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RELATION OF CHANGES IN STORM TIDES ON THE COAST OF THE GULF OF MEXICO TO THE CENTER AND MOVEMENT OF HURRICANES.

By ISAAC M. CLINE, District Forecaster.

[Weather Bureau, New Orleans, La., Mar. 10, 1920.]

SYNOPSIS.

A brief summary of what is known bearing directly on this subject concerning wind and waves is given.

Hurricanes are in all instances preceded by storm tides. The water commences rising on the coast in front of the cyclonic area, one to two days before the storm in experienced.

The wind velocities and directions in different parts of the hurricane, as deduced theoretically, do not meet the requirements in this study to explain the rises in tides. Composite charts showing the actual wind directions and velocities determined from stations in the different parts of the cyclonic area are submitted. In the right-hand rear quadrant the winds blow with much greater velocity and persist in the same direction longer than in any other part of the hurricane. At stations in this quadrant the wind has been found to blow for 24 hours or longer with a direction in line with the advance of the hurricane, with an average velocity of 60 miles per hour, and for 13 hours at 70 to 85 miles per hour. In other parts of the cyclonic area the wind continues to blow over the water in the same direction for only a few hours.

Winds in the cyclonic area over water develop waves of a size and length which bear a relation to the sustained velocity of the wind and the length of time the waves are under the influence of the same wind direction. Waves of different sizes are developed in proportion to the winds which prevail in the different parts of the cyclonic area. The largest and longest waves are created in the rear right-hand quadrant; these waves pass on through the cyclonic area and move to shore where they cause a rise in the water in the front of and on the right of the line over which the center of the hurricane is advancing. This rise begins when the center of the hurricane is 300 to 500 miles distant, and continues until the hurricane moves inland. The heights of the water reached at shore near the center of the storm vary from 8 to 15 feet above mean Gulf level.

Changes in the position of the rise of the storm tide indicate changes in the course of the storm.

Bold-face figures in parenthesis refer to authorities preceded by the same figure in the bibliography at the end of this paper.

STORM WAVES AND SWELLS.

Waves and tides that appear along our coasts, many hours and at times one or two days in advance of hurricanes, convey some definite information regarding the position and direction of movement of the storm still many miles distant in the Gulf. Swells and waves break upon the shore and the water rises as the result of winds prevailing in the Gulf sometimes 400 to 500 miles distant.

The relations which the movements and actions of the waves and tides bear to the position and movement of the meteorological disturbances, which develop and carry these phenomena to shore, have not received the attention the importance of the subject justifies.

Ocean waves and their action under winds have received the attention of investigators, and we will summarize briefly the more important results obtained that bear directly on this subject. Their height, length, and speed have been carefully studied and recorded in both deep and shallow water. In the Atlantic and other oceans with 600 to 1,000 miles sea room it has been found in ordinary storms that waves of 35 to 40 feet in height are developed and in exceptional storms waves may exceed 45 feet. The crossing of two large waves will sometimes send up a peak of water which has been estimated to be 50 to 55 feet in height. The quotient obtained by dividing the wind velocity in miles per hour by 2.05 represents the average height in feet of the waves developed by that wind; however, this average will be exceeded when the wind has full opportunity to exert its force. Waves produced upon the deep sea communicate their motion to the water to a depth of about one-fourth the wave length; when the waves run into water which has depth less than one-fourth the wave length a reduction of the speed of the wave results and continues as shallower water is reached; the diminishing speed causes the wave crests to close up, the space separating them becomes less and less as the depth of the water diminishes; but the interval of time between the arrival at shore of successive crests remains unchanged. The average storm wave in deep water moves forward with a velocity a few miles per hour less than the wind velocity that produces it. Long waves and swells that move through the storm and break upon the shore travel when in deep water with a greater speed than the highest waves in storms travel. In seas partly inclosed the speed and length of waves are less than on the open ocean, these being determined by the length of fetch as well as winds. (**3.**)

In the Gulf of Mexico there is a distance or length of fetch over deep water for 600 miles from the Yucatan Channel to the middle Gulf coast and 800 miles to the west Gulf coast. From the Florida Straits to the middle and west Gulf coast the distance or length of fetch ranges from 600 to 1,000 miles.

In a cyclonic area with a progressive movement of 12 to 15 miles per hour large waves of considerable length are driven through and beyond the cyclonic area and by gravity and inertia are carried on far in advance of the area covered by the cyclonic circulation.

In discussing the propagation of waves of the sea in this connection Cornish says: (**6**)

> The breakers which arrive (at shore) somewhat irregularly during storms do so at intervals which, as far as I have noticed them, do not differ much from the intervals observed on board ship in the deep sea during storms. When waves are driven outside the wind area and left to themselves to travel over considerable distances the originally complex and irregular waves are analyzed into a series

of simple, regular waves of graduated lengths. The longer and swifter are in front, the shorter and slower in the rear; the shorter components flatten out very quickly as they travel, whereas the longer components preserve their height with but little diminution for long distances and reach places far distant from the windward shore, where the water will heave with a long period undulation. At a considerable distance from the windward shore the state attained by the sea during a storm does not depend only on what the wind does there but by the transmission by gravity, independently of the wind of the longer-period component of the irregular waves which the storm has created to windward. The greater the length of the fetch the greater is the distance from which the surface water draws the reinforcement of its long period heaving and the greater, therefore, is that part of the wave disturbance which is of greater wave length than the dominant wave.

Darwin says: (2)

The point we have to note is that an isolated disturbance will generate long waves and they will run ahead of the small ones; the long waves are more persistent, * * * but I do not understand how it is that the separation of the long from the short waves is so complete nor what governs the length of the wave.

Dr. George Stokes showed nearly half a century ago that there is a transfer of water in the direction in which the wave is moving. The speed of the transfer depends on the depth and diminishes rapidly as the depth of the water increases. (4)

Coast currents observed as resulting from cyclonic storms in the Bay of Bengal have a steady set or drift to the west. Eliot says: (1)

It is probable that the strength of a cyclone advancing to the northward coast of the bay could be roughly ascertained by the strength of the westerly set at the head of the bay. Data are, however, wanting to test this. * * * The drift near the center of large storms in the Bay of Bengal may be so much as 6 to 8 knots * * *.

Observations of construction engineers indicate that the effects of waves on such structures as rubble breakwaters are generally not appreciable beyond a depth of 15 to 16 feet below the water surface. This varies, however, in different localities. At Port Elizabeth, South Africa, blocks of rubble stone weighing 100 to 150 pounds, in 22 feet of water, were not disturbed by waves 15 to 20 feet high. At Colombo stones weighing three tons, in water 10 to 14 feet deep, were disturbed by waves not exceeding 15 feet in height. At Algiers, Africa, stones 33 to 39 feet below the surface of the water were moved by waves or currents. (7)

The most destructive element in hurricanes is the breaking wave. A cubic yard of water weighs about 1,500 pounds and the waves, driven by the wind, break on the coast with the water moving forward at a speed of many feet per second, and cause destruction which exceeds description.

TIDE RECORDS.

The Port Eads tide gage is about 2½ miles up the South Pass from the Gulf, and the Burrwood gage in Southwest Pass is 5 miles from the Gulf.

The tide gage at Galveston is at the foot of Twentieth Street. The tide records used with the Mobile (Ala.) meteorological records are Pascagoula, Miss., 1909, and for the other years, Fort Morgan, Ala.

Mean low water at Port Eads, La., is 0.3 of a foot and at Burrwood, La., is 0.7 of a foot above mean Gulf level. At Fort Morgan, Ala., mean low water is 0.3 of a foot above mean Gulf level. For Galveston the United States Coast and Geodetic Survey gives mean low water (1917) 0.5 of a foot below mean Gulf level.

The zero of the tide gage at Port Eads, La., is 3.16 feet and at Burrwood, 2.26 feet below mean Gulf level, and at Fort Morgan, Ala., the zero of the tide gage is 1.22 feet below mean Gulf level; therefore, mean low water on the Port Eads gage reads 3.46, on the Burrwood gage 2.96, and on the Fort Morgan gage, 1.52.

Darwin, in speaking of tides, says: (2) "The word 'tidal' should only be used when we are referring to regular and persistent alternations of rise and fall of sea level." He suggests that changes of water level due to wind and other atmospheric influences should be referred to as a "meteorological tide." The meterological tide may be either low water or high water.

In referring to tides generally, mean low water as used by the United States Coast and Geodetic Survey will be used as the reference plane. The tide graphs shown with the graphs of meteorological conditions will give the tides above mean low water, in order that the records for Galveston, Burrwood, and Mobile, may be easily compared as the cyclonic area advances.

The term "Storm tide" will be used to represent the height of the water in excess of the predicted tide at a given hour. A study of the relationship existing between hurricanes and tides has been made possible through the complete records of tide conditions which we have had the good fortune to secure for this study.

Each hurricane, during the 20 years, 1900 to 1919, inclusive, will be taken up in chronological order, and we will deal especially with the relation of the tides to the center and movement of the hurricane.

METEOROLOGICAL RECORDS AND HURRICANE TIDES.

September 1–12, 1900.—This disturbance reached the Florida Straits, September 5, and moved in a northwesterly direction across the Gulf, a distance of nearly 1,000 miles, with its center passing inland over the western part of Galveston Island about 9 p. m., September 8. A graphical representation of the wind, barometric pressure, and tides at Port Eads, La., and Galveston, Tex., during the passage of this storm through the Gulf is shown in Plate I. At Port Eads the barometer commenced falling on the morning of the 6th and fell steadily until the night of the 7th, when 29.56 was recorded at the 8 p. m. observation. The wind was from the northeast during the 6th and until 8 a. m. of the 7th, with steadily increasing velocity, but not exceeding 44 miles per hour. The wind shifted to the east in the afternoon of the 7th, and the highest hourly velocity was 47 miles at 4 p. m. and 5 p. m. At 8 a. m. the wind was from the southeast and the velocity 30 miles per hour.

The tide gage at Port Eads showed a slight rise in the water above the regular tides during the 6th, and the water continued to rise steadily, reaching 2.8 feet above mean low water at 9 p. m. on the 7th, the rise caused by the hurricane in 24 hours being 1.2 feet. The oscillations of the regular tides were not overcome, but the water at lowest tide on the afternoon of the 7th was 1.6 feet higher than the lowest water on the previous day. Port Eads was about 150 miles to the right of the line of advance of the center of the hurricane at the time of the highest water. In this instance the water at shore commenced rising at Port Eads 150 miles to the right of the line of advance of the hurricane, when the center was 400 miles distant and 36 hours before that place was on a line drawn through the center of the hurricane at right angles to the line of advance. The highest water occurred with the passage of the center of the cyclonic area and coincident with the lowest barometer and highest winds.

At Galveston the barometer commenced falling at 5 p. m. on the 6th and continued falling steadily, but slowly, up to noon of the 8th, when it read 29.42 inches. The barometer then fell rapidly, recording 28.48 inches at 8:30 p. m. of the 8th, the lowest pressure recorded up to that time at a Weather Bureau station. The wind blew steadily from the north from noon of the 6th until 3 p. m. of the 8th, except that it blew from the northeast during the hours ending at 9 a. m. and 10 a. m. of the 8th. The prevailing wind was from the northeast from 3 p. m. to 8:30 p. m., September 8; east from 8:30 p. m. to 10 p. m., southeast from 10 p. m. to 11 p. m., and after that time from the south. The wind velocity was above mean low tide, showing nearly 2 feet of storm tide. At this time the center of the hurricane was 300 miles distant in space and 30 hours in time, and its line of advance was toward Galveston. The water stood one foot higher at Galveston at this hour than at Port Eads, which was only about 175 miles distant, from the cyclonic center, to the right of the line over which it was advancing. The crest of high water at Port Eads was 2.8 feet, and was reached at 9 p. m. of the 7th.

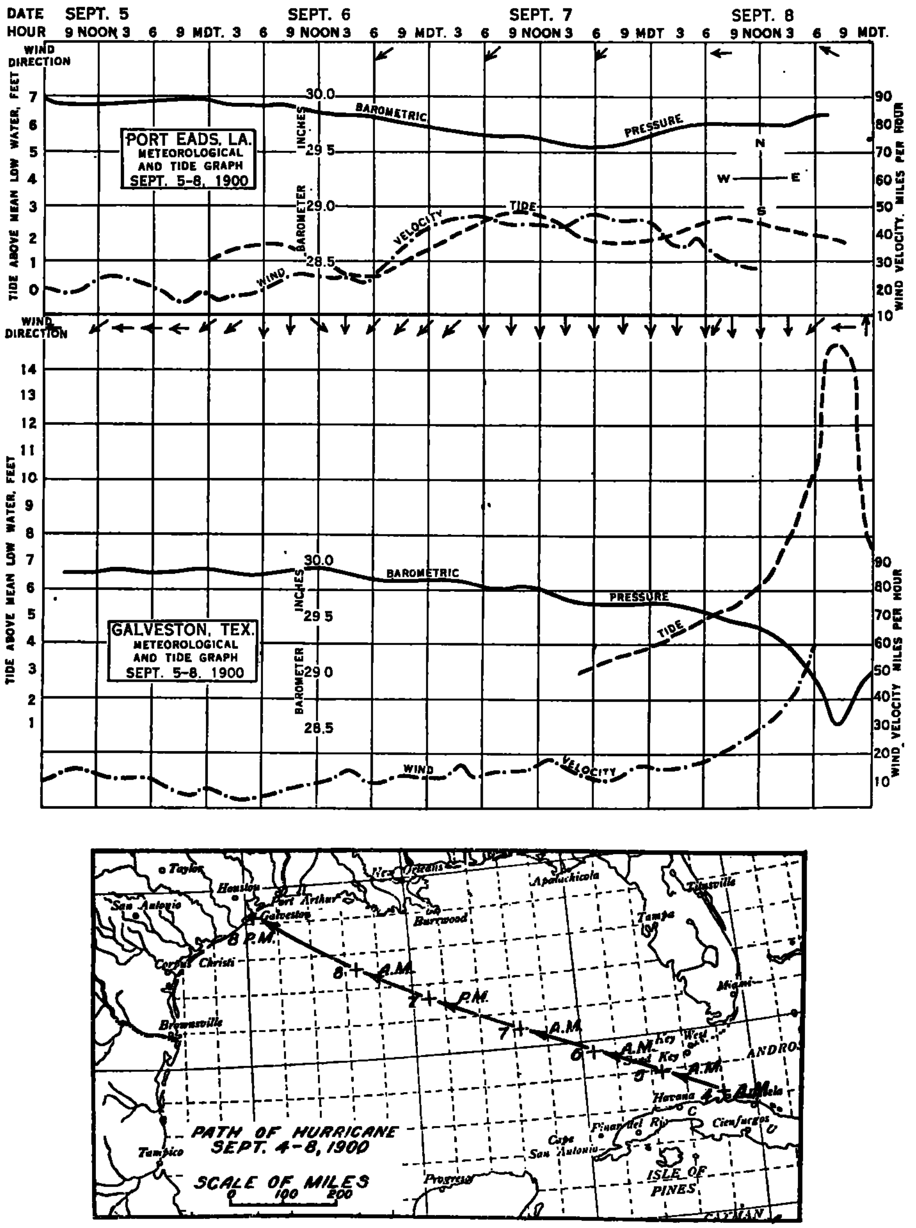


PLATE I.—*I. M. Cline.*

less than 20 miles per hour up to 6 a. m. of the 8th, after which the velocity increased steadily, reaching 30 miles per hour at noon of the 8th, and was 60 miles during the hour ending 6 p. m. when the anemometer blew away. The velocity was increasing rapidly at that hour, 2 miles having been recorded at the rate of 100 miles per hour. It is estimated that a velocity of 120 miles per hour was reached about the time of the shift of the wind to the east.

There are no tide observations at Galveston prior to 4 p. m. of the 7th, when the water already stood 3 feet

The water continued to rise rapidly at Galveston, and was 8 feet at 3 p. m. of the 8th, notwithstanding there had been up to this time a prevailing offshore north wind of 20 to 40 miles per hour; such winds ordinarily give a tide below low water. After 3 p. m. of the 8th, when the wind shifted to northeast and east the tide rose with phenomenal rapidity, reaching 15 feet at 8 to 9 p. m., a rise of 1.4 feet per hour. The rapid rise during the last five hours is attributed to the effects of the off shore north winds prior to 3 p. m. having retarded the rise in the water as the storm approached, by forcing it back and banking it toward the storm center, and when the wind changed to northeast and east this water was forced in rapidly with favorable winds. The rise in the storm tide was not noticeable on the coast 50 miles to the left of the line of advance of the hurricane.

