

HURRICANES OF THE 1950 SEASON

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GENERAL SUMMARY

The hurricane season of 1950 was an active one in the Atlantic. It gave 12 storms, 11 of which developed full hurricane force. Eleven is the largest number of full hurricanes reported for a season, in history. However, the record number of starts is 21, set in 1933; only 10 of these 21 storms developed into full hurricanes. One of the 11 hurricanes of 1950 developed hurricane force twice in its course with a wave stage between. In reality, it might be classed as two separate hurricanes that developed at different times from the same easterly wave, in which case the number of full hurricanes would be 12. Four of the storms entered the United States mainland and two others came close enough to give strong winds at Cape Hatteras or Cape Cod, but did not move inland. Property and crop damage in the United States was about \$35,-850,000 and 19 lives were lost. These numbers include damage of \$2,000,000 and loss of 12 lives in New England coastal areas.

The first hurricane of the 1950 season was noted August 12. Before this, the tropical Atlantic had been remarkably quiet; not even an "easterly wave" worthy of note had appeared. The August 12 hurricane was the first of a family of six that scarcely gave a break until September 16. Much of the time during this period of 37 days, there were two or three hurricanes in progress at the same time. Beginning with September 17, there ensued 14 days without hurricane formation, but on October 1, the first of another family of six storms appeared. These gave but a few days respite until October 21, when the season ended. The 70-day period from August 12 to October 21 constituted the hurricane season of 1950. It began late and ended early, but while it lasted was packed with activity seldom, if ever, before observed.

From the forecasters' point of view and the experience of airplane reconnaissance crews, the season presented more exasperation and hard work to keep track of the storms than any other year of our experience. The track chart (fig. 1) shows many slow movements, blockings, changes in course, and even loops. In addition, increases and losses of intensity of a number of the storms over short periods of time presented unusual difficulties. For example, the hurricane of September 1 to 7 made two small loops in the northeastern Gulf area and another

180° turn over Florida which gave four abrupt changes in course in 3 days [1]. The late October hurricane in the Gulf added rapid deepening and filling to an erratic course, and caused subsequently needless warnings and public anxiety on the Florida West Coast. During the last 12 hours as it approached the coast, it lost force rapidly from a hurricane of 100 m. p. h. to a storm of only moderate gale force as it moved inland in the Cedar Keys-Cross City area.

Another unusual feature that may be noted from figure 1 is the number of times two or more hurricanes were in progress simultaneously. During the period August 27 to 31, two hurricanes were in progress in the Atlantic; and from September 2 to 6, three fully developed hurricanes were noted, two in the western Atlantic and one in the Caribbean-East Gulf area. From October 1 to 5, there was a hurricane in the Atlantic and a tropical storm in the western Gulf of Mexico; again, from October 14 to 16 and on October 18-19, two hurricanes were in progress at the same time. It is not without precedent to have more than one hurricane in the Atlantic hurricane area at one time, but the writer has never seen so many twins and triplets on the map of the western Atlantic before. Two of the maps with multiple storms are reproduced in figure 2.

During this busy hurricane season the Miami Hurricane Central issued 270 advisory bulletins and coordinated many others for release by other forecast centers. The total ran well over 300. The Navy dispatched 60 reconnaissance flights into hurricanes during this period, and the Air Force made slightly more; about 130 reconnaissance flights were completed in all. This is by far the greatest number of hurricane reconnaissance missions flown during any season since this observation method was introduced in 1943. This grilling pace was exhausting to both men and machines, including those who did the reconnaissance work and those at the Central who charted the storms and issued the advices.

INDIVIDUAL HURRICANES

Able—August 12-21. The first hurricane of the season was suspected on the afternoon of August 12 from general conditions several hundred miles northeast of the Leeward Islands. A reconnaissance plane located the developing

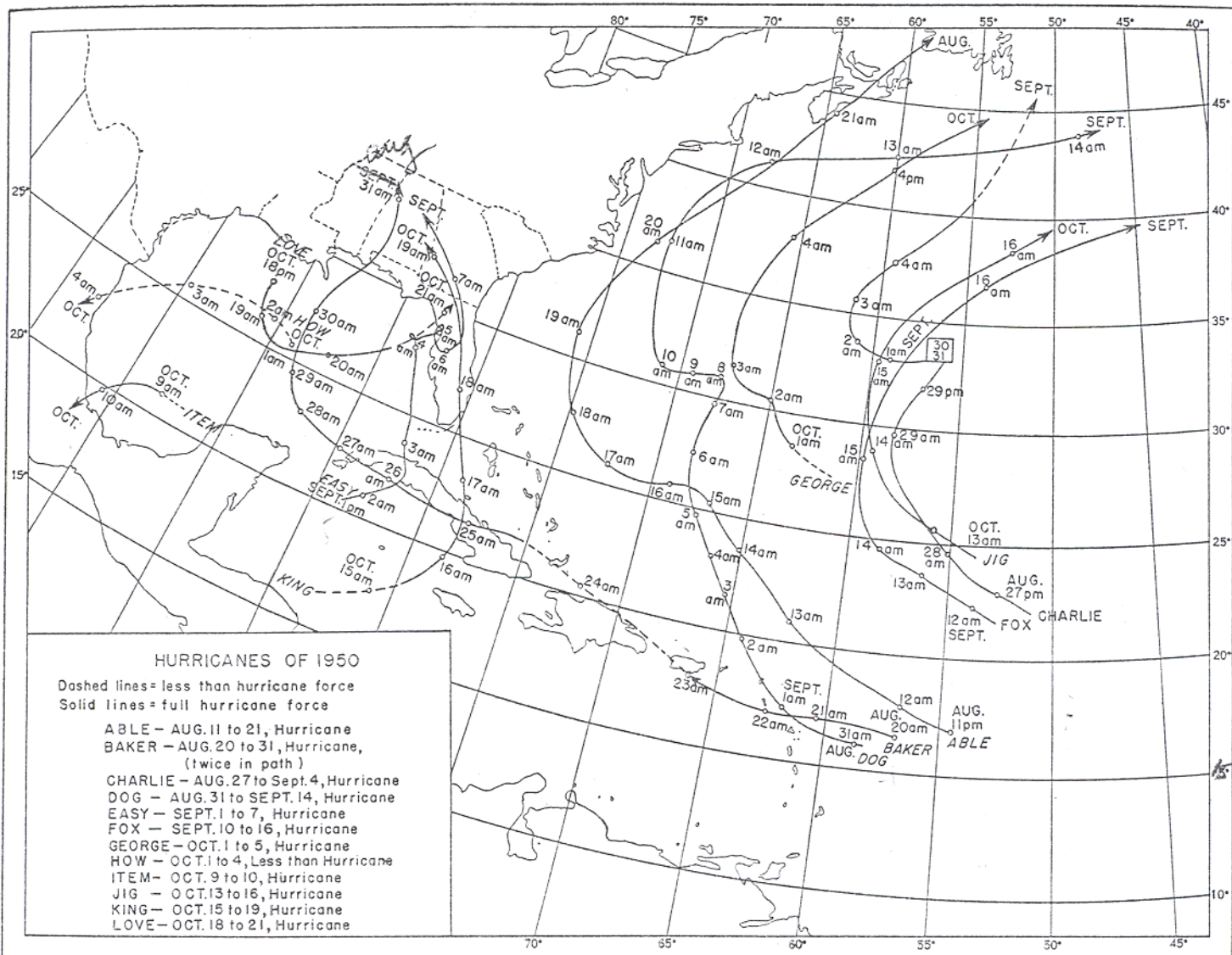


FIGURE 1.—Tracks of the Atlantic hurricanes and tropical storms of 1950 named alphabetically in chronological order. Points on the paths are identified by date and time (a. m. or p. m.) of observation.

hurricane on the morning of the 13th near 21° N., 62° W. It soon increased to hurricane force and moved slowly on a variable northwesterly course which brought the center a short distance east of Cape Hatteras during the night of the 19th, and thence northeastward into Nova Scotia on the 21st. It caused strong winds on Cape Hatteras and Cape Cod, but hurricane force was not experienced on land, except in parts of Nova Scotia. The strongest winds reported in this hurricane were about 140 miles per hour and lowest pressure about 28.15 inches (953.3 mb.) recorded by aircraft at sea.

Baker—August 20–31. This hurricane appeared east of the Leeward Islands on August 20. It passed about over the island of Antigua during the night of the 21st with winds reported at 90 to 120 miles per hour. It progressed slowly west-northwestward losing force, and was only a minor disturbance on the 23d when it reached

Puerto Rico, where strongest winds were 35 to 40 miles per hour. Thereafter, it was in the nature of a squally wave until the evening of the 25th when signs of another developing center were noted off the south Cuban coast. This center developed slowly, moved westward across the western tip of Cuba into the Gulf, made a curve to northward, and increased to hurricane force. Aircraft and ship reports on the afternoon of the 30th estimated strongest winds at about 115 miles per hour some distance south of the Alabama coast. This was the strongest reported in connection with this storm. It lost some force before moving inland during the night of the 30th between Mobile and Pensacola. Winds on the coast were 75 to 85 miles per hour; a total of about \$2,550,000 damage to property and crops resulted from winds and tides in a zone from near Mobile to St. Marks, Fla. There were two tornadoes reported in connection with this hurricane, one

