ANALYSIS OF RAINS AND SNOWS AT MOUNT VERNON, IOWA, 1935–36

By NICHOLAS KNIGHT

[Cornell College, Mount Vernon, Iowa, June 1936]

During the year 1935–36, 51 samples of precipitation were analyzed in the Cornell College chemical laboratories. There were 29 samples of rain and 22 samples of snow.

The rains of October 13 and 31, 1935, were accompanied by thunder and lightning. In the 0.10 of an inch rainfall on November 10, the chlorine, nitrates, and nitrites were unusually high. These results show what one would naturally expect, that most of these substances are dissolved in the first part of an ordinary precipitation. The same is true of the sulphate. Our experiments tend to show that the sulphates in the Mount Vernon precipitations come from the sulphur in the coal that is burned.

On January 4, 1936, the precipitation was both rain and snow equivalent to 0.2 of an inch rain. In Chicago the storm was accompanied by thunder and lightning.

TABLE 1.—*Parts per million*

Date	Rain or snow	Chlorine	Free NH_3	Alb. NH_3	N in nitrite	N in nitrite	Sulphate SO_3
1935							
June 6	Rain in 0 to 0.3	3.55	0.056	0.04	0.3	0.00	0.08
16	0.6 inch	2.13	.04	.05	.55	.00	.00
18	1.2 inches	3.00	.20	.02	.25	.00	.00
Oct. 10	0.5 inch	3.55	.40	.72	.15	.05	.05
13	0.35 inch	2.13	.22	.16	.09	.05	.00
17	1/3 inch rain	1.42	.24	.24	.20	.25	.01
21	1/4 inch rain	3.55	.40	.32	.04	.10	.003
31	1/2 inch rain	2.00	.20	.04	.035	.09	.00
Nov. 4	2.6 inches rain	3.55	.08	.24	.06	.16	.00
10	1/10 inch rain	7.10	X	X	.25	.47	.025
19	3/10 inch rain	2.13	.32	.30	.30	.35	.005
27	1 1/4 inch rain	2.00	.056	.40	.11	.46	.00
28	2 inches rain	.71	.050	.24	.15	.09	.008
Dec. 7	1/2 inch rain	2.50	.025	.65	.20	.40	.007
15	4 inches snow	3.55	.112	.80	.20	.10	.005
23	do	2.13	.08	.36	.25	.08	.003
25	4 inches snow	3.55	.24	.03	.25	.15	.003
28	2 inches snow	3.75	.20	.32	.15	.25	.005
1936							
Jan. 2	6 inches snow	2.15	.02	.40	.08	.30	.005
4	0.4 inch rain	1.42	.40	.40	.35	.20	.005
6	2 inches snow	3.55	.28	.40	.15	.25	.005
7	1/4 inch snow	1.42	X	X	.19	.60	X
8	3 inches snow	2.13	.08	.40	.075	.30	.00
16	2 inches snow	1.40	.136	.24	.10	.35	.002
18	9 inches snow	.71	.056	.22	.05	.25	.002
22	2 inches snow	7.10	.45	.20	.15	.45	.005
29	2 inches snow	3.40	.24	.112	.15	.20	.00
Feb. 4	4 inches snow	2.13	.45	.36	.20	.12	.006
9	3 inches snow	2.80	.45	.32	.10	.25	.003
12	do	1.42	.32	.45	.20	.25	.005
14	2 inches snow	2.10	.40	.32	.17	.25	.0014
17	do	2.13	.24	.32	.12	.35	.00
26	0.2 inch rain	3.55	.50	.80	.15	.40	.010
Mar. 11	1/2 inch rain	2.10	.28	.45	.13	.33	.009
14	3 inches snow	3.55	.24	.44	.175	.30	.002
19	0.02 inch snow	3.55	.24	.48	.23	.50	.016
Apr. 1	2 inches snow	.9	.40	.20	.10	.20	.004
2	3 inches snow	3.55	.16	.38	.10	.50	.00
5	do	3.55	.45	.28	.10	.35	.006
14	0.12 inch rain	2.84	.80	.50	.17	.50	.007
20	1/4 inch rain	3.55	.42	.44	.20	.30	.00
24	1/10 inch rain	2.13	X	X	.25	1.00	.025
27	7/10 inch rain	1.42	.42	.40	.30	.5	.004
1936							
May 1	1/5 inch rain	3.55	.40	.20	.20	.05	.007
4	1/10 inch rain	7.10	X	X	.10	.12	.004
10	do	3.55	X	X	.20	.03	.002
12	1/5 inch rain	2.00	.24	.16	.15	.02	004
23	2/5 inch rain	2.13	.45	.40	.10	.15	.04
June 12	2.9 inches rain	.6	.24	.16	.10	.02	.004
6	0.3 inch rain	1.42	.40	.42	.16	.02	.009
9	1.2 inches rain	2.00	.38	.50	.10	.015	.004

