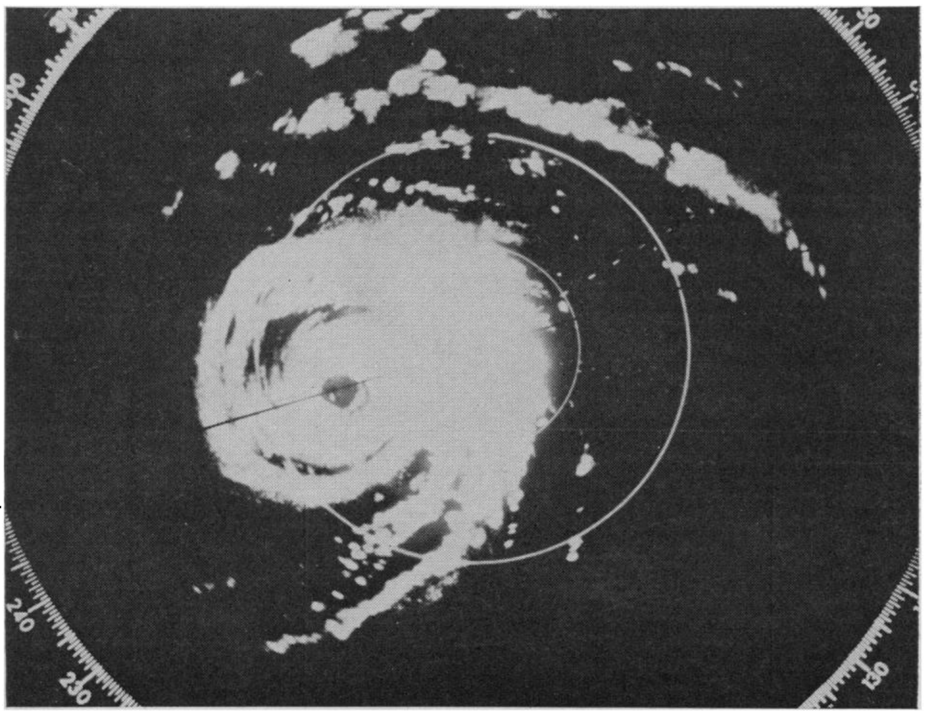


Fig. 1. The spiral-banded structure of hurricane Donna, 10 September 1960.

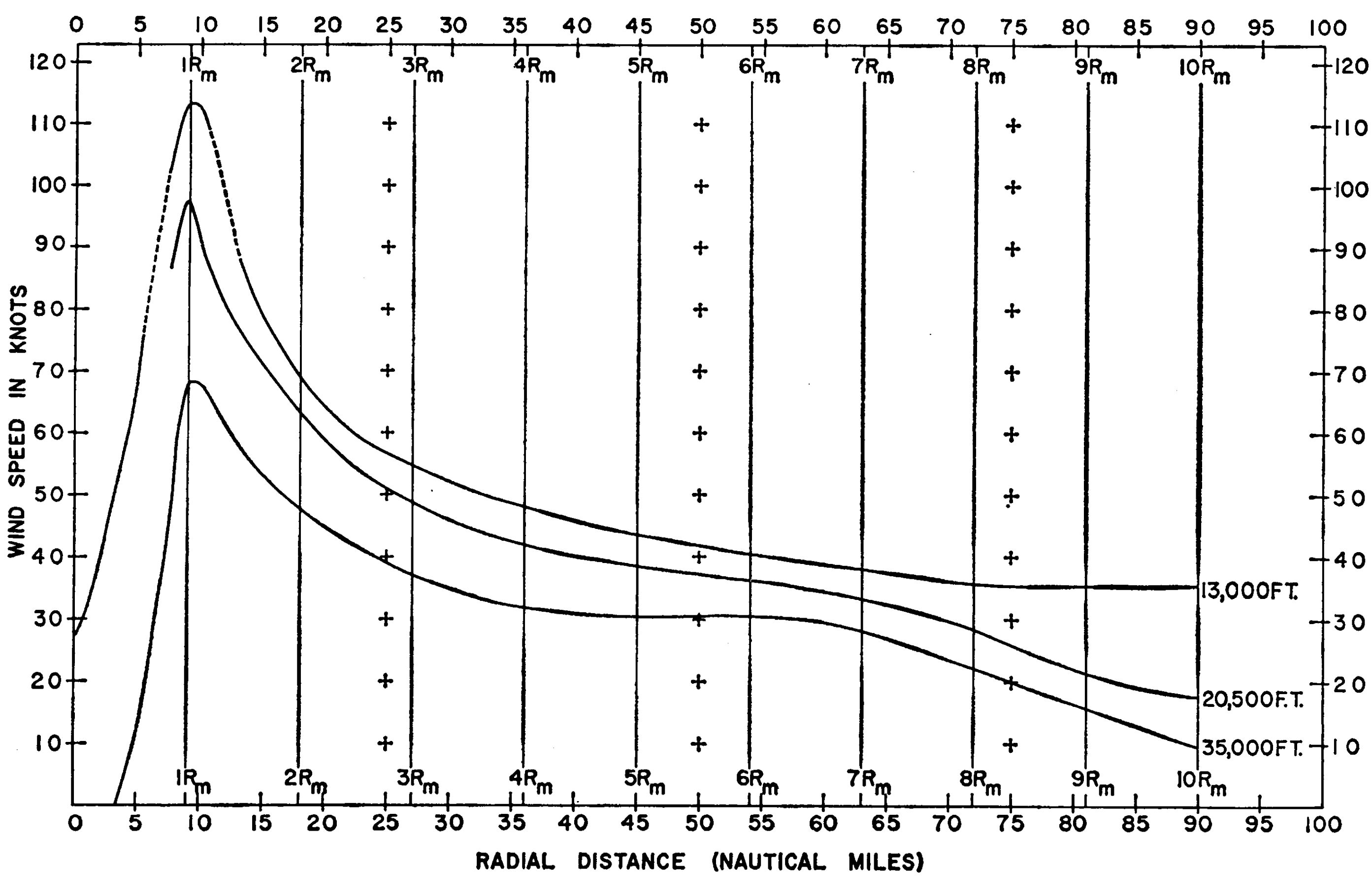


Fig. 2. Wind profiles of hurricane Daisy, 27 August 1958, based on measurements by aircraft (*4*).

many records of rainfall, to even suspect that the rainbands might assume a spiral character. This spiraling, plus the fact that the eye of the hurricane is relatively free of precipitation, facilitates identification of a hurricane by airborne or land-based radar, thus providing an effective means of tracking the progress of a storm.

The advent of weather satellites has resulted in improvement of identification and location of tropical cyclones, especially in remote portions of the oceans where conventional meteorological information may be lacking. In April 1960, for example, Tiros I, an experimental weather satellite, made meteorological history (*2*) by photographing an unreported fully developed hurricane or typhoon about 1300 kilometers east of Brisbane, Australia; its existence was later verified by the Australian Weather Service. Satellites have also revealed some important aspects of characteristics of hurricane clouds and dynamics, some of which I shall discuss later.