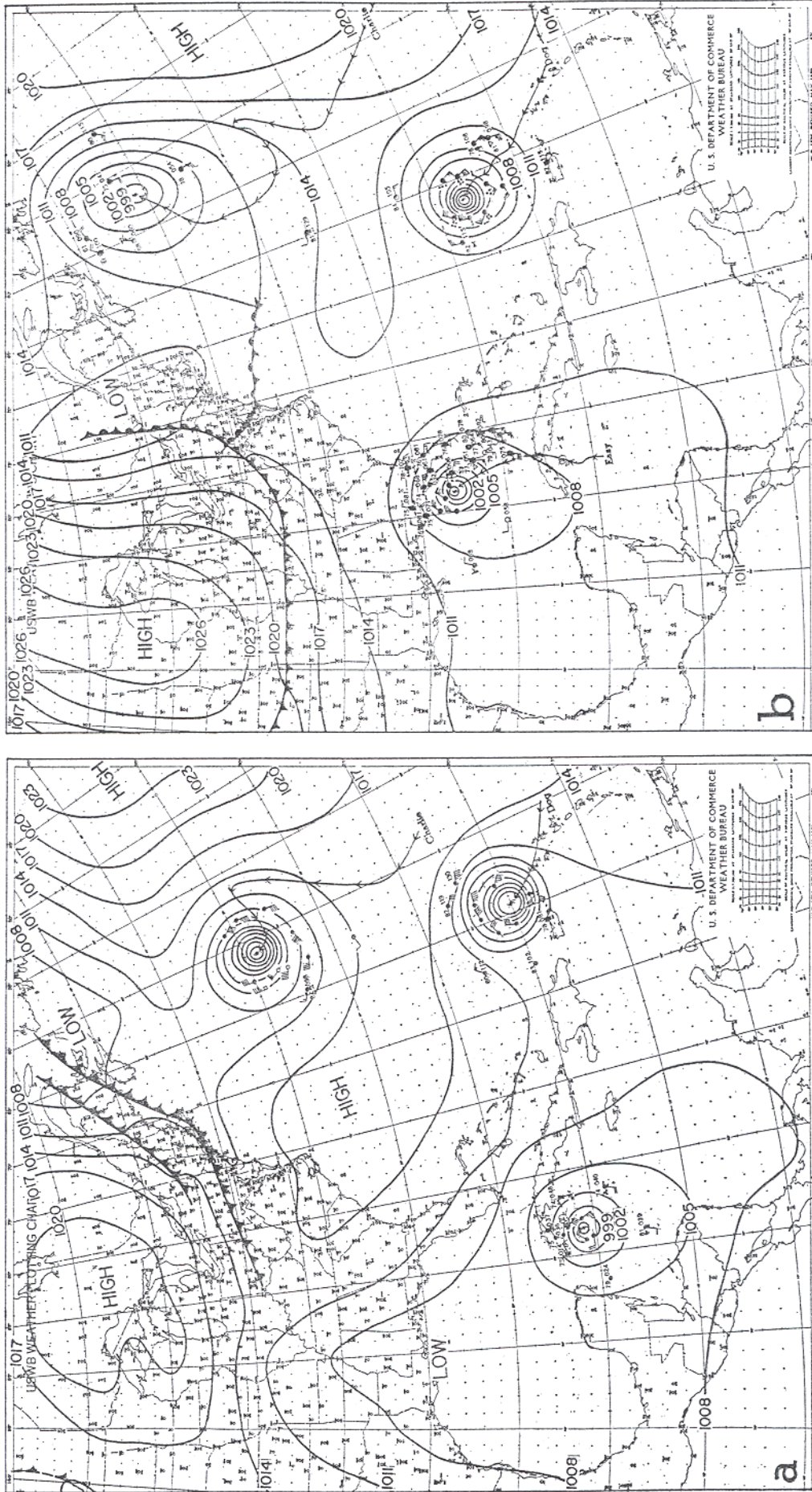


FIGURE 2.—(a) Section of surface chart for 0730 EST, September 2, 1950, showing three fully developed hurricanes, Dog, Easy, and George. (b) Chart for 0730 EST, September 4, 1950, showing the position of the same hurricanes

of which demolished four dwellings and a store building, and damaged 11 other buildings at Apalachicola. The other tornado occurred in Jackson County, Fla., but only one home was destroyed. Heavy rain and winds resulted in heavy crop damage in southern Alabama and northwest Florida. Gusts of 50 miles per hour were recorded as far inland as Birmingham Airport, and were estimated as high as 75 miles per hour atop adjacent mountains. One person was killed and two injured in Birmingham by fallen live wires.

Charlie—August 27–September 4. This hurricane remained far out in the Atlantic during its life span. It was noted on August 27 near 23° N., and 53° W. whence it moved northwestward to about 29° N., 58° W. and recurved to the northeast. On the 30th when it had reached the vicinity of 34° N., 56° W., its progress was blocked by high pressure to the north. After becoming quasi-stationary, or perhaps making a loop in this area, it drifted very slowly westward to 34° N., 62° W. on September 2 when it resumed northward and northeastward movement and rapidly became extratropical several hundred miles southeast of Nova Scotia. Strongest winds reported in this hurricane were about 115 miles per hour recorded by aircraft.

Dog—August 31–September 14. This hurricane was located August 30 when the S. S. *Sibrodin* reported gale winds and falling pressure near 16.5° N., 57° W. It might have been the same storm whose beginnings were reported near the Cape Verde Islands on August 24, but there were no reports of it after it left the Cape Verde area until the *Sibrodin* reported on the 30th. It proved to be the most severe hurricane of the 1950 season, with winds estimated by aircraft at over 160 knots (184+ miles per hour) and waves 100 feet high. It moved on a northwesterly course and passed close to Antigua, Barbuda, and other islands of the northeastern Leeward group on September 1. Residents of Antigua, where highest winds were estimated at over 130 miles per hour and hurricane force lasted for 6 hours, reported it to be the most severe hurricane in the history of that island. Many homes and business houses were destroyed or damaged, crops destroyed, roads blocked by washouts and fallen trees, communications and power lines down, and many small craft wrecked. Two persons were drowned when their small boat capsized. The island of Barbuda also estimated winds of 130 miles per hour or greater, with equal or worse devastation than experienced at Antigua. Damage has been placed at over \$1,000,000 on these small islands.

The hurricane continued to move slowly on a northwesterly course after leaving the Leeward Islands and curved northward toward Bermuda, but its progress was blocked about 200 miles southwest of Bermuda near 31° N., 67.5° W. on September 8. It drifted slowly westward for 2 days before resuming a north to northeast course, and finally turned eastward south of Nova Scotia and Newfoundland on the 13–14th. It gave strong winds on Cape Cod when

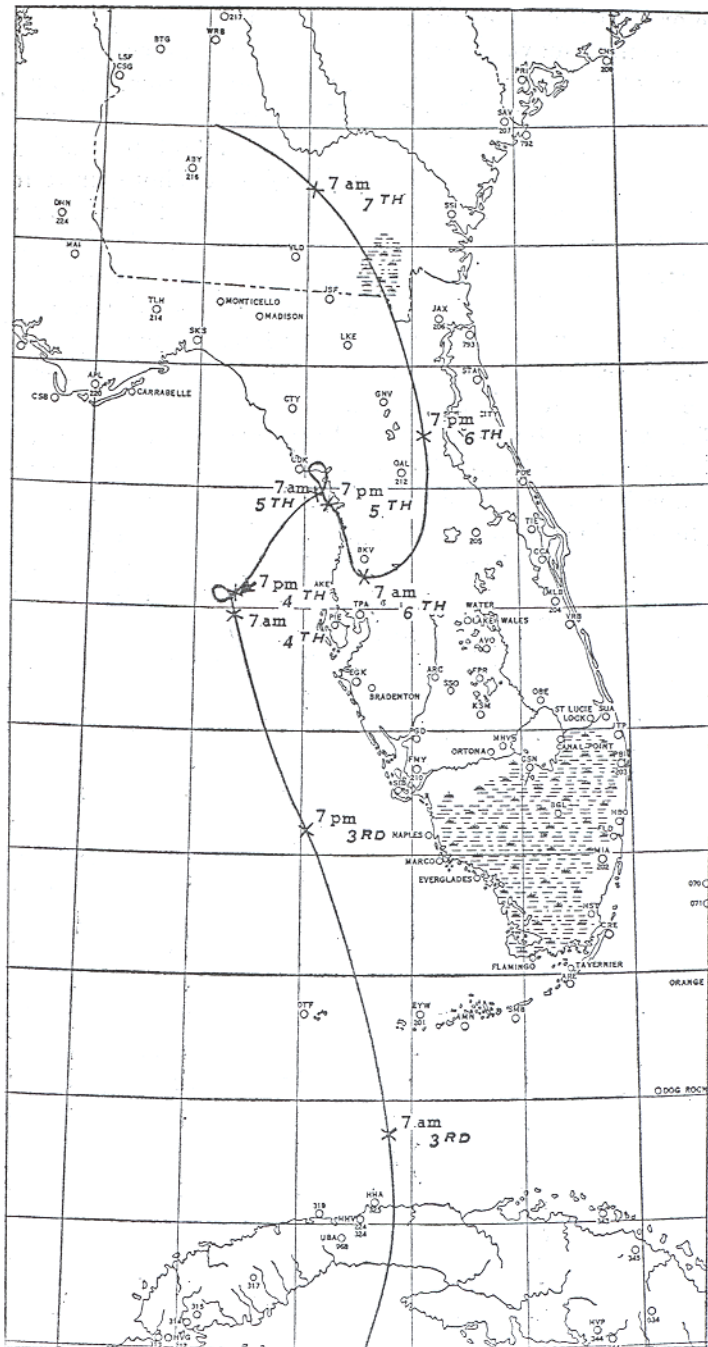


FIGURE 3.—Erratic path of hurricane Easy, September 1–7, 1950. Hourly readings from two radar sets confirm this track [1].

it was passing some distance offshore on the 12th, and the station at Nantucket reported gusts of near hurricane force. Although winds along the New England coast were less than full hurricane force, damage amounted to \$2,000,000 and 12 lives were lost, 11 in capsized boats. It was fortunate that this great hurricane remained at sea and did not seriously affect other coastal areas for it was indeed a giant of potential destruction.

Easy—September 1–7. Long before the Atlantic giant was out of the way, the next hurricane developed in the northwestern Caribbean Sea south of the Isle of Pines on September 1. It remained nearly stationary for 2 days,

before moving northward across Cuba near Havana. The center moved north-northwestward thereafter as a storm of just about the lower limit of hurricane force and passed between Key West and Dry Tortugas around noon of September 3 (fig. 3). It continued about parallel to the west Florida coast 30 to 50 miles offshore until it reached a point some 70 miles northwest of Tampa on the 4th. Here it described the first of two loops and started moving northeastward. The center reached the coast a short distance south of Cedar Keys the morning of the 5th, where it made another loop; in making this loop the calm center moved over the town of Cedar Keys from the southeast and then away toward the south. This gave the town the unusual experience of exposure to the same side of a hurricane twice, with 2½ hours of calm center between. About the time of the first loop, the intensity increased to 125 miles per hour, the strongest wind reported at Cedar Keys, but the loop described over that place resulted in hurricane force or higher from 0600 EST to 1800 EST on the 5th, except for the 2½ hours of calm from 1100 EST to 1330 EST. Long-time residents reported it the worst hurricane experienced at that place in more than 70 years. This fishing village of about 1,000 population was badly wrecked. Half of the houses were destroyed or rendered unfit for habitation, and 90 percent of the remainder were damaged. The fleet of fishing boats which was the principal source of livelihood for the community was completely destroyed. But the hurricane was not through with its gymnastics. It moved southward about 70 miles to a point about 30 miles north of Tampa where it turned eastward and made a rather sharp curve back to northward over Florida on the 6th. This made four abrupt changes in course in 3 days! (See fig. 3.) It had lost hurricane force by this time, however, and dissipated as it moved into southern Georgia on the 7th.

