

AN ANALYSIS OF  
AN UNUSUAL RAINFALL DISTRIBUTION  
IN A HURRICANE



by

Edward Morgan Brooks

A.B. cum laude Harvard College 1937  
S.M. Massachusetts Institute of Technology 1939

SUBMITTED IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF  
D O C T O R    O F    S C I E N C E

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
1945

Signature of Author Edward Morgan Brooks  
Department of Meteorology, February 1, 1945

Signature of Professor  
in Charge of Research W. M. Davis

Signature of Chairman of Department  
Committee on Graduate Students

## TABLE OF CONTENTS

## Chapter

## I Introduction

1. Discussion of the Problem . . . . . 1

## II Synoptic Conditions

2. Surface Conditions over Southeastern States  
in October, 1941 . . . . . 4
3. Upper Air Conditions over Southeastern States  
in October, 1941 . . . . . 7
4. Movement of the Hurricane Center . . . . . 9
5. Intensity of the Tropical Cyclone. . . . . 12
6. Precipitation Pattern. . . . . 15

III Approximate Relationships between Pressure, Wind,  
Convergence, Vertical Velocity, and Precipitation

7. Pressure and Wind in the Hurricane in Southern  
Florida. . . . . 18
8. Frictional Convergence . . . . . 20
9. Vertical Velocity and Precipitation Rate . . . . 23

## IV Interpretations of the Precipitation Data

10. Hourly Precipitation Amounts . . . . . 27
11. Inflow Rate for the Belt of Heavy Rain . . . . 33
12. Conclusions about the Location of the Heavy  
Rain Belt. . . . . 35

References. . . . . 39

Abstract. . . . . 41

Biographical Note . . . . . 46

Acknowledgments . . . . . 48

## FIGURES AND TABLES

Figures	Following Page
1-12 Hourly Surface Maps October 6th, 1941 A.M. . . . .	3
13 Paths of Tropical Cyclones, October, 1941 . . . . .	4
14 Isobars of Hurricane on October 6th, 7th, 8th . . . .	14
15 Total Precipitation and Path of Hurricane . . . . .	16

Tables	On Page
I Summaries for October, 1941 . . . . .	5
II Pensacola Upper Air Data for October, 1941. . . . .	8
III Miami Airport Winds Aloft . . . . .	11
IV Average Precipitation Rates for Different Circles .	28
V Observed Hourly Precipitation Amounts . . . . .	32
VI Duration of Rainy Zone in Terms of Distance . . . .	36

## I. INTRODUCTION

### 1. Discussion of the Problem

The purpose of this thesis is to investigate the reason for the surprisingly light rainfall in a recent tropical hurricane. In most meteorology textbooks, hurricanes are said to be accompanied by heavy rainfall. This is verified in many storms, but meteorologists tend to overlook the fact that this relationship does not apply to all hurricanes. Some authorities on tropical meteorology are inclined to believe hurricanes exhibit so many differences that they are as varied as extra-tropical storms.

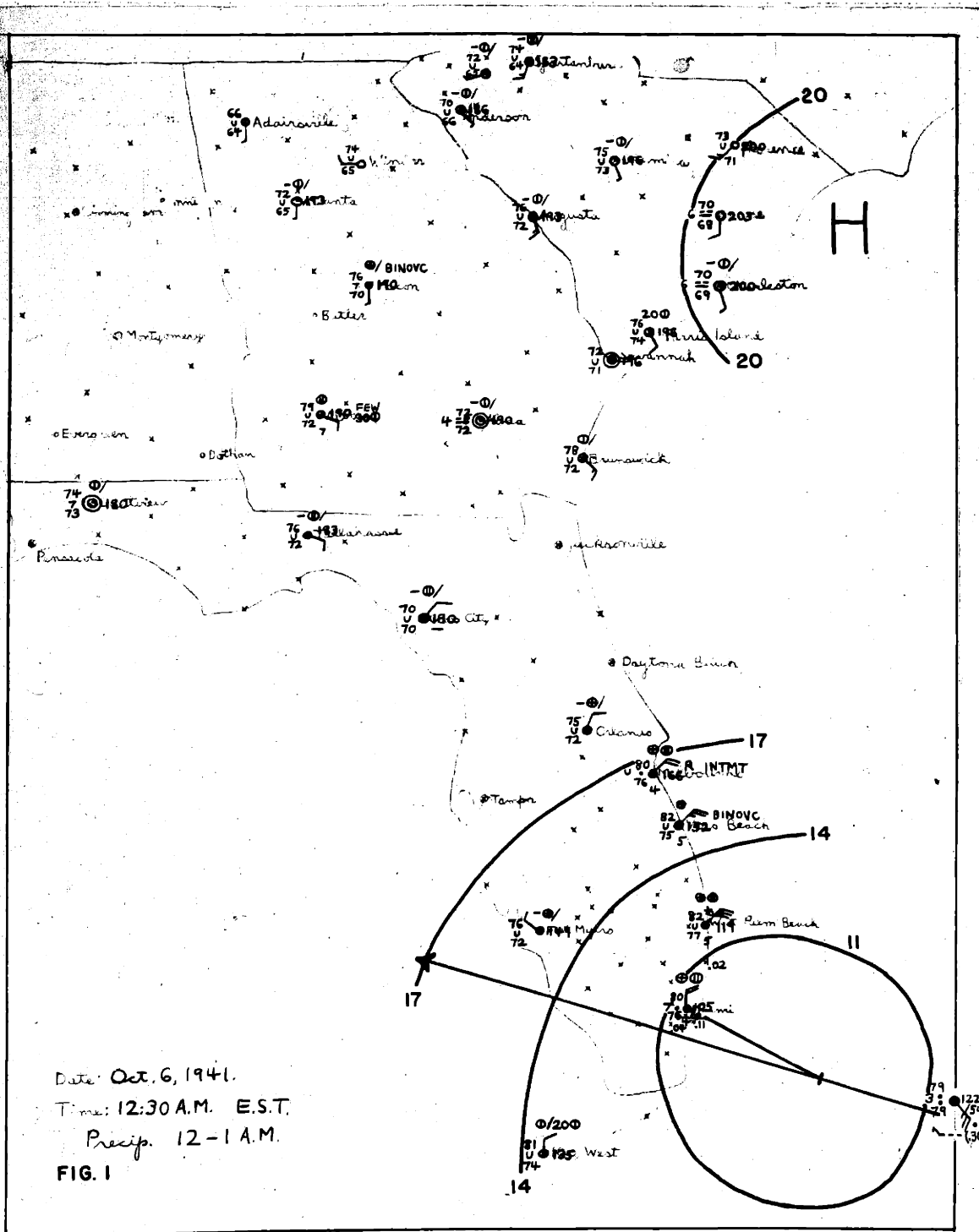
The peculiarity of light rainfall in a hurricane was first noted by the writer at Blue Hill Observatory in the New England hurricane of September 21, 1938. The maximum 5 min. wind velocity was 121 miles per hour, indicating a very intense hurricane; yet the total rainfall at Blue Hill was only 0.13 in., of which 0.12 in. fell in two hours at the peak of the storm. At the East Boston Airport, where the 5 min. wind reached 73 miles per hour, only 0.10 in. of rain was recorded on that day, but of this rain just a trace was recorded during the hurricane. These rainfall records were typical of southeastern New England. However, rainfall was very heavy on the other side of the storm center's path, in western New England. This large rainfall was attributed

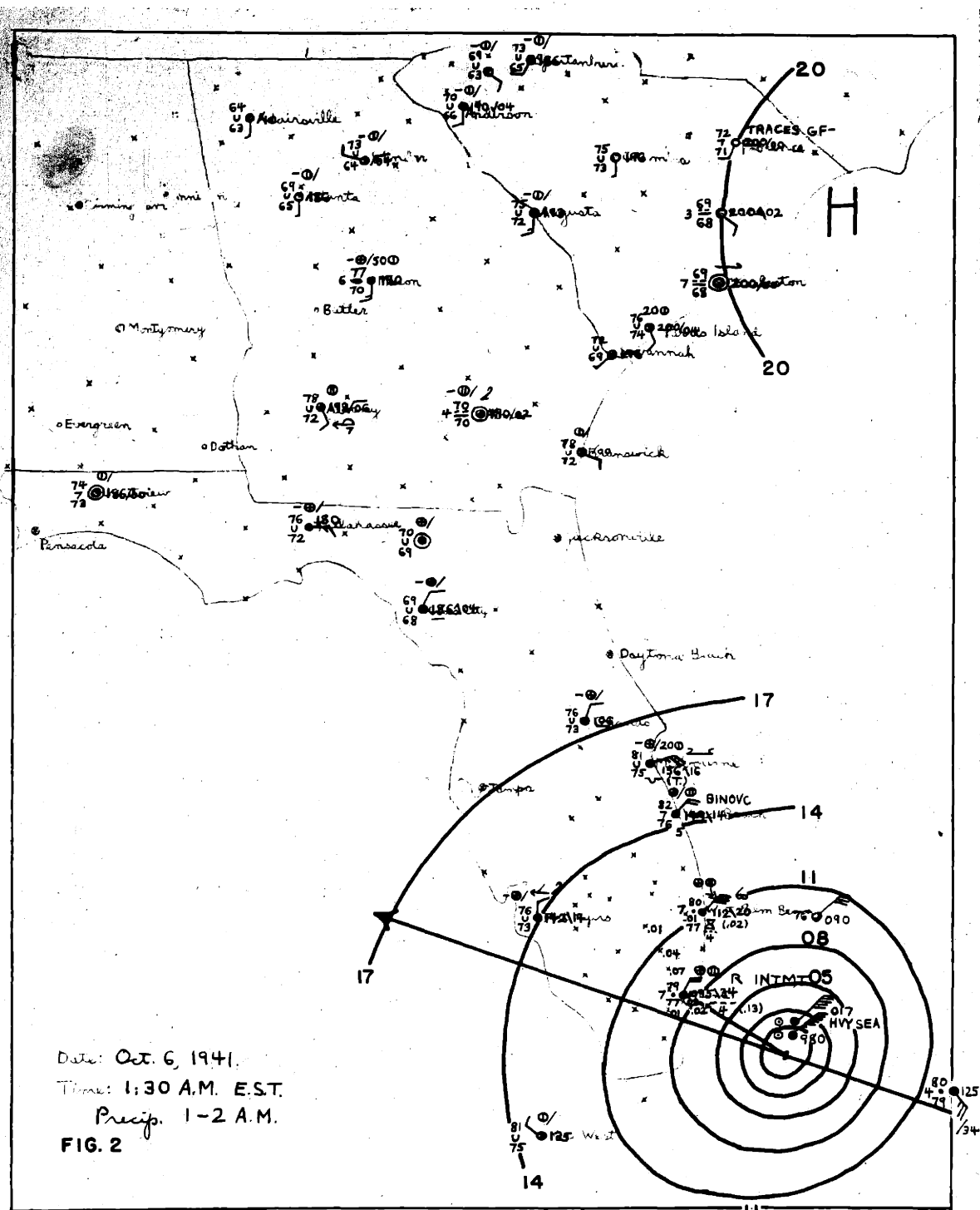
primarily to frontal ascent of the tropical air over the polar air to the west. In other words, it was evidently due to newly developed extra-tropical characteristics of the hurricane in middle latitudes (Pierce). Although this explanation seems adequate for the rainfall in the New England hurricane, it cannot account for an uneven rainfall distribution in a hurricane within a uniform tropical air mass. In the hurricane of early October 1941, the wind at Nassau reached an extreme of 104 miles per hour (Ref. 8) yet only 0.39 in. (Ref. 9) of rain fell. Similarly, at the Dinner Key Air Base at Miami, the peak gust reached 123 miles per hour (courtesy Pan American Airways), whereas the rain at the Miami city office was only 0.35 in. (Ref. 10). Fig. 15 shows that this light rainfall was typical of all southeastern Florida except in the thunderstorm area over the Florida Keys. This heavy rain was so far from the storm track that no rainfall in excess of two thirds of an inch was observed within 30 km from the storm center anywhere in the Miami region (Fig. 15).

