CHAPTER 2
HURRICANES AND HURRICANE TIDES

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Most of the maximum tides of record between Cape Hatteras, N.C., and Brownsville, Tex., have been produced by tropical cyclones, or, as they are generally known in the United States, hurricanes. Some of the highest tides of record northward along the coast from Cape Hatteras to Cape Cod have been produced by hurricanes. From time to time our "northeasters", which are extra-tropical storms, may also cause millions of dollars of damage along the Atlantic coast between Miami, Fla., and Eastport, Me.

The Atlantic hurricane is identical with the Pacific typhoon and the tropical cyclone of the Indian and South Pacific Oceans. The term "hurricane" is defined as a storm of tropical origin with a cyclonic wind circulation (counter-clockwise in the northern hemisphere) with winds of 75 mph or more. However, in popular terminology, any winds of 75 mph or more are often described as hurricane winds.

FORMATION

Tropical cyclones develop in essentially homogeneous warm moist tropical air with no fronts or temperature and moisture discontinuities. The exact nature of the physical processes involved in the formation of hurricanes is not definitely known. However, there appears to be a number of meteorological conditions essential for tropical storm formation: (1) comparatively warm water 80-81°F or higher; (2) a pre-existing wind or pressure perturbation; (3) some outside influence which will intensify this disturbance, and (4) a type of wind flow in the high troposphere which will permit ready removal of the excess air and heat to other regions outside the hurricane area. These conditions are frequently present during the hurricane season but not necessarily in the proper relationship, and hurricane formation is relatively rare. It must be admitted meteorology does not yet have a complete answer to the problem of hurricane formation.

Hurricanes form only in those oceans and in those seasons in which sea surface temperatures are the highest. Here the accumulation of latent and sensible heat in the atmosphere reaches its maximum. The energy for the intensification of an ordinary disturbance in the tropics into a hurricane comes from the release of energy in the form of latent heat (latent heat of condensation) during the precipitation process.

Frequently in the early stages of development and even for a few days after reaching hurricane intensity, the hurricane may be quite small, almost a pinpoint on the usual weather chart. As it becomes

older, it also becomes larger, although it may not, and indeed usually does not, become any more intense. The most intense hurricane of record on land, the Labor Day storm on the Florida Keys in 1935, with a central pressure of perhaps 892 mbs or 26.35 inches, was quite small and had a path of destruction only 35 to 40 miles wide. The largest Atlantic hurricanes may have damaging winds over an area some 400 to 500 miles wide and full hurricane winds 300 miles wide. The average diameter of hurricane winds is perhaps 75 to 100 miles.

FREQUENCY

The number of tropical storms (winds of 40 mph or higher) has averaged about 8 per year for the past 75 years, 9 per year for the last 40 years, and 10 per year for the last 20 years. During the past 70 years, the largest number of tropical storms noted in any one year was 21 in 1933. In 1914 only one tropical storm was reported and that was not of full hurricane intensity. About 58% reach full hurricane intensity and on the average only about two storms per year bring hurricane force winds to the coastline of the U. S.

AREAS OF DEVELOPMENT

Easterly waves, in which Atlantic hurricanes frequently develop, may move more than 2000 miles before any indication of intensification can be detected. Even after the transition from stable to unstable conditions has begun, a period of 3 to 6 days may be required for the initial vortex circulation to grow to full hurricane intensity. During this period the wave may travel an additional 1000 to 2000 miles. Where should it be said the hurricane formed? Where the easterly wave first began to intensify, where the tropical storm reached hurricane intensity or perhaps at some other point in its life history?

The approximate positions where tropical storms reached hurricane intensity during the period 1901-1957 have been plotted on Fig. 1. Only those storms where this point could be estimated with reasonable accuracy have been used. It can be seen that the density of hurricane formation increases steadily from the extreme eastern Atlantic to Longitude 56°. It is noted that almost no tropical storms reached hurricane intensity between Hispaniola and South America in the Caribbean but elsewhere in the tropical and sub-tropical Atlantic south of Latitude 30°, hurricanes are about as likely to develop in one place as another. For many years textbooks have described the doldrums as the area where most hurricanes develop. This is certainly not true if the position where hurricane intensity is reached is considered as the place of development. Indeed, many tropical storms attain hurricane intensity in the area where the trade wind has the greatest strength and persisten