TABLE 2.—*Pounds per acre*

Date	Rain or snow	Chlorine	Free NH_3	Alb. NH_3	N in nitrate	N in nitrite	Sulphate SO_3
1935							
June 6	3 inches rain	0.24	0.04	0.003	0.02	0.00	0.005
16	0.6 inches rain	.29	.005	.007	.075	.00	.00
18	1.2 inches rain	.81	.05	.005	.068	.00	.00
Oct. 10	0.5 inch rain	.4	.045	.08	.017	.006	.0057
13	0.35 inch rain	.17	.018	.13	.007	.004	.00
17	1/3 inch rain	.114	.019	.019	.029	.016	.008
21	1/4 inch rain	.2	.023	.018	.0023	.006	.0002
31	1/2 inch rain	.23	.023	.005	.004	.01	.00
Nov. 4	2.6 inches rain	2.09	.047	.014	.035	.095	.00
10	1/10 inch rain	.16	X	X	.0058	.011	.0006
19	3/10 inch rain	.1449	.022	.02	.02	.024	.0004
27	1 1/4 inches rain	.56	.016	.112	.031	.13	.0003
28	2 inches snow	.067	.002	.009	.006	.003	.0003
Dec. 7	1/2 inch rain	.28	.03	.07	.023	.046	.0008
15	4 inches snow	.16	.085	.09	.019	.0075	.0004
25	do	.27	.016	.0023	.019	.011	.0002
28	2 inches snow	.15	.008	.0012	.006	.01	.0002
1936							
Jan. 2	6 inches snow	.245	.0023	.046	.009	.034	.0006
4	0.2 inch snow	.54	.015	.015	.013	.008	.002
Dec. 23	4 inches snow	.162	.0061	.027	.019	.006	.0023
Jan. 6	2 inches snow	.16	.013	.018	.007	.011	.0002
7	1/4 inch snow	.007	X	X	.001	.0030	X
8	3 inches snow	.12	.0046	.023	.0057	.017	.00
16	2 inches snow	.052	.005	.009	.0004	.013	.0007
18	9 inches snow	.12	.110	.037	.0085	.0425	.0003
22	2 inches snow	.263	.017	.007	.006	.017	.0002
29	do	.13	.009	.004	.0056	.007	.00
Feb. 4	4 inches snow	.162	.034	.027	.015	.009	.0005
9	3 inches snow	.16	.026	.018	.006	.014	.0002
12	do	.081	.018	.026	.0114	.014	.0003
14	2 inches snow	.08	.015	.0122	.0065	.009	.0002
17	do	.081	.009	.0122	.0046	.013	.0038
26	0.2 inch rain	.16	.0225	.036	.0068	.018	.0004
Mar. 11	0.5 inch rain	.24	.032	.051	.0147	.037	.001
14	3 inches snow	.20	.014	.0251	.010	.017	.0001
19	2 inches snow	.135	.009	.018	.19	.009	.0061
Apr. 1	do	.034	.015	.008	.004	.008	.002
2	3 inches snow	.20	.009	.022	.0057	.029	.00
5	do	.20	.016	.026	.0057	.0209	.0004
14	0.12 inch rain	.077	.022	.014	.0046	.013	.0002
20	0.25 inch rain	.20	X	X	.011	.017	.00
24	1/10 inch rain	.05	.024	.025	.006	.023	.0006
27	7/10 inch rain	.227	.067	.064	.048	.08	.0006
May 1	1/5 inch rain	.016	.018	.009	.009	.002	.0002
9	1/10 inch rain	.16	X	X	.002	.003	.0001
10	do	.08	X	X	.0046	.0009	.00005
12	1/5 inch rain	.096	.011	.007	.007	.0009	.0002
23	2/5 inch rain	.20	.041	.036	.009	.0014	.0036
6	0.3 inch rain	.10	.027	.029	.011	.0014	.0006
9	1.2 inches rain	.54	.103	.14	.01	.0041	.0011
June 12	2.9 inches rain	.40	.16	.11	.066	.013	.003

SEA SWELLS IN RELATION TO MOVEMENT AND INTENSITY OF TROPICAL STORMS

By I. R. TANNEHILL

[Marine Division, Weather Bureau, Washington, July 1936]

Tropical storms, like other phenomena that cause disturbances of the sea surface, result in the formation of waves which move outward in all directions from the region of origin. The precursory indications given by sea swells preceding the storm are generally appreciated, and have been discussed by a number of writers. Of these, mention may be made of Lt.-Col. William Reid [1] who prepared the diagram of swells and cross seas reproduced in figure 1. Other investigators have studied waves caused by storms at sea, notably Cornish,[2] Wheeler,[3] and Fleming.[4] The effects of a storm's progressive travel on the character and direction of movement of sea swells in the various parts of the storm area have been discussed by Cline [5] who originated the diagram reproduced in figure 2.

[1] Reid, Lt.-Col., William. The Progress of the Development of the Law of Storms and of the Variable Winds. London, 1849.

[2] Cornish, Vaughn. Ocean Waves. Cambridge, 1934.

[3] Wheeler, W. H. A Practical Manual of Tides and Waves: London, 1906.

[4] Fleming, J. A. Waves and Ripples. London, 1912.

[5] Cline, I. M. Relation of Changes in Storm Tides on the Coast of the Gulf of Mexico to the Center and Movement of Hurricanes. MONTHLY WEATHER REVIEW. 48: 127–146. March 1920.

Cline presented no observations of swells at sea to support his conclusions, which appear to be based on theoretical

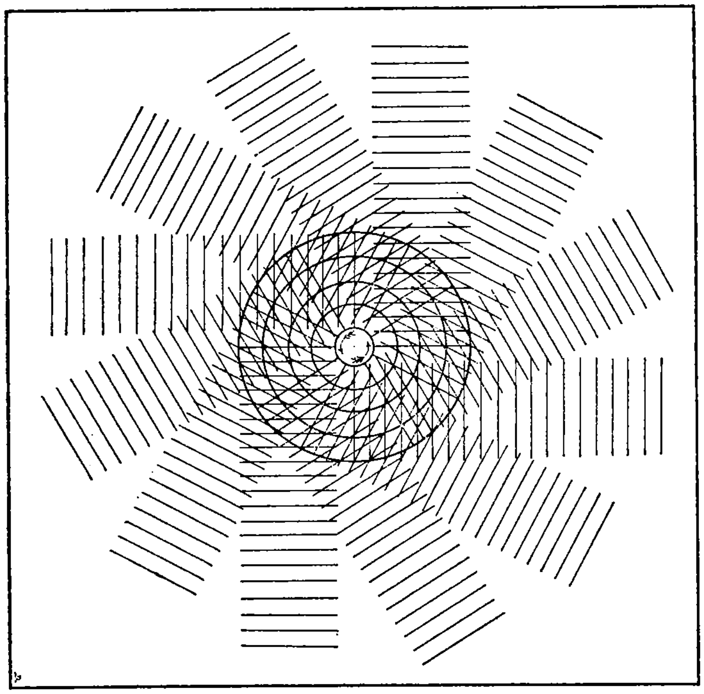

Figure 1.—Swells and cross seas in a hurricane, according to Reid.

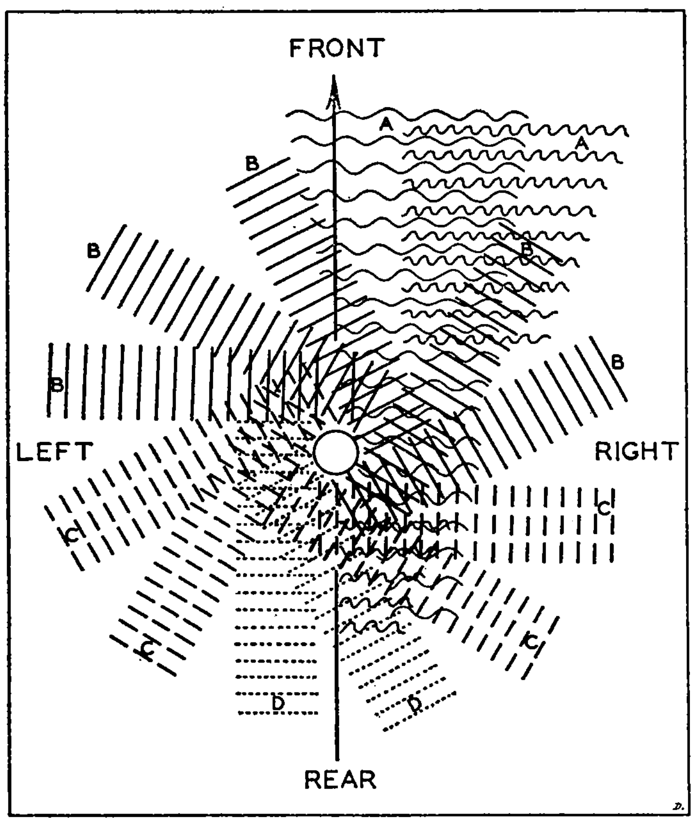

Figure 2.—A. Swells of greatest length and magnitude, traveling in the line of advance of the hurricane. B. Swells and waves of moderate length and magnitude in the front segment of the hurricane, moving outward to right, and left of the line of advance. C. Swells and waves of smaller length and lesser 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.*

considerations. In all of these investigations very little has been done with actual observations of swell in tropical cyclones.