In 1956 the National Hurricane Research Laboratory (NHRL) was established. Through an intensive research program, either conducted by the Laboratory's staff or sponsored by the Laboratory under contracts with or grants to universities and other research organizations, NHRL has produced an almost complete description of the circulation and thermal structure of hurricanes, better understanding of the transformations of energy that take place in hurricanes, improved methods of forecasting, and additional basic knowledge about the meteorology of the lower latitudes.

Hurricane Circulations

In his description of the winds of a hurricane, Tannehill (*1*) wrote:

> At the outer limits of the hurricane, the winds are light to moderate, and gusty. As the center approaches, they increase gradually, growing to squalls, then furious gales, and finally, in the fully developed hurricane, the winds immediately surrounding the center blow with indescribable fury. On the ocean the winds of the hurricane create tremendous seas and blow the tops of them away in sheets and spray, so that the mariner can scarcely tell where the ocean ends and the atmosphere begins.

Dunn and Miller (*2*) suggested that low-level circulation in hurricanes could be considered as three distinct regions:

1) The outer portion extends from

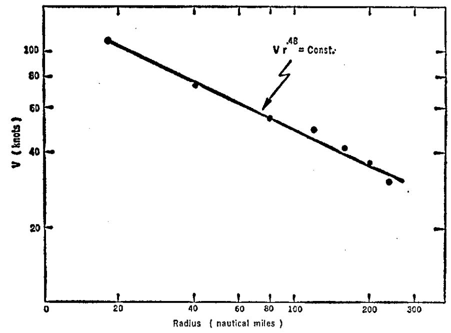


Fig. 3. Radial profile of low-level winds in hurricane Donna, 10 September 1960.

the periphery of the storm inward to the region of maximum winds. The winds increase nearer the center, not infrequently reaching velocities of 200 to 240 kilometers per hour.

2) The region of maximum winds surrounds the eye. This region averages 8 to 16 kilometers in width, with a radius ranging from 13 to 16 kilometers, for small intense hurricanes of the type of Daisy (1958) and Cleo (1964), to 50 to 65 kilometers or more for large cyclones of the Carla (1961) class. The ring of concentrated winds, the most outstanding characteristic of the mature tropical cyclone, coincides with the wall cloud surrounding the eye. The wall cloud is a ring of violent convection and is usually accompanied by heavy rainfall and constant winds.

3) The eye is the innermost portion of the storm. Winds diminish with amazing rapidity in this region, but seldom approach absolute calm.

Figure 2 shows the radial profiles of wind speeds at three levels in hurricane Daisy (1958). These profiles, prepared by Hawkins (*4*) from measurements by aircraft, show a large anticyclonic wind shear between radii of 10 to 20 nautical miles (1 nautical mile = 1.853 kilometers) and the even stronger cyclonic shear inside the radius of maximum winds. Since Daisy was a small but intense hurricane, with maximum winds of about 115 knots (1 knot = 1.853 kilometers per hour) at 4000 meters, the radius of hurricane-force winds (65 knots) was only 20 to 25 nautical miles. In contrast, Fig. 3 shows a radial profile of the low-level winds for hurricane Donna (1960), plotted on a logarithmic scale; the profile does not extend inside the radius of maximum winds, since no data on winds were available from the eye. Because Donna was a large hurricane, the radius of hurricane-force winds was about 60 nautical miles, while gales (about 35 knots) extended outward to about 200 nautical miles. Many radial profiles of hurricane winds can be reasonably well expressed by a (VR^x = constant) vortex for radii greater than the radius of maximum winds (V is the wind speed; R, the radial distance from the hurricane center). Typical values of x range from about 0.5 to 0.65; the best value in Fig. 3 was 0.48, but the radial profiles for Daisy (Fig. 2) are much steeper, indicating that a larger value of x would be required to fit a (VR^x = constant) curve to these data.

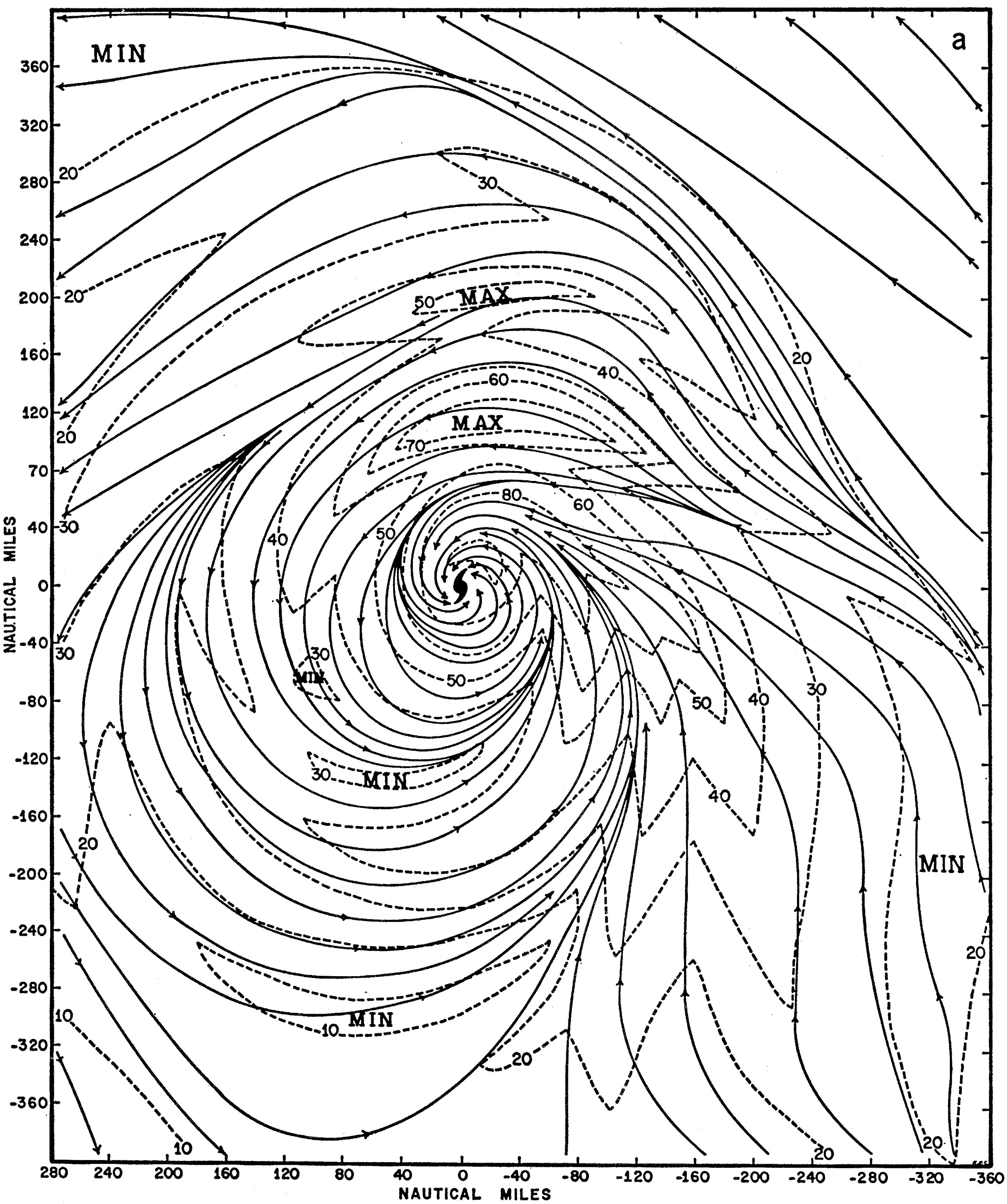
Vertically, the circulation of a major hurricane extends upward to around 14,000 or 15,250 meters—close to the tropopause. Data gathered by U-2 flights suggest that during intense hurricanes small circulations may still be detectable in the stratosphere (*5*). Since a hurricane is a warm-core circulation, thermodynamic considerations tell us that the cyclonic circulation should decrease with height, and Fig. 2, showing wind data from three levels, confirms this fact. The vertical shear, however, is small through the first 6100 meters (*4*). The maximum speed decreased in this particular storm by 15 knots between 4000 and 6250 meters. At 10,700 meters the maximum winds had decreased to 70 knots, a significant reduction from the 115 knots observed at 4000 meters, but the radius of the maximum winds changed little with elevation.

