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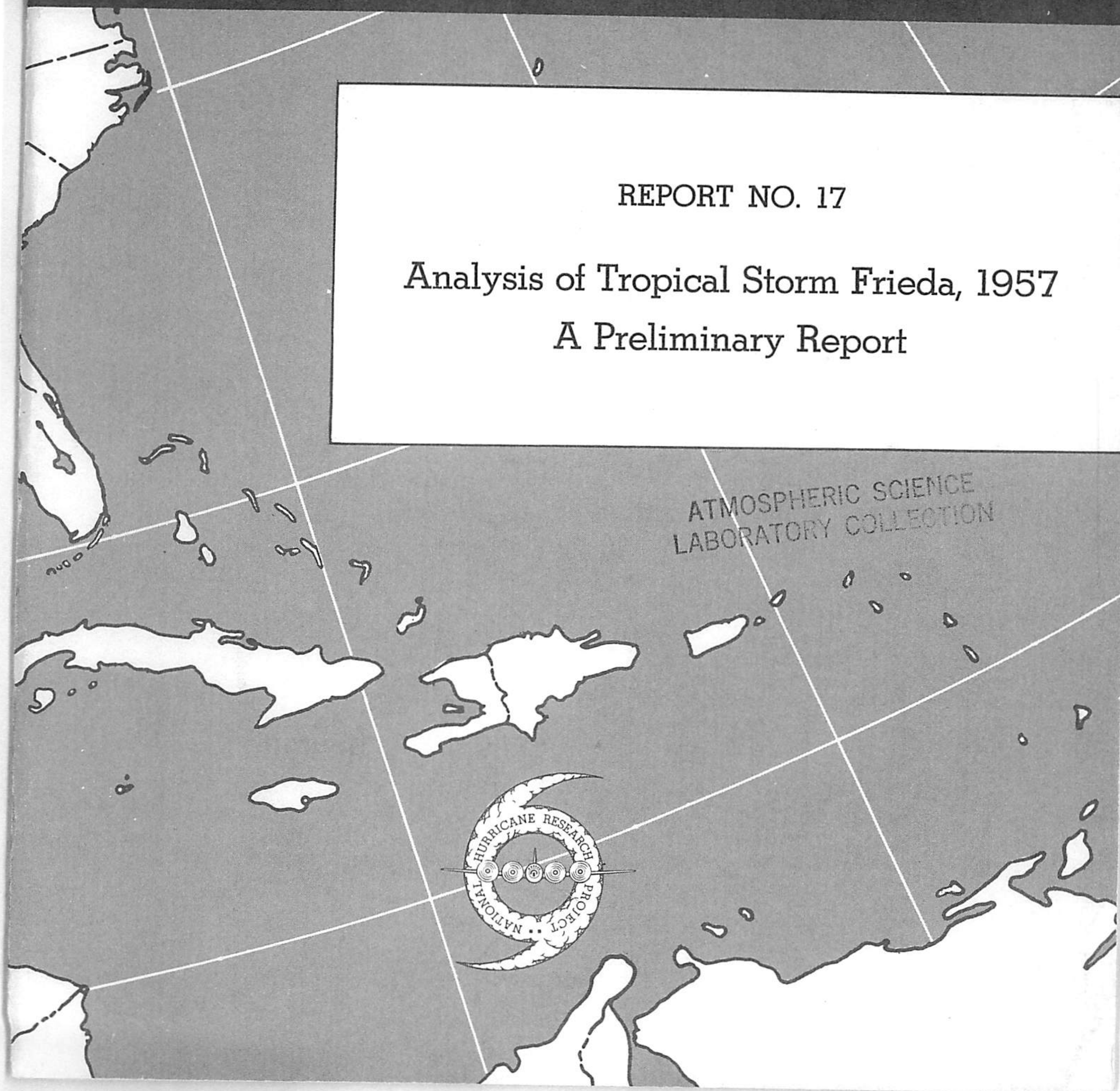

REPORT NO. 17

Analysis of Tropical Storm Frieda, 1957
A Preliminary Report

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

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Analysis of Tropical Storm Frieda, 1957
A Preliminary Report

by
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Washington, D. C.
June 1958

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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ANALYSIS OF TROPICAL STORM FRIEDA, 1957

A Preliminary Report

by

Herbert Riehl and R. C. Gentry

INTRODUCTION

One of the principal aims of the National Hurricane Research Project [5] is to gain greater understanding of the structure and dynamics of the hurricane, with a view toward improving forecasts of formation, intensity, and movement of hurricanes. The Research Operations Base of the Project at West Palm Beach, Fla., has been principally engaged in the data collection phase of the experiment for the last two years. The purpose of the present paper is to present a case study, using data collected by the Project, to illustrate some of the approaches toward understanding the tropical cyclone and its evolution, as made possible by the new observations.

During the 1957 hurricane season, one developing disturbance occurred within range of the three aircraft operated by the Air Force in support of the Project. This situation later developed into hurricane Frieda. On three successive days before the storm reached its greatest intensity, flights were made into the storm area by these research aircraft, which include two B-50's for operation in the low and middle troposphere and one B-47 for operation in the high troposphere. In addition to the flights made by the research aircraft, operational missions were carried out by the hurricane reconnaissance squadrons of the Air Force and Navy. These data were analyzed in conjunction with the upper air and surface reports from established weather stations and from ships at sea.

This discussion of the development of tropical storm Frieda will describe the situation first near the surface (approximately 1200 to 1500 feet), then in the middle troposphere and, finally, in the upper troposphere. Charts will be presented showing detailed analyses of the wind, temperature, and pressure fields for September 21, 22, and 23, 1957.

SUMMARY OF DEVELOPMENT

Figure 1 gives the track of Frieda. Here the brackets show the portions of the path covered by the research aircraft. The disturbance developed in a surface trough which remained after dissipation of a weak cold front. This trough was present on September 20; and on September 21, when the first research flight was made the maximum winds in the disturbed area reached 48 knots. Superficial examination of the storm at that time might have indicated that the disturbance was about to intensify into a hurricane. Actually, how-