During the hurricane season of 1935, the Weather Bureau was enabled by a special appropriation to secure for the first time by radio, daily reports of swells from ships at sea in connection with hurricanes. Systematic observations of sea swells were begun also at Coast Guard stations in 1935. This reorganization of the hurricane reporting service has been described by Calvert.[6]

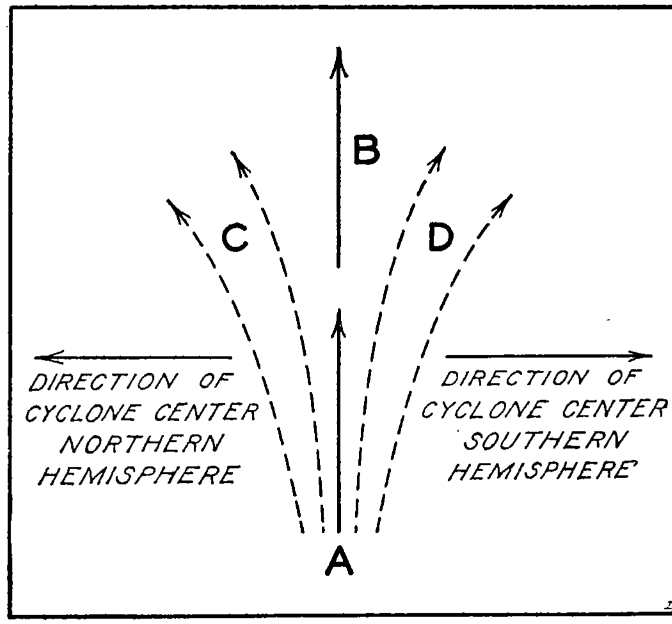

Figure 3.—Deviation of wind (dotted arrows) from waves (solid arrows) in tropical cyclones of both hemispheres.

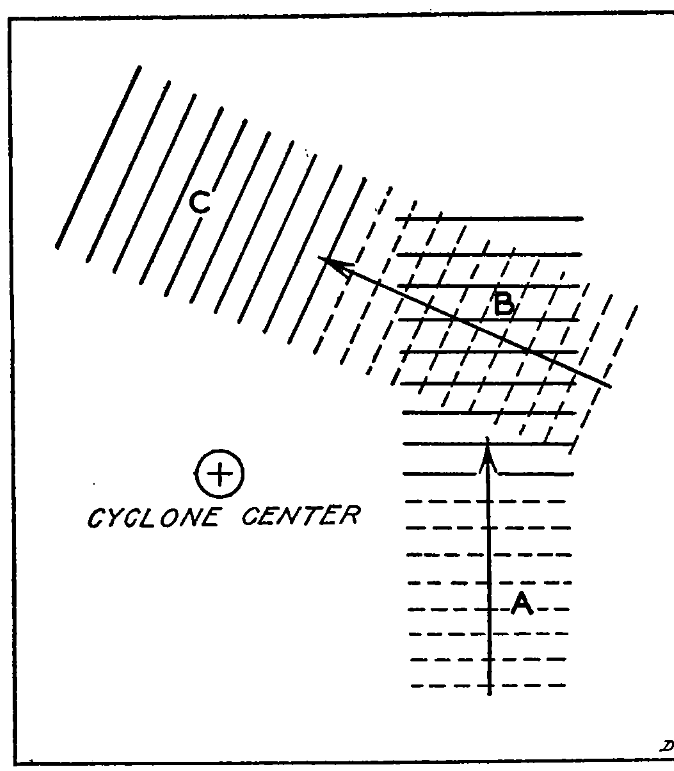

Figure 4.—Dominant waves (solid lines) moving into wind fields where new waves (dotted lines) are being developed.

With the ultimate object of aiding the mariner to secure the greatest practical benefit from the observations of swell now collected by radio, the writer has prepared a

[6] Calvert, E. B. The Hurricane Warning Service and Its Reorganization. Monthly Weather Review. 63: 85-88, March 1935.

number of synoptic charts for a study of wind and swell attending tropical cyclones. The charts reveal features of movement of swell which have not, to the author's knowledge, been previously described in print. This paper is intended as a preliminary discussion of the available observations of sea swell in connection with tropical cyclones.

CHARACTERISTICS OF WAVES CAUSED BY WINDS

When wind begins blowing over a water surface it produces at first a series of ripples moving with the wind. As the ripples move forward with the wind, they steadily increase in size so long as the wind continues. The ultimate size of the waves depends upon the force of the wind and the "fetch" or length of water surface to windward. Thomas Stevenson's formula for the maximum height of a wave in relation to length of fetch is

$$H=1.5\sqrt{L},$$

where H is the height of the wave in feet and L the length of fetch in nautical miles. For a body of deep water 9 miles in length the maximum wave would be 4½ feet in height; for a stretch of 900 miles of deep sea, the maximum wave height would, theoretically, be 45 feet.

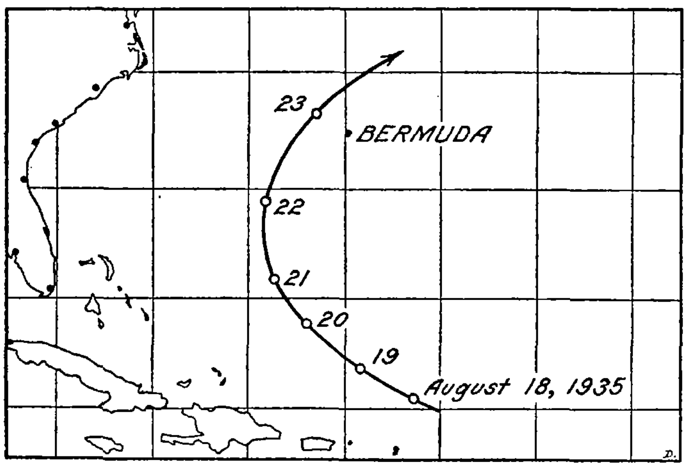

FIGURE 5.—Partial track of hurricane of August 18 to 25, 1935.

