THE HURRICANE SEASON OF 1966

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1. GENERAL SUMMARY

The 1966 hurricane season began early and ended late. While the number of storms was only slightly above normal, hurricane days totalled 50, well above the yearly average of 33 and the second highest of record tabulated since 1954 (table 1). Hurricane days for June and November exceeded the previous 12-year totals. Except for a late May–early June hurricane in 1825, Alma, the first tropical cyclone of the 1966 season, made landfall in the United States earlier in the season than any other hurricane of record. Faith and Inez were tracked over very long distances (fig. 1). The 65 advisories on Inez were the most ever issued for a hurricane and the total of 151 bulletins and advisories also exceeded previous advices on a hurricane. The unusual path of Inez made her the first single storm of record to affect the West Indies, the Bahamas, Florida, and Mexico. She was also the first of record, so late in the season, to cross the entire Gulf of Mexico without recurvature.

The season continued active through July. Since 1871, there have been only three other years when the fifth tropical cyclone developed as early as July. These were 1933 (fifth tropical cyclone on July 25, total of 21 cyclones), 1936 (July 27, 16 cyclones), and 1959 (July 22, 11 cyclones).

According to Wagner [14], the June 700-mb. heights were below normal over the southeastern Gulf of Mexico and the western Caribbean and above normal from the Great Lakes eastward into the central Atlantic. This pattern corresponded fairly well to Ballenzweig's [2] composite charts for maximum tropical cyclone incidence for North America. Hurricane Alma and a tropical depression formed in the northwestern Caribbean during the month. There were four tropical cyclones in July, but circulation patterns, as depicted by Posey [8], were not considered ideal or favorable for such an active month. The anomaly charts by Andrews [1] show that the unfavorable circulation persisted in August, when only one hurricane formed. The westerlies dipped far southward in the United States in September (Green [4]), but in spite of this, there were four tropical cyclone developments. However, considering the intensity and areas of development, the September activity, in relationship to the mean circulation, was probably not unusual. Stark [11] reports that monthly height anomaly changes over the United States were slight in October and this implies no significant shift of the westerlies from September to October. No tropical storms developed in October and there was only one in November, well below the average for the two months. In summary, it would seem that the general circulation features corresponded fairly well with the monthly frequency of tropical cyclone development for the beginning (June) and end (October and November) of the 1966 hurricane season. The correlation was poorest during the months of July and September, the two months with the highest frequency.

There were fewer casualties in the United States in all of 1966 than in hurricane Betsy of 1965, even though there were two hurricanes which made landfall. Alma and Inez were less intense (during landfall) than Betsy and this accounts for the difference. Also, 45 of the 54 deaths in 1966 occurred in a single marine accident—Cuban refugees attempting to cross the Florida Straits. Damages in the United States from Alma and Inez do not compare with losses from other hurricanes of past years. Contributing factors to the relatively low figures were the relatively minor storm surges in Inez and the fact that the surges in Alma affected a relatively sparsely populated area. Sugg [13] (in this issue) has estimated the damage attributed to Betsy of 1965 and has listed

TABLE 1.—*Hurricane days*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1954	----	----	----	----	----	1	----	5	8	16	----	1	31
1955	4	----	----	----	----	----	----	22	28	2	----	----	56
1956	----	----	----	----	----	----	1	9	2	----	3	----	15
1957	----	----	----	----	----	3	----	----	19	----	----	----	22
1958	----	----	----	----	----	----	----	14	16	5	----	----	35
1959	----	----	----	----	----	1	2	----	10	11	----	----	24
1960	----	----	----	----	----	----	4	2	13	----	----	----	19
1961	----	----	----	----	----	----	4	----	*35	9	1	----	49
1962	----	----	----	----	----	----	----	1	----	10	----	----	11
1963	----	----	----	----	----	----	----	11	7	23	----	----	41
1964	----	----	----	----	----	----	----	7	33	6	----	----	46
1965	----	----	----	----	----	----	----	6	*21	3	----	----	30
1966	----	----	----	----	----	7	8	9	11	10	5	----	50
Total	4	----	----	----	----	12	19	86	203	95	9	1	429

*If two hurricanes are in existence on one day, this is counted as two hurricane days.

*Portions of this article are based upon individual storm accounts or official tracks prepared by G. B. Clark, G. E. Dunn, P. J. Hebert, E. C. Hill, R. H. Kraft, P. L. Moore, J. M. Pelissier, J. G. Taylor, and C. W. Wise of the Miami Weather Bureau office. Other contributors were W. C. Connor of the New Orleans Weather Bureau office; J. A. Colón and H. Hoose of the San Juan Weather Bureau office; and R. C. Schmidt and E. W. Hoover of the Washington Weather Bureau office.

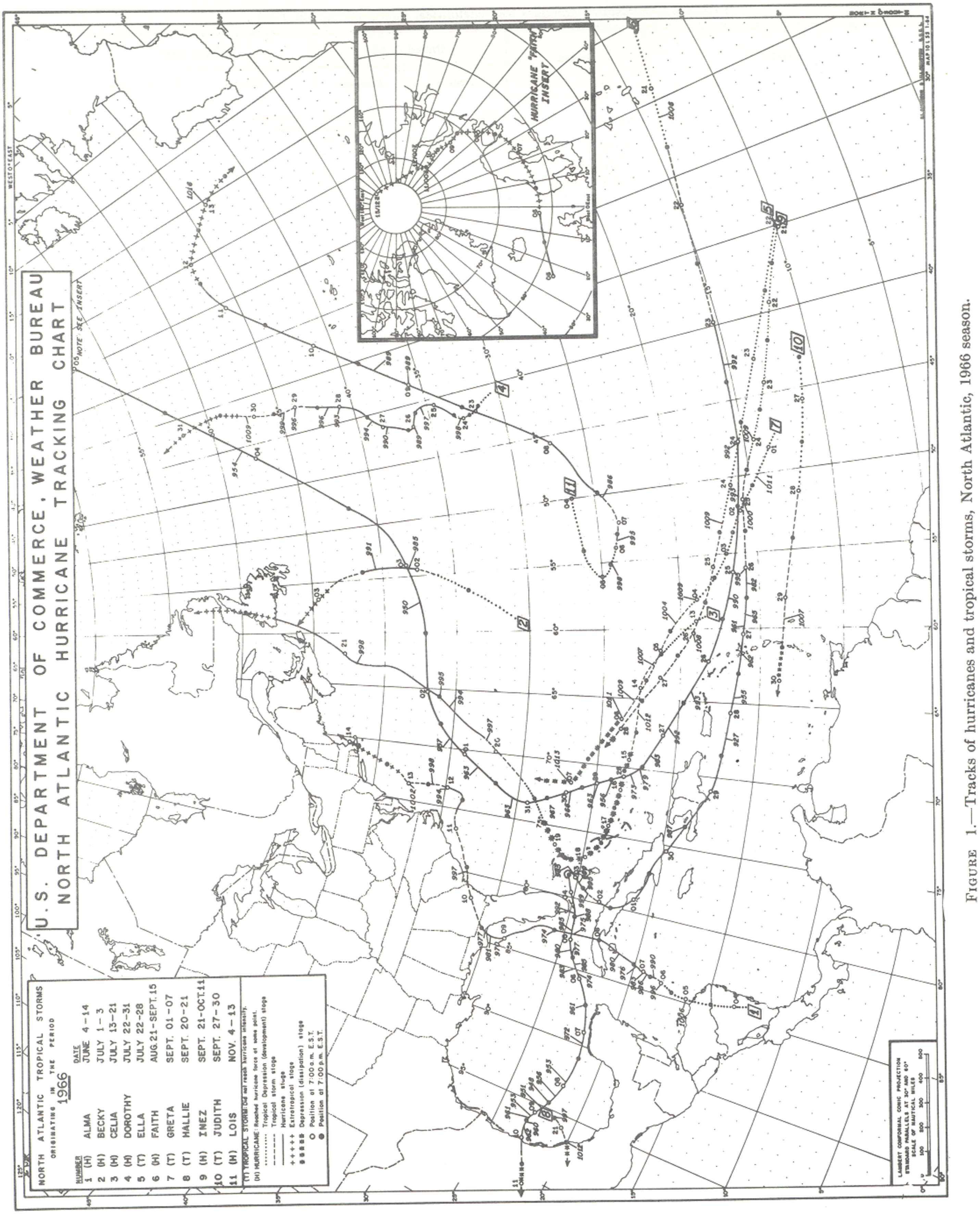

FIGURE 1.—Tracks of hurricanes and tropical storms, North Atlantic, 1966 season.

TABLE 2.—*Estimated damages and casualties, hurricane season 1966*

Date	Storm	United States		Other areas	
		Deaths	Damages	Deaths	Damages
June 4–14	Alma H	Fla. 6	$10,000,000	Honduras 73	Unknown
		Ga. 0	50,000	Cuba 11	$200,000,000
June 30–July 2	TD	0	100,000	0	0
July 1–3	Becky H	0	0	0	0
July 13–21	Celia H	0	0	0	0
July 22–31	Dorothy H	0	0	0	0
July 22–28	Ella T	0	0	0	0
July 24–27	TD	0	0	0	0
Aug. 21–Sept. 15	Faith H	0	0	4	0
Sept. 1–7	Greta T	0	0	0	0
Sept. 20–21	Hallie T	0	0	0	0
Sept. 21–Oct. 11	Inez H	Fla. 3	5,000,000	Mexico 65	100,000,000
		Fla. Straits 45	0	Dominican Rep. 100	12,000,000
				Guadeloupe 27	50,000,000
				Haiti 750	20,000,000
				Cuba 5	20,000,000
				Bahamas 5	15,500,000
Sept. 27–30	Judith T	0	0	0	0
Nov. 4–13	Lois H	0	0	0	0
Total	4(T) 7(H) 2(TD)	54	15,150,000	1,040	417,500,000

H=hurricane. T=tropical storm. TD=tropical depression.

other damage figures for selected hurricanes of recent years. The reader is referred to that paper for comparative damage figures and to table 2 of this paper for a breakdown of casualty and damage figures for the 1966 season.

The first sounding within the eye of a hurricane was taken at Tampa, Fla., on October 19, 1944 at 1030 GMT and was analyzed by Riehl [9]. One of his main conclusions was that the tropopause was higher above the eye than over the surrounding area. A more detailed analysis was made by Simpson [10] on a second eye sounding, also made at Tampa, on October 8, 1946 at 0600 GMT. Although tropopause data were lacking, Simpson found other features virtually identical with the sounding taken in 1944. A third sounding in an eye was made on August 9, 1963 at 1600 GMT as hurricane Arlene moved over Bermuda. According to Stear [12], there was a definite rise in the height of the tropopause over the eye. There were other features which were in good agreement with Riehl's model of a mature hurricane. Figure 2 gives a plot of the Inez eye sounding made at Boca Chica, Fla. on October 5, 1955 at 0200 GMT; also shown are the hurricane Arlene eye sounding, the one taken at Tampa in 1946, and a plot giving Jordan's [5] mean eye sounding, from dropsonde data, for hurricanes of moderate intensity. Since tropopause heights before and after the eye sounding (not shown, but 108 and 110 mb., respectively) were higher than the last point observed on the Inez eye observation, no conclusion can be drawn about how the tropopause height varied as Inez approached and moved over Boca Chica.

2. INDIVIDUAL HURRICANES

HURRICANE ALMA, JUNE 4–14.—During the early days of June, a trough in the westerlies moved across the southeastern United States and extended deep into the Tropics. That portion from about Florida northward fractured from the southern extremity, leaving a closed Low near Cape Gracias on June 3. The circulation developed downward from the middle troposphere to the surface over Nicaragua and Honduras on the morning of the 4th. At this point it was recognized that there was a definite threat of intensification, and air reconnaissance was scheduled for the following day. On the morning of the 5th, the plane found a tropical depression of 1006 mb. (29.71 in.) over the Gulf of Honduras.

Heavy rains had been occuring over Central America (mainly in Nicaragua, Honduras, and Swan Island) for several days. On the night of June 5, the town of San Rafael, Honduras, reported 30.00 in. of rain, resulting in 73 deaths—the town was virtually destroyed. It is quite possible that this was a rather local rain-burst and was probably on the periphery of the circulation. Nonetheless, it probably would not have occurred had the synoptic feature not existed and for this reason the heavy rains and subsequent tragedy should be attributed to Alma.

By June 6, Alma had intensified to hurricane strength. The rather rapid intensification can be attributed to a number of things including the well developed and deep circulation, the warm waters, abundant rainfall, and a good outflow in the higher atmosphere. Even though the trough at 500 mb. had moved eastward into the Atlantic, there remained a good southwesterly jet at 200 mb. from the Yucatan Channel across western Cuba and southern Florida. It appears that the jet provided the necessary outflow mechanism and was most important in the deepening process.

Alma moved slowly during June 7 but was accelerating and threatening western Cuba by early morning of the 8th. The hurricane passed over the Isle of Pines, and winds reached 110 m.p.h. at the Institute of Meteorology in Havana. The barometer fell to 979.7 mb. (28.93 in.) in Havana. Considerable structural damage and loss of crops were incurred over western Cuba.