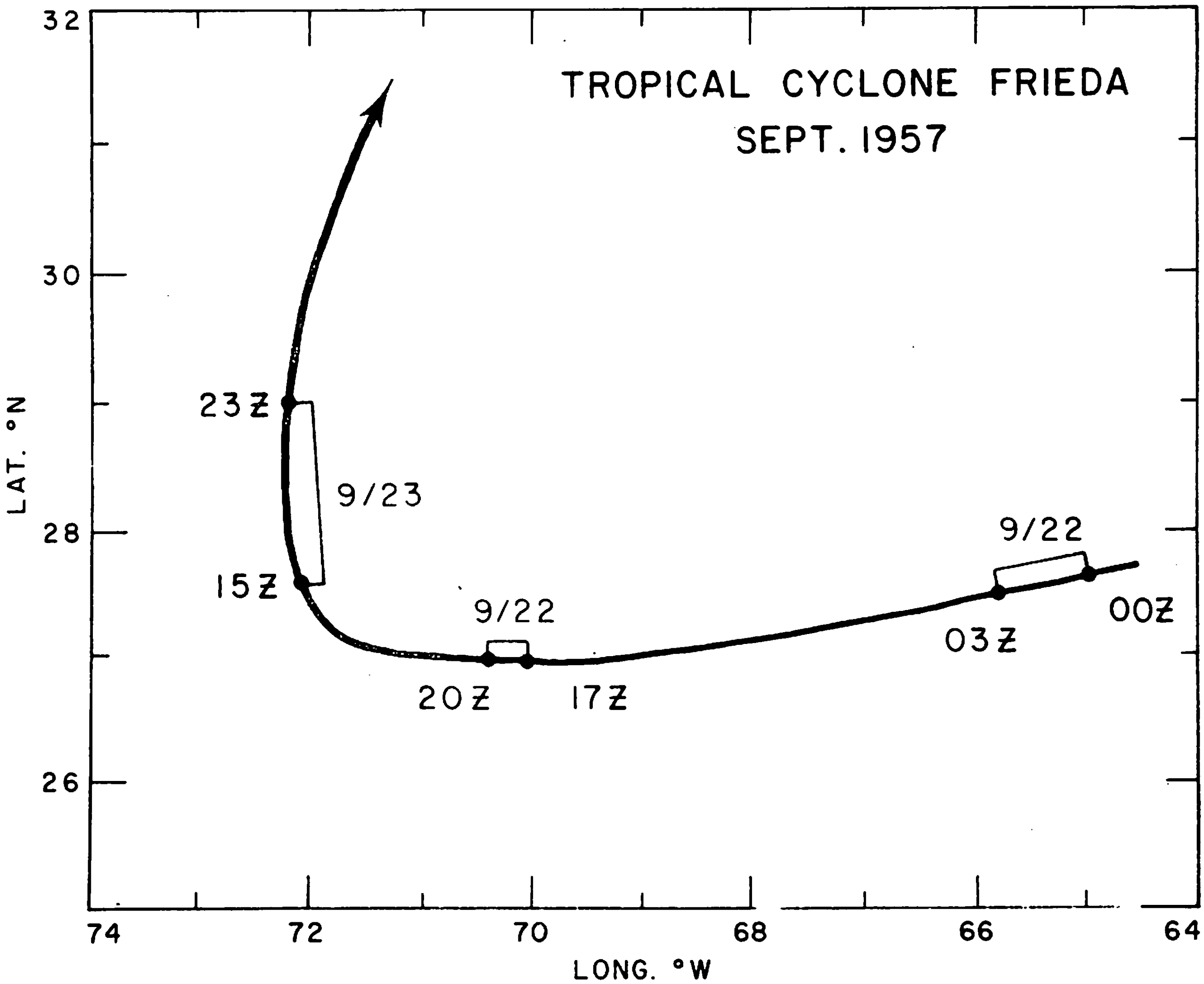


Figure 1. - Track of tropical storm, September 21-24, 1957.

ever, the storm weakened, and on the 22d there was relatively little cloudiness. Subsequently, on the 23d a renewed increase in wind speed and a large increase of cloudiness occurred. It will be shown that on the 23d a type of simple atmospheric heat engine was operating which produced the increase in kinetic energy. This heat engine was not present on the 22d when the decrease in intensity was observed.

Despite the intensification observed on the 23d, the strongest winds were located farther from the center than on earlier flights: at a radial distance of 150 miles in the important eastern quadrant. On September 24, slow intensification continued, and on the 25th the winds reached hurricane force as the storm came in contact with an extratropical disturbance. No research missions were flown on these days. Operational flights, however, were conducted by the Air Force and Navy. This combination of data collection made it possible to measure changes of the various parameters following the storm center.

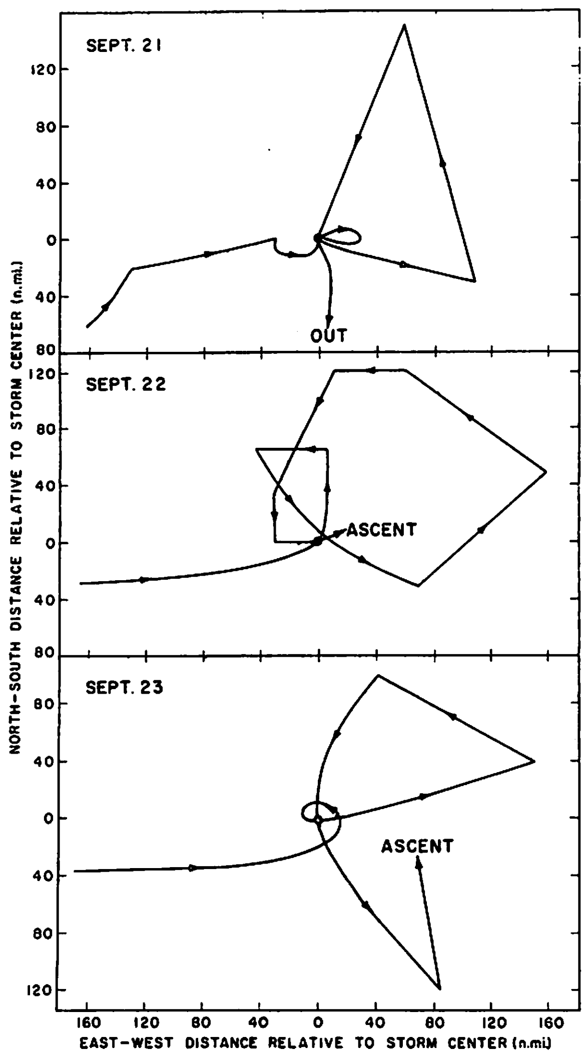


Figure 2. - Flight paths executed relative to tropical storm by B-50 aircraft at 1200-1500 feet, September 21-23, 1957.

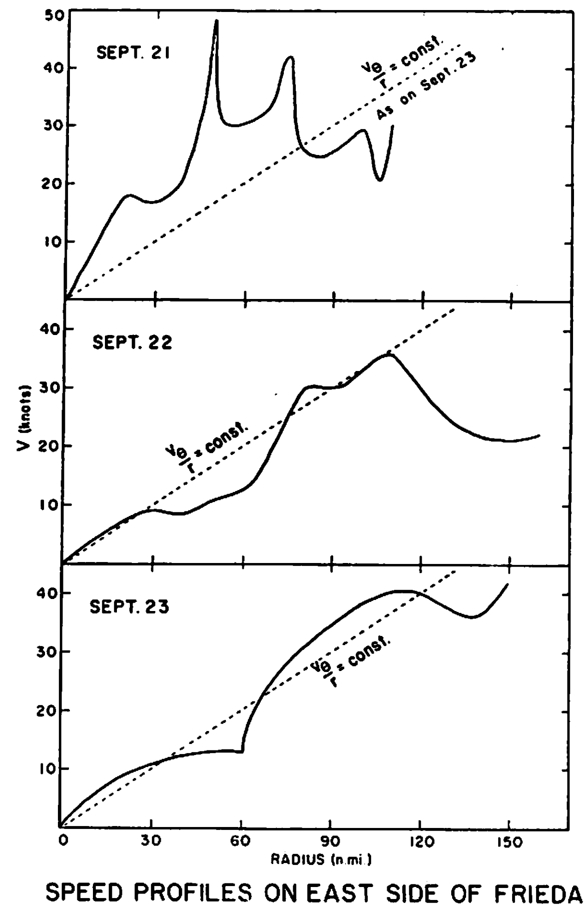


Figure 3. - Profiles of wind speed (V) on eastern side of center, September 21-23, also line of v_θ/r = constant, fitted for September 22.

THE SITUATION NEAR THE SURFACE

Figure 2 illustrates the tracks of the research aircraft through the storm at 1200-1500 feet (pressure altitude). On each chart, the black dot represents the center of circulation at the surface. The flight pattern relative to the storm center chosen on each of the three days was similar, and this facilitates computation of time variations with respect to the center.

Let us now consider the distribution of (1) wind field, (2) pressure field and its relation to the wind field, and (3) the thermodynamic properties of the low-level air mass.