Extremely heavy rainfall occurred in connection with this storm over central and northeast Florida. Cedar Keys had 24.50 inches in 3 days while many other stations had from 10 to 20 inches of rainfall. These rains caused much flooding and some crop damage which, when added to the damage by high tide and wind on the west Florida coast, amounted to about \$3,300,000. Two persons were killed by fallen live wires and 27 others were injured in various ways. The small damage figure is due to the sparsely settled area where the worst part of the hurricane occurred. The lowest pressure reported was 28.30 inches (958.3 mb.) at Cedar Keys.

The warning service in connection with this hurricane was very good despite its erratic course; however, warnings were issued for a larger area than actually experienced hurricane winds. The extremely erratic movement, which presented the most difficult forecasting problems that we have encountered, has been discussed in detail by Gentry [1].

Fox—September 10–16. This hurricane was discovered by aircraft reconnaissance on September 10 near 19° N.,

50° W., or about 1,000 miles east of Puerto Rico. At that time it was a small hurricane with winds estimated at 70 to 80 miles per hour. The wind speed increased to about 140 miles per hour as it moved in a curving path toward the northwest and north during the next few days. It passed more than 300 miles east of Bermuda on the 15th, and thereafter moved rapidly northeastward over the Atlantic. This hurricane remained small throughout its course, but maintained maximum velocities of about 140 miles per hour until it moved out of range of reconnaissance.

George—October 1–5. A strong easterly wave was noted on September 27 over the Atlantic far to the southeast of Bermuda. It developed a large low pressure system that drifted slowly northwestward, but daily reconnaissance failed to find a storm center of strong circulation until October 1. At 0730 EST on the 1st, the S. S. *Alcoa Regasus*, about 170 miles south of Bermuda at 29.5° N., 64.4° W., reported a southwest wind 65 miles per hour, which indicated hurricane development. An airplane later in the day found the center with highest wind about 100 miles per hour. It moved slowly northward until the morning of October 2 with a threat to Bermuda since it was only 90 to 100 miles away. It changed course, however, and swung westward far enough to miss Bermuda before resuming a northward and northeastward course. It passed south of Newfoundland on the 5th. The strongest wind reported was about 110 miles per hour on the morning of October 4 when the center was near 39° N., 65° W.

How—October 1–4. A tropical storm of less than hurricane force developed in the Gulf of Mexico October 1 near 25.5° N., 89° W. It moved on a northwest, west, and then southwest course and entered Mexico north of Tampico on the 4th. The strongest winds reported in connection with this storm were about 55 miles per hour. Squally winds of 45 to 55 miles per hour prevailed during most of its life in the Gulf of Mexico, and were confined mostly to the northern semicircle of the disturbance. This was the only disturbance of the season that did not develop hurricane force.

Item—October 8–10. This small hurricane began to develop on the 8th in the Gulf of Mexico northwest of the Yucatan Peninsula. On the morning of the 9th, a reconnaissance plane located the small center with 90 miles per hour winds at 21° N., 94° W., about 200 miles northeast of Vera Cruz, Mexico. It moved southwestward and entered Mexico a short distance south of Vera Cruz on the morning of the 10th. The strongest wind reported was 110 miles per hour at Vera Cruz. Damage in Vera Cruz and vicinity was reported in the press as "heavy" but no estimate of the amount of damage or number of casualties has been received.

Jig—October 13–16. At 0800 EST on October 13 the S. S. *Rio Primero* reported a northeast gale wind and rapidly falling pressure at 27° N., 57° W., which indicated that a hurricane center was in the vicinity of 25.5° N.,

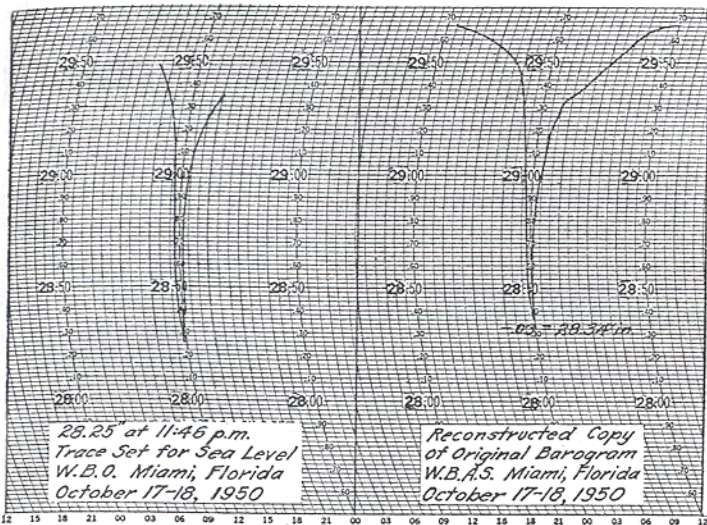


FIGURE 4.—Barogram traces for 2 recording stations in Miami, October 17-18, 1950, during passage over city of hurricane King.

56.5° W. at the time. A subsequent report at 1000 EST from the *Rio Primero* gave northwest gales and rapidly rising pressure indicating the passage of the small but sharp hurricane center nearby to the east. A plane out of Bermuda early on the 14th located the small, mature hurricane at 29° N., 59.3° W. It moved on a curving path passing 300 miles east of Bermuda during the night of October 14 and turned northeastward over the Atlantic. This was a small hurricane throughout, and strongest winds were estimated to be around 115 or 120 miles per hour.

King—October 15-19. This small, but violent, hurricane passed directly over the city of Miami about midnight of October 17 and caused property damage that amounted to an estimated \$15,000,000 in the city and its vicinity. Total damage for Florida in crops and property was about \$27,750,000, which, when increased by the \$250,000 damage done in Georgia, brings the grand total for this hurricane to \$28,000,000. Three persons were killed in Florida and one in Georgia, with injuries to 199 others, 16 of whom were injured seriously.

This hurricane formed in the northwestern Caribbean Sea on October 15 and moved on a northeasterly course

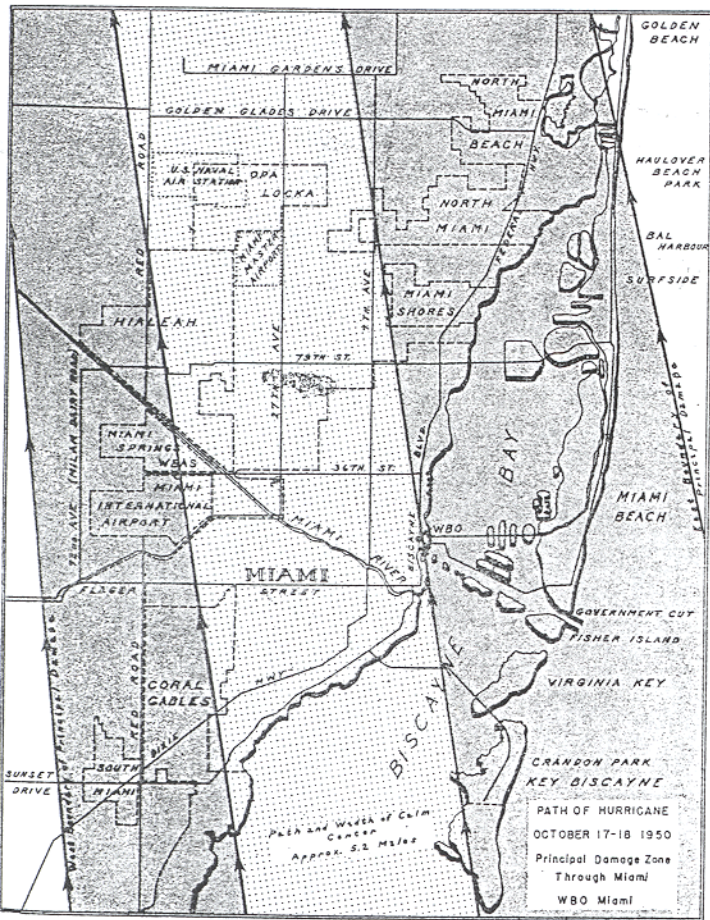


FIGURE 5.—Map showing hurricane King's path across Miami and vicinity. Darker shading indicates areas of greatest damage.

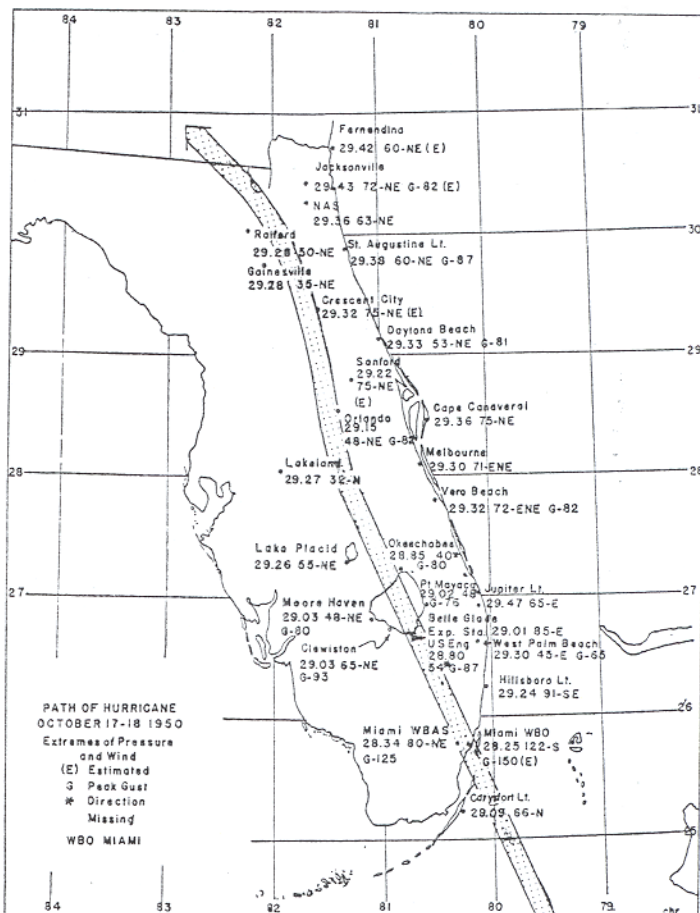


FIGURE 6.—Path of hurricane King across Florida showing pressure and wind velocity (m. p. h.) at selected points.

at first, past the western end of Jamaica, then turned northward across Cuba just west of Camaguey during the night of the 16th. It was a small hurricane at that time; strongest winds at Camaguey were only around 65 miles per hour. The course turned more to north-northwest as it moved through the Florida Straits on the 17th. A reconnaissance plane entered the "eye" at about 0900 EST on the 17th north of the Cuban coast and found strongest winds about 85 to 90 knots with some gusts estimated at 100 knots. The minimum pressure in the center at that time was 988.0 mb. (29.18 in.), and the "eye" was about 20 miles in diameter. When it reached Miami at midnight, the central pressure was 955.0 mb. (28.20 in.), and the central calm area was only about 5 miles in diameter. Maximum sustained winds had increased to 122 miles per hour with gusts of about 150 miles per hour. Thus in the period from around 0900 EST to midnight there was considerable intensification; central pressure fell 0.98 inch (33.2 mb.), the wind increased greatly, and the central "eye" contracted from 20 miles to 5 miles in diameter. The barograph traces for the two recording stations in Miami are shown in figure 4. They indicate the small, intense vortex. These stations were on the edges of the "eye," with center midway between them.