The hurricane passed between Dry Tortugas and Key West, and damage to the lower Keys was estimated at one-third million dollars. The pressure was 970.2 mb. (28.65 in.) at Dry Tortugas. This was the lowest baro-

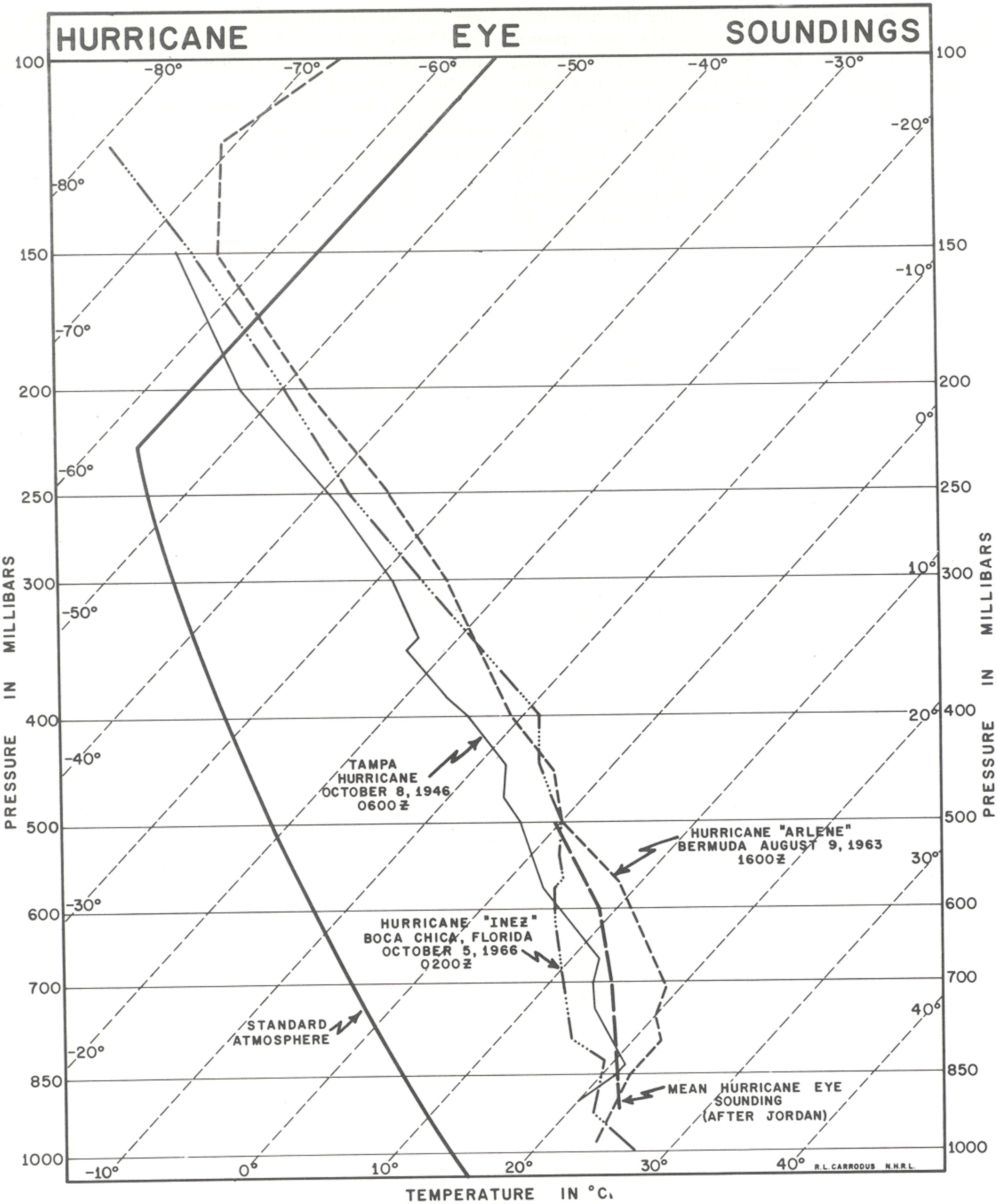

FIGURE 2.—Soundings made within the hurricane eye.

metric reading at a land station during the hurricane's history. Air reconnaissance reported the same pressure over water in the northeastern Gulf of Mexico the next morning; however, some weakening occurred just before landfall in the Apalachee Bay area. The highest wind speed, 125 m.p.h., was also recorded at Dry Tortugas.

Alma's track through the eastern Gulf of Mexico was generally a little west of due north and is explained by the formation of an upper cyclone in the extreme northern Gulf. The steering around this cyclone directed the hurricane into a slight turn away from the Tampa Bay area and allowed the center to move almost parallel to the Florida west coast. This event was not entirely unanticipated since it was reflected in the early morning forecast of June 8.

Although sea surface temperature data were not plentiful, those that were recorded in the Gulf during the hurricane indicate that Alma did not seek out the warmest waters. Temperatures in the Lower Keys ranged from 3° to 7° F. lower than those off Miami Beach and those reported in the vicinity of 25° N., 84° W.

Hurricane force winds decreased to gales over northern

TABLE 3.—*Hurricane Alma, Meteorological Data, June 4–13, 1966*

Station	Date	Pressure (in.)		Wind (miles per hour)				Highest tide (ft.)	Date/time	Storm rainfall
		Low	Time (EST)	Fastest mile	Time	Gusts	Time			
CENTRAL AMERICA										
San Rafael, Honduras										30.00
CUBA										
Institute of Meteorology, Havana	8	28.93				SE 110	0715			
UNITED STATES										
FLORIDA										
Key West	8	29.42	1255	SE 60		SE 70	1231	3.5 MLW		3.56
Boca Chica						89				
Dry Tortugas	8	28.65	1315	N 125	1322					
Tavernier	8	29.74	1555	SSE 60*	1530			1.0 AN		3.59
Miami (WBAS)	8	29.73	1730	E 55	1200					7.70
Miami (NHC)	8	29.75	1730			E 61	1225	2.7 MLW		7.65
West Palm Beach (WBAS)	8	29.76	09/0256	E 39	1527	ESE 52	1830			5.18
Everglades City								2.2 MLW		2.48
Jupiter						75				
Fort Myers (WBAS)	8	29.46	1955	ESE 46	1915	ESE 64	2040			2.36
Fort Myers Beach	8	29.45	2000	55*		80*		5.0 MLW		
Punta Gorda	8	29.43				88	2200	1.5 AN		
Punta Rasso	8	29.45	2000							
Captiva	8	29.30	2000							3.56
Corkscrew Fire Tower										4.75
Fory Myers, Gulf Oil						85		2.5 AN		
Fort Myers, NASA	8					73	2215			
Treasure Island	8	29.53	09/0240	82	2345	92*	09/0000	2.9 AN		5.10
St. Petersburg (Coquina)	8	29.37	2230	SE 65		SE 95	2330	3.5 AN		4.22
Tampa (WBAS)	9	29.42	0140	ESE 46	0057	E 68	08/2354	3–5 AN		3.38
Tampa Marina						90				
New Port Richey								7–10 AN		
Bayport	9	29.51	0430					4.5 AN		3.46
Red Level								7.5 MLW		2.36
Cedar Key	9	29.47	0600					7–10 AN		
Apalachicola	9	29.34	1300	N 42	0802	N 52	0835			3.78
Tallahassee	9	29.15	1745	NE 44	1510	NE 62	1657			6.90
Pensacola (WBAS)	9	29.76	1630C	N 36	1224C			0.5 MLW		0.01
Pensacola (NAS)	9					N 42	1350C			
Eglin Field	9					N 48	1115C			.29
Tyndall Field	9					NW 46	1500C			.41
Alligator Point	9	29.06	1425	75		90		1.8 AN		
St. Marks**	9	29.00	1600			NE 50	1500	6.0 MLW		
Shell Point								3.0 AN		
Crawfordsville	9					NNE 100*	1400			
Orlando	9	29.67	0308	E 38	08/2304	E 53	08/2210			2.20
Daytona Beach	9	29.67	0250	E 37	0259	E 55	0132			3.29
Lakeland	9	29.56	0215	NE 34	08/2116	E 45	08/2000			1.97
Gainesville	9	29.65	0425	S 25	1458	SE 48	0425			2.97
Jacksonville (WBAS)	10	29.63	0300	E 48	09/0550	E 48	09/0550	2–3 AN		1.40
GEORGIA										
Savannah	10	29.50	1115	E 29	09/1338	SE 44	09/1958	2.4		2.18
SOUTH CAROLINA										
Charleston (WBAS)	10	29.52	1700	29	0642	S 46	0637	5.5 MLW		2.07
Charleston Custom House	10	29.55	1715	29	0800					1.49
Edisto Beach						65				
Columbia (WBAS)	10	29.67	1700			N 25				2.32
NORTH CAROLINA										
Wilmington	11	29.55	0145	N 35	0553	NNE 48	0558	2.0 AN		7.80
Carolina Beach						60				
Cape Hatteras	11	29.68	1345	NNE 43	1019	NNE 62	1122			5.10
New Bern								5.0 AN		2.37
VIRGINIA										
Norfolk	13	29.97	0215	E 35	11/1043	N 39	12/1340	4.0 MLW		.07
Cape Henry	12			N 40	12/0636					
NEW JERSEY										
Atlantic City	13	29.97		N 17	1124	NE 26	0046	4.5 MLW	12/1600	.14

*Estimated. **Eye passage 1605. MLW Mean Low Water. AN Above Normal.

Florida and southern Georgia but the storm regained hurricane status for about 18 hours off Cape Hatteras. Cold waters north of this area and colder and drier air from the mainland finally reduced Alma to an extratropical storm about midday on the 13th.

Hurricane warnings were displayed in the Florida Keys and along the Florida west coast to Apalachicola in plenty of time for adequate preparation against winds and tides. Interests in western Cuba were advised to take necessary precautions against the hurricane 24 hours prior to the onset of high winds.

Besides the structural damage in the Lower Keys and in West Florida, the mango crop in the southwestern portion of the State and the grapefruit crop around Pinellas County were hard hit. The wind caused considerable damage to tobacco in northern Florida. Tides were variable on the west coast, ranging up to 10 ft. above normal. Highest were in the New Port Richey, Red Level (near Crystal River), and Cedar Key areas. A large portion of Cedar Key was inundated.

There were nine tornadoes associated with the hurricane although some of these must be considered only funnel clouds or waterspouts. There were two in Miami, three in Sarasota, one in Jacksonville, two in Marianna (all in Florida), and one on the Island of Cayman Brac, south of Cuba. No deaths are attributed to the tornadoes nor was there any good evidence of any significant amount of damage along the tornado paths. Heart attacks (2), drownings (2), and electrocutions (2) were the causes of the deaths in Florida.

Even though the path of hurricane Alma, during the most critical times, was fairly straight, the forecasting problems were not easy. For one thing, high-level steering would have taken the hurricane northeastward from western Cuba; this would have presented a considerably different warning situation than that which materialized. It is not known why Alma did not follow the high-level southwesterlies over southern Florida but did appear to react later to the circulation of the high-level cyclone in the extreme northern Gulf. Secondly, the eye was large, ragged, and ill-defined, and seemed to be constantly changing shape. Not only is this difficult for the radar observer but makes the short-term forecasting anything but easy, especially with the center so close to land. For the most part, the eye was from 30 to 65 n. mi. in diameter and there was considerable evidence of some slope in the vertical. This was noticed in the Gulf as well as along the Georgia and South Carolina coasts. Thirdly, a path parallel to a coastline always presents problems, particularly in storm surge estimates and evacuation advices. See table 3 for pertinent meteorological data.

TROPICAL DEPRESSION, JUNE 30–JULY 2.—A weak tropical depression formed over the northwestern Caribbean Sea on June 28. During the succeeding four days it moved slowly northward, crossed Cuba, passed along the west coast of Florida and moved inland near Cross City, then turned northeastward and finally dissipated over southeastern Georgia late on July 2. Winds associated with this depression did not reach tropical storm speeds. However, the storm attracted considerable attention because its track closely followed that of hurricane Alma, the tropical cyclone which had preceded it by about three weeks.

Throughout the life of this depression its center remained poorly defined; radar reports showed no evidence of an eye or a wall cloud formation. Its closed cyclonic wind circulation extended outward about 200 mi. from the main center of rotation. Around the outer periphery of the cyclone the wind field was well organized, at least in the northeastern semicircle, with speeds of 10 to 20 m.p.h. Within the central area, winds were very light and two or more smaller cyclones were evident in both wind and pressure fields. Except for a few hours during its passage across Cuba, the northeasternmost of these subcyclones appeared to be the dominant one. Its rate of movement was approximately 8 m.p.h., except during a 6-hour period when it remained almost stationary near St. Petersburg.

Winds associated with this depression were generally less than 25 m.p.h., except in brief squalls. However, an apparent tornado touched down at Palm Beach Airport and destroyed two aircraft. Another tornado was reported near Vero Beach and heavy thundershowers occurred over most of Florida and the southern parts of Georgia and Alabama. During the passage of the depression approximately 10 in. of rain were recorded at Everglades City, near the southern tip of the Florida peninsula, and at Jacksonville; but 2 to 4 in. were more representative for most parts of Florida.