Wind Field. - Approaching the storm from the west, the aircraft encountered nearly uniform northerly winds of 10-20 knots. The weather was rela-

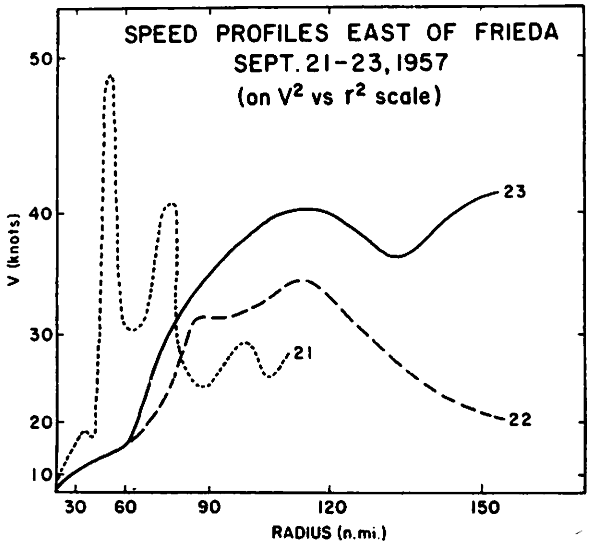


Figure 4. - Profiles of wind speed against radius on eastern side of storm (on V^2 vs r^2 scale), September 21-23, 1957.

tively fair from the mainland to the center of the storm; this was true on all three days. The most interesting feature was the distribution of winds to the east of the center where the principal convergence occurred. Figure 3 shows profiles of wind speed in this area plotted against the radius for each of the three days. The strongest speeds, 48 knots, were observed on the 21st, 50 miles from the center. On the 22d the strongest winds were removed to the 110-mile radius and had decreased to 35 knots. On the 23d winds had again picked up and were about 45 knots, but had moved out even farther. Strongest winds at flight level were encountered 150 miles east of center - the farthest point reached by the aircraft. A survey of surface ship winds indicates that the winds decreased beyond this radius.

The broken line in figure 3 represents profiles of the tangential wind components (v_θ) for solid rotation; i.e., the ratio v_θ/r is a constant. Note how closely the actual distribution of wind speed on September 22 and 23 approached this line (the wind speed V and the tangential component v_θ were nearly equal). The same line is reproduced for comparison on the graph of September 21. Although total kinetic energy on the 23d was greater than on the 21st, the profile for the 21st was more typical of that of a hurricane - since the strongest winds were concentrated around the center. The winds increased in speed from the 22d to 23d but the strongest winds became less concentrated around the center instead of moving nearer to it as would have occurred during hurricane formation.

Figure 4 illustrates the course of kinetic energy on the eastern side of the storm. Here wind speed is plotted against the radius on a V^2 vs r^2 scale in order to make the area beneath the wind speed curves proportional to kinetic energy in the eastern sector. Close to the center of the storm, the kinetic energy was much greater on the 21st than on either of the two succeeding days. Aircraft data were not available to the 150-mile radius on the 21st but, as shown also by ship reports, the kinetic energy was greater in the outer area on the 23d. The distribution, however, was quite different. On the 23d the high kinetic energy was due mainly to the fact that moderately high winds occurred over a large area, whereas on the 21st the kinetic energy per unit mass was greater but it was restricted to a small area in the belt from 40 to 80 miles from the center.

Perhaps the most intriguing feature of the successive profiles is that the kinetic energy on the 23d was equivalent in amount to that which would have been observed had the storm reached full hurricane intensity with maximum winds concentrated close to the center. Figure 5 gives the comparison between the kinetic energy on September 23 and that in a hurricane with 70-

knot winds at 25 miles and 90-knot winds at 16 miles from the center. The areas beneath these two curves, i.e., the total kinetic energy, are about equal.

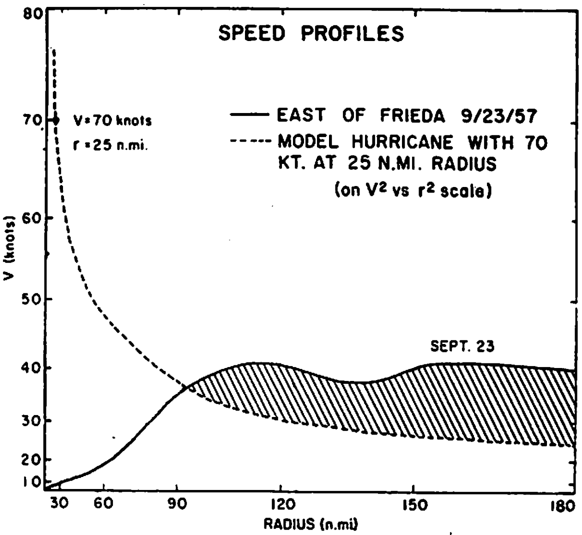


Figure 5. - Profiles of wind speed against radius for Sept. 23, repeated from fig. 4, and for hypothetical hurricane with a profile of tangential speed given by $v_\theta r^{1/2}$= constant. It is assumed that V and v_θ are nearly equal.

Pressure Field. - The surface pressure field on each of the three days was relatively flat. Central pressure was 1002 mb. on September 21, slightly higher (1005 mb.) on the 22d, and then dropped to 1001 mb. on the 23d. Sea level isobars on September 22 are shown in figure 6; streamlines of the low-level wind field observed by the B-50 aircraft are superimposed. This is the day on which the storm lost intensity. In the southern semicircle the streamlines crossed the isobars toward lower pressure, as is typical for developing tropical cyclones. What is not typical is that in the northern quadrant the streamlines crossed toward higher pressure indicating reduction of kinetic energy. In a developing situation the air in the lowest layer usually has a net component toward the center in the entire rear semicircle. The dotted line in figure 6 represents the boundary between areas in which flow is toward lower or higher pressure; the broken line separates areas of radial inflow and outflow. The two lines do not coincide because of asymmetries in the surface pressure field. Most of the clouds and radar echoes occurred in the southeastern quadrant where the air was moving toward lower pressure. The fact that the air did not flow toward the center in all quadrants indicates that centrifugal acceleration in the current moving toward the storm from the south became too large to permit the flow to continue inward to the point of lowest pressure utilizing the full pressure gradient for generation of kinetic energy. Further calculations of this aspect of the problem are planned and will be presented in the final report.

Thermodynamic Properties. - The thermodynamic properties of the lower layers were favorable for intensification of the storm on each of the three days. Ocean temperatures were high (83° to 84°F.) (see fig. 7) and several Fahrenheit degrees above the long period mean. Several studies have indicated that this should be favorable for hurricane formation; e.g., see Fisher [1] and Palmen [2]. The gradient in the temperature and dewpoint fields was very weak - even on September 21. The only low temperatures on that day (2°C. below average tropical air mass properties) measured by the aircraft were far north of the storm; air with this low temperature did not penetrate to the storm center, hence could not have inhibited development. Thus, from consideration of thermodynamic properties near the surface, there is no reason to expect that the storm could not easily become a hurricane. Further aspects of the temperature and dewpoint fields will be discussed in the final report.