Figure 5 shows the path through the greater Miami area on an enlarged scale. The principal damage zone, which is indicated by the shaded area, was only about 14 miles wide. In this narrow strip structural damage was extensive, and it was so sharply outlined that many at first thought the damage was caused by a tornado or a series of them. In a distance of about $\frac{1}{4}$ to $\frac{1}{2}$ mile damage increased from light to heavy, but a careful examination immediately after the storm by experienced meteorologists failed to find evidence of tornadic action. The damage was simply that of violent hurricane winds, the most severe to visit Miami since the great hurricane that devastated the city in 1926.

There have been numerous reports of lightning and thunder in hurricane vortices, especially in the tropics, and numerous other instances of thunder in peripheral areas, but this is the first occasion observed in Florida, to this writer's knowledge, of lightning and thunder right near the center where wind velocities were 95 to 125 miles per hour. There were several brilliant lightning flashes with thunder during the height of the storm, observed by the writer, and one discharge occurred very near the Weather Bureau Office with a sharp crack of thunder heard above the deafening scream of the wind, only a few minutes before the lull occurred.

After leaving the Miami area, the center continued a north-northwesterly course, crossed over Lake Okeechobee, and continued through eastern Florida into Georgia. Figure 6 shows the path of the hurricane with pressures and wind velocities at many places. Hurricane force winds in squalls extended nearly to the Georgia line, espe-

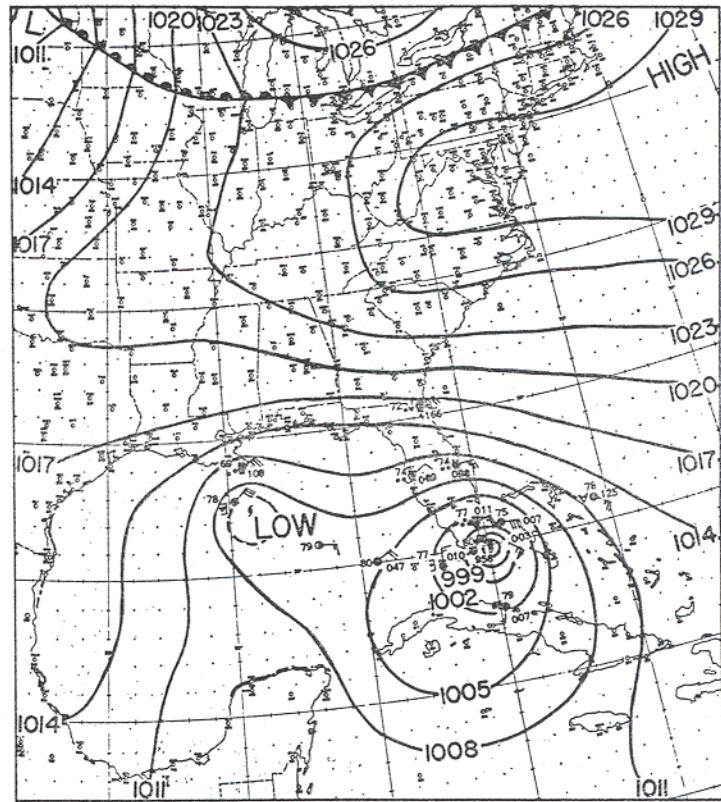


FIGURE 7.—Section of surface chart for 1930 EST October 17, 1950, showing beginning of formation of a second hurricane south of Louisiana coast in offshoot trough of low pressure from hurricane King.

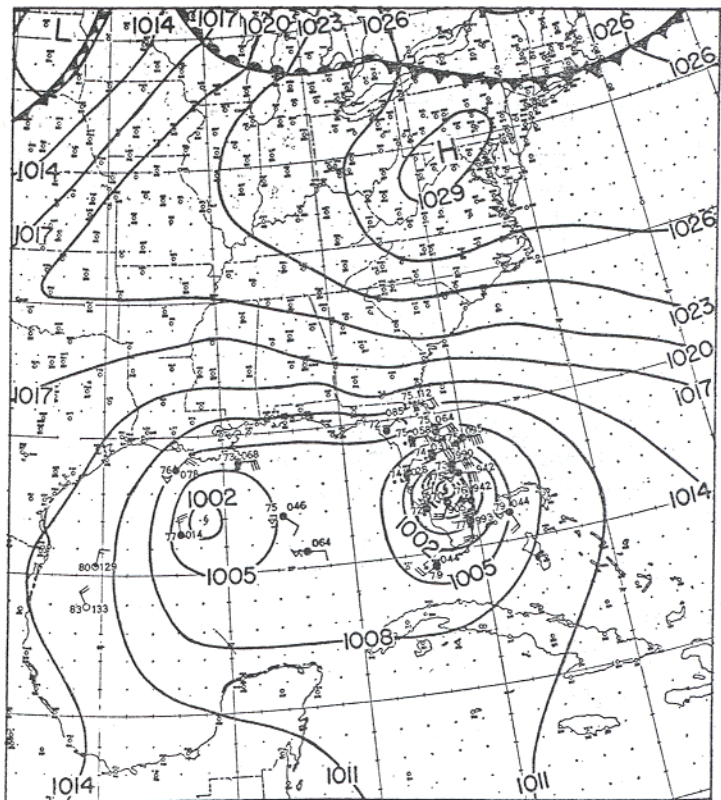


FIGURE 8.—Chart 12 hours later than figure 7 (0730 EST, October 18, 1950) showing development of second hurricane (Love).

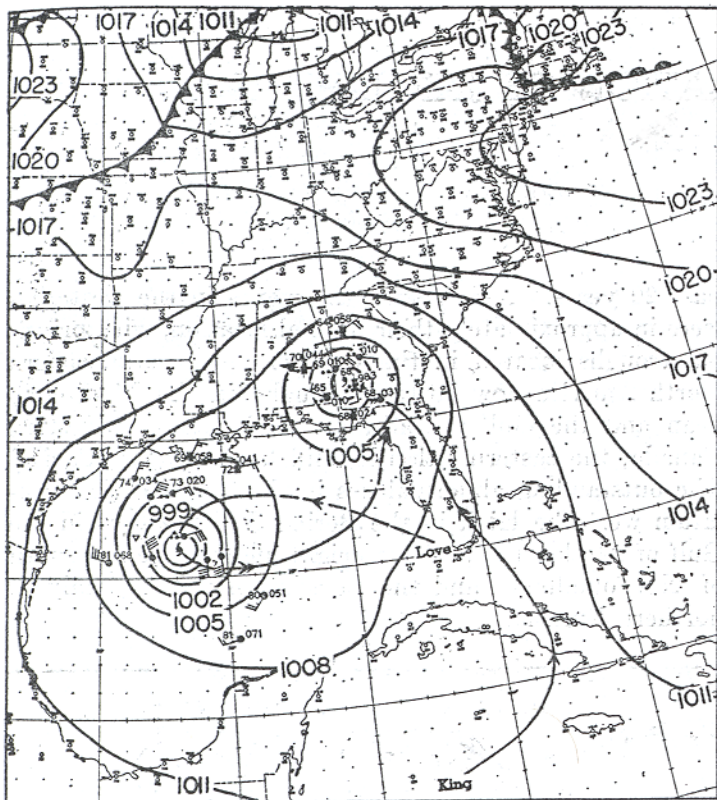


FIGURE 9.—Chart 24 hours later than figure 8 (0730 EST, October 19, 1950). Second storm (Love) is now near hurricane force while hurricane King is filling over southwestern Georgia. Tracks are inserted to indicate complete path of each.

cially along the Atlantic coast, and considerable damage resulted in all the eastern counties of Florida. Very heavy squalls extended out a considerable distance northeast of the barometric center after it reached the middle peninsula. By this time, however, the center was beginning to spread out and break up, and winds were weakening on the south and west sides.

The warning service was excellent and provided ample time for all possible hurricane preparation. This doubtless saved many lives and much property. A hurricane alert was ordered for south Florida 36 hours ahead of the storm and hurricane warnings were ordered 18 hours ahead of the hurricane winds by the Miami Hurricane Center. Despite the good warning service, many people remained complacent and failed to take adequate precautions.

This resulted in increased damage when glass windows blew out, and the interiors and contents of buildings were damaged by rainwater.

Love—October 18–21. The last hurricane of this most trying season certainly belied its romantic designation. It was more bewildering and exasperating, if possible, than the others of the season's disturbances. It began forming in the Gulf of Mexico south of the Louisiana coast at the time the severe hurricane was moving northward through Florida on the 18th, and in some respects was an "offshoot" of it. (See figs. 7, 8, and 9.) As the Florida hurricane was moving north-northwestward from the Caribbean Sea, an elongation of low pressure extended ahead of it over Florida. As the hurricane progressed this pressure trough moved northwest and west, with a tendency to move counter-clockwise around the hurricane. On the 18th (fig. 8) it developed a center of circulation of its own south of the Louisiana coast. This center continued its counter-clockwise movement and swung down into the central Gulf on the 19th (fig. 9) and increased to hurricane force. On the 20th, aircraft reported maximum winds of 75 to 85 knots (85 to 98 miles per hour), especially in the northeastern quadrants. The movement by this time had completed the swing to the east and northeast, which caused it to offer a threat of hurricane winds to the upper west Florida coast. During the night of the 20th, however, it lost force rapidly, apparently due to dry air having completely encircled the center, and when it reached the coast on the early morning of the 21st, winds were of only moderate gale force. The presence of dry air from the West Gulf States had been noted on its western side since the time of its development, but it continued to increase in force, despite this, until the dry air had worked its way around to the south and east of the center. When this stage was reached, the loss of intensity was rapid.

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FORECASTING THE FORMATION AND MOVEMENT OF THE CEDAR KEYS HURRICANE, SEPTEMBER 1-7, 1950¹

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ABSTRACT

The Cedar Keys hurricane of September 1-7, 1950, formed south of Cuba and crossed the west coast of Florida near Cedar Keys. Thus its entire life was spent in an area where considerable upper air data were available, and during September 3-6 it was tracked almost constantly by either airborne or land-based radar. Its path was extremely erratic. Analyses of surface and upper air data are used to explain the formation and various changes in rate and direction of movement of the storm, including two loops in its path. The concept of steering, as used in the Weather Bureau's Hurricane Warning Center at Miami, and other forecasting tools are discussed.

