THE HURRICANE SEASON OF 1957

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1. GENERAL SUMMARY

Eight tropical storms developed in the North Atlantic and Gulf of Mexico in 1957 and three of these reached hurricane force. The normal for recent years is 10 storms with about 5 developing into hurricanes. The pattern of movement (see fig. 1) was similar to that of 1956 with storms striking the Gulf coast but sparing the eastern seaboard as those in the Atlantic recurved offshore. Hurricane Audrey, which struck near the Louisiana-Texas border in June, was one of the most destructive June hurricanes of record and the first to occur in that month since 1945. The other two hurricanes, Carrie and Frieda, remained at sea in the Atlantic. Carrie persisted as a hurricane for more than two weeks and was responsible for the sinking of a ship near the Azores with the loss of 80 lives. Frieda was of minor importance and reached hurricane force only a few hours before it began losing its tropical characteristics.

Including hurricane Audrey, five tropical storms reached the United States, all on the Gulf coast between eastern Texas and northwestern Florida. None affected other coastal areas of the Gulf of Mexico or the Caribbean and there were no landfalls along the entire eastern seaboard. Property damage approximated $152,500,000 for the United States; none occurred in other areas. Audrey left 390 known dead, including 263 identified and 127 unidentified. There were 192 persons reported missing many of whom may be among the 127 unidentified dead. The loss of life in Audrey was the greatest of any tropical storm in the United States since the New England hurricane of 1938 and emphasized the difficulty of insuring the carrying out of adequate safety precautions and evacuation, even with the most recent methods of tracking and early warnings.

2. INDIVIDUAL STORMS

Tropical Storm (unnamed), June 8–14.—Pressures were abnormally low over the southwestern Gulf of Mexico and Yucatan area on June 7 but lack of upper-air wind observations from Mexico made the amount of circulation uncertain. However, late on the 7th and early on the 8th it became evident that a tropical depression existed. It moved rather rapidly northeastward with some deepening but little organization and crossed the Florida coastline in Apalachee Bay during the early evening. Two ships, one about 150 to 200 miles southeast of the center and later another 100 to 150 miles west of the center, reported winds of 45 knots. However, over coastal areas all strong winds were on the east side of the storm. Exposed places along the coast from Sarasota to north of Cedar Keys, Fla., experienced winds of 40 m. p. h. or more and tides 2 to 3 feet above normal with some damage. The storm weakened as it moved inland but set off an active frontal wave after moving off the Georgia coast on the 9th. Late on the 9th when the storm became extratropical off the Atlantic coast, ship reports indicated winds up to 65 knots.

Exceptionally heavy rain attended passage of this storm, particularly in Suwannee and all adjacent counties; 48-hour amounts of nearly 15 inches at official stations and some unofficial amounts as high as 19 inches. There was considerable damage to field and truck crops, particularly to tobacco and watermelons. Between 100 and 200 families were evacuated near Perry, Fla. According to the Meteorologist in Charge at Jacksonville, at least nine tornadoes or damaging wind storms were reported in northeastern Florida on the afternoon and evening of the 8th and another tornado over Jekyll Island in southeastern Georgia. No deaths were reported from these tornadoes and the damage and injuries were small.

One small craft capsized in the Gulf of Mexico and five of the seven persons aboard were apparently drowned. Damage in northwestern Florida from sea and rainfall flooding from the mouth of the Suwannee River to Port St. Joe was estimated at $30,000 and damage from tidal action along the Florida west coast was about $10,000. Tornado damage is estimated at $12,000. Therefore, total damage from this tropical storm was around $52,000 and there were five deaths.

Hurricane Audrey, June 25–28.—Hurricane Audrey, which struck the Gulf coast near the Texas-Louisiana border on June 27 with devastating effect, first became well defined over the Bay of Campeche, in the southwestern Gulf of Mexico, on June 24. A weak easterly wave which moved into the area a day or two earlier, as evidenced by changes in the wind field across the western Caribbean and Yucatan and by increased shower activity, was probably instrumental in initiating the disturbance. Klein [7] has discussed the formation and behavior in relation to the mean circulation for the period. He found that it was possible, using the 5-day 700-mb. height anomaly patterns, to track a negative anomaly center associated with Audrey back to its appearance in the western Caribbean during the period June 11–15. Namias [11] has demonstrated the relation of hurricane genesis to areas of negative anomaly on such mean charts. Two

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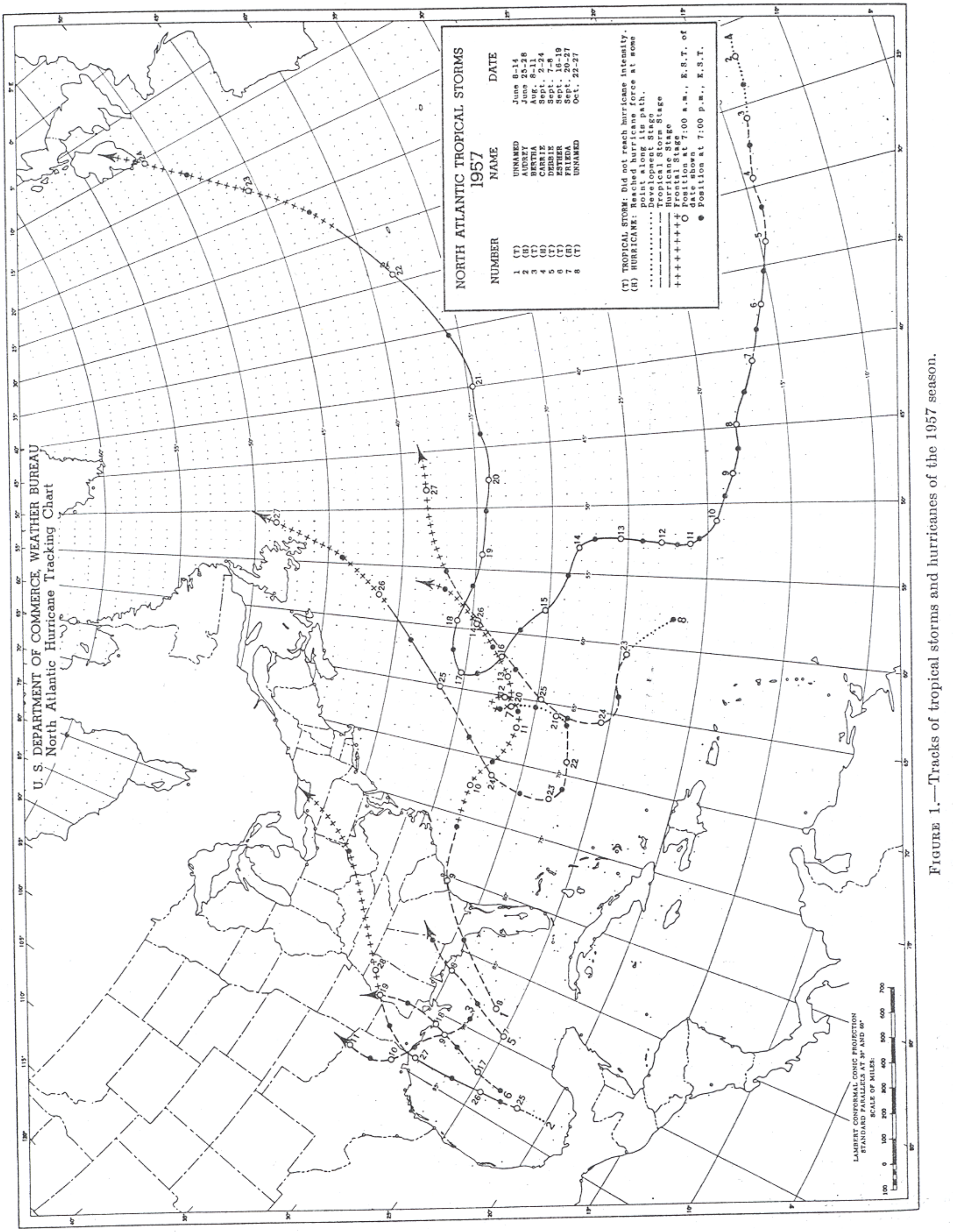

FIGURE 1.—Tracks of tropical storms and hurricanes of the 1957 season.

other factors recognized as important in hurricane formation—warm sea-surface temperatures and the proper divergent pattern at high levels—were present. While Klein used the techniques of the Extended Forecast Section of the Weather Bureau, applying 5-day or longer means to his analysis, the importance of some of the contributing factors is also apparent when viewed from a short-range aspect. For instance, the 200-mb. 5-day mean flow was shown to conform to the pattern suggested by Riehl [13] as conducive to deepening. The 200-mb. charts for the 25th to 27th show a marked intensification of the ridge over the middle and east Gulf, and, inferentially, of the high-level outflow from the storm area during this period.

The mean sea-surface temperatures for the Gulf of Mexico for June were generally 2° to 3° F. above normal. In addition, warming was evident preceding the development of Audrey with the highest temperatures (85° F.) in the area where the hurricane formed.