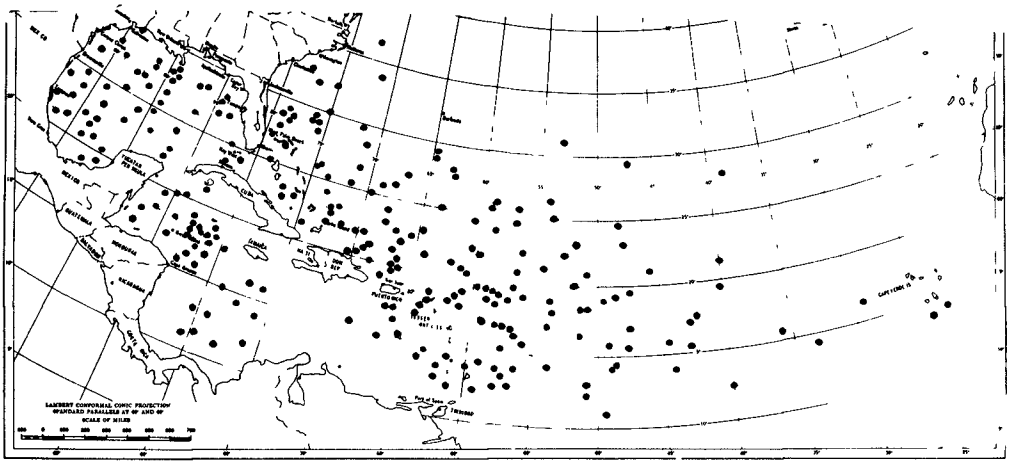

Fig. 1. Locations where Tropical Storms reached hurricane intensity, 1901-1957.

TABLE I

1. July 1896
2. Sept. 28, 1896
3. Oct. 8, 1896
4. Aug. 2, 1898
5. Aug. 31, 1898
6. Oct. 2, 1898
7. Aug. 1, 1899
8. Aug. 17-18, 1899
9. Oct. 30, 1899
10. Sept. 8, 1900
11. July 10-11, 1901
12. Aug. 14, 1901
13. Sept. 11, 1903
14. Sept. 14, 1904
15. Oct. 17, 1904
16. June 17, 1906
17. Sept. 17, 1906
18. Sept. 27, 1906
19. Oct. 18, 1906
20. July 30-31, 1908
21. Aug. 31, 1908
22. July 21, 1909
23. Sept. 20, 1909
24. Oct. 11, 1909
25. Oct. 17, 1910
26. Aug. 11, 1911
27. Aug. 28, 1911
28. Sept. 13, 1912
29. Sept. 3, 1913
30. Aug. 16, 1915
31. Sept. 4, 1915
32. Sept. 29, 1915
33. July 5, 1916
34. Aug. 18, 1916
35. Oct. 18, 1916
36. Sept. 28, 1917
37. Aug. 6, 1918
38. Sept. 14, 1919
39. Sept. 21, 1920
40. June 22, 1921
41. Oct. 25, 1921
42. Sept. 15, 1924
43. Oct. 20, 1924
44. Nov. 30, 1925
45. Dec. 2, 1925
46. July 28, 1926
47. Aug. 25, 1926
48. Sept. 18, 1926
49. Sept. 20, 1926
50. Aug. 7-8, 1928
51. Sept. 16, 1928
52. June 28, 1929
53. Sept. 28, 1929
54. Sept. 30, 1929
55. Aug. 13, 1932
56. Sept. 1, 1932
57. July 30-31, 1933
58. Aug. 4, 1933
59. Aug. 23, 1933
60. Sept. 4, 1933
61. Sept. 5, 1933
62. Sept. 16, 1933
63. June 16, 1934
64. Sept. 2, 1935
65. Nov. 4, 1935
66. July 31, 1936
67. Aug. 7, 1940
68. Aug. 11, 1940
69. Sept. 23, 1941
70. Oct. 6, 1941
71. Oct. 7, 1941
72. Aug. 30, 1942
73. July 27, 1943
74. Aug. 1, 1944
75. Oct. 19, 1944
76. Aug. 27, 1945
77. Sept. 15, 1945
78. Sept. 17, 1945
79. Sept. 17, 1947
80. Sept. 19, 1947
81. Oct. 11, 1947
82. Oct. 15, 1947
83. Sept. 21, 1948
84. Oct. 5, 1948
85. Aug. 26, 1949
86. Oct. 4, 1949
87. Sept. 5, 1950
88. Oct. 18, 1950
89. Aug. 30, 1952
90. Aug. 13, 1953
91. Sept. 26, 1953
92. Oct. 15, 1954
93. Aug. 12, 1955
94. Aug. 17, 1955
95. Sept. 19, 1955
96. Sept. 23-24, 1956
97. June 27, 1957