There seem to be two possible conditions which might account for such light rainfall in the October 1941 hurricane: (1) the air might have been too dry, (2) the horizontal convergence of air might have been insufficient to produce a large enough transport of moisture upwards. Maritime tropical air surrounded the cyclone at the surface, as shown

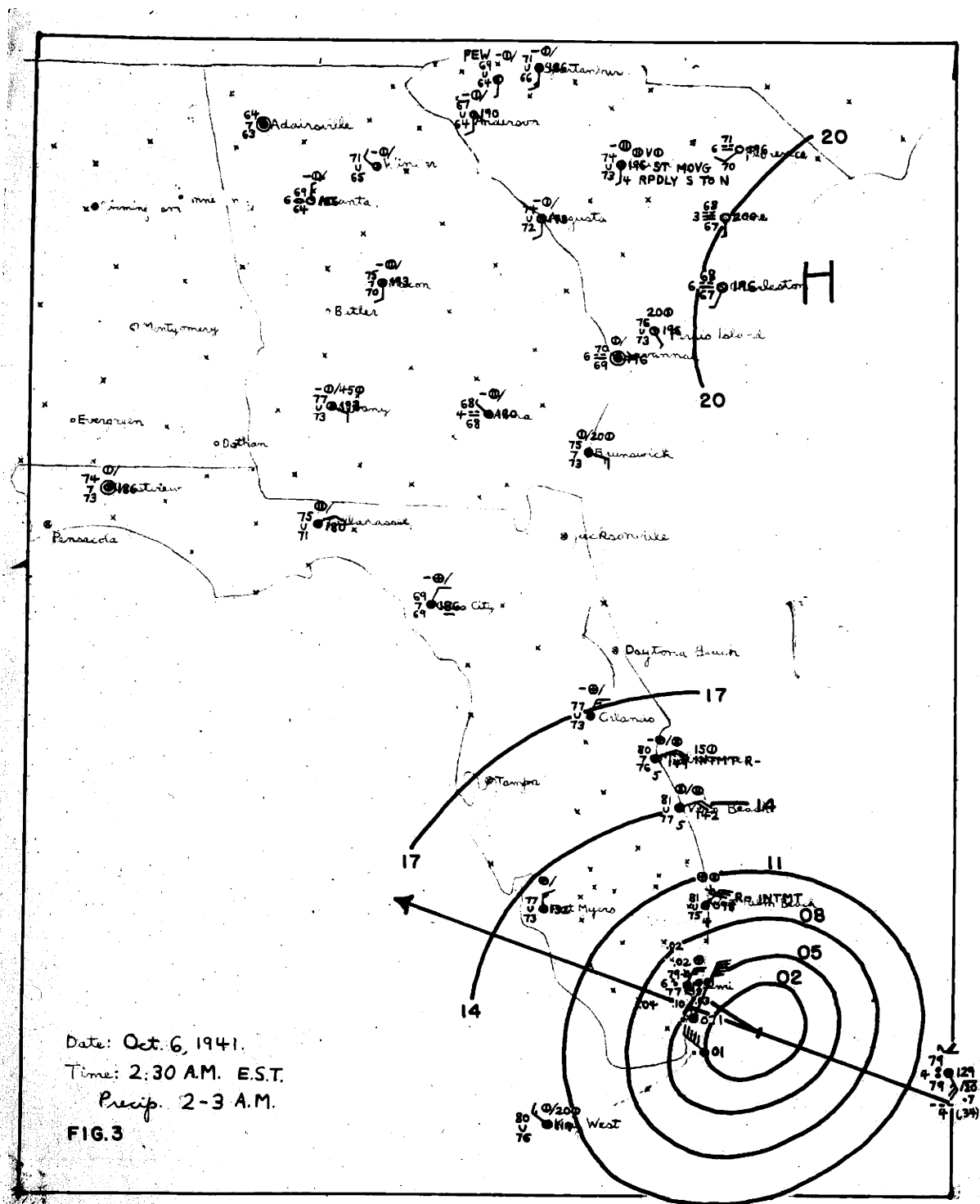
by the fact that all dew points in Florida were above 70°F (Figs. 1-12). Hence there was ample vapor to give large amounts of precipitation if there had been sufficient vertical motion. Therefore the second alternative is to be investigated in preference to the first. The problem then is to determine theoretically the horizontal convergence of the wind field in a moving cyclone, and to compare the amounts of precipitation which would be expected from this convergence with the actual amounts. If there are any discrepancies, the actual convergence can be computed from the amounts of rainfall which it produced.

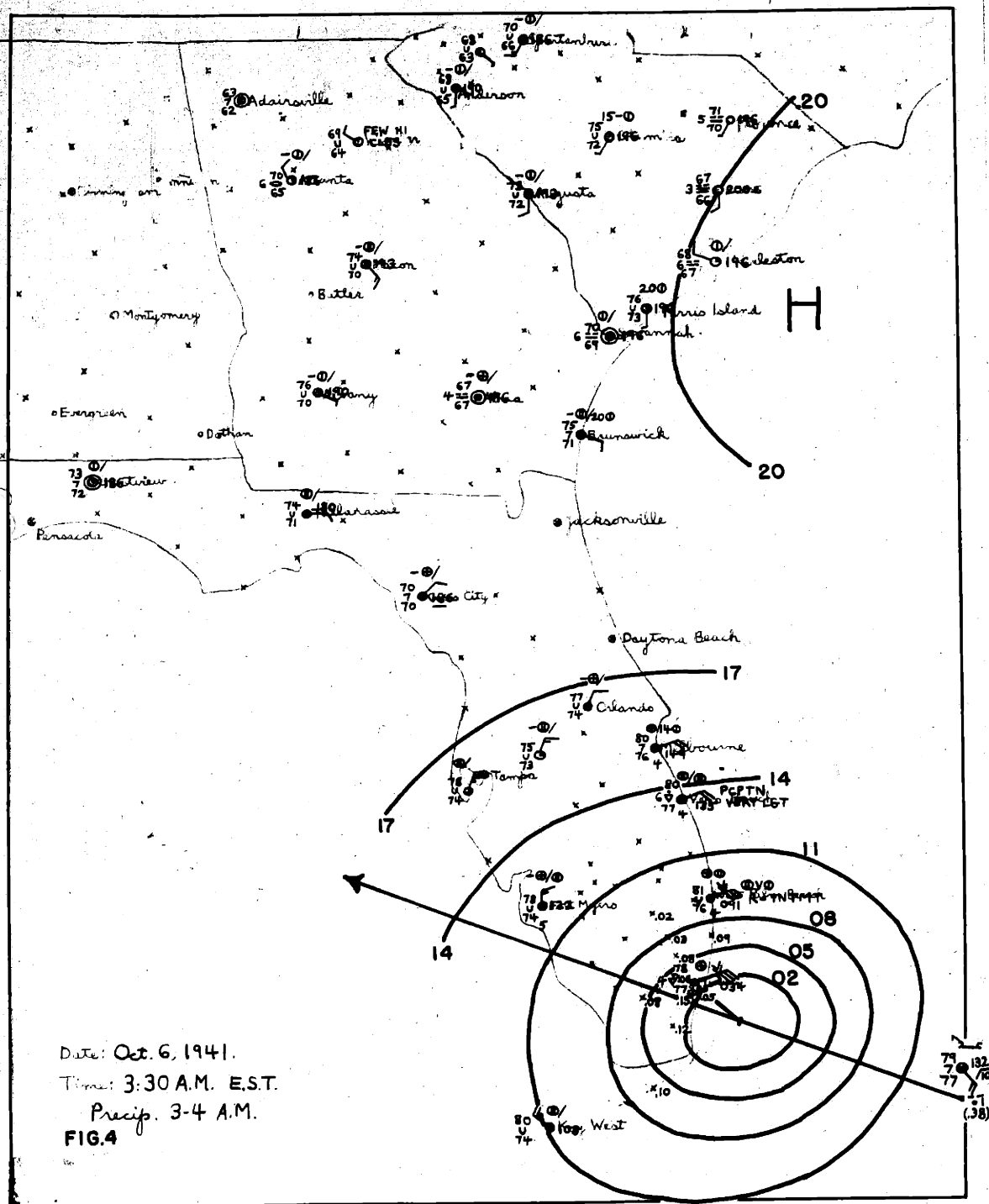
Before these computations are made, a survey of the synoptic conditions associated with this hurricane will be presented. This survey will facilitate the interpretation of the meteorological data and will suggest some of the conclusions.