Audrey deepened during the night of June 24 while remaining nearly stationary. Aircraft reconnaissance on the morning of the 25th reported maximum winds of 85 knots and minimum pressure 989 mb. Although moderate to severe turbulence was encountered, radar presentation was characterized as "poor," a feature which usually indicates that a tropical storm is not as active or as "wet" as those with more definite rain bands. Rapid deepening would therefore not normally be expected. Late on the afternoon of the 25th a second flight reported that the maximum observed wind was 75 knots and the minimum pressure 979 mb. On June 26 both the size and intensity of the hurricane increased slightly. Reconnaissance showed maximum winds of 90 knots and a minimum pressure of 973 mb. A radar tracking flight during the night of the 26th reported the precipitation field as considerably more intense than observed 24 hours previously. However, no central pressure measurement was obtained. The only additional observation of central pressure prior to the landfall of the storm was that by the Tanker *Tillamook* near latitude 28.7° N., longitude 94.0° W. from 0910 to 1025 GMT, June 27. The minimum pressure observed was 969 mb. (The barometer was subsequently calibrated and the figure of 969 mb. is the corrected value.) Indications are that the ship was in the western portion of the eye and that the pressure observed was not the absolute minimum in the center at that time.

From June 26 until the center crossed the coast about 1430 GMT on the 27th, Audrey increased its forward speed from about 7 m. p. h. to 15 m. p. h. At the same time it intensified markedly. The central pressure when it struck the coast was some 30 mb. lower than that last reported by reconnaissance and there is no doubt that there was considerable deepening in the five hours between time of the observation of the *Tillamook* and landfall. The exact minimum pressure as the center reached the coast has not been determined. The Calcasieu Coast Guard station, 20 miles east of the center, reported 960 mb. and at Port Arthur, Tex., about an equal distance west of the center, the lowest pressure was 966 mb. The lowest pressure observed was 958 mb. by the Fish and Wildlife Service at Hackberry, La.

The Hydrometeorological Section of the Weather Bureau [9] has described the radial profile of sea level pressure of a model hurricane as:

$$\frac{p-p_0}{p_n-p_0}=e^{-R/r}$$

where p is the pressure at radius r, p_0 the central pressure, p_n the pressure to which the profile is asymptotic at some distance from the center and R the radius at which the wind speed is greatest. Because of sparse data and the lack of symmetry of the hurricane there is some leeway in values which can be assigned to the parameters in this case, particularly p_n and R. However, a minimum pressure of 938 mb. as computed from the formula, seems consistent with reports of wind, storm surge, and damage.[1]

Calculations using empirical formulae pertaining to maximum wind and storm surge and based on an estimated central pressure of about 940 mb. agree well with the data collected for the hurricane. A peak wind speed of 105 m. p. h. in a gust was read by eye from a wind dial at Sulphur, La., before the anemometer blew away. An oil rig reported winds up to 180 m. p. h. and a pressure of 925 mb. (It is not known whether this was a sustained wind or a gust, or whether it was measured or estimated.) Four sea tenders of the Continental Oil Company lost their anchors and were adrift in the hurricane just a short distance southeast of the center. The anemometers with which these tenders were equipped (not calibrated following the hurricane), all indicated winds in excess of 100 m. p. h. The three nearest the center indicated winds of 140 to 150 m. p. h. (These were peak gusts rather than sustained speeds and were read by eye from the anemometer dial indicators. The anemometers were 65 ft. above water.) Fletcher [3] has presented an empirical formula for calculating maximum winds in a topical storm. The formula, which is of the same form as those developed by Takahasi [15] and Myers [9], uses the difference between central and environmental pressure as a parameter. Fletcher's formula, which according to Myers [10] gives gust and not sustained speed, has proven very reliable in operational use when the central pressure was known. If this formula is applied, using the central pressure now believed to have existed in Audrey, the indicated maximum wind is about 150 m. p. h. While this is in agreement with several unofficial reports of extreme winds, the exact speed which occurred must remain in doubt.

As is usual in hurricane catastrophies, the most damaging feature was not the wind but its indirect effects through the storm surge. Nearly all the deaths can be attributed

[1] A manuscript by Hudson [5] has since come to our attention. In this, with the methods outlined in [9], the most likely value of central pressure was calculated to be approximately 946 mb. with a 70 percent probability that the true value was between 914 mb. and 958 mb.

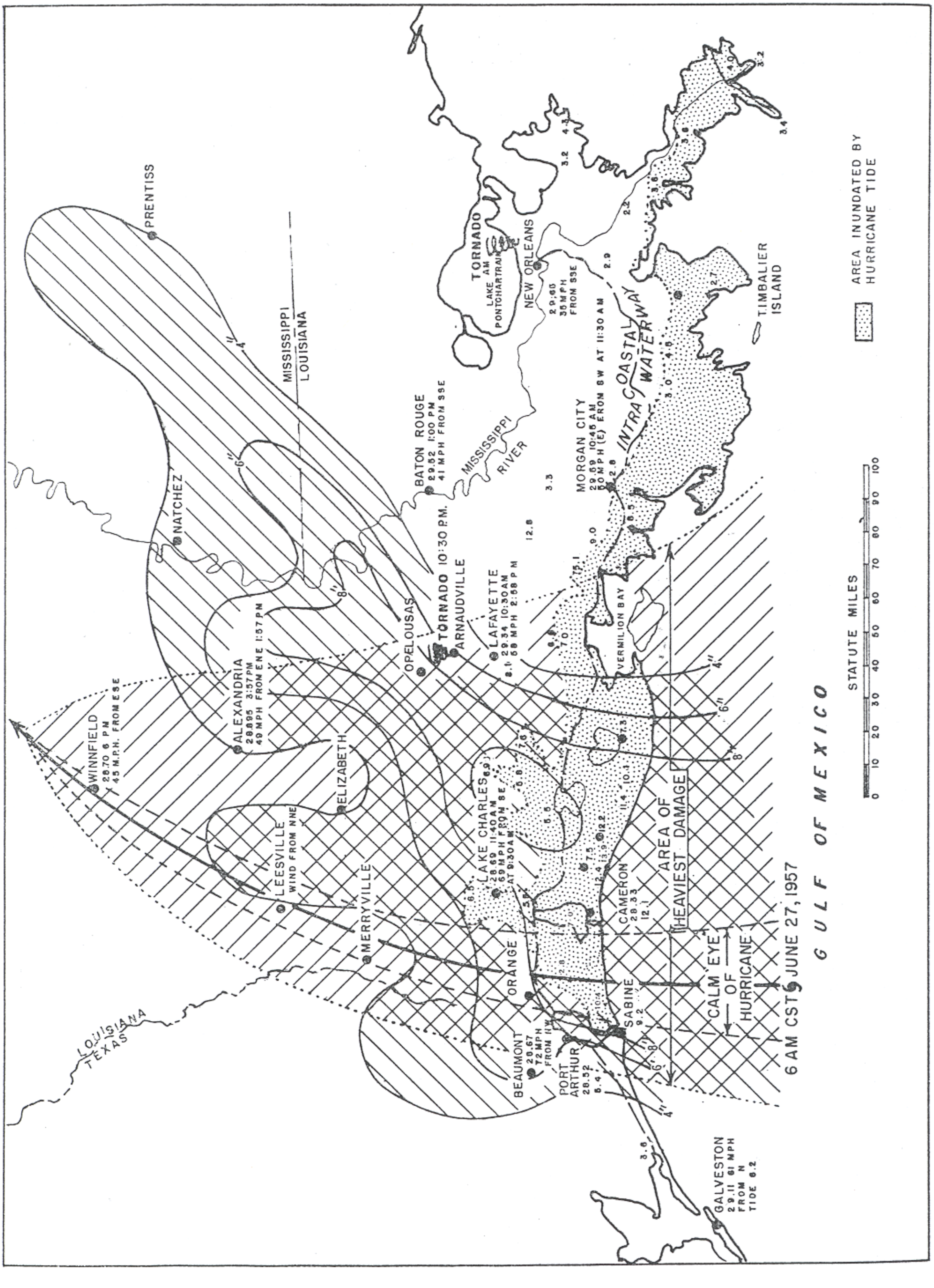

FIGURE 2.—Map showing landfall and track of hurricane Audrey in Louisiana on June 27. Windspeeds given are the fastest mile or the highest 1-minute speed; (E) = estimated. Pressure (inches) is the lowest observed at the point plotted. Tide heights are in feet above mean sea level, and were measured by the Corps of Engineers.