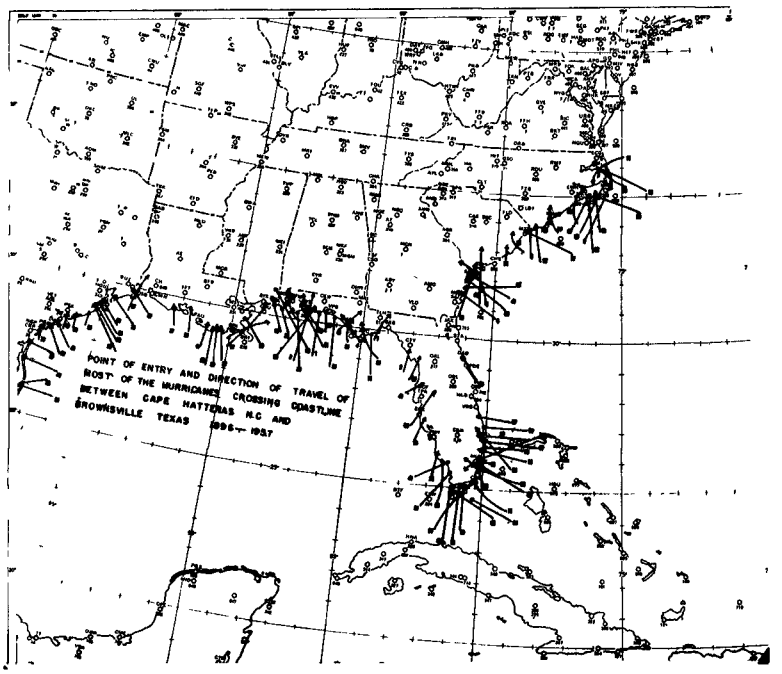

Fig. 2. Point of Entry and Direction of Travel of most of the hurricanes crossing the coastline between Cape Hatteras, N. C., and Brownsville, Tex., 1896-1957 (Number at beginning of arrow refers to number of storm in Table I.)

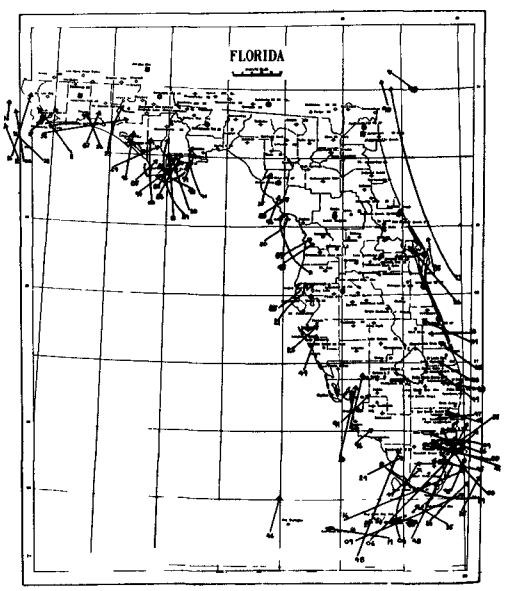

Fig. 3. Point of Entry and direction of travel of all Tropical Cyclones giving hurricane winds in Florida, 1885-1957 (Number at beginning of arrow indicates year of storm).