The relation of fetch to size of wave is of considerable importance in dealing with tropical cyclones; the length of fetch is only a fraction of the storm diameter, and not necessarily the length of the gulf or sea in which the storm lies.

After the wave moves beyond the influence of the winds which caused it, there is a change in its form. The most rapid change at first is a decrease in height. The wave becomes a relatively low, undulating movement of the sea surface known as a swell. To the mariner a swell is distinguished by two features; first, its relatively smooth, undulating form without the steep and ragged crests characteristic of waves actively driven by the wind and, second, the movement of winds and waves in different directions indicating that the waves have been formed elsewhere by winds from another quarter. There is no very satisfactory definition of swells as distinguished from ordinary wind-driven waves because there is an endless variety of conditions of wind and swell, sometimes with newly developed waves moving across the swells. The typical case is the sea swell moving far in advance of the storm into regions where winds are of insufficient force to produce any local confusion of the sea surface.

According to Cornish [2] the speed of deep-sea waves in statute miles per hour is obtained approximately by multiplying the period in seconds by 3½. The period is the time between the passage of successive crests, taken as an average for the series of wave crests passing in 1 minute or, preferably, 3 minutes. Hence a swell with a period of 12 seconds (or 5 swells per minute) would be moving at 42 miles an hour. The length may be obtained roughly by multiplying the square of the period in seconds by 5⅛, giving a length of 738 feet for a wave with a period of 12 seconds.

Many estimates of wave dimensions have been recorded in the open ocean. However, it is difficult to make accurate estimates from shipboard; and neither on the open sea nor from the shore have wave observations frequently been associated with accurate measurements of wind speed at the place of observation. Seldom has the investigator been adequately informed as to the wind movement over the considerable stretches of sea surface on which the waves are produced. Hence, the relation between waves and wind in the open ocean has been deduced chiefly from series of rather rough estimates of both wind and wave.

The relative proportions of waves caused by winds of various forces cannot be worked out to complete satisfaction by formula. The length of wave may vary from 5 to 30 times the height in short waves, and from 10 to 40 times the height in long waves. The dimensions of the wave depend upon many factors, such as the speed and gustiness of the wind, the fetch, the changes in direction and the persistence in any given direction, all of which are difficult to estimate for a long stretch of open water surface; hence calculations from formulas are only rough approximations.

The relations stated in the foregoing paragraphs apply to waves finally produced by winds blowing over long stretches of open ocean. Actually there are limitations to the length of fetch of the wind in any given direction. In cyclonic systems, the winds do not blow over great distances in approximately straight lines. The greatest fetch of gale winds is usually found in extratropical cyclones of large diameter where the direction of the wind over a large area coincides roughly with the direction of travel of the cyclone, and the rate of travel of the cyclone is comparable to the speed of the swells. In tropical cyclones the fetch is considerably less than in extratropical cyclones of large diameter and, although the winds are much more violent, observations indicate that the maximum waves possible for such wind velocities are not actually developed because of insufficient fetch.

OBSERVATIONS OF SWELLS IN TROPICAL CYCLONES AT SEA

In the southern North Atlantic Ocean, including the Caribbean Sea and Gulf of Mexico, tropical cyclones have an average progressive movement of only about 12 miles an hour. Hence, the waves developed by the winds of the storm, moving at speeds of 30 to 50 miles and more an hour, soon pass through the wind system of the cyclone, even when the direction of wave movement and storm travel are coincident. Waves in the open sea do not involve a bodily transfer of water and are not subject to the deflective effect of the earth's rotation; but the winds are deflected and in the Northern Hemisphere are directed counterclockwise around the cyclone center. After waves are formed by winds in any part of the storm area, they move straight forward, while the winds turn to the left in the Northern Hemisphere and to the right, or clockwise,

[2] Cornish, Vaughn. Ocean Waves. Cambridge, 1934.

in the Southern Hemisphere. This is illustrated in figure 3. If the winds represented by the dotted arrows at A produce waves moving in the direction shown by the solid arrow at A, the waves move straight onward as shown by the solid arrow at B. If the winds are part of a tropical cyclone in the Northern Hemisphere, they turn to the left as shown by the dotted arrows at C; if they are part of a tropical cyclone in the Southern Hemisphere, they turn to the right as shown by the dotted arrows at D. This deviation of wind from swell is found in all quadrants of the tropical cyclone. However, observations show that the amount of deviation in any quadrant depends upon the direction and rate of travel of the cyclone.

In any part of the cyclone the dominant swells are those produced to the windward. Some time is required for the winds to develop large waves, and by the time they approach maximum development they are moving rapidly straight forward while the winds have turned to the left (in the Northern Hemisphere) and are developing new waves in another direction. This is shown in figure 4, where the winds at A are producing the waves shown there by dotted lines; those waves become the dominant waves (solid lines) moving into the wind field at B where new waves (dotted lines) are being developed, later to become in turn the dominant waves at C.

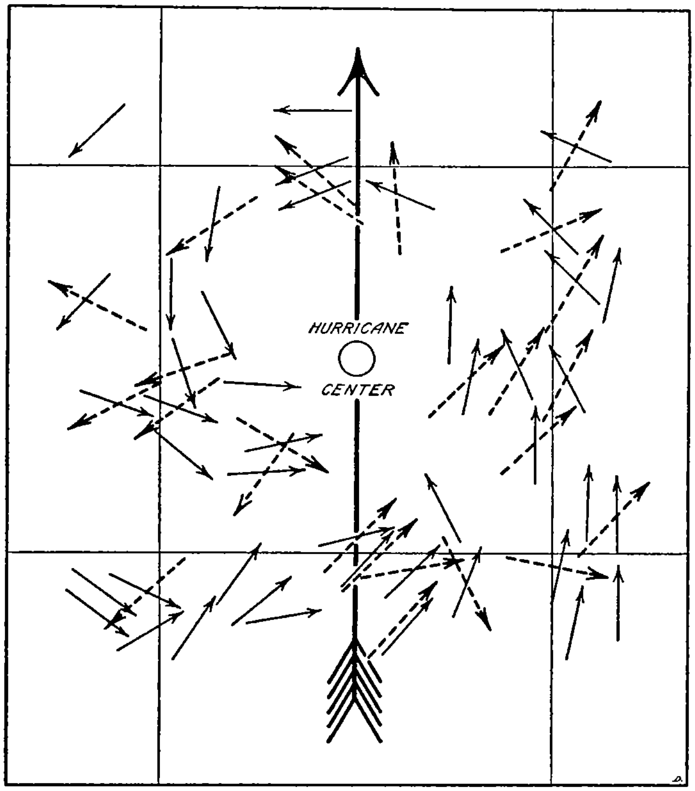

FIGURE 6.—Composite chart showing direction of swells (dashed arrows) and direction of wind (solid arrows) in tropical cyclone, August 20–22, 1935. Large arrow shows direction of storm travel.