The destruction of property by the winds and waves in this hurricane amounted to about $30,000,000 and 6,000 persons were drowned.

July 5–10, 1901.—A storm of small extent and moderate intensity moved through the Yucatan Channel into the Gulf of Mexico on the 7th and reached the Texas coast west of Galveston on the 10th. This disturbance was northeast during the 13th; on the morning of the 14th it was southeast. The velocity increased steadily after 6 a. m. of the 13th, and was 62 miles per hour at 5 a. m. on the 14th, when the record was lost. The wind and pressure records at New Orleans are shown on Plate II, along with the wind, pressure, and tide records at Port Eads. (We have no automatic tide record for Mobile and Galveston for this storm.) The highest wind velocity, 40 miles per hour at New Orleans, occurred at 11 a. m. on the 15th.

Tide records at Port Eads show the water rising before midnight on the 12th when the center of the storm was

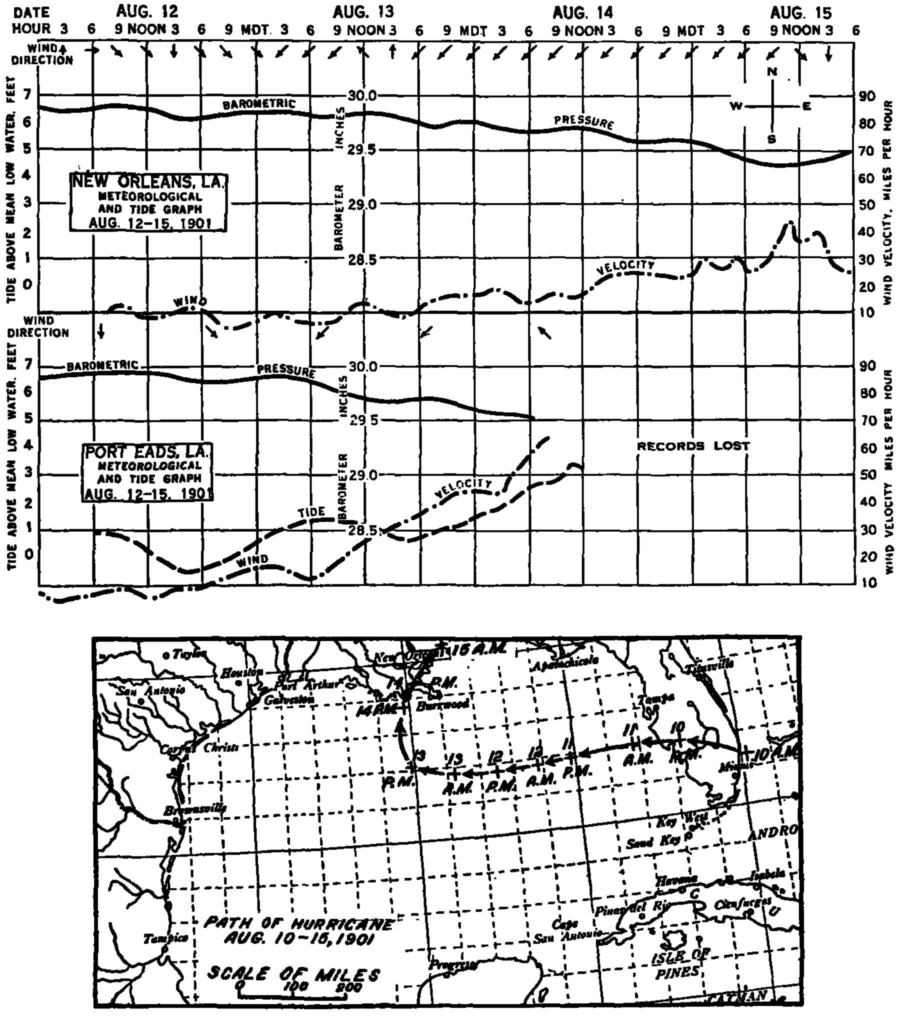


PLATE II.—*I. M. Cline.*

gave a rise in water at Galveston of 4.5 feet at 3:30 a. m. No tide records of this disturbance are available. No damage of consequence resulted.

August 9–15, 1901.—This disturbance first appeared to the north of Cuba on August 9. It moved across southern Florida and into the Gulf of Mexico on the morning of the 11th, continued its course westward until the 90th meridian was reached, when, during the 14th, it recurved and on the morning of the 15th passed northeastward between New Orleans and Port Eads. This disturbance was of small diameter, but of considerable intensity. Its course was unusual.

The barometer at Port Eads fell steadily, commencing about noon on the 12th and was 29.50 at 8 a. m. on the 14th, when the last observation was taken. The wind direction was northwest on the afternoon of the 12th and about 200 miles distant. The water reached a height of 4.2 feet above mean low water at 11 a. m. on the 14th, the record after that time being lost. The Mississippi River at New Orleans rose from 5.9 feet to 11.4 feet on the morning of the 15th, the water forced up the river by the hurricane winds amounting to 5.5 feet.

At Mobile the water was driven in and was awash of the wharves from 12 noon to 1 p. m. of the 14th. At 10 a. m. of the 15th the water began to come over the wharves, rising at the rate of nearly 1 foot per hour until 3:30 p. m., when it was 5 feet over the wharves and 8.2 feet above mean low tide.

Ten persons were drowned and the damage caused by the storm was $1,000,000.

September 23–27, 1906.—This disturbance passed through the Yucatan Channel on the morning of the 24th, traveled in nearly a straight line, and moved in on the Mississippi coast on the morning of the 27th. The tide records at Port Eads, charted with the wind and pressure records of New Orleans (Port Eads meteorological records being missing) and the Galveston pressure, wind, and tide records during the storm are shown on Plate III. This was a hurricane of large extent and unusual intensity. The tide at Galveston during the passage of this disturbance through the Gulf showed only normal changes. At Port Eads, 50 miles to the left of the line of advance of the center of the storm, the storm tide commenced rising during the afternoon of the 25th, when either Mobile or Pensacola during this hurricane. The United States engineers at Fort Barancas on the bay below Pensacola, give the extreme storm tide at that place, 10.8 feet. At Mobile, the water was 9.9 feet above mean low tide. Thus we have the highest water at Port Eads, 50 miles to the left of the line of advance of the center of the hurricane, 3.8 feet, and at Pensacola, 100 miles to the right, 10.8 feet.

The damage from the hurricane at Pensacola was $2,120,000, and in the vicinity of Mobile, $1,850,000. The total known deaths at Pensacola were 32, and in the vicinity of Mobile 31 persons lost their lives.

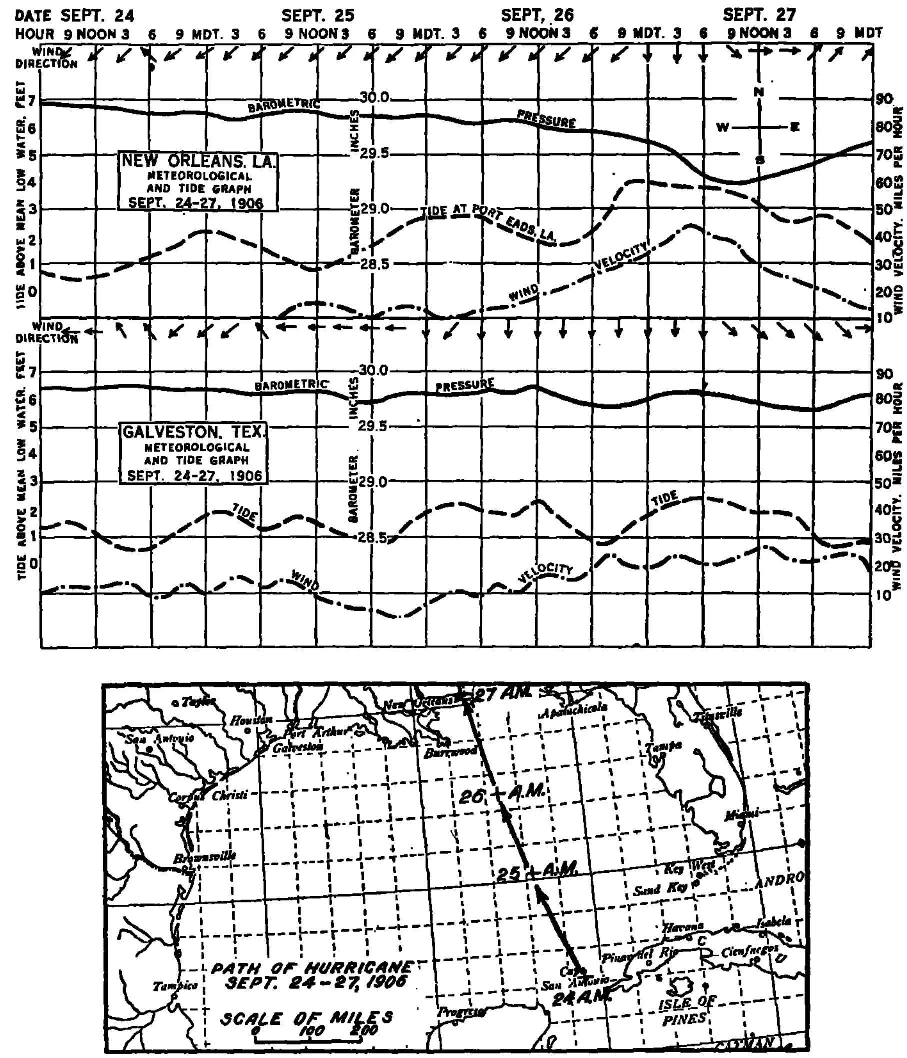


PLATE III.—*I. M. Cline.*

the hurricane was 250 miles distant in space and 28 hours in time. The rise in water shown at Port Eads on the afternoon of the 25th must have started from the southeast Gulf during the afternoon of the 24th and traveled, during 20 hours, a distance of more than 500 miles, at the rate of about 25 miles per hour. The cyclonic area advanced at the rate of about 10 miles per hour. The highest tide at Port Eads was 3.8 feet at midnight of the 26th. There was 3-foot rise in the river at New Orleans on the morning of the 27th as a result of the hurricane. Mobile and Pensacola were situated in the eastern segment of the cyclonic area, where they experienced the severest part of the hurricane. Both places reported the severest hurricane in their history. Unfortunately, we have no automatic tide records for

July 18–21, 1909.—This disturbance moved from the Caribbean Sea through the Yucatan Channel on the 18th and moved inland on the Texas coast with its center near Velasco. The cyclonic area was about 100 miles in diameter and no hurricane winds attended it. High waves, swells, and tides prevailed as far to the right of the center as Galveston. We have no tide records for this storm.

The damage to property amounted to $100,000 and 4 lives were lost.

September 12–21, 1909.—This was a storm of great intensity and of large extent, its effects being distinctly felt from east of Pensacola, Fla., to the west of Galveston, Tex. The disturbance passed through the Yucatan Channel during September 17 and moved inland on the

Louisiana coast, its center a little distance to the right of the mouth of the Atchafalaya River, September 20. This disturbance advanced at the rate of about 8 miles per hour.

The meteorological and tide records at Mobile, Ala. (tide records from Pascagoula, Miss.), Port Eads, La., and Galveston, Tex., are shown on Plate IV. The storm tide began rising at Pascagoula, Miss., and Port Eads, La.,

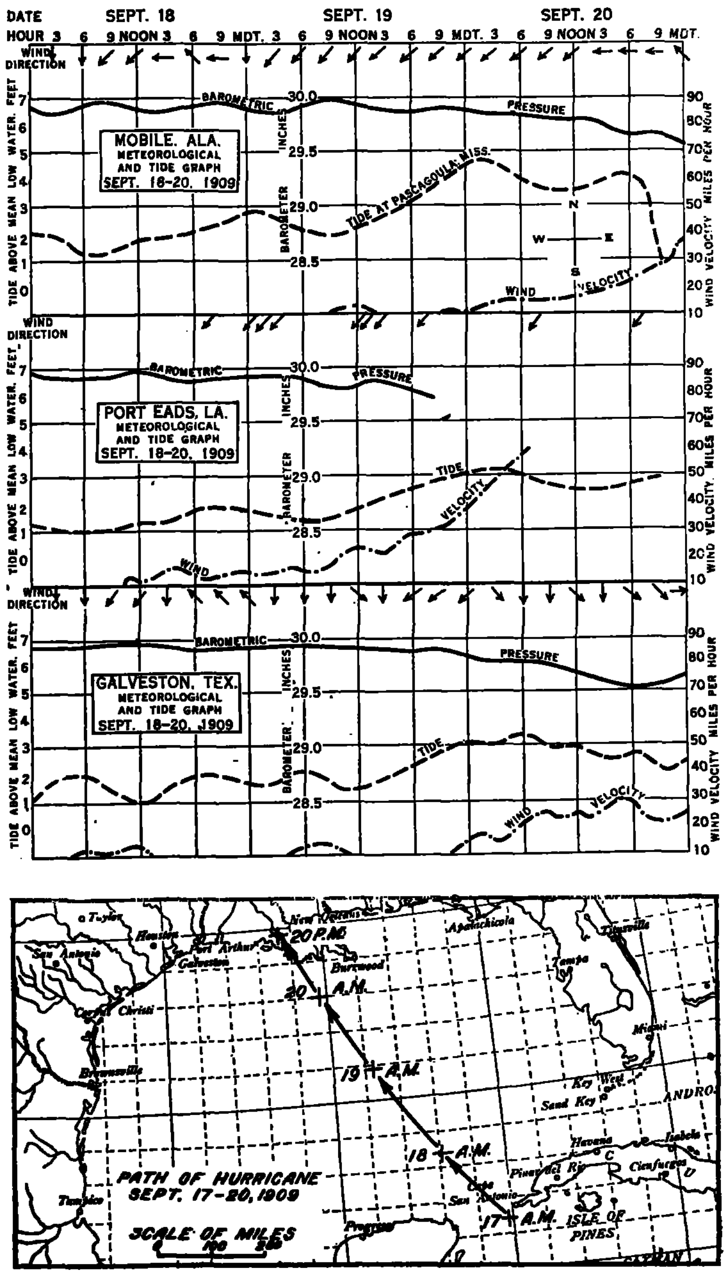


PLATE IV.—*I. M. Cline.*

about the same time on the afternoon of the 18th, when the center of the disturbance was nearly 400 miles distant in space and 40 hours in time. The rise which commenced at Port Eads and Pascagoula at 8 p. m. of the 18th had started from the southeast Gulf about 18 hours previously and had traveled about 500 miles at the rate of 28 miles per hour. By noon of the 19th there had been a rise at Pascagoula of 1.1 feet, and at Port Eads of 0.8 foot, and by midnight of the 19th the water had risen 2.4 feet at Pascagoula and 2 feet at Port Eads. No material changes in the tide other than the regular change were shown at Galveston until the night of the 19th. The storm tide from the forenoon of the 18th to the forenoon of the 20th at Pascagoula, Miss., was about 2.8 feet, and at Port Eads, La., 2.2 feet, and at Galveston, Tex., 1 foot. The rise in the tide at Galveston all occurred during the night of the 19th-20th.

The wharves at Mobile were overflowed and the water was within half a block of Royal Street, the height of the water at that place being 8.7 feet.