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INTRODUCTION

The Cedar Keys hurricane of September 1-7, 1950, was notable for its erratic course (fig. 1 A). It was first discovered by aerial reconnaissance south of the Isle of Pines during the afternoon of September 1. For 36 hours it moved northward at 3 to 4 m. p. h., then it suddenly started moving 22 to 23 m. p. h. in a direction between north and north-northeast. This rate continued for about 10 hours during which the course gradually changed to one between north and north-northwest. For the next 14 hours it moved toward the north-northwest at 12 to 13 m. p. h.

Then just as suddenly as it had started moving, it became nearly stationary again for 14 hours while it moved slowly in a counterclockwise loop. After completing the loop, it moved at 7 m. p. h. toward the northeast. It continued this course for 12 hours and again became quasi-stationary while making another counter-clockwise loop. After completing this loop, it moved toward the south or south-southeast at 4 m. p. h. for 12 hours. Finally, it gradually curved toward the east and then the north to a track that was more conventional for hurricanes. Throughout its history, the storm continuously threatened Florida, and from 0700 EST, September 3 until it lost its hurricane force early September 6, hurricane winds were either affecting the Florida coast or were within about 60 miles of the coast.

Because of the storm's nearness to land, sufficient data were collected to plot its path in detail. Furthermore, the hurricane was within the network of the United States and Cuban upper air stations from the time it developed until it dissipated. Thus, considerable data are available for the study of this storm that is especially interesting because its erratic movements presented great problems to the forecasters.

This research was started in the hope that solutions to certain definite problems could be found: (1) Why did the hurricane form? (2) Why did the hurricane accelerate

¹ Paper presented at 108th National Meeting of the American Meteorological Society in Tallahassee, Fla., December 5-7, 1950.

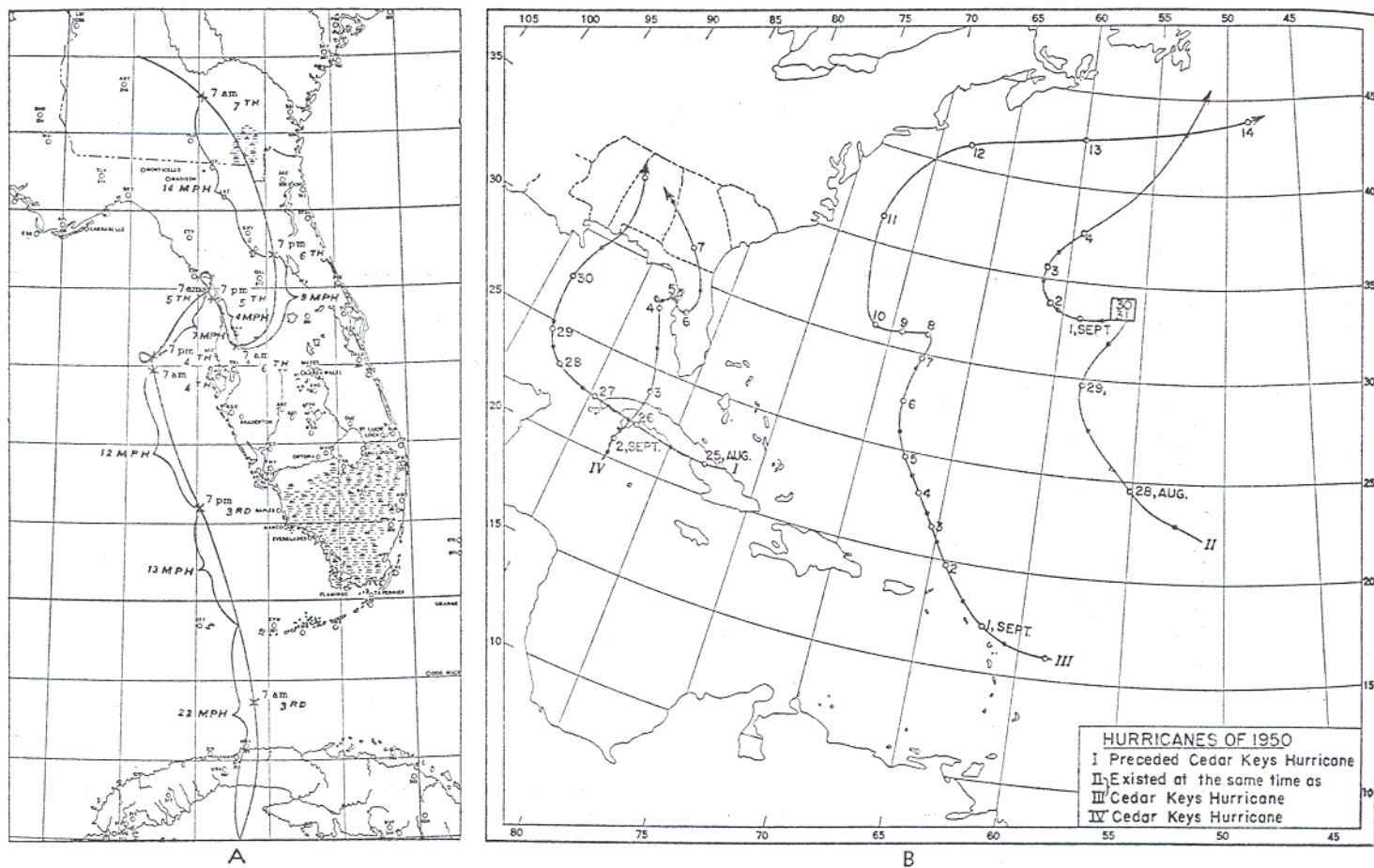


FIGURE 1.—A. Map section showing track of Cedar Keys hurricane in detail. B. Tracks of hurricanes which existed prior to and during the time of the Cedar Keys hurricane (IV). Open circles mark position of center at 0730 EST; solid circles, 1930 EST position.

so rapidly on the night of September 2-3? (3) Why did the hurricane move so slowly and make two loops on September 4-5? (4) How could the movement toward the south or south-southeast on September 5-6 have been forecasted? (5) What was the best available method for forecasting movements of this hurricane?

In studying the movement and formation of the hurricane, the following maps and charts were used: Sea level weather maps; constant pressure maps at 850 mb., 700 mb., 500 mb., and 300 mb.; pibal charts at selected levels from 2,000 feet to as high as the winds were reported; pseudo-adiabatic charts of the upper air soundings at Tampa, Miami, and Havana; time cross section for Tampa; and mean virtual temperature charts for the layer between 700 mb. and 500 mb. Most of the final conclusions were based on the constant pressure charts. Tracks on the 300-mb. charts give 12-hour positions of the height centers at that level. Tropical storm symbols on the constant pressure maps give the concurrent surface location of the storm's center.

FORMATION

On August 26 another hurricane had passed near the Isle of Pines moving from the east (fig. 1B). It crossed the western end of Cuba, intensified in the Gulf of Mexico, turned northward, and crossed the Gulf coast just east

of Mobile. A trough of low pressure remained over the Western Caribbean after this earlier storm had passed into the Gulf, and the Cedar Keys hurricane formed in this trough. It was first located by aerial reconnaissance on the afternoon of September 1. However, rain had been very heavy over all of western Cuba and the waters between Swan Island and Cuba for 2 days previously, and a closed Low had developed in the levels near the surface.

On the night of August 31-September 1, the widespread heavy rain seemed to become concentrated in the area south of the Isles of Pines. By this time, the sea level pressure had fallen to 1,005 mb. (fig. 2) and possibly lower. Thus conditions were ripe for tropical storm development according to Riehl [1] if some mechanism were in the higher levels above the area of surface low pressure to remove some more air and cause deepening of the disturbance. Although upper air data are too sparse to make a quantitative analysis of divergence of the wind field at higher levels, data available indicate that horizontal divergence took place above the incipient center.

The equation for gradient winds on the rotating earth is

$$\frac{1}{\rho} \frac{dp}{dn} = fv \pm \frac{v^2}{r}$$

where ρ is density; p is pressure; n is distance measured normal to the isobars; f , the Coriolis parameter; v , the

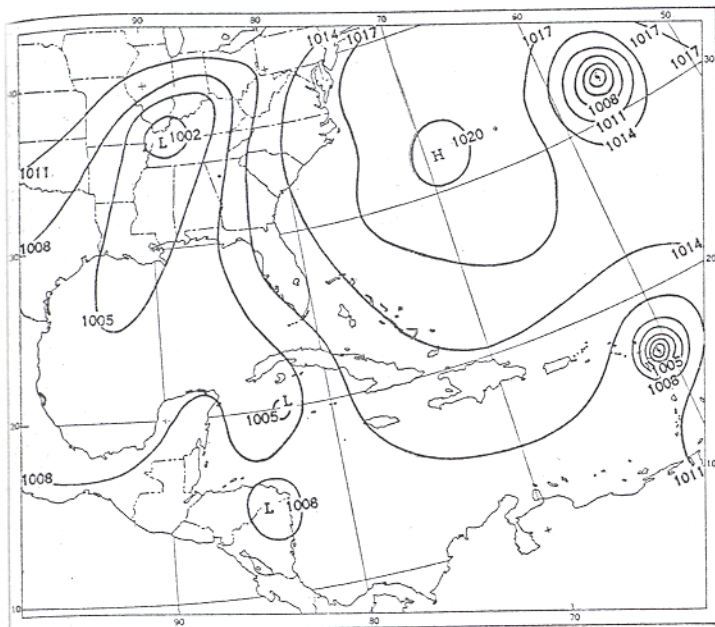


FIGURE 2.—Chart showing sea level isobars for 1930 EST, August 31, 1950.