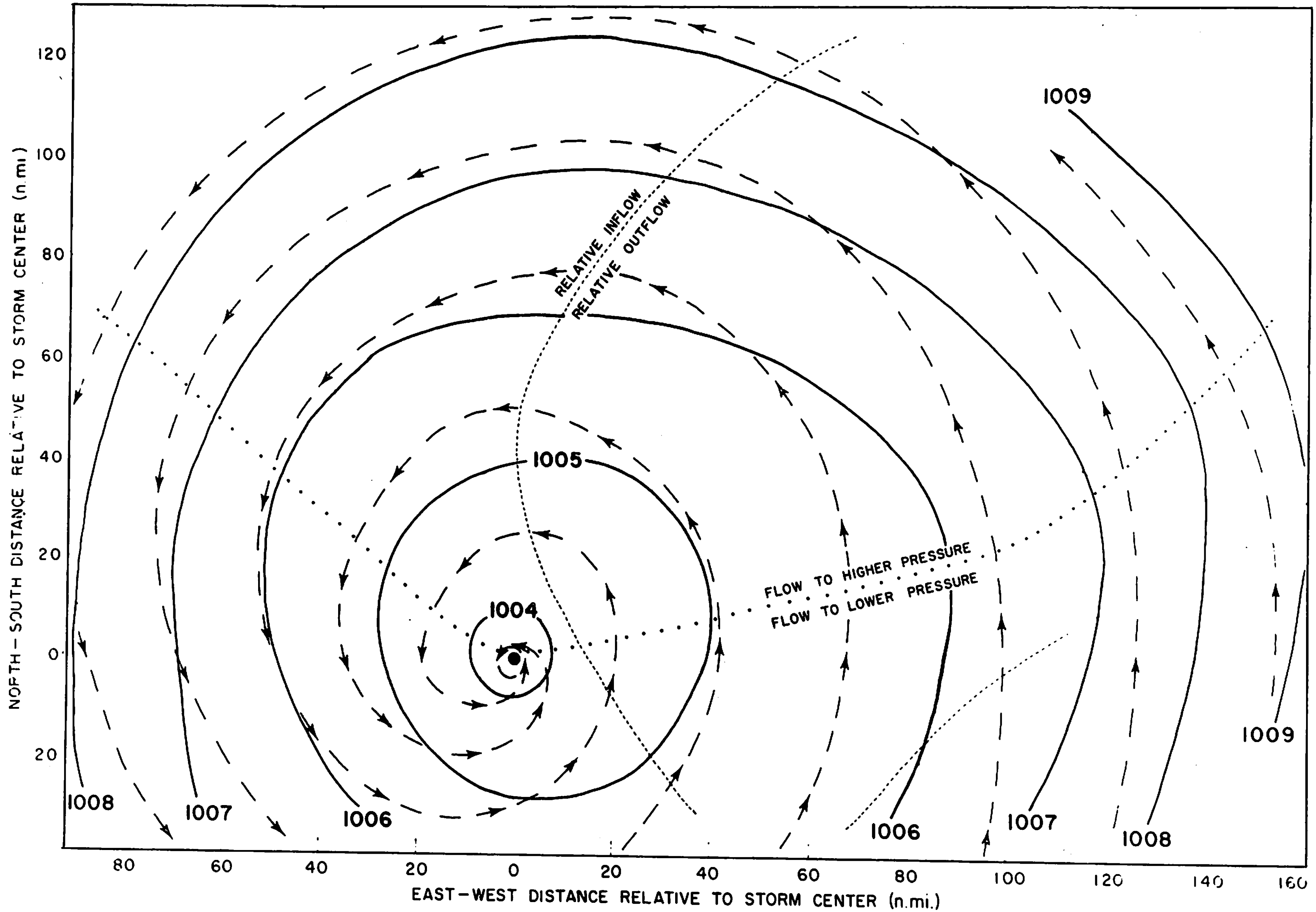


Figure 6. - Surface isobars and 1200-foot streamlines, September 22, 1957.

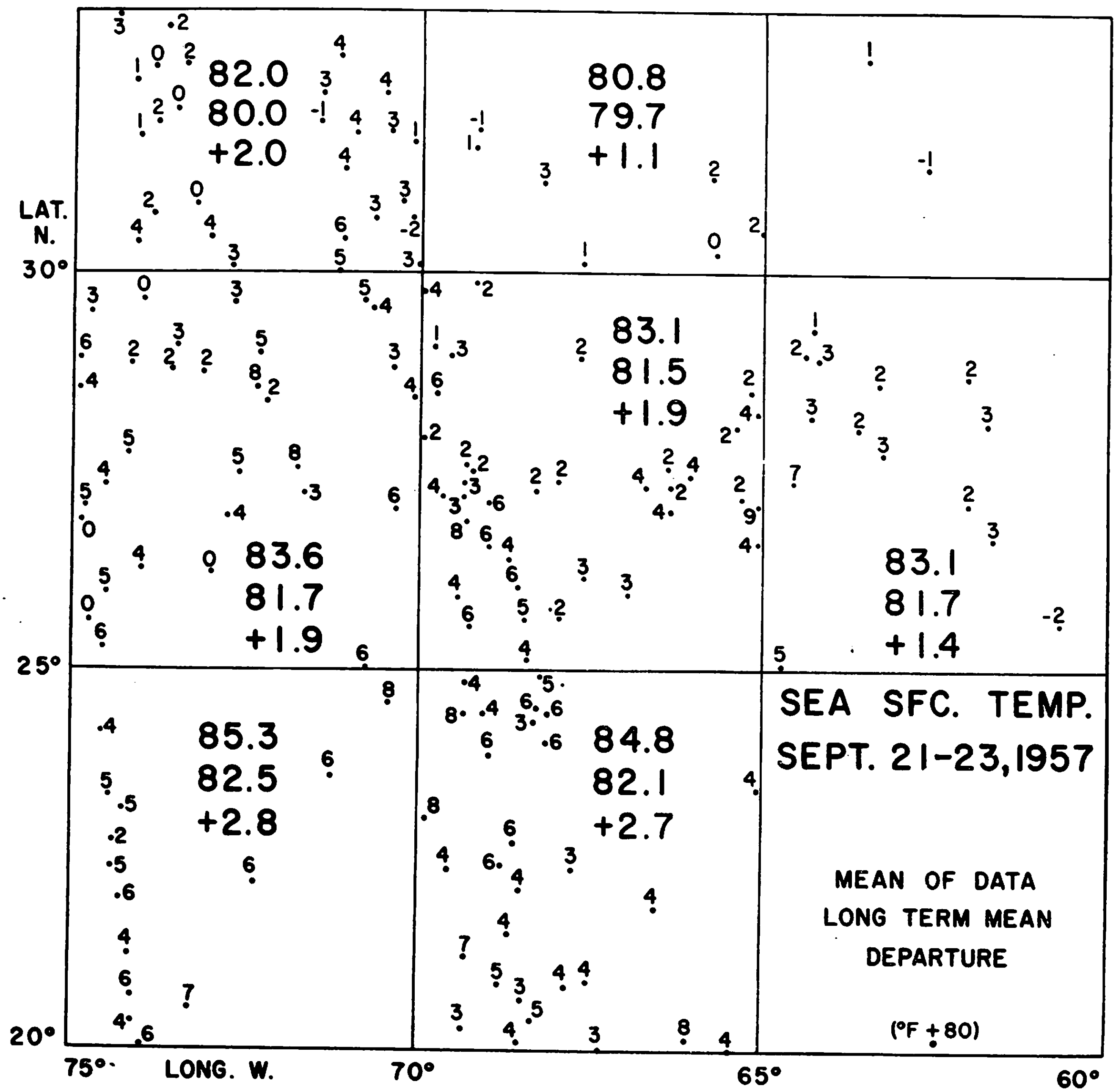


Figure 7. - Sea surface temperatures during the formation of Frieda. The small numbers are individual reports of ships. The large numbers give the means and departure from the long term mean.