That this is the case is clearly shown by observations in the lee of islands within the tropical cyclone. The dominant waves are dissipated on reaching the island; and to the leeward of the island the only waves present are those in process of development and moving in the same direction as the wind. Thus, in figure 4, an island intervening between A and B will prevent the waves developed at A from entering the area B, and the dominant waves in the lee of the island will then be the smaller waves, indicated by dotted lines in the area B.

On the 18th of August 1935, a tropical storm appeared to the northeastward of Puerto Rico. It moved slowly northwestward, then recurved to the northeastward and passed a short distance to the northwest of Bermuda on the 23d. Owing to its relatively slow progressive movement and its location in the open ocean from the 20th to 22d, inclusive, this storm afforded an excellent opportunity for the study of sea swells. The path of the storm is shown in part in figure 5. During these 3 days, ships' weather observations were secured by the Weather Bureau at intervals of 6 hours—at 0000, 0600, 1200, and 1800 G. M. T. Many of the reports contained observations of swells in the international code, giving character of the swells and the direction from which they were moving.

From these reports, 12 synoptic maps were prepared showing direction of wind and swell. These 12 maps were then combined to form the composite chart shown in figure 6. Each of the individual maps was oriented so that the line of progression of the storm center lay on the central meridian of the composite chart before transferring the observations. Thus the movement of wind and swell is shown in the figure in a 7° ocean square as related to a storm center with a progressive movement due northward.

The observations in figure 6 show the deviation of swells to the right of the wind; that is, an observer standing with his back to the wind would find the swells moving off to his right.

By computation for a 10° square from the individual charts, it was found that the deviation of swell from wind averaged 61° in the two front quadrants of the storm, 104° in the left rear quadrant and only 20° in the right rear quadrant.

This difference in the amount of deviation in the two rear quadrants is apparently owing to the progressive movement of the storm. The forward movement of the wind field in the right rear quadrant, at some distance from the storm center, results in a prolonged action of wind in the direction in which the swells are running. In the left rear quadrant the wind field moves away from the swells, resulting in a more pronounced deviation. Along the line of progression at the rear of the storm there is a discontinuity in swell movement. A similar discontinuity is shown in the observations in connection with other tropical storms; it appears to be a genuine feature of the movement of swell in traveling cyclones.

In front and to the right of the storm center the swells in general move forward roughly in the direction of travel of the storm or a little to the right. If the storm continues to move in the same direction over the ocean, these swells become larger and reach far in advance of the storm. It is worthy of note that this feature of movement of swell as shown by actual observations agrees with the conception of Cline as illustrated in figure 2.

The tropical storm previously mentioned as appearing northeast of Puerto Rico on August 18, 1935, was encountered by a number of steamers, including the S. S. *A. C. Bedford*. On the 20th, at noon G. M. T., the *A. C. Bedford* was at 31°45′ N., 68°00′ W., bound for Cartagena. The wind was east to east-southeast with an increasing swell from the south. By 0600 G. M. T. of the 21st, there was a long heavy swell from the south, wind east, force 7. The swell became confused by noon of the 21st, direction south. This situation continued until 0600 G. M. T. of the 22d when the ship was in latitude 28°22′ N., 66°24′ W. The chart given as figure 7 shows the location of the *A. C. Bedford* at 0600 G. M. T. on August 21 and 22 and at subsequent times of observation, with wind and directions of swell for each, and also corresponding positions of the storm center. By noon of August 23 the ship had passed beyond the wind field of the storm but was still experiencing a long swell, which by that time was coming from the northwest.

From 0600 G. M. T., August 22, to the same hour on August 23, *A. C. Bedford* made little progress against head winds and seas, hence it is not practicable to enter the intervening observations on the map in figure 7. The map shows, however, the changes in direction of swell as the ship passed through the storm field. In each instance the observer on shipboard, facing in the direction from which the swell came, would have found the storm center on his right and the wind coming from a point on his left,

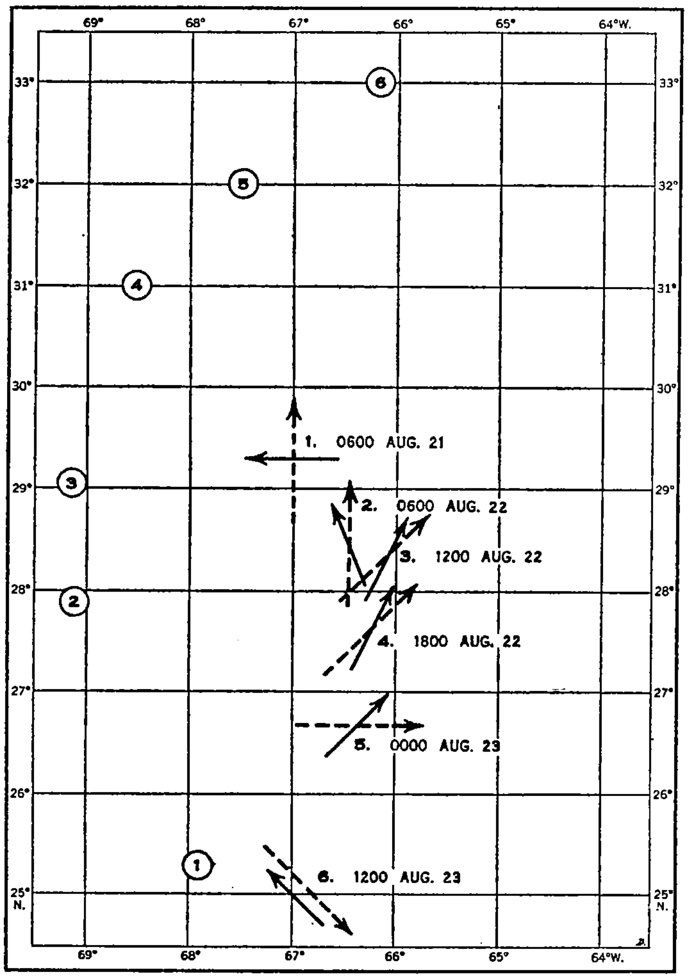

FIGURE 7.—Wind direction (solid arrows) and movement of swell (dashed arrows) observed on S. S. *A. C. Bedford* in hurricane, August 21–23, 1935.

except that the wind and swell came from opposite directions at observation numbered "6", the wind at that time being no longer definitely related to the storm.

Figure 8 shows wind and movement of swell at some distance from the center of a tropical storm in the western Caribbean Sea, at 0000 G. M. T., on September 27, 1935. No reports were received nearer the storm center. The apparent line of discontinuity in movement of swell at the rear of the cyclone is shown by the double dashed line. The ship reports in this instance also showed very clearly the deviation of winds to the left of the swells.