Hurricane circulation may be divided into three vertical layers: the lowest extends through a depth of about 3050 meters and is frequently referred to as the inflow layer since it contains a pronounced component of motion toward the center of the hurricane. In the inflow layer—essentially the engine that generates the storm's circulation—the radial component of the wind flows from higher to lower pressure, thereby converting potential energy to kinetic energy. This radial inflow is largely controlled by the frictional forces resulting from the shearing stresses exerted by the winds upon the ocean. (This may seem somewhat paradoxical, since generation of circulation of the hurricane depends on the existence of friction, which is an energy sink.) Figure 4a shows the low-level circulation of hurricane Donna (1960), with striking convergence of the streamlines to the right of the center.

Tropical cyclones have as their primary source of energy the release of latent heat. The moisture that later falls as rain also enters the hurricane through the inflow layer by evaporation from the ocean and through lateral advection by the inflowing air; this convergence of moisture initiates the hurricane's development.

In the middle layer (3050 to 7600 meters) the circulation is mostly tangential, with little or no radial motion. Figure 4b [based on aircraft measurements of Daisy (1958), made the day after the data shown in Fig. 2] shows some convergence of the streamlines behind the center, but the motion nearer the center is predominantly cyclonic; the hurricane had expanded somewhat between the two flights. The 100-knot isotach right of the center, and the marked lack of symmetry in the speed field are typical of the patterns of hurricanes moving rapidly north or northeast.

The outflow layer extends from about 7600 meters to the top of the storm; for a mature hurricane the maxi-

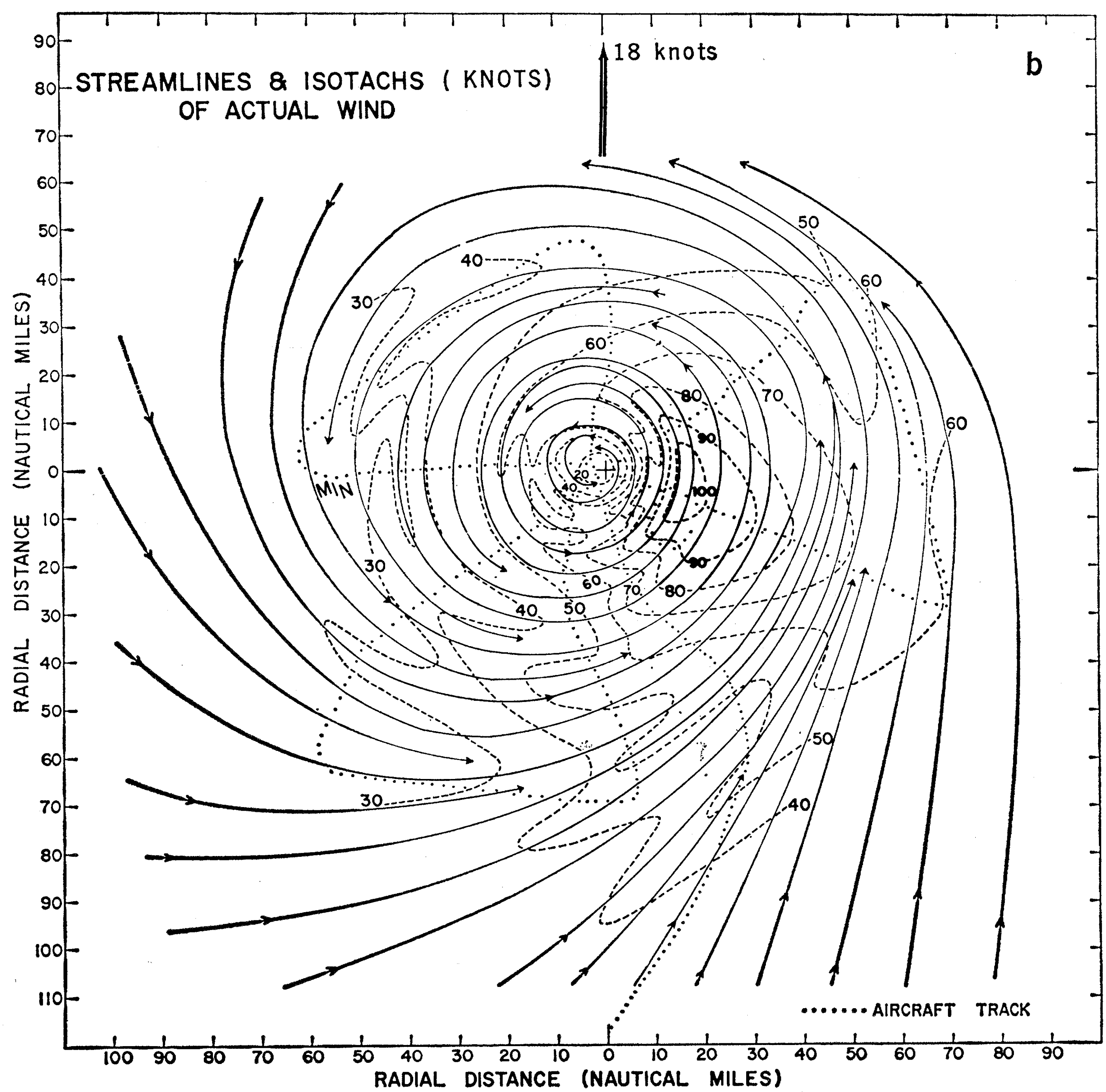


mum outflow occurs near 12,200 meters. In the outflow layer, kinetic energy may be converted to potential energy as air flows outward toward higher pressure. Through much of the outflow layer, winds decrease, change direction, and frequently become anticyclonic because the hurricane is warm-core and because the absolute angular momentum tends to be conserved in the outflow layer. Figure 4c shows the circulation near 12,200 meters for hurricane Donna on 10 September 1960, the day on which the data of Fig. 4a were measured. A small cyclonic circulation continues at 12,200 meters, but an anticyclonic turning of the wind predominates as the air moves away from the center. South of the center a pronounced anticyclonic eddy appears, and at the low level definite cyclonic indraft occurs.