SUSCEPTIBLE COASTAL AREAS

The points of entry and the direction of travel of each hurricane which has crossed the U. S. coastline from Cape Hatteras, N.C., to Brownsville, Tex., from 1896 to 1957 are shown on Fig. 2. The dates of these storms can be found in Table I. All sections from Palm Beach, Fla., southward and along the entire Gulf coast are subject to hurricane visitation from 1 in every 7 years to 1 every 20 years or more on the average. The remainder of the South Atlantic coast is visited less frequently. Hurricanes are comparatively rare north of Cape Hatteras and especially so from north of the Virginia Capes to New York City. However, New England is occasionally subject to major hurricanes and was frequently struck by these storms between 1938 and 1955.

The points of entry and the direction of travel of all Florida hurricanes from 1885 through 1957 are shown in Fig. 3. The sections with highest frequency are the extreme southern portion of the Florida peninsula and the panhandle section on the Gulf coast. The hurricane frequency is very low on the northeast Florida coast. The reason for the low frequency is that the coastline is parallel to the normal storm track and if the storm recurves to the extent that it misses the southeast coast, it will also miss the northeast coast. This section is more susceptible to the fall and winter northeasters. The apparent low frequency on the Gulf coast between Cedar Keys and St. Marks is not believed real. This area is very sparsely settled and the exact point where many of the centers actually reached the coastline is not known, and there has been a tendency to place the centers too close to the regular Weather stations with the lowest pressure.

Of the 74 Florida hurricanes occurring during the past 75 years, 31 are known to have been attended by damaging tides. However, many of the centers made landfall in relatively uninhabited areas and the exact storm tide is unknown. It is estimated that a 6' storm tide occurs somewhere along the Florida coast on the average at least once every two years and probably more often.

LIFE SPAN OF HURRICANES

The average life span of a hurricane is about 9 days. August storms normally last the longest or about 12 days. The factors which determine the lifetime of a hurricane are the time and place of origin and the general circulation features existing in the atmosphere at the time of occurrence. Very few hurricanes dissipate while they remain over tropical or sub-tropical waters unless some abnormal feature of the wind flow pattern surrounding the storms acts to bring cold or dry air into the hurricane circulation.

Obviously those storms that develop in the Cape Verde region in August and September, when the semi-permanent Azores-Bermuda HIGH is at its greatest intensity, will have the longest life spans, since they normally travel westward for several thousand miles before recurving northward and eventually northeast or eastward around the western and northern sides of the HIGH. One hurricane has been tracked for over a month. This year (1957) hurricane Carrie was picked up, already a hurricane of great intensity, on September 6. In the wave stage it can be tracked back to near the African coast on the 2nd, Fig. 4. It was still of hurricane intensity on September 22nd as it moved through the Azores. It finally became extra-tropical and eventually moved across the British Isles.

AVERAGE DAMAGE AND FATALITIES

In this century in the United States alone, at least 12,322 persons have been killed by hurricanes, or an average of over 200 per year. During this same period hurricanes have also caused at least 3 billion dollars of damage in this country, or over fifty million dollars per year. It is estimated that over 90% of all fatalities were from drowning and about 75% of all damage was from hurricane induced sea action or floods. The rapid continuing growth of population and construction along vulnerable coastal areas is increasing potentia casualties and property losses from tropical storms. If occasional catastrophic property losses are to be avoided, better coastal zoning and scientific coastal engineering are necessary.

THE WIND FIELD

The mean wind field for the lowest 1000 meters around the center has been calculated by Miller(1) for a large number of observations in some twenty hurricanes. The wave heights (over the open oceans) depen upon the wind velocity, the length of time the wind operates upon the wave, and the fetch or distance over which the wind has blown in a rel tively straight path. It can be seen from Fig. 5 that the highest win occur in the right semi-circle, and also that the winds operate upon t waves there for the greatest length of time in the direction in which the storm is advancing. Thus the largest waves and swells are generat in the right semi-circle. These move faster than the storm and may mo many hundreds of miles out ahead of the center and eventually reach th coastline. The direction from which these swells approach the coast i determined by the storm's direction of motion and its bearing from the place of observation at the time the swells were generated. Lines or zones of convergence can also be seen in this composite picture, which in individual hurricanes may form or dissipate or rotate a considerabl distance around the center within a few hours. Although there is some difference of opinion among storm surge specialists, it is not believe these convergence lines have any significant effect on storm tides.