The height of the water above mean Gulf level over the Louisiana coast region in the hurricane of September 20, 1909, has been determined by engineers of the Department of Agriculture in connection with the reclamation of marsh land (18). These records show the greatest height of the water in different parts of the hurricane with reference to the line of advance of the center, and from a study of

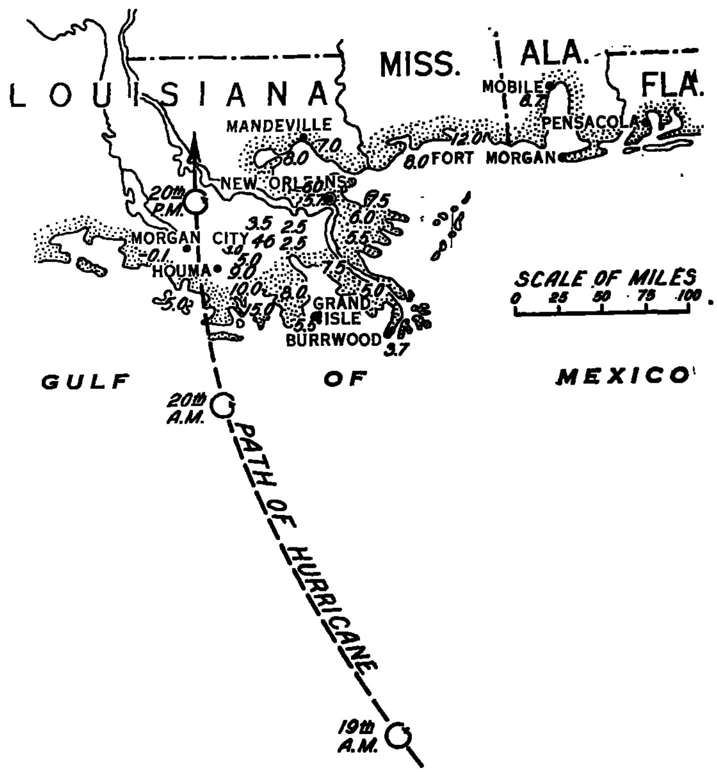


FIG. 1.—Height of storm tide above mean Gulf level in right and left hand segments of the hurricane, September 20, 1909. This shows the area overflowed when storm moves inland at nearly right angles to the coast line.—*A. M. Shaw* (18) and *I. M. Cline.*

these we may learn where to expect dangerous storm tides with the approach of a hurricane. The height of the water at several places in southeastern Louisiana during the hurricane of September 20, 1909, is shown in figure 1. Seven parishes were flooded, the height of the water being 6 to 10 feet over the greater portion of the area. The actual height of the water over the land in the right-hand segment of the cyclonic area resulted from the accumulation of water forced forward by the winds and checked in speed by the marsh lands, swamp forests, and levees. This is distinctly shown by the increased depth of 2 to 4 feet of water 30 to 50 miles inland from Burrwood and Port Eads. The depths of 7 to 10 feet occurred at points where the greatest resistance to the advancement of the water, forced forward by the winds, was encountered. To the left of the line of advance of the center of the hurricane, the water did not get high enough at any point to attract attention and at Morgan City, La., near the center and in the left-hand segment of the cyclonic area, the water was 0.1 of a foot below mean Gulf level, while 75 miles to the right of the center the water was 5 to 7 feet above.

The damage to property by this storm amounted to $6,400,000, and 353 lives were lost.

October 13–18, 1910.—This disturbance moved into the Florida Straits on the 14th, moved toward the northwest during the 15th, southward during the 16th, and then eastward to the Florida Straits by the morning of the 17th, after which it moved northward over Florida during the 18th. Barograph records of the French S. S. *Texas* from the 13th to the 17th confirm this movement.* We have no tide records for this disturbance. The official in charge, Weather Bureau Office, Tampa, Fla., reports the tide 6.6 feet below mean low water on the morning of the 18th, the lowest water of record, the cyclonic area at that time was moving northward with its center to the right of Tampa. After the passage of the center of the storm and its recurve northward, the water rose 10.1 feet, to 3.5 feet above mean low tide.

August 13–17, 1915.—This hurricane moved across the western end of Cuba into the Gulf of Mexico during the forenoon of the 14th, traveled in a direct line and passed inland on the Texas coast a short distance to the left of Galveston on the morning of the 17th. The disturbance advanced with a speed of about 12 miles per hour.

The wind, pressure and tides at Mobile, Ala. (tide at Fort Morgan), Burrwood, La., and Galveston, Tex., are shown on Plate V. The storm tide began rising slowly at Galveston, Burrwood, and Fort Morgan during the forenoon of the 15th, just 24 hours after the disturbance had moved into the Gulf of Mexico. These rises in the water over a coast line more than 500 miles long all on the right of the line of advance of the hurricane resulted from waves started out from the region covered by the hurricane in the southeast Gulf during the 14th. The distance of the center of the storm at that time from Fort Morgan and Burrwood was 450 miles and from Galveston, 700 miles. This would indicate that waves and swells were carried forward in the front of the right-hand segment in the line of advance of the hurricane at a velocity of 40 to 50 miles per hour and those going toward shore farther to the right of the line of advance traveled with a little less than half that speed. The highest water at Fort Morgan, 2.8 feet, was recorded at 6 a. m. on the 16th and showed a rise of 1.8 feet in 24 hours. At Burrwood, 2.6 feet was recorded at 1 a. m. of the 16th, a rise of 1 foot in 24 hours. The tide did not rise after that to any extent, at either of these places, but high water continued at Fort Morgn and Burrwood until the storm moved inland; the regular tides were not obscured.

At Galveston the tide continued to rise and was 4.1 feet at 6 :30 a. m. on the 16th, a storm tide of about

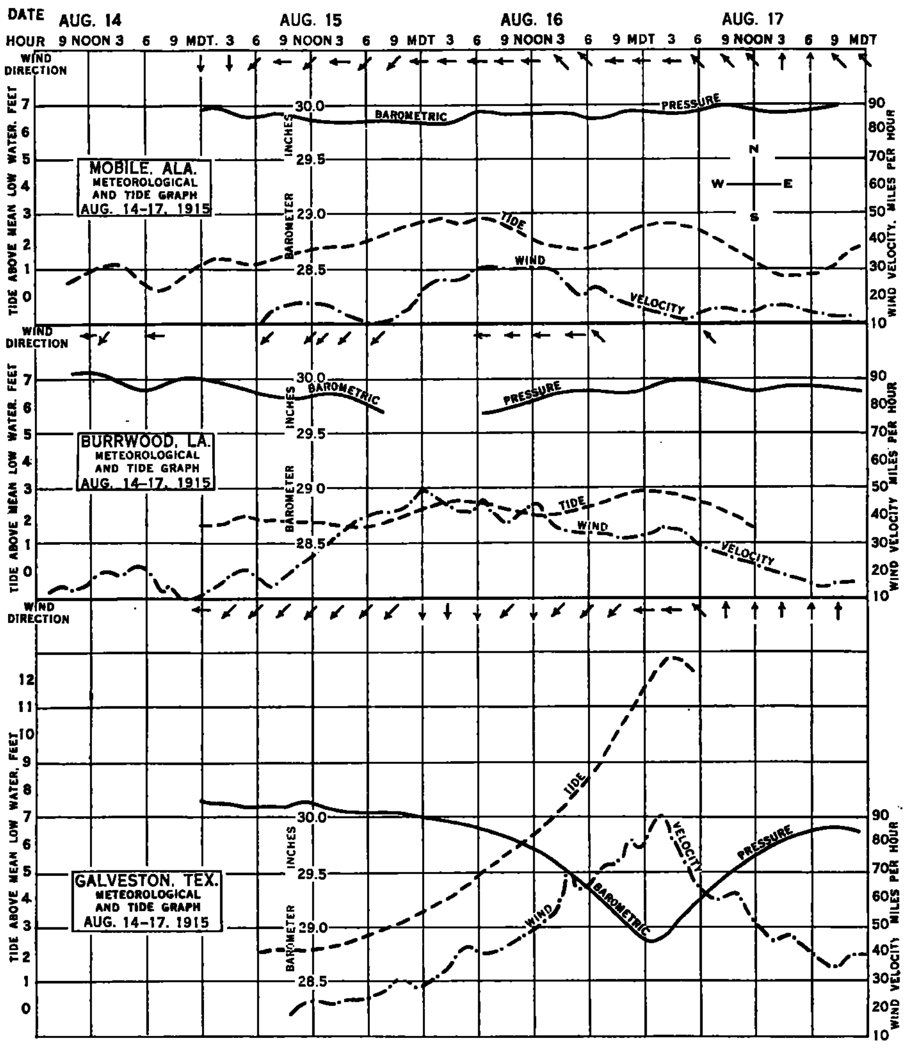


PLATE V.—For path and movement of hurricane, August 14-17, 1915, see figure 2.—*I. M. Cline.*

* It is hoped at a later date to publish a full discussion of all reports of this remarkable storm.—EDITOR.

3.1 feet in 24 hours. The center of the disturbance at this time was nearly 300 miles from Galveston and 21 hours distant in time. The rise in the water in front of the storm at this hour at Galveston was nearly twice the rise of 1.8 feet at Fort Morgan, 300 miles to the right of the line of advance of the hurricane, and was three times greater than the rise at Burrwood. The water continued to rise at Galveston until about 3 a. m. of the 17th, when it was 12 feet. The tide changed very little at Fort Morgan and Burrwood after 3 a. m. of the 16th and commencing at 3 a. m. of the 17th, fell to about normal on the afternoon of that date.

The heights of the water above mean Gulf level along the coast during this storm are shown in figure 2. This shows the height of the water in feet and tenths along the Gulf coast at different distances from the line over which the center of the hurricane advanced.

During the passage of this hurricane, the action of waves and currents in moving objects in the open Gulf was brought out by the movement of light and whistling buoys that were within its range. Trinity Shoals gas and whistling buoy, weighing 21,000 pounds, anchored in 42 feet of water, with 6,500 pound sinker and 252 feet of anchor chain weighing 3,520 pounds, was carried 8 to 10 miles westward of its proper location in latitude 29° 07′ N. and longitude 92° 15′ W. The shape and exposure of the buoy are shown in figure 3. The location of this buoy was 100 miles to the right of the line of advance of the center of the storm.

Galveston Bar gas and whistling buoy, same as shown, anchored at the end of Galveston Jetties in 36 feet of water was carried 4½ to 5 miles in a southwesterly direction from its proper location. This buoy was about 20 miles from the center of the storm.

A buoy of the same class, with the same moorings in 42 feet of water, located on Heald Bank, 28 miles off the entrance to Galveston Bay, was not moved from its proper position, although its lights were extinguished. The Heald Bank buoy was a little to the left of the line of advance of the center of the hurricane. From the action of the water on these buoys we can get some information concerning the effects of currents and waves attending hurricanes.

The property damage in this storm was about $21,000,000, and 275 lives were lost.

September 2–4, 1915.—A disturbance of considerable intensity crossed western Cuba, moved into the east Gulf and recurving slowly, moved inland near the mouth of the Apalachicola River during the early morning hours of the 4th. Pressure, wind and tide graphs for Mobile (tide, Fort Morgan), Ala., and Burrwood, La., are shown in Plate V. These stations were located, Fort Morgan, 100 miles, and Burrwood, 200 miles to the left of the line of advance of the center of the storm. The tides at these stations were not influenced in any manner by the disturbance and there was no high tide at Pensacola. Along the Florida coast, to the right of the line of advance high water prevailed generally. At St. Petersburg, Fla., water was 4.9 feet above any previous high water.

September 22–30, 1915.—This was one of the most intense hurricanes in the history of the Gulf coast. The cyclonic area moved through the Yucatan Channel during the night of the 27th, and traveling northwestward moved inland on the Louisiana coast to the left of and

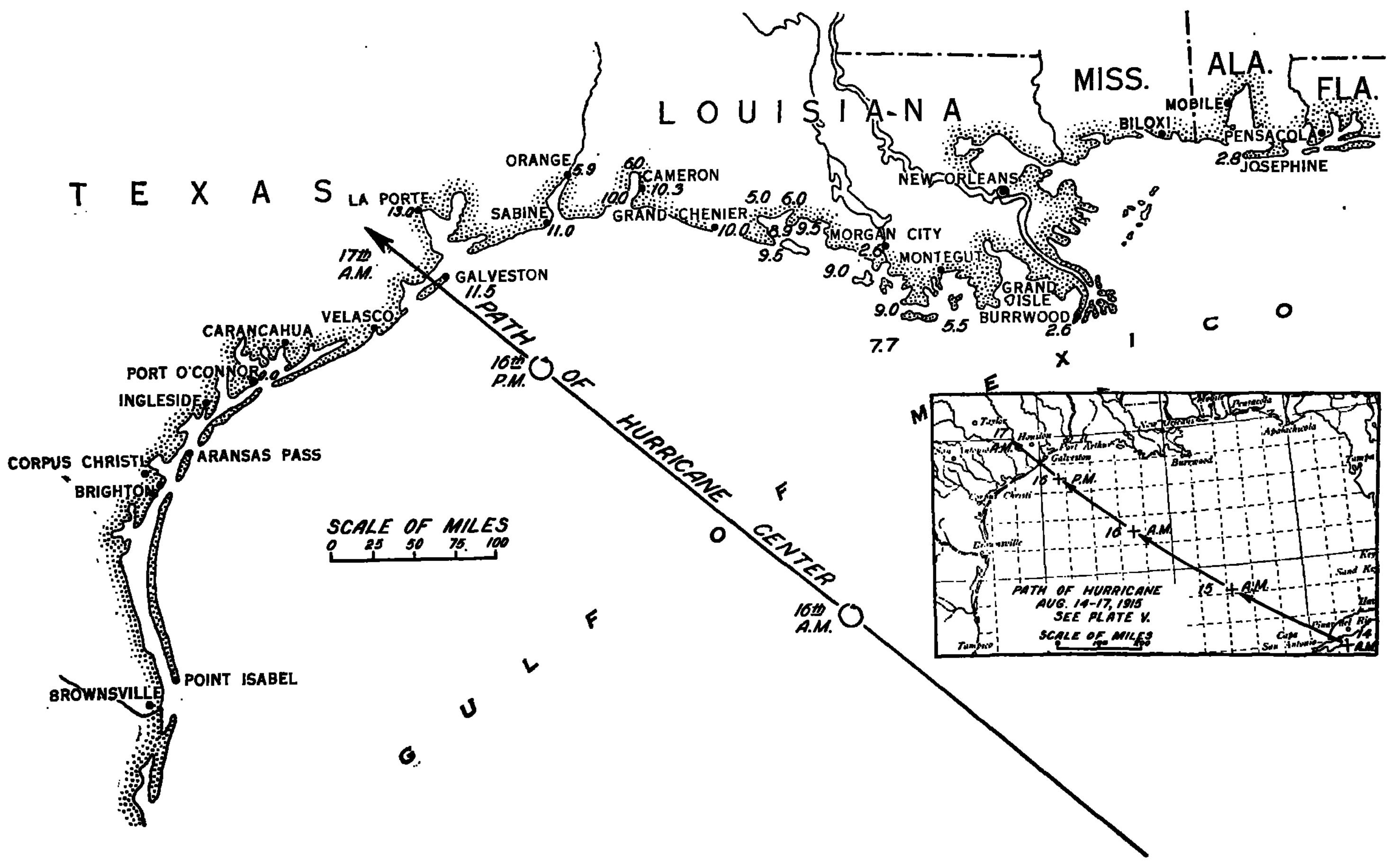


FIG. 2.—Height of storm tides along the Gulf coast, above mean Gulf level in the hurricane, August 16–17, 1915. This shows the storm tides at various distances from the center of a hurricane which moves through the Yucatan Channel and thence across the Gulf to the Texas coast.—*I. M. Cline.*

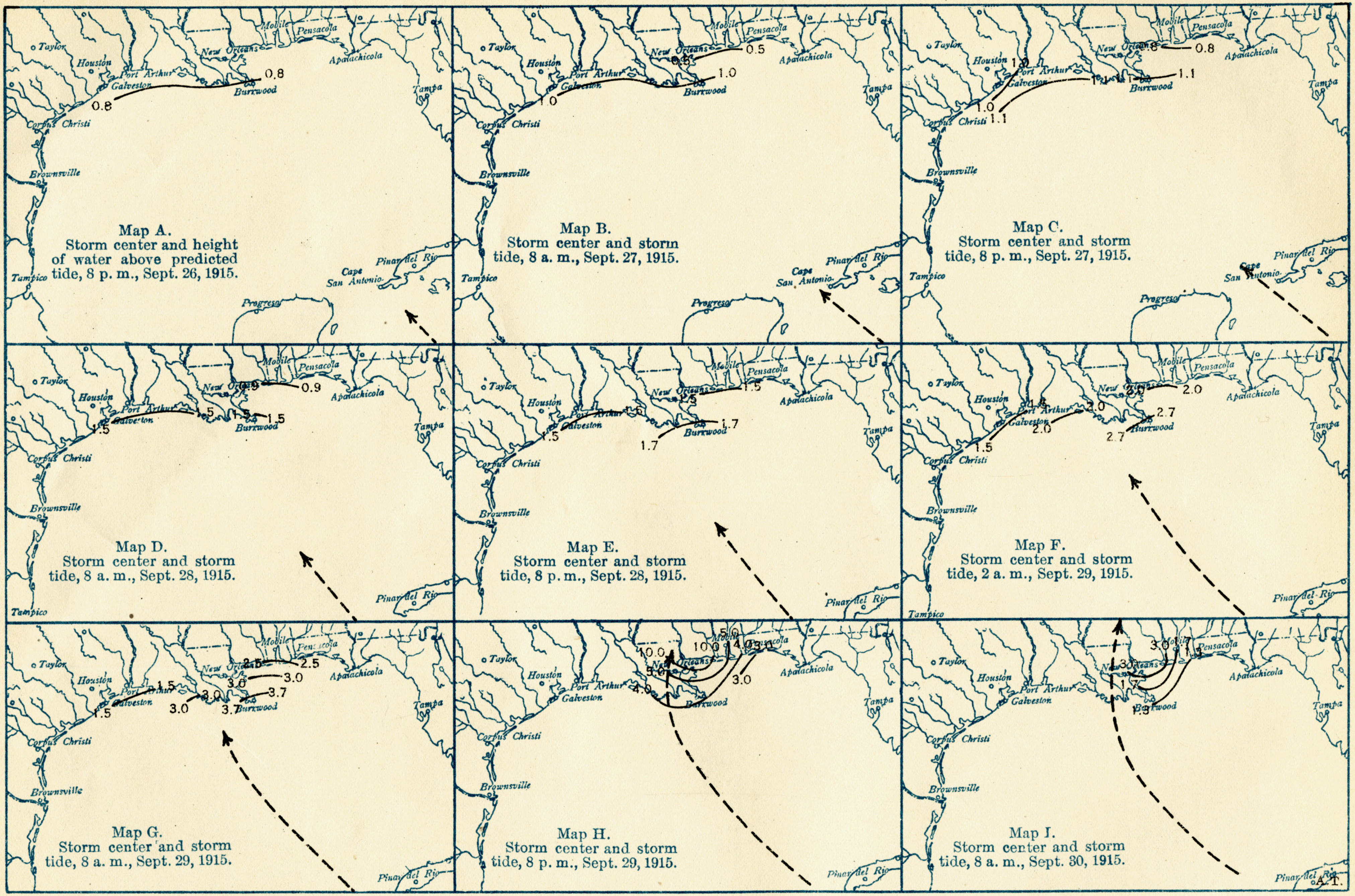


FIG. 4.—Storm tides on the Gulf coast, September 26–30, 1915. Maps A, B, C, D, E, F, G, H, I. The point of the arrow indicates the position of the center of the hurricane. The figures at the ends of the lines drawn near the shore show the rises of the storm tide on the coast as the storm advanced; that is, the height of the water above the predicted tide at that hour. This is for a storm that recurved slowly.

near Grand Isle, La., during the 29th. This disturbance recurved slowly after crossing latitude 27° N. and moved slowly northward.