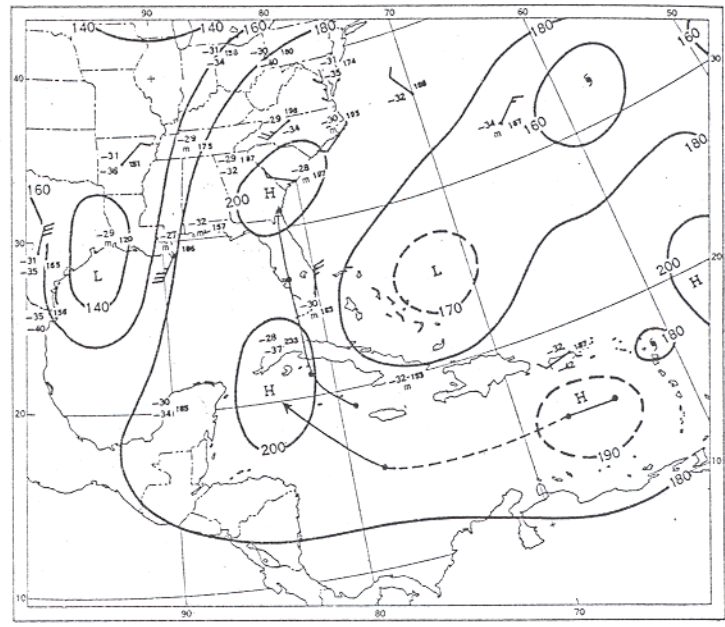


FIGURE 3.—300-mb. chart for 2200 EST, August 31, 1950. Tracks show 12-hour movement of Highs.

wind velocity; and r , the radius of curvature of the particle path. The positive sign is used for cyclonic paths and the negative sign for anticyclonic paths. Thus in steady flow the force due to the pressure gradient is balanced by the deflecting forces and the wind flows parallel to the isobars or contours. However, if the pressure gradient is increased, the terms on the right no longer balance it; for due to the conservation of momentum, air particles may not assume immediately the velocity called for by a changed pressure gradient. Since the deflective forces vary with the velocity, they will not balance the pressure gradient force until the wind is steady again.

Tracks on maps of 2200 EST August 31 (fig. 3), and 2200 EST September 1 (fig. 4) show that at 300 mb. a high pressure system moved over the developing storm on the night of August 31, and stayed in that vicinity for about 24 hours before resuming its northwestward course. At the same time cyclogenesis occurred in the trough to the east. Stagnation of the High and deepening of the trough resulted in increased pressure gradient and accelerating winds at 300 mb. above and east of the storm, e. g., the winds at Miami and Havana accelerated considerably at 300 mb. and higher levels. So long as the winds were sub-gradient, there would be horizontal divergence over the developing center, for the pressure gradient force would be larger than the deflecting forces in our equation. Since the pressure force is directed toward low pressure (to the left when looking downstream), this would cause a net movement of air from high toward low pressure. That is, it would cause air at 300-mb. and higher levels to move from the High above the developing storm center toward the low pressure trough to the east.

Once the storm had started there was plenty of energy

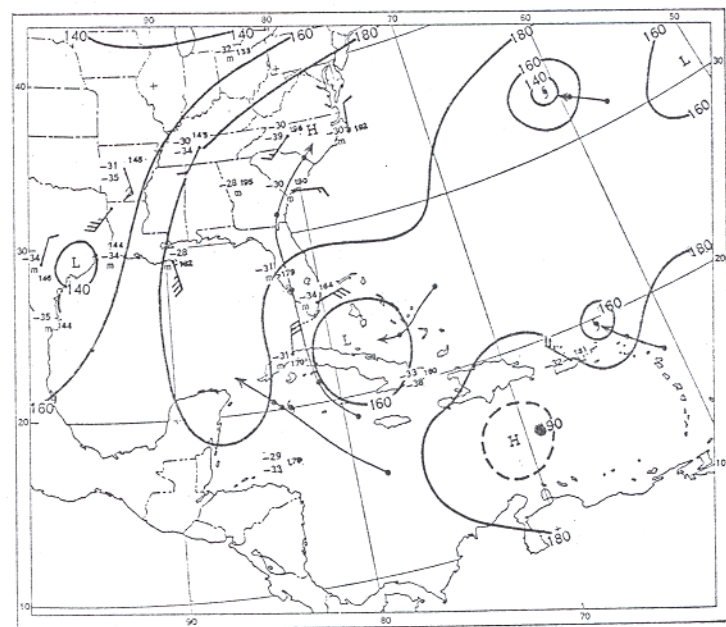


FIGURE 4.—300-mb. chart for 2200 EST, September 1, 1950. Tracks show 12-hour movement of Highs and Lows.

available to keep it going and to cause intensification. Palmén [2] has explained that once a hurricane is formed, its solenoidal field is such that it will maintain itself as long as the air feeding into it near the surface is warm and moist and there is not too much surface friction. The air south of Cuba on September 1 met all specifications.

OBSERVED MOVEMENT

Once the storm had formed, the next problem was to predict its course and rate of movement. The difficulty of doing this has already been suggested by the erratic course shown in figure 1A, and it is of interest to evaluate

the observational evidence for this path before discussing the forecasting problem in detail.

The hurricane path was plotted from a combination of reports from aerial reconnaissance and land stations. As stated previously, the center was first located by aerial reconnaissance. While the storm was south of Cuba, two fixes a day on the center were secured by reconnaissance. The storm passed over the Isle of Pines and just east of Havana where the wind dropped off to 10 or 15 m. p. h. (fig. 1A). It passed between the weather stations at Key West and Dry Tortugas. Reconnaissance crews flew into the center several times September 3-4, and either airborne or land-based radar tracked it almost constantly from the time it left Cuba early September 3 until it lost its hurricane force in the area just north of Tampa early September 6. Reports from points along the Florida coast including the lighthouses furnished approximate positions of the storm and confirmation of the more precise fixes furnished by radar. Also, some ships in the eastern Gulf at the time gave valuable reports.

The loop in the path when the center was west of Anclote Key (fig. 1A) was very small in diameter. However, five successive radar fixes secured September 4, outline the loop. Also at that time, the hurricane had almost no forward movement. Thus we may conclude that external forces moving the storm were very weak. Under such conditions, movement of the storm would be due to the internal forces in the storm itself. In this case it would tend to move in a circle counterclockwise if the storm was perfectly symmetrical [3]. The loop in the path just east of Cedar Keys is partially based on the radar observations of the center and partially on observations at Cedar Keys. The wind at Cedar Keys gradually backed from east-northeast to north as the eye approached on September 5. The calm eye was over the station for about 2½ hours. After the lull the wind started from the east-northeast and again gradually backed to the north as the eye moved farther away. Thus the people there had the unique experience of being exposed to the same side of the hurricane twice. The observed wind shifts indicate that the center first approached the Florida coast to the east of Cedar Keys then moved westward until the western edge of the eye was over the station. When the storm started moving again, it was toward the east or southeast and thus a loop to the east of Cedar Keys was completed.

As the storm approached the coastline, it was tracked by two radar observers. One was at the University of Florida at Gainesville, the other was airborne in a Navy plane. Seven fixes furnished the Hurricane Central at Miami from the Navy plane coincided in time with fixes furnished by the University of Florida. Although it is impossible to say which of the two groups of fixes is more nearly correct, we can obtain some idea of the accuracy of the fixes by comparing them. They were obtained by two different crews, using two different radars, and working entirely independently of each other.

The situation was nearly ideal for use of radar in tracking. The hurricane was at or near the peak of its development. It had a well developed eye that varied in diameter from about 18 to 25 miles. It was near enough to land for the Navy crew to use land fixes in pinpointing the center, and it was within range of the land-based radar set at the University. Thus, if ever accurate fixes should be obtained by use of radar, it should have been at this time. Table 1 summarizes the differences in the fixes.

TABLE 1.—Differences in location of hurricane center, September 5, 1950

Time	Distance between two fixes	Approximate distance from Navy fix to nearest land	Approximate distance of University fix from radar set
	Miles	Miles	Miles
0630.....	10	42	104
0830.....	10	35	88
0900.....	13	34	88
1000.....	10	30	84
1030.....	11	28	83
1130.....	5	21	80
1230.....	5	10	73
Average.....	9.1	-----	-----

If we assume that either of the crews made absolutely accurate fixes, the errors made by the other group varied from 5 to 13 miles. If we assume that the true position of the hurricane was half way between the corresponding fixes, the average error was 4.6 miles. This is certainly acceptable from the standpoint of accuracy.

In earlier days, forecasters ordinarily used fixes at least 12 hours apart in calculating direction and rate of movement of hurricanes. While that may not be necessary now with the more complete data that are available, a smoothed path such as that given by the 12-hour fixes is still best in computing long-period direction and rate of movement. Short-period fluctuations in direction and rate of movement of the hurricane's center as determined from fixes by the two radars are illustrated by table 2.

From 1000 GMT to 1130 GMT the University of Florida reports indicated that the hurricane was moving at 3 m. p. h. in a direction of 40°, and the Navy radar reports indicated that the hurricane was moving at 8 m. p. h. in a direction of 80°. It is not within the scope of this report to determine the sources of error leading to these conflicting indications, but it is obvious that even though individual fixes on the center are relatively accurate, two succes-

TABLE 2.—Direction and rate of movement of hurricane

Time (GMT)	Movement indicated by fixes from University of Florida		Movement indicated by fixes from Navy radar plane	
	Direction (degrees)	Speed (m. p. h.)	Direction (degrees)	Speed (m. p. h.)
0630-0830.....	20	8	20	8
0830-1000.....	50	3	50	3
1000-1130.....	40	3	80	8
1130-1230.....	40	8	50	10
0630-1230.....	30	5	40	6
0245-1230.....	-----	-----	40	8
0245-0830.....	-----	-----	30	6

sive fixes taken too close together can give erroneous indications of movement if both happen to be off in such a manner as to make the errors additive.

Radar reports have been very helpful to forecasters during the past few years, though knowledge of maximum winds in the circulation and distribution of winds around the center is also necessary to do an acceptable job of forecasting the storm. Furthermore, in using radar reports, forecasters must keep in mind that the reported position of the storm center is only an estimated point in the radar rainfall pattern around which the spiralling bands of precipitation seem to circulate; i. e., it is the eye in the rainfall pattern. It is often difficult to pick this point. An inexperienced observer may be tempted to call the center of the innermost band of precipitation the eye, rather than to trace carefully the echoes on the scope long enough to pick the center of rotation. If this band is not symmetrical with respect to the center (and it often is not), an error is introduced. Moreover, the estimated center observed by radar is not necessarily the center of the wind field, nor the point of lowest pressure. Ordinarily, it is the same as the pressure center for all practical purposes, but in immature storms, dissipating storms, or storms that have had their lowest layers disturbed while passing over land, this center observed by radar may be vastly different from the pressure center. Ordinarily radar observers recognize such situations and so report in their remarks.

In the case under discussion, as the storm approached Cedar Keys, the eye was well defined and the center observed by radar should have corresponded very closely to the pressure center. The small differences between the two series of reports can be accounted for by human errors of observation and by mechanical errors of the two radar sets.

After the storm crossed the Florida coast, it was tracked by the radar crew at the University of Florida until it began to dissipate early September 6, north of Tampa. In addition, reports from the regular weather stations supplemented by reports from laymen over which the storm passed, enabled us to track it accurately through Florida.