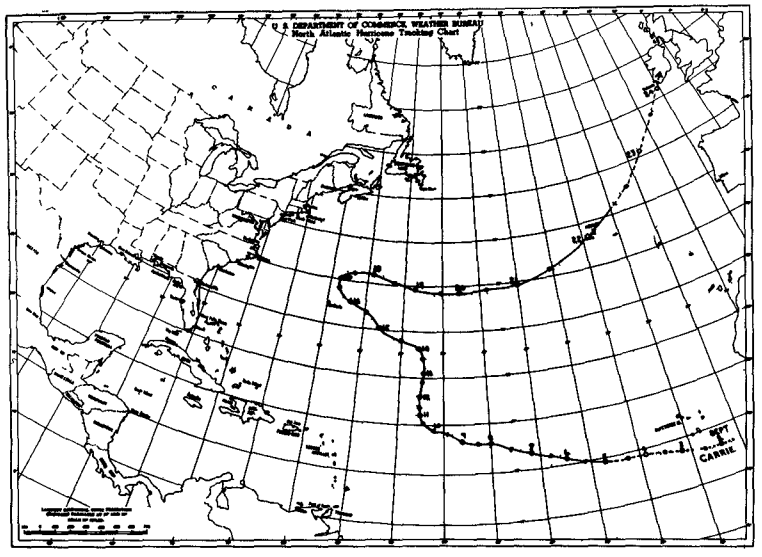

Fig. 4. Track of Hurricane Carrie, 1957.

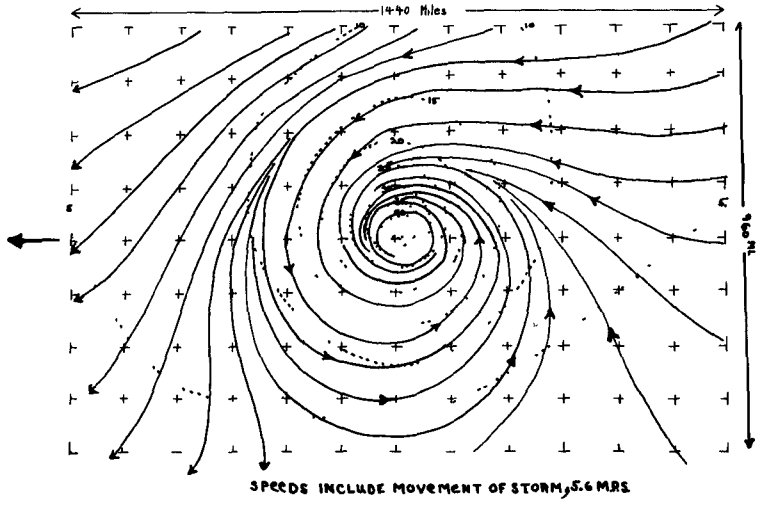

Fig. 5. Miller's Mean Wind Field 0-1 km Layer Movement of Storm.

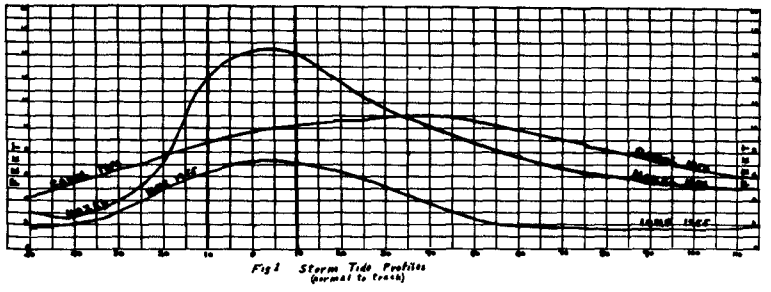

Fig. 6. Profile of Carol, Hazel, Ione.