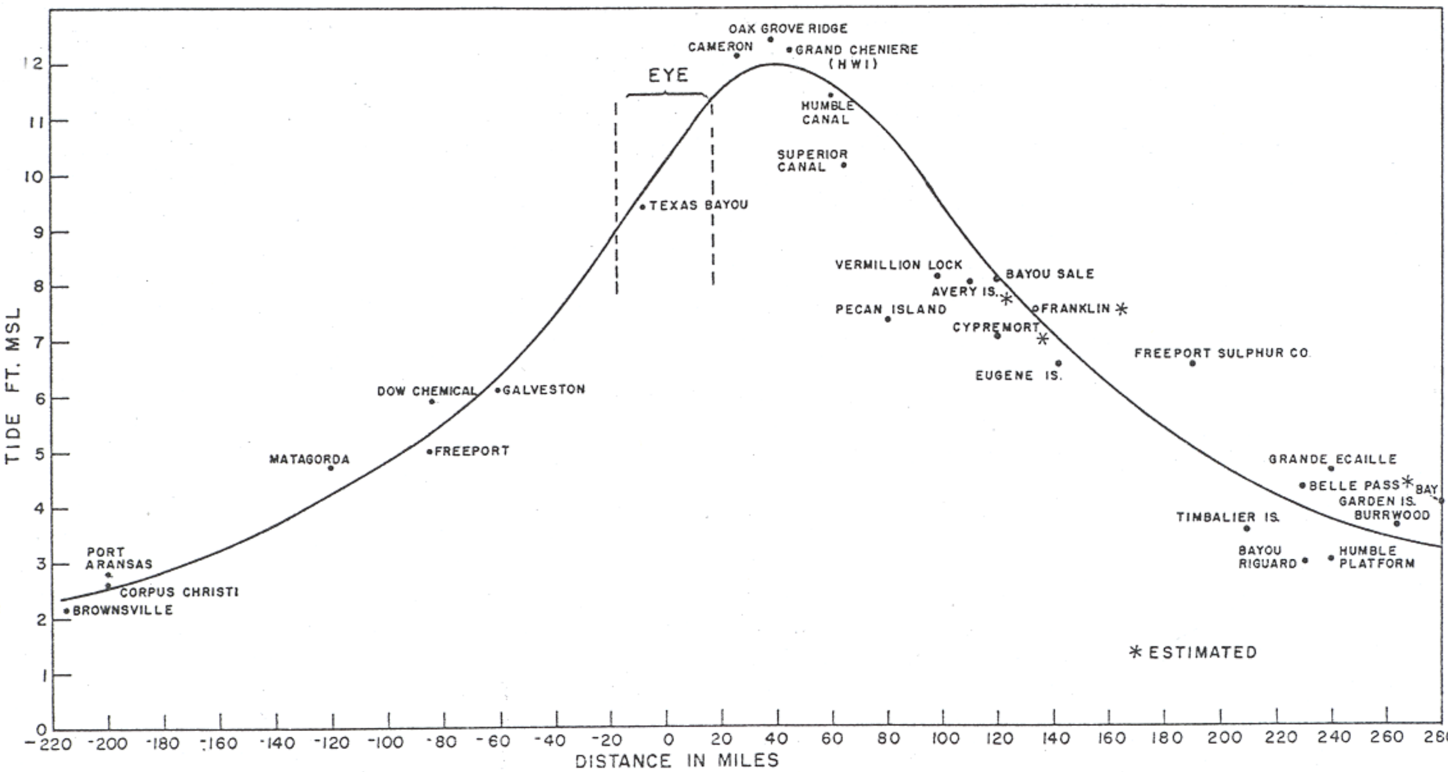

FIGURE 3.—Maximum tide heights recorded during the passage of hurricane Audrey.

to drowning by high tides. (See figs. 2 and 3.) Tides were reported to be more than 12 feet above mean sea level in Louisiana from the Coast Guard Station at Calcasieu Pass to Grand Cheniere, a distance of 24 miles.[2] Storm surge forecasts are extremely difficult and beset with many complicating factors other than meteorological, such as funnelling by coastal configuration or in bays, slope of the continental shelf, and the astronomical tide stage. A formula has been developed by Conner, Kraft, and Harris [1] for computing the probable height of the storm surge as a function of central pressure. Using 940 mb. as the minimum pressure, the formula indicates about 12 feet as the probable height. There is a vital difference between this value and the forecast of 7.5 feet which would be obtained using the 973-mb. central pressure last reported before the storm struck the coast. The capacity of the hurricane to generate a deadly storm surge was greatly increased by the rapid deepening just prior to landfall.

While it is not now possible to explain the rapid deepening or to suggest how it might be anticipated in the future, two possibly significant factors may be suggested. On June 26, rises in the 200-mb. heights over the storm area accentuated the high-level pattern indicated by Riehl [13] and Miller [8] as favorable to intensification. (A computation made on that date, using the procedure suggested by Miller, indicated 936 mb. as the potential depth of the hurricane.) Sea surface temperatures, recognized as an important factor in development of tropical storms, were abnormally warm and increasing. It also seems possible that sea surface temperatures near the coast may have been even higher than those generally indicated by ship reports over the Gulf, since very shallow waters extend a considerable distance from shore in this particular area.

In its later stages, the interaction of Audrey with the westerlies also created some forecast problems. As in some other notable hurricanes of recent years, strong baroclinic developments accompanying this interaction coincided with, and probably contributed to, radical readjustment of the broad-scale pattern. Since this, as well as the entire synoptic history of Audrey, is covered in a recent article by Ross and Blum [14], it will not be discussed here.

The exact number of deaths from Audrey will probably never be known. The list of known dead includes 371 in and near Cameron and 19 in other areas. To this list must be added a large number of others presumed dead from the 192 still listed as missing, although many of these may be among the 127 unidentified dead. The loss of life was the greatest in the United States since the New England hurricane of 1938 and about equal to the total for all other tropical storms in the United States in the past decade.

Property damage in Audrey is estimated at $150,000,000. In the Cameron to Grand Cheniere area, 60 to 80 percent of the houses were destroyed or floated off their foundations. Inundation extended inland as much as 25 miles over the low-lying area (see fig. 2). As the hurricane moved northeastward from Louisiana, it gradually weakened and began losing its tropical characteristics but was still attended by some damaging winds on the

[2] A high water mark found on Oak Grove Ridge, just north of the mouth of the Mermentau River, was subsequently established as 13.9 ft. m. s. l. by Corps of Engineers.

28th. Several tornadoes formed southeast of the storm center and injured 14 persons in Alabama. Re-intensification occurred due to extratropical processes as the storm moved from the Ohio Valley through the eastern Great Lakes region and there was a large amount of flood damage in States south of the Great Lakes, particularly in Illinois and Indiana, and some damage from high winds and thundersqualls from western Pennsylvania through New York. Winds were reported as high as 65 m. p. h. at Pittsburgh, Pa., and 95 to 100 m. p. h. at Jamestown, N. Y.

Tropical Storm Bertha, August 8–11.—A weak extratropical Low entered the northeastern Gulf of Mexico on August 6 and drifted slowly westward for the next 2 days. It developed into a tropical storm about 100 miles south of the mouth of the Mississippi River on August 8, then moved in a general northwesterly direction, crossing the coast near Cameron, La., late on August 9. Since it was moving toward the same portion of the coast devastated by hurricane Audrey 2 months earlier, Bertha was viewed with alarm by the population and full safety precautions and evacuations were evidently carried out promptly. Fortunately, Bertha did not develop to full hurricane intensity. Highest winds were estimated by ships and land stations at 50 to 70 m. p. h. The fastest mile at Beaumont, Tex., was measured at 44 m. p. h. with gusts to 52. Tides did not approach the disastrous proportions of those in Audrey, the highest reported being 4.7 feet at the west end of Vermilion Bay. The heaviest rainfall observed was 10.73 inches at Livingston, Tex.

The storm weakened and turned northward after moving inland, reaching southeastern Oklahoma on August 11. Although the storm was not identifiable as a surface circulation thereafter, it was apparent in the circulation aloft and in the accompanying heavy rains as it turned eastward across Arkansas. Two deaths resulting from Bertha were reported; property damage was slight, and the accompanying rain has been described by the Meteorologist in Charge at New Orleans Weather Bureau Office as over-all more beneficial than harmful.

The failure of Bertha to intensify similarly to Audrey may have been related to the broad-scale flow pattern. Green [4] has noted that in June, a strong trough prevailed in the 700-mb. mean pattern over the central United States, while in August this had been replaced by a strong High. The 200-mb. charts also indicate that the high-level outflow pattern was less favorable for deepening than in the case of Audrey.

Hurricane Carrie, September 2–24.—In early September the circulation pattern over the eastern Atlantic resembled that found by Namias and Dunn [12] to be characteristic of periods in which tropical storms develop in the Cape Verde area. The northeastward extension of the Azores High produced above-normal pressures in the area of western Europe while a trough prevailed near the west coast of Africa. Observations from the Cape Verdes on September 2 showed evidence of a vortex passing just to the south of the islands, and a message from Panair do Brasil reported a tropical storm developing near latitude 11° N., longitude 25° W. On September 6 the SS *African Star*, about 700 miles west of the Cape Verde Islands, forwarded a succession of special reports showing falling pressure, increasing winds, and squalliness. The existence of hurricane Carrie was confirmed when the 1600 GMT report (somewhat delayed) showed an east-northeast wind of 92 m. p. h. and a pressure of 1,001 mb. Later analyses indicate that the vortex noted on the 2d was the genesis stage of Carrie and that it moved west-northwestward at about 12 m. p. h. to the position at which it was encountered by the *African Star*.

