Canaveral Harbor

Part 1

WIND, WAVES, AND WIND TIDES

Daytona Beach

CHAPTER 1

WINDS AND PRESSURES IN HURRICANES

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The hurricane is one of the most dangerous and at the same time one of the most interesting weather phenomena with which the citizens of the United States have to deal. We have more hurricanes on our southern and eastern seaboards than any other major continental area, except Southeast Asia (1, 2). These storms of course are very familiar to certain Island countries: Cuba, Haiti and the Dominican Republic, Japan, the Philippines. Mexico and Australia receive their share also.

Under Congressional directive the Weather Bureau in collaboration with other Federal Agencies and universities is at the present time pursuing an expanded program of research on hurricanes, termed the National Hurricane Research Project (3). The most spectacular phase of the program are the reconnaissance flights of three especially instrumented Air Force aircraft assigned to the Project base at West Palm Beach, Florida. These planes, especially during the hurricane season just ended, have gathered some very excellent data on the structure of hurricanes, superior in detail and reliability to anything available before. However, the aircraft for safety reasons do not fly near the surface, and the surface winds and sea-level air pressures are the factors of immediate concern to coastal engineers. The stress of surface winds produces surges and waves in bodies of water, and the sea-level pressure deficit in the inner part of a hurricane permits a corresponding rise in the water level by hydrostatic equilibrium principles. It will be some time, perhaps several years, before more refined models of the surface layers of hurricanes can be deduced by indirect analysis from the West Palm Beach data.

This paper will summarize some of the pertinent information available up to now on surface winds and pressures and will make no further reference to the West Palm Beach investigations. There will also be a brief treatment of rainfall in hurricanes which is of interest to coastal engineers because of flooding produced by rain-water behind seawalls and in estuaries where a flood can result from an abnormal tide or an abnormal stream flow or both at the same time.

ENERGY SOURCE

We shall pass over how a hurricane starts except to say that it is always over warm ocean waters and always in an area of squally weather and take a look at what makes it keep going once it has started. Descriptions of the formation and life cycle of hurricanes are given by Tannehill (4), Dunn (5), and Rhiel (6). The key to hurricane

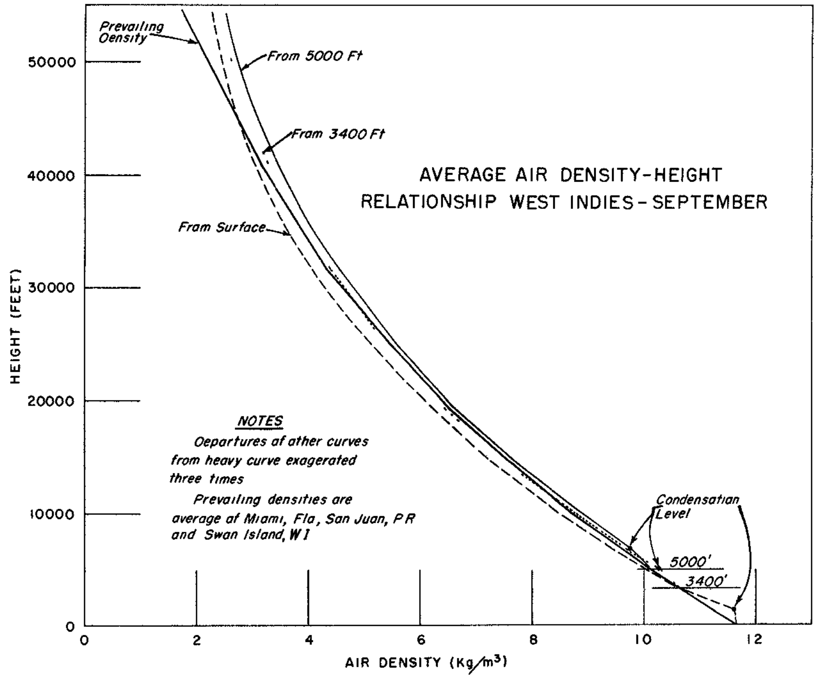


Fig. 1

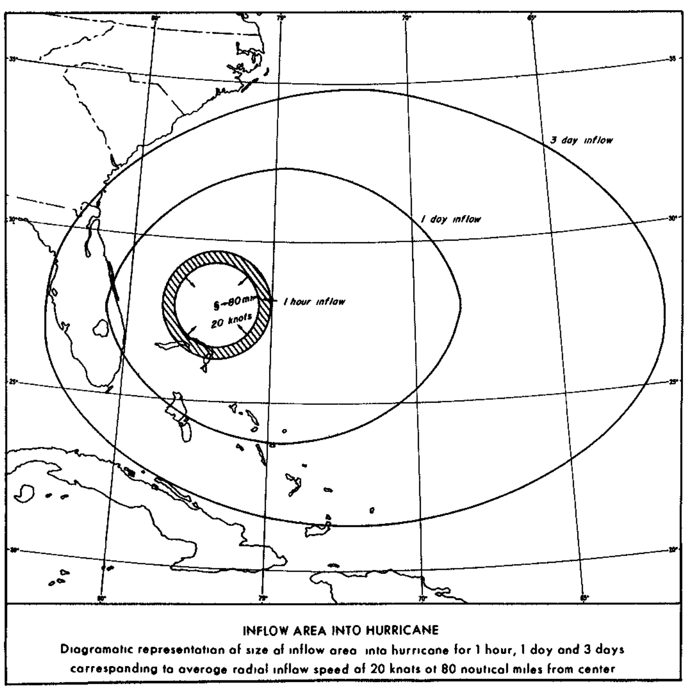


Fig. 2. Schematic diagram of inflow area into a hurricane.