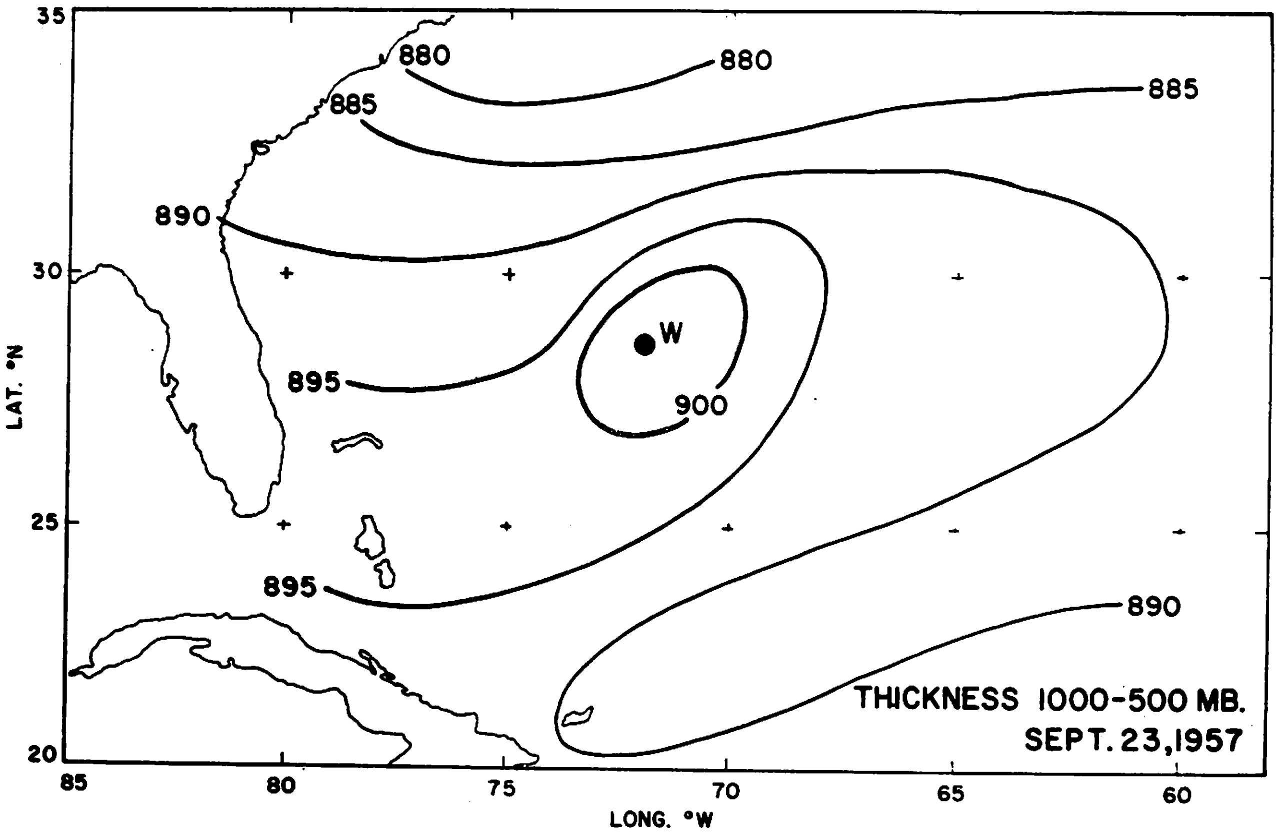


Figure 8. - Thickness 1000-500 mb. (tens of feet, first digit omitted), September 23, 1957. Station data for September 24, 0000 GMT.

THE SITUATION IN THE MIDDLE TROPOSPHERE

Measurements in the middle troposphere were made by the research aircraft on September 22 and 23, and by reconnaissance aircraft from the Air Force Squadron at Bermuda on the 23d. The thickness pattern for the layer 1000-500 mb. on the 23d, based on aircraft data, is presented in figure 8. From this diagram it is clear that Frieda had a warm core on the 23d.

The middle troposphere will be discussed further in the final report. For the present we shall turn to the upper troposphere where the most significant developments occurred.

THE SITUATION IN THE UPPER TROPOSPHERE

<u>September 22.</u> - The upper troposphere usually contains the principal outflow in developing and mature hurricanes [3]. This layer was investigated by B-47 flights at 35,000 feet (pressure altitude) on September 22 and 23. The analysis of figure 9 is based on wind data collected on the flight of September 22, supplemented by rawins. The aircraft left southern Florida and proceeded eastward to the storm, identified in figure 9 by the black dot.

It had been planned that the aircraft would cross over the storm area two or three times before returning to base. When the plane reached a point about 180 miles northeast of the center, however, the airborne data recording system began malfunctioning and no further observations were collected. Fortunately, the most important information had been obtained. The winds recorded northeast of the storm show the location of a trough line at 250 mb., which we believe was of vital importance to the development of Frieda. This trough line is also shown by the wind shift at Bermuda and by the upper wind reports over the Antilles. There was a concentration of cyclonic vorticity over and to the east of the surface center. If the upper trough propagated westward in relatively steady state, this flow pattern would call for convergence to the west and divergence to the east of the 250-mb. trough through conservation of potential vorticity. Assuming a top of the whole circulation near 150 mb., this implies descent in the middle and upper troposphere above the surface center, and ascent in the layers far to the east.

The temperatures measured by the B-47 on September 22 gradually increased as the plane proceeded eastward from Florida to a point south of the surface center. From the preceding reasoning these increasing temperatures near the storm center should have been due to subsidence. This hypothesis is supported by cloud photographs. Time-lapse cloud movies taken out of the side of the plane nearest the storm showed that the plane passed only four isolated cumulonimbus towers in 350 miles while traveling around the southern and eastern quadrants of the storm, the very area in which the heaviest convection occurred at low levels. Very few cirrus clouds were observed at any time until the plane crossed the trough line well to the east of the storm. Then the plane was in clouds most of the time. It appears that subsidence in the upper troposphere over the stormy area at the surface acted as a lid to prevent low-level ascent from extending upward to form an organized outflow shield. It also prevented the development of a thermally direct circulation.

This is considered to be the principal reason for the weakening of the storm on September 22, a conclusion further supported by deductions made from observations at low levels. As already seen, there was flow toward lower pressure in the southern quadrants, and toward higher pressure in the northern quadrants, but very little, if any, net inflow occurred on the eastern side of the storm where the precipitation area was situated. We may suppose that it was this lack of organized inflow which prevented hurricane formation, rather than lack of requisite thermodynamic properties in the surface layer or lack of suitable ocean temperatures. We may further suppose that development of organized inflow near the surface was inhibited by convergence and subsidence in the high troposphere. Instead of consolidating in a general outflow shield, the air rising in individual cloud bands was forced to descend in the immediate vicinity of the clouds producing local compensation. While this process of quasi-cellular motion produced warming of the whole storm area (fig. 9) it did not lead to a circulation in the vertical plane that was capable of releasing potential energy through ascent in the warm core with descent of cooler air in the surroundings.

September 23. - The trough line located to the east of the surface center on the 22d subsequently bypassed this center going westward, and by the next day (fig. 10) had reached a position about 250 miles to its west (large black