On September 7, in an unusually long flight, the regular Air Force Gull reconnaissance plane from Bermuda was diverted to the storm area. The observer reported maximum winds of 138 m. p. h. at the 700-mb. level with a well-defined eye 20 miles in diameter and a minimum surface pressure of 945 mb. Using this central pressure, as obtained by dropsonde, and the formula developed by Fletcher [3], maximum surface winds were calculated to be about 130 m. p. h. Reconnaissance on the next 4 days showed a gradual rise in central pressure and on the 11th the minimum pressure was 984 mb. and the highest winds were reported as about 70 m. p. h. The weakening of the hurricane was apparently due to decreasing pressure gradient to the north as a low pressure trough formed across the subtropical High to a deepening Low near Newfoundland. This Low moved southward, reaching its most southerly position on the 11th, after which it began a slow retreat to the north. Carrie, having curved to a northerly course at this time, continued northward at 7 to 10 m. p. h. until September 14 when rebuilding of the high pressure ridge over the north Atlantic forced it to change course toward the northwest. This change in direction was accompanied by reintensification, and on the 12th reconnaissance aircraft found maximum winds of 108 m. p. h. and minimum sea level pressure of 960 mb. There were heavy wall clouds in all quadrants except the southwest. A continued increase in intensity and in size culminated on the 16th in what National Hurricane Research Project observers characterized as one of the most perfectly formed hurricanes they had seen. The winds of 138 m. p. h. reported on this date were the maximum surface winds observed during the life of Carrie but it is likely that higher wind speeds occurred during the period of lowest central pressure on September 7 and 8.

When the hurricane passed to the northeast of Bermuda on the 16th, poor radar definition and an increase in the diameter of the eye to 40 to 70 miles indicated weakening. However, as it curved eastward in advance of a trough moving into the North Atlantic, it still maintained maximum winds of near 100 m. p. h. for the next several days. On the 21st the German sailing ship *Pamir* encountered the storm southwest of the Azores and went down with the loss of 80 of her 86 crew members. Insufficient reports were obtained to indicate the maximum wind and lowest pressures observed as it passed through the Azores the next day but it is likely that winds of hurricane force persisted. Carrie began to assume extratropical features thereafter and accelerated to the northeast, lashing the British Isles with high winds on the 24th and 25th and causing tremendous waves on the coast and floods over parts of the Isles.

Carrie was charted over one of the longest tracks, probably the longest track, of record—approximately 6,000 miles from its origin off the African coast to near Bermuda and back across the Atlantic to the British Isles. Formal advisories were issued from September 6 to 21 and additional advices were issued through the NSS bulletin (report from Navy Radio station at Annapolis) after it passed east of longitude 35° W. on that date. Aircraft reconnaissance of Carrie was of unusual quality. The Air Force flights from Bermuda on the 7th and 21st went farther east than any previous hurricane reconnaissance flight and the initial flight on the 7th covered approximately 3,700 miles with almost 17 hours in the air.

Tropical Storm Debbie, September 7–8.—On September 5 there was evidence of a weak easterly wave moving from the Caribbean into the Gulf of Mexico where a stagnant upper trough prevailed. This wave was apparently the trigger which set off a weak circulation in the central Gulf on September 7. This depression moved northeastward and only barely reached storm force before going inland near Fort Walton, Fla., about 40 miles east of Pensacola, on the morning of the 8th. Highest winds reported were around 40 m. p. h. at St. Marks. Tampa had gusts to 52 m. p. h. in a squall. The highest tide reported was some 150 miles east of the center on Apalachee Bay where it ranged from 2½ to 4 feet. Some flooding occurred due to the tides and rains, which were locally heavy, with 9.10 inches at Crawfordsville, Fla. There were no fatalities as a direct result of the storm although it was indirectly responsible for four deaths.

The failure of Debbie to intensify further may be attributable to two factors. The upper-air pattern never conformed to that found to favor intensification [8, 13]. In addition, there was evidence that cooler air entered the circulation as it moved near the coast.

Tropical Storm Esther, September 16–19.—Squalliness and abnormally low pressure in the southwestern Gulf of Mexico on September 15 indicated that a tropical depression might be forming. For about 2 days prior to this date a weak cyclonic circulation aloft had been drifting northwestward across Central America toward the Gulf. On the evening of the 15th the New Orleans Weather Bureau Office issued a bulletin announcing the development of a depression and forecasting intensification. Esther grew to storm intensity by late on the 16th and began moving northward at about 10 m. p. h. It never developed into a typical tropical storm with a small, well-defined eye but remained with a large area of relatively light winds roughly 100 miles across. This area passed inland on the southeastern Louisiana coast about daybreak on September 18, subsequently moving up the Mississippi Valley and weakening. As in the case of the first storm of the season (unnamed) and Debbie, much of the squalliness and high wind was a considerable distance to the east of the center. The highest reported wind speed was 52 m. p. h. at Pensacola airport, with gusts to 75 m. p. h. The lowest pressure observed on land was 1003 mb. at New Orleans and McComb, La., with 1000 mb. reported by reconnaissance aircraft before the storm reached land.

Squalls and heavy rains occurred in advance and to the east of the central area and continued along the Mississippi and Alabama coasts and near the mouth of the Mississippi River well after it passed. Five inches of rain fell at Buras, La., in 2½ hours with a total of over 13 inches there. Amounts ranging upwards from 6 inches through southeastern Louisiana and near the Mississippi and Alabama coasts resulted in some flooding in those areas. The property damage chargeable to Esther was estimated at $1,500,000 and three deaths were attributable to the storm.

Hurricane Frieda, September 20–27.—Hurricane Frieda spent its life at sea and was of hurricane force for only a few hours. The circulation which developed into this storm began on September 20. A cold front pushing southward to the rear of Hurricane Carrie passed Bermuda and a low center of 1010 mb., appearing at first to be nothing more than an incipient frontal wave, rapidly developed. Elsewhere, significant features were a 1020-mb. surface anticyclone some 700 miles to the north, and northerly winds of near 55 m. p. h. at 500 mb. and higher over the surface cyclone. By early morning of the 21st, strong easterly winds of 63 m. p. h. were observed at the gradient level at Bermuda. The LST *Narvik* reported the central pressure in the developing storm, about 400 miles south-southwest of Bermuda, as 1005 mb. Several factors favored intensification at this time. The strong low-level easterly winds north of the area resulted in a strong cyclonic shear, the sea surface temperatures were very warm, raobs from the *Narvik* and from Bermuda indicated that the cold front had dissipated, and there were favorable high-level winds for evacuation. By evening of the 21st, aircraft reconnaissance showed that central pressure had fallen to 1001 mb. and winds were up to 60 m. p. h. in squalls east of the center. Frieda was a reality. The movement was rather slow to the southwest.

Reconnaissance on the morning of September 22 found maximum winds of 50 to 60 m. p. h. in gusts with sustained winds generally 30 to 40 m. p. h. Shower activity was considerably less than normal and there was no extensive cloud shield. Meanwhile, upper winds at Bermuda were rapidly veering from northerly to southeasterly with decreasing speeds. This occurred as a high-level anticyclone northwest of the storm weakened and split in response to the approach of a short wave in the westerlies. This left the upper ridge with two cells, one over Florida and the other northeast of Bermuda.

With a less favorable circulation for intensification, Frieda showed little change through the 23d. At the same time, recurvature was favored by the new circulation pattern around the storm and it began to move toward the northwest and north at about 10 m. p. h. during the night of the 23d. Simultaneously, as the short wave in the westerlies progressed eastward, the upper trough weakened and, perhaps in response to a more favorable high-level evacuation mechanism, the cloud systems began to show more organization and radar coverage became feasible for the first time. Forward velocity increased to 20 m. p. h. toward the north-northeast on the 24th and little change was observed in surface pressures. However, by morning of the 25th, the Canadian merchant ship *Irvingbrook* reported a barometer reading of 992 mb. and 80-m. p. h. winds. Frieda now was a hurricane—but only for a few hours for the cold front associated with the short wave mentioned previously was dropping into her circulation. Some further decrease in central pressure occurred as shown by a report from the ship *African Lightning*, giving a pressure of 978 mb. However, this was interpreted as the result of extratropical deepening since the storm was spreading out and there was no observed wind speed such as the 115 m. p. h. that Fletcher's [3] formula would indicate under true tropical conditions with such a pressure.