Roadway damage in the Jacksonville area was estimated at $50,000. However, there were some compensating factors in other areas. Beneficial rains fell in South Carolina.

Since this cyclone and the one which intensified and became hurricane Alma both formed in the same region during the same month and followed almost identical tracks, they might provide valuable material for a case study on the mechanics of tropical storm development.

HURRICANE BECKY, JULY 1–3.—Becky developed at an unusually high latitude. The initial depression appeared some 300 miles southeast of Bermuda on July 1. A cloud area photographed by the ESSA 2 satellite at about 1200 GMT on that date showed evidence of a spiral structure near the incipient storm. The system moved northeastward under an upper-level trough and intensified to storm intensity by early the next day. At 1545 GMT the M. S. *Johannes Russ* (log received later) passed through the center and observed a minimum pressure of 985 mb. (29.09 in.). The ship experienced winds of hurricane force for about one-half hour.

On July 3 the hurricane began to move northwestward under the influence of a cold Low which formed in the upper trough. As it moved over the colder waters south of Newfoundland it rapidly weakened and lost its tropical characteristics.

Becky did not strike any land area and there were no reported casualties or losses to shipping.

HURRICANE CELIA, JULY 13–21.—Celia formed some 200 mi. northeast of the Leeward Islands on July 13. Ship reports indicated winds up to 40 m.p.h. and evidence of a circulation center near 19° N., 59.5° W. at 1200 GMT. There had been earlier indications of disturbed weather in the area near and to the east and southeast of this point, but no history of a well-defined easterly wave or other synoptic feature. On the afternoon of the 13th, reconnaissance aircraft located a poorly defined cloud eye 40 mi. in diameter with maximum winds of 46 m.p.h. The storm moved first toward the northwest, then on a west-northwesterly course with little change in intensity through July 14. The following morning, reconnaissance data indicated that Celia had degenerated into an area of showers with winds less than 35 m.p.h. There were no significant effects in the Lesser Antilles during the passage of the storm to the north.

Five days later, Celia developed on the southwestern edge of a cloud mass some 3° in diameter as indicated by ESSA 2 and Nimbus satellite photographs. This cloud area had persisted although without evidence of a storm circulation, after Celia's dissipation on July 15. The area could be followed, along with a minor perturbation in the low-level flow, to the vicinity of the northwestern Bahamas and then northeastward on the 19th. At 0100 GMT, July 20, a ship located under the southwestern edge of this cloud mass reported squalls to 43 m.p.h. Intensification proceeded rapidly, and when reconnaissance aircraft reached the area early on the morning of July 20, winds of 80 m.p.h. and a central pressure of 997 mb. (29.44 in.) were observed. The hurricane maintained this intensity as it raced north-northeastward at forward speeds up to 45 m.p.h. in advance of a frontal trough moving off the eastern coast of the United States. Celia finally began to weaken and lose tropical characteristics just before reaching western Newfoundland where it moved inland on the afternoon of July 21, accompanied by squalls of 45 m.p.h., then continued northward to merge with the frontal system over Labrador.

No casualties or damages were reported in connection with Celia.

HURRICANE DOROTHY, JULY 22–31.—Dorothy developed as a tropical storm near 32° N., 42° W. on July 23. Several ships in the area reported heavy rain and rough seas with winds as high as 58 m.p.h. A photograph from the ESSA 1 satellite revealed a dramatic spiral cloud pattern on this date where only a small isolated area of clouds with no apparent circulation existed on the previous day.

Dorothy remained quasi-stationary for the next two days and intensified to hurricane strength late on the 24th. Finally the storm commenced a north-northeastward course on July 25.

The lowest recorded pressure, 989 mb. (29.20 in.), was attained at 1200 GMT on July 26. Dorothy's course continued primarily northward with small east-west oscillations.

On the 27th the track became more northeastward as the storm attained its maximum forward speed, about 15 m.p.h. As Dorothy progressed farther north and passed over progressively colder water its strength gradually diminished. Finally, early on the 29th the hurricane decreased to tropical storm intensity. At this time its course was influenced by the circulation around a massive cyclone which was moving eastward off the northeastern coast of the United States. Thus, on the 30th, its northward speed increased and on the 31st, as the storm turned toward the northwest, it lost its tropical characteristics. The closest point the storm track came to land was about 400 mi. west of the western Azores. A more detailed and complete analysis of the development of hurricane Dorothy is given by Erickson [3] in this issue.

TROPICAL STORM ELLA, JULY 22–28.—Satellite pictures taken on July 22 and 23 appear to provide the best continuity prior to the discovery of a large calm area noted by aircraft reconnaissance on the 24th. Since data were sparse during these three days, one can only say that development was slow and not unusual. Reconnaissance on the 25th and 26th indicated surface pressures no lower than 1008 mb. (29.77 in.). There was no visual cloud eye and organization was generally very poor. Indeed, at times, the system resembled a strong decelerating easterly wave. There were never any good low-level inflow or high-level outflow patterns, and temperatures and temperature trends never really favored intensification. Ella dissipated east of the Bahamas on the 28th. No loss of life or damage can be attributed to the storm.

TROPICAL DEPRESSION, JULY 24–27.—A weak tropical low moved west-northwestward across the Florida Peninsula and into the extreme northeastern Gulf of Mexico on July 24. By noon of the 25th, the rain pattern on coastal radars indicated a fairly well organized circulation. The Low crossed the southeastern Louisiana coast near Boothville about 0600 GMT on the 26th and continued very slowly westward, losing its identity in south-central Louisiana during the morning of the 27th.

Heavy thunderstorms accompanied the Low along the southeastern Louisiana coastal area as the center moved inland. Satellite and radar pictures, taken while the center was near New Orleans, showed good similarity in the weather bands associated with it. Fishing activities were curtailed but no damages were reported.

HURRICANE FAITH, AUGUST 21–SEPTEMBER 15.—Faith maintained hurricane intensity for a period of 15 days while traveling a circuitous route around the southern, western, and northern periphery of the Bermuda high pressure system. With the advantages of hindsight, the system can be tracked in embryonic form from a position over Africa, near 8° N., 5° W., on August 18. At that time, there was only a poorly defined depression and a circular cloud mass as depicted by a TIROS IX photograph.

The insert map on figure 1 indicates an extension of the track[1] into the Arctic Ocean. The entire track of Faith represents one of the longest, if not the longest, hurricane track of record.

Highest winds in Faith, while in the southwestern North Atlantic, were estimated at 120 m.p.h. The lowest pressure recorded during the hurricane's life history was 950 mb. (28.05 in.). The center of the hurricane passed within 25 mi. of St. Maarten, Leeward Islands. There were gale force winds in the northern islands of the Leewards, the Virgin Islands, and along the northern coast of Puerto Rico, but there was only minor damage reported.

Prior to reaching Scandinavia, Faith passed over the Faeroe Islands. There was no known loss of life on the Islands or in Scandinavia and only minor damage was reported, similar to the usual autumn storms.

One crewman lost his life when high seas battered the *Alberto Benati* in the western Atlantic, one person was missing and assumed drowned while abandoning a Norwegian ferryboat off the coast of Denmark, and two men were lost attempting to cross the Atlantic in a rowboat.

TROPICAL STORM GRETA, SEPTEMBER 1–7.—The circulation which developed into Greta was first indicated by the weather report from the SS *San Marcial* and a cloud mass photographed by the Nimbus 2 satellite some 600 mi. east of Barbados on September 1. Air Force reconnaissance aircraft investigated the area the same day and found a circulation and an area of showers but no strong winds. The depression remained weak with maximum winds of about 35 m.p,h. as it moved northwestward during the next two days. Moderate intensification occurred on September 4 and Navy reconnaissance aircraft reports indicated maximum surface winds of 58 m.p.h. and a central pressure of 1004 mb. (29.65 in.), the lowest reported during the life of the storm. However, by the next day, the trend had reversed and reconnaissance aircraft reported that Greta was very poorly organized. Highest reported surface winds were only about 35 m.p.h. in a few squalls. The system became even weaker as it continued northwestward to a point some 300 mi. northeast of the central Bahamas on September 7 and then turned northward. The cloud area associated with the dying surface circulation remained identifiable in satellite photographs through September 8 when it merged with a prefrontal cloud mass between the United States east coast and Bermuda.

The intensity changes in Greta presented difficult forecasting problems. The storm acquired a warm core and wall cloud in a climatologically favored area for hurricane development, yet failed to progress beyond the storm stage. On September 4, when the most active intensification occurred, the center had moved out from beneath an upper-tropospheric trough and under the southern portion of an upper-level anticyclone, a favorable factor for intensification from an empirical standpoint. In addition, at this point, a trough extending southward from hurricane Faith to the area north of Greta had receded, allowing the surface ridge to build and providing another favorable indication. However, the deepening failed to persist, and within 24 hours after reaching its maximum intensity, the system had weakened to a minor depression. A dropsonde at 0530 GMT, September 6, showed that the temperature in the center of the storm from the surface to above the 800-mb. level was about 2° C. higher than the average for a weak hurricane and there was no front or source of cool or dry air in the vicinity. A possible clue to the weakening is the fact that the current in which the vortex was embedded was basically divergent. Surface wind reports indicated that there was no low-level inflow. Outflow apparently prevailed in the area of the depression during this period. It is interesting that both Celia and Ella lost tropical storm intensity in the same general area in July.

Tropical Storm Greta did not affect any land area and resulted in no casualties or property losses.

TROPICAL STORM HALLIE, SEPTEMBER 20–21.—A tropical depression located just to the south of a weakening stationary front in the extreme southwestern Gulf of Mexico developed into tropical storm Hallie on September 20. On the previous two days, ESSA 2 satellite photographs indicated a large disorganized cloud mass in the southwestern Gulf merging into a frontal cloud band extending to the northeast. Early on the 20th, shower activity along the Mexican coast from Tampico southward increased as a cut-off surface Low developed off the coast. At about the same time, satellite pictures revealed that the cloud pattern in the area was becoming dissociated from that of the front and showed evidence of a developing circulation.

On the afternoon of the 20th, Navy reconnaissance reported that the central pressure had fallen to 997 mb. (29.44 in.) and that winds were 50 m.p.h.

After remaining nearly stationary during this intensifying process, Hallie commenced a southwestward drift during the night. The Mexican coastal town of Nautla experienced gusts to 40 m.p.h. with heavy rain during the early morning hours and the pressure fell to 1002.4 mb. (29.60 in.) at 1300 GMT September 21.

As the storm entered the coast, relatively cool, dry air was introduced, and this, together with the frictional effect of the coastal hills, caused the storm to weaken rapidly. By 1600 GMT the pressure at Nautla had risen to 1010.5 mb. (29.84 in.) and the wind and rain had subsided. Although the satellite photograph at 1522 GMT showed fairly good organization of the clouds, a reconnaissance flight could find little evidence of circulation.

There were no reports of damage or loss of life from the storm.

HURRICANE INEZ, SEPTEMBER 21–OCTOBER 11.—Inez originated as a weak tropical depression moving off the west coast of Africa on the morning of September 18. Genesis was determined on the basis of sparse land and ship reports and an ESSA 2 satellite photograph. For

[1] Based upon communication with Dr. Olov Lönnqvist of the Swedish Meteorological Service.

the next three days the associated cloud mass was tracked west-southwestward with the aid of satellite pictures until the morning of the 21st at which time the cloud mass was centered near 10° N., 35° W. No satellite or ship information was received during the next 48 hours but on the morning of the 23d ESSA 2 and the Nimbus satellite pictures showed that the depression had moved west-northwestward to approximately 13° N., 45° W. A reconnaissance aircraft was able to reach the area on the morning of the 24th and found that only slight intensification had taken place during the six days. By afternoon, significant intensification appeared underway and the first advisory on tropical storm Inez, located about 800 mi. east of Martinique in the French West Indies, was issued.

After reaching tropical storm intensity Inez took a more westerly course at a somewhat slower forward speed and continued to intensify until the morning of the 26th when hurricane intensity was attained about 330 mi. east of Guadeloupe in the French West Indies. Inez continued on a west to west-northwestward course while intensifying rapidly. This rather rapid intensification that occurred after Inez turned west-northwestward on the southwestern periphery of the subtropical high pressure ridge is in good agreement with climatology and studies by Miller [7] and others on intensification.

The center of the hurricane moved almost directly over Guadeloupe during the early afternoon of the 27th; winds of 80 m.p.h. were reported on the island before communications failed. Reconnaissance aircraft during the morning, however, had reported a central pressure of 961 mb. (28.38 in.) and maximum winds of 120 m.p.h. Inez was a small storm at this time with hurricane force winds extending outward only 50 mi. from the center. The central pressure increased to 970 mb. (28.64 in.) after the hurricane had passed over the Guadeloupe Islands where the contact between the circulation and the ocean surface was partially lost.