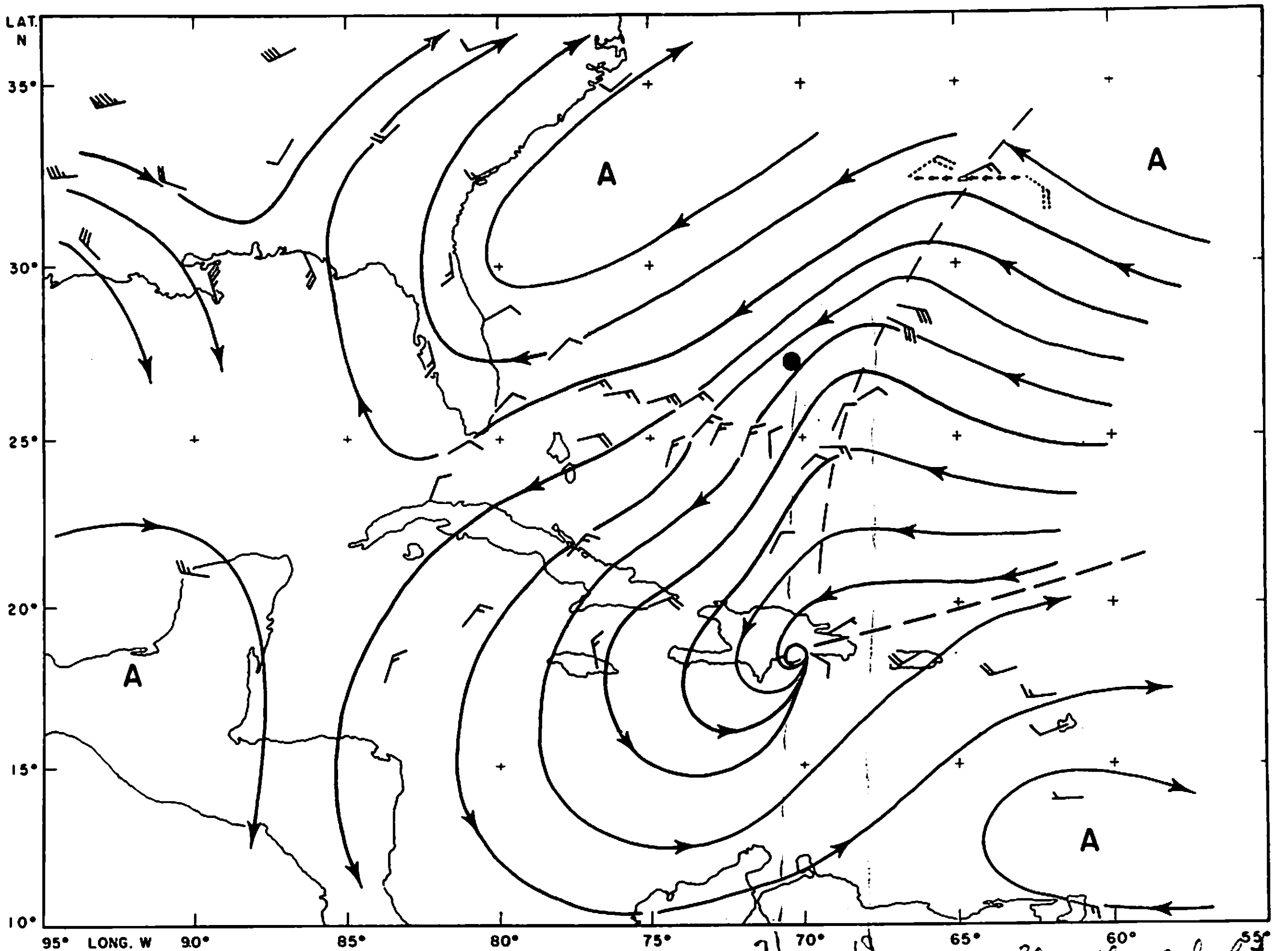


Figure 9. - 250-mb. streamlines, September 22, 1957. Station data for 1200 GMT.

dot). The previous position of the trough was occupied by a well-developed anticyclonic cell. Due to lack of observations in the central Atlantic it is not possible to make a definite statement about the earlier history of this anticyclone. It is likely, however, that it formed in the area where it is situated in figure 10 as part of the development of a thermal heat engine now to be described. With this relative shift of surface center and upper trough the storm again deepened, the kinetic energy in the low levels increased moderately, and the cloudiness increased very much. There was a notable increase in convective activity compared to September 22, and an outflow shield of cirrus clouds appeared for the first time on this day. This cirrus shield was observed from the B-50 flying at low levels and it was recorded by the cloud camera mounted in the B-47 which was in clouds about 80 to 90 percent of the time while within 100 miles of the storm center.

The 35,000-foot isotachs for September 23 are presented in figure 11. About 50 miles west of the surface center there was jet-like wind concentration with speeds of 40 knots and higher. The broken line in figure 11 in-

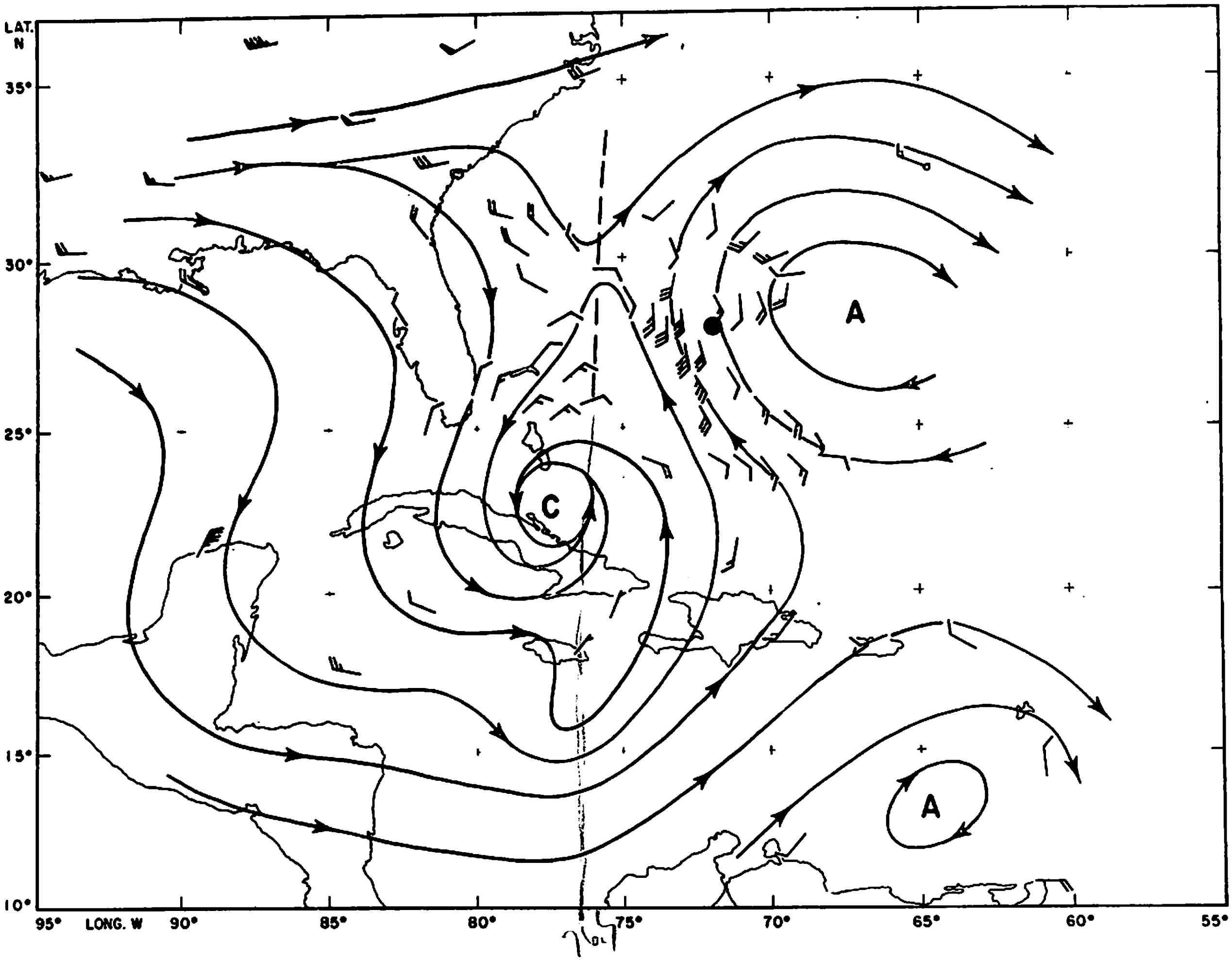


Figure 10. - 250-mb. streamlines, September 23, 1957. Station data for September 24, 0000 GMT.

dicates the axis of this jet which also corresponded closely to the western edge of the cloud shield flowing out from the intensifying storm. The cirrus clouds observed on the 23d were typical of the outflow pattern that should be expected from a warm core system.