The maps discussed herein have been selected to portray conditions attending cyclonic storms in the open sea. It is believed that they show what will actually appear whenever careful observations of swell are secured from cyclonic storm areas in such situations. However, there are observations on many of the maps that require interpretation both as to accuracy of observation of sea swells and the effect of land areas on their development.

From an examination of many observations of swell and wind from ships at sea it appears that, in the absence of a cyclonic storm, there is little or no deviation between wind and swell. As a test, 50 reports taken at random

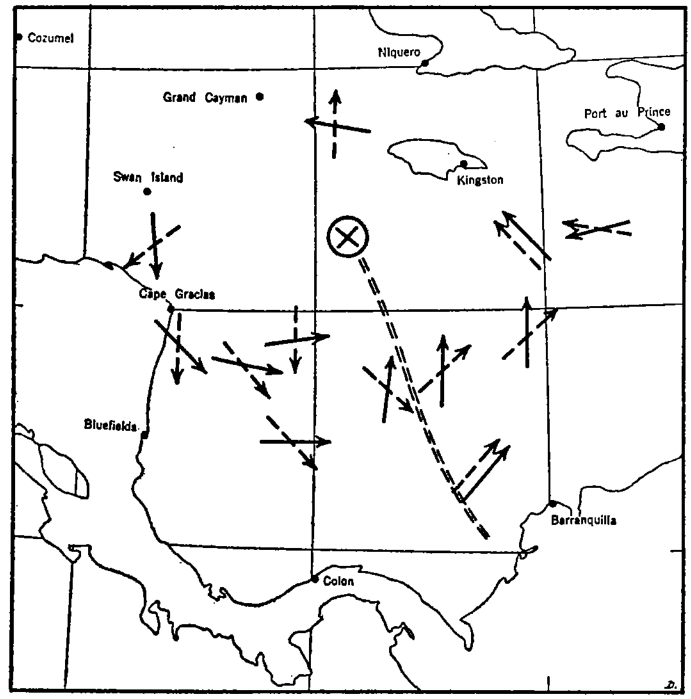

FIGURE 8.—Wind direction (solid arrows) and movement of swell (dashed arrows) in hurricane in Caribbean Sea, 0000 G. M. T., September 27, 1935.

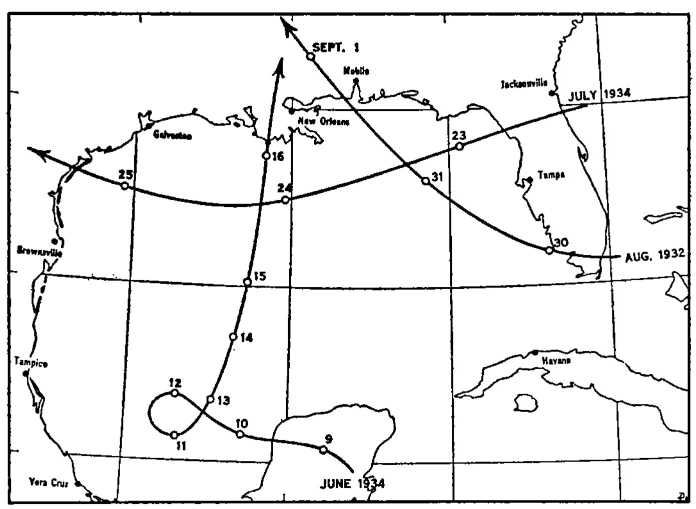

FIGURE 9.—Tracks of tropical cyclones causing heavy swells on the Gulf Coast.

from the Caribbean Sea in August 1935, when no cyclonic storm was in progress, showed an average deviation of less than one degree between wind and swell. There are individual cases of considerable deviation, apparently attributable to temporary or local wind variations, but these appear to be as likely to occur in one direction as another so that on an average the deviation between the trade wind and its swells in the Caribbean Sea appears to be practically nil.

OBSERVATION OF SWELL AT COASTAL STATIONS

The period of waves created by a storm at sea does not change materially as the waves move out of the storm field; even when the swells reach shore, where the waves move more slowly, they become shorter so that the time interval is not affected.

On approaching shore the storm swell appears to be affected in two ways. First, on reaching shallow water, the lower part of the wave meets with resistance, and the top of the wave spills forward. Second, if the orientation of the shore line is not at right angles to the direction of movement of the swell, then one end of the wave reaches shallow water and is retarded first so that the remainder of the wave gains upon it. This results in a turning movement that tends to bring the wave front parallel to the shore line. However, this is seldom fully accomplished, hence swells that approach the shore obliquely will usually arrive at some deviation from the normal to the shore line, though the deviation may be slight. Therefore, the direction of movement of storm swells, as observed on shore, is not a dependable indication of the direction in which the storm center lies, unless the observer understands the effect of shallow water on the direction of wave movement.

As an example, observations of swell taken at Santa Rosa Island, near Pensacola, in 1933, with tropical storms in progress in the Gulf of Mexico, showed an extreme variation of direction of only 45 degrees (SE to S) during the entire time of 17 days with 110 observations. During these periods, two tropical storms moved entirely across the Gulf of Mexico from east to west, and the variation in direction of swells should have been much greater in the open Gulf in that vicinity. The direction of swells as observed at Santa Rosa Island could not, therefore, be taken as an indication of the true direction of the storm center.

From the observations charted in connection with this study, it is evident that the observer facing in the direction of the storm in the Northern Hemisphere will nearly always find the swell coming from the storm center or somewhat to the left. The farther the observer's position from the storm center, the more nearly the direction of movement of swell in the open sea approaches the direction of the center.

In ascertaining the direction of the storm center from movement of swell, especially along the coast when the storm is a great distance at sea, it is necessary to take account also of the time required for the swells to reach shore. To move 400 miles, say, at a rate of 40 miles an hour, 10 hours are required, in which time the storm center, at a progressive rate of, say, 12 miles an hour, will have moved 120 miles, making an appreciable change in the direction of the storm center with reference to the distant shore. After a storm moves inland its swells sometimes continue to break on distant shores for several hours.

The period of swells observed from the shore under normal conditions varies with the length of fetch of the average winds. On small bodies of water the winds do not create waves of long period. On the shore of Corpus Christi Bay, for example, the writer has often observed waves created by the afternoon sea breeze in summer. These waves arrive at the rate of about 20 to 24 per minute, indicating that they are relatively short waves moving at a rate of about 10 miles an hour. At Galveston the usual sea wind of summer from the open Gulf is not so strong as at Corpus Christi but it is accompanied by waves arriving at the rate of about 12 to the minute or with a probable speed of about 18 miles an hour.