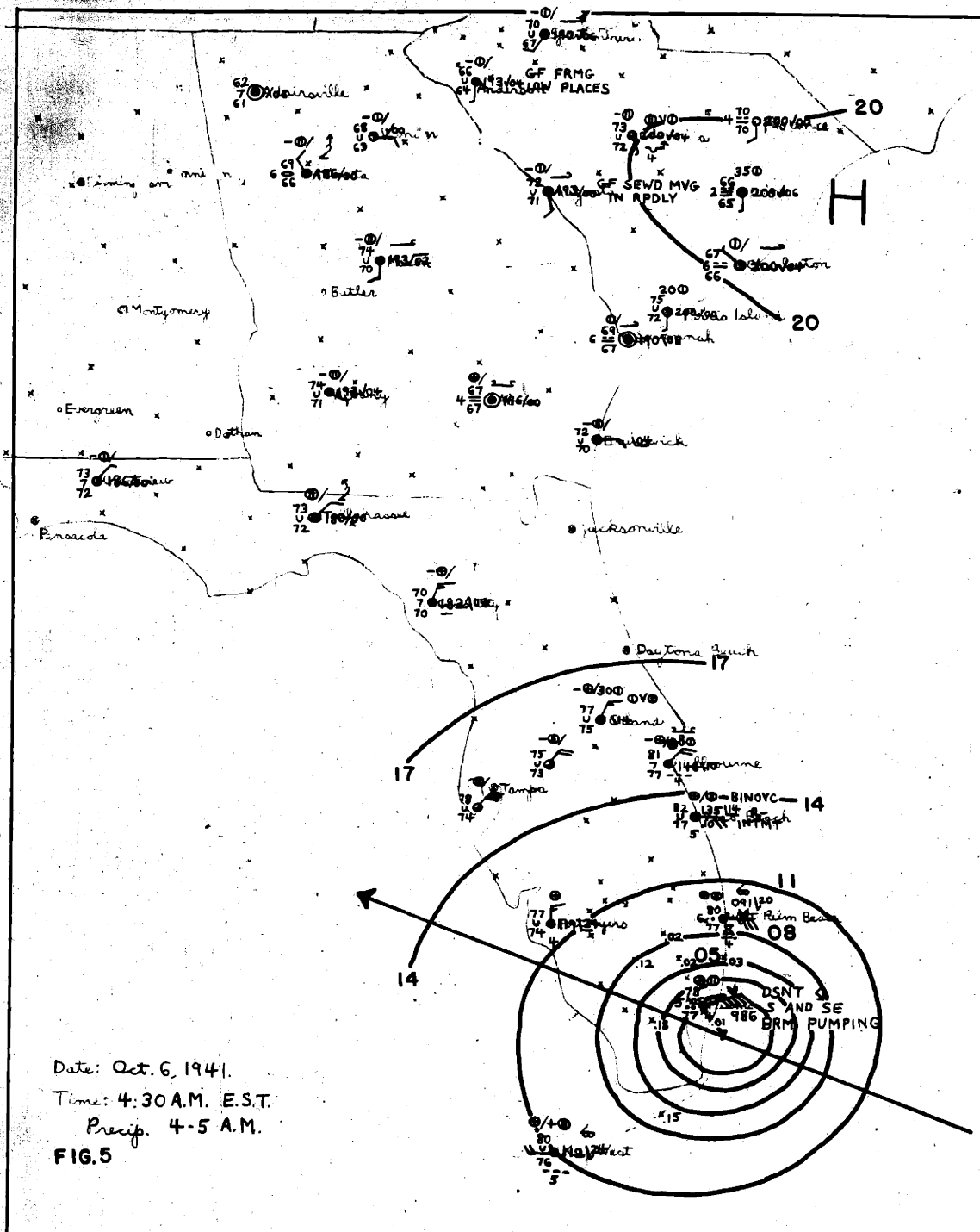


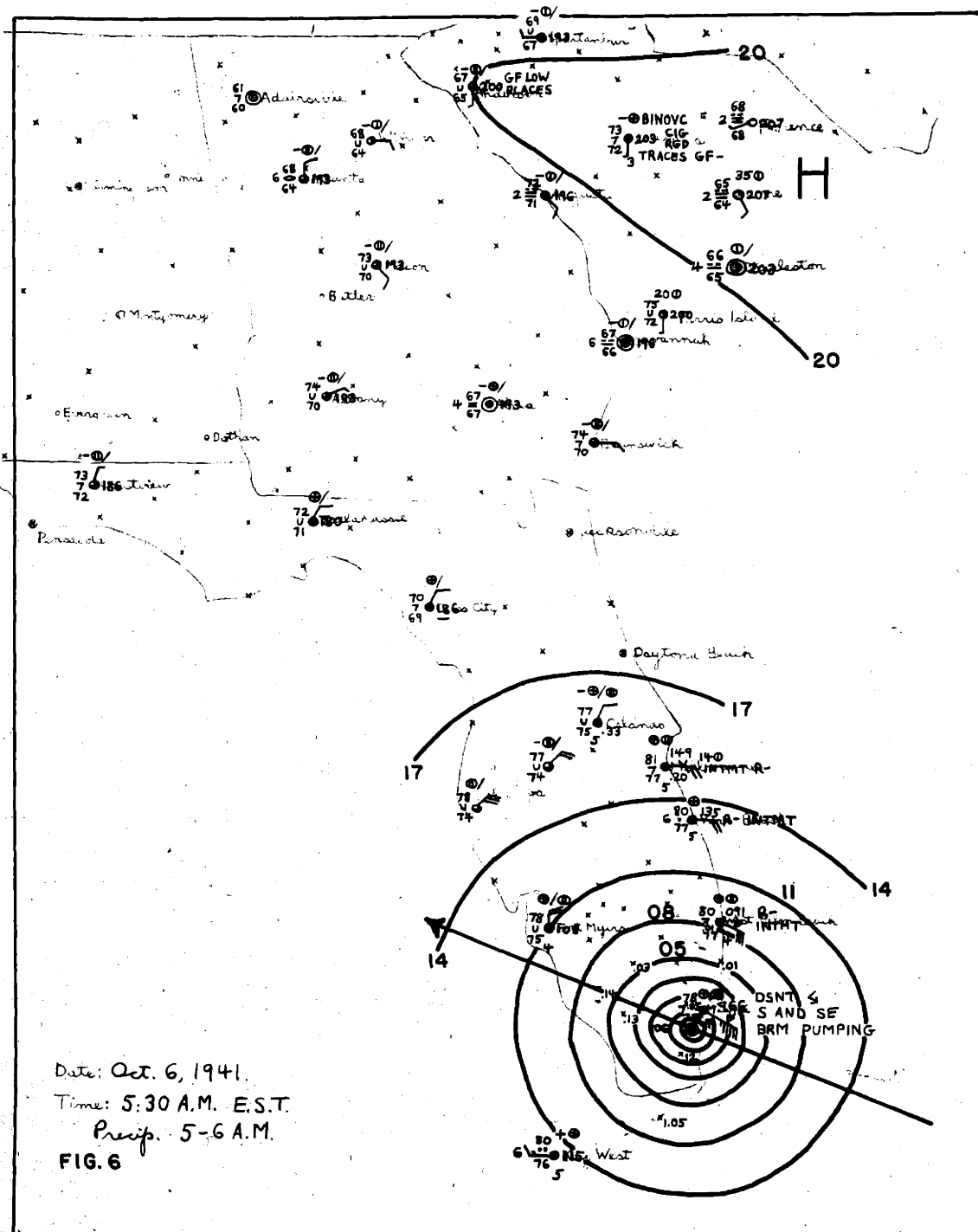


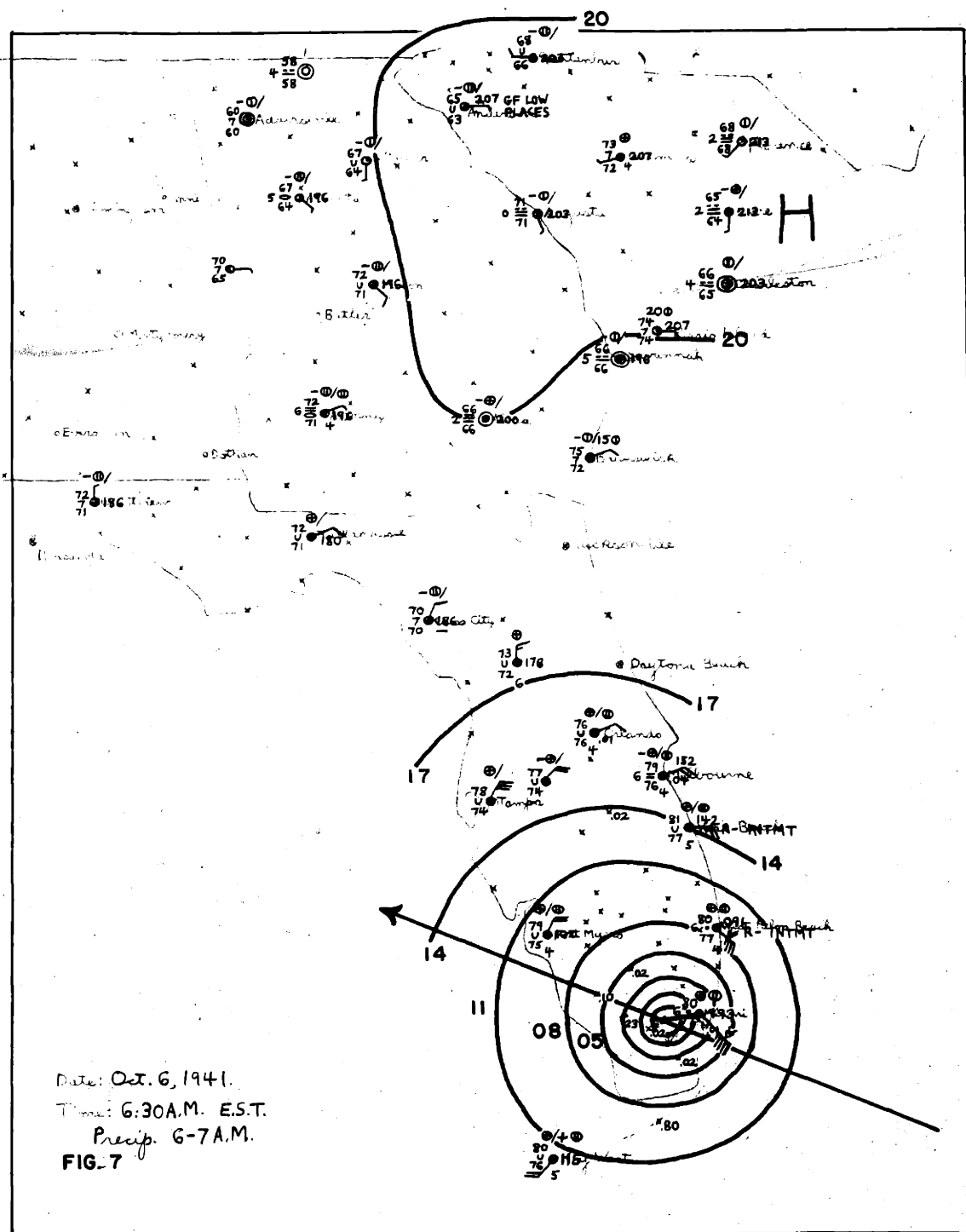


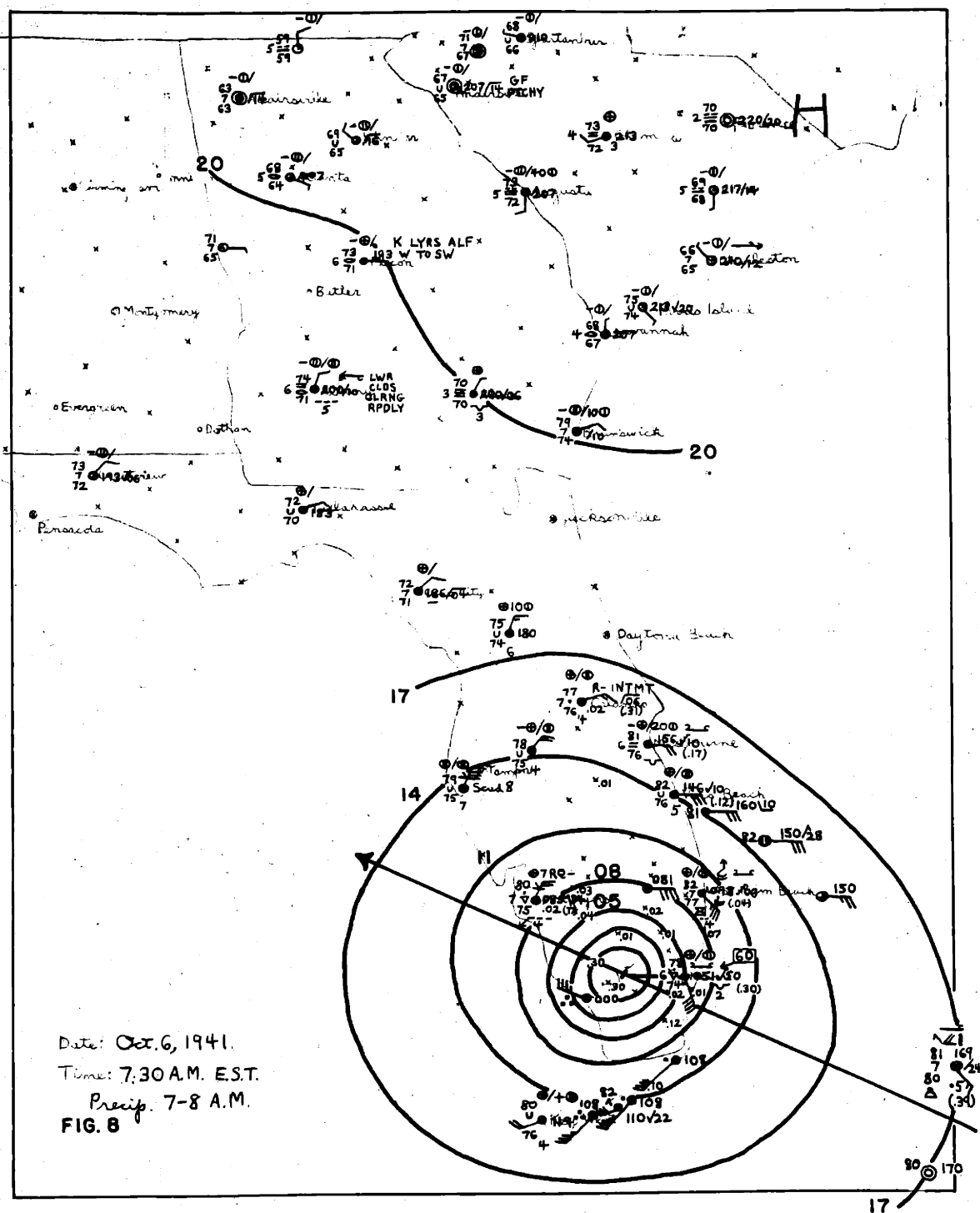


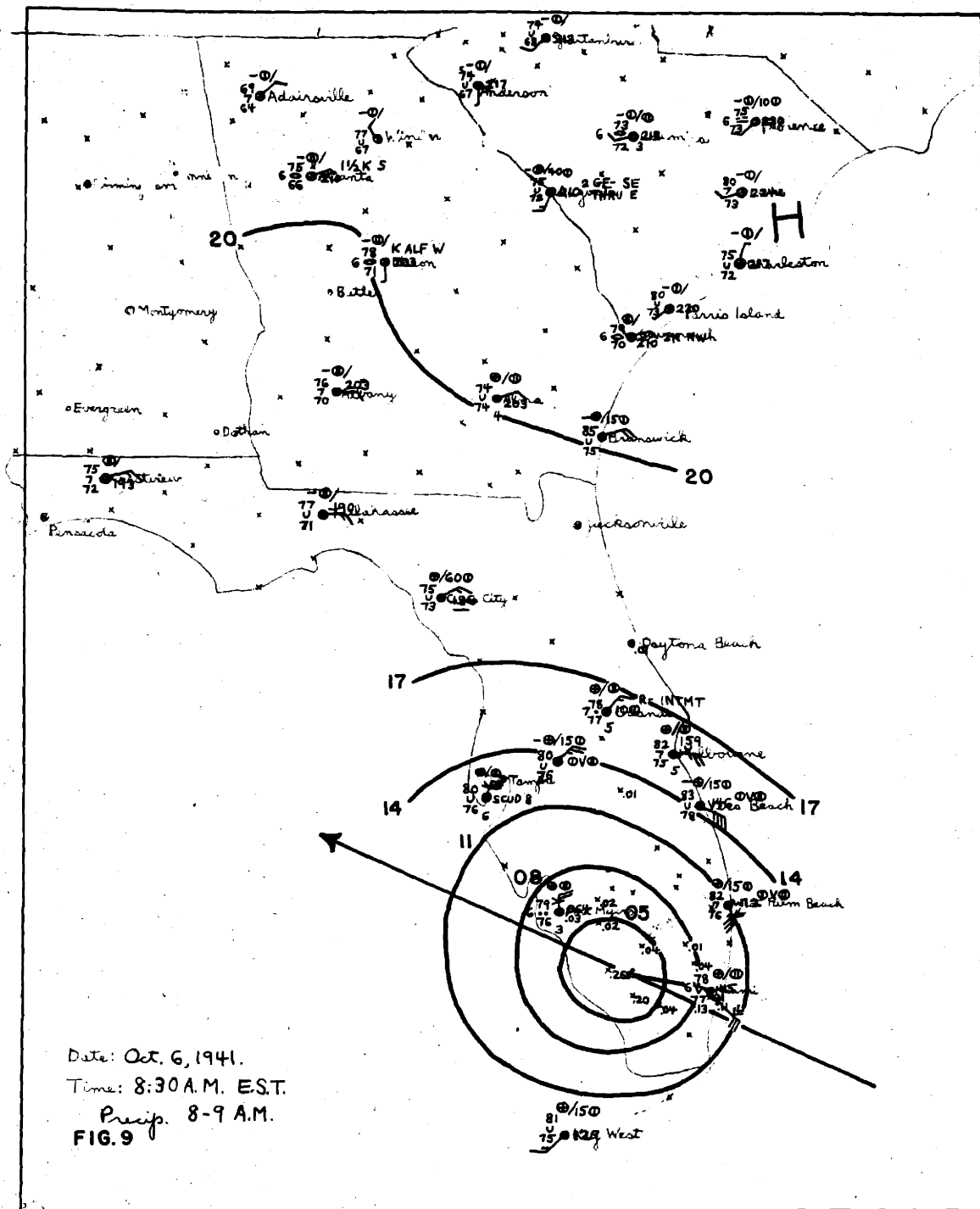




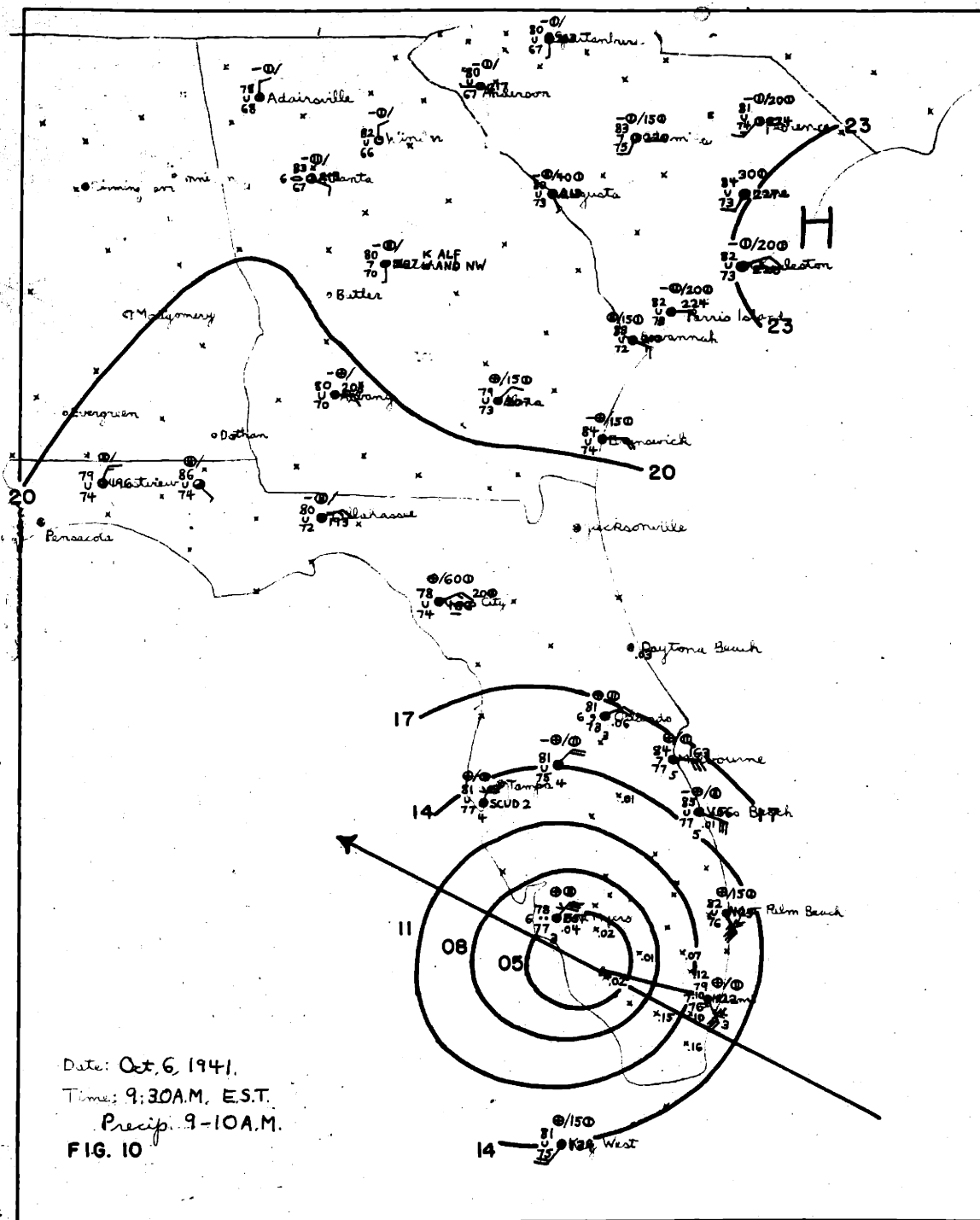




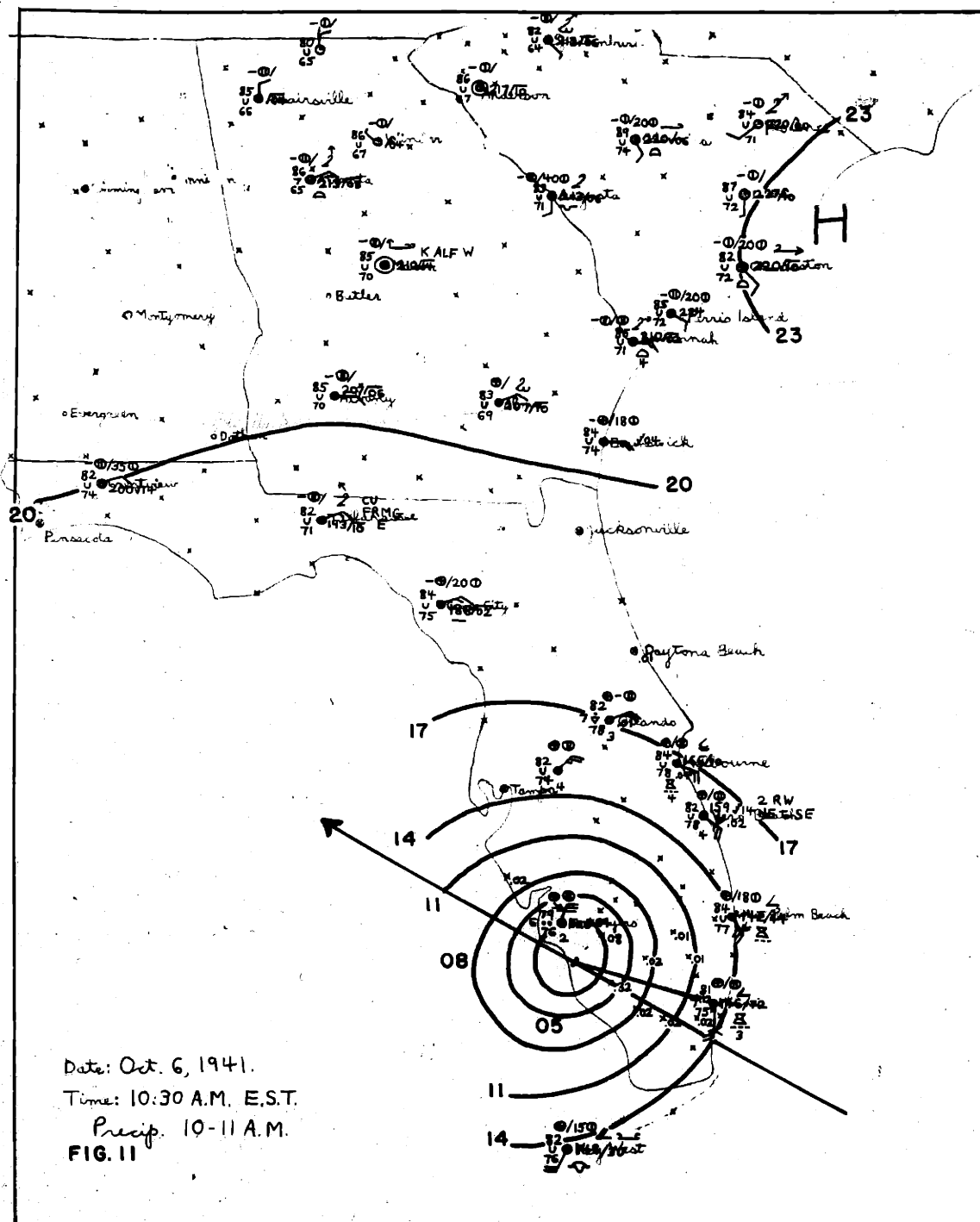


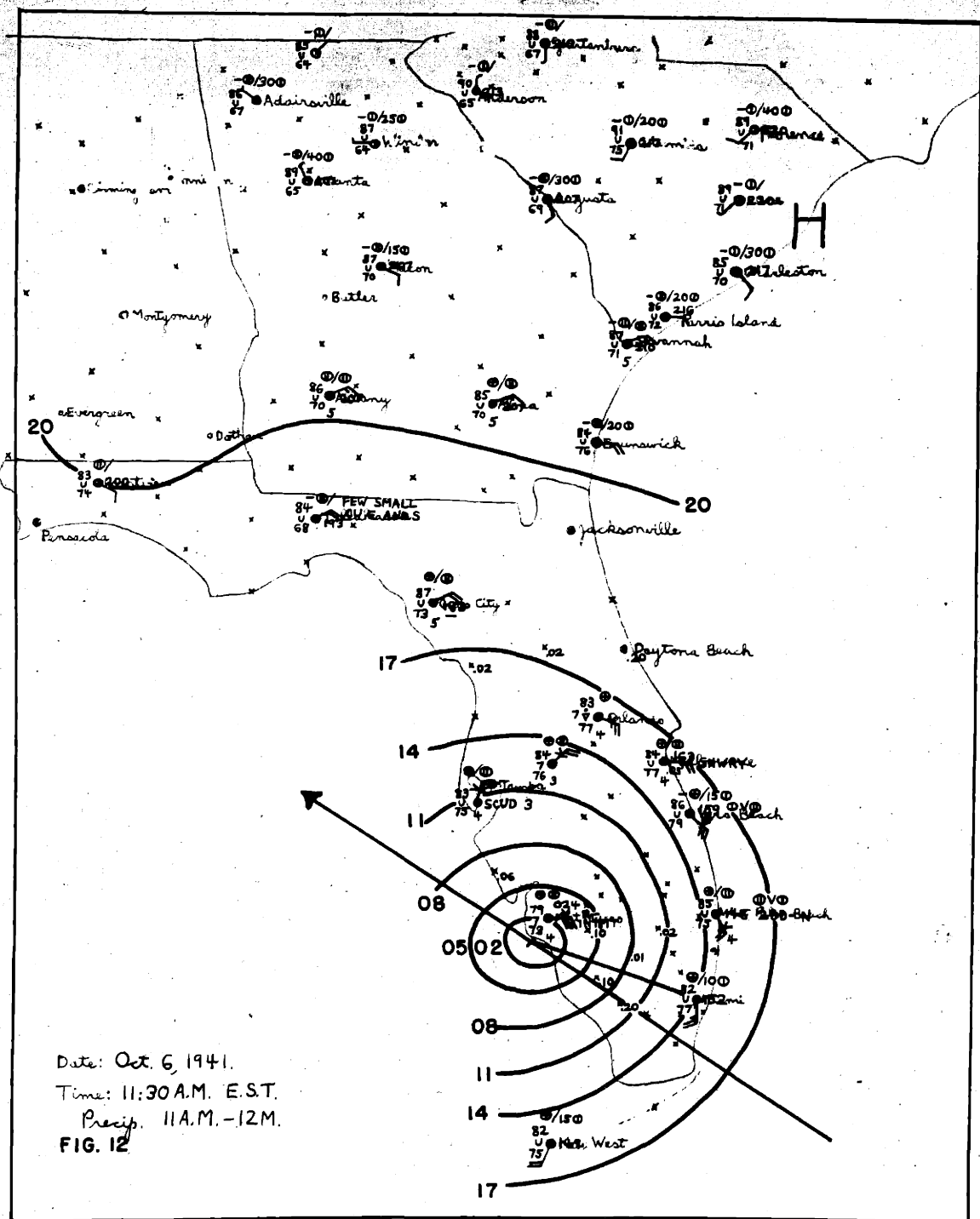


Date: Oct. 6, 1941.  
 Time: 8:30 A.M. E.S.T.  
 Precip. 8-9 A.M.  
 FIG. 9









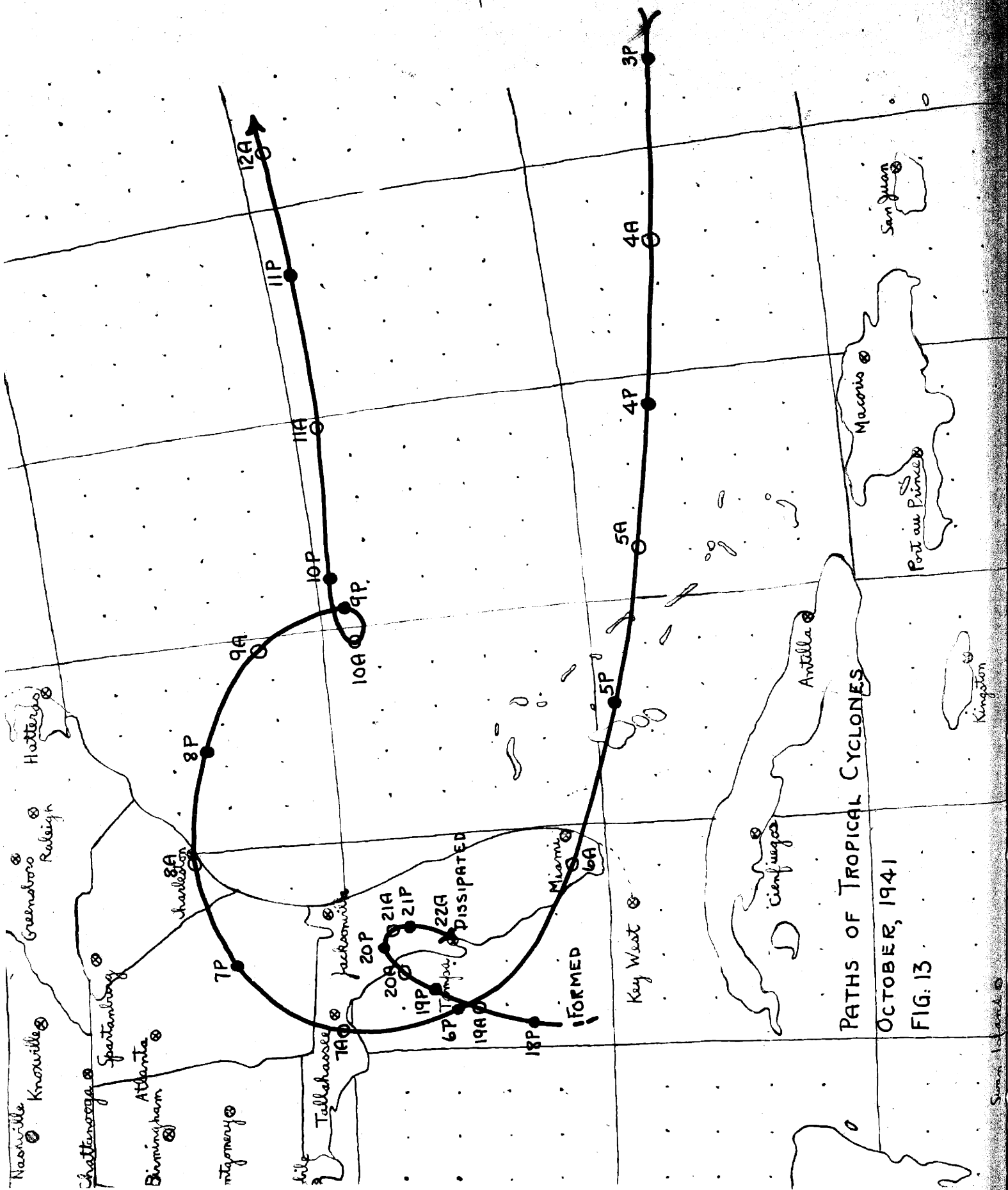
## II. SYNOPTIC CONDITIONS

### 2. Surface Conditions over Southeastern States in October, 1941

During the month of October, 1941, two tropical cyclones occurred in the southeastern part of the United States (Fig. 13). The first disturbance, of hurricane intensity in Florida and Georgia, affected the region from October 5th to 8th. The second disturbance, not of hurricane intensity, affected Florida from October 18th to 22nd, giving flooding rains in northeastern Florida. For example, at Jacksonville 8.03 in. of rain fell during these five days, raising the total precipitation for the month to 9.00 in. (Ref. 10), or twice the normal amount for October (Table I).

In spite of these two disturbances, the mean sea level pressure for October, 1941 in the southeastern United States was above the October normal everywhere. Positive departures of more than 1.7 mb were observed near 80°W. longitude from southern Florida to West Virginia. A mean high center of 1021 mb was centered over western Virginia and the mean 1020 mb isobar extended almost as far south as Atlanta and Charleston, whereas the normal pressure for October is below 1020 mb everywhere in the region (Shaw).