energy is the vertical distribution of air density, which is, in turn, related to temperature and moisture content. The solid curve of figure 1 shows average air density vs. height in September in the West Indian tropics, based on atmospheric soundings at Miami, San Juan, P. R., and Swan Island (7). At the first glance it looks like a stable arrangement; every layer of air has a smaller density than the layer immediately beneath and therefore will tend to float on top of it. Next we must consider how air behaves when it changes elevation. Rising air encounters progressively lower pressure and therefore cools adiabatically. There is one standard well known rate of cooling for unsaturated air. There is a different rate for saturated air because the release of latent heat decreases but does not overcompensate the adiabatic cooling. Now let us consider what will happen if a square mile or so of a layer of air near the ocean surface should somehow be lifted through its environment. The density this lifted surface air would acquire at each level is shown by the curve with long dashes in figure 1. The density decrease is first along the unsaturated adiabatic rate to the condensation level and then along a standard curve for saturated air. It is seen that this air at about 3000 feet will become less dense than its environment (heavy solid curve); it will then of course continue to rise spontaneously to great heights, perhaps over 40,000 feet. Similar curves of the density changes associated with lifting are shown for a 3,400-ft parcel, which contains very little of this potential relative density decrease (called latent instability) and for a 5,000-ft parcel which contains none. When a hurricane forms, layers of air rather close to the surface of the ocean break through the slightly stable layer above to the level when they can rise spontaneously. Once this great chimney of convection (perhaps 50-100 miles in diameter) has been established the hurricane will maintain its vigor and will continue to drift so long as it can feed on air of the proper vertical density distribution. The air processed by the hurricane is drawn from a large area. This is shown in figure 2. The figure shows schematically the size of area required to feed air to a hurricane for an hour, a day, and for three days. The figure is based on an average component of the surface wind of 20 kts toward the storm center at a distance from the center of 80 miles. This is a moderate value of the inflow rate. Another way of emphasizing the vast low-level indraft and high-level outflow needed for hurricane maintenance is to look at the distortion of a cube of saturated air several miles on a side required to produce one, two, and five inches of rain. This is shown in figure 3.

The latent instability necessary for hurricane formation requires a strong heat and moisture source at the bottom of the atmosphere, occasioned by strong insolation and warm sea-water. On the other hand, the stabilizing subsidence, or settling, of the atmosphere that is always found in large high pressure areas must be absent. These factors limit the seasons and places that hurricanes may

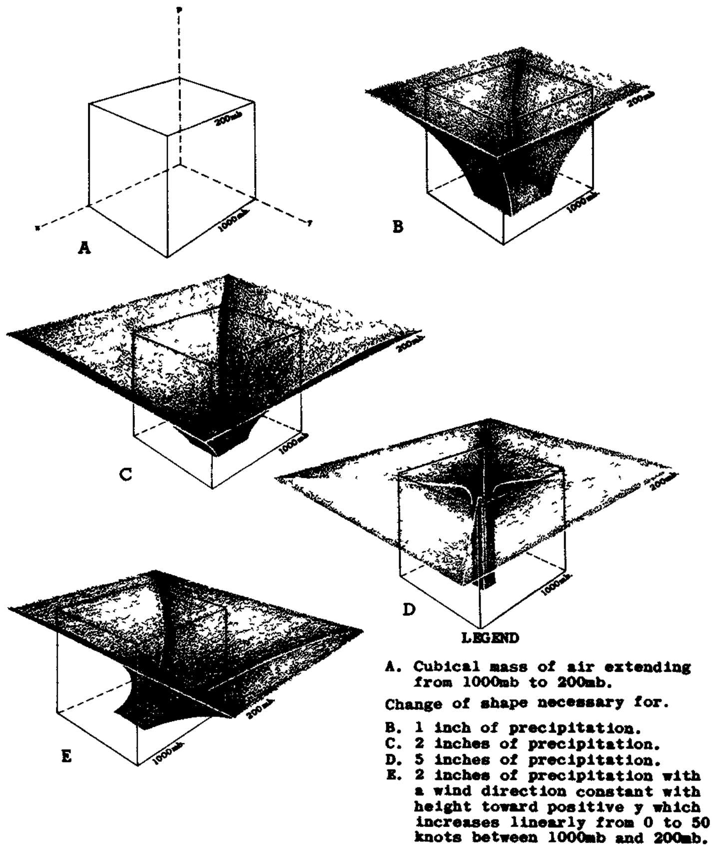


Fig. 3. Change of shape of cubical mass of air necessary for various rainfall amounts.

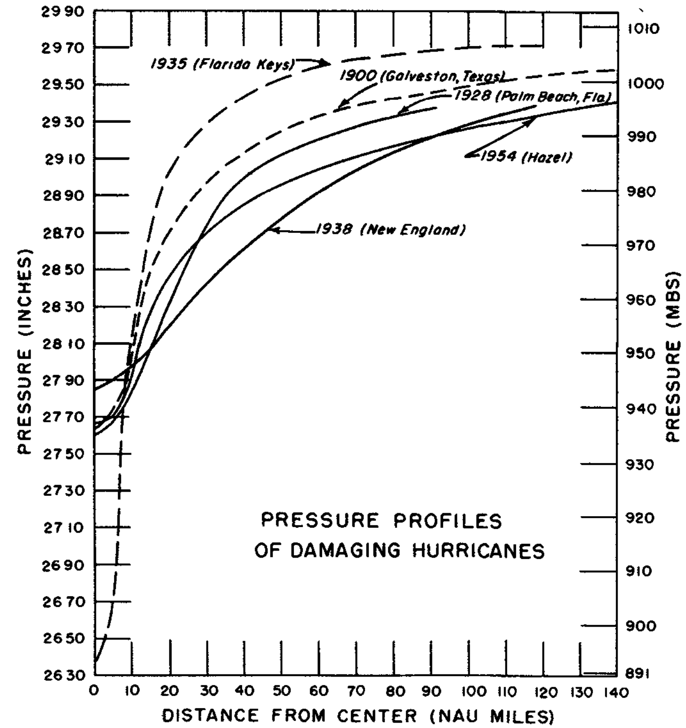


Fig. 4. Pressure profiles of damaging hurricanes.

form. The United States hurricane season is mid-June to mid-October, approximately. In this connection it should be noted that the highest water temperatures in the hurricane genesis areas of the Atlantic and Gulf of Mexico lag behind the most intense insolation of June and July and do not occur until August or early September.

If relatively dry air is drawn into a hurricane, the storm must weaken. If it moves over extensive land it will die because among other things the friction upsets the delicate balance between the vast indraft required of the surface layers and the compensatory upper outflow; if it turns into a more northerly latitude it may acquire an additional energy source namely, a non-homogeneous horizontal density distribution; colder air sinking on one side of the storm and warmer air rising on the opposite side. Usually in such cases there will be a temporary increase in energy followed by a decrease or at least a dispersion of the concentrated kinetic energy (winds) of the hurricane.