The primary hurricane circulation is horizontal in the r-θ plane (Fig. 4, a–c). Superimposed upon this flow, however, is a vertical circulation in the r-z plane, which is determined by the radial motion. Air flows into the hurricane through the inflow layer, then rises, principally in the region of the wall cloud, and finally sinks some distance from the hurricane. A small sinking motion also occurs inside the eye of the hurricane.

Thermal Structure

The hurricane is a warm-core, direct atmospheric circulation; that is, warm air rises and cold air sinks, thereby converting heat energy to potential energy and potential energy to kinetic energy. Calculations (*2*) indicate that in the average hurricane from 2.0 to 6.0×10^{26} ergs are liberated daily in the form of latent heat. Riehl (*6*) has compared the hurricane to a simple although very inefficient heat engine, since only about 3 percent of the total latent heat released is converted into kinetic energy. Much of the remainder is converted into potential energy and



exported through the outflow layer.

At a given pressure, warm air is lighter than cold. A rapid decrease in central pressure, extremely low pressure on the following day, and intense radial pressure gradients all result from the development and concentration of very warm air near the core of a storm.

Figure 5 shows the departures of the observed temperatures from the mean tropical atmosphere (*7*). The warming was maximum in the vicinity of the 12,200-meter level, where the temperatures were more than 10°C above normal. Strong radial temperature gradients were concentrated in a narrow band extending from the edge of the eye out to the exterior of the wall cloud, although little gradient was found in the eye itself, especially in the low levels. No positive anomalies outside the eye were found below 2440 meters. Patterns were similar in other storms, particularly in Daisy (1958) (*8*) and Hilda (1964) (*9*); in both, however, the temperature anomalies above 12,200 meters were substantially greater than those indicated by Fig. 5.

The warming of the upper level is caused by the oceanic heat source. In the absence of a surface heat source, air at lower levels (see Fig. 4a) should be cooled by adiabatic expansion as it flows into the center of an intense hurricane; the result is equal to a pressure drop of 50 millibars or more. Over the oceans the expected adiabatic cooling does not normally occur; inflow into a hurricane at sea level is almost isothermal. It was Byers (*11*) who first correctly interpreted this isothermal expansion as being made possible

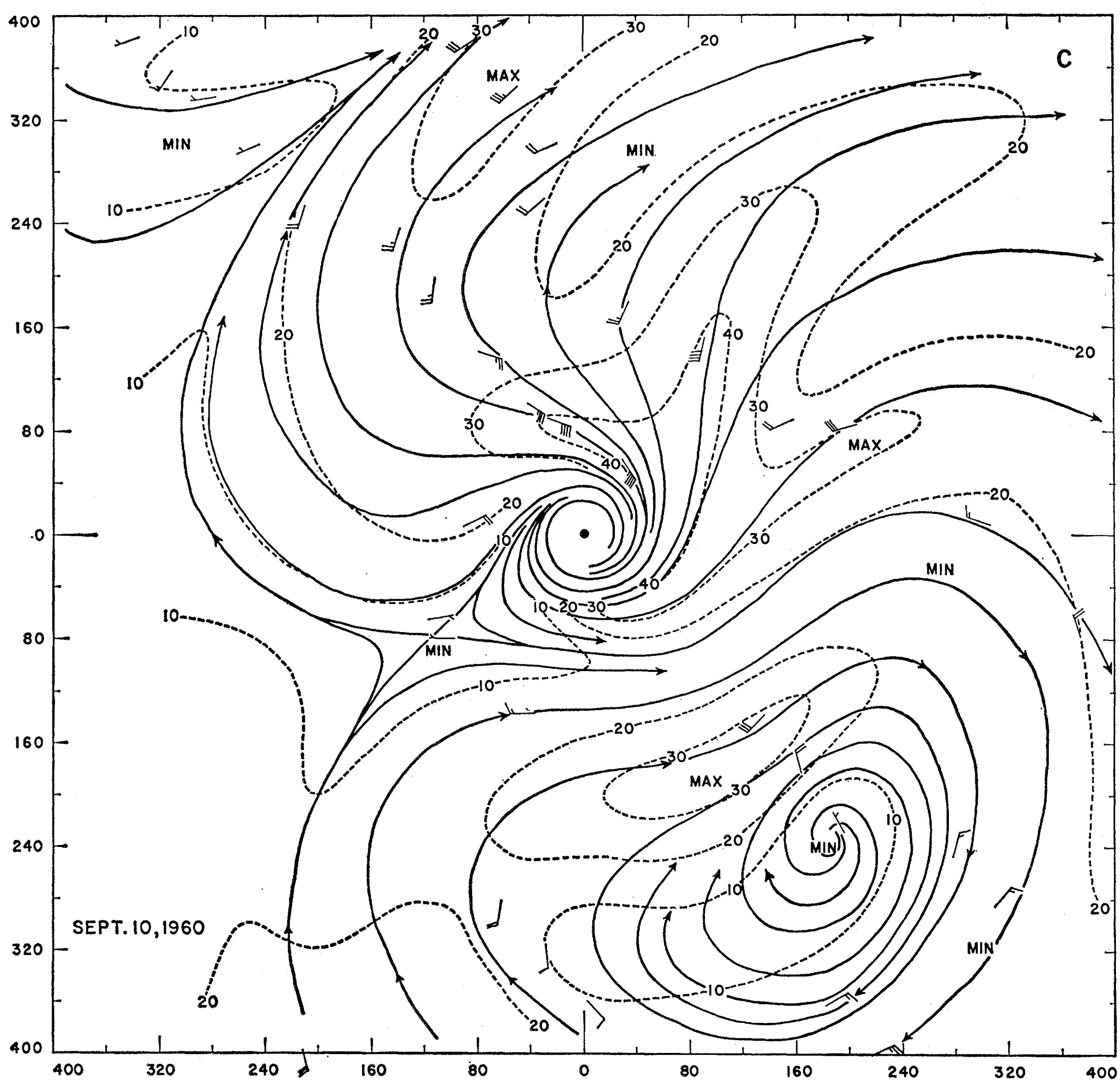


Fig. 4 (pages 1392–1394). Streamline (solid lines) and isotach (dashed lines) analyses showing hurricane circulations at three levels; wind speeds in knots. (a) Low-level circulation in hurricane Donna, 10 September 1960. (b) Hurricane Daisy at 4000 meters, 28 August 1958 (*8*). (c) Hurricane Donna at about 12,200 meters, 10 September 1960.

by the oceanic heat source, which adds sensible heat and moisture to the surface air as it spirals inward along its trajectory into the core of the storm. The equivalent potential temperature is determined by the temperature, moisture content, and pressure; thus the addition of heat and moisture at reduced pressure causes the equivalent potential temperature to rise. The equivalent potential temperature of normal tropical surface air is about 345°K, but this value may increase to 370°K or higher in the wall clouds of intense hurricanes (*12*).