As the center moved westward into the eastern Caribbean Sea, Inez resumed intensification and by late afternoon on the 28th reached its lowest observed sea level pressure of 927 mb. (27.38 in.). Maximum surface winds were estimated to be 150 to 175 m.p.h. near the center. ESSA Research Flight Facility aircraft measured winds of 197 m.p.h. at 8,000 ft., the highest speed ever recorded by the research aircraft. At this time the center was located about 160 mi. southwest of San Juan, Puerto Rico and 170 mi. southeast of Santo Domingo, Dominican Republic moving west about 16 m.p.h. The great danger to the Barahona Peninsula of the Dominican Republic and to southern Haiti was emphasized in the hurricane advisories.

The hurricane was under continuous surveillance by land-based radar in Puerto Rico, with the eye visible for 23 hours from 9:45 a.m. AST on the 27th to 8:45 a.m. AST on the 28th. This was mentioned frequently in advisories and bulletins in order to relieve uneasiness about any sudden change in course of this small but severe hurricane.

Inez struck the Barahona Peninsula of the Dominican Republic shortly before noon AST on the 29th and continued west-northwestward across the southwestern peninsula of Haiti between 2 p.m. and 4 p.m. AST. The eye entered at a point east of Jacmel on the southern coast of Haiti and emerged near Leogane on the northern coast. Reconnaissance aircraft found a central pressure of 987 mb. (29.15 in.) just west of Port au Prince, Haiti on the evening of the 29th. This was a rise of 60 mb. or 1.80 in. from the value reported just before the eye struck the Barahona Peninsula.

After leaving Haiti, Inez continued northwestward toward eastern Cuba and struck Guantanamo City, a short distance west of Guantanamo Bay, on the morning of the 30th. Winds of 138 m.p.h. were reported as the center moved ashore. Therefore, rather rapid reintensification must have taken place over the Windward Passage.

Forecasting the future path of the hurricane became a real challenge as Inez moved over Cuba. The hurricane was influenced by the terrain of the island as well as by the synoptic steering currents. It appeared that Inez would recurve northwestward over eastern Cuba and then continue northward east of the United States mainland by breaking through a weakness in a high pressure ridge aloft to the north of the storm. The center of the storm became disorganized over the rugged terrain, however, and the weak steering currents were not sufficient to allow the eye to cross Cuba. Instead, it reorganized along the southern coast and moved slowly west-northwestward for about 36 hours, entering central Cuba just about due south of Miami. A slow northward movement of about 5 m.p.h. brought the center across central Cuba where it briefly lost hurricane force. Slow intensification occurred as Inez moved north-northeastward into the western Bahamas on the night of October 2 and morning of the 3d. A small tornado occurred in Nassau, Bahamas, on the 2d killing a 15-month-old child. This was the only tornado reported during Inez. Nassau had a peak gust of 64 m.p.h. and recorded nearly 15 in. of rain in the three-day period October 2–4. Although Nassau did not receive hurricane force winds as a part of the strong winds near the center of Inez, an anemometer in the vicinity of the tornado showed a rapid increase to over 100 m.p.h. in 10–15 sec. as the tornado approached. The highest wind reported in the Bahamas was 90 m.p.h. at West End, Grand Bahama.

At this time the location of the center of Inez was in close proximity to the position originally anticipated and forecast for it after recurvature. The delay of approximately 24 hours caused by the reorganization of the eye along the southern coast of Cuba had allowed the weak pressure ridge to the north to build. This came about by the extension northeastward of the warm upper-level anticyclone in the western Gulf of Mexico. A somewhat similar occurrence in 1965 resulted in the unusual path taken by hurricane Betsy although in that case the ridge was initially over the northern Gulf of Mexico and moved east-northeastward rather than just building northeastward.

It is interesting at this point to compare Inez with hurricane Cleo of 1964. The paths of the two hurricanes, both of which were small intense storms prior to striking Cuba, were very similar until they left the northern coast of Cuba. Cleo moved generally northward at an accelerated rate and intensified rapidly just prior to striking Miami. Inez, on the other hand, intensified very slowly as it moved north-northeastward and maintained a rather large diffuse eye of 30–40 mi. diameter. Lack of intensification in spite of fairly favorable low-level conditions appears to be tied-in to the weak upper-level trough in which Inez was situated with little outflow at high levels. This was borne out in part at this time by satellite pictures which indicated little cirrus outflow.

Late on October 3, a trend toward the west-southwest was indicated by radar and aircraft reconnaissance and this was fairly well established during the early morning hours of the 4th. Once this course was established it was maintained with only minor fluctuations until late on the 7th. During this time the strong upper-level anticyclone over the western Gulf of Mexico remained nearly stationary and Inez moved around its southeastern periphery gradually encountering more favorable upper-air conditions for high-level outflow.

The eye of Inez moved directly over all of the Keys from Key Largo to Key West and the U.S. Navy Weather Office at Boca Chica was able to obtain a rather rare hurricane eye sounding which is shown in figure 2. The highest wind reported on the Florida mainland was a gust to 92 m.p.h. at Flamingo. All of the Keys reported winds of hurricane force. See table 4 for other meteorological data.

Inez continued west-southwestward just south of Dry Tortugas and brushed the northern coast of Yucatan, Mexico, with hurricane conditions on October 7. At this point Inez once again began to recurve into a weakness in the high pressure ridge over the western Gulf of Mexico. The hurricane also reached its maximum intensity in the Gulf of Mexico at this time with a pressure of 948 mb. (28.00 in.) reported by reconnaissance aircraft at 0000 GMT on the 9th. The weakening of the ridge permitted Inez to drift on a northwestward course on the 9th and this increased the threat to the Texas coast for about 24 hours. Rising surface pressures to the north in Texas beginning late on the 9th finally forced Inez west-southwestward into Mexico just north of Tampico on the morning of the 10th. Numerous storms in the past have veered to the southwest when very close to the Mexican coast. This is probably related in some way to the mountainous terrain, and this type of motion possibly augments that induced by steering forces. Tampico reported gusts to 127 m.p.h. before communications were lost as the center was moving inland. Torrential rains later caused widespread floods in the area.

Inez was under almost constant surveillance by satellites, U.S. Navy, Air Force, and ESSA reconnaissance aircraft, and/or land-based radar after it neared the Antilles. Warnings of hurricane conditions were issued at least 24 hours in advance for all areas except the southeastern Florida coast where the erratic movement and minimal hurricane force winds precluded such advance notice. Other hurricanes such as Ginny in 1963 and Gracie in 1959 presented serious forecasting problems for the United States mainland as a result of loops and slow movement. Inez probably became nearly stationary closer to the United States mainland than any other storm, although the hurricane of September 1929 took three days to move slowly west-southwestward through the western Bahamas and Florida Straits.

Estimated total deaths are approximately 1,000. Damage to crops and property was relatively small compared to other hurricanes which have struck so many land areas, probably because of the size of the storm and the lateness of the season. Crop damage in countries such as Cuba, Haiti, Dominican Republic, Mexico, and the Island of Guadeloupe is always of severe economic impact.

The minimum central pressure of 927 mb. (27.38 in.) and maximum estimated winds of 150–175 m.p.h. classify Inez as a great hurricane and it has been added to the list prepared by Kraft [6]. As indicated above, the path will have to be considered somewhat unusual at the very least.

TROPICAL STORM JUDITH, SEPTEMBER 27–30.—This was a minimal storm. Ship reports and satellite photographs on the 26th and 27th of September gave some indications of circulation in the south-central North Atlantic. On the 28th the ESSA 2 photograph showed an area of cloudiness larger than that associated with hurricane Inez, but with only slight indications of circulation. The following day reconnaissance aircraft reported the central pressure as 1007 mb. (29.74 in.) and the maximum flight-level wind speed 50 m.p.h. Judith was centered a short distance north of Barbados and was apparently decreasing in intensity at that time. After passing through the island chain Judith was no longer of storm intensity. It continued to weaken and was downgraded to easterly wave status on the 30th. It is interesting to note that during the period of decreasing intensity Judith was under the area of expanding outflow from hurricane Inez.

The strongest surface winds reported in the island chain during the passage of Judith were 37 m.p.h. at Martinique and 40 m.p.h. on a ship near the west coast of Marie Galante.

KENDRA, OCTOBER.—The name Kendra was given to a low pressure system in the extreme eastern Atlantic. Post analysis indicates that Kendra was not a tropical storm.

HURRICANE LOIS, NOVEMBER 4–13.—Lois first revealed itself as a small cloud vortex on the ESSA 2 satellite photograph on the morning of November 4. Weather charts showed a low pressure area in the region extending from the surface up through the middle levels

TABLE 4.—*Hurricane Inez, meteorological data, September 21–October 11, 1966*

Station	Date	Pressure (in.)		Wind (miles per hour)				Highest Tide (ft.)	Storm Rainfall (in.)	Remarks
		Low	Time	Fastest mile**	Time	Gusts	Time			
LESSER ANTILLES										
Guadeloupe	27	28.68	1300 A	80		94			6.5	
PUERTO RICO										
Penuelas	28					52	1345 A			
Ricon	28					35				
Ponce	28			20	1300A	30	1300 A			
Mona Island	28					*80	1930 A			
Magueyes Island	28					*60				
Cabo Rojo Lighthouse	28					*40	1930 A			
VIRGIN ISLANDS										
St. Croix				30		45				
St. Thomas				20		30				
HAITI										
Port-au-Prince		29.49								
CUBA										
Guantanamo City				138					12.00	
BAHAMAS										
Green Turtle Cay, Abaco	3	29.64	1500 E	SE 50	04/0200 E				9.82	29.64 04/0100 E
Hope Town, Abaco	3	29.70	1900 E	33					5.27	
Freeport, Grand Bahama	3	29.45		ESE 64					5.19	Two waterspouts
Alice Town, Bimini	3	29.16	04/0300 E	NNE 63	1700 E				6.48	
West End, Grand Bahama	3	29.50	1400 E			90	2359 E		1.43	29.50 03/1900 E
Carter Cay						80				
Nassau	3	29.52	1900 E	45		64	0737 E		14.31	wind 100+ vicinity of tornado
FLORIDA										
Hillsboro Light	4	29.37	0400 E	72	0515 E			3.0 AN		
Fort Lauderdale	4			45	0900 E	60	0830 E		1.53	
Port Everglades	4	29.54	0400 E	ESE 45	1200 E	ESE 55	1200 E		1.85	
Miami (NHC)	4	29.38	0713 E	ENE 46	1035 E	ENE 60		2.7 AN	2.51	
Miami (WBAS)	4	29.41	0640 E	NE 41	0754 E	NE 63	0750 E		3.24	
Key Biscayne	4	29.39	0730 E	ENE 55	1100 E	ESE 65	0830 E		3.87	
Tamiami Trail (40-Mile Bend)	4	29.54	1345 E	N 29	0800 E	NE 42	1545 E		1.22	
Homestead AFB	4	29.24	1135 E	NNE 46	0955 E	NNE 79	0932 E		.62	
North Key Largo	4	29.04	1120 E	ESE 75	1215 E	ESE 96	1230 E		3.00	eye 0915–1215.
Flamingo	4	29.04	1315 E	SSE 81	1800 E	SSE 92	1800 E		1.02	eye 1645–1650.
Tavernier	4	29.11	1400 E	SE 90	1600 E	SSE 100+	1700 E	2.0 AN	.97	eye 1115–1430.
Plantation Key	4	29.22	1330 E	ESE 98	1645 E	ESE 110	1640 E	3.5 AN	4.21	eye 1145–1300.
Grassy Key	4	29.10	1405 E	SSE 86	1855 E	SSE 92	1915 E	3.0 AN	3.25	eye 1410–1620.
Marathon Shores	4	29.10	1455 E			*130				eye 1500–1755.
Key West, Boca Chica	4	29.20		SE 69	2342 E	S 94	2342 E		1.19	eye 1940–2240.
Key West (WBAS)	5	29.18	1936 E	SSE 84	0006 E	SSE 90	0013 E	2.0–4.0 AN	4.15	eye 2000–2245.
Dry Tortugas	5	29.15				E 120	1000 E			
Fort Myers	4	29.66	1600 E			38	0530 E		.09	
Islamorada		29.03								
Big Pine Key	4	29.18	1700 E	*SE 150	2130 E	*SE 165	2130 E	5.0 AN	3.92	eye 1615–2020.
MEXICO										
Merida	7			69		81				
Tampico	10			115		127				
Soto la Marina									10.12	
TEXAS										
Brownsville	9	29.78	1555 C	N 22	1555				T	
Corpus Christi	9	29.83	1700 C	E 17	1555			3.1 MLW	T	

*Estimated. **Or one minute. A=AST. E=EST. C=CST. AN=Above Normal. MLW=Mean Low Water. T=Trace.

of the atmosphere. However, because of the rather cold temperatures near the center, the circulation at that time did not appear to be tropical in nature.

During the next two days the system showed little movement while a gradual warming was noted at all levels. The satellite revealed a progressive enlargement and degree of organization of the associated cloud spiral and on November 6 a U.S. Air Force reconnaissance flight found that an eye had formed with surrounding winds of 55 m.p.h.