Figure 12 depicts the isotherms at 35,000 feet (pressure altitude). The warmest air was located over and slightly to the east of the surface center. There was colder air to the west of the broken line which marks the axis of strongest 35,000-foot winds as in figure 11. A study of radar echoes and of the cloud observations shows that the heaviest concentration of radar rainbands and of increased cloudiness coincided closely with the warmest air at 35,000 feet.

The warm air in the upper troposphere was situated relative to the storm center at about the same place as on the 22d. It is plausible, however, on the basis of the evidence presented, that while the warm air on the 22d was produced by subsidence, that on the 23d was produced by the release of latent

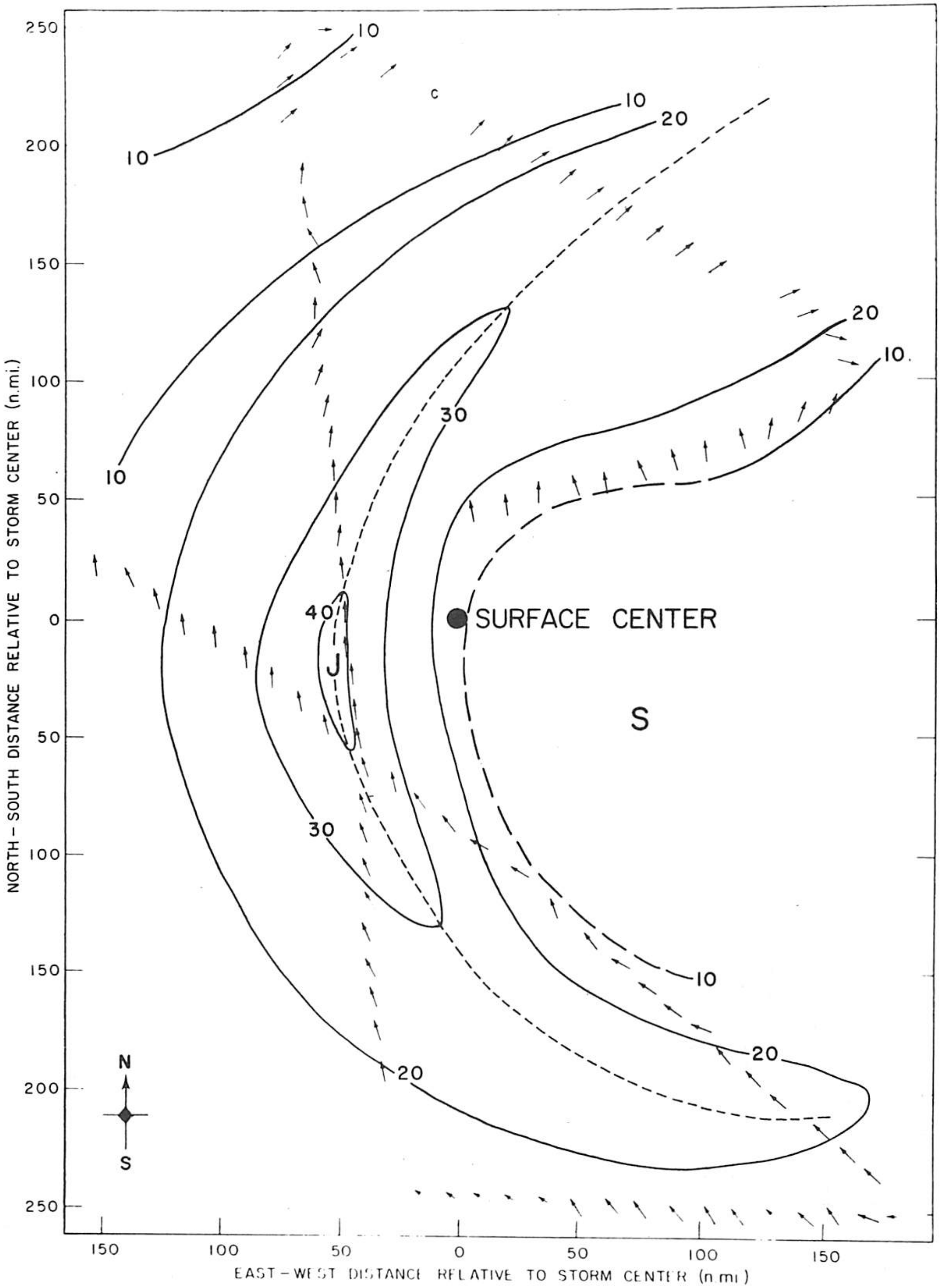


Figure 11. - Isotachs (kt.) and wind arrows for 35,000 ft. for B-47 flight, September 23, 1957.