If surface air ascended through an unstable atmosphere without any mixing with its environment, it would follow a moist adiabatic path along which the equivalent potential temperature would be constant. Mixing does occur, however, so that it is difficult to predict exactly how much warming should be expected to follow its ascent in the wall cloud. Figure 6 shows two ascent paths of surface air in hurricane Donna (1960), for equivalent potential temperatures of 353° and 374°K; the lower value characterized the surface air in Donna about 60 nautical miles from the center; the higher value was the best obtainable estimate for the surface air in the wall cloud. At 6100 meters, curve *A* is about 6°K warmer than curve *B*; at 12,200 meters, *A* is nearly 12°K warmer. Although mixing of the ascending air with the surrounding atmosphere could materially reduce these differences, the role of the ocean surface in producing the warm core of the hurricane is clear.

Calculations of the energy budgets of tropical cyclones (*12, 13*), in which the total energy (sensible heat, potential energy, and latent heat of condensation) is integrated over the volume occupied by the hurricane, have demonstrated that the hurricane *exports* more energy than it imports through its lateral boundaries; the additional energy must come from the oceanic heat source. Theoretical calculations (*14*) also show that an oceanic heat source is needed to produce the typical wind-temperature distributions observed in mature hurricanes. When a hurricane moves away from its surface heat source, isothermal inflow at the surface no longer occurs; the flow of the air into the center is more nearly along a moist adiabat—that is, cooling of the surface air does take place (*11*). Cooling of the surface air eventually results in decay of the hurricane as forced ascent of the cooled air in the interior destroys the warm core.

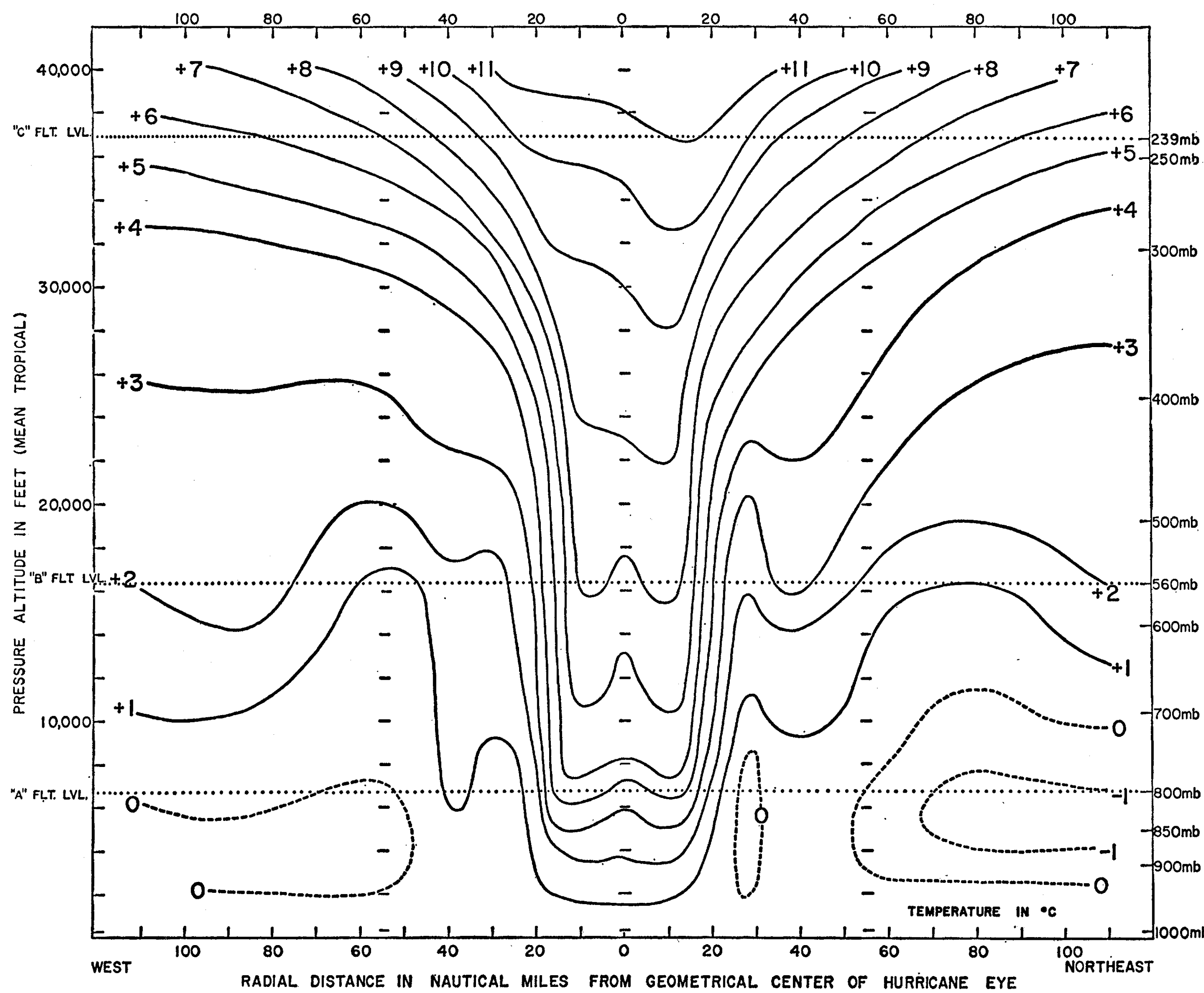


Fig. 5. Vertical cross section of temperature anomalies (°K) relative to mean tropical atmosphere; hurricane Cleo, 1958. [From La Seur and Hawkins (*7*)]

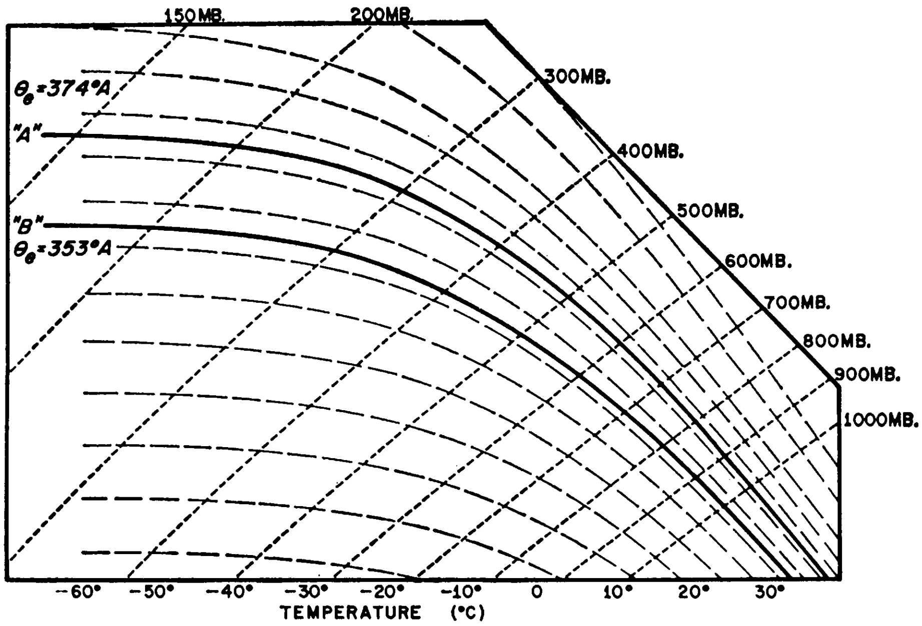


Fig. 6. Vertical temperature profiles following vertical ascent of undiluted surface air having equivalent potential temperatures of 353° and 374°K (absolute).