The pressure, wind and tides at Mobile (tide records Fort Morgan), Ala., Burrwood, La., and Galveston, Tex., are shown in Plate VII. The tide was about 0.8 of a foot above the predicted tide at 8 p. m. on the 26th. At 8 a. m. on the 27th the water had commenced rising at Fort Morgan and was 1 foot above the predicted tide on the Gulf coast from Burrwood to Galveston; at 8 p. m. the excess was 1.1 feet. At 8 a. m. of the 28th, there was 1.5 feet of water in excess of the predicted tide at Burrwood and Galveston and 0.8 foot at Fort Morgan. At 8 p. m. of the 28th, when the storm was about 250 miles distant, there was a storm tide of 1.7 feet at Burrwood and 1.5 feet at Fort Morgan. When the storm began recurving to the right, the water ceased rising at Galveston, and no storm tide was recorded there after 8 a. m. of the 28th. At 2 a. m. of the 29th, the tide had continued rising on the middle Gulf coast and showed 2.7 feet at Burrwood and 2 feet at Fort Morgan. At 8 a. m. of the 29th, the storm tide had risen to 3.7 feet at Burrwood and 2.5 feet at Fort Morgan. The rise of the storm tide is shown in figure 4.

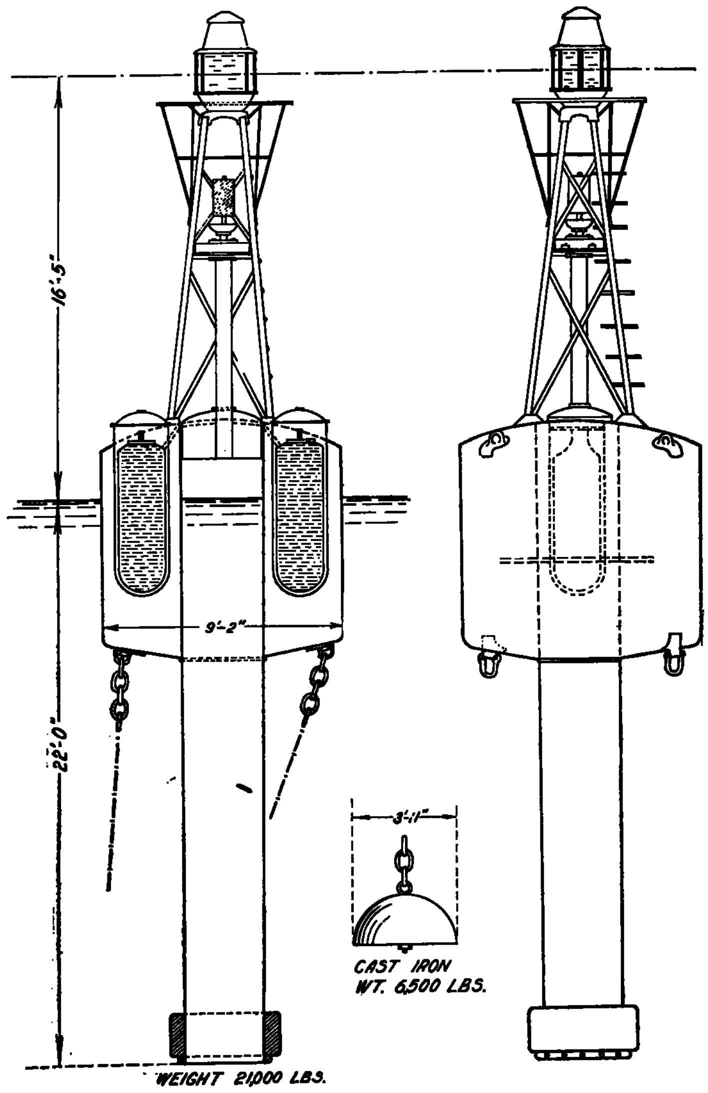
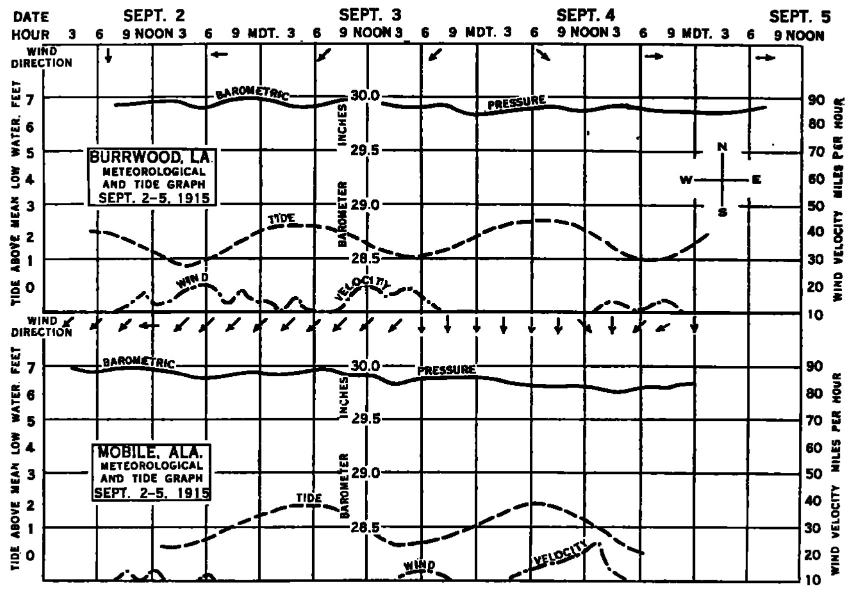


FIG. 3.—Design of gas and whistling buoy anchored at Trinity Shoals, Louisiana coast; Galveston Bar, off jetties and Heald Bank, Tex. Trinity Shoals and Heald Bank buoys are anchored in 43 feet and Galveston Bar in 36 feet of water.

The storm waters were carried over southeastern Louisiana and the depth was more than 12 feet on the shore of Lake Pontchartrain and 10 to 11 feet on the Louisiana and Mississippi coasts. High water prevailed to the right of the center of the hurricane to the eastward of Pensacola, where the water was 4 feet high, and at Mobile the storm water was banked up 7.2 feet. The distribution of the storm waters along the middle Gulf coast in the different parts of the hurricane are shown in figure 5. The height of the water in the open Gulf, as nearly as we can expect to get records, was 4.6 feet, 45 miles to the left of the center of the storm at a lighthouse about 10 miles out in the Gulf from Raccoon Point; 8.4 feet at Timbalier Light, a few miles to the right of the center, which is 10 miles from land; and 5.8 feet at Burrwood, about 60 miles to the right of the center. No water was carried inland to the left of the line of advance of the center of the hurricane, and at Morgan City, 15 miles from the Gulf, the tide was 0.4 of a foot below mean Gulf level. At Pensacola, 175 miles to the right of the center, the tide was 4 feet; at Mobile, 150 miles, it was 7.2 feet; at Gulfport, Miss., 80 miles, it was 9.6 feet; at Bay St. Louis, 65 miles, it was 11.8 feet.

The center of the storm passed between Lake Pontchartrain and Lake Maurepas. In Lake Pontchartrain, to the right of, but nearly in the center of the hurricane, the water was 13 feet at Frenier, due to the wind forcing the water up against a dense growth of timber in that



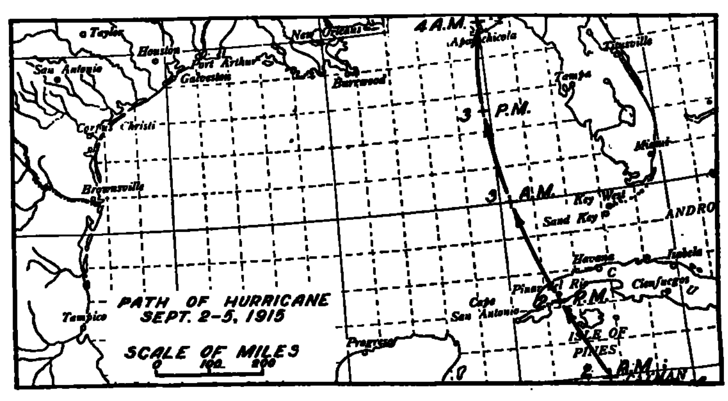


PLATE VI.—*I. M. Cline.*

locality. A few miles further along the line of advance of the center of the storm, near the connection between Lake Pontchartrain and Lake Maurepas, where there was open space, the height of the water was 6 feet. At Frenier we find that the force of the wind, with about 25 miles open waterway, banked the water 13 feet against an obstruction of only a few miles extent, 7 feet higher than on either side.

The damage resulting from this hurricane is estimated at $13,000,000, and 275 persons were drowned.

July 1-6, 1916.—This disturbance made its appearance in the Caribbean Sea on the afternoon of the 1st, moved almost in a straight line through the Yucatan Channel on the 3d and reached the Mississippi coast late in the afternoon of the 5th. The storm covered a considerable area and was of geat intensity.

The wind, pressure, and tides at Mobile (tide records, Fort Morgan), Ala., Burrwood, La., and Galveston, Tex., are shown in Plate VIII. The tide at Mobile and Burrwood was rising at noon of the 4th when the disturbance was centered 400 miles distant in space and 26 hours in time. This rise of water had traveled from the Yucatan Channel a distance of 500 miles in 18 hours in the front and to the right of the line of advance of the center of the cyclonic area. At midnight of the 4th the water had risen 1 foot at Burrwood and 1.4 feet at Fort Morgan. At 8 a. m. on the 5th the storm tide was 2.8 feet at Port Eads and Burrwood and 3 feet at Fort Morgan. The highest water at Fort Morgan was 5.3 feet and occurred at 1 p. m. of the 5th; at Burrwood the highest water was 3.8 feet at 10 a. m. of the 5th. Burrwood was about 25 miles to the left and Fort Morgan about 75 miles to the right of the line of advance of the center. The distance traveled by the center of the disturbance after passing Burrwood before coming in a line with Fort Morgan was 50 miles.

The difference in time between the passage of the crest of high water at Burrwood and Fort Morgan, 3 hours, would indicate speed of about 15 miles per hour, which is the same as the progressive speed of the cyclonic area. The location of these stations is such that no great banking up of water by physical obstruction was likely to have taken place. Therefore, these records serve as a good illustration of the heights reached by storm tides on the different sides of the hurricanes where the open space of water represents as nearly the condition in the open Gulf as we can expect to find. Fort Morgan was three times farther than Port Eads from the center. As the shore was approached the water banked up much higher, this being due to physical obstructions. The height of the water at Mobile was 11.6 feet, which is 6.3 feet above the actual height reached by the water at Fort Morgan. High water did not occur as far west as Biloxi and Pass Christian. The damage at Mobile and on the Alabama coast amounted to $2,500,000, and 12 persons were drowned. The height of the water at Pensacola, Fla., was 5 feet.

The damage at Pensacola amounted to $1,000,000. The storm did not influence the tide in any manner at Galveston, Tex.

August 12-19, 1916.—This disturbance passed through the Yucatan Channel into the Gulf of Mexico during the

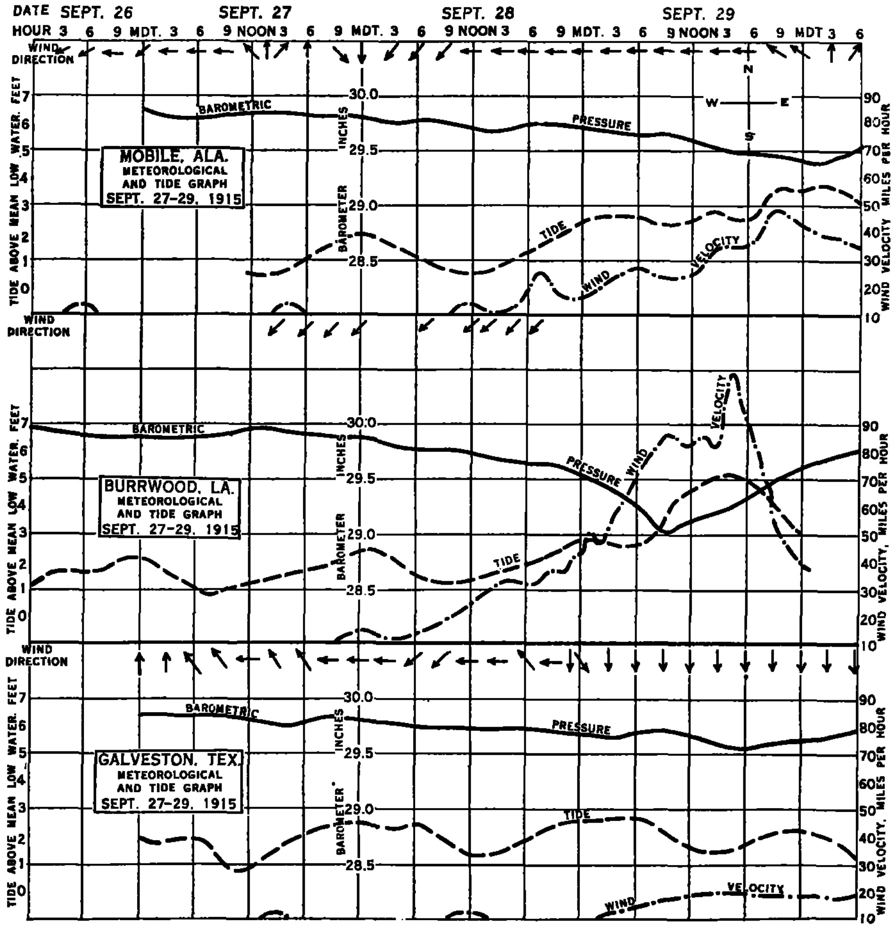


PLATE VII.—For path and movement of hurricane, September 27-29, 1915, see figure 4.—*I. M. Cline.*

night of the 16th, advanced northwesterly in nearly a straight line, and moved inland on the Texas coast midway bewteen Corpus Christi and Brownsville during the afternoon of the 18th.