Lois commenced a slow east-northeastward course while steadily increasing toward hurricane intensity, which was achieved on the afternoon of November 7. Thereafter, hurricane Lois accelerated on a northeastward track, a direction it was to maintain during the next four days and 2,000 mi. Throughout this period the hurricane was kept under surveillance by reconnaissance flights and weather satellites. Little change in speed, intensity, or direction was observed as it passed some 300 mi. west of the Azores. On the 10th, gale force winds of 50 m.p.h. occurred at Corvo in the Azores.

Finally, as Lois traveled over the cooler waters to the north, it began to slow down and weaken. By the 12th the storm had lost most of its tropical characteristics and began a slow turn to the east and southeast as a weakened low pressure area. On the 13th, the remnants of Lois finally became unidentifiable in a region about 300 mi. west of Portugal.

Except for its brief fringe effects on the Azores, Lois never posed a threat to any inhabited area.

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SOME ASPECTS OF THE DEVELOPMENT OF HURRICANE DOROTHY

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ABSTRACT

Hurricane Dorothy, July 1966, possessed both extratropical and tropical features. A number of factors contributed to storm development, including a well-defined pre-existing disturbance, high-level advection of vorticity and kinetic energy, baroclinicity of both the extratropical and tropical-storm types, and a moderate degree of latent instability.

1. INTRODUCTION AND SUMMARY

Dorothy, the fourth storm of the 1966 season, developed in the central North Atlantic, near 32° N., 42° W., on July 22–23 [1]. The storm attained winds of 50 kt. on July 23 and hurricane-force winds of 65 kt. late on July 24. The area of formation (north of 30° N. and in the general environment of an upper-tropospheric cold Low), the seeming absence of a well-developed wall cloud and warm core on July 23–24, and the unusual appearance of the storm in the satellite photographs suggested to forecasters that Dorothy may not have been a true tropical storm during that time.

Dorothy did indeed possess some extratropical features. One purpose of this paper is to present evidence of that. A second purpose is to evaluate, where possible, some of the factors contributing to the cyclogenesis. Just prior to storm formation, the initially weak disturbance received a rather strong influx of kinetic energy and cyclonic vorticity at upper-tropospheric levels. This was associated with a vigorous short-wave trough advancing toward the area from the north and northwest. Storm development occurred as the high-level perturbation approached and moved over the lower-level disturbance. At Weather Ship "E", located some 400 mi. to the northwest of the storm center, pronounced mid-tropospheric cooling, stratospheric warming, and a lowering of the tropopause occurred during and after the day of storm formation. The temperature changes at ship "E" strongly suggest some influx of baroclinicity into the area, although no low-level frontal zone can be defined.

These events indicate that Dorothy very probably derived a considerable portion of its energy from extratropical sources during the period July 22–23, although convective instability and the release of latent heat undoubtedly contributed to development. In this sense, Dorothy was, at best, a "half breed".[1] Later, during July 25–28, there is some evidence to indicate that Dorothy did develop a weak warm core and was more nearly a true tropical cyclone.

This paper is confined largely to the developmental period, July 22–23. The more general history of Dorothy, the storm track, and discussions of other 1966 Atlantic storms are given by Sugg and Staff [1] elsewhere in this issue.

2. SYNOPTIC SITUATION AT 0000 GMT, JULY 22

Figure 1 shows the surface charts for 0000 GMT and 1200 GMT on July 22 and 23. Figures 2a–d give the 300-mb. analyses for the same hours. On both sets of charts all available data are plotted within the region 20°–60° W. and 20°–45° N. At 300 mb. some surrounding data also are shown, and the analyses are extended to include a somewhat larger area.

The general situation aloft over the North Atlantic at 0000 GMT, July 22, featured a large blocking High centered well north of 45° N. South and east of the High was a complex upper-tropospheric cold Low. At 300 mb. (fig. 2a), the main center of the Low was located near the Azores, but there were several rather well-defined perturbations revolving about the main center and extending many hundreds of miles outward. As seen in the subsequent charts (figs. 2 b, c, d), one of these perturbations—the upper-level trough extending far to the northwest of the low center at 0000 GMT—later advanced southward and passed over the disturbed area, accompanied and preceded by a pattern of considerable cyclonic vorticity advection. This is believed to have been a significant factor in the development of Dorothy. However, at 0000 GMT, July 22, that upper-level perturbation was still quite far from the disturbed area. The disturbance lay under a weak trough, almost midway between the large Azores Low and an anticyclone centered northeast of Bermuda.

At the surface at 0000 GMT, July 22 (fig. 1a), can be seen the well-defined but weak disturbance in the shape of an inverted trough embedded in the southern sector of the

[1] This term was used by Dunn and Staff [2] and Frank [3] to describe a similar Atlantic storm that occurred in 1963. They indicate that several such "half breeds" may occur each year.

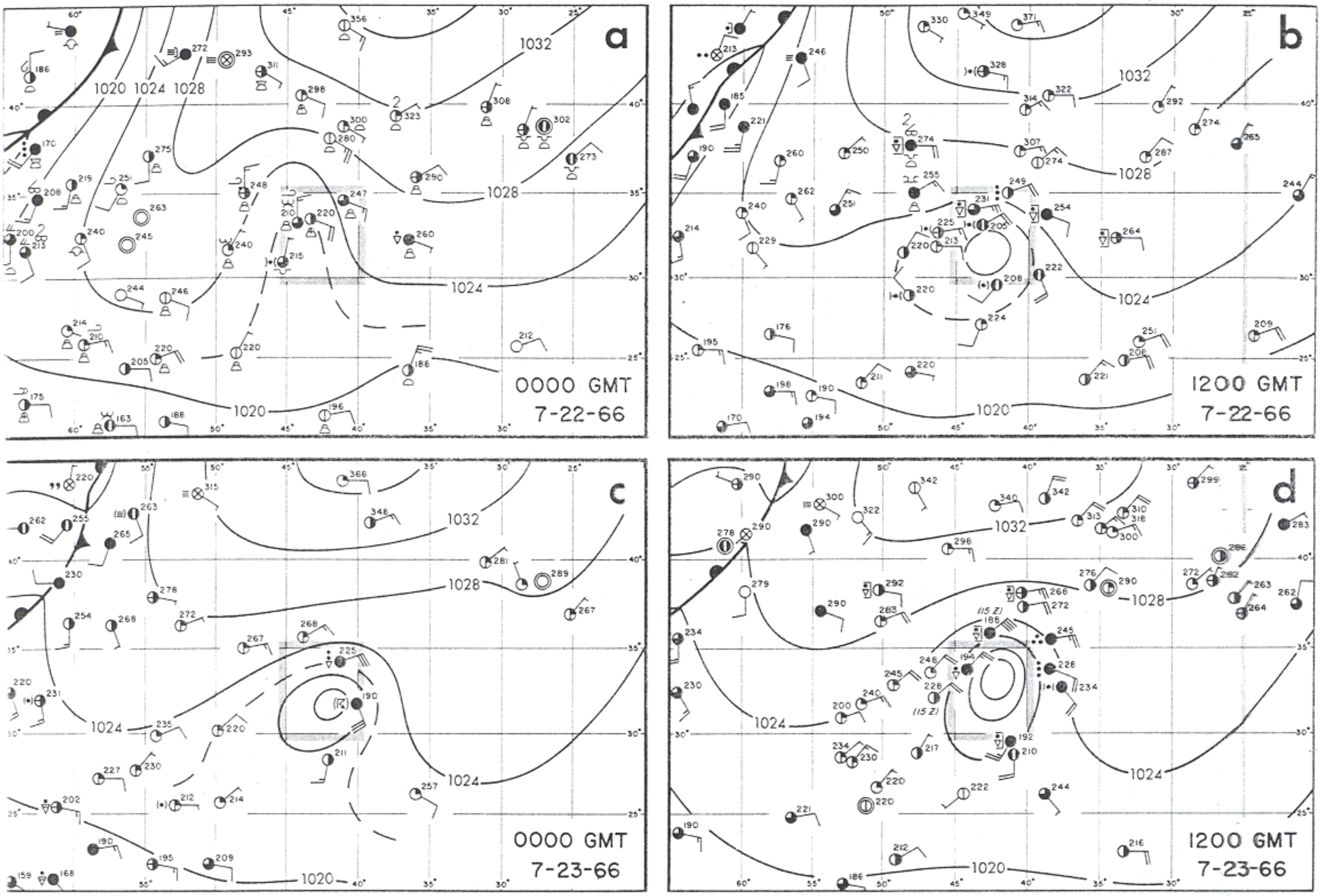


FIGURE 1.—Surface synoptic analyses in vicinity of developing storm Dorothy for (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966. All available ship reports are plotted. In most cases only sea level pressure, wind, sky cover, and present weather are shown.

large High. Forecasters had been aware of its existence for several days. However, at 0000 GMT, July 22, no closed isobar could be drawn, and it is remarkable that the lowest pressure in the area of subsequent storm formation was above 1020 mb.! An ESSA-1 cloud photograph taken some 8 hr. earlier (fig. 3a) reveals a bright cloud mass with geometric center near 32° N., 39° W.—slightly east of the surface trough. A very faint and small-scale spiral array of cloud lines is centered near 31.5° N., 43.5° W.—west of the main cloud mass and in good positional agreement with the nearly stationary inverted trough. That small-scale spiral array appears to be composed of low or middle clouds and is interpreted as indicating cyclonic vorticity at lower-tropospheric levels but not necessarily a closed cyclonic circulation. The latter, if it existed, must have been small and weak.

3. STORM DEVELOPMENT ON JULY 22–23

By 1200 GMT, July 22, a small surface low center had formed (fig. 1b), but the lowest pressure was still near 1020 mb. At 300 mb. for the same time (fig. 2b), the upper-level trough to the north had advanced somewhat southward from its previous position at 0000 GMT, as evidenced by the pronounced shift in the wind at Weather Ship "D" (44° N., 41° W.) from 030° to 100°. Some intensification of the trough appeared likely. At Weather Ship "E" (35° N., 48° W.), located south of the approaching trough and northwest of the low-level disturbance, increased winds from the north-northwest and north had begun to appear in the 300–200-mb. layer (see also time section, fig. 5). An ESSA-1 photograph taken 3 hr. later (fig. 3b) shows the bright cloud mass of the disturbance centered near 32.5° N., 40° W.—again slightly east of the surface Low. No well-defined bands are visible, but the cloud mass appears to be more compact than it was on the previous day, and some cirrus outflow is seen in the northeast fringes.

Storm formation occurred July 23 [1]. Surface ship data are not adequate to define the period of most rapid deepening, but it probably occurred sometime between

0000 GMT and 1500 GMT, July 23. Winds up to 30, 40, and 50 kt. were reported at 0000 GMT, 1200 GMT, and 1500 GMT, respectively (see surface maps, figs. 1c, d). The storm was named Dorothy later the same day. The concurrent 300-mb. charts for 0000 GMT and 1200 GMT (figs. 2c, d) show that the advancing upper-level trough continued to move toward the storm area, forming a small low center as it dropped southward. A strongly difluent flow pattern developed in advance of the oncoming trough and over the area of the deepening storm.

Figure 4 presents a striking series of photographs taken over a period of about 4½ hr. during the July 23 deepening. No eye is visible. Instead one sees the progressive development of a tightly wound spiral configuration in which both the major cloud band and the relatively cloud-free zone spiral inward to the center in much the same fashion as in many extratropical cyclones!

4. FACTORS CONTRIBUTING TO CYCLOGENESIS

The approach of a vigorous upper-tropospheric trough toward the area of a pre-existing low-level disturbance is known to favor subsequent cyclogenesis through the mechanism of high-level vorticity advection (Petterssen [4]). Neglecting small terms, the vorticity equation may be written

$$\frac{\partial Q}{\partial t}+V\frac{\partial Q}{\partial s}=(V-C)\frac{\partial Q}{\partial s}=-QD \qquad (1)$$

where Q is the absolute vorticity, D is the horizontal divergence, s is the direction along the streamlines, V is the wind speed, and C is the phase speed of the system (trough speed). If upper-level winds are blowing through the trough with great speed ($V>>C$), the area immediately in advance of the trough may see the vorticity advection term, $V\partial Q/\partial s$, become a large negative quantity relative to $\partial Q/\partial t$. Positive upper-level divergence may be accompanied by semicompensating low-level convergence in such areas.