At the center of the storm's circulation is the 'eye' of the hurricane. Formerly the eye was defined as the central portion of the storm where the winds were light and variable and the skies partly cloudy with no precipitation. In the classical hurricane, a cumulonimbus type cloud, or 'wall' cloud, extending to 30 to 40,000 feet or more tightly encloses this relatively calm area and within five miles the wind may increase from 15 to as much as 125 mph depending upon the intensity of the storm. However, from radar it is evident that the diameter of the precipitation eye is often much larger than the wind eye. The precipitation eye is occasionally 40 to 60 miles in diameter while at the same time the wind eye may be only 15 miles across. The complicated relationships between the size of the eye and the maturity and intensity of the storm are beyond the scope of this paper except to say that extremely high tides are rare in hurricanes with large wind eyes; i.e., wind eyes with diameters in excess of 30 miles.

ENERGY CONSIDERATIONS

A tremendous amount of energy is released in a hurricane through the process of condensation which has been estimated by some meteorologists as the equivalent of several hundred atomic bombs per minute. About 15 to 20% of this energy is needed to drive the wind circulation of the storm(2). A large portion is necessary to maintain convection in the hurricane, where the atmosphere is very close to the moist adiabatic. Only about 2% is used to overcome the effects of surface friction(3). While the hurricane is over water, waves and swells are formed by the frictional action of the winds on the surface of the water. These result in a dispersal of energy from the storm in all directions.

Energy both in the form of sea action and maximum winds concentrates the hurricane's destructive forces along the immediate coastline. Friction and often other factors tend to increase the atmospheric pressure at the center of the storm diminishing the pressure gradient and consequently the maximum winds near the center as the entire storm circulation moves over land. The energy which the sea receives from the wind is dispersed radially from the storm. Part of the energy directed toward the coast is used to raise the water level over the continental shelf before the main wind system of the storm arrives at the shore. The energy arriving at the coast becomes progressively more concentrated until it reaches a maximum in the form of wind, storm tide and storm waves with the arrival of the storm's central area.

The rise in the ocean level induced by meteorological conditions should not, strictly speaking, be called a 'tide' since that term implies a periodic rise and fall of the level of the oceans. Since it seems likely the term 'storm tide' and 'hurricane tide' will continue in popular usage within the foreseeable future they will be used in this paper interchangeably with the more technically correct 'storm

surge'. Definitions of the storm surge and the storm tide and discussion of the equations of motion governing storm surge generation have been discussed by Harris(4).

The storm tide, or meteorological tide, resulting from hurricanes can often be described as having two stages. The first is the 'forerunner' which is a slow rise due to the shoreward transport of water by shoaling swells and waves irrespective of local wind direction. The rate of this rise in sea level varies as the concentration of energy radiated from the storm through the water. The second is the 'surge' which is usually a more rapid rise caused by direct transport of water by hurricane winds and sometimes believed to be intensified by a gravity wave possibly produced by a shoaling of the 'inverted barometer' wave. Dr. I. M. Cline, Meteorologist in Charge of the Weather Bureau Office at Galveston at the time, reported a rise of 4 feet in as many seconds at about the time of lowest pressure during the famous Galveston hurricane of 1900 and there have been similar observations in other hurricanes. The rate of the storm tide rise near and a short distance to the right of the center of hurricane Audrey, 1957, was about 1.5 feet per hour along the immediate Gulf coast for the 4 or 5 hours preceding the arrival of the center but there was no authentic evidence of a bore or very rapid rise there.

Several outstanding storm tides, all in connection with hurricanes, have occurred along the Atlantic and Gulf coasts in this century, namely: Galveston 1900 and again in 1915; Tampa Bay in 1921; Miami 1926; Palm Beach and Lake Okeechobee 1928 and again in 1949; the Florida Keys in the Labor Day storm 1935; New England, particularly Narragansett Bay 1938 and again in 1954; Hazel, south of Wilmington, N.C., 1954, and Audrey, Cameron, La., 1957. This list does not include all the outstanding storms with high tides since 1900. The maximum reported tides of all these storms averages 12.5 feet above mean low water.

Of the 24 best documented storm tides along the coast of the Gulf of Mexico, the maximum storm tide heights averaged 10.3 feet with a range between 5 and 15 feet. The average maximum reported height of 14 fairly well documented storm tides of the Atlantic coast was 9.7 feet with a range between 3 and 15.5 feet. This group does not include some entering the Florida peninsula where the average height of 15 major storm tides between 1900 and 1955 was 9.8 feet, MSL. The number of documented storm tides is not great enough to attach much significance to the differences between the averages for the various sections given above but because of the predominately shallow coastal waters of the Gulf of Mexico and the concavity of the coastline, a higher average might be expected there. Very high storm tides will occur at the heads of bays and estuaries, particularly when the storm center moves inland on a course at an angle of 90° or less to the coast line (right quadrant).