We have no tide records in the vicinity of the center of this hurricane, but wind, pressure, and tide records at Burrwood, La., 400 miles to the right, and Galveston, Tex., 250 miles to the right of the line of advance of the center of the hurricane, are shown in Plate IX. No appreciable influence was shown on the tide at Burrwood. At Galveston, 250 miles to the right of the line of advance of the center, the water commenced rising about 6 p. m. of the 17th, when the center of the disturbance was nearly 400 miles distant. The water that caused this

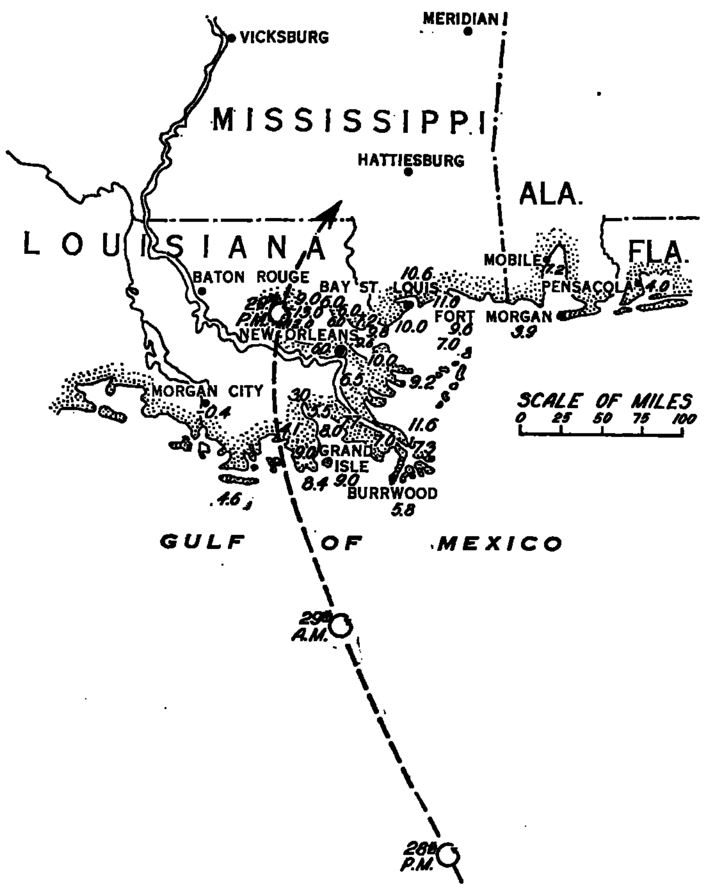
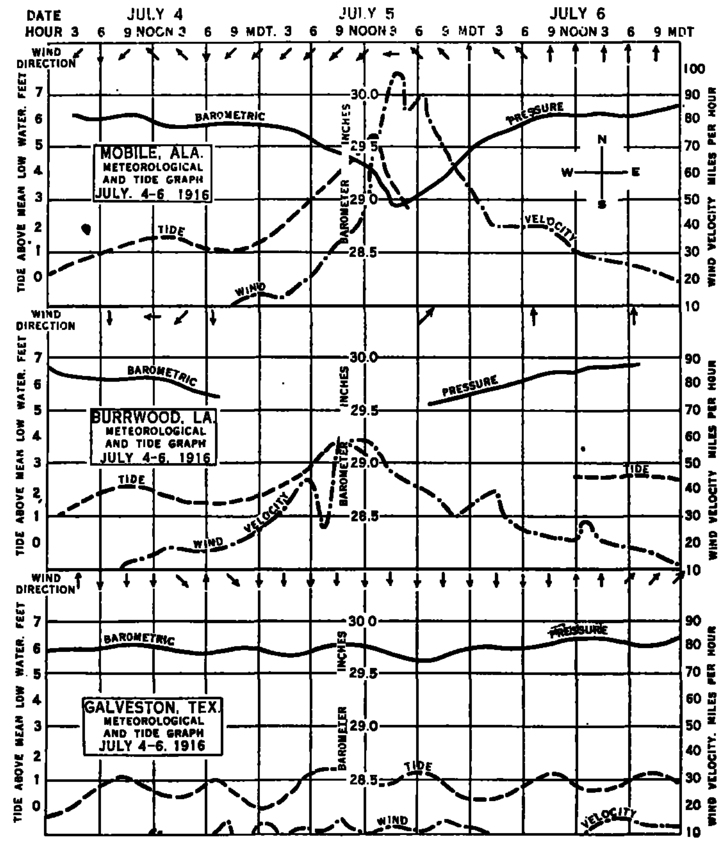


FIG. 5.—Height of storm tide above mean Gulf level. in left and right hand segments of the hurricane, September 29, 1915. This shows the distribution of high water on the middle and east Gulf coast with a slowly recurving hurricane.—*C. W. Okey* (18) and *I. M. Cline.*

rise must have started on its journey toward the Texas coast when the storm was passing through the Yucatan Channel and had traveled a distance of nearly 800 miles, showing a speed of about 40 miles per hour. The cyclonic area advanced at the rate of about 18 miles per hour. The water at Galveston rose steadily from 6 p. m. on the 17th until 6 p. m. of the 18th, when the height of the water was 4 feet, about 3 feet being storm tide. Galveston, at the time of the occurrence of the highest water, was 200 miles from the center, and a line drawn through Galveston and the center of the storm at that time crossed the line of advance at right angles. The advance of the hurricane was more prominently shown in the rise of the water at Galveston than in the pressure or wind changes.

The damage caused by this hurricane was estimated at $1,800,000, and 15 persons were killed or drowned.

September 21–29, 1917.—This disturbance moved through the Yucatan Channel into the Gulf of Mexico during the night of the 25th and advanced in a direction a little west of north toward the mouth of the Mississippi River. When within about 50 miles of Port Eads the storm began recurving to the right, and the center, passing about 50 miles to the right of Port Eads, La., moved inland to the right of Pensacola, Fla.



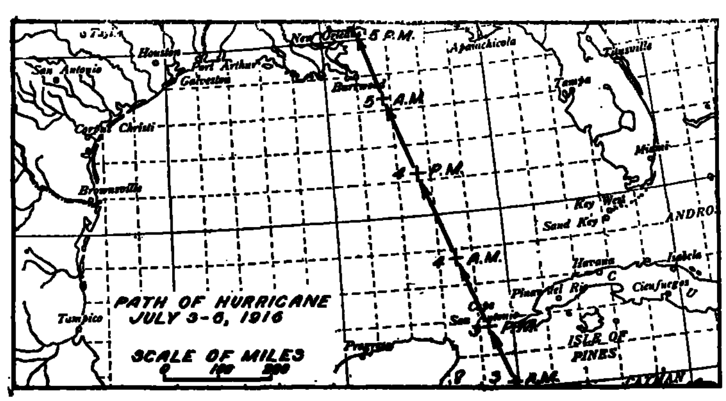
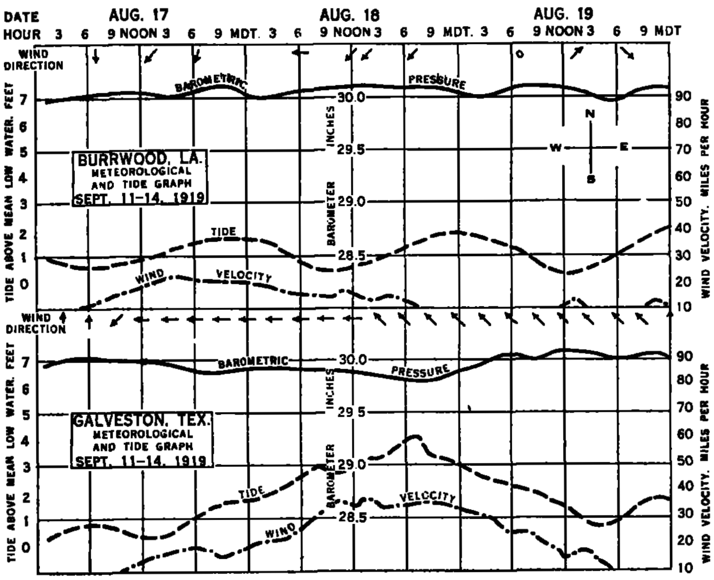


PLATE VIII.—*I. M. Cline.*

The pressure, wind, and tides for Pensacola, Fla. (the tides are drawn from the observations made by the observer of the Weather Bureau except the highest stage, which was obtained from the United States Engineers), Burrwood, La. (tide Port Eads), and Galveston, Tex., are shown in Plate X.

The changes in the height of the water with the advance of the hurricane are shown in figure 6. The changes in the tide in a recurving hurricane are shown in this case. The tide commenced rising at both Pensacola and Port Eads during the night of the 26th and was 0.6 to 0.7 of a foot above the predicted tide at 8 a. m. of the 27th, when the disturbance was centered about 200 miles from Port Eads and 300 miles from Pensacola. At 8 p. m. of the 27th there was 1.0 foot of storm tide at both Pensacola and Port Eads. On the morning of the 28th the line of advance of the center, if continued, would have carried the center of the storm over Port Eads, which place had a storm tide of 2.7 feet, and Pensacola only 1.1 feet. At 10 a. m. reports from Pilottown showed the storm had shifted its course to the right. The tide began rising rapidly at Pensacola and by 2 p. m. the storm tide at that place was 2.8 feet. The storm tide about 8 p. m. on the 28th at Fort Barancas, Fla., was 5.8 feet, the height of



(Dates in cut should be Aug. 17-19, 1916.)

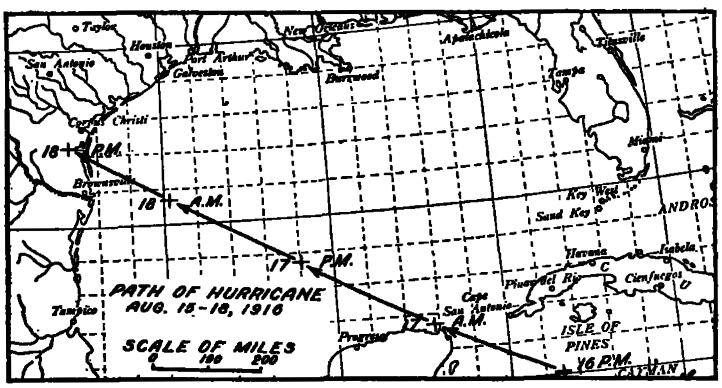


PLATE IX.—*I. M. Cline.*

the water being 7.8 feet. The water in the river at Mobile fell 5 feet below low water on the afternoon of the 28th.

The damage at Pensacola amounted to $170,000. This place was near the center of the storm, but being to the left of the line of advance, suffered very little damage, notwithstanding the intensity of the hurricane.

August 1–6, 1918.—This disturbance moved through the Yucatan Channel into the Gulf of Mexico during the night of the 4th, traveled in a northwesterly direction and passed inland over Lake Charles, La., during the 6th. The hurricane was small but of marked intensity. We have no tide records for this storm, but at Morgan City, 150 miles to the right of the line of advance of the center of the storm the tide rose 3 feet, and 28 miles west of the center, at Johnsons Bayou, there was a tide of 2.8 feet.

The damage from the hurricane amounted to $5,000,000 and 34 deaths resulted.

September 6–14, 1919.—This disturbance passed through the Florida Straits during the night of the 9th, moved very slowly during the 10th, 11th, and 12th, with its line of advance pointing toward the Louisiana coast west of the Atchafalaya River. On the 13th the disturbance changed its course to the westward, moved rapidly in almost a straight course, and passed inland with its center a short distance to the left of Corpus Christi, Tex., during the afternoon of the 14th.

The pressure, wind, and tides at Burrwood, La., and Galveston, Tex., are shown on Plate XI. The tide record at Galveston was incomplete after 12 noon of the 13th. The highest point reached by the water has been obtained from the United States Engineers and other records from tide heights telegraphed by the observer at Galveston with observations, and these data have been supplemented by other reports. We have thus been able to complete the tidegraph with a fair degree of accuracy. The long stretch of open water, more than 1,000 miles, traversed by this hurricane after entering the Gulf of Mexico, furnishes a splendid opportunity to study the changes in the stages of the water along the coast both in front and along the line of advance of the center of the hurricane.

The storm tides and their changes with the advance of the hurricane from the morning of the 11th until the afternoon of the 14th, when the hurricane moved inland, are shown in figure 7. There was a rise of 0.3 foot above the predicted tide at Burrwood, La., at 8 a. m. of the 11th, when the center of the storm was 400 miles distant. At 8 p. m. of the 11th the rise of 0.3 foot had reached Galveston, traveling from the longitude of Burrwood, about 500 miles, in 12 hours, nearly 40 miles per hour, and the storm tide at Burrwood at this time was 1.1 feet. Galveston was at this time 600 miles distant from the center of the hurricane and Burrwood about 350 miles distant. By 8 a. m. of the 12th the storm tide was 1.7 feet at Burrwood and 0.7 of a foot at Galveston; and at 8 p. m. the height of the water in excess of the predicted tide was 1.9 feet at Burrwood and 1.6 feet at Galveston.

On the morning of the 13th the hurricane tide was 2.6 feet at Galveston, 300 miles in front of the center, and 2.4 feet at Burrwood, about 200 miles to the right of the line of advance of the center. No increase in the height of the water took place at Burrwood during the 13th, but at Galveston the storm tide at 8 p. m. was 3.6 feet, a gain of 1 foot in 12 hours; at this hour the water had commenced rising slowly at Aransas Pass, Tex. At 3 a. m. on the 14th the storm tide was 7.6 feet at Galveston, and 4 feet at Aransas Pass. At 8 a. m. of the 14th the height of the water had not changed at Galveston, but had risen 2 feet at Aransas Pass, during the preceding five hours and stood 6 feet. When the storm moved inland, about 3 p. m. on the 14th, there was a storm tide of 11.1 feet at Aransas Pass. The water, driven before the wind with the passage of the hurricane inland, banked up in places to depths of 12 to 16 feet.

This storm furnishes a good example for the study of the changes in the depth of the water along the coast in hurricanes which are moving coastwise. These heights are represented in figure 8. The rise of the storm tide in bays and estuaries to the right of the line of advance of the hurricane lags behind the rise on the coast. At Morgan City the highest water, 7 feet, occurred at 4 a. m. on the 14th, six hours after it had occurred on the near-by coast. At La Porte, Tex., near the upper end of Galveston Bay, the highest water, 8.5 feet, was at 1 p. m.

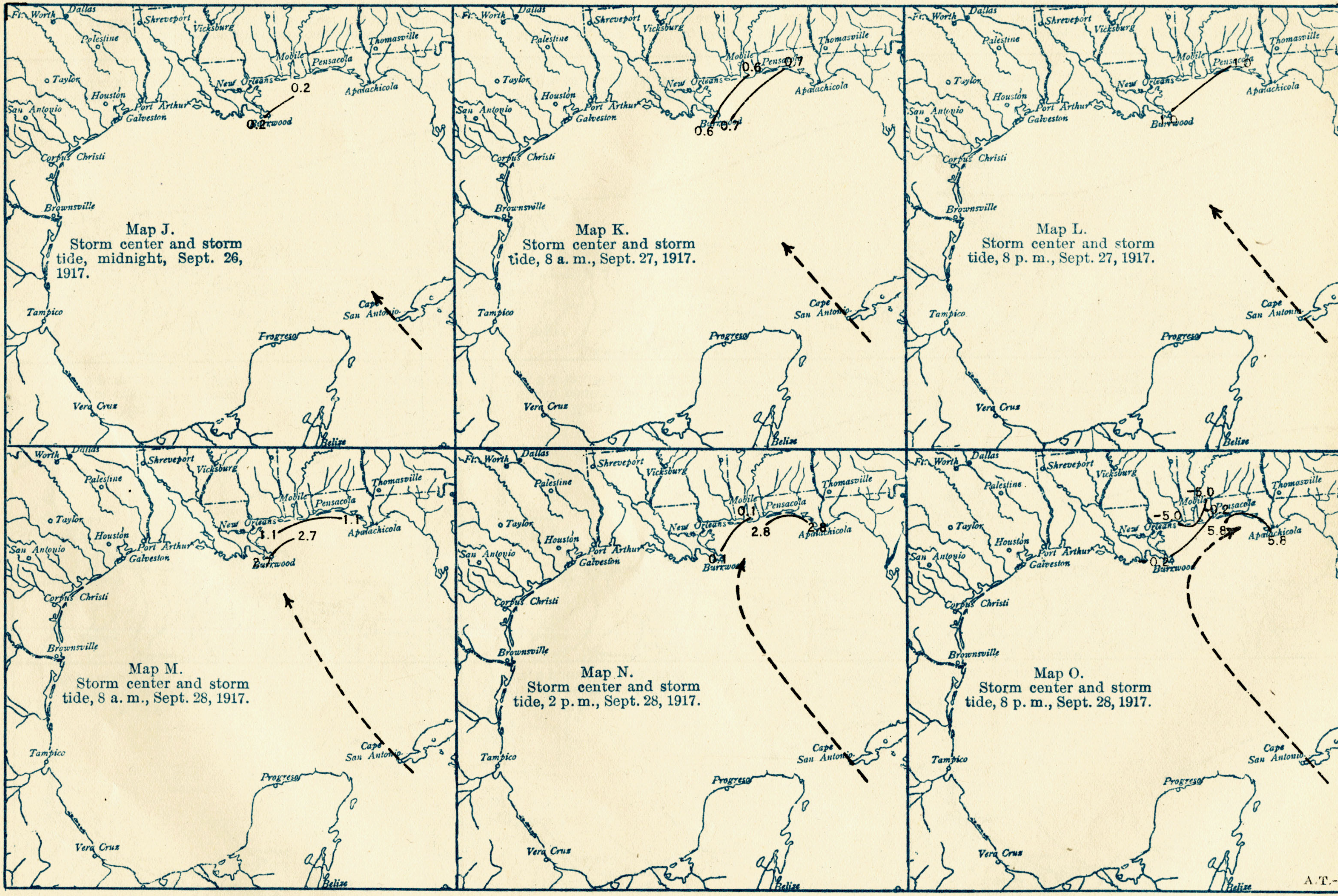


Fig. 6.—Storm tides on the Gulf coast, September 26–28, 1917. Maps J, K, L, M, N, O. The point of the arrow indicates the position of the center of the hurricane. The figures at the ends of the lines drawn near the shore show the rises of the storm tide on the coast as the storm approached; that is, the height of the water above the predicted tide at that hour. This is for a storm that recurved rapidly.