PRESSURES

In discussing winds and the pressures in hurricanes, we prefer to present the pressures first because the data are easier to handle. Hurricanes are not quite circular but are frequently considered so for purposes of analysis of the pressures. Figure 4 shows radial profiles of sea level atmospheric pressure for several famous hurricanes. In the center of the storm the pressure can fall to values 6 to 10% or more below normal atmospheric pressure. The tremendous horizontal pressure forces acting inward in a hurricane are balanced in largest measure by the centrifugal force, to a lesser degree by friction and by the coriolis force from the earth's rotation; and then, of course, there is not a complete balance of forces; the inward-moving air parcels are accelerated.

Frequently it is convenient to have an analytical expression that approximately describes the usual shape of a hurricane pressure profile. Such an expression is:

$$P = P_o + (P_n - P_o)\ e^{-R/r} \qquad (1)$$

where P is the pressure at radius r, P_o the minimum pressure at the center of the storm, P_n the pressure "outside" the storm, (theoretically at $r = \infty$) and R is a characteristic radius. An alternate form is

$$P = P_n - (P_n - P_o)\ (1 - e^{-R/r}) \qquad (1a)$$

Equation (1) has been found empirically to fit a good many hurricanes fairly well (8). One application of this expression by the authors of this talk and their colleagues was to estimate systematically the central pressures of all hurricanes affecting the United States since 1900 by plotting all observed pressure data at the appropriate distance from the center of the hurricane on a radial profile, such as those of figure 4, and then extrapolating into distance zero by fitting a curve described by the formula (9). The accumulated frequenc of central pressures of hurricanes affecting the eastern United Stat Coast obtained in the manner just described is shown in figure 5, sep arated into regions. All of the central pressures are at the point storm center entering the coast.

These regions are the Florida Keys, the Florida Peninsula, th Texas Coast, The Gulf Coast from the Texas-Louisiana border to Apalachee Bay, and the Atlantic Coast from Georgia to just south of Cape Hatteras, and the Atlantic Coast from Cape Hatteras northward. Clea ly the Florida Keys experience the lowest pressures in hurricanes. the other curves there is a suggestion of a latitudinal variation wit lowest pressures in the south but the data do not demonstrate this conclusively.

There is a considerable range in the reliability of the centr pressure estimates on which figure 5 is based. The factor having mo influence on the reliability of the central pressure estimate for an individual storm is the length of radius from the storm center to th closest pressure observation.

WINDS

Relation of maximum wind to central pressure

The central pressure of a hurricane is a convenient though so what approximate index of the strength of the storm. An expression for the maximum wind in a hurricane which has some both empirical and theoretical support is of the form (9), (10), (11), (12):

$$V_x = K\sqrt{P_n - P_o}, \qquad (2)$$

where P_o is the central pressure; P_n the pressure outside the storm; the highest wind speed. With wind speed in knots and pressures in mi libars, average values of K in the August 1949 hurricane at Lake Okee chobee were 7.5 for off-shore winds averaged over 10 minutes, 9 for o shore winds, and 14 for peak on-shore gusts (12).

Lake Okeechobee 1949 hurricane

Perhaps the best detail of surface wind observations in a hurr cane anywhere was in the hurricane of August 26-27, 1949 which crosse Lake Okeechobee, Florida. The Corps of Engineers, charged with the d sign, construction, and operation of protective levees around this Lake, for data gathering purposes established a special meteorologica network in the area (13). There are seven autographic wind and pressure stations on the shore of the Lake, which is some 30 miles across at the time of the 1949 hurricane there were three such stations moun ed on navigation--light pylons out over the water surface of the Lake These data have been intensively studied by the Weather Bureau and th

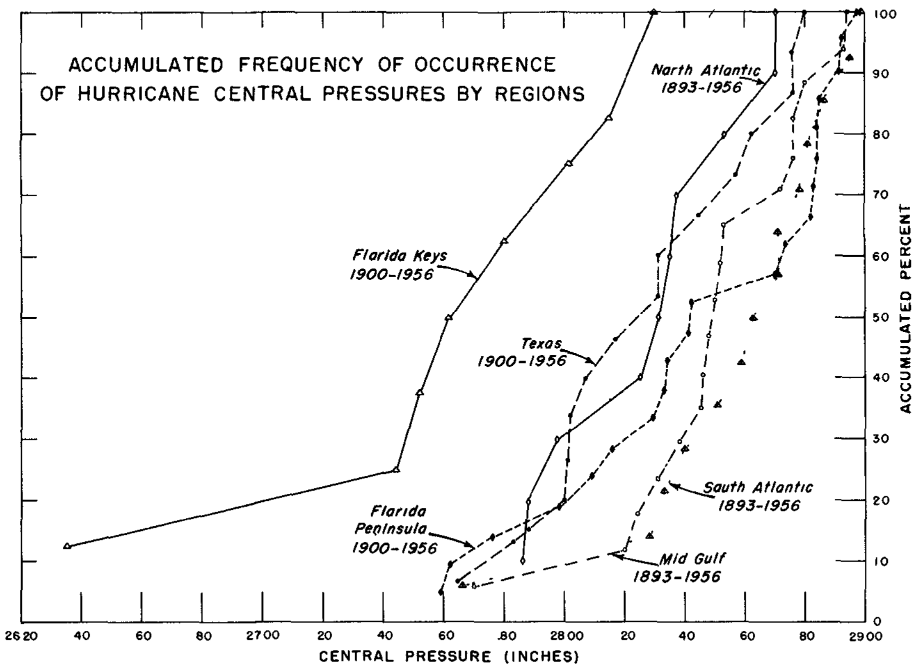


Fig. 5. Accumulated frequencies of hurricane central pressures by regions.