FORECASTING THE MOVEMENT

METHODS OF FORECASTING

In next considering the problem of predicting the course and rate of movement of the Cedar Keys hurricane, it is well to recall that there are several methods used to predict the course of a hurricane. It is well known of course, that there is a tendency for hurricanes to recurve into any polar trough passing to the north if the trough extends far enough south. However, there may be some element controlling both the movement of the hurricane and the movement and location of the trough rather than the trough attracting the hurricane.

From the beginning forecasters have used persistence in making their forecasts. That is, they forecast what has

been happening will continue to happen. From the track chart (fig. 1A) it is obvious that depending on persistence would have given very poor results because the course and rate of movement changed many times.

Simpson [4] argues that hurricanes tend to move parallel to the axis of the warm core that extends in advance of the storm. This gives good results in many instances.

Riehl and Burgner [5] have developed an objective method of forecasting the zonal component of hurricane movements using 5-day mean 700-mb. maps. Since most of the movements of the Cedar Keys hurricane were north-south rather than east-west, this method was not used in the present study.

Fujiwhara [6] observed that two co-existing typhoons often rotate around each other and more recently, Haurwitz [7] presented a theory on the motion of tropical cyclone pairs. These theories are particularly interesting for this study because another hurricane was located in the Atlantic east of the Bahamas at the same time the Cedar Keys storm was tracing its erratic course.

In the Weather Bureau's Hurricane Warning Center at Miami, a concept of steering has been developed, mostly by Mr. Grady Norton, and through the years it has been considered the most dependable of any of the methods when sufficient data were available. Bowie [8] was one of the first forecasters to argue that movements of hurricanes were controlled by currents high in the atmosphere, but even in the earliest of the hurricane literature, one can find references to hurricanes following currents at the cirrus level.

The concept of steering developed by Mr. Norton differs somewhat from that used by many forecasters. The difference lies largely in the selection of the steering level. Mr. Norton does not use the same level all the time. In fact, he may use several different levels for the same storm, varying the level with the stage of development of the hurricane. In principle, he argues that a hurricane will move with the current that flows across the top of the warm core of the hurricane or rather that it will cut across this current at an angle of 10° to 20° toward high pressure. In practice, this method requires that one study the pibal charts and select the lowest level where winds over the surface position of the hurricane are not in the circulation of the hurricane, i. e., the winds over the hurricane seem to fit into a smooth pattern with the winds upstream and downstream from the hurricane. For example, in figure 5 which gives upper winds from an earlier storm, winds at Hatteras are obviously affected by the circulation of the hurricane up to at least 30,000 feet. From data at Hatteras, Charleston, and other nearby stations, one can deduce that the winds over the storm are still in the hurricane's circulation as high as 35,000 feet. However, at 40,000 feet the flow appears to be relatively smooth over the top of the hurricane, and this should be selected as the steering level. The hurricane symbol gives the position of the hurricane at the time of the pibal observations,

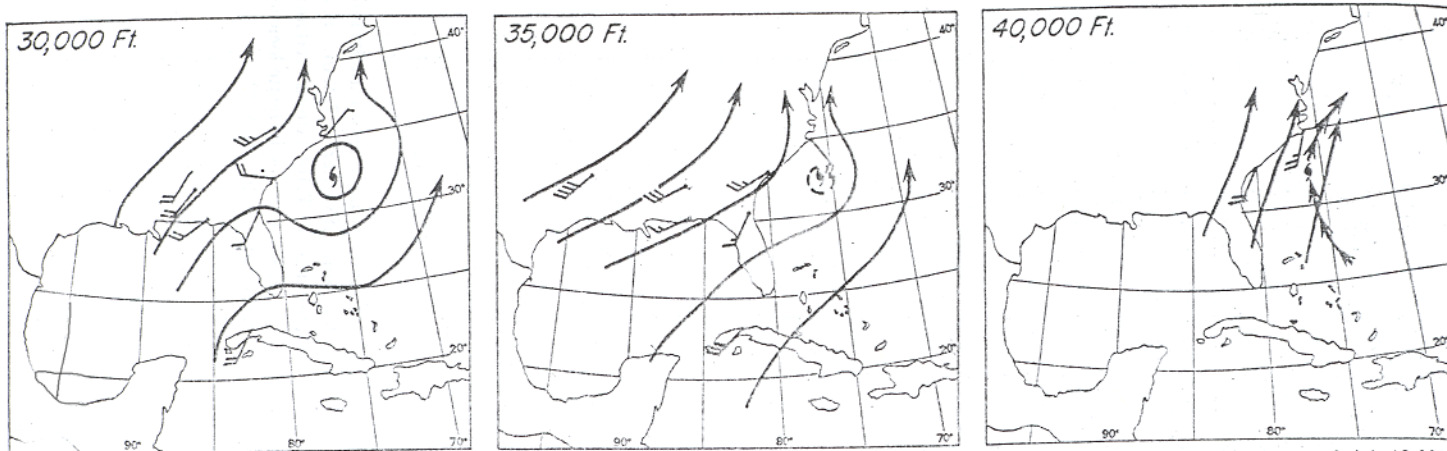


FIGURE 5.—Charts showing air flow over the southeast United States at 1600 EST, August 19, 1950, at (a) 30,000 feet, (b) 35,000 feet, and (c) 40,000 feet.

and the arrow gives the path of the hurricane before and after the pibals were taken. Using the concept of steering, forecasters were able to successfully predict that the center would pass to the east of Cape Hatteras. Previously, this concept of steering has given consistently good results when sufficient data were available for using it. Mr. Norton also believes that the rate of movement is highly correlated with the speed of the steering current. Qualitatively, this idea has been used and found correct, but unfortunately, there have never been sufficient data to check it quantitatively.

For some of the mature Cape Verde storms, the steering level is as high as 55,000 to 60,000 feet. Of course, data are seldom available to that height immediately over the storm. However, when pressure systems at the steering level are all large and streamlines relatively smooth, one can often deduce what the winds are over the storm from data at stations 500 to 1,000 miles away. However, when

the flow at the steering level is broken up into several small vortices, it is very risky to make any deductions from data at long distances from the center. This was true of the Cedar Keys hurricane. Even a casual study of the 300-mb. maps in this series (figs. 3, 4, 6, 8, and 9) reveals that Highs and Lows in the vicinity of the hurricane were comparatively small in diameter.

In studying this storm, all of the forecasting methods were tried which were applicable to the situation. Since the high level steering concept gave best results, it is the only one that will be discussed.

APPLICATION OF THE STEERING CONCEPT

The first problem in forecasting the movement of the Cedar Keys hurricane was to account for the change on the night of September 2-3, when it accelerated from a forward speed of 5 or 6 m. p. h. to one of 22 or 23 m. p. h. At this stage of the storm development, one would have

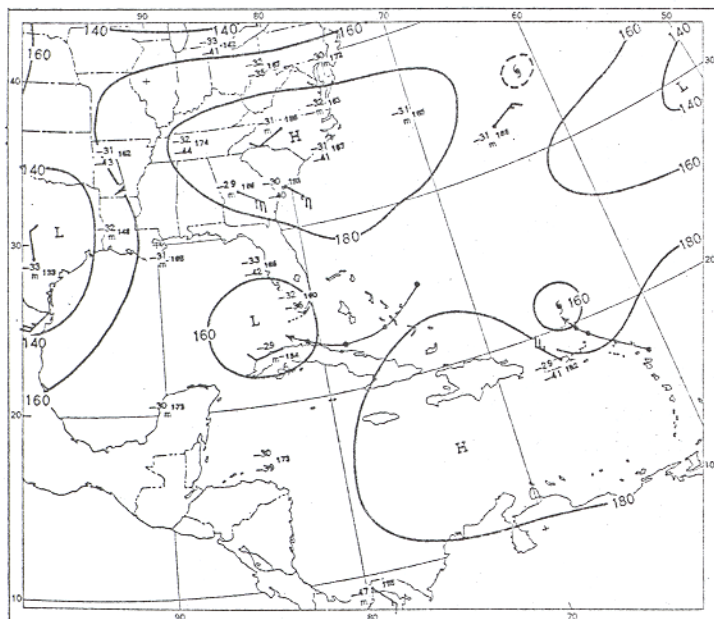


FIGURE 6.—300-mb. chart for 2200 EST, September 2, 1950. Tracks show 12-hour positions of Lows.

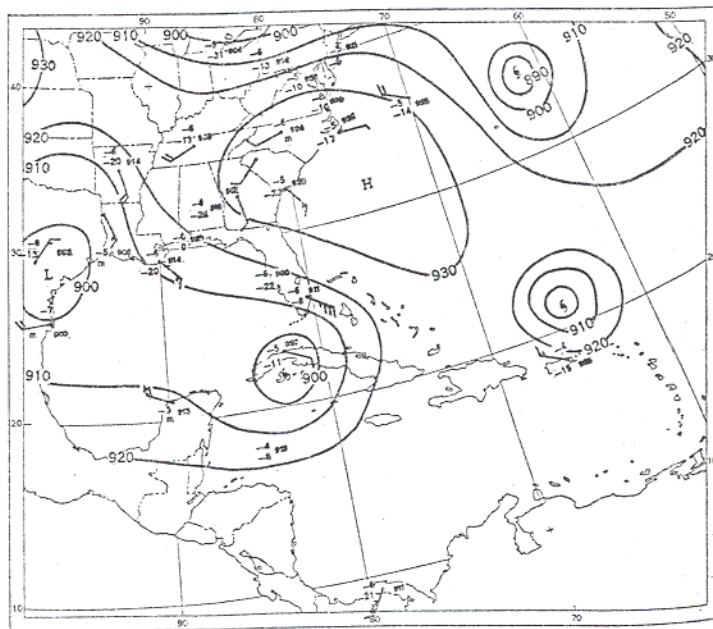


FIGURE 7.—500-mb. chart for 2200 EST, September 2, 1950.

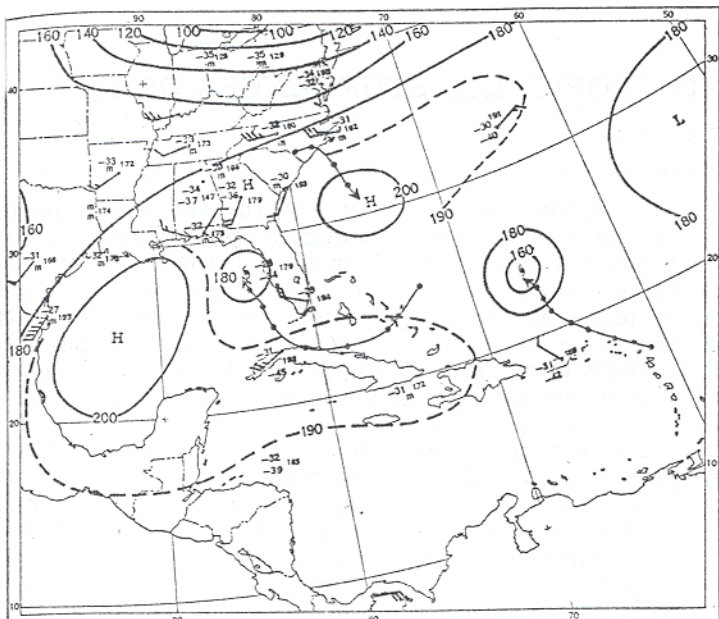


FIGURE 8.—300-mb. chart for 1000 EST, September 4, 1950. Tracks show 12-hour movement of Highs and Lows.