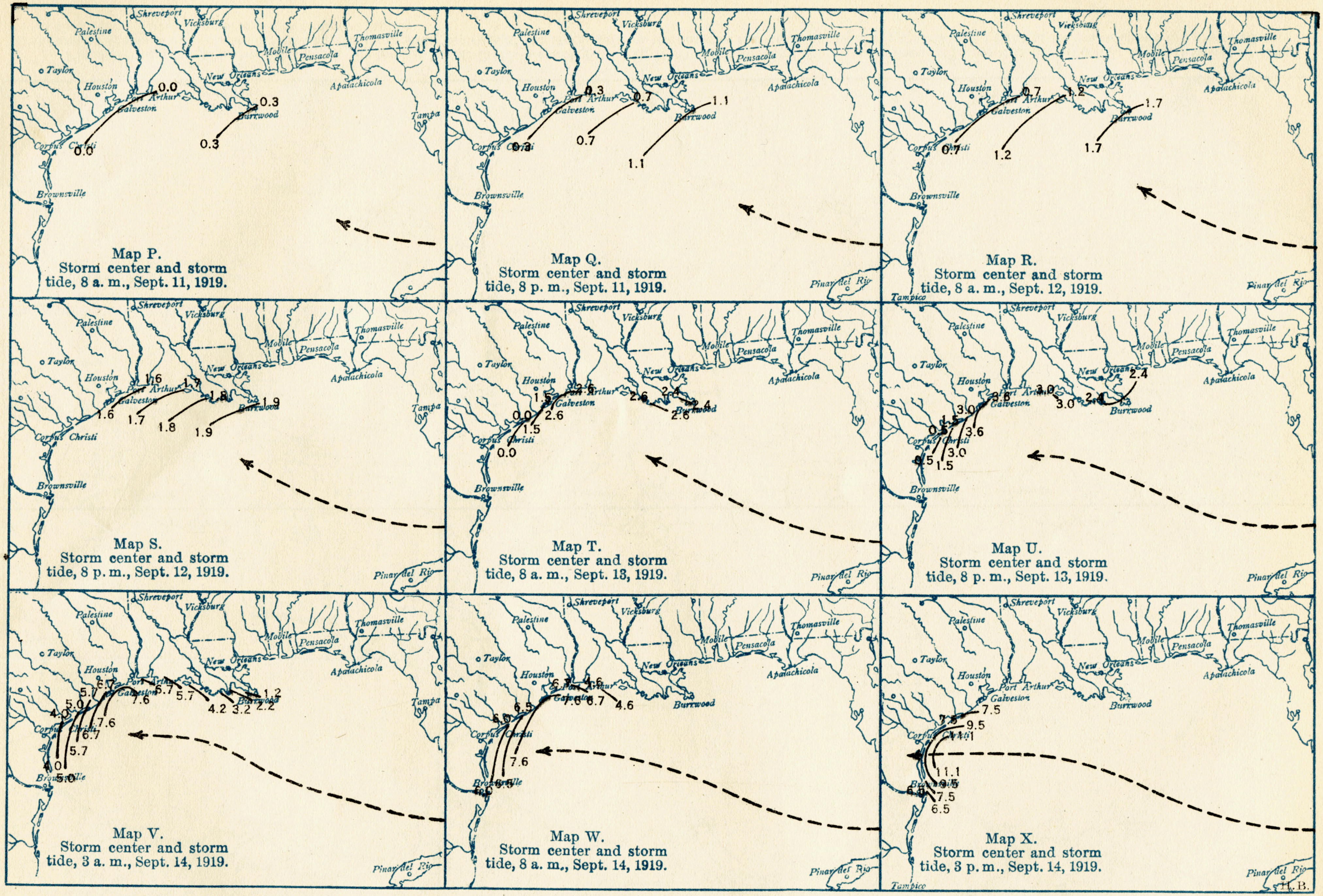


FIG. 7.—Storm tides on the Gulf coast, September 11–14, 1919. **Maps P, Q, R, S, T, U, V, W, X.** The point of the arrow indicates the position of the center of the hurricane. The figures at the ends of the lines drawn near the shore show the rises of the storm tide on the coast as the storm approached; that is, the height of the water above the predicted tide at that hour. This is for a storm that moved coastwise.

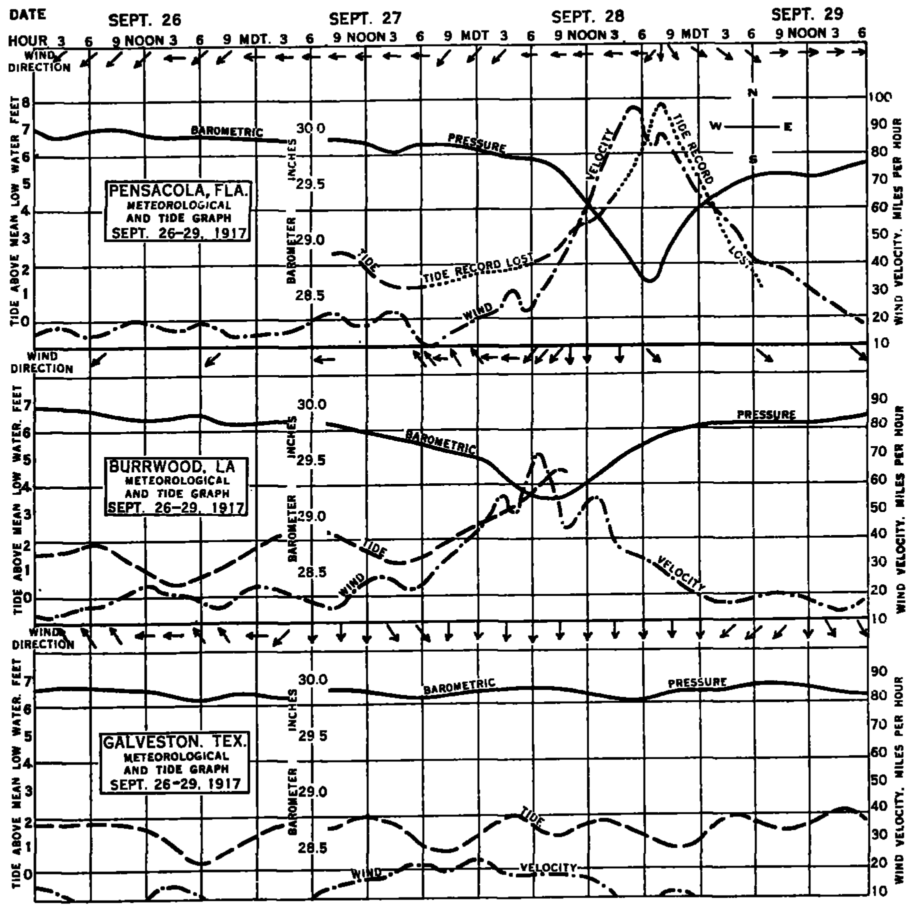


PLATE X.—For path and movement of hurricane, September 26-28, 1917, see figure 6.—*I. M. Cline.*

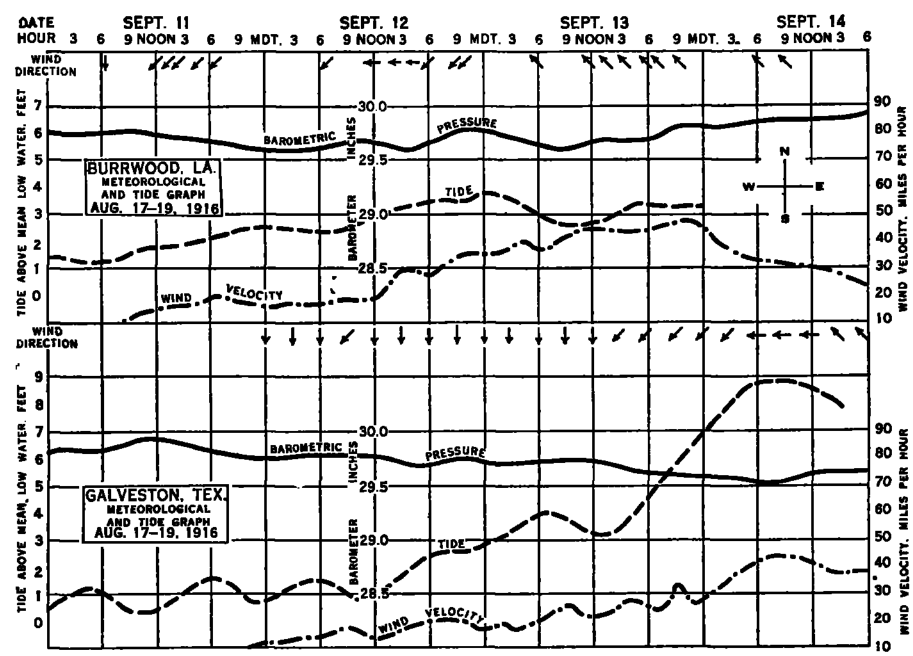


PLATE XI.—For path and movement of hurricane, September 11-14, 1919, see figure 7. (Dates in cut should be Sept. 11-14, 1919.)—*I. M. Cline.*

on the 14th, about 12 hours after it had reached Galveston. At Carancahua, Tex., a tide of 10 feet occurred at 5 p. m., about 2 hours later than at Aransas Pass and at Ingleside, 12 feet at 10 p. m. on the 14th, nearly 9 hours after Aransas Pass.

During the passage of this storm Trinity Shoals gas and whistling buoy (described under hurricane of Aug. 17, 1915), anchored in 42 feet of water, was carried $2\frac{1}{2}$ miles to the westward.

Galveston Bar gas and whistling buoy was carried $1\frac{1}{2}$ miles to the southwest.

Aransas Pass gas and whistling buoy anchored in 42 feet of water, latitude 27° 50′ N., longitude 92° 02′ W., was carried 5 miles nearly parallel to the coast and a little in toward the coast. This buoy weighs 8,000 pounds, the anchor 5,000 pounds, and 252 feet of chain weighing 3,528 pounds.

At Sabine Bank Lighthouse, 15 miles off Sabine Pass, cast-iron plates $\frac{3}{8}$ inch thick, 27 feet above the surface of the water were crushed in and bent up by the waves. This place was about 125 miles to the right of the line of advance of the center. This is cited as showing the power of the wave in that part of the hurricane.

The area along the Gulf coast, which has been flooded by storm tides, is shown by the heights of the water given on figures 1, 2, 5, and 8.

The damage caused by this hurricane amounted to $20,272,000 and 284 lives were lost.

During the 20 years 1900 to 1919 hurricanes on the coast of the Gulf of Mexcio have caused damage to property amounting to $105,642,000, and 7,225 lives have been lost.

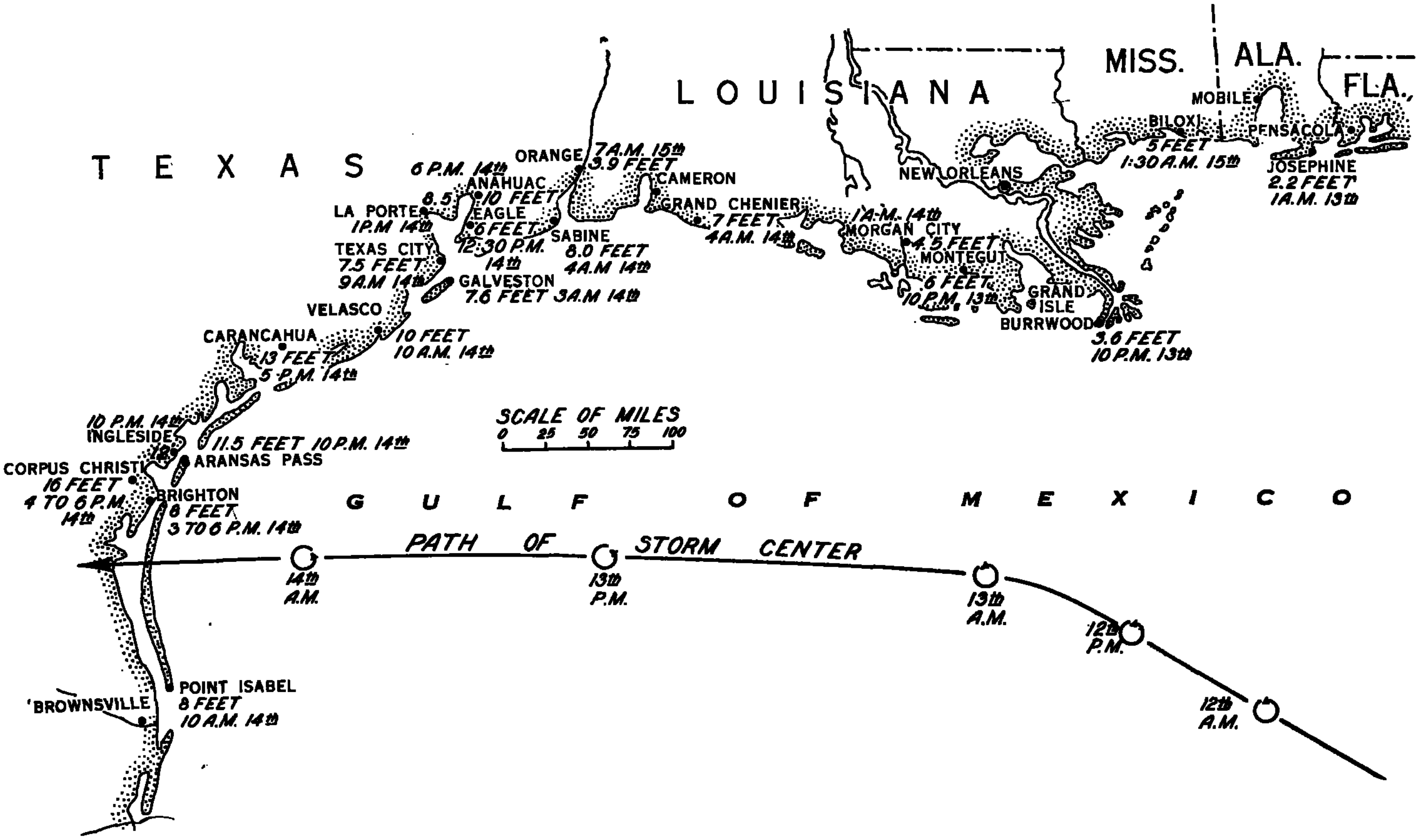


FIG. 8.—Height of storm tides along the Gulf coast above mean Gulf level and the time of their occurrence as related to the movement of the hurricane center through the Gulf of Mexico, September 11-14, 1919. This shows the storm tides in their relation to the path of a hurricane which moves in through the Florida Straits and thence across the Gulf to the Texas coast. The highest tide at stations, 30 to 50 miles inland, on bays and estuaries, occurred 8 to 12 hours later than at points on the coast line.—*I. M. Cline.* NOTE.—The path of storm center shown here is subject to slight revision after all available reports have been carefully studied; e. g., the position on the 13th A. M. may have been farther west.—*F. G. T.*

CONCRETE KNOWLEDGE OF WINDS IN HURRICANES.