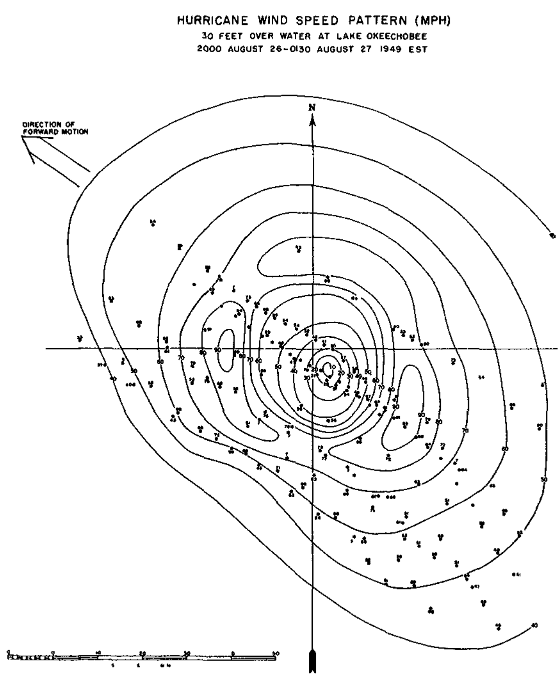


Fig. 6. Hurricane wind speed pattern, August 26-27, 1949.

Corps of Engineers in connection with a design study by the latter agency. Figure 6 shows a map of the wind speeds in the 1949 hurric as it crossed the Lake. This is a composite picture of all 10-minut average wind speeds during a total elapsed time of about 5 hours. Each speed is plotted at its bearing and distance relative to the c ter of the hurricane. Adjacent data do not always match in part be· cause of inaccuracies of factors used to adjust speeds to a common frictional surface, but also because the wind field of a hurricane i far from unvarying. Superimposed on the overall wind pattern depict ed here by the solid isopleths are gust-type variations of all kinds of scales from a few yards and fractions of seconds of time up to 1C or 20 miles and twenty or thirty minutes. Radar has revealed that there are spiral bands in hurricanes where the rainfall is heavier than other places. The wind directions and speeds may show a slight discontinuity at these bands. Note that the band of highest wind speeds is not a smooth symmetrical circle; the most extreme speeds a generally found somewhere on the right side of the storm though ther seems to be considerable variation from one storm to another as to the exact bearing from center of the highest speeds.

Applications of 1949 hurricane data

The average radial profiles of wind speed in the same Lake Okeechobee hurricane are shown in figure 7. From this diagram illus trates several things: First, the curves show the typical general shape of the wind profile for a severe hurricane, gradual rise in speed from the outskirts to a maximum value at some point at a radiu of about 22 miles in this case and then a sharp decrease in speed to almost calm conditions at a center of the wind circulation. Secondly, the curves show the variation of hurricane speeds over different kinds of frictional surfaces. The lowest three curves are for 10-minute average speeds at Lake Okeechobee, respectively for off-land winds at the shore, off-water winds, and over-water winds. The last is from the speeds measured at the pylons in the Lake several miles from shore. Empirical factors from these three curves have been use for adjusting hurricane wind speeds measured over land along much of the coast of the United States to over-water values. We have been able to make a few supplementary wind speed comparisons of limited a plication; these include comparing Nantucket Island, Mass. with Nantucket Light Ship, the Friendship International Airport at Baltimore with speeds at the Chesapeake Bay Bridge, and the New Orleans Weathe Bureau Office with speeds at the Huey Long Bridge. There are a few other pairs of nearby stations that have not been fully exploited data-wise yet.

The third deduction from figure 7 is the relation of gusts to sustained speeds. The two top curves are smooth plots of the highes point in each 10-minute interval on a wind speed trace from the Dine pressure-tube type of anemometer. The gust defined in this way averaged about 1.4 of the sustained 10-minute average speeds. Probably the most satisfactory way to analyze hurricane wind fields for engineering purposes is to make the basic analysis in terms of sustained average speeds over 5, 10 or 15 minute intervals. For building design appropriate gust factors are applied to these mean speeds.

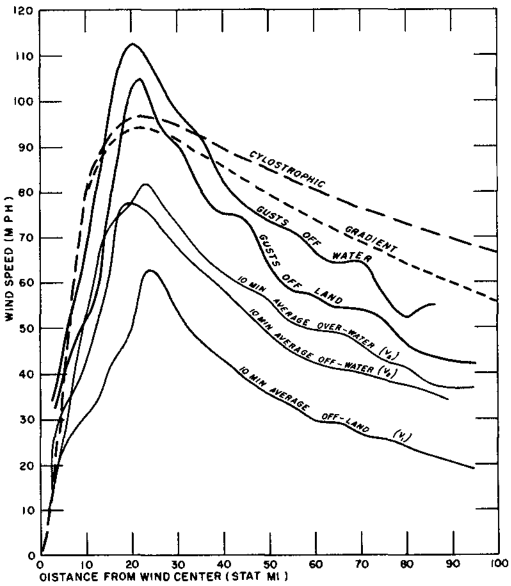


Fig. 7. Hurricane wind speed profiles August 26-27, 1949.

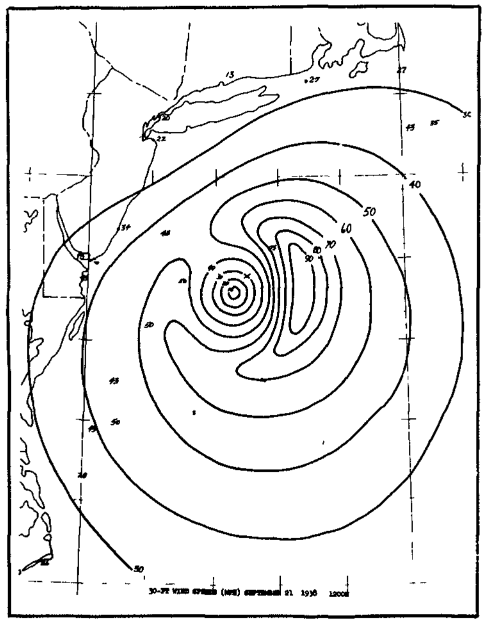
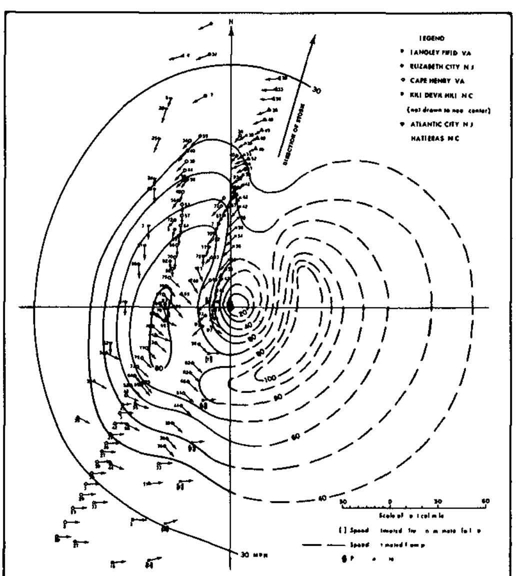