Although Frieda began under conditions not clearly tropical and became extratropical shortly after reaching hurricane force, soundings taken in the storm averaged slightly warmer than the mean tropical atmosphere. Aircraft data and surface pressures also showed good agreement with the relation given by Jordan [6] for tropical cyclones. However, throughout the life of the storm, the favorable parameters for hurricane formation and maintenance seem never to have operated concurrently or for long enough periods to produce a typical hurricane. After becoming extratropical, Frieda continued rapidly northeastward, with gradually decreasing intensity, and passed across Newfoundland on the night of the 26th.

No deaths or property losses have been charged to this storm.

Tropical Storm (unnamed), October 22–27.—On October 22 and 23, shower activity increased and pressures began falling near and to the north of the Lesser Antilles. A strong upper trough extended from the vicinity of Bermuda to Puerto Rico and on October 23 a small cut-off Low developed in this trough. The surface circulation increased markedly on this date, and in the evening a ship near the center of the circulation at about latitude 25° N., longitude 63° W., reported a barometer of 999 mb. and winds up to 35 m. p. h. On the 24th reports showed that there had been further intensification with winds in squalls up to 50 to 60 m. p. h. just north of the center and winds of 30 to 35 m. p. h. prevailing 200 to 400 miles from the center. The storm gradually curved from a northwesterly to a northerly direction at 12 to 15 m. p. h. The lowest surface pressure reported was 993 mb. by a ship near 28° N., 65° W. at 0600 GMT on the 25th. A gradual weakening and filling began thereafter with acceleration to the northeast. When the storm passed just east of Bermuda on the evening of October 25, there were strong winds east of the center but only moderate winds to the west in the area of Bermuda, the pressure gradient there having been weakened by the approach of an extratropical system which gradually absorbed the remnants by the 27th. This storm never developed many of the characteristics of a true tropical cyclone and in many respects was similar to tropical storms Dora and Ethel of 1956 and a quasi-tropical Low of October 1956 [2]. It caused no deaths or property damage.

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HURRICANE AUDREY, 1957

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1. INTRODUCTION

On the morning of June 27, hurricane Audrey swirled across the Gulf coast near the Texas-Louisiana border. Communications were disrupted, and as reports dribbled in it was some time before a shocked nation learned the full extent to which the hurricane had devastated the coastline. The death toll mounted to 100—then 200—and finally over 500. Property damage was estimated at 150 to 200 millions of dollars [1, 2]. Entire communities in the tidal region of Louisiana were demolished. Even after the storm had assumed extratropical characteristics, ten lives were lost and property was destroyed in Indiana, Illinois, and New York due to heavy rains and high winds. The storm's influence extended even into Canada, were four persons were killed and winds of 80 m. p. h. were recorded.

During the period June 20 to June 25, an ill-defined easterly wave had moved across the Caribbean Sea to a position at 22.5° N., 93° W., in the Gulf of Mexico, where a tropical depression developed. This easterly wave was difficult to follow as it progressed westward due to the uneven distribution of reports from this area. In correspondence with the Weather Bureau office in New Orleans, La. [2], regarding the formation of hurricane Audrey, the following was received:

> Light westerly winds aloft (mid-levels) were reported from Carmen (Mexico) on June 24th. This was the first definite indication of circulation over the southwest Gulf. That evening the following message was received from Brownsville (Tex.):
>
> CKT 7062 ABRO 250230Z SHRIMP DOCK AT PORT BROWNSVILLE REPORT ONE SHRIMP BOAT IN GULF OF CAMPECHE IN ROUGH WEATHER AT 2230N 9430W WIND STEADY AT 35/40 KTS G55 IN SQUALLS BAROMETER READING THIS MORNING 2990 THIS EVENING 2978 STRONG SEA SENT 0233 HRR

An investigation by Klein [3] on the formation of this tropical depression which developed into Audrey is reported in this issue. He discusses the importance of the broad-scale flow patterns and the sea surface temperature.

2. TROPICAL PHASE

At 0430 GMT on June 25, the first bulletin from the New Orleans Weather Bureau Office [4] was released on the tropical depression which had formed over the Bay of Campeche in the southwestern Gulf of Mexico. Highest winds were estimated to be about 35 to 40 m. p. h. The depression remained nearly stationary for several hours and showed signs of rapid intensification. On the basis of a Navy reconnaissance flight and an earlier excellent report from the SS *Terrier*, the first hurricane advisory was issued by the Weather Bureau at 1800 GMT June 25, stating the tropical depression had reached hurricane strength and was centered near 22.5° N., 93.0° W., or about 380 miles southeast of Brownsville, Tex. The storm was forecast to move northward at 5 m. p. h. and to increase slowly in size and intensity. As the storm moved northward, the winds near the center increased in speed from 75 to over 100 m. p. h., and by 1200 GMT on the 26th it had moved to a position 250 miles east-southeast of Brownsville. At this time the storm was moving northward at about 10 m. p. h. This rate gradually increased until it reached 15 m. p. h. early on the 27th. By 1300 GMT on the 27th the storm was centered just off the Texas-Louisiana coast south of Port Arthur, Tex. Up to this time the highest winds reported on the coast were 75 m. p. h. and the highest tide reported was 7 ft. m. s. l. These were the last reports received from Sabine, Tex., before their communications failed.

At 1530 GMT on the 27th a report from Orange, Tex., stated that after having experienced winds of over 100 m. p. h., the town was now in the dead calm associated with the eye of the storm and awaiting the return of strong winds. The maximum winds at Lake Charles, La., as the storm passed just to the west were 105 m. p. h. Having entered the mainland, the storm rapidly increased its forward momentum and recurved toward the northeast.

The major portion of the damage in the Gulf coast region resulted from high water. Normal diurnal range of the tides for this region is from 1 to 2 ft. Increased heights of the water as a result of Audrey were apparent as early as noon on the 26th at Galveston, Tex., and reached a peak there of 6.2 ft. m. s. l. at 1030 GMT on the 27th. The area affected by tides of 6 ft. m. s. l. or over extended from Galveston to a point 330 miles eastward.

At Cameron Coast Guard Station, La., the water began to rise prominently by 1000 GMT on the 27th and rose at the rate of 1.5 ft. per hour for several hours, reaching a peak in Cameron of 10.6 ft. m. s. l. between 1600 and 1700 GMT on the 27th. This peak was reached after the initial impact of the high winds of the hurricane and before the rise of the secondary winds associated with

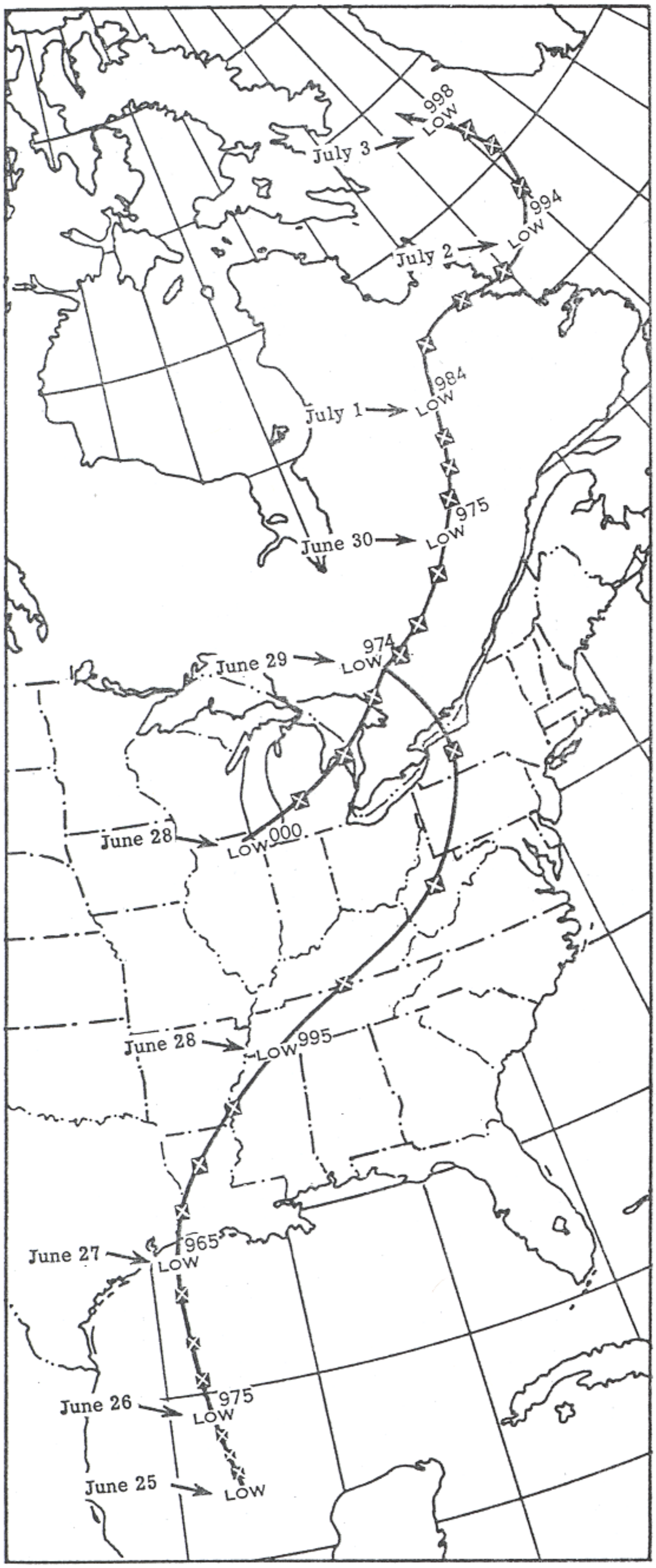

Figure 1.—Track of hurricane Audrey, 1957. Positions shown are at 6-hour intervals.

the passage of the eye of the storm on shore some 23 miles to the west of Cameron. Waves of between 4 and 5 ft. with a few peaks possibly reaching 8 to 10 ft. were superimposed on this high water. The water remained high until around 2000 GMT, at which time the winds shifted to an offshore direction and the water began to recede.