Storm tides, in conjunction with hurricane winds, are such destructive agencies that it is of primary importance that we have definite information relative to the distribution of the winds in these disturbances. These winds are the physical agents that furnish the energy that develops and carries the storm waves and tides to shores far in advance of the arrival of the hurricanes and on the approach of the cyclonic area causes the inundation of our coasts and the destruction of property and lives over considerable areas. Concrete information regarding the winds in hurricanes that produce the swells and tides is limited and, therefore, these are subjects that must be investigated in this connection. Definite knowledge of the action of these agents might be obtained if the wind directions and velocities in hurricanes could be charted simultaneously at a number of places in the different quadrants of the cyclonic area. However, the courses of hurricanes are mainly over water, and, therefore, it is not practicable to get simultaneous observations at a sufficient number of stations to give us definite knowledge of the actual winds in the different parts of the cyclonic area, and we must look for some other method by which we can obtain this information. We have the theoretical ideal conclusions and charts giving the direction and velocity of wind in hurricanes (3) (5), but these do not meet the requirements in the study of this subject, for here we have need for knowedge of conditions as they actually exist.

During the last 20 years two hurricanes have moved in at points on the middle Gulf coast, where sufficient records have been kept to enable a very complete study of the actual wind directions and velocities in different parts of the cyclonic areas over water. These hurricanes while moving into extra-tropical regions, retained in a marked degree their tropical characteristics.

BIHOURLY STUDIES OF WINDS IN HURRICANES.

The hurricanes of September 29, 1915, and July 5, 1916, moved inland with the center of the first near Grand Isle, La., and the center of the latter east of Gulfport, Miss., and we secured very complete automatic records at New Orleans (1), and Burrwood (2), La., Mobile (3), Ala., and Pensacola (4), Fla. The southeastern portion of Louisiana, and the Mississippi, Alabama, and Florida, coasts are low lying, near sea level, and sparsely timbered. The physical features of the area over which these hurricanes moved, much of it being water surface, give as nearly ideal conditions for the study of the winds in the different quadrants of the cyclonic area during its passage as we can expect to find. These were typical hurricanes and both of great intensity. The progressive velocities of the cyclonic areas were determined for 100 miles after passing the latitude of Burrwood, La. The hurricane of September 29, 1915, advanced at the rate of about 12 miles per hour, and at this rate of progress the center was in the Gulf about 150 miles off the mouth of the Mississippi River at midnight of September 28. The hurricane of July 5, 1916, advanced with a velocity of 15 miles per hour, and it was centered in the Gulf about 275 miles off the Mississippi coast at midnight, July 4.

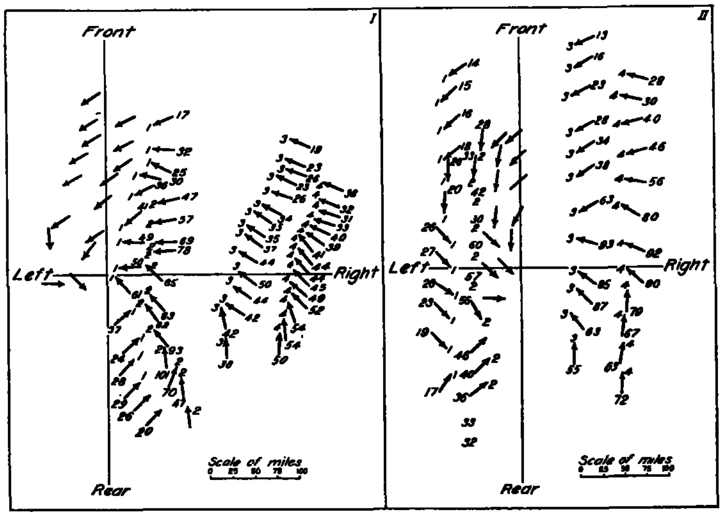
Based on a progressive movement of 12 miles per hour for the September 29, 1915, hurricane, and 15 miles per hour for the July 5, 1916, hurricane, maps were made every two hours during the passage of the hurricanes, using the automatic records at New Orleans (1), Burrwood (2), Mobile (3), and Pensacola (4), and observed pressure and wind directions from Morgan City and Lafourche, La., and Pass Christian and Gulfport, Miss. The sustained direction and velocity of the wind being of primary importance in producing waves, the prevailing direction for the preceding hour and the average velocity for the two hours preceding the time of each map have been used on these maps, instead of the direction and velocity at the hour. This gives us on the composite charts the sustained velocity of wind, not only for the two preceding hours, but during the entire passage of the hurricane. When the center of the hurricane of September 29, 1915, was 150, and that of July 5, 1916, was 275 miles distant from land, commencing at 2 a. m., at a time when the effects of the front of the storms were first being felt at Burrwood, La., and Pensacola, Fla., and at the end of each two hours following, the position of the center of the storm was carefully located geographically and charted from the automatic records mentioned above. A line was drawn on each map, through the center of the cyclonic area, the arrow pointing in the direction in which the storm was advancing at that time, dividing it into right and left segments; another line was drawn through the center at right angles to the first, dividing the storm into front and rear segments and also into quadrants.

COMPOSITE CHARTS SHOWING WIND DIRECTIONS AND VELOCITY.

From the maps we have prepared composite charts showing the actual winds, both direction and velocity, in different parts of the hurricane, viz., Charts I and II.

Chart I shows the distribution of wind direction and velocity in the hurricane of September 29, 1915, and Chart II shows the wind direction and velocity in the hurricane of July 5, 1916. In these charts the long arrow points in the direction of the line of advance of the hurricane and the intersection of the cross lines represents the center of the cyclonic area. The figures 1, 2, 3, and 4, at the points of the short arrows show the positions of the stations they represent, on the charts, with reference to the cyclonic center at the times when the wind directions and velocities were recorded. The arrow flies with the wind and shows the prevailing direction for the preceding hour. The figures at the butts of the arrows are the average wind velocities for the preceding two hours.

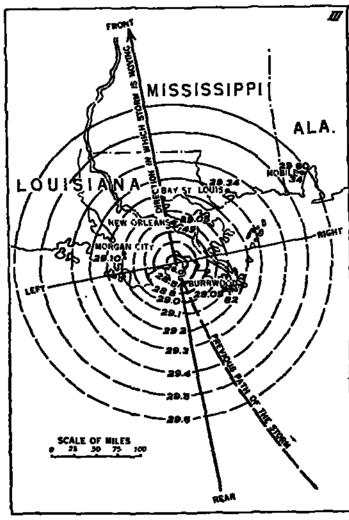
The composite wind charts for September 29, 1915, and July 5, 1916, were prepared in the following manner: The intersection of the cross lines on Chart I was placed over the center of the cyclonic area as shown on the map at 2 a. m. September 29, 1915, the long arrow on this chart pointing in the direction toward which the cyclonic



CHARTS I and II.—Composite wind charts. Prevailing wind direction for hour preceding and average wind velocity for two hours preceding time of observation in different parts of the hurricane. Chart I, September 29, 1915; Chart II, July 5, 1916.—*I. M. Cline.*

area was advancing at that time. The prevailing wind direction for the preceding hour and the average wind velocity for the preceding two hours as recorded on the map at 2 a. m. at New Orleans (1), Burrwood (2), Mobile (3), and Pensacola (4) were entered on Chart I, as shown by the first set or arrows and figures at the front of this chart. The positions of the numbers 1, 2, 3, and 4 at the points of the arrows bear the same relation to the intersection of the cross lines on this chart that the position of the stations they represent, occupied with reference to the center of the cyclonic area on the 2 a. m. map. Chart I was then placed over the 4 a. m. map in the same manner and the second set of figures from the front were entered on this chart, representing the wind directions and velocities as they appeared in that part of the cyclonic area on the 4 a. m. map. This was repeated for each map, the wind directions and velocities at the four stations being entered at their correct locations in respect to the center of the cyclonic area, on Chart I, at the end of each two hours as the cyclonic area advanced. The last set of entries in the rear of Chart I is for 6 a. m. September 30, 1915.

The same procedure was followed in preparing Chart II, composite wind chart for July 5, 1916, the first set of arrows and figures on this chart being 2 a. m. July 5, 1916, and the last set being for 12 midnight, July 5, 1916. Fifteen maps were made for the September 29, 1915, hurricane, covering 30 hours, and there are 15 entries of wind direction and velocity from the front to the rear of Chart I, for each station except Burrwood, the record for that station being missing for the last three entries. The hurricane of July 5, 1916, moved rapidly and diminished in intensity very soon after reaching land; therefore, only 12 maps, covering 24 hours, were used in preparing the composite wind chart for that hurricane, and there are 12 entries of wind direction and velocity, from the front to the rear of Chart II, for each station. There was very little change in the intensity of these hurricanes during the periods covered by the maps used in preparing the composite charts. Each entry of wind direction and velocity on Charts I and II has been made so that the figure at the point of each arrow is the same distance, in the same direction, from the intersection of the cross lines on these charts that the station which it represents, New Orleans (1), Burwood (2), Mobile (3), and Pensacola (4), was from the center of the cyclonic area on the map



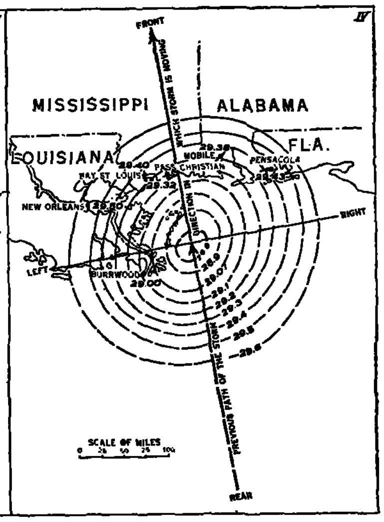


CHART III.—Hurricane, September 29, 1915. Pressure map at 2 p. m. midway of series used in preparing Chart I.

CHART IV.—Hurricane, July 5, 1916. Pressure map at 12 noon, midway of series used in preparing Chart II.—*I. M. Cline.*

at the hour when these directions and velocities were actually recorded.

The hurricane of September 29, 1915, recurved slowly during the 30 hours for which the maps were drawn. The greatest deviation from a straight line in the 360 miles traveled by the hurricane during this time was about 45 miles and occurred midway of the period. The hurricane of July 5, 1916, moved in nearly a straight line.

Chart III shows the pressure distribution and winds at 2 p. m. September 29, 1915, midway of the series of observations on which Chart I, composite wind chart, for that hurricane is based.

Chart IV shows the pressure distribution and winds at 12 noon, July 5, 1916, midway of the series of observations on which Chart II, composite wind chart, for that hurricane is based.

Charts I and II taken in connection with Charts III and IV show the relations of the winds to the isobars; both maps have been drawn from pressure reduced to sea level. These maps are considered preferable to composite pressure charts for these hurricanes.

WINDS IN DIFFERENT PARTS OF CYCLONIC AREA.

Wind directions and velocities shown on Charts I and II approximate closely what would have been found to prevail if simultaneous observations could have been taken at the point of each arrow on the charts and the direction and velocity of the wind determined at the end of any hour during the progress of the hurricanes of September 29, 1915, and July 5, 1916, respectively.

In the hurricane of September 29, 1915, one that recurved slowly, the wind velocity for four stations in the right-hand front quadrant averaged 43, and in the right-hand rear quadrant 52 miles per hour. The winds in the right-hand front quadrant near the path of the center blow across the line of advance, and 150 to 200 miles to the right of the line of advance of the center of the storm they blow at an angle of about 45° across the line of advance in the direction in which the hurricane is traveling, while in the rear right-hand quadrant the winds are mainly in the same direction as the line of advance of the hurricane. Effects of the wind, in the western segment of the September 29, 1915, hurricane, indicate velocities considerably less than those recorded in the right-hand segment. The highest wind occurred at a distance of 50 to 75 miles to the right of the line of advance after the passage of the center of the storm. The destructive power of the winds 40 miles east of New Orleans showed a greater force than at New Orleans. If we had automatic wind records for the September 29, 1915, storm from a point 50 miles east of New Orleans, such reports would show an increase in the wind velocities in the right-hand rear quadrant over those actually averaged from Chart I.

Burrwood, La., located in the right-hand segment, 50 miles to the right of the line of advance of the center of the cyclonic area, September 29, 1915, furnishes an excellent example for the study of the wind in that part of a cyclonic area at an individual station. Commencing at the time the center of the storm passed near that place, we get sustained wind velocities, in the rear right-hand quadrant, blowing mainly in a direction in line with the advance of the hurricane, as follows:

Sixty miles per hour or above prevailed for a period of 13 hours.

Seventy miles per hour or above prevailed for a period of 12 hours.

Eighty miles per hour or above prevailed for a period of 11 hours.

Ninety miles per hour or above prevailed for a period of 3 hours.

One hundred and eight miles per hour prevailed for 2 hours.

One hundred and sixteen miles per hour prevailed for one-third of an hour.

There was a gust with 1 mile at the rate of 140 miles per hour.

The wind velocity at Burrwood from 10 p. m., September 29, 1915, to 8 a. m., September 30, 1915, was not recorded, but the direction up to 9 a. m., September 30, 1915, continued mainly in the same direction as the line of advance of the hurricane. The wind velocity at 9 a. m., September 30, 1915, was 23 miles and by interpolating for the 11 hours following the 13 hours with a sustained velocity of 60 miles per hour or above, we find that an average velocity of 35 miles per hour prevailed. The average velocity was 85 miles per hour during the first 13 hours and 35 miles per hour for the next 11 hours after the passage of the center of the hurricane, making a total period of 24 hours with the average wind velocity exceeding 60 miles per hour. During this time the wind was mainly in the same direction as the line of advance of the cyclonic area. Burrwood continued, during this 24 hours, in the rear right-hand quadrant of the cyclonic area.

In the hurricane of July 5, 1916, which progressed in nearly a straight line, the wind velocity averaged for all stations, 48 miles per hour in the right-hand front quadrant, 72 miles per hour in the right-hand rear quadrant, 29 miles per hour in the left-hand front quadrant, and 34 miles per hour in the left-hand rear quadrant. In this storm the stations in the left-hand and right-hand segments were nearly equi-distant from the path of the center of the hurricane.

Pensacola, Fla., located in the right-hand segment, 100 miles to the right of the center of the hurricane of July 5, 1916, furnishes a good example for the study of winds at an individual station in that part of the cyclonic area. Commencing at the time the center passed that station we get sustained wind velocities blowing mainly in a direction in line with the advance of the hurricane as follows:

Forty miles per hour or above prevailed for a period of 24 hours.

Fifty miles per hour or above prevailed for a period of 19 hours.

Sixty miles per hour or above prevailed for a period of 10 hours.

Seventy miles per hour or above prevailed for a period of 5 hours.

Eighty miles per hour or above prevailed for a period of 3 hours.

For a period of 24 hours after the passage of the center of the hurricane the average velocity was 59 miles per hour, with the wind blowing in a direction mainly in line with the advance of the hurricane. During this time Pensacola was in the rear right-hand quadrant of the cyclonic area.

The foregoing records from Burrwood and Pensacola, both on account of their location with respect to the centers of these storms and their positions on the coast, may safely be assumed to represent the winds which prevail in those parts of a hurricane in the open Gulf. The velocities may be greater or less, depending on the intensity of the hurricane.

The high winds which occur, as indicated in the above hurricanes, in the right-hand rear quadrant of the cyclonic area, are sustained velocities which persist in the same direction as the line of advance of the hurricane during the life of the hurricane. Taking into account the diameter and progressive movement of the cyclonic area, we get a length of fetch of 300 to 400 miles in the rear right-hand quadrant of storms such as those represented in Charts I and II, with the wind 35 to 100 miles per hour for 24 hours, blowing mainly in the direction of the line of advance of the hurricane.

DEVELOPMENT OF WAVES AND TIDES BY THESE WINDS.

The wind velocities in the left-hand segment of a cyclonic area are never strong as compared with the winds in the right-hand segment (3) and are not long sustained in the same direction over the same area. Furthermore, the progressive movement of the cyclonic area causes the winds over the greater part of the left-hand segment to recede continually from the waves which these winds create; and thus their force for developing waves is diminished. Therefore there can be no great development of waves in this part of the hurricane.

In the right-hand front quadrant of the hurricane the winds near the center of the cyclonic area blow in a direction which carries the waves they develop across the line of advance of the hurricane; but at a distance of 100 to 150 miles to the right of the line drawn through the center of the cyclonic area in the direction in which it is advancing the winds coincide more nearly with the direction of advance of the cyclonic area. Furthermore, in the front right-hand quadrant the winds change direction as a result of the progressive movement of the cyclonic area so rapidly that one direction does not persist over a distance or fetch of 75 miles during a period of as much as four hours. This condition, even with the high wind velocities that occur in this quadrant, would not furnish sufficient energy for large wave development.