Fig. 8a



HURRICANE OF SEPT 14 1944 WIND SPEEDS (MPH) AND DIRECTIONS NEAR CAPE HATTERAS
Speeds plotted relative to pressure center and adjusted 30 ft over open water and 0820 EST strength of storm

Fig. 8b

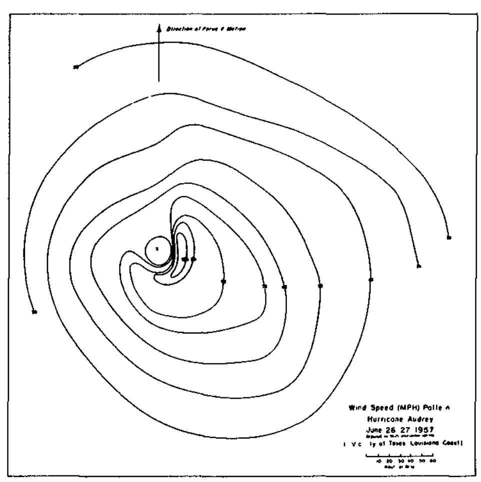


Fig. 8c

Fig. 8. Hurricane wind fields over the sea.

A fourth deduction of engineering usefulness from figure 7 is the relation of the actual winds to theoretical winds computed from the pressure field. The dashed curve is the so-called gradient wind which is the speed necessary for the pressure gradient force, centrifugal force, and coriolis force from the earth's rotation to be in balance. Wind fields in other hurricanes have been reconstructed by computing the pressure fields from pressure observations and then computing the gradient wind and reducing to actual wind by empirical factors derived from this diagram. The Hydrometeorological Section of the Weather Bureau has reconstructed the wind fields in a number of hurricanes along the coast for the Corps of Engineers (/14/for example). The purpose is for a check-out of procedures for computing the hurricane surge in the various coastal reaches from the winds. In almost none of these reconstructed hurricanes, even for so recent hurricanes as Hazel of 1954 and Audrey of 1957 has there been much wind data available over the water surface itself where the wind fields are needed and considerable reliance has had to be placed in estimating winds from pressure by the Lake Okeechobee empirical factors and in adjusting winds at land stations. A few of these wind fields for certain famous hurricanes are depicted in figure 8.

The great size of hurricanes warrants emphasis. As can be seen from figure 8 a typical hurricane is hundreds of miles across; it also extends several miles vertically. A hydrogen bomb is small compared to the total kinetic energy of a hurricane.*

Trajectory method for hurricane wind models

There are few wind data on the right side of the Lake Okeechobee hurricane; it is here that the highest winds in the storm are thought to occur. Composite patterns of the wind flow in hurricanes obtained by combining data from a number of storms by Hughes (15) and others give good pictures of the nature of the flow in the outer parts of the storm but are lacking in the detail necessary for surge studies in the zone of maximum winds near the center. To refine our empirical wind model from the Lake Okeechobee hurricane, especially with respect to the asymmetry of the wind field, at present we are experimenting with synthetic wind fields constructed by a trajectory method. Starting with low-speed winds on the outskirts of a hurricane, the accelerations of the air are computed from the estimated forces (real and apparent): pressure gradient, centrifugal, coriolis force, and friction. Horizontal motion at 30 feet is assumed and the work is

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*The kinetic energy of the winds of a typical hurricane has been estimated as about 5 x 10^{26} ergs at any one time. The mechanical equivalent of the energy released by a bomb equal to 10^{7} tons of TNT is about 1/1000 of this.

restricted to this anemometer level. The resulting trajectories of air parcels are computed. The friction is the so-called eddy stress and incorporates the transfer of momentum from one level to another by turbulence. Empirical values of the friction are being developed by comparing computed trajectories in the same Lake Okeechobee hurricane with trajectories reconstructed from the data. It is interesting to note that at the 30-foot level the effects of stress have a component not only opposite to the mean wind but also a component normal to the direction of the mean wind that is almost as large. This is due in part to the fact that the effects of the turbulent components of the wind are not linear and do not cancel out.

Variation of wind with height

The variation of wind speed with height is directly applicable to building construction rather than to work with bodies of water but is indirectly used in the latter instance when observed wind speeds at various anemometer levels are adjusted down to the standard 30-foot surface. The best available data on the variation of wind speed in hurricanes up to heights of several hundred feet were obtained at the Brookhaven Laboratory wind tower on Long Island where winds at three or four levels were measured with laboratory-calibrated anemometers in hurricanes Carol and Edna of 1954 (16). At the top of the tower at 410 feet winds almost up to a hundred miles an hour were observed in Carol. The variation of wind speed with height in the two hurricanes was about the same and is depicted in figure 9. The Brookhaven curves should tentatively be regarded as showing the extreme of the variation with height. The increase of speed with height at Lake Okeechobee in an October 1953 tropical storm, as measured by the Jacksonville District of the Corps of Engineers (13), was relatively smaller. Other data at lower speeds from other wind tower sites also indicate that Brookhaven has a relatively large wind speed increase with height. It is assumed that the surface there is dynamically relatively rough.

Wind direction

The overall average anemometer-level wind direction in a hurricane at sea is about 25° to 35° to the left of a tangent to a circle drawn about the storm center. There are variations in this angle from quadrant to quadrant and between storms. This vast indraft or convergence compensates vast updrafts, strongest in the region of maximum winds outside the eye. There are turbulent departures from the mean direction at all times in all parts of the storm which obscure the systematic variations of this angle of deflection which probably exist from front to rear and left to right. It is hoped that our trajectory studies will yield a more refined model of the wind direction in hurricanes, especially the variation from one quadrant to another.

WEAKENING OVER LAND

The next topic is weakening of hurricanes over land surfaces. This is of importance to coastal engineers concerned with inland bodies of water such as Lake Okeechobee, Lake Pontchartrain, Chesapeake Bay or even New York Harbor. At New York City the extreme surge presumably would be associated with a hurricane moving inland over New Jersey and having some over-land trajectory before reaching the latitude of New York.