That such a mechanism was operating to some degree in this case seems extremely likely. The author offers the hypothesis that it was a vital contributing factor in the development of this storm. Although the terms of equation (1) cannot be evaluated with any precision, it is obvious from the analyses presented in figures 2c and d and the strong upper winds shown in figure 5 that upper-level vorticity advection was large over and immediately upstream from the area of low-level cyclogenesis. At a point near Weather Ship "E" (35° N., 48° W.) at 0000 GMT, July 23, in the upper troposphere, some reasonable but very crude estimates of the quantities of equation (1) might be:

$$V=40 \text{ m./sec.},$$
$$C=10° \text{ lat. per 24 hr.} \approx 13 \text{ m./sec.},$$
$$\partial Q/\partial s=-10^{-4} \text{ sec.}^{-1} \text{ per 600 km.},$$
$$Q=2 \times 10^{-4} \text{ sec.}^{-1}$$

TABLE 1.—*Computed estimates of mean horizontal divergence, $\overline{D}$, and mean relative vorticity, $\overline{\zeta}$, for the 5-degree "square", 30°–35° N., 40°–45° W., at sea level. Units are 10^{-5} sec.$^{-1}$*

	July 22–1200 GMT	July 23–1200 GMT
$\overline{D}$	−1.1	−3.0
$\overline{\zeta}$	4.1	8.3

Insertion of these quantities into equation (1) yields a value of $D\approx 2.3\times 10^{-5}$ sec.$^{-1}$ Although the accuracy of this computation must be considered very low, it seems fair to say that D was certainly positive in sign over that area, and probably was relatively large. Petterssen [4] quotes values of D of 0.8×10^{-5} sec.$^{-1}$ and 3.2×10^{-5} sec.$^{-1}$ as representative of moderate and intense synoptic-scale systems, respectively.

Several years ago Namias [5] stressed the importance of injection of cyclonic vorticity from troughs in the westerlies into the Tropics for providing a favorable "climate" for tropical storm formation. The present case, although it occurred somewhat north of the Tropics, seems a good illustration.

Table 1 shows the results of two kinematic computations of mean divergence and mean relative vorticity at sea level for the 5-degree "square" within which storm development occurred. The computations are for 1200 GMT, July 22 and 23. A considerable number of ship data existed in the vicinity at both those hours (figs. 1b, d). These data permitted fairly definitive streamline-isotach analyses (not shown), which served as the basis for the computations. Of course no great accuracy can be claimed, but the large convergence at 1200 GMT, July 23, is significant, and it seems realistic in view of the cyclogenesis that was then occurring. From continuity considerations, it is also consistent with the indicated divergence aloft.

There is evidence that similar motions in lesser degree existed in the disturbed area on July 22. The surface depression (figs. 1a, b), the moderately difluent upper-level flow (figs. 2a, b), and the cloud mass (fig. 3) together strongly suggest that an organized pattern of high-level divergence, low-level convergence, and middle-level upward motion was present in the region of the disturbance during July 22 and probably earlier. This pre-existing pattern was itself undoubtedly a factor favorable for cyclonic development and was probably a necessary but not sufficient condition. The arrival of high-level vorticity advection from outside the area thus augmented a pre-existing vertical motion-divergence pattern which had not produced a storm by itself but which provided a favorable "breeding ground" for storm formation. Generally, the importance of the pre-existing disturbance for subsequent tropical storm development is well known and has been discussed by Dunn and Miller [6], Riehl [7], and others.

An invasion of cooler air into portions of the developing circulation is characteristic of extratropical cyclogenesis.

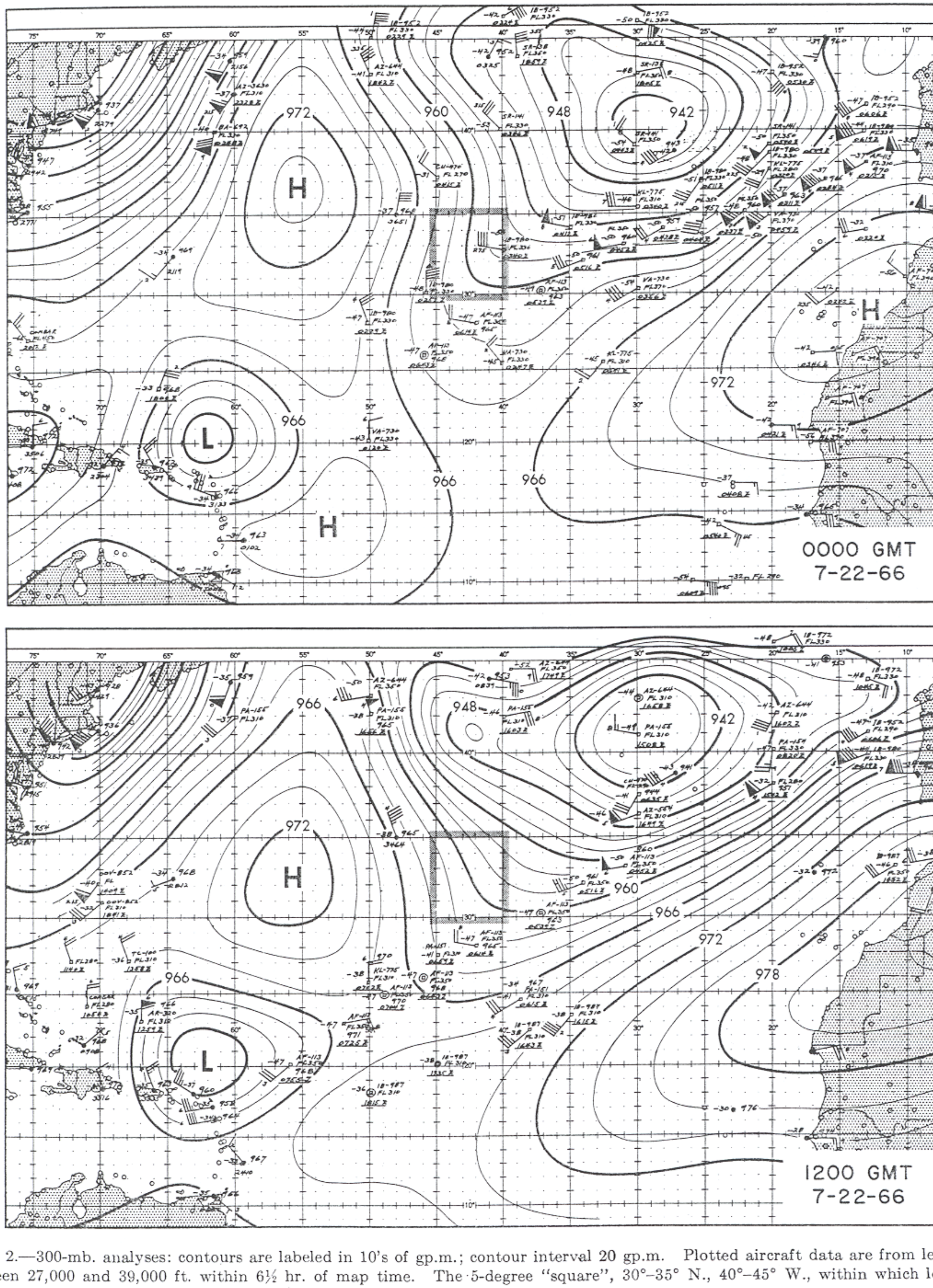
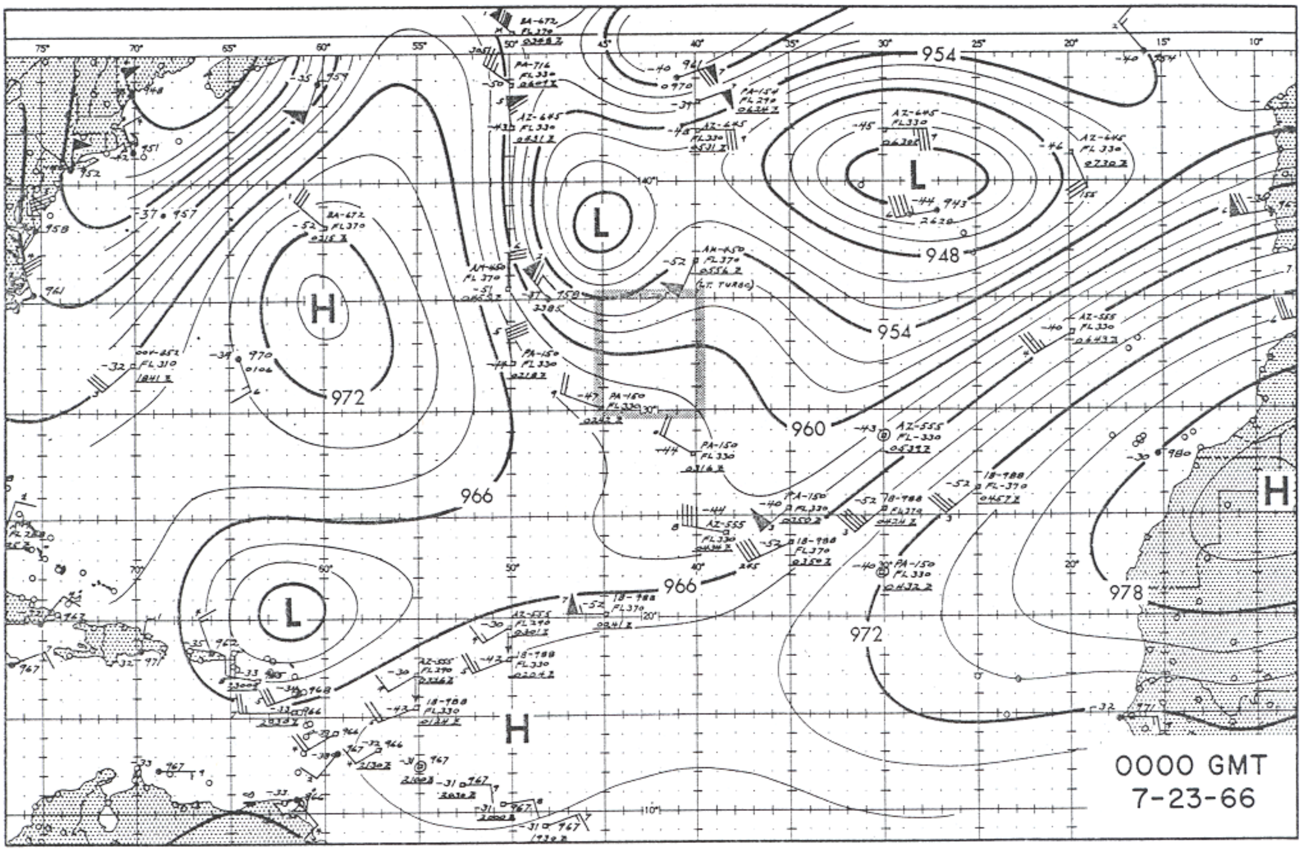
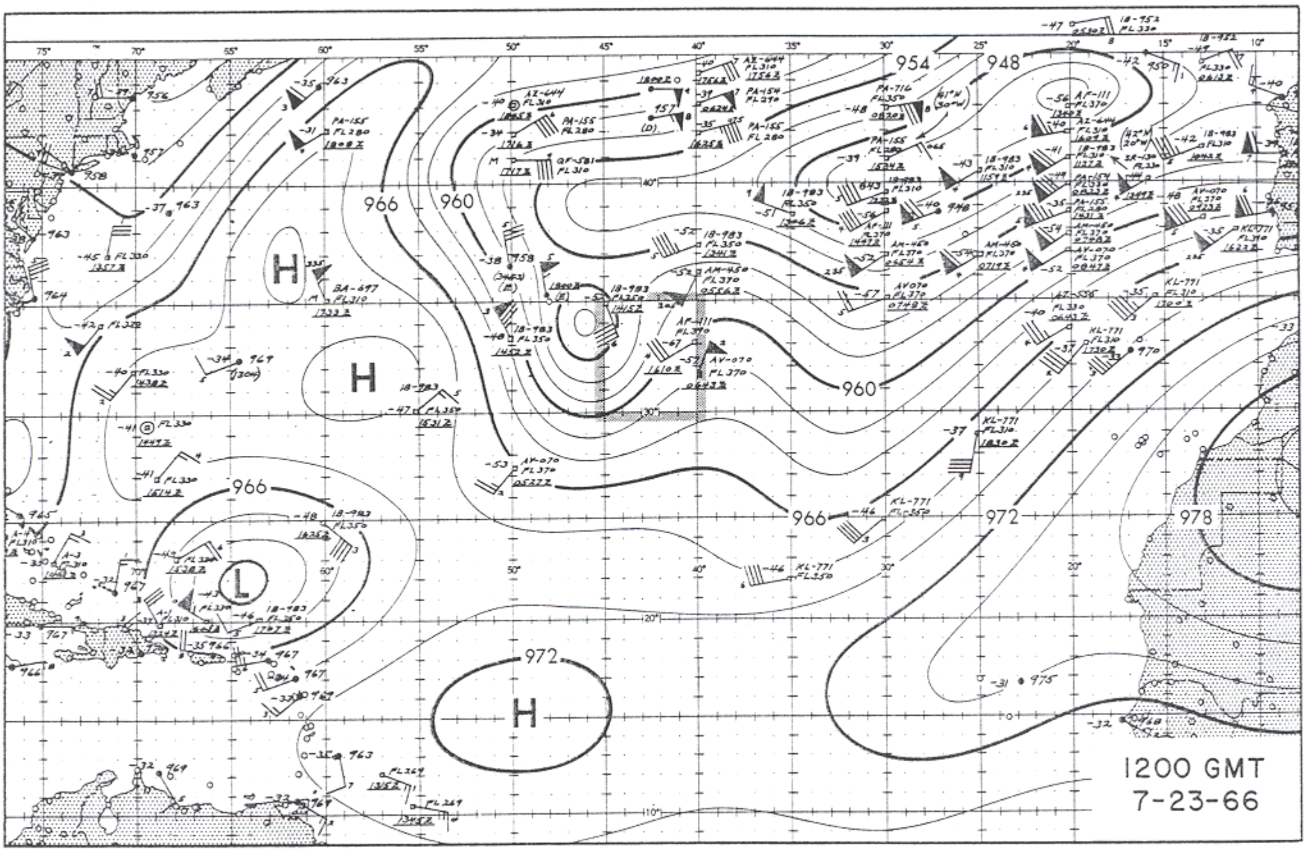


FIGURE 2.—300-mb. analyses: contours are labeled in 10's of gp.m.; contour interval 20 gp.m. Plotted aircraft data are from levels between 27,000 and 39,000 ft. within 6½ hr. of map time. The 5-degree "square", 30°–35° N., 40°–45° W., within which low-level





cyclogenesis occurred is outlined by shading. (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966.