The highest tides occurred about 40 miles to the east of the region where the center of the hurricane crossed the coast. They were highest on the coast and decreased somewhat inland. At Lake Charles, La., a tide of 7 ft. m. s. l. was recorded. The tidal region along the Gulf coast affected by the high water is quite extensive, being near sea level, and in some instances below sea level, for considerable distances inland. For the period of high water, these tidal regions were inundated as far as 10 to 20 miles inland.

Some of the reported low barometric readings and the times of their occurrence on June 27 are as follows:

	(*mb.*)	(*GMT*)
Galveston, Tex	986	1200
Cameron, La	959	1430
Port Arthur, Tex	966	1523
Beaumont, Tex	971	1528
Lake Charles, La	972	1740

On the morning of the 28th the storm, which was centered over west central Tennessee, had lost its hurricane strength winds and had entered its extratropical phase. As the storm was moving from the coast to this position, several tornadoes developed in Mississippi, Louisiana, and Alabama. In Mississippi and Louisiana, one life was lost and several buildings were damaged. In Alabama 14 people were injured and property damage was estimated at $600,000 as a result of these tornadoes [1]. For Audrey's track and associated surface features, see figures 1 and 2.

Between 0000 GMT and 1200 GMT on the 25th, a polar trough at the 200-mb. level moved eastward through the Mississippi Valley. An extension of this trough produced a shear line through south-central Texas (fig. 3). The northern portion of the polar trough continued its eastward movement, while the shear line through Texas was accentuated and slowly retrogressed. By 1200 GMT on the 25th, the 200-mb. winds at Brownsville and Corpus Christi, Tex., which had been north-northwesterly, had backed sharply and were blowing from 210°. These winds continued to back slowly as Audrey moved northward. At this time a weak anticyclonic circulation in the eastern Gulf region, which had become more pronounced, facilitated the outflow above the storm and favored the further development of the hurricane [5].

3. EXTRATROPICAL PHASE

The extratropical phase of the storm presented some noteworthy dynamic aspects in conjunction with the

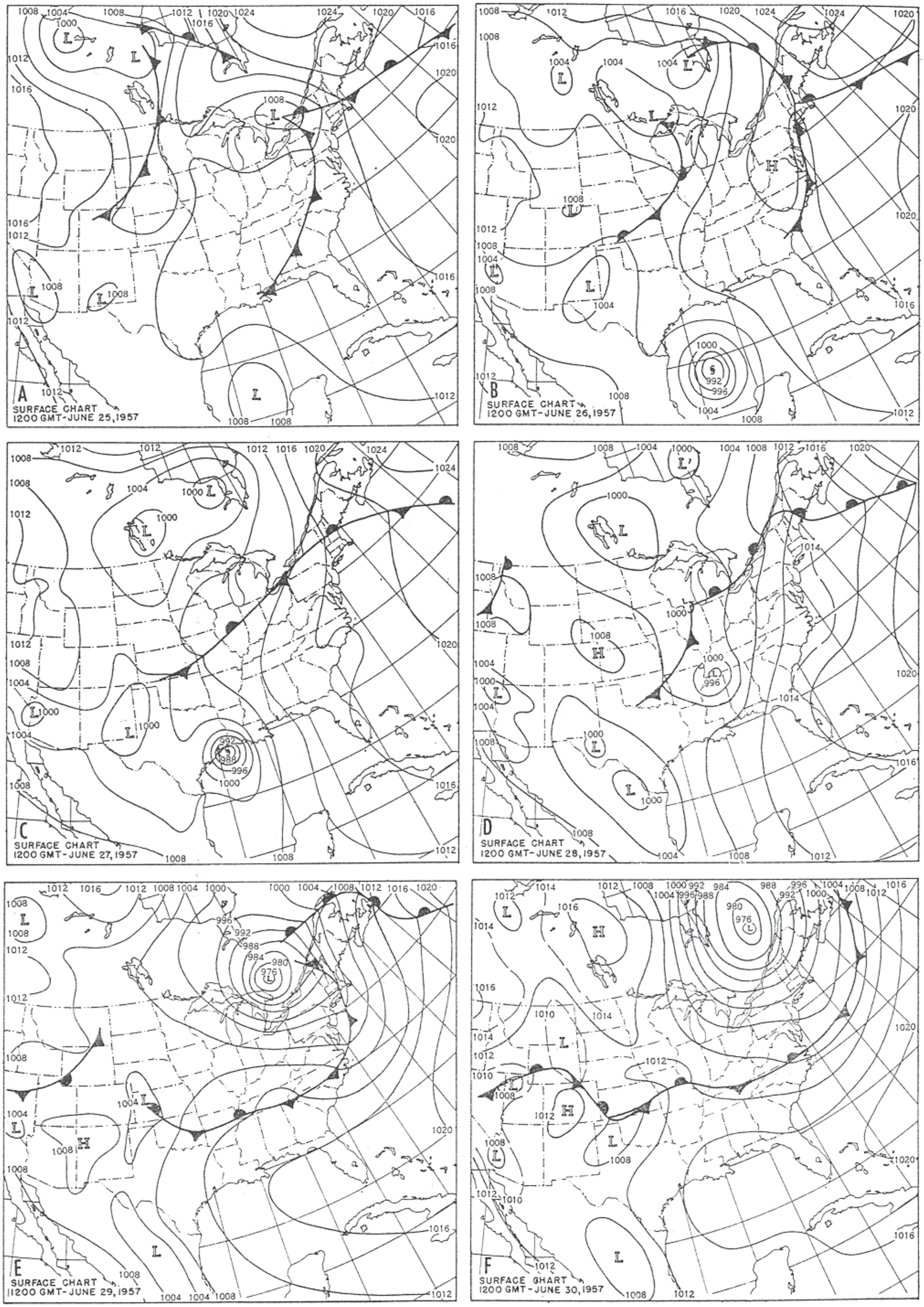

FIGURE 2.—Surface weather charts for 1200 GMT June 25–30, 1957.