The critical hurricane path for the worst surge for the places named, of course, is not a track along the shortest distance to the sea, but rather a track that will give the longest duration of winds from the critical direction.

It is a common observation that the winds decrease markedly as a hurricane moves inland. We should distinguish carefully between tw different effects in this connection. First, for a storm of a given intensity of pressure gradient, the surface wind will be less over th land surface than on the open coast because of the greater impedance of the surface roughness. The other effect is a weakening of the pressure gradient itself. If only the former effect dominates, then a hurricane approaching Lake Okeechobee or Lake Pontchartrain could be expected to regain its over-water vigor over the Lake.

Survey of a large number of hurricanes suggest the following. First, that the decrease in intensity of hurricanes over land is part ly a frictional effect, and partly because the hurricane frequently encounters drier air which is less favorable for its maintenance. Over the Florida Peninsula, where in general during hurricane weather the air will be just about as humid as over the sea, there may be ver little decrease in the overall intensity of a storm, only the immediate surface-layer winds decrease. There are individual variations. In 1930 a small-diameter but very intense hurricane was very destructive in the Dominican Republic. The center passed directly over the Island including some rather rugged terrain (4). The storm did not amount to much after leaving the Island. Two years earlier the center of an intense hurricane passed directly over the Island of Puerto Rico, and then continued but little diminished, if any, to the Florid coast and produced the famous Palm Beach and Lake Okeechobee disaster. This of course was a larger hurricane and a smaller island with lower mountains than in 1930. The Florida 1947 hurricane was the most seve of the last decade in this area. It passed close to Miami (over Ft. Lauderdale), diminished in intensity a little as it crossed the Flori Peninsula, but then regained its strength over the Gulf, passed over New Orleans with great intensity. Some average empirical factors for weakening of hurricanes over land have been developed and are listed in Table 1.

RAIN

The final consideration for hurricanes is rain. The release o latent heat and rain is a necessary and always present feature of the storm in the tropics though it will not necessarily rain heavily in every quadrant of the storm during every hour. To further augment the flooding risks from hurricane rains it not infrequently happens, especially with hurricanes moving up the Eastern Seaboard, that there are rather heavy rains a day or so in advance of the arrival of the actual storm circulation itself and therefore the rain immediately associated with the hurricane may fall on already swollen streams. This combination prevailed, for example, in the September 1938 hurricane in New England and more recently in hurricane Diane of 1955. The Diane flood, of course, was further augmented by a previous hurricane only ten days before.

Tropical storms of less than hurricane intensity on the average give almost as much rain as hurricanes. Extensive hurricane rainfall statistics have been compiled by two of our collaborators. A few samples will be shown.

A typical isohyetal pattern for a storm moving up the East Coast, is shown in figure 10 and three similar isohyetal patterns for East Texas--Louisiana hurricanes in figure 11 (17). Time distributions of heavy hurricane precipitation are illustrated in figure 12. These are for the heaviest 12-hour precipitation at a U. S. Weather Bureau recorder station within 30 miles of a hurricane center on the middle Atlantic U. S. coast. These were suggested as prototypes for an interior drainage design problem behind a sea wall at Norfolk, Va. Figure 13 shows the penetrations of hurricane rains inland. This envelopes all hurricanes since 1900 excepting a 1915 Texas hurricane and Hazel of 1954. Both of these joined up with fronts and became sort of combined frontal and tropical storms. Both carried 5" isohyets much farther inland than shown here.

Table 1

AVERAGE FACTORS FOR REDUCING HURRICANES FOR FILLING OVER LAND

Time (hours)	Adjustment ratio for wind speed
T (at coast)	1.00
T + 1	0.93
T + 2	0.88
T + 3	0.85
T + 4	0.82
T + 5	0.80
T + 6	0.78
T + 7	0.76
T + 8	0.74

The factors in Table 1 will yield speeds for portions of the storm that are still over water. Further reductions would be required to obtain the speeds over land.

Based on observed pressure changes in eleven hurricanes that entered the United States and equation (2).

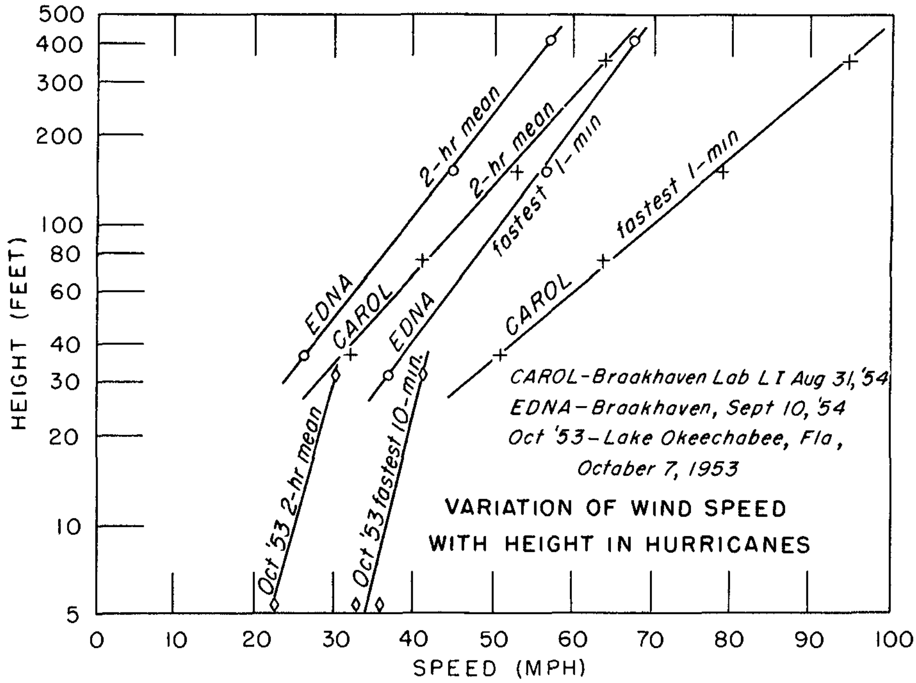

Fig. 9. Variation of wind speed with height in selected hurricanes.