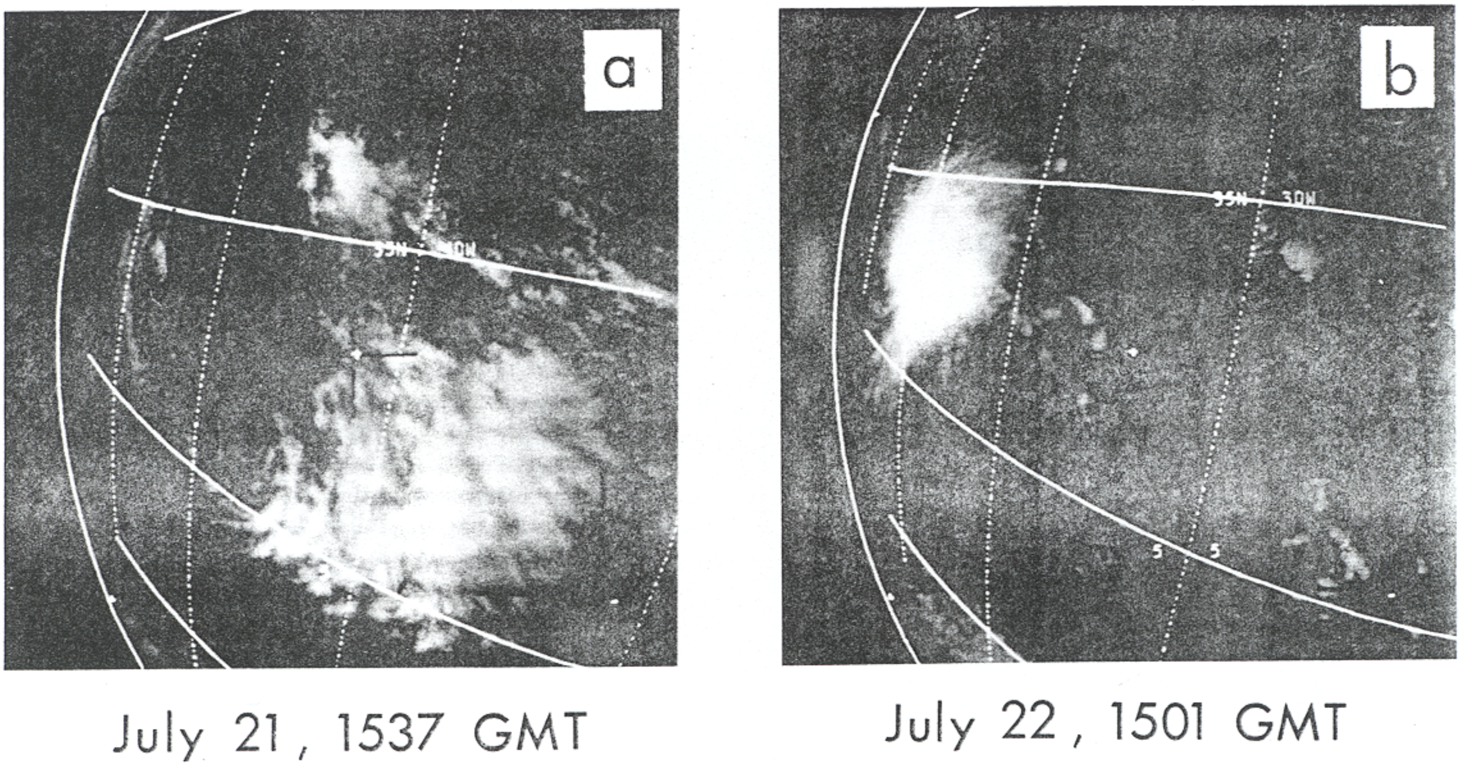


FIGURE 3.—ESSA-1 photographs of disturbance on July 21 and 22, 1966. (a) Pass 2415, camera 2, frame 4, 1537 GMT; (b) Pass 2429' camera 2, frame 8, 1501 GMT. Grid interval is 5 degrees.

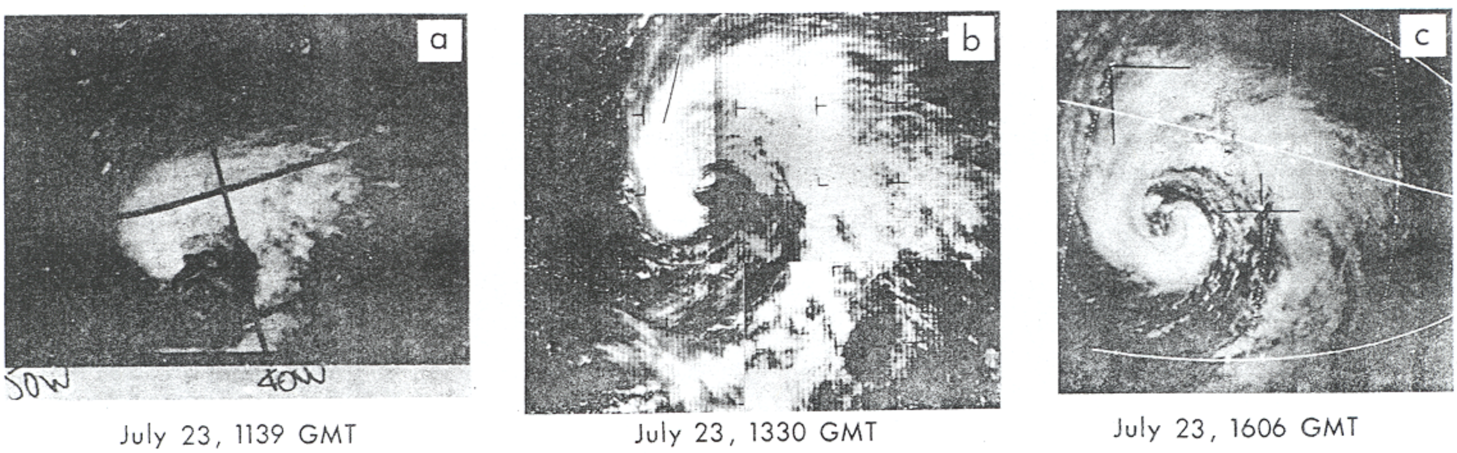


FIGURE 4.—Three views of developing storm on July 23, 1966. (a) ESSA-2 APT, Pass 1838, 1139 GMT; (b) Nimbus-2 AVCS (composite of four photos), Pass 922, approximately 1330 GMT; (c) ESSA-1, Pass 2444, camera 1, frame 4, 1606 GMT.

The development of a warm core, on the other hand, is a feature of intense tropical cyclones. In the case of Dorothy, the evidence indicates that both occurred. However, neither the cold air invasion nor the warm core was present to the degree that usually exists singly in vigorous extratropical and tropical storms, respectively.

That cooler air did at least reach an area northwest of Dorothy is seen in figure 5, a time-section of the upper-air and surface observations at Weather Ship "E", some 400 mi. northwest of the storm, for the period immediately preceding and during storm development. Pronounced midtropospheric cooling, stratospheric warming, and a general lowering of the tropopause had occurred by July 23, the day of storm formation. On July 24 maximum deviations of −7° and +13° C. were observed (at 450 and 150 mb., respectively). This large midtropospheric cooling in the area northwest of the surface cyclone together with the general northerly flow over that area indicates that the cooler air must have invaded at least the outer portions of the storm circulation. A

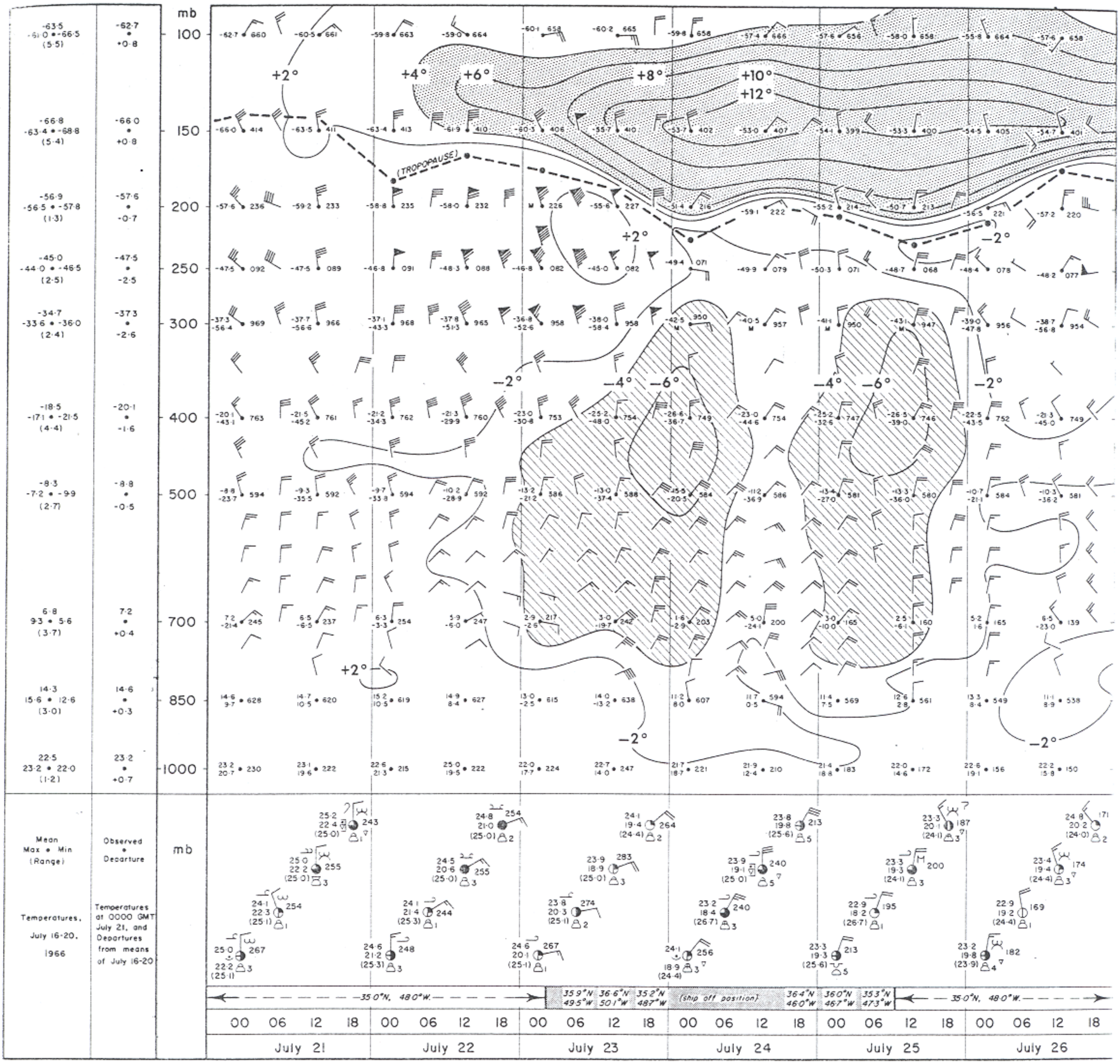


FIGURE 5.—Vertical time-section for Weather Ship "E" (approximate position 35.0° N., 48.0° W.), July 21–26, 1966. Isolines enclose areas of temperature deviations greater than 2° C. from observed values at beginning of period (0000 GMT, July 21). Areas of deviations greater than 4° C. are shaded. Comparative temperature data for the previous 5-day period are shown at left. Surface data are plotted in the standard synoptic code except for sea, air, and dew-point temperatures, which are given to tenths of degrees Celsius.

considerable penetration appears likely, but it is not known whether any such penetration actually reached the storm center.

At the surface at Weather Ship "E", changes were small compared to those that occurred aloft. No clearly defined frontal zone passed that location during the period. However, even at the surface a slight but definite trend toward cooler and dryer air was observed during July 22–24 (see fig. 6).

Thickness analyses, 1000–300 mb., for July 22–23 in the region of the developing storm are presented in figure 7. These are based on the analyses of figures 1 and 2.