In the right-hand rear quadrant the winds are more inclined toward the center and blow, in the main, in the same direction as the line of advance of the hurricane at sustained velocities averaging 72 to 85 miles per hour for 13 hours and 55 to 60 miles per hour for 24 hours. It is in this part of the cyclonic area that the greatest length of fetch exists, for here the high winds persist mainly in the same direction as the line of advance of the hurricane over a distance of 300 to 400 miles. The waves are under the influence of the wind from the same general direction not only over this entire distance but also for another 100 to 200 miles, for waves started in the rear do not pass out of the front of this area for many hours, during which time the fetch region has advanced a third to half a day's journey. For these waves, then, the actual length of the fetch is 400 to 600 miles in cyclones of the size and intensity similar to those illustrated in Charts I and II. When the size and speed of the cyclone and the velocity with which the waves are moving forward are known, the length of fetch for these waves may be computed, roughly, from the following equation by Dr. C. F. Brooks:

$$F_w = F + \frac{S}{W}F + \left(\frac{S}{W}\right)^2 F + \left(\frac{S}{W}\right)^3 F + \cdots\cdots\cdots$$

in which F is the length of fetch at any moment, S the forward speed of the cyclone, and W the progressive motion of the waves.

This sustained direction and velocity of the wind in the right-hand rear quadrant, prevailing during the life of the hurricane, furnishes the energy that develops and carries forward the larger waves of long length which move on through the smaller and shorter waves, pass on beyond the limits of the storm, and are carried by their inertia, in the line of advance of the hurricane, to shore long before even the front of the cyclonic area reaches there.

In this connection Eliot says (1): "The waves, when originally produced by the action of the moving air on the surface of the sea, move at a rate which is mainly dependent upon the velocity of the wind, and are hence called forced waves, because their rate of motion is determined by the body or action which produces them, viz, in this case the moving air. Waves when produced by such action do not cease when the action stops, or when they pass in their motion beyond the sphere of action of the producing winds. In such cases they pass onward in the same general direction as before, but gradually become smaller and smaller until at last they become imperceptible." He also in speaking of large waves, says: "Whatever explanation be adopted of the production of these large waves, there is no doubt of the general principle that air moving over a water surface always produces waves, and that the magnitude of the waves is dependent upon the extent of the water area over which they blow and upon the force of the winds. It is evident that the strength of the swell or the distance at which it will be sensibly felt in the open sea, will depend partly upon the strength of the producing winds and partly upon the distance over which the producing winds act with no considerable change in direction. The rapid movement of air over the surface of the sea gives rise, by some species of cumulative action to a continuous succession of large parallel waves so long as the winds are fairly steady in character. Waves that are produced in this manner travel steadily onward in the same general direction so long as they meet no obstruction, and if they pass beyond the area of strong winds, they decrease slowly in height and force." He also says, in

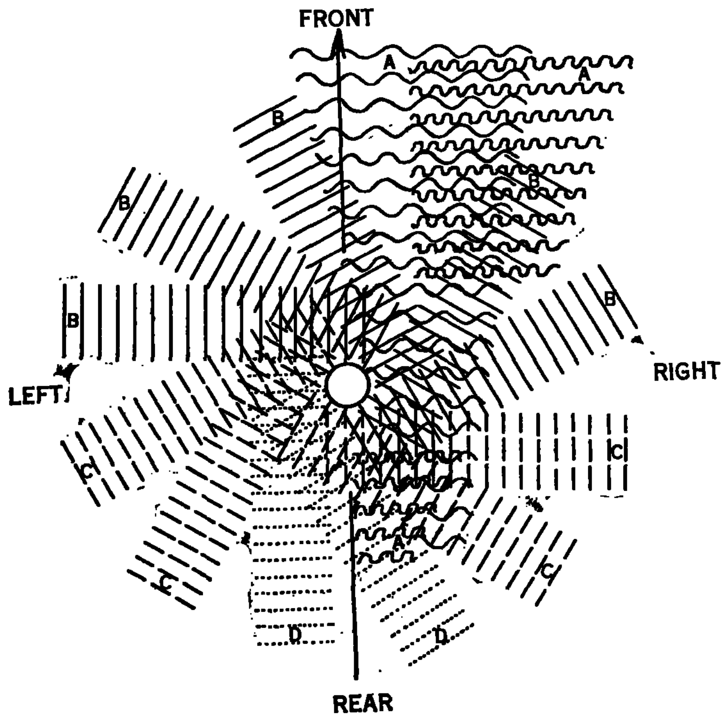


FIG. 9.—A. Swells of greatest length and magnitude, traveling in the line of advance of the hurricane.
B. Swells and waves of moderate length and magnitude in the front segment of the hurricane moving outward to right and left of the line of advance.
C. Swells and waves of smaller length and lesser magnitude in the rear segment of the hurricane moving outward to right and left of the line of advance.
D. Swells and waves of least magnitude moving outward from the rear of the hurricane.—*I. M. Cline.*

speaking of the swell produced by cyclones in the Bay of Bengal: "It has been distinctly felt when the storm was at least 400 miles distant in space and 48 hours distant in time. In these extreme cases the storm was approaching the coast where the swell was observed."

It appears that no effort has been made to illustrate the differences in the relative sizes of the waves and swells produced by the winds which prevail in the different parts of the cyclonic area. Col. Reid, as early as 1849, gave us a diagram illustrating the power of the winds of a cyclonic storm to give rise to swells moving outward in all directions from the storm area, (1) but he did not differentiate between the size and persistency of the swells produced by the winds in the different parts of the storm. With the wind directions and velocities which prevail in the different parts of the cyclonic area, as shown in the foregoing discussion and on Charts I and II, we are able to illustrate the relative size and persistency of the swells which move out from the different parts of the cyclonic area and these are illustrated in figure 9, where the size of the swells going out from each part of the cyclonic area is shown to bear a certain and well-defined relation to the producing winds.

CONCLUSIONS.

1. The waves and swells of greatest size and length are developed in the rear right-hand quadrant of the cyclonic area and move through the smaller waves in the front of the storm and are carried by inertia to shore in the direction in which the cyclonic area was advancing at that time. The waves sent out in other directions, being smaller and shorter, do not persist long after leaving the cyclonic area and soon flatten out and disappear.

2. The transference of water with the long waves and swells causes rises in the water along the coast, which increase as the storm approaches. The rise in the water on the coast in front of the line of advance of the cyclonic area, beginning 12 to 24 hours after the hurricane enters the Gulf, indicates the rapid movement of the waves through the storm area and across the Gulf. From a study of the movements shown on the different charts and figures with this paper, the speed varies from 30 to 45 miles per hour. The rapidity with which the waves travel depends both upon the extent of the cyclonic area and the intensity of the winds that develop the waves and swells. The water rises at the shore in the front, and to the right, of the point toward which the center of the hurricane was moving at the time the waves started on their journey.

3. The rise at shore, of the water from the hurricane, shows long in advance of any change in the barometer. Take, for example, the hurricane of September 11–14, 1919. When the barometer at Burrwood, New Orleans, Galveston, and Corpus Christi was either stationary or falling only a few hundredths of an inch, the water, first at Burrwood, later at Galveston, and then at Aransas Pass was rising in feet, telling the story of the movement, and of the change in the course of the storm as plainly as could possibly be told.

4. In using the information conveyed by the tides in forecasting the movements of hurricanes, the tides as predicted by the Coast and Geodetic Survey should be plotted for each hour whenever a storm appears in the Gulf. The height of the tide above mean low tide should be telegraphed from coast stations with each observation and these should be plotted over the predicted tides. The place where the water exceeds the predicted tides and continues rising is in the line of advance of the hurricane at the time that water started on its journey.

5. The intensity and extent of the hurricane is indicated when the disturbance is at a considerable distance in space and time, by the rapidity of the rise in the water and the extent of the coast over which the rise is taking place.

6. The time between the commencement of the rise in the water at shore and the arrival of the hurricane will depend upon the rapidity with which the cyclonic area is advancing and the intensity of the hurricane.

7. If the point of greatest rise shifts to the right or left, this indicates that the storm is changing its course in that direction toward which the increased rise is taking place.

8. When the crest of the storm tide is coincident with the crest of the regular tide the height of the water

will be greater by more than one foot for hurricanes of equal intensity than when the crest of the storm tide is coincident with low tide, and in forecasting storm tides this must be borne in mind.

9. The regular tides are not obscured at any time by the storm tide, except at or near the point where the center of the storm moves inland, and then for only about twelve hours before the passage of the center of the hurricane.

10. The highest water occurs a few miles to the right, and about the time, of the passage of the center of the cyclonic area. At points on the coast some distance to the right of the line of advance of the center, the highest water occurs on a line drawn through the center of the cyclonic area at right angles to the line of advance of the hurricane, about the time of the passage of the center of the storm across that line.

11. The high water extends for only a short distance to the left of the point where the center of the storm moves inland. High water, however, is experienced to the right of the center for a distance of 100 to 200 miles.

12. The water commences rising at the shore toward which the cyclonic area is advancing in less than 24 hours after the center of the cyclonic area has entered the Gulf. The waves and swells which give this rise must have moved through and out of the rear right-hand quadrant of the storm area within 12 to 15 hours after the center of the storm entered the Gulf of Mexico. This indicates that with a fetch of 150 to 200 miles in the rear right-hand quadrant of the cyclonic area the winds furnish sufficient energy to develop waves and swells of a size and length that travel 30 to 45 miles per hour, reaching the middle Gulf coast, 400 miles distant, in 10 to 15 hours, and the Texas coast, 800 miles distant, in 15 to 20 hours.

13. Strong currents are created in the right-hand segment of the cyclonic area which move in the main coastwise toward the line along which the cyclonic area is advancing. The fact that two gas and whistling buoys in August, 1915, and three in September, 1919, were carried 2 to 8 miles nearly parallel to the coast, shows the force of these currents. If these buoys had been moved by waves they would have been carried in toward the shore and not along the coast.

NEITHER A STORM NOR A TIDAL WAVE.

14. The high water attending the hurricane is frequently referred to as a "tidal wave," or "storm wave," but it is not a wave in any sense of that term. It is a cumulation of the water from successive "storm waves" reaching shore, covering a period of two or more days, with a gradual rise which increases as the center of the storm approaches. The "storm tide" results from the physical forces of the hurricane, driving the large waves forward and transferring the water in the same direction as the line of advance of the hurricane. In the open sea this storm tide is not so great, probably not exceeding, in the greatest storm, more than 5 feet. The obstruction formed by the coast line acts as a barrier and the water gradually banks up as it does against a dam across a stream. The rise in the water at shore is frequently against opposing off-shore winds as was the case at Galveston, Tex., in 1900 and in 1915, and at Corpus Christi, in 1919. In such cases the off-shore winds force the water back on the storm, retarding the rise; then when the winds shift and come in with the storm, the rise in water is much more rapid and consequently more destructive. The diminished pressure near the center of the hurricane will have some effect on the height of the water. The weight of 1 inch of mercury is equal to that of about 1 foot of water. The increase in the height of the water due to diminished pressure at Galveston, for example, in 1900, with the barometer 28.48 inches, could not have exceeded, under most favorable conditions, 1.5 feet, whereas the storm tide was 15 feet.

RECORDS OF WAVES AND SWELLS.

There are no records available for use in the study of the individual storm waves and storm swells and groups which reach the coast and cause the storm tides. A knowledge of the size and speed of these would aid in the study of the movements of water in hurricanes. A definite knowledge of these waves would aid in determining the location and intensity of hurricanes. Observations should be made along the coast, especially when hurricanes are approaching, of the speed and direction of waves and swells. The velocity of water waves and ripples is determined by the wave length. "Wave velocity = wave length × wave frequency."

Fleming says this relation may be stated in another manner: "We call the period of a wave the time taken in making one complete movement. The period in time, is, therefore, inversely proportional to the frequency. Hence, we can say that the wave length, divided by the periodic time, gives us the wave velocity. * * *"

"A formal and exact proof of the law connecting speed and wave length for deep-sea waves requires mathematical reasoning of an advanced character, but its results may be expressed in a very simple statement by saying that in the case of waves in deep water, the speed with which the waves travel, reckoned in miles per hour, is equal to the square root of 2¼ times the wave length measured in feet * * *."

"The above rule for the speed of deep-sea waves, viz, wave velocity = square root of 2¼ times the wave length combined with the general rule, wave velocity = wave length multiplied by the frequency, provides us with a useful practical method of finding the speed of deep-sea waves which are passing any fixed point * * *." Count the number of waves which pass the fixed point per minute and divide the number into 198; the quotient is the speed of the waves in miles per hour. Thus, if ten waves per minute race past a fixed buoy, their velocity is nearly 20 (19.8) miles per hour. If V is the velocity of the wave in feet per minute, and V' is the velocity in miles per hour, then $V' \times \frac{5280}{60} = V$. But $V' = 2\sqrt{\tfrac{1}{4}l}$ and $V = nl$, where "l" is the wave length in feet and "n" the frequency per minute; from which we have $V' = \frac{198}{n}$, or the rule given in the text.

ACKNOWLEDGMENTS.

Valuable suggestions and references have been received from the Chief of the United States Weather Bureau and other officials at the central office, Washington, D. C., and assistance has been given by officials at Gulf coast stations, and especially at New Orleans.

Automatic tide records for Port Eads and Burrwood, La., and Fort Morgan, Ala., have been furnished by the district engineers, United States Engineers Corps, New Orleans, La., and Mobile, Ala. Staff-gage tide

records for 1909, 1915, and 1919, and other important matter for Galveston, Tex., have been furnished by the district engineer at Galveston, Tex.

Automatic tide records at Galveston for 1906, 1909, 1916, 1917, and 1919, and important references have been furnished by the Superintendent and other officials of the United States Coast and Geodetic Survey, Washington, D. C.

Reports from lighthouses in the Gulf, and the movement of buoys in storms have been furnished by the Inspector of the Light House District, New Orleans, La.

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THE FORECASTING OF SWELLS ON THE COAST OF MOROCCO.

By LOUIS GAIN.

[Abstracted from Revue général des Sciences, July 15, 1919, pp. 408-411.]

The great damage which was frequently wrought to shipping along the coast of Morocco by great ocean swells has been the subject of a number of studies. The author's studies have led him to the conclusion that these destructive swells can be forecast from the pressure distribution in the portion of the Atlantic to the east and northeast of Morocco. The conclusions, based upon the study of the effects of 210 low-pressure areas, are as follows:

I. A swell produced at Casablanca is the consequence of—

1. A depression on the ocean between the Azores and the British Isles, and light northwest winds in the region between the African coast and the depression. If the depression is intense, the swells will be correspondingly greater. These waves originating within the LOW require from 2 to 5 days to reach the coast of Morocco.

2. A depression moving eastward between the Azores and Portugal. In this case the swells are rarely large at Casablanca. They require from 24 to 48 hours to reach the coast.

3. Secondary depressions arising from LOWS in the north, moving southward over western Europe from the region of Norway and the British Isles, and giving rise to depressions over the Mediterranean.

II. A swell is weakened or made ineffective at Casablanca—

1. When there is an anticyclone over the region between the coast of Morocco and the depression.

2. When the depressions pass north of the British Isles.

3. In the case where depressions descend upon Europe when passing between Norway and the British Isles.

4. When an intense LOW with strong winds moves rapidly eastward.

The forecasting of swells can be either made directly at Casablanca by means of comparison of the daily wireless reports from Paris with those of the preceding day, or at Paris; the forecast itself can be forwarded to Casablanca. The author considers that more study should be given the problem, but that it is now possible to avoid such catastrophes as have been experienced along the coast of Morocco.—*C. L. M.*

MEAN SEA LEVEL.

By D'A. W. THOMPSON.

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The level of the sea, or more generally, the form of its surface, is the resultant of two kinds of forces after eliminating the effects of the tides. There is the action of the sea currents and densities (intrinsic forces); and that of wind and barometric pressure (extrinsic forces). Witting thus summarizes the effects of the extrinsic forces: (1) Every barometric distribution of any permanency produces a deformation of the surface of the sea. (2) The ascending slope so produced is not identical in direction with the barometric gradient, but deviates to the right in the Northern Hemisphere. (3) The amount of slope is greater than that which would correspond with the hydrostatic pressure, induced by the barometric distribution. With regard to the intrinsic forces we know enough to choose a point at sea where no movements are caused by the distribution of densities. This is the zero pressure level. A geodetic surface drawn through this point may be considered the datum level. Proceeding outward from such a point, Witting has calculated the hydrodynamical gradient due to densities, and added to it the effect of barometric pressures. He has found that levels thus calculated for the Baltic area agree to a surprising closeness with the determinations of precise levels.

The question of secular changes of level is beset with difficulties. But assuming the coast from Wismar to Pillau has kept at constant level, Witting mapped the changes in level in the Baltic from 1898 to 1912. Some minor fluctuations are related to seismic phenomena; e. g., there was an interruption in the general upheaval at the time of the Scandinavian earthquake, 1904. For some centuries past the elevation of the Fennoscandian