In October, 1941 no extra-tropical cyclones were centered east of the Mississippi River and south of the Ohio River and



PATHS OF TROPICAL CYCLONES

OCTOBER, 1941

FIG. 13

TABLE I

Summaries for October, 1941

Station	Temperature				Pressure		Rainfall	
	Mean °F	Dep. °F	Max. °F	Date Max.	Mean mb	Dep. mb	Total in.	Dep. in.
Atlanta	69.6	-	91	9th	1019.6	+1.4	0.57	-
Charleston	73.8	+6.0	89	10th	1019.6	+1.7	2.55	-0.7
Jacksonville	77.0	+5.9	94	9th	1018.6	+2.0	9.00	+4.5
Miami	80.6	+3.6	91	10th	1016.6	+1.7	3.04	-5.4
Pensacola	76.2	+6.3	93	8th	1018.0	+1.0	2.30	-1.9
Raleigh	68.2	-	96	6th	1021.0	+2.7	1.93	-0.9
San Juan	80.1	+0.3	90	16th	1013.9	-	6.61	+0.8
Savannah	75.8	+7.9	94	5th	1019.3	+1.7	2.36	-0.6
Tampa	79.4	-	95	9th	1017.3	+2.0	2.34	-0.8

Pennsylvania (Ref. 11). Cold fronts from cyclones passing across the Great Lakes and southeastern Canada occasionally extended into the Virginias, but they weakened rapidly as the frontal troughs filled to pressures of about 1020 mb. All the cold fronts dissipated in the Carolinas or moved northward again as warm fronts without ever reaching Georgia or Florida. Only two of these fronts were accompanied by any precipitation. In Virginia, light rain fell on October 10th and moderate or heavy rain on October 27th and 28th (Ref. 10). The total precipitation for the month was much below normal throughout the southeastern states, except in regions which received heavy rains from either of the tropical cyclones. The small rainfall amounts over most of the region can be attributed to the persistent anticyclonic circulation and absence of frontal lifting during the month.

The cold fronts were followed by polar anticyclones moving more eastward than southward. The centers of the migratory highs did not pass south of the Virginias during the entire month and no strong outbreaks of polar air occurred in the southeastern states. Throughout the region, October, 1941 was the second warmest October on record (being surpassed only by October, 1919). The mean temperature for the month was more than 6°F above normal over a large area from Louisiana to Delaware. The maximum temperature for the

month was over 90°F in most of the region, and occurred between October 5th and 10th near the time of the hurricane (Table I).

3. Upper Air Conditions over Southeastern States in October, 1941

Temperatures for the month were above normal not only at the surface, but also at upper levels. For example at Pensacola, temperature departures of +3.5°C (+6.3°F) at the surface decreased to +2°C at 2 km and remained +2°C up to at least 5 km (Normals from Ref. 7).

The mean relative humidities for the month were low at all heights except at the surface (Table II). At Pensacola, the mean relative humidity decreased gradually from 61% at the surface to 38% at 5 km. The high relative humidity at the surface combined with high temperatures at the surface and aloft suggest predominantly maritime tropical air masses. The mean high pressure area was thus not just a shallow polar high, but was a branch of the deep, warm subtropical anticyclone, displaced west and north of its normal position. This is verified by the fact that it appeared as a mean anticyclonic circulation up to at least 10 km, at which level it was centered over the Gulf of Mexico. At 3 km, the center was between Charleston and Jacksonville, as shown by the mean winds of WNW force 2 and SE force 2, respectively. The persistent deep anticyclonic circulation most of the month prevented penetrative convection and air-mass rainfall.

TABLE II

Pensacola Upper Air Data for October, 1941

Altitude	No. of	Pressure	Rel. Hum.	Temp.	Normal	Dep.
m	Obs.	mb	%	°C	(1937) °C	°C
Surface (24m)	23	1015	81	22.7	19.2	+3.5
500	23	961	75	21.4	18.0	+3.4
1000	23	907	71	19.2	15.9	+3.3
1500	23	856	70	16.3	13.7	+2.6
2000	23	806	64	13.8	11.7	+2.1
2500	23	759	53	11.7	9.5	+2.2
3000	23	715	46	9.5	7.1	+2.4
4000	23	634	39	4.2	1.8	+2.4
5000	22	560	38	-1.6	-3.7	+2.1
6000	22	493	36	-8.0	-	-
7000	20	433	36	-14.2	-	-
8000	12	378	31	-21.3	-	-



Subsidence was undoubtedly present since the relative humidities at 3 km averaged only 46%, and were even less above 3 km. This cannot be considered unusual because normal relative humidities (Ref. 7) are equally low, due to the usual prevalence of subsiding, dry polar air in a normal October.

#### 4. Movement of the Hurricane Center

An unusual feature of the hurricane's path was that the storm finally passed beyond ship reports at a point ( $29\frac{1}{2}^{\circ}\text{N}$   $63^{\circ}\text{W}$  at 7:30 A.M.E.S.T. on October 12th) only about 800 km north of the point ( $22\frac{1}{2}^{\circ}\text{N}$   $64^{\circ}\text{W}$  at 7:30 P.M. on October 3rd) where it had first appeared more than a week earlier (Fig. 13). Yet, during that period, it travelled a total distance of about 5000 km, or more than 6 times as far. The average speed of the center was about 6 m/sec, which is the normal speed for hurricanes in low latitudes.

The track of the hurricane (Fig. 13) extended from about 300 km north of Puerto Rico; through the Bahama Islands; across southern Florida; over the northeastern Gulf of Mexico; across northwestern Florida, southern Georgia, and South Carolina; and finally over the Atlantic Ocean about 250 km south of Bermuda. The center passed south of Nassau, Miami, and Fort Myers, west of Tallahassee, just south of Charleston; and then performed a small loop at  $29\frac{1}{2}^{\circ}\text{N}$   $75^{\circ}\text{W}$  north-northwest of the Bahamas.

The rate of general air flow in which the hurricane was moving in southern Florida was measured by the Miami winds aloft one day before and one day after the storm (Table III). From 1000 ft. to 14,000 ft. above sea level the average wind was force 5 before the hurricane and force 4 after the hurricane. This gives a mean value of about 30 km/hr or  $8 \frac{1}{3}$  m/sec for the winds aloft. In crossing southern Florida, the hurricane moved 271 km from 12:30 to 9:30 A.M. on October 6th, or at a speed of  $8 \frac{1}{3}$  m/sec. It may be concluded that this hurricane moved at the speed of the winds below 15,000 ft. The small magnitude of the vertical wind shear in this layer is explained by the small horizontal temperature gradient, a condition typical of subtropical regions during the hot season.

The hurricane center recurved near Apalachicola at  $30^{\circ}\text{N}$ , which was  $5^{\circ}$  north of the normal latitude ( $25^{\circ}\text{N}$ ) of recurvature for October, and its translation was faster than normal as it was moving west-northwestward before recurvature. These abnormalities resulted from an unusually well developed subtropical high with a center of 1022 mb to 1027 mb west of Bermuda from October 3rd to 6th. With the approach of two cold fronts crossing North Carolina on October 8th and 10th, the Bermuda high was displaced southward to  $30^{\circ}\text{N}$  and diminished to less than 1020 mb at its center. The renewal

TABLE III  
Miami Airport Winds Aloft  
(Direction and Force)

Date	Time		1000'	4000'	7000'	10,000'	14,000'	20,000'
Oct.								
1941	EST							
<u>Before Storm</u>		<u>Hours Before Center</u>						
4	11P.M.	30 $\frac{1}{2}$	E 5	E 5	E 5	E 6		
5	5A.M.	24 $\frac{1}{2}$	ENE5	ENE5	ENE5	ENE5	E 5	
	11A.M.	18 $\frac{1}{2}$	ENE5	ENE4	E 5	E 5	E 4	ESE7
Average			ENE5	ENE5	E 5	E 5	E 5	ESE7
<u>Near Storm</u>								
5	5P.M.	12 $\frac{1}{2}$	NNE3	NE5				
	11P.M.	6 $\frac{1}{2}$	NNE6					
		<u>Hours After Center</u>						
6	5P.M.	11 $\frac{1}{2}$	S 5	S 7	S 6	S 5	S 5	
<u>After Storm</u>								
6	11P.M.	17 $\frac{1}{2}$	SSE4	S 4	S 5	S 5	SSE4	
7	5A.M.	23 $\frac{1}{2}$	SE4	SSE4	S 3	SSE4		
Average			SE4	SSE4	S 4	SSE4	SSE4	

of westerly winds aloft at  $30^{\circ}\text{N}$  gave the tropical disturbance a large recurvature and then carried it on a general eastward course. After passing off the Carolina coast on October 8th, it was overtaken by the northwesterly flow behind the first cold front. This carried the cyclone southeastward to south of  $30^{\circ}\text{N}$  on October 9th. The anticyclone between the two cold fronts caused the tropical storm to retrograde slightly westward while the high center north of the cyclone was moving rapidly eastward. Again, the tropical storm started to move eastward in response to the second cold front trough reaching the coast on October 10th, and followed along with the cold front due eastward until after October 12th.

##### 5. Intensity of the Tropical Cyclone

The intensity of the vortex, as measured by the wind speed, depends on the size of the vortex, and on the depression of the barometer at the center of the vortex. Since the size of the vortex was easier to measure than the central pressure because of the absence of reports at the immediate center, observed surface winds were used to check the relative intensity of the tropical cyclone at different stages along its path.

The tropical cyclone appeared on October 3rd as a storm of unknown intensity. If it formed on that date rather than advancing from beyond the field of observations, it probably was not yet of hurricane intensity. On October 4th it showed

signs of some strength, as judged by several ship reports from the Bahama Islands. At the Bight on Cat Island, the wind reached 63 miles per hour at 12:30 P.M.E.S.T. on October 5th, 20 minutes before the center passed just south of the station (courtesy U.S. Weather Bureau). During these 20 minutes the pressure dropped 10 mb from 972.0 mb to a minimum of 962.4 mb, while the hurricane moved 10 km. Therefore the pressure gradient at about 10 km from the center must have been about 1 mb/km. (Compare this with the values given in section 7.)

In spite of weaker pressure gradients in southern Florida, even higher wind velocities occurred at Miami and Nassau (introduction) because of the smaller curvature of the trajectories at greater distances from the center. There were some indications that the cyclone was filling, as the lowest pressure became progressively higher from 986 mb at Nassau to 995 mb at Miami and 1001 mb at Fort Myers, all of these cities being equally far north of the cyclone center. The contraction of the isobars as the storm crossed southern Florida is shown by the hourly maps (Figs. 1-12). Winds at Fort Myers reached only force 8, indicating the loss of full hurricane intensity.

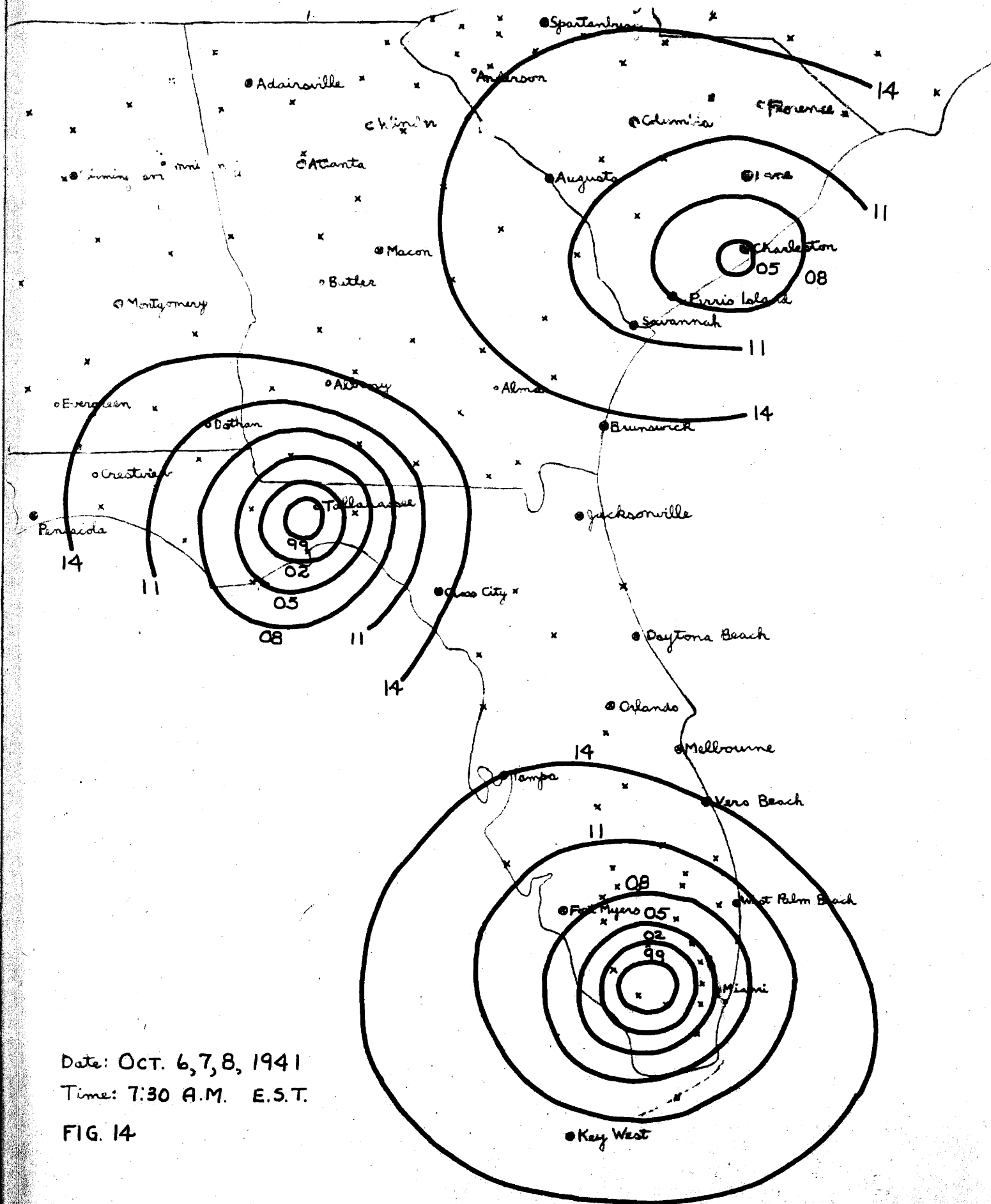
In the Gulf of Mexico, the cyclone again deepened to a full hurricane as shown by the occurrence of winds of 65 to 75 miles per hour and a lowest sea level pressure of 982 mb in the calm center at Carrabelle when the storm entered northwestern Florida on October 7th. However, the cyclone did not

regenerate to as large or as intense a hurricane as it had been in southern Florida (Fig.14). Full hurricane intensity was maintained as far north as Albany, Georgia, where a maximum wind velocity of 65 to 75 miles per hour was reported.