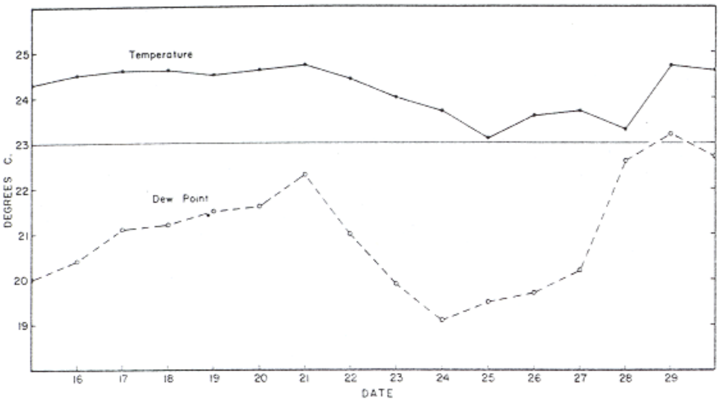


FIGURE 6.—Surface air temperatures and dew points for Weather Ship "E" July 15–30, 1966. Individual values are daily averages of the eight 3-hourly synoptic observations, 0000–2100 GMT.

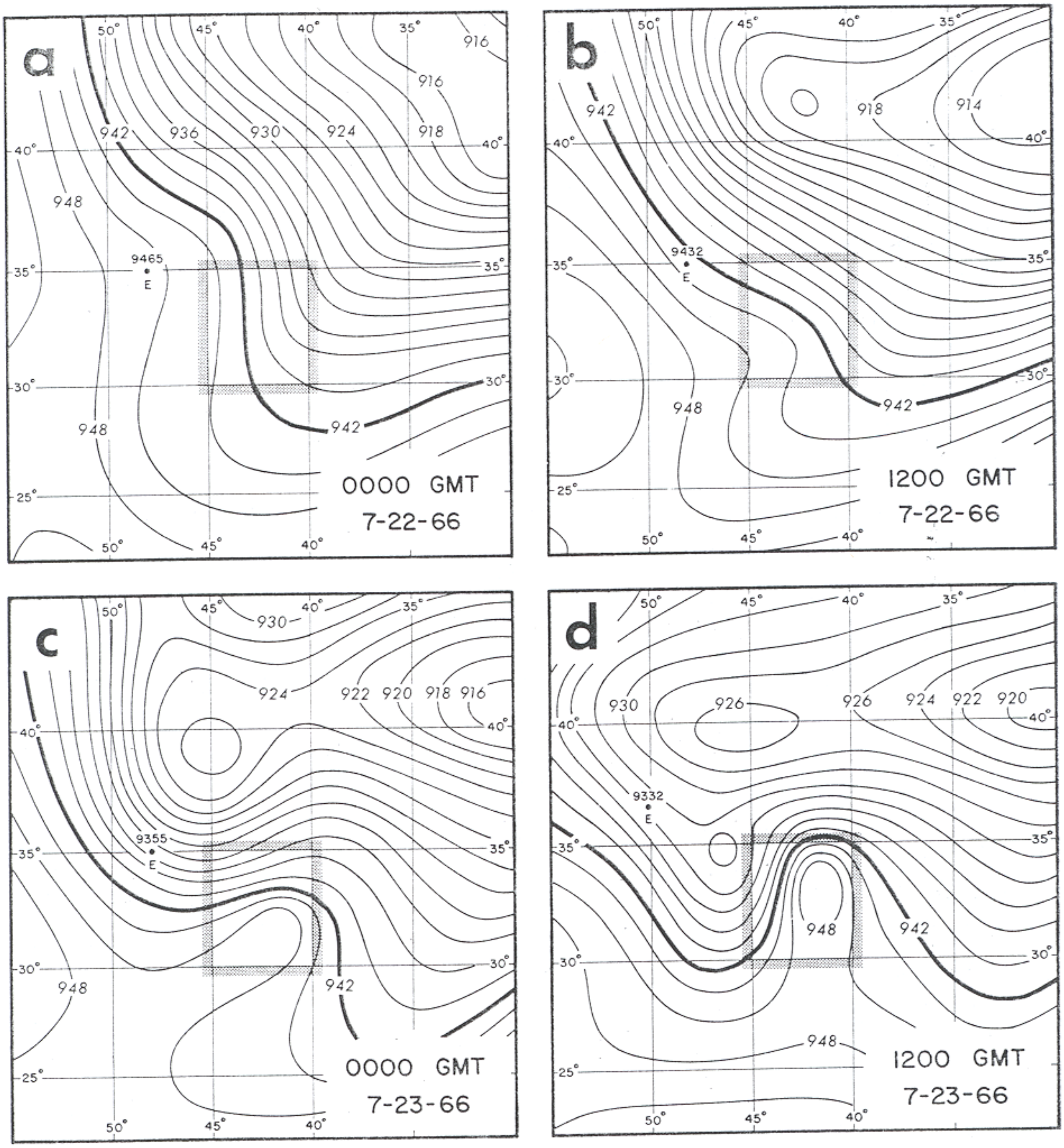


FIGURE 7.—1000–300-mb. thickness contours in vicinity of developing storm Dorothy for (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966. Contours labeled in 10's of gp.m.; contour interval 20 gp.m. Analyses are based essentially on the surface and 300-mb. charts for the same hours (figs. 1 and 2). The 5-degree "square" within which storm development occurred is outlined by shading.

The contour interval of 20 gp.m. corresponds to a difference in mean virtual temperature for the air column of 0.6° C. It is interesting that a moderate gradient of mean temperature already existed at 0000 GMT, July 22, before cyclogenesis occurred. At that time colder air lay to the northeast of the incipient storm and warmer air to the west. As development progressed, warming spread toward the area of the surface cyclone from the west, southwest, and south, while cooling occurred to the north and northwest in conjunction with the approach of the upper trough over that region. By 1200 GMT, July 23 (fig. 7d), these differential changes had produced a zone of considerable baroclinicity over the area immediately west and northwest of the storm center. While details may be questionable because of analysis uncertainties, the gross pattern seems well established. The progressive invasion of the clear tongue spiraling inward from the west and southwest in the satellite photos of figure 4 is corroborative evidence that dryer and probably cooler air was being drawn into the circulation from those quadrants. The photos suggest that some of the dryer air may have penetrated to the storm center on July 23. However, the later formation of an eye (and therefore at least a weak warm core) on July 25–26 indicates that if any such penetration continued, the air must have become so modified as to have differed little from that originally present.

Altogether, it seems likely that the invasion of cooler air contributed to storm development by augmenting convection through large-scale forced uplift of warmer unstable air. Some contribution to cyclogenesis may also have been realized through conversion of potential to kinetic energy. At the same time, the invasion of the dryer, cooler air on July 23 may have interfered with the development of the warm core.

Figure 8 shows that the static stability and the vertical temperature distribution at Weather Ship "E" at 0000

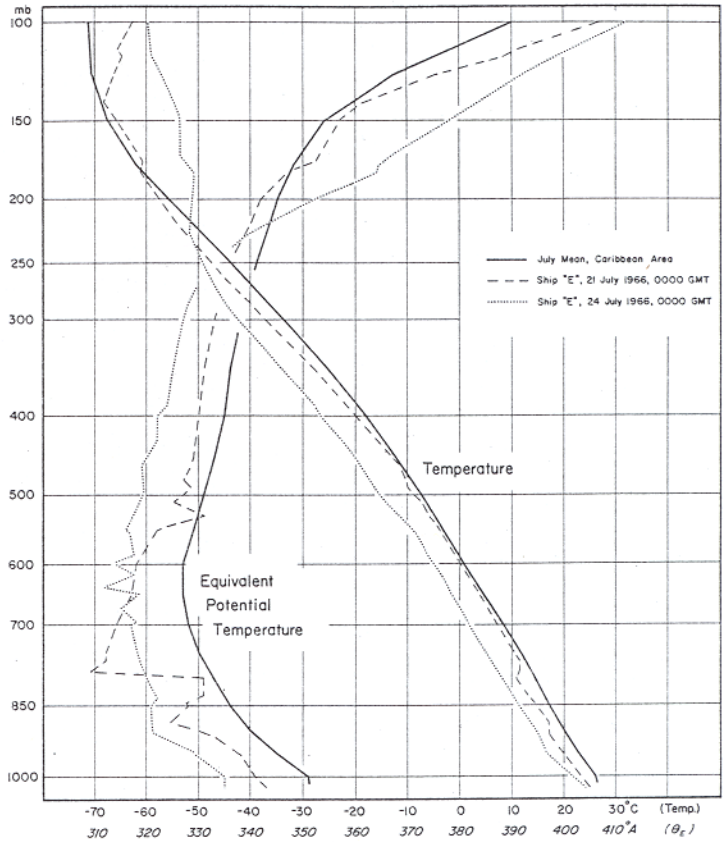
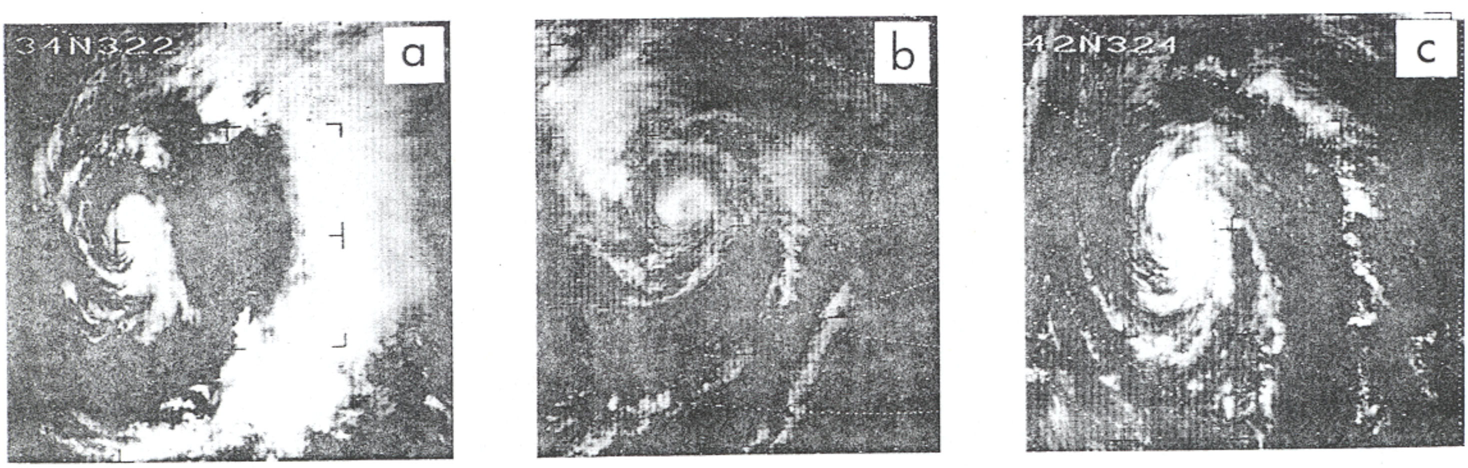


FIGURE 8.—Soundings of temperature and equivalent potential temperature (θ_e) for Weather Ship "E" at 0000 GMT, July 21 (dashed lines) and 0000 GMT, July 24 (dotted lines), 1966. Mean July values for the Caribbean area also are shown (heavy solid lines), based on data published by Jordan [8].



July 24, 1301 GMT July 25, 1415 GMT July 28, 1236 GMT

FIGURE 9.—Nimbus-2 AVCS photographs of Dorothy on July 24, 25, and 28, 1966. (a) Pass 935, camera 1, 1301 GMT; (b) Pass 949, camera 3, 1415 GMT; (c) Pass 988, camera 1, 1236 GMT.

GMT, July 21, were comparable to those of the mean Caribbean atmosphere for July [8]. Tropospheric temperatures were only 1° to 3° C. lower than those of the mean Caribbean atmosphere, with lapse rates very slightly greater than the moist adiabatic in both cases. The upward decrease in equivalent potential temperature in the lower troposphere, a measure of convective instability for lifted layers, was in fact larger at 0000 GMT, July 21, than it is for the mean Caribbean atmosphere, although in the latter the instability exists through a deeper layer.

Sea-surface temperatures in the vicinity of the disturbance on July 21–22 were mostly in the range 25°–26° C. This is slightly cooler water than normally observed near incipient hurricanes but is consistent with the slightly cooler air aloft. Thus, conditions favorable for upward transport of heat and moisture—factors necessary for tropical cyclone development—were also present in this situation, but the latent instability did not extend as far aloft as is usually observed in the vicinity of tropical cyclones.

5. LATER EVENTS

Three later views of Dorothy are seen in figure 9. On July 24 (fig. 9a), the major cloud band had become almost completely separated from the smaller area of the storm itself, as the latter remained almost stationary while the former continued to move eastward in advance of the weakening upper trough. A general cyclonic flow pattern aloft remained over and west of the storm area on July 24, but a small and weak warm core may have existed at the center or may have been developing. On July 25 (fig. 9b), an eye was visible. On July 28 (fig. 9c), the general appearance was typical of many tropical storms as seen in satellite photographs.

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