Along the Atlantic coast the average wave is much larger than on the coast of the Gulf of Mexico. The averages of numbers of waves per minute as observed at Coast Guard stations along the South Atlantic coast and on the Texas coast from September 1 to 28, 1935 are shown in table 1. Two regular observations were taken daily. Records for stations having less than 50 of the scheduled observations during the period were omitted.

TABLE 1.—*Average number of waves per minute*

South Atlantic coast:	
Bogue Inlet (34°40′ N., 77°05′ W.)	6.7
Cape Lookout (34°40′ N., 76°30′ W.)	7.6
Chester Shoals (28°30′ N., 80°30′ W.)	7.6
Oak Island (33°53′ N., 78°04′ W.)	9.1
Sullivan Island (32°45′ N., 79°50′ W.)	7.6
Texas coast:	
Aransas Pass (27°50′ N., 97°03′ W.)	11.5
Velasco (29°00′ N., 95°15′ W.)	10.8

The average for the South Atlantic coast stations was 7.7 waves per minute; on the Texas coast it was 11.2. The difference in size is indicated by the dimensions computed by formula; the average Atlantic wave is thus indicated to be about 400 feet from crest to crest, and the average Gulf wave about 140 feet. The speeds of these waves by formula would be about 31 and 18 miles an hour, respectively.

Regardless of the exactness of these results, the important consideration here is that the greater average size of the waves in ordinary weather along the Atlantic coast, as compared with the Gulf coast, makes it more difficult at Atlantic observation posts to identify the swells caused by tropical storms.

During the progress of a hurricane in the Gulf of Mexico from June 10 to 15, 1934, the number of swells as observed by Paul Watson at Galveston, Tex., varied from 5 to 7 per minute. On the 11th, after this storm had moved from Yucatan to the Bay of Campeche the swells were observed arriving on shore at Galveston at the average rate of 5½ per minute. There was no change in frequency until the 13th, when it increased to about 6 per minute, continuing until the 15th, when it again decreased to 5. On the 16th, as the storm moved inland over Louisiana the swells at Galveston decreased in size and ceased by nightfall.

In this instance, the period of swells arriving from the storm in the Bay of Campeche on the 11th did not differ materially from the period observed on the 15th when the storm was approaching Louisiana and was much nearer to Galveston.

In July 1934, a disturbance apparently originated off the Atlantic coast and pursued an erratic course across Florida and the Gulf of Mexico. It was of slight intensity until it passed south of Louisiana on the 24th of July; at that point it increased rapidly in intensity. Coincident with or shortly after this development, the period of the swells at Galveston increased. As recorded by Watson, the observations are shown in table 2:

TABLE 2.—*Observations of swell, Galveston, July 24, 1934*

Time	Character and motion of swells		Number of swells per minute
10 a. m.	No swell		
11 a. m.	Waves		14
12 a. m.	Slight swell	ESE	10
1 p. m.	Swell	ESE	7½
2 p. m.	Broken swells		6½
3 p. m.	Stronger swells		6
4 p. m.	Rough sea	SE	5½
5 p. m.	Heavy swells, broken		5
6 p. m.	Very rough, cross seas		5
7 p. m.		SSE	5

In this instance, increase in storm intensity was attended by an increase in size of swells.

In a similar case, in August 1932, a tropical disturbance approached the Coast Guard station on Santa Rosa Island with increasing intensity. The observations of swell, taken by the Coast Guard personnel up to noon of August 31 are given in table 3. Owing to the approach of the storm the Coast Guard personnel were obliged to abandon the station at 1 p. m.

TABLE 3.—*Observations at Coast Guard Station at Santa Rosa Island, August 1932*

Time	Character and direction of swells		Number per minute
Aug. 30, 1932:			
6 a. m.	Light	SE	12
10 a. m.	do		10
4 p. m.	do		12
Aug. 31, 1932:			
6 a. m.	Moderate	SE	8
8 a. m.	Heavy	SE	7
11 a. m.	do		6½
Noon	Very heavy	SE	6

A chart showing tracks of centers of the three tropical storms discussed in connection with records of swell at Galveston and Santa Rosa Island appears as figure 9.

The observations available show that a fully developed tropical storm in the Gulf of Mexico causes swells that arrive on shore at a rate of about 5 per minute, decreasing in exceptionally severe hurricanes to a rate of 4 per minute. This corresponds with time intervals of 12 to 15 seconds between crests. From these periods, Cornish derives a wave speed of 42 to 52 miles an hour, which he believes to be only a little less than the speed of the wind. By formula a wind velocity of 50 to 60 miles an hour would be indicated. However, tropical storms of the type producing swells in the Gulf of Mexico with periods of 12 seconds are certainly attended by much higher wind velocities. From this it is reasonable to infer that the length of fetch is insufficient to permit the full development of waves corresponding to the actual wind velocities as computed from formula for great lengths of fetch over open ocean.

In connection with extratropical cyclones, long series of observations at coastal points have been recorded by Cornish [2] which show wave periods running regularly between 18 and 24 seconds. It is doubtful if tropical cyclones ever create waves of that magnitude while in the Tropics. If the formulas for wave dimensions in relation to wind velocity are accurate when applied to the winds of the extratropical cyclone, as appears to be the case, then certainly these formulas are not applicable to tropical storms. The writer prefers to judge the intensity of a storm in the Gulf of Mexico by assuming that the force of the wind on the Beaufort scale is the same as or slightly less than the period of the swell in seconds.[7] For example, a period of 10 seconds (6 waves per minute) would indicate a wind force of 9 or 10 (Beaufort); and a period of 13 or more seconds would indicate a full hurricane or force 12 (Beaufort).

CONCLUSION

While there is a large body of observations of sea swells, part of which were connected with tropical storms, much remains to be accomplished in acquiring suitable records for study. This discussion is presented as an indication of the probable value of collecting and studying adequate and systematic series of observations, both under normal weather conditions and when tropical storms are in progress.

The available records appear to show definite relations of storm intensity and movement to the period and direction of swells, as follows:

1. Within the tropical cyclone, the winds turn to the left of the swell in the Northern Hemisphere, to the right in the Southern Hemisphere.
2. The progressive movement of the tropical cyclone results in differences in the amount of deviation of wind from swell in the different parts of the cyclone.
3. In the tropical cyclone, the length of fetch of the winds is insufficient to develop waves of the maximum length and period theoretically possible under favorable conditions with winds of hurricane force acting upon long stretches of deep sea.
4. The period of storm swells is indicative of the intensity of the storm and is not dependent upon the distance between the storm center and the point of observation.
5. There is a line of discontinuity in the movement of swell, along the line of progression to the rear of the storm center.
6. When storm swells move into shallow water along the shore, a turning movement results, so that the direction of swell tends toward the normal to the coast line.
7. Waves do not deviate from the wind in the absence of a cyclonic storm or other unusual weather conditions.
8. As a storm increases in intensity the period of the swell increases.
9. The size of waves caused by winds depends upon the extent of the water surface over which the winds blow. Waves along the southern Atlantic coast of the United States are much larger under average weather conditions than waves during ordinary weather in the Gulf of Mexico.
10. The winds over a considerable part of the storm field to the right of the center of a traveling cyclone (in the Northern Hemisphere) are directed continuously forward, roughly along the line of progression. The progressive movement of the cyclone increases the force of these winds upon the water, hence the largest swells are developed there. They run far ahead of the cyclone.