Filling of the tropical cyclone was observed as it crossed southern Georgia on October 7th and southern South Carolina on October 8th, for the pressure at Charleston did not go below 1002 mb although the center passed near enough to the station to cause a marked decrease in wind. As the highest wind at Charleston was only force 7, the cyclone was at its weakest there.

Although the cyclone regenerated over the Atlantic Ocean on October 8th, no hurricane winds were reported at any later time, although one ship reported force 11 on October 8th. The lowest pressure reported by ships after October 7th was 1001 mb on October 10th.

It is to be noted that the cyclone deepened three times, in each case while it was over the ocean. But both times while it was crossing the southeastern states, it was filling. The deepening of the cyclone at sea can be explained by the relatively small frictional inflow of air into the cyclone and the large supply of moisture available to supply energy by condensation; whereas the filling of the cyclone over land can be attributed to the large frictional inflow and the limited moisture supply.



Date: Oct. 6, 7, 8, 1941  
 Time: 7:30 A.M. E.S.T.

FIG. 14

One curious exception was found in the filling of the hurricane while it was crossing the Bahama Islands (mostly a water surface) and the Gulf Stream. This cannot be explained by surface conditions, but may be due to the effect of the abnormally well developed subtropical high center to the north of the hurricane. Soundings at Miami showed abnormally warm air with relative humidities as low as 38% above 2 km. before the hurricane arrived. This suggests a possible damping effect on the convection, thereby limiting the amount of latent heat energy released by condensation.

In spite of its long duration, the tropical cyclone never became a hurricane of large size, but always remained as small as a hurricane in an early stage of development. This behavior was not like that of most storms, which expand while moving into higher latitudes. The long time that it was over a warm water surface should have given it ample opportunity to spread laterally into a large storm. The fact that this did not occur is an indication that the margins of the cyclone were unfavorable regions for convective activity, probably due to the anticyclonic subsidence over the entire region.

#### 6. Precipitation Pattern

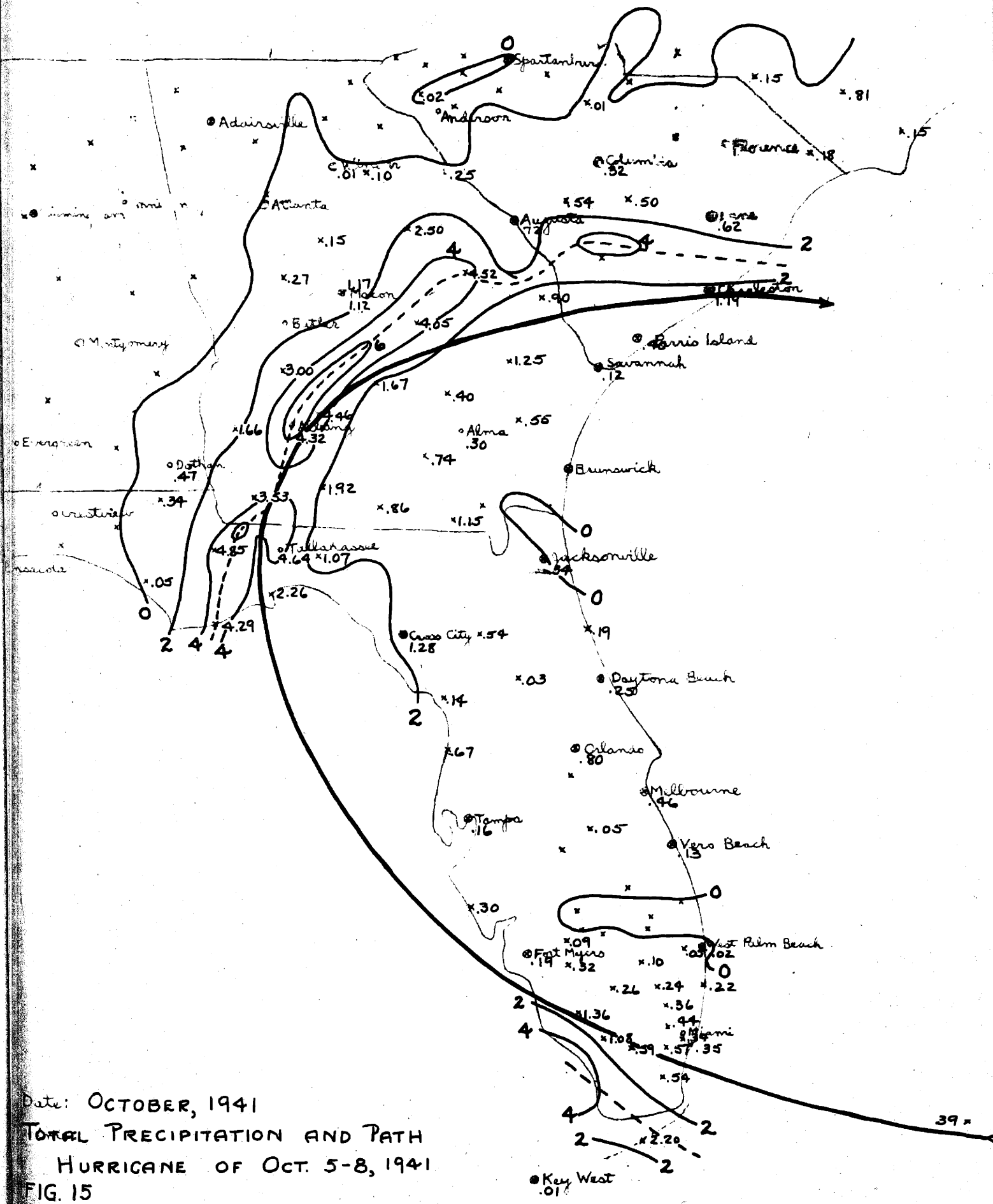
The precipitation pattern was perhaps the most peculiar feature of the hurricane. Unfortunately, most of the path was over the ocean in regions devoid of islands. The only



measurements of precipitation amounts were made in the United States and the Bahama Islands. The analysis of the map of total precipitation (Fig.15) does not include the Bahamas (where data were too sparse to warrant drawing isohyetal lines), and is based on more United States observations than are entered in the figure.

When the hurricane first struck land, just south of the Bight on Cat Island, it produced a rainfall of 1.62 in., which was larger than any other precipitation total reported in the Bahama Islands. This precipitation amount was somewhat subnormal for a point which experienced the hurricane center. This abnormality of light rainfall along the path of the center became more pronounced when the storm reached the western Bahamas and southern Florida, as shown by the small values reported from Nassau and Miami (introduction).

An even stranger abnormality developed in the western Bahamas and persisted until the storm passed off the coast of South Carolina. The belt of maximum rainfall was at considerable distances to the left of the path of the cyclone center, as shown by the dashed line in Fig. 15. These distances averaged 65 km in southern Florida, 35 km in northern Florida, 50 km in eastern Georgia, and 55 km in South Carolina. At only one section, in southwestern Georgia, did the heaviest rain occur along the path itself, but even there the rainfall was less than it was along the path north



Date: OCTOBER, 1941  
 TOTAL PRECIPITATION AND PATH  
 HURRICANE OF OCT. 5-8, 1941  
 FIG. 15

and south of that location. Tallahassee with a rainfall of 4.64 in. reported the heaviest precipitation on the right side of the path, whereas amounts of over 6 in. were reported on the left side of the path in Georgia.

The hourly rainfall amounts in the United States showed that the maximum precipitation rates occurred near the line dividing the left front quadrant from the left rear quadrant (Figs. 6 and 7). The position of the heaviest rain directly to the left of the center of this hurricane was in sharp contrast to its normal position in the right front quadrant of a moving hurricane (Cline(1)).

In order to explain the precipitation distribution associated with the hurricane, the horizontal convergence of the air flow, which is presumably the cause of the precipitation, must be examined. The results of a study of the convergence will now be given.

III. APPROXIMATE RELATIONSHIPS BETWEEN PRESSURE,  
WIND, CONVERGENCE, VERTICAL VELOCITY, AND  
PRECIPITATION

7. Pressure and Wind in the Hurricane in Southern Florida

The shape of the hurricane can be judged by the isobars belonging to the cyclone. The hourly weather maps of the hurricane in southern Florida (Figs. 1-12) show that it had no marked eccentricity. Although Visher found that most tropical cyclones are slightly elliptic (Tannehill) usually being elongated along their paths, the effect of this ellipticity on the horizontal convergence of the gradient wind was found by the writer to be very small. The computations were so tedious that they will not be given here. It may be assumed that the hurricane was circular within the 1011 mb isobar, which had an average radial distance of about 150 km in southern Florida.

The hourly maps (Figs. 1-12) also show that the translation of the center was very nearly constant in speed and direction across the Florida peninsula. The pressure gradient required to give a geostrophic wind velocity equal to this translation speed of 30 km/hr at 26°N latitude  $L$  would be as follows:

$$\frac{\partial p}{\partial n} = \rho (2\omega \sin L) c = 0.0062 \text{ mb/km},$$

where  $\rho$  is the air density,  $\omega$  is the angular velocity of the earth, and  $c$  is the speed of translation of the

cyclone center.

The pressure gradient in the hurricane was computed from the hourly changes in pressure at Miami and was found to be consistent with the observed Miami surface winds. The following two values were obtained at two different radial distances,  $r$ :

$$\frac{\partial p}{\partial r} = 0.32 \text{ mb/km at } r = 50 \text{ km,}$$

$$\frac{\partial p}{\partial r} = 0.06 \text{ mb/km at } r = 135 \text{ km.}$$

These pressure gradients were about 50 and 10 times as great as a pressure gradient corresponding to the translation. The computations showed that if the latter were present in the pressure field, it would not be more than about 10% of the total pressure gradient within a radial distance of 135 km. Consequently, the isobars representing the sum of the circular rotation and translation pressure gradients would be nearly circular. For example, an isobar which was 132 km ahead of and behind the center would be situated about 120 km to the right and 150 km to the left of the center. A circle through the right and left points of this isobar would pass 134.2 km ahead of and behind the center. This shows that there would be a flattening of the circle (in the direction of motion) which would amount to 2.2 km in 134 km, or less than 2%. Isobars closer to the center would be even more circular. The similar lack of eccentricity of the isobars on the

maps (Figs. 1-12) shows that such a combination of pressure gradients may have existed while the hurricane was in southern Florida.

By solving the equations of motion, Exner found the pressure gradient corresponding to a combined uniform circular rotation and a uniform translatory air flow in a moving cyclone (Haurwitz (1)). He found that this pressure gradient was the sum of the pressure gradient which would give the rotation as a gradient wind (if the cyclone were stationary) and the pressure gradient which would give the translation as a geostrophic wind. Conversely, the assumed motion was found by the writer to result from this combined pressure gradient. This motion was not just the gradient wind in the moving cyclone, but included the deviation from the gradient wind due to acceleration. It is therefore not contradictory to the observations that a moving hurricane with nearly circular isobars would produce an air flow consisting of the sum of uniform rotation and translation where friction is negligible, that is, above the frictional layer. From surface wind observations in a large number of hurricanes, Cline detected the presence of this translation (Cline (2)).

#### 8. Frictional Convergence

Since both a uniform rotation and a uniform translation

have no horizontal convergence, the sum of these two motions has no convergence. The writer found that the gradient wind alone in a moving cyclone has a pronounced convergence ahead of the center and an equal divergence behind the center. However, the deviation due to acceleration has a compensating divergence ahead of and convergence behind the center. Consequently, the conclusion is that the convergence in most of the hurricane area in southern Florida must have resulted from an additional wind component not given by the assumed wind field. The chief factor causing this component and its convergence in most of the hurricane area in southern Florida is believed to have been friction.

It is important to recognize the limitations of this conclusion in view of the simplifying assumptions upon which it is based. For example, even though the actual wind field approximated a non-convergent theoretical wind field, the wind component representing the vector difference between the actual and the theoretical winds may have been convergent. The convergence of this component may have been large if the horizontal variations of the component were large, even though the component itself was small. A wind component which cannot be computed from the circular isobars must have existed where convective activity was observed. Convergence of such a component probably occurred on the Florida Keys in the

belt of heavy rain, where there was strong convection as shown by the thunderstorms, producing 2 inches of precipitation in 2 hours (Figs. 6 and 7).

For convenience, the average convergence within an area instead of the negative of the mathematical divergence at a single point will be used in the computations. To find the average frictional convergence at the surface for an area inside a circular isobar it is necessary to know the rate of surface flow into the area. If the surface wind  $v_0$  makes an angle  $\alpha_0$  with the direction of the pressure gradient, the wind component  $v_{i0}$  toward the center is given by the formulas,

$$\begin{aligned} v_{i0} &= v_0 \cos \alpha_0, \\ v_0 &= v_\theta (\sin \alpha_0 - \cos \alpha_0) \end{aligned} \quad (\text{Haurwitz (2)}),$$

where  $v_\theta$  is the wind velocity normal to the radial direction above the frictional layer. The surface inflow  $I_0$  is equal to the surface wind component inwards multiplied by the length of the isobar (of radius  $r$ ):

$$I_0 = 2\pi r v_{i0}.$$

The average surface convergence  $C_0$  is equal to the surface inflow divided by the area  $A$ :

$$C_0 = \frac{I_0}{A} = \frac{2\pi r v_{i0}}{\pi r^2} = \frac{2 v_{i0}}{r}.$$

According to this formula, the average surface convergence is equal to twice the inward component of the surface wind



divided by the radius of the area.