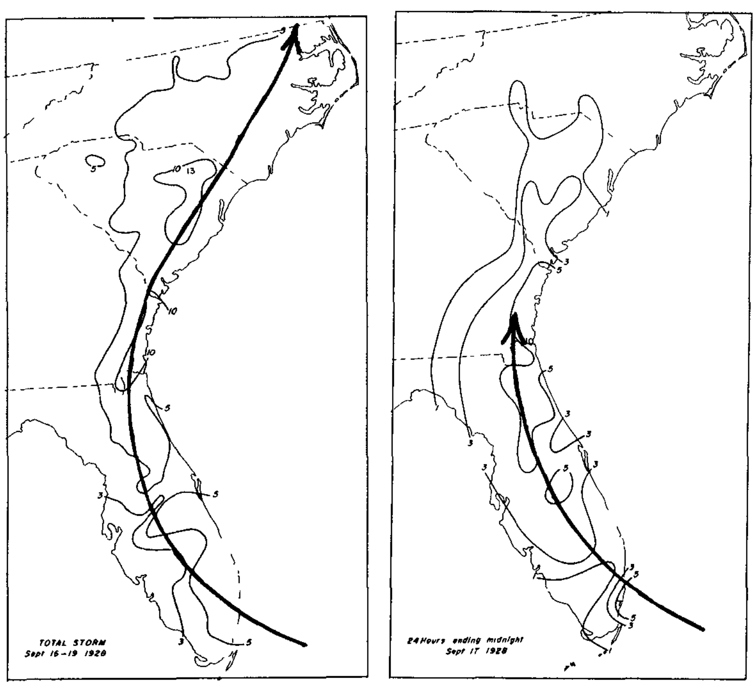

Fig. 10. Typical isohyets (inches) for East Coast hurricane.

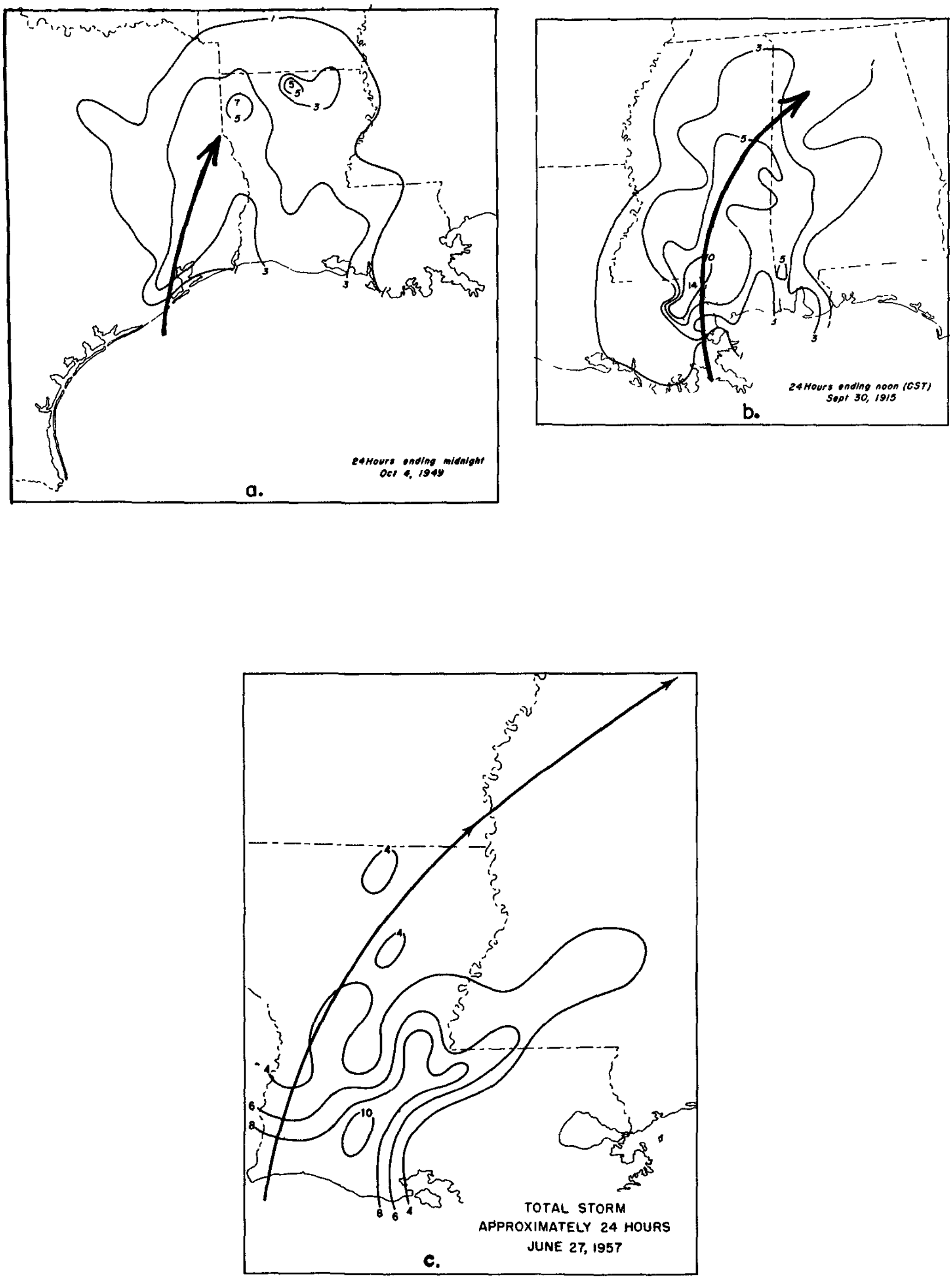

Fig. 11. Typical isohyets (inches) for Gulf Coast hurricanes.