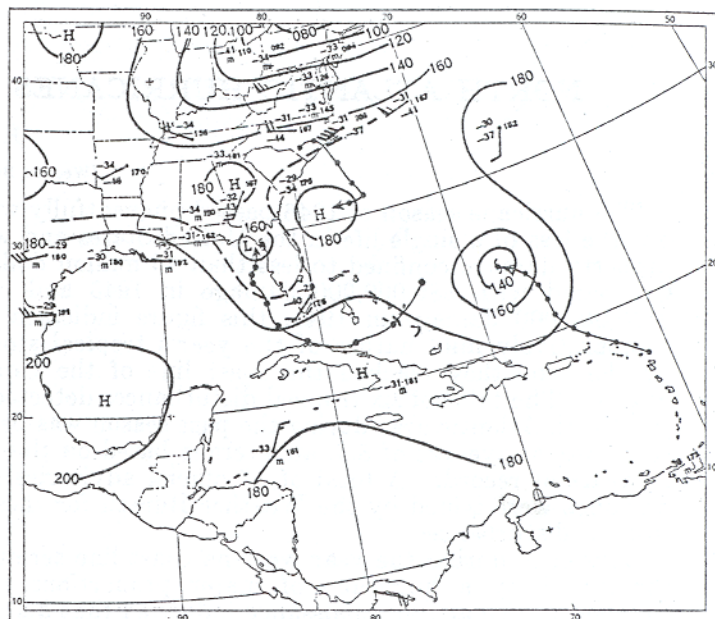


FIGURE 9.—300-mb. chart for 1000 EST, September 5, 1950. Tracks show 12-hour movement of Highs and Lows.

expected to find the steering level somewhere near 30,000 feet. The 30,000-foot winds at Havana at 2200 EST, September 2, (fig. 6) were taken at about the time of the acceleration and they were from a westerly direction and very weak—nothing there to indicate a sudden acceleration toward the north-northeast. However, at 300-mb. cyclogenesis had taken place east of Miami and by 2200 EST September 2, the resulting Low had moved to a position north-northwest of Havana. (See figs. 3, 4, and 6 and the tracks thereon.) Before 2200 EST the top of the circulation of the hurricane was apparently shortly above the 500-mb. level (fig. 7). However, at about this time the circulation of the Low at 300 mb. which had moved in from the east was nearly superimposed on the circulation of the hurricane. This 300-mb. Low was moving at about 15 m. p. h. and when it reached this position north-northwest of Havana, it recurved toward the north—following about the same path taken by the High that preceded it. (See track of High centered over North Carolina on 300-mb. map for 2200 EST, September 1, (fig. 4).) At 2200 EST, September 2, this 300-mb. Low was centered north of the hurricane, but it was close enough to join the circulation of the hurricane. However, because of its northward position, it made the vertical axis of the hurricane tilt toward the north an abnormal amount. The acceleration was probably due to the circulation of the storm being picked up by the circulation of the 300-mb. Low which was steered by some current quite a bit higher. Unfortunately, data from high levels were not secured, and the steering level for the 300-mb. Low cannot be located. The hurricane moved at the speed of the 300-mb. Low plus an additional speed required for the lower part of the hurricane to catch up with the upper part. Thus the surface center moved at about 23 m. p. h. until it caught the 300-mb. Low. The latter had been mov-

ing about 15 m. p. h. but it slowed down some when it recurved to the north. As soon as the surface center caught the 300-mb. Low, it slowed down to 12 to 13 m. p. h.

On September 4 the hurricane became quasi-stationary so far as forward movement was concerned and traced the first of the loops in its track. At this time, the hurricane and the 300-mb. Low were apparently just one Low, and the steering level was apparently somewhat above the 300-mb. level. Again winds at the higher levels were not available in sufficient quantity to pick a steering current. However, from the height distribution on the 300-mb. chart, one can deduce that the steering winds were very light, for gradients near the storm were weak, and the hurricane was located about midway between the High in the Gulf of Mexico and the High in the Atlantic east of Jacksonville (fig. 8). There is no obvious reason for thinking that either of these Highs would predominate over the other at the levels shortly above the 300-mb. surface. Thus one could not be sure from the steering that the storm would stay stationary, but there is no reason for expecting much movement.

During the night of September 4, the hurricane moved slowly toward the northeast and reached the Cedar Keys area about 0700 EST, September 5. The next question is, how would the storm move when it reached the Florida coast? Sufficient winds still were not available at higher levels to accurately determine the steering level. From the flatness of the gradient near the storm at the 300-mb. level at 1000 EST, September 5 (fig. 9), it could be concluded that the steering level was not far above it, and that any movement should be rather slow.

Winds were available at Miami for higher levels. Therefore, let us study the contours on the 300-mb. map and try to deduce what winds should appear at Miami at higher levels if the north-northwest current which was

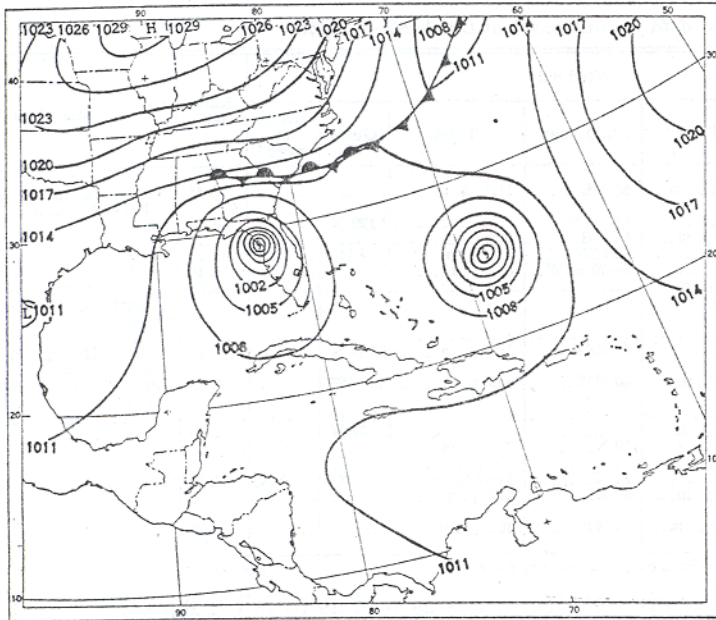


FIGURE 10.—Chart showing sea level isobars and fronts, 1330 EST, September 5, 1950.

west of the hurricane at the 300-mb. level were to appear farther east at the higher levels.

Let us assume for the sake of argument, that the entire contour pattern in the vicinity of Florida shifted farther east with height (fig. 9). Then, depending on how far east it shifted, the winds at Miami would be west, north-west, north, or possibly northeast if there were just a slight change in the shape of contours. Actually, at 35,000 feet, Miami had north winds of about 5 knots; and at 40,000 feet, had north winds of about 20 knots. This partially confirms that the steering current over the storm was from the northwest or north. Six hours later at 1600 EST while the hurricane was still moving toward the south-southeast, Valparaiso, Fla., which was west-northwest of the hurricane, reported north-northeast winds of about 20 knots. Thus all data available tend to confirm that at higher levels the flow over the hurricane was from a direction between northwest and northeast. Therefore, we can decide that the hurricane was still being steered by winds flowing over the top of the warm core. However, for this particular storm, with so many small vortices in the vicinity and with the usual scarcity of data at the higher levels, it was particularly difficult to locate the steering level and to ascertain the direction of the steering current.

At the time the hurricane became quasi-stationary near Cedar Keys, there was a large sea level high pressure system centered over Lake Michigan and its circulation extended far enough south to make contact with the outer circulation of the hurricane (fig. 10). It would have been simpler to have said that the High to the north blocked the advance of the hurricane. However, the circulation of the High never seemed to come in close contact with the stronger portion of the circulation around the hurricane. Furthermore, the High seemed to be more fa-

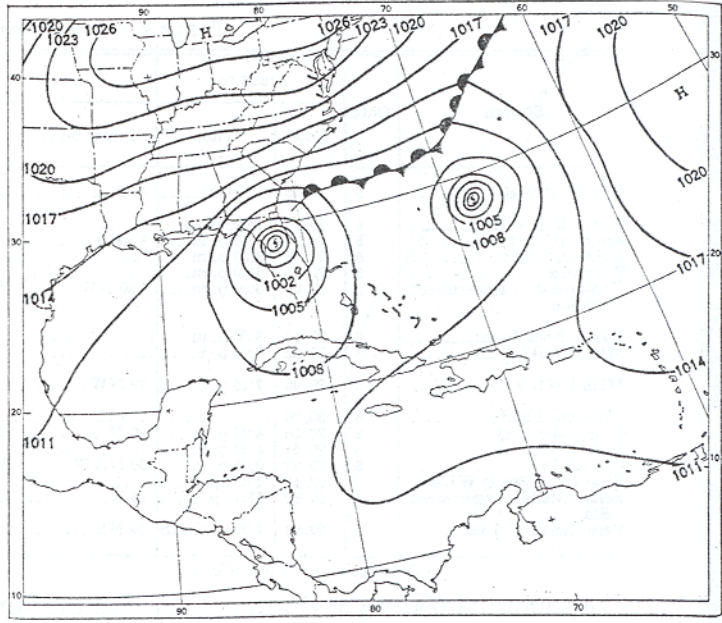


FIGURE 11.—Chart showing sea level isobars and fronts, 1330 EST, September 6, 1950.

vorable to blocking the forward movement of the hurricane during the next day (fig. 11) when the storm was actually moving toward it than it did during the period when the storm was first quasi-stationary near Cedar Keys and then moved away from the High toward Tampa.

CONCLUSION

We have accounted for the development of the hurricane and have shown that high level steering could account for the various accelerations and changes in direction at all times when sufficient data were available. The acceleration on the night of September 2-3 could be accounted for by the movement of the warm core Low at 300 mb. and the effort of nature to return the inclination of the hurricane's axis to the vertical.

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