Similarly, the average convergence at any level is equal to the inflow at that level divided by the area. It follows that the mean values (subscript m) within the frictional layer are related by the same equations:

$$C_m = \frac{I_m}{A} = \frac{2v_{im}}{r}.$$

By integration of the inflow of the Ekman spiral between the surface and the gradient wind level, it was found that the mean wind component inwards in the frictional layer is approximately one half of the surface component. This is reasonable in view of the fact that the inflow generally decreases with height and becomes zero at the gradient wind level.

$$v_{im} = \frac{1}{2} v_{io}.$$

$$C_m = \frac{v_{io}}{r}.$$

Thus the mean value in the frictional layer of the average convergence over the area is approximately equal to the surface wind component inwards divided by the radius of the area.

## 9. Vertical Velocity and Precipitation Rate

The equation of continuity can be written in the following form:

$$\frac{1}{\rho} \frac{d\rho}{dt} = - \frac{\partial v_x}{\partial x} - \frac{\partial v_y}{\partial y} - \frac{\partial v_z}{\partial z} = C - \frac{\partial v_z}{\partial z}.$$

The writer found that in a hurricane the term involving the rate of change of the air density for a given air

parcel in horizontal motion is negligible compared with the other terms in the equation above. To a good approximation, the vertical variation of the vertical velocity is given by the horizontal convergence:

$$\frac{\partial v_z}{\partial z} = C.$$

The average vertical velocity  $v_{z0}$  at the top of the frictional layer is related to the mean average convergence as follows:

$$v_{z0} = \int_0^D \frac{\partial v_z}{\partial z} dz = \left( \frac{\partial v_z}{\partial z} \right)_m \int_0^D dz = C_m D.$$

The equation states that the average vertical velocity at the level D is equal to the mean average convergence multiplied by the depth of the layer of convergence (the frictional layer).

Formulas have been developed by others for the height of the gradient wind level in terms of the curvature of the isobars and the coefficient of eddy viscosity. Unfortunately, these formulas cannot be applied to a hurricane unless they are considerably modified to allow for the extreme surface turbulence sometimes augmented by convection which would carry frictional effects above the theoretically low gradient wind level in a cyclone. Also, the eddy viscosity coefficient and its vertical variations in a hurricane have abnormal values, which

have not been accurately determined. Therefore, to obtain the approximate vertical extent of the frictional inflow, it was assumed that the depth of the turbulent layer was equal to the height of the gradient wind level computed only for the outer part of the hurricane.

The average rate of vertical transport,  $T$ , of air upwards at level  $D$  is the vertical velocity multiplied by the density,  $\rho_D$ , at that level:

$$T = \rho_D v_{zD}$$

On the assumption that there is no convergence and no divergence above level  $D$ , the vertical transport above level  $D$  is the same as at  $D$ . This should hold essentially true up to the level of ice-crystal clouds, where there is an observed horizontal divergence of cirriform clouds outwards from the hurricane.

The average rate of vertical transport  $T_w$  of water vapor upwards is the air transport multiplied by the specific humidity  $q$ :

$$T_w = q T$$

The average rate at which water vapor is lost in air rising from the frictional layer (subscript 1) to the ice level (subscript 2) is the difference between the average moisture transports at the two levels:

$$T_{w_1} - T_{w_2} = (q_1 - q_2) T$$

But this loss in vapor represents approximately the average

precipitation rate, P.R., in the area:

$$P.R. = (q_1 - q_2) T.$$

To obtain the correct units for the precipitation rate, it is necessary to divide out the unit ratio of  $1 \text{ gm/cm}^3$  of water.

By a combination of the formulas above, it is possible to express the average precipitation rate in terms of the moisture loss, the air density, the depth of the frictional layer, the surface wind component inwards, and the radius of the area:

$$P.R. = (q_1 - q_2) \rho_o C_m D = (q_1 - q_2) \rho_o D \frac{v_{io}}{\lambda}.$$

From the observed average precipitation rate, it is possible to compute the mean inflow required in the layer of inflow by the use of the same formulas:

$$v_{im} = \frac{\lambda}{2} C_m = \frac{\lambda}{2} \frac{P.R.}{(q_1 - q_2) \rho_o D}.$$

#### IV. INTERPRETATIONS OF THE PRECIPITATION DATA

##### 10. Hourly Precipitation Amounts

The large number of hydrographic stations in southern Florida gave a close enough network of hourly precipitation observations to make possible the determination of the average precipitation rates within different sized circles of the hurricane. These averages were compared with those computed from the frictional inflow according to the formulas given above. Computations were carried out for the total area within these overlapping concentric circles, with radii of 50 km, 100 km, and 135 km (Table IV). Convergence at a distance of more than 150 km from the center of the hurricane was not sufficient to produce any more than widely scattered light rains.

First of all, the wind at the gradient wind level was computed from the observed pressure gradient at each of these distances from the center. Then the surface wind and its component toward the low center were found by setting  $\alpha_0 = 70^\circ$ , the average observed value at Miami. After the mean average convergence was found, the vertical velocity at the top of the frictional layer was found for  $D=500m$ , which was computed for a radial distance of 135 km in the hurricane (Haurwitz (3)). The vertical transport was computed on the assumption of  $\rho_0 = 1.1 \times 10^{-3} \text{ gm/cm}^3$ , and finally the average precipitation rate was worked out

TABLE IV  
Average Precipitation Rates  
for Different Circles

$r$	50	100	135	km
$\frac{\partial p}{\partial h}$	0.32	0.12	0.06	mb/km
$\frac{1}{\rho} \frac{\partial p}{\partial h}$	2.7	1.0	0.5	cm/sec <sup>2</sup>
$v_0$	42.1	31.9	24.3	m/sec
$v_0$	25.2	19.1	14.5	m/sec
$v_{i0}$	8.6	6.5	5.0	m/sec
$C_m = \frac{v_{i0}}{r}$	17.2	6.5	3.7	$10^{-5} \text{sec}^{-1}$
$v_{j0} = C_m D$	8.6	3.25	1.85	cm/sec
$T = \rho_0 v_{j0}$	9.5	3.6	2.0	$10^{-3} \text{gm/cm}^2 \text{sec}$
$P.R. = (q_1 - q_2) T$	14.2	5.4	3.0	$10^{-5} \text{cm/sec}$
Computed P.R.	.20	.08	.04	in./hr
Observed P.R.	.12	.06	.04	in./hr
No. of stations	5	14	24	

for  $q_1 = 20 \text{ g/kg}$  and  $q_2 = 5 \text{ g/kg}$  corresponding to the levels of inflow and outflow, respectively.

These values of the average precipitation were converted into inches per hour and compared with the observed averages in southern Florida for the hour of 7-8 A.M., October 6, 1941. For the circles with radii of 135 km and 100 km the computed averages (.04 and .08 in./hr) agreed well with the observed averages (.04 and .06 in./hr). But for the circle with the 50 km radius, the computed (.20 in./hr) was almost twice the observed average (.12 in./hr). However, since the observed average was based on only 5 reports, the discrepancy at first appeared to be due to an insufficient number of observations.

To obtain a better verification of the computed average for the smallest of the three circles, a greater number of observations were obtained by using all the southern Florida reports within 50 km from the center for all hours of October 6th instead of just 7-8 A.M. on that date. The 40 reports obtained gave an observed average precipitation rate of only .055 in./hr as compared with the computed average of .20 in./hr. This result shows that the original, smaller discrepancy between the computed and observed averages could not be explained away by the smallness of the sample representing the observed average.

Therefore, the observed average was not too small, but

the computed average was too large, because other factors causing divergence may have been present, or one or more of the assumptions about friction did not apply within 50 km of the center. First, the angle between the wind direction and the radial direction may have been greater than  $70^\circ$  at the radial distance of 50 km, since theoretically this angle increased to  $90^\circ$  at the outer edge of the hurricane "eye", into which no inflow should have occurred. Second, the specific humidity at the level of outflow may have been much greater than 5 g/kg if the moist ascending air in the vortex did not reach the ice level. This would be particularly true near the inner edge of the hurricane vortex, where the boundary between the vortex and the relatively warm, dry central core ("eye" aloft) was below the ice level, thereby requiring outflow at an even lower level without precipitation of the condensed vapor (Bergeron theory). Both of the effects given above not only tended to give less rainfall than computed within the 50 km circle, but also tended to give more rainfall than computed outside this circle. Since the average hourly amount of rainfall was computed satisfactorily for the entire 100 km circle (one quarter of which consists of the 50 km circle), the extra rainfall must have fallen between 50 and 100 km from the center.

In order to detect this zone of surmised greater rain-



fall, the hourly observations for each of the 13 stations within 50 km from the path of the center were tabulated with reference to the hour during which the center was nearest to the station (Table V). The average rainfall for each hour and the number of stations reporting measurable amounts during that hour both showed two maxima, 2 hours before and 3 hours after the center passed. As the center was traveling at a speed of 30 km/hr, these time intervals corresponded to distances of 60 km and 90 km, respectively, which were both in the 50-100 km zone of surmised greater rainfall. It is worthy of note that the average amount reported (.04 in./hr) during the hour nearest the center was less than half of the maximum average (.09 in./hr) 2 hours before the center. The October, 1941 hurricane cannot be regarded as unique in this respect because most storms have their heaviest rainfall even earlier (Cline (1)). Also less than half of the stations reported measurable rain during the central hour, whereas nearly all stations reported measurable precipitation both 2 and 3 hours from the center. These results suggest that the central core of dry air aloft and the small flow into the inner part of the vortex had a measurable effect on the hourly rainfall rates in different parts of this hurricane. The hourly rainfall in most hurricanes occurs closer to the center than in this one, probably because of the normally steeper boundary between the vortex and the central core.

TABLE V

Observed Hourly Precipitation Amounts

	Hour when Center was Closest A.M.	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
Deep Lake	9-10		.14	.10	.30	.26	.02	.32	.10			.12
Felda	10-11			.04	.02	.02	.08	.10	.04	.02		
Fort Myers	11-12		.02	.03	.04				.03	.02		.05
Hialeah	5-6	.02	.03	.13	.05					.21		
Homestead	5-6				.12		.12	.02	.12		.16	
Miami	5-6	.11	.02	.03	.05	.01		.01	.01	.11		
Monroe	7-8				.13	.23	.30	.20		.02	.20	
N. New R. Canal (20 mi. bend)	6-7	.07	.02	.08					.04	.12		
Pennsuco	6-7			.06	.05	.05				.10	.12	
Seminole Indian Reservation	8-9		.12	.03	.02	.01	.04	.01	.02	.01		
Tamiami Trail (40 mi. bend)	6-7		.04	.08	.18	.06	.02		.04	.15	.02	
Tamiami Trail (Krome Ave.)	5-6	.04	.01	.10	.15				.02	.13	.10	.02
Venice	2-3P.M.	<u>.02</u>	<u>.06</u>	<u>.04</u>	<u>.01</u>	<u>—</u>	<u>—</u>	<u>.03</u>	<u>.14</u>	<u>—</u>	<u>—</u>	<u>—</u>
Total		.24	.42	.74	1.15	.65	.58	.69	.56	.89	.60	.19
Average		.02	.03	.06	.09	.05	.04	.05	.04	.07	.05	.01
No. of Stations Reporting at least .01 in.		4	9	11	12	8	6	7	11	10	5	3

### 11. Inflow Rate for the Belt of Heavy Rain

The magnitude of the rainfall in the belt of heavy rain on the left side of the storm's path was much greater than the rainfall that could have been expected from frictional inflow alone. For example, the rainfall rate of one inch per hour at Lignumvitae Key (Fig.6) was more than 10 times as much as the observed averages in different sized circles of the hurricane (section 10). The air within the lower layers in this hurricane was convectively unstable as shown by a decrease of equivalent potential temperature from  $349^{\circ}\text{A}$  at the surface to  $347^{\circ}\text{A}$  at 2km at Miami 100 km ahead of the center. The frictional inflow might have produced enough lifting to release the instability of the air. If this was so, the large vertical velocities which gave the heavy rain were developed by horizontal density differences between rising air columns and their environments after being started by an initial forced lifting.

It should be remembered that such a release of convective instability cannot produce any more rain than the total amount of moisture in the air. Therefore, the heavy rainfall, which persisted for at least 2 days, would have ended within a few hours without a new supply of moisture. For example, for a mean vertical velocity of 0.5 m/sec (42.7 cm/sec computed below), the surface air would reach a height of 5 km in only about 3 hours. Because evaporation from the

surface was much slower than the precipitation rate, this moisture must have been brought into the hurricane by an advection of moist air from other regions. The large inflow required to maintain the convection was not indicated by the theory for the moving circular cyclone that the air was moving along with the cyclone. Even though other factors may have contributed to the convergence, a large convective cell must have been superimposed on the cyclonic circulation. This is in agreement with the convective theory for the maintenance of a hurricane, but it is peculiar that the convective cell in this hurricane was not symmetrically situated with respect to the center of the cyclone.