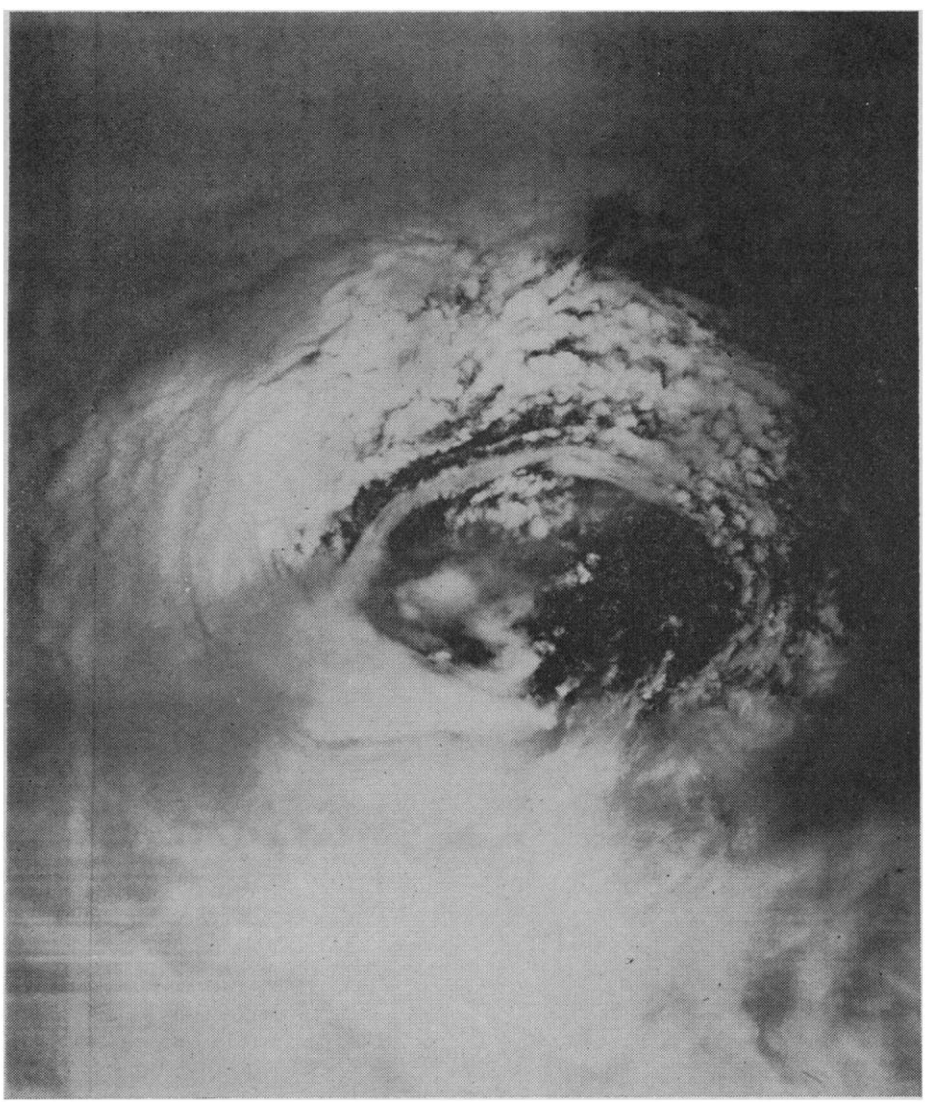


Fig. 7. Aerial photograph of hurricane Betsy, 2 September 1965, made from U.S. Air Force plane flying above 18,300 meters.

Cloud Systems

The strongest radial temperature gradients in a mature hurricane are concentrated within a narrow zone extending from the eye to the exterior of the large cumulonimbus wall cloud (*7*), within which much of the latent heat required to maintain hurricane circulation is released. Strong updrafts of 10 to 25 knots have been reported in these clouds, which are the channels through which the heat is carried upward. These convective elements fall into a spirally banded structure (Fig. 1). Gentry (*15*) estimated the amount of kinetic energy generated within the spiral rainbands, concluding that a significant portion of the total conversion of energy takes place there.

Although cumulonimbus towers are vital to heat transport, only a small percentage of the total area of the hurricane is covered with active convective elements. Malkus, Ronne, and Chaffee (*16*), for example, estimated that in hurricane Daisy only 1 percent of the area inside the 200-nautical-mile radius was covered by photographically well-defined cumulonimbus with tops higher than 11,285 meters on 25 August, the day the hurricane formed; the percentage had increased to 2.5 by the 26th and to about 4 by 27 August, the day of greatest intensity. In analyzing four hurricanes, Gentry (*15*) found that only about 20 percent of the area inside the 80-nautical-mile radius was covered with clouds capable of producing echoes on 3-centimeter radar; his data also showed positive temperature anomalies in less than 25 percent of the clouds that produced echoes, so that only about 5 percent of the area of each storm was occupied by warm, buoyant clouds.

Riehl and Malkus (*13*) and Gentry (*15*) suggest that the area covered by echo-producing clouds varies directly with the intensity of the storm. The number of active cumulonimbus, for example, increased by a factor of more than 3 during a 2-day period during the intensification of hurricane Daisy; this increase in areal coverage appears to render less likely mixing of the air rising in the wall cloud with unmodified tropical air. Even though mixing takes place between the rising air and the ambient atmosphere, the rising air near the core is mixed with modified tropical air—air with equivalent potential temperatures higher than normal. This shielding seems to permit something approaching undiluted ascent in narrow channels, or "hot towers" (Fig. 6), thus allowing greater warming at upper levels.

Figure 7 clearly shows the wall cloud and eye of hurricane Betsy; there are weak spots in the wall cloud to the right of the eye. The wall cloud is almost vertical, as in most hurricanes, a fact opposing an older belief that it was funnel-shaped, widening at the top. The eye is not completely cloudless, although no high cloudiness is present; in most cases a fair amount of low-level cloudiness is observed. Apparently the sinking motion in the eye does not normally extend all the way down to the surface of the ocean.