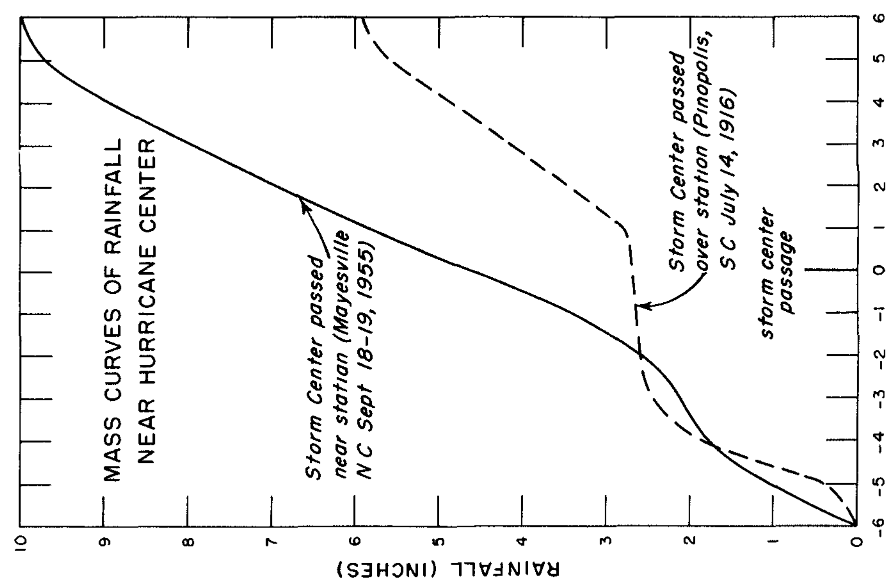

Fig. 12. Typical mass curves of rain-

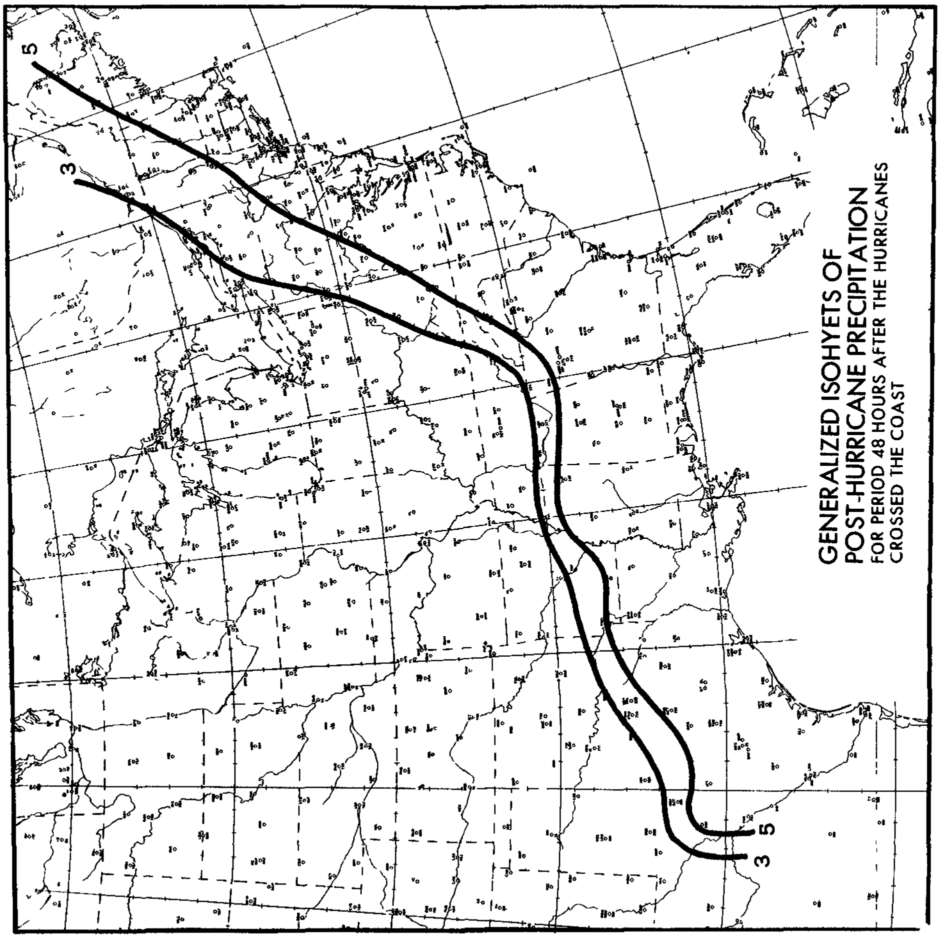

Fig. 13

WINDS AND PRESSURES IN HURRICANES

SUMMARY

Hurricanes are vast, somewhat circular storms that originate only over ocean areas at seasons of strong insolation and warm water temperature, but which frequently move over land. The immediate driving force to the winds is the horizontal pressure gradient directed toward the low pressure always present at the center of the storm. The ultimate source of energy in the tropics is the potential density difference between air near the surface, continually warmed and moistened from below, and at higher levels. Horizontal density gradients are a supplementary source of energy for storms moving into middle latitudes. The mere presence of these energy sources are not sufficient to initiate a hurricane. There are other necessary conditions not discussed in this paper.

The extreme minimum pressure in a hurricane in the vicinity of the United States was 26.35 inches (892 mb) in the Florida Keys in 1935. Pressure experienced in various reaches of the mainland coast have ranged down close to 27.50 inches (931 mb). Empirical relations between pressure gradients and winds have been developed that are useful in reconstructing winds over the sea in past hurricanes that have caused important surges.

The well-known typical wind speed pattern is for a small region of light or near-calm winds to be encircled by a band of very strong winds, tapering off more gradually to moderate winds at some scores of miles, or even a hundred miles or more, from the center. There are variations with azimuth from direction of storm motion as well as along a radius, with the strongest winds generally on the right side. Very detailed wind hurricane observations were obtained at Lake Okeechobee, Florida on August 26-27, 1949. From these data empirical relationships have been developed of the comparative strength of winds off-land at a shore, onshore, and over open water that have been useful in reconstructing other hurricanes over the sea.

In assessing reported winds in hurricanes care must be taken to distinguish between sustained winds averaged over several minutes and peak gusts. The relation of the latter to the former, depending on exact definition of a gust and other circumstances, is about 1.4 or 1.5. The gust factors are applied for building design according to standards in that branch of engineering. The variation of wind speed with height over a moderately rough land surface was measured at Brookhaven, Long Island in hurricanes Carol and Edna of 1954.

Hurricane winds diminish over land. Always present is the increased surface friction as compared with the sea, which slows down the anemometer-level winds. Usually present also is a weakening of the pressure gradients in the storm.

Rainfall is an inherent and necessary part of hurricanes. Some typical rainfall patterns were shown.

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