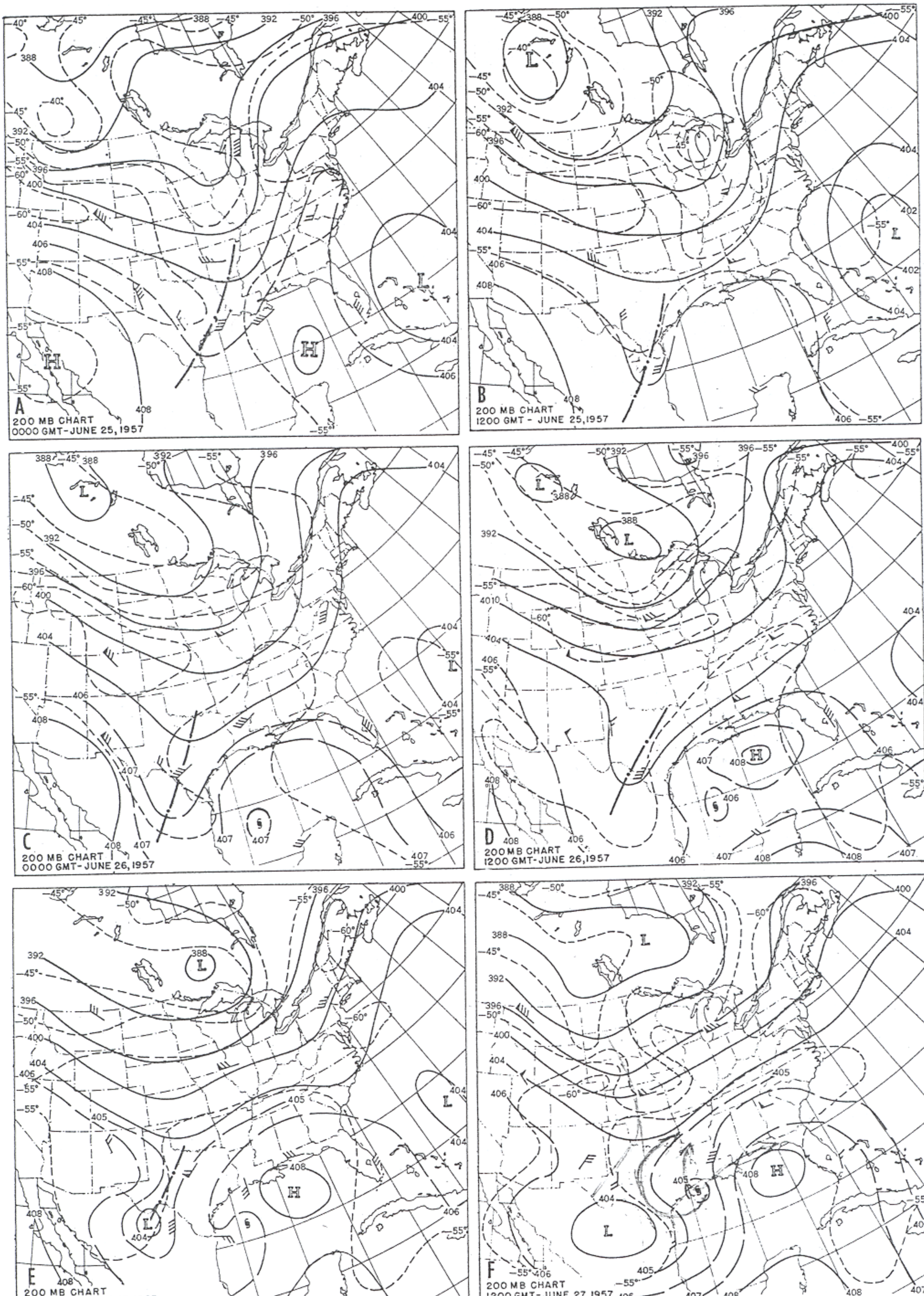

Figure 3.—200-mb. charts shown at 12-hour intervals from 0000 GMT June 25 to 1200 GMT June 27, 1957. Contours (solid lines) are in hundreds of geopotential feet; isotherms (dashed lines), in ° C.

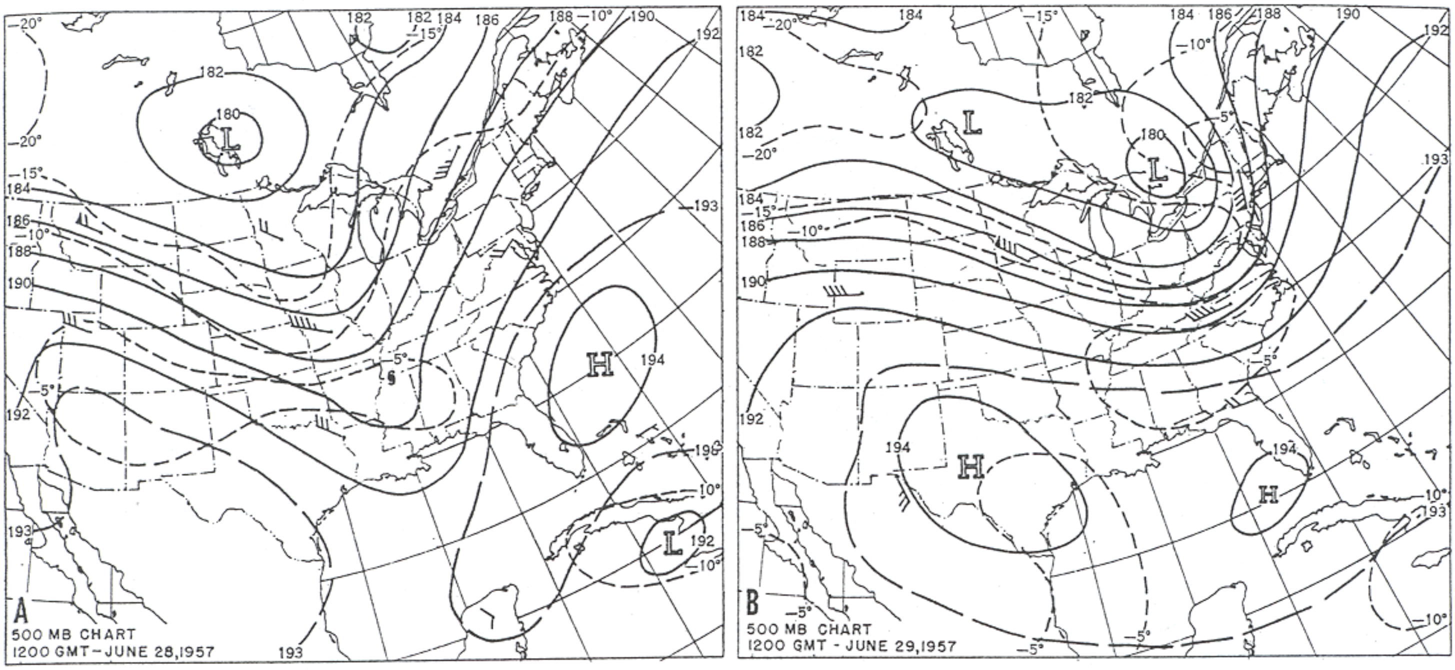

FIGURE 4.—500-mb. charts for 1200 GMT, June 28 and 29, 1957. Contours (solid) are in hundreds of geopotential feet; isotherms (dashed), in ° C.

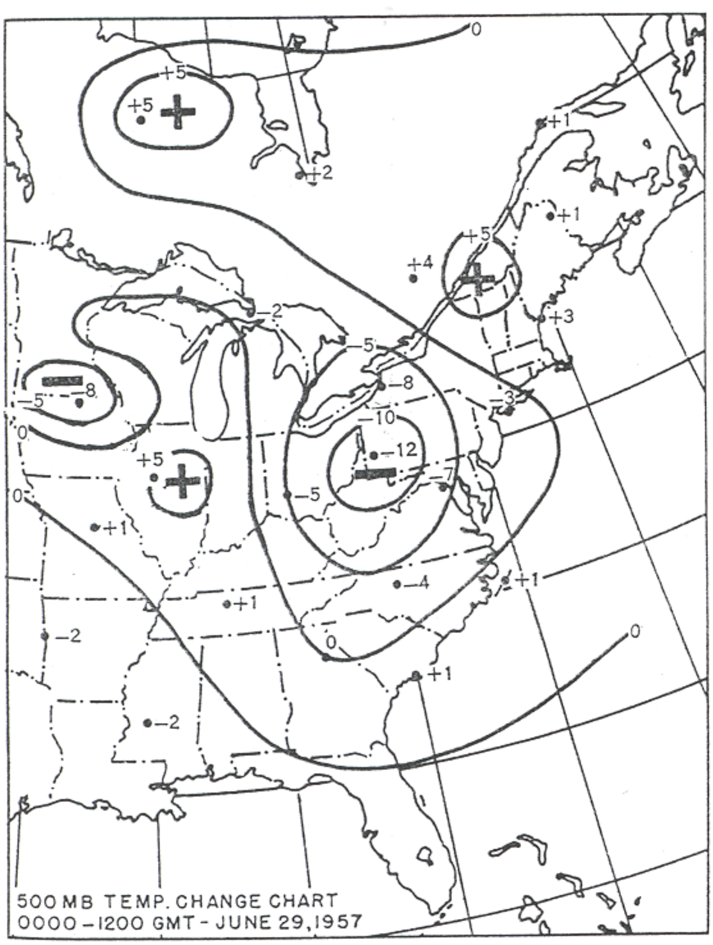

FIGURE 5.—500-mb. 12-hour temperature change chart for the period 0000 GMT to 1200 GMT June 29, 1957. Isolines of temperature change are at 5° C. intervals.

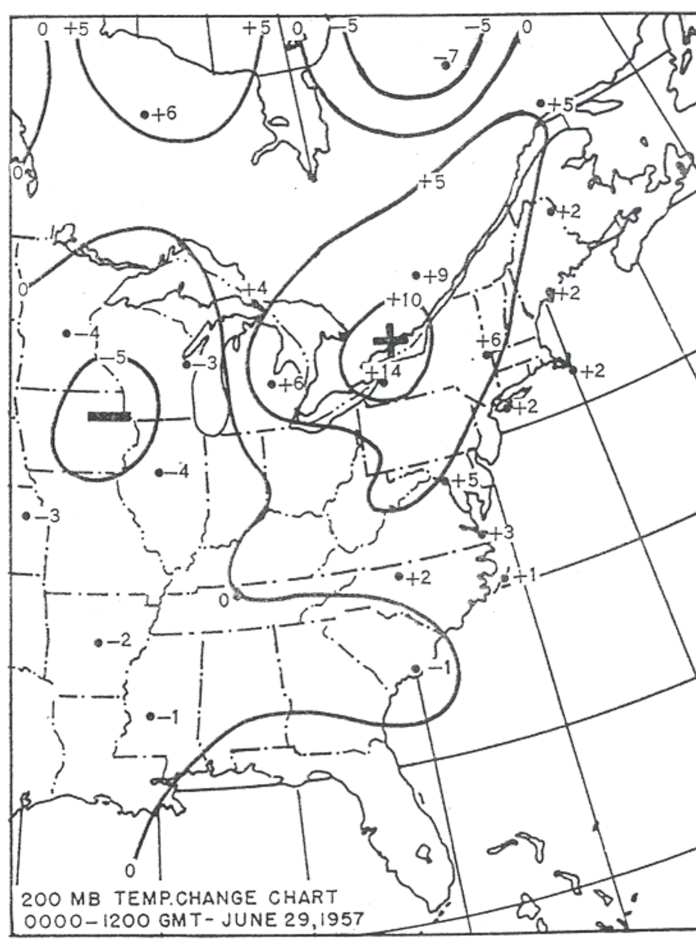

FIGURE 6.—200-mb. 12-hour temperature change chart for 0000 to 1200 GMT June 29, 1957. Isolines of temperature change are at 5° C. intervals.