Figure 8 shows hurricane Gladys on 18 September 1964; it is a gray-scale simulation of the high-resolution measurements of infrared radiation made by Nimbus I. The eye of the hurricane is clearly visible, as is the cirrus shield, which the radiation data indicated was at an altitude of 10 to 14 kilometers. To the left of the cirrus shield is a relatively cloud-free area, probably indicating the sinking of air that had risen nearer the center of the hurricane. Outside this cloud-free area a band of convective clouds is seen to spiral into the storm.

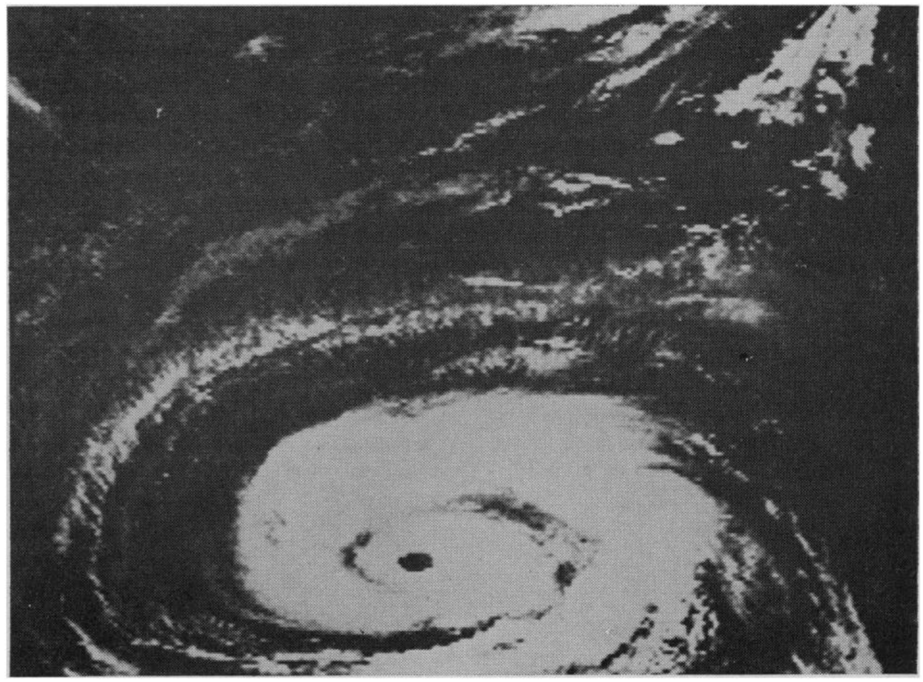


Fig. 8. Hurricane Gladys, 18 September 1964, as "seen" by infrared measurements by Nimbus I.

Formation of Hurricanes

Riehl (*17*) and Yanai (*18*) have recently discussed problems associated with the formation of hurricanes and typhoons. One may say that meteorologists know less about the formation of hurricanes than about their existence. The disturbances from which hurricanes grow occur almost daily somewhere over the tropical oceans, yet few develop into full-grown hurricanes. "The formation of a hurricane is a rare event, and we do not yet understand all the links in the chain which causes these events to occur" (*17*).

For example, a hurricane is known to form from some preexisting disturbance, but no one knows what distinguishes development from nondevelopment. Most of these disturbances are initially cold-core, and a disturbance must go through what Yanai called the "warming stage" before development begins. Heat is transported upward by the convective elements. Numerical models have demonstrated that in an unstable atmosphere the convective-scale motions grow while the larger-scale (hurricane) circulations do not. It seems reasonable to suppose that the energy is transferred from the cumulus-scale motions to the larger-scale hurricane circulations in a manner analogous to the eddy transfer of energy from the cyclones of the middle latitudes to the gross-scale general circulations of the atmosphere; but how this transport (which must be a turbulent process) is accomplished is not clear. Random distribution of convective elements will not result in growth of the disturbance; the convection must be "organized"—that is, transformed into the patterns characteristic of the spiral bands. How this organization begins, or why it originates in some disturbances and not in others, is not clear.

Certain features of the disturbance, however, are more favorable than others; in some instances where data are available these features can be identified. For example, increased low-level inflow into a disturbance is associated with intensification, and the mass transport into large storms is greater than in small or weak storms; but one cannot yet determine which came first—the increased inflow or the deepening. The location of the low-level disturbance under the western or southern edge of an anticyclone, at some upper level near 12,200 meters, is somewhat favorable for development, yet in some instances the disturbance began to develop below the upper-level cyclone, and the release of latent heat created its own high-level anticyclone.

Thickness greater than normal in the 500- to 200-millibar layer is favorable (*19*) for intensification. Since the thickness between two constant-pressure surfaces is a function of the temperature only, a pattern of greater thickness than normal can be interpreted as corresponding to Yanai's warming stage; the configuration of the thickness pattern just before the rapid development of hurricane Hattie is shown in Fig. 9. However, not all disturbances with warmer-than-normal air above them become hurricanes. Moreover, disturbances have been seen to start east of the Lesser Antilles early in the hurricane season, weaken sometimes between Puerto Rico and Bermuda, and then reintensify farther west; often the weakening stage could be associated with passage of the storm below a colder-than-normal 500- to 200-millibar layer, which fact supported the hypothesis that high-level warming is favorable to development.

Hurricane Control

Limited success in modification of precipitation patterns by seeding of clouds (*20*) has encouraged meteorologists to dream of the possibilities of eventual control of the weather.

Among the more challenging problems is possible modification of hurricanes. No serious-minded meteorologist yet believes that we can alter the structure or the energetic process of the mature hurricane, but it is probably equally true that no serious-minded meteorologist would question the wisdom of trying to do so. Some preliminary trials (*21*) have already produced rather ambiguous results.

It is axiomatic that, before one can undertake to tamper intelligently with a hurricane, one should understand how it works. The real missing link in our knowledge is the manner of hurricane formation, and it is perhaps this area that we should understand best before we begin serious attempts at modification. More basic research is needed before a sound working hypothesis for hurricane control can be formulated. Concentrated efforts to acquire such data are now being made by NHRL.

Because of their irresistible urge to move northward away from the tropical oceans, hurricanes transport large quantities of heat toward the pole, helping to maintain Earth's heat balance. Many hurricanes do more good than harm by bringing much needed rainfall. Perhaps a realistic goal in hurricane modification should be the weakening of destructive forces without changing the beneficial aspects.

Summary

Tropical cyclones derive their energy from the release of latent heat of condensation; they have been compared to simple heat engines (*6*), although they are not very efficient ones since only about 3 percent or less of the heat released within the cyclone is converted into kinetic energy. Tropical cyclones are warm-core, direct circulations in the sense that ascent takes place at warmer temperatures than does descent, thus converting heat energy into potential energy and potential energy to kinetic energy.