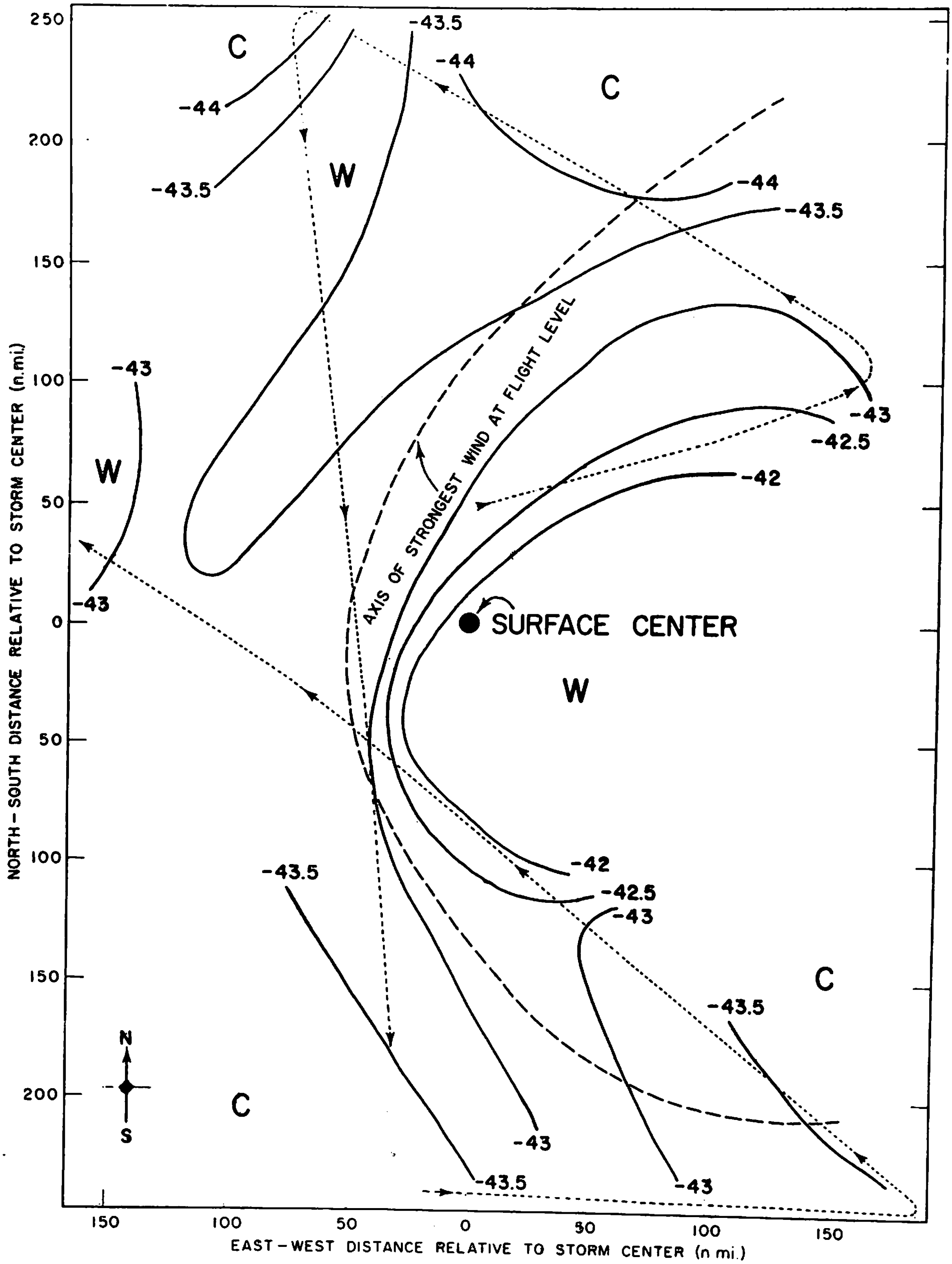
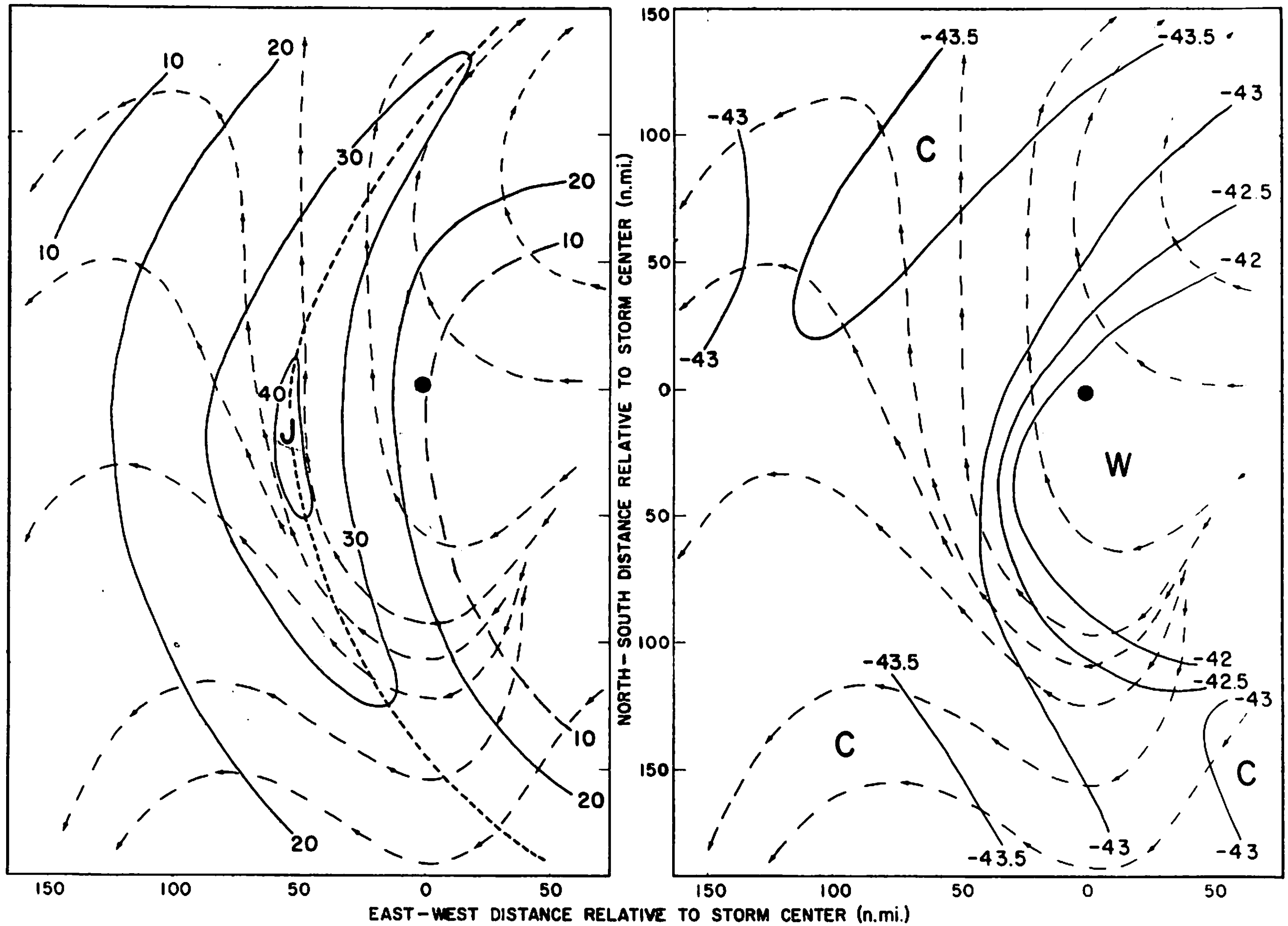


Figure 12. - Isotherms (°C.) at 35,000 ft. for B-47 flight, September 23, 1957. Broken lines with arrows indicate flight path.



ISOTACHS AND RELATIVE STREAMLINES

ISOTHERMS AND RELATIVE STREAMLINES

238 MB. SEPT. 23, 1957 (B-47 FLIGHT)

Figure 13. - Streamlines relative to moving surface center for winds observed by B-47 aircraft, September 23, 1957. Relative streamlines are superimposed on isotachs (left) and on isotherms (right).

heat in ascending air currents. Considering the 35,000-foot temperatures (fig. 12), the thickness of the layer 1000-500 mb. (fig. 8), and the distribution of convective clouds on September 23, it is quite clear that the air ascended in the area where the air was warmest, and descended in surrounding areas where the air was relatively cool and dense. It is strongly suggested by the distribution of the cirrus shield and by the wind pattern at 35,000 feet that the air ascended up to the line of velocity maximum. Beyond this line to the north and northwest the weather was generally fair and even low cloudiness was quite suppressed. In this area, then, a part of the descending current was located.

Relative streamlines showing the flow with respect to the moving surface center are given in figure 13. To the extent that we can assume that intensity and configuration of the storm changed only slowly, the relative streamlines indicate the air travel for at least a few hours after the time of observation. The isotachs and isotherms superimposed on the relative streamlines show that the relative motion was such as to produce flow from low to high velocity at 250 mb. in the area of temperature maximum. Thus we see here the high tropospheric part of a simple heat engine. The distribution of ascent and descent indicates release of potential energy by the mass circulation which by this time had increased considerably compared to the preceding day. The potential energy is restored by the release of latent heat. Thus, a heat engine has been established which produces useful work leading to an increase of kinetic energy both at low and high levels.

CONCLUSION

The increase in kinetic energy from the 22d to the 23d is attributed to organization of a simple heat engine, and this was made possible by a change in the type of superposition of upper and lower wind systems. This heat engine could not be established until the trough in the upper troposphere and its attendant divergence field moved across the surface center. It is of interest that superposition of upper and lower circulation systems was fairly independent since the upper system was moving much faster than the center near the ground. This important contribution of the upper flow to cyclogenesis had previously been deduced by Riehl [3] and Simpson [4] but in the present case detailed observations are available for the first time to support the hypothesis fully.

Since the low-level wind field took the form of solid rotation up to a great distance from the center rather than of a hurricane-type circulation, we do not yet know the sufficient conditions for hurricane formation. In this study, however, we do have an answer to some of the necessary conditions for formation of hurricanes and for increase of kinetic energy. It is hoped the data can be collected in comparable situations that develop into hurricanes, and that the missing link can be supplied which will enable us to list also the sufficient conditions for tropical cyclogenesis.

NOTE: It is expected that the final report of this case will be completed within the next few months. This preliminary report is a summary of a paper presented at the New York Meeting of the American Meteorological Society in January 1958.

ACKNOWLEDGMENTS

Mr. Arthur W. Johnson and Mr. R. H. Simpson each participated in one of the research flights and made large contributions in the data collection efforts; and the data were processed by the staff at the Research Operations Base. The authors also wish to acknowledge the many helpful suggestions made by Mr. R. H. Simpson, Director of the National Hurricane Research Project, during the preparation of this study and his assistance in reworking the manuscript.

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