From the precipitation rate of 1 in./hr, the wind velocity of inflow was computed by means of the formulas of Chapter III. By use of the same assumptions as listed in section 10, the vertical transport was found to have the value of  $47.0 \times 10^{-3} \text{ g/cm}^2 \text{ sec}$ , and the mean convergence was  $85.4 \times 10^{-5} \text{ sec}^{-1}$ , the vertical velocity at the top of the turbulence layer being 42.7 cm/sec. The mean velocity of inflow depends on the size of the area. By Fig. 15, the width of the heavy rain belt on the Florida Keys was about 50 km. If the rain area was circular, the radius was about 25 km. For this area the mean velocity of inflow was found to be as follows:

$$v_{im} = \frac{1}{2} C_m = 10.7 \text{ m/sec.}$$

If such a velocity of inflow had actually occurred, it would have been apparent in the wind field. That there was no evidence of this flow in the observed winds indicates that the mean convergence was probably much less than the amount computed above. An inspection of the assumptions showed that there was not sufficient reason for assuming 500m for the depth of the inflow layer, inasmuch as the inflow was not frictional, but was part of a convective cell. If the outflow in the convective cell was above the level of the zero-degree isotherm, between 5 km and 6 km above the surface, the inflow may have extended through a depth of 3 km. If this was the correct thickness of the inflow layer, the mean convergence was  $14.2 \times 10^{-5} \text{sec}^{-1}$  and the mean velocity of inflow was 1.8 m/sec. This small wind velocity when superimposed on the hurricane winds of 35 to 40 m/sec would not be detected, which is in agreement with the Florida Keys surface wind reports (Fig.8), showing the effects of friction only.

## 12. Conclusions about the Location of the Heavy Rain Belt

In section 10 it was shown that the average hourly rainfall rate was greatest between 50 km and 100 km from the center of the hurricane. On the assumption that there were no other major irregularities in the rainfall, the maximum amount of total rainfall should have fallen at stations which were in the 50-100 km zone for the longest period of time. This time interval,  $t$ , was expressed as a

function of the distance,  $r_o$ , from the path of the hurricane center, moving at the speed of 30 km/hr in a straight line. The values obtained are given in the following table.

Table VI  
Duration of Rainy Zone in terms of Distance

$r_o$	$t$	$r_o$	$t$
km	hr	km	hr
0	3.3	60	5.3
10	3.4	70	4.8
20	3.5	80	4.0
30	3.7	90	2.9
40	4.1	100	0.0
50	5.8		

This table shows that stations which were 50 km from the path remained in the 50-100 km rainy zone almost twice as long as stations along the path itself. Even stations as far as 80 km from the path were in the zone longer than stations within 30 km from the path. Since the maximum time interval was for  $r_o=50$  km, the belt of heaviest rainfall should have been about 50 km from the path of the cyclone center. This is verified for the left side of the path along most of its length over land, as shown in Fig.15 and by the values at the end of Chapter II. Heavier rainfall failed to develop on the right side of the path except in the vicinity of Tallahassee, Florida, which was only 20 km from the path. Possible reasons for the development of heavier rain on the left side of the path than on the right side will now be

presented.

In southern Florida, the surface over which the hurricane was passing was not uniform. Although most of the surface was flat land, 100km to the left of the center was almost entirely a warm water surface. This water surface had two effects on the air: it offered less resistance to the development of a convective cell, and increased the temperature and dew point by about  $2^{\circ}\text{F}$  (Figs.1-12). Both of these effects favored a better development of convection at night over the water than over the land. Also the extreme SW coastline of Florida produced slight convergence between the stronger winds over the water and the lighter winds over the land.

In northern Florida and southwestern Georgia, none of the effects listed for southern Florida applied, because the left side of the hurricane was over land and the winds were off-shore. This might account for the small difference between the rainfall on the left and right sides of the path in this region.

In eastern Georgia and South Carolina, the path of heaviest rainfall was on the north side of the path, where the land surface had the highest elevation. The distinct break in the heavy rain belt (Fig.15) in the valley of the Savannah River, separating Georgia and South Carolina, indicates the importance of orographic lifting in releasing

the convection. Another factor was a surface temperature gradient which appeared in this region as a result of a weak cold front that had moved into the Carolinas and dissipated. The air in the northern part of the cyclone, which was about 5°F cooler than the air on the coast, must have acted as a wedge over which the warmer air ascended, even in the absence of any definite frontal surface. The slope of this wedge (with reference to the horizontal) must have been steeper than the slope of the ground.

From the indications above, it appears that the asymmetry of the precipitation pattern with respect to the cyclone path cannot be attributed to any single cause, but rather to a combination of effects. The peculiarity of the effects all combining to give the heaviest rain on the left side of the path would not be expected to happen in most tropical cyclones. This is verified by the fact that a hurricane usually has heavy rain on both sides of its path over a greater distance than was true of this storm.



REFERENCES

1. Bergeron, Tor. "On the Physics of Cloud and Precipitation." Reviewed in the Bulletin of the American Meteorological Society, v. 17, no. 2, Feb., 1936, pp. 43, 44.
2. Cline, I. M. Tropical Cyclones. Macmillan, 1926, (1) pp. 185, 186, 189, (2) p. 14.
3. Haurwitz, Bernhard. Dynamic Meteorology. McGraw, 1941, (1) p. 164, (2) p. 360, (3) p. 209.
4. Pierce, C. H. "The Meteorological History of the New England Hurricane of September 21, 1938." Monthly Weather Review, v. 67, no. 8, Aug., 1939, p. 241.
5. Shaw, Sir Napier. Manual of Meteorology, v. II. Cambridge, 1928, pp. 236, 238.
6. Tannehill, I. R. Hurricanes, Their Nature and History. Princeton, 1942, p. 87.
7. U. S. Dept. of Agriculture, Weather Bureau. Monthly Weather Review, v. 65, no. 10, Oct., 1937, pp. 372, 373.
8. U. S. Dept. of Commerce, Weather Bureau. Climatological Data, Florida Section. v. XLV, no. 10, Oct., 1941.
9. U. S. Dept. of Commerce, Weather Bureau. Climatological Data, West Indies and Caribbean Service. v. XXI, no. 10, Oct., 1941, p. 74.

10. U. S. Dept. of Commerce, Weather Bureau. Daily  
and Hourly Precipitation, Hydrologic Network,  
Southeast District. Oct., 1941.
11. U. S. Dept. of Commerce, Weather Bureau. Monthly  
Weather Review, v. 69, no. 10, Oct., 1941,  
Chart III.

ABSTRACT

In this thesis an attempt was made to account for the unusual rainfall distribution observed in the tropical hurricane of October 6th to 8th, 1941 in the southeastern part of the United States. Not only was the rainfall along the path of the center abnormally light, but also a belt of heavy rainfall was situated at an average distance of about 50 km to the left of the path. The New England hurricane of September 21, 1938 had a similar one-sided rainfall distribution, which was considered to be frontally produced. Such an explanation could not be used for the October, 1941 hurricane while it was in the subtropical regions of the Bahama Islands and Florida as a result of the absence of significant air mass contrasts there. In view of the high moisture content of the tropical air observed in this hurricane, the lightness of the rainfall could not have resulted from any abnormal dryness, but rather from insufficient horizontal convergence to establish large vertical currents.

The general synoptic conditions in the southeastern United States during the month of October, 1941 were abnormal in a number of respects. In spite of the occurrence of two tropical cyclones, the mean pressure

for the month was above normal over the entire region, as a result of persistent anticyclonic conditions and the absence of any extra-tropical cyclones. The rainfall associated with this condition was generally subnormal except in certain areas affected by one of the tropical cyclones. Also October, 1941 was the second warmest October on record for the region. The conditions aloft reflected the same abnormalities of high pressure and high temperature observed at the surface.

In response to the deep anticyclonic circulation, the hurricane moved farther west and north before recurving than usual for October cyclones. The anticyclone apparently prevented the hurricane from spreading out into a large-scale storm. The intensity of the hurricane oscillated, the tendency generally being for deepening over the ocean and filling over the land. An exception to this was the peculiar filling of the hurricane as it crossed the Bahamas, which is primarily a warm water surface.

The hurricane was characterized by nearly circular isobars while it was crossing southern Florida. The general pressure gradient associated with the high pressure area was found to be so weak compared with the gradient in the hurricane that it could not be detected within the hurricane itself. The winds corresponding to

the pressure fields of translation and rotation in a moving cyclone were found by solving the equations of motion. The solution showed that, in the absence of friction, the motion was the sum of the uniform translation and uniform rotation corresponding to each of these two pressure gradients separately. Since neither of these two motions has convergence or divergence, the convergence in most of the hurricane area must have been due to friction and have occurred within the frictional layer.

The formula for the average frictional convergence within a circle showed that it was proportional to the component of surface inflow and inversely proportional to the radius of the circle. The vertical velocity was found theoretically to be equal to the mean average convergence multiplied by the depth of the frictional layer. The precipitation rate was expressed as the product of the vertical transport of air and the difference between the specific humidities at the levels of inflow and outflow.

Computations by means of these formulas were made for circles with radii of 50, 100, and 135 km concentric with the hurricane center. The computed average hourly rainfall rates agreed very well with the observed amounts for 7-8 A.M. on October 6th within the 100 and 135 km circles, but did not agree within the 50 km circle

Due to the scarcity of reports within the smallest circle during this hour, the observed rate there was extended to include all hours of October 6th. A comparison showed that the computed average was about 4 times as great as the new observed average. The deficiency of rainfall in the 50 km circle and the correctness of the computed amount in the 100 km circle indicated that an excess of rainfall must have occurred in the zone between 50 and 100 km from the center.

This supposition was checked by a tabulation of the hourly rainfall amounts at stations within 50 km from the path of the center. The results of this tabulation showed that the heaviest rainfall rates of nearly .10 in./hr fell 2 hours before and 3 hours after the center passed. Since the center was moving at 30 km/hr, this put the heavy rain zone about 60 km ahead of the center and 90 km behind the center, in both cases within the 50-100 km zone.

The final phase of the study dealt with the belt of very heavy rainfall on the left side of the path. From the observed rainfall rate of about 1 in./hr on the Florida Keys, the computations were worked in reverse to find the inflow necessary to produce such precipitation. A mean inflow of 10 m/sec was found to be required if the layer of inflow extended through only

500 meters. However, since such a rapid inflow was not observed in the surface winds, it was concluded that the depth of inflow must have been much greater than 500 meters. This is reasonable in view of the fact that the very strong convection in this area, indicated by thunderstorms, must have required an inflow in excess of frictional leakage across the isobars. Also the convection carried frictional effects to higher levels. For inflow occurring through a depth of 3 km, the velocity required for the mean inflow was only about 2 m/sec, which would not be detected within the hurricane circulation.

In accordance with the zone of maximum hourly rainfall between 50 and 100 km from the center, the total rainfall during the passage of the hurricane was expected to be greatest at stations which remained in the 50-100 km zone the longest. It was apparent that this applied to stations 50 km from the path. This was verified by the location of the heavy rainfall belt on the left side of the path, but no corresponding rainy belt appeared on the right side. Conditions favoring the rainfall on the left side were listed as follows: (1) The presence of the ocean surface in reducing friction and raising the temperature and dew point and hence increasing the degree of convective instability, (2) on-shore convergence and orographic lifting over higher land, and (3) lifting of warm moist air over slightly cooler air.

BIOGRAPHICAL NOTE

Birth

New Haven, Conn. March 19, 1916

Education

Harvard College, 1933-37

Mass. Inst. of Tech., 1937-39, 1942-45

Teaching and Professional Experience

Part-time asst. observer and research asst., Blue Hill and Mt. Washington Observatories, Harvard University, summers of 1933-39

Research fellow at the Woods Hole Oceanographic Inst., summer of 1938

Asst. at radiosonde station and analyst of surface and upper air data at the Mass. Inst. of Tech., spring and summer of 1939

Map analyst, terminal forecaster at Pearl City, Hawaii, 1939-40, meteorology tutor at San Francisco, Cal., 1940; and meteorology instructor at Coral Gables, Fla., 1941-42 for Pan American Airways.

Instructor in Meteorology at Mass. Inst. of Tech., 1942-45

Publications

"Several Cloud Spouts". Monthly Weather Review, v. 59, no. 12, Dec., 1931, p. 482.

"Big Hail". Bulletin of the American Meteorological Society, v. 14, no. 6-7, June-July, 1933, p. 178.



"Climatic Maps of North America" (Folio of 26 maps).  
Harvard University, May, 1936 (minor joint author)

"Small Tornado at Silver Lake, N. H., July 17, 1937".  
Bulletin of the American Meteorological Society, v. 19,  
no. 2, Feb., 1938, p. 93.

"Transport and Convergence of the North Atlantic Drift  
Current computed from the Average January Pressure  
Distribution". Sears Foundation: Journal of Marine Research,  
v. II, no. 2, Nov. 15, 1939, pp. 163-167

"Simplification of the Acceleration Potential in an  
Isentropic Surface". Bulletin of the American Meteorological  
Society, v. 23, no. 5, May, 1942, pp. 195-203

#### ACKNOWLEDGMENTS

The author is very grateful to his advisers, Professor H. C. Willett, Professor B. Haurwitz, and Professor J. M. Austin, for their guidance in the development of the thesis. He also appreciates the assistance of Professor H. G. Houghton and other members of the Meteorology Department, and Professor C. F. Brooks of Harvard on different phases of the problem.

He is indebted to many of the Weather Bureau personnel for furnishing the meteorological data for the October, 1941 hurricane. In particular, he wants to thank Mr. H. C. S. Thom, the Chief of the Statistics Division; Mr. Glen Jefferson, Regional Director at Atlanta; Mr. W. J. Bennett, Meteorologist in Charge at Jacksonville; Mr. E. A. Carson, Assoc. Meteorologist at Miami; Mr. Grady Norton, Head Forecaster of the Special Hurricane Service at Miami; and Mr. R. L. Higgs, formerly at Miami.

He wishes to acknowledge additional information received from Mr. R. S. Bush, Eastern Division Meteorologist of Pan American Airways at Miami, Commodore H. M. Matheson at Miami, Mr. Otto I. Bergh at Miami, and Mr. E. G. Bice at the University of Chicago.

Final thanks go to Miss Dorothy Green and to Mrs. Sarah Brooks for help in putting the thesis in its final form.