The outstanding characteristic of the tropical cyclone is the ring of concen-

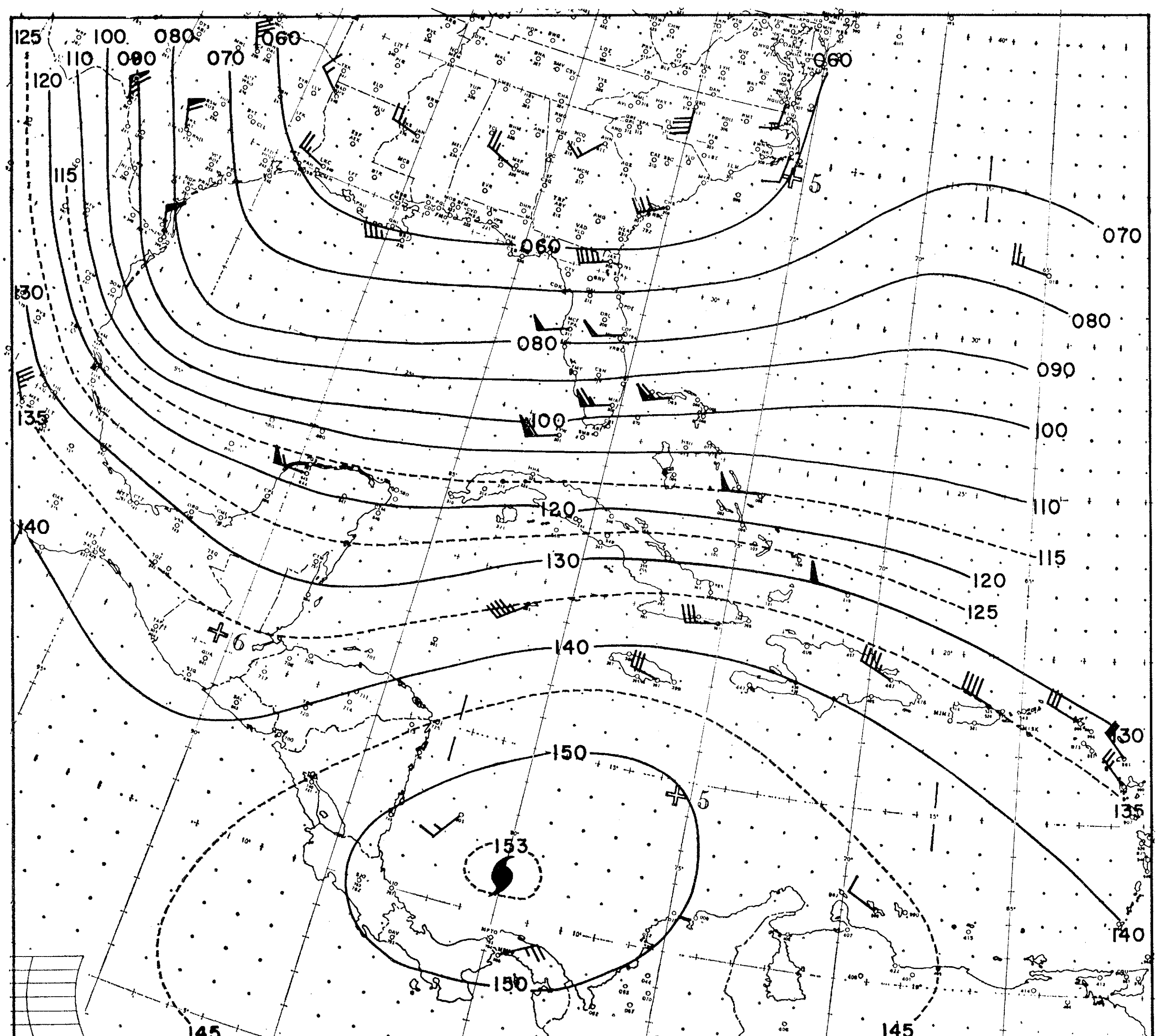


Fig. 9. Thickness chart for the 500- to 200-millibar layer. The hurricane symbol marks the center of the tropical depression which is about to intensify rapidly (*19*).

trated winds of maximum force surrounding the eye; there winds are almost constant, their speeds frequently exceeding 240 kilometers per hour. In the high-energy core of the storm, wind speeds change but little in the vertical through the first 6100 meters above the ocean; higher, winds usually decrease, change direction, and may become anticyclonic. The decrease in speed and turning of the winds are caused by the warm core and by the tendency for the absolute angular momentum to be conserved at higher levels.

Air flows into the center at low levels, rises near the wall cloud, and then flows outward at some upper level, usually around 12,200 meters in a mature hurricane. The low-level inflow is controlled largely by the frictional forces resulting from the shearing stresses exerted by the winds upon the ocean surface.

The greatest temperature anomalies are found in the upper levels (10,675 to 13,725 meters), where temperatures are frequently 10°C or more above normal. The greatest radial temperature gradients occur in the region extending from the eye outward to the exterior of the wall cloud. The warm core of the hurricane, created along with development of the storm, results from warming of the surface air and the addition of moisture by the oceanic heat source.

Many features of the tropical atmosphere that favor formation of hurricanes such as increased low-level inflow, above-normal warmth in the upper troposphere, and the existence of an anticyclonic circulation at some upper level over a low-level cyclonic disturbance, have been identified. Meteorologists know less, however, about the mechanics of formation of hurricanes than of any other phase of their existence.

The possibilities of controlling hurricanes are intriguing. Project Stormfury, a joint undertaking by ESSA and the U.S. Navy, is designed to explore ways of modifying hurricanes. No fully satisfactory hyopthesis for the control of hurricanes yet exists, and formulation of such a hypothesis may have to await better understanding of the manner in which hurricanes form.

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The Nucleon-Meson Cascade and Shielding

When a high-energy particle passes through matter, a nucleon-meson cascade develops.

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With the advent of very-high-energy accelerators and manned space flight, shielding against high-energy particles, of energy of the order of 100 million electron volts (1 Mev = 1.6×10^{-6} erg) and greater, has become of increasing significance. While the cost of the shielding is only a small fraction of the cost of a large accelerator, it is high enough so that one cannot afford the luxury of overshielding. Furthermore, the massive shields required for large accelerators often interfere with other desirable design features, and this interference can be kept to a minimum only by careful shield design. In the case of manned space vehicles, weight limitations are very severe, and it is obvious that shielding must be kept to the minimum consistent with adequate protection against radiation.

In both accelerator and spacecraft shielding, the determination of the intensity, energy, and kind of radiation incident on the shield is an important part of the shielding problem, but usually this incident radiation is determined by considerations which cannot easily be influenced. For instance, in the case of accelerators this radiation is determined by such things as the manner of acceleration and the fraction of the beam that strikes the walls of the accelerator during the acceleration cycle, whereas in the case of manned space flight the incident radiation is determined by such considerations as the duration of the flight and the orbit flown.

If the incident radiation is assumed to be known, the shielding problem is to determine the thickness of shield that will reduce this radiation to an acceptable level—that is, to a level which is considered to be not detrimental to a mammalian system. In general, it is not feasible to solve all shielding prob-

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