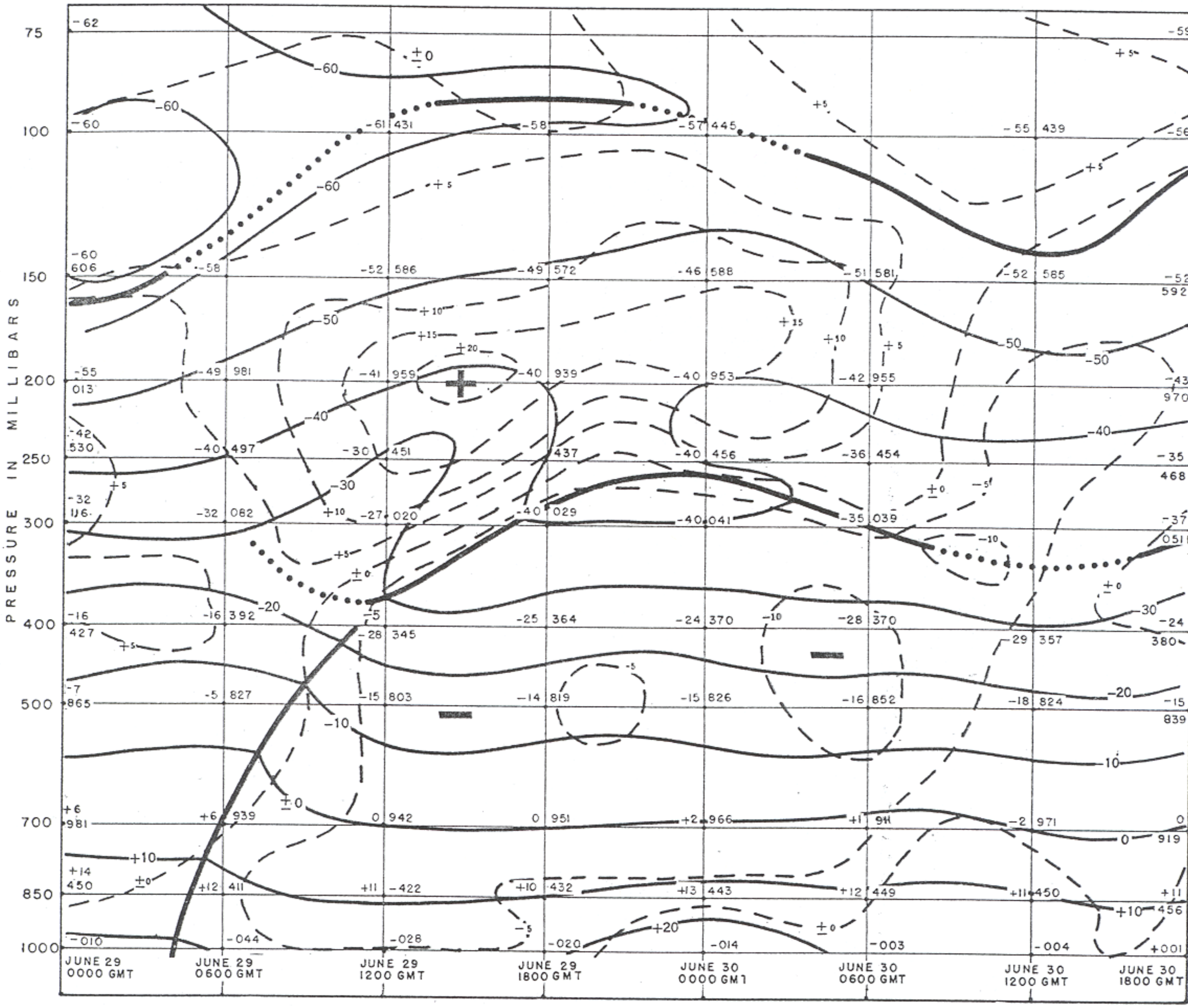

FIGURE 7.—Time cross section for Buffalo, N. Y., from 0000 GMT June 29 to 1800 GMT June 30, 1957. Isotherms in ° C. are light solid lines. 24-hour temperature changes at 5° C. intervals are dashed lines. Fronts and tropopauses are heavy solid lines, heavy dotted where indistinct.

amalgamation of Audrey with a polar wave. This union resulted in a storm of major proportions which affected much of the Mississippi-Ohio Valley region, eastern United States, and eastern Canada. In the Mississippi-Ohio Valley region most of the storm damage resulted from heavy rains, while high winds accounted for nearly all the damage in the eastern United States and Canada. The heavy, flood-producing rains which occurred in the Mississippi-Ohio Valley on June 27, 28, and 29 cannot be attributed completely to Audrey. These rains were frontal in nature. However, there is little doubt that Audrey augmented the available precipitable moisture contributing to the heavy rains [1].

On the 28th, when Audrey was in the process of assuming extratropical characteristics, a wave formed on a polar front in the vicinity of Chicago, Ill. At 1200 GMT on the 28th, the central pressure was 995 mb. for Audrey and 1,000 mb. for the wave on the polar front (fig. 2D). Just 24 hours later the union of these storms was complete, with the storm centered about 140 miles north of Buffalo, N. Y., in southwestern Quebec, Canada. At this time, the storm had reached maximum intensity as an extratropical storm with a central pressure of 974 mb. This approached the lowest pressure associated with Audrey in its tropical phase. It was this rapid intensification of the storm which resulted in the high winds observed in the eastern United States and Canada. Winds of 95 to 100 m. p. h. were reported at Jamestown, N. Y. [1].

In the deepening of the polar wave, it was difficult to differentiate between the contribution made by the remnants of Audrey and that made by cyclogenesis in the westerly flow aloft. As Audrey moved inland she became aligned with, and eventually absorbed into, an intensifying polar trough progressing eastward. At the 500-mb. level, the warm air moved rapidly northeastward, which resulted in an intensifying thermal gradient over the northeastern United States (fig. 4). In the 24-hour period between 1200 GMT on the 28th and 1200 GMT on the 29th, maximum cooling in the troposphere was centered near Pittsburgh, Pa. (fig. 5), where at the 500-mb. level 9° C. of cooling occurred; 8° of this cooling was in the last 12 hours. In the stratosphere during the same interval, maximum warming at the 200-mb. level was centered near Buffalo, N. Y. (fig. 6), where 16° C. of warming occurred, 14° of which took place in the last 12 hours of the period. The time cross section for Buffalo (fig. 7) graphically shows the temperature change which occurred in the troposphere and stratosphere.

Maximum intensification of the surface storm ensued when the upper-air low pressure center became nearly vertical with the surface feature. In conjunction with this intensification, a low tropopause formed as shown on the time cross section (fig. 7). The baroclinic nature of this development, which contributed to the rapid intensification of the storm, can be seen by an inspection of the isotherm field on the 500-mb. chart shown in figure 5. The 24-hour change shown in the temperature field with the intensification of the thermal gradient in northeastern United States is quite spectacular.

It appears that even without the influence of Audrey the baroclinic structure in the westerlies would have been sufficient to develop a storm of major proportions. Stratospheric warming is considered to have been of prime importance in the extratropical cyclogenesis. Vederman [6] has discussed the importance of stratospheric influences to cyclogenesis at the surface. Haurwitz [7] relates the stratosphere to the troposphere in the development of cyclones. The time cross section for Buffalo (fig. 7), with the 24-hour temperature changes, shows the spectacular magnitude of the stratospheric warming just above the formation of the low tropopause in relation to the cooling which took place in the troposphere.

Audrey's contribution cannot be ignored—certainly with the absorption of the tropical Low into the polar trough cyclonic vorticity was added and the thermal distribution was affected, contributing to the baroclinicity of the development. The limited time allotted to the preparation of this article, however, precludes any attempt to assign quantitative values to the tropical influences adding to the development of the extratropical storm.

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