In Fig. 6, three storm tide graphs with height plotted as a function of distance normal to the track of the storm center clearly shows the maximum tide occurring at or immediately to the right of the center. This slopes rapidly down to about the level of the pre-storm tide height or the height of the 'forerunner' and then very slowly diminishes with distance along the coast. It is obvious that a forecast of storm tide levels must be based on an accurate forecast of the point of entry of the storm center, which, unfortunately, is not always possible.

The present methods of forecasting the hurricane tide are largely empirical, and perhaps the one by Conner, Kraft and Harris(5) is the most widely used. The basic tide producing capacity of the storm is assumed to be indexed by its minimum central pressure. Other modifyin factors such as (1) slope of the continental shelf; (2) shape of the coast (concave or convex); (3) coastal topography and presence of bays estuaries, etc., which tend to accentuate convergence or divergence of ocean currents, must be evaluated qualitatively.

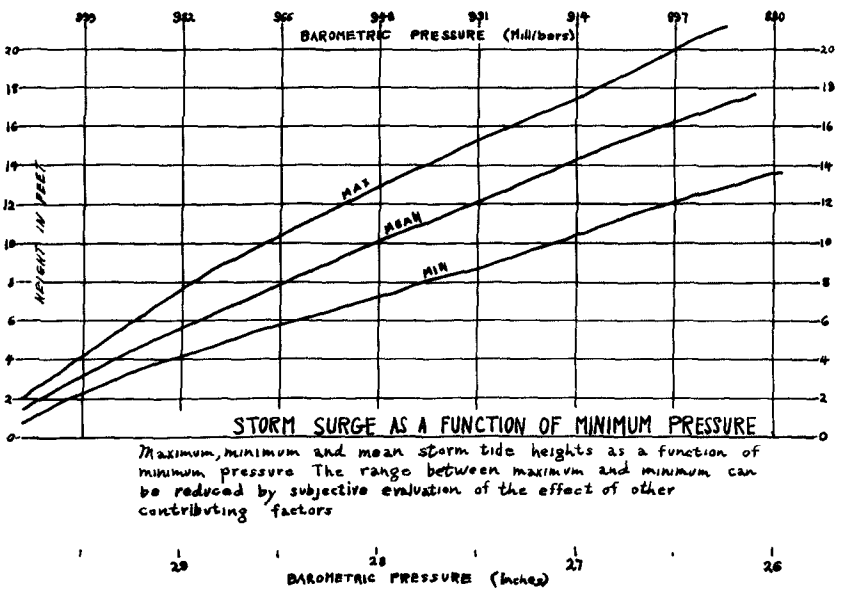

Fig. 7. Storm Surge as a Function of Minimum Pressure (After McGehee).

In Fig. 7, tide heights are plotted as a function of lowest pressures observed within a group of Florida and South Atlantic storms. This results in a graph with considerable scatter. However, two lines can be drawn, one representing the maximum and the other the minimum tide heights produced by storms with the same central pressure. A tide height is forecast which is a value between the maximum and minimum as determined from a subjective evaluation of the modifying factors described in the preceding paragraph. The central pressure of a hurricane is usually, but not always, known. Probably hurricane Audrey of this year was intensifying rapidly as she reached the Louisiana coast and her minimum pressure was not available to the forecaster. It is well known there are other important factors which contribute to the total storm height. Mention of these is omitted since at the present time there is no known method of evaluating their contribution.

A scientific analysis of a hurricane tide presents manifold difficulties. Construction of a laboratory model would present several difficult if not insoluble problems. The moving short radius of curvature with proportionate pressure distribution of the hurricane wind field probably defies duplication. And, in nature, the quantitative contribution of the numerous factors determining the total storm tide have proven impossible to evaluate separately up to this time.

In conclusion, I would like to acknowledge the very considerable contribution of Mr. William McGehee, storm surge forecaster at the Miami Hurricane Forecast Center, in the preparation of this paper.

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