While there is a considerable body of observational data which unquestionably support the foregoing statements, there is nevertheless a disappointing lack of information regarding some features of hurricane swells, in particular the following:

1. Practically nothing has been done toward charting the character of sea swells that exist during the prevalence of average weather conditions in the southern North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. A better knowledge of average conditions is essential for a proper understanding of storm swells.

[7] Tannehill, I. R. Preparation and Use of Weather Maps at Sea, p. 38. Washington, 1935.

2. Systematic observations of sea swells at Coast Guard stations on the southern Atlantic and Gulf coasts of the United States are now being taken daily during the hurricane season. Each situation on the coast, where observations of swell are made, has its own peculiarities, which should be carefully studied to ascertain the effect upon direction of swell and to determine whether the observations in that situation are sufficiently representative of ocean conditions to justify use of the data recorded.

3. Although systematic observations of swell are reported by ships at sea, the elements included in the reports are only direction and general character, but not the period. The direction is sometimes improperly recorded as that toward which the swells are moving rather than the direction from which they come. Cross seas in the storm field make it difficult in some cases to determine the dominant swell; in other cases the waves are so confused that the observations can show only that the sea is very rough.

4. Even on shore in excellent locations for observing sea waves, the storm swells are often confused by local waves so that it is difficult to determine the true direction and period of storm swells. At Galveston, for example, a tropical disturbance in the southwest Gulf of Mexico is likely to cause an increase in force and a change of the prevailing wind at Galveston to easterly, producing local waves of considerable size running across a light storm swell from the southeast or south. Oftentimes in such cases, however, the storm swell is discernible to the experienced observer.

5. When observations of swell on shore and on shipboard have been completely standardized and after adequate records have been accumulated for study, reports of sea swells should prove increasingly valuable in the hurricane warning service. Preliminary studies indicate that the elements of real value are direction and period of swell. The period of swell gives information as to the intensity of storm winds which cannot be obtained with any precision from descriptions of swells in terms of height and length.

6. As to observation of period of swell on shipboard, Cornish [8] stated, as a result of observation during voyages through the Caribbean Sea:

> It has been pointed out that a single observer upon a vessel under way can readily and quickly determine the period of the waves by noting the time taken by a patch of foam in falling and rising. If a swift running, slow heaving swell be present, its period of oscillation can also be determined by the foam spots, for the slower heave is easily watched, not, as might be expected, camouflaged by the shorter waves.

ACKNOWLEDGMENTS

The writer has used data supplied by Mr. Paul Watson of Galveston who has studied sea swells in connection with tropical storms for more than 25 years. Acknowledgment is also made of the assistance of Messrs. Earl C. Thom and Robert B. Evans of the Marine Division, who examined ships' observations and prepared maps from which some of the illustrations in this article were selected.

[8] Encyclopedia Brittanica, 14th edition. Waves of the Sea. Article by Vaughn Cornish, London, 1929.

TROPICAL DISTURBANCES, JULY 1936

By J. H. GALLENNE

[Weather Bureau, Washington, August 1936]

Two well-defined tropical disturbances occurred during July 1936. One crossed the Louisiana coast on the 27th; the other moved from the Atlantic through extreme southern Florida and passed inland east of Pensacola on the 31st. The synoptic weather map, Noon G. M. T., of July 27 is reproduced in chart IX, with the tracks of these two disturbances.

There were two other disturbed conditions originating over tropical waters, one during the period July 12 to 14, in the western Gulf of Mexico, and the other on July 22 near Puerto Rico; but neither appears to have developed more than slight intensity. The available reports do not show definite progressive movements to any considerable distances beyond the areas in which they were first observed.

July 26–28.—From the ships' weather observations taken at 7 a. m., E. S. T., on July 26, it was evident that there was a tropical disturbance in the southeastern portion of the Gulf of Mexico; and by 7 p. m. its position could be fixed, from ship reports, as being near latitude 26° north and longitude 89° west, with relatively slow movement in a northwesterly direction. At that time the disturbance appeared to be of slight intensity and confined to a small area, although there was a fairly definite cyclonic wind circulation. At 5 p. m. the S. S. *Davanger* near 26½° north, 88° west, reported squally weather, wind force 8, barometer 29.82 inches.

This depression moved on a north-northwesterly course during the next 12 hours, being located approximately 60 miles south of the coast of Louisiana, near the 90th meridian, at 8 a. m., E. S. T. of the 27th. At 7 a. m. the S. S. *San Gil*, at 28°15′ north and 89°30′ west, reported south-southeast winds of force 5 (Beaufort scale) with barometer reading 29.76 inches.

During the early afternoon of the 27th, the disturbance moved inland over southern Louisiana. At Delta Farms, Lafourche Parish, the lowest pressure was 29.62 inches (corrected) at 1:30 p. m. E. S. T. This is the lowest barometer reading of record during the progress of the disturbance. It was accompanied by an estimated wind velocity of 50 miles an hour. At the New Orleans Weather Bureau Office, a short distance to the right of the path of the center, the lowest pressure was 29.74 inches, at 5 p. m. on the 27th. Advancing farther inland with a recurve to the northeastward, the disturbance moved into Mississippi and dissipated on July 28.

Storm warnings for the Louisiana coast were issued at 9:15 a. m. E. S. T. on July 27 and all interests were advised to prepare for storm winds and rising tides. The conditions which occurred during the afternoon were fully and accurately heralded in the bulletin disseminated by the forecaster at New Orleans at 12:30 p. m., E. S. T.:

> July 27. Bulletin 12:30 p. m. E. S. T.: Tropical storm is turning northward and will move inland during next few hours over Lafourche and eastern Terrebonne Parishes, La., attended by shifting gales from Grand Isle westward to near Houma, La., with tides considerably above normal in area named.

There was no loss of life, and no important storm damage was reported.

July 27–August 1.—The history of this disturbance is not clearly shown by the observations until the morning of July 27 when a well-formed but weak cyclonic circulation was charted a short distance south of Cat Island, Bahamas. Progressing on a west-northwesterly course, with increasing intensity, the disturbance crossed Andros