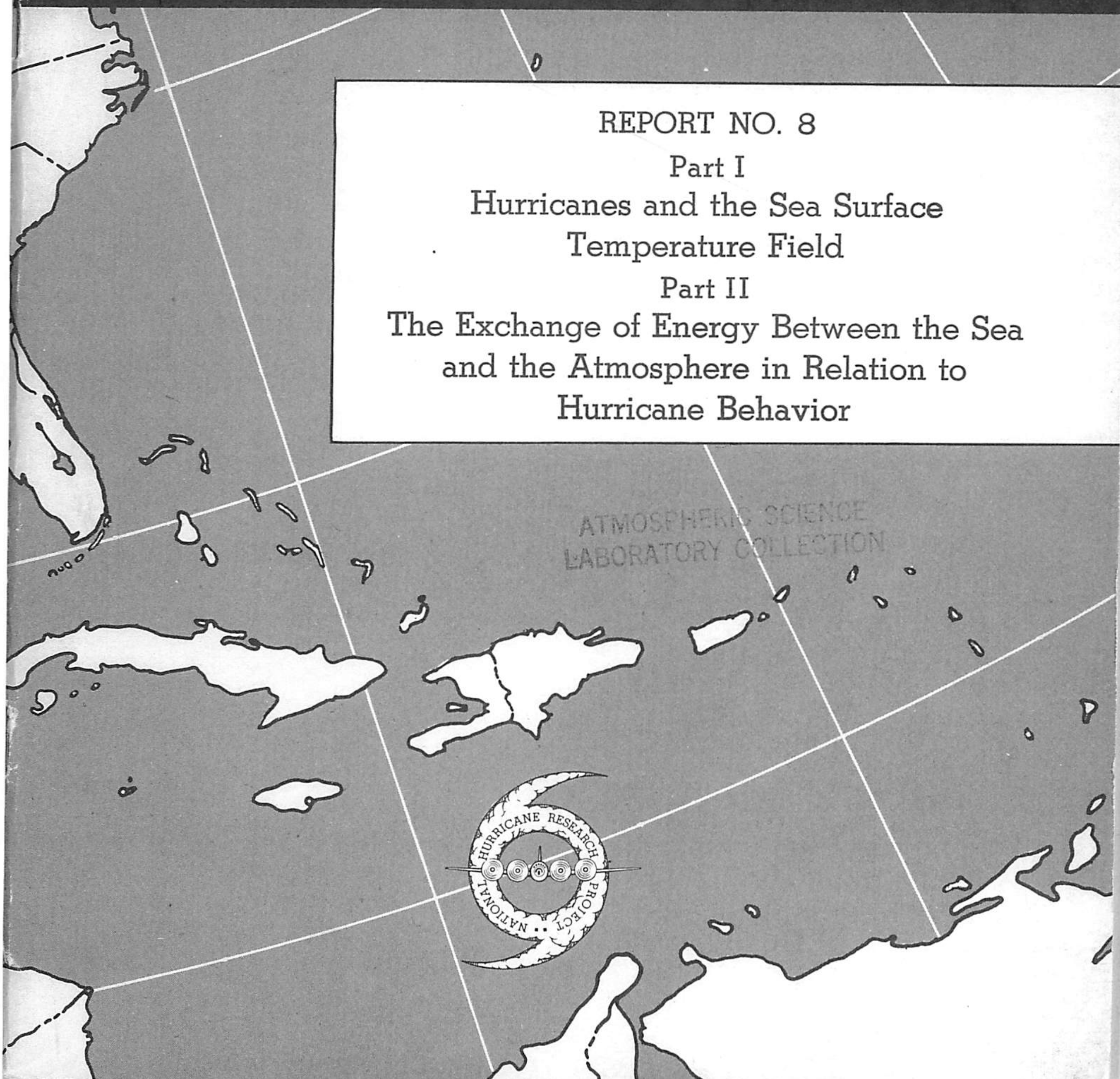
NAL HURRICANE RESEARCH PROJECT



REPORT NO. 8

Part I
Hurricanes and the Sea Surface Temperature Field

Part II
The Exchange of Energy Between the Sea and the Atmosphere in Relation to Hurricane Behavior

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL HURRICANE RESEARCH PROJECT

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Part I
Hurricanes and the Sea Surface Temperature Field
Part II
The Exchange of Energy Between the Sea and the Atmosphere in Relation to Hurricane Behavior

by

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Washington, D. C.
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Commerce-Weather Bureau, Washington, D. C.

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ABSTRACT

In Part I of this report the behavior of hurricane tracks and the variations of the intensity of hurricanes are investigated in a study of the sea surface temperatures around eleven hurricanes. By the use of several methods of analysis, it is found that there is distinct, although not conclusive, evidence that hurricanes tend to form near relatively warm ocean areas, that they tend to follow tracks along the areas of warmest water, and that they tend to weaken when they move over pronouncedly colder water.

The study reported in Part I having suggested a relationship between sea surface temperatures and hurricane behavior, it was felt that the mechanism producing this effect must be the eddy flux of energy from sea to air in the vicinity of a hurricane. In Part II this is investigated synoptically by means of the equations used by Jacobs, and it is concluded that there is some evidence of a relationship.

PART I. - HURRICANES AND THE SEA SURFACE TEMPERATURE FIELD[1]

[Manuscript received December 14, 1956; revised April 25, 1957]

INTRODUCTION

It has long been obvious that there must be an intimate relationship between the life cycle of the hurricane and the sea. Since hurricanes are known to form only over the oceans during those portions of the year and over those areas where the sea surface temperatures are normally very high, it is natural to study the sea surface temperature field to discover if any direct relationship can be found. From a climatological point of view, Palmén [11][2], Byers [3], Bergeron [1], and others have already demonstrated the reasonableness of this approach. However, whenever attempts have been made to examine this relationship more closely, the difficulties imposed by the nature of the data have made such studies complex and inconclusive. Riehl [13] has recently completed a study of the monthly sea surface temperature anomaly field in relation to hurricane formation and tracks, and he reports that he could find little evidence of a relationship except on a very long-term basis.

In the present study, an attempt has been made to approach the problem from a somewhat different point of view. Bleeker (unpublished) has drawn the sea surface temperature field for the North Atlantic Ocean averaged over a 3-day period, and has met with some success. Here, we have attempted to draw the sea surface temperature charts on a daily basis in the hurricane areas of the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Charts have been prepared for most of the hurricanes of 1954 and 1955 along with one hurricane in 1953, a total of 16 storms. Before launching into a discussion of the results, it is advisable to examine the amount and nature of the data available.

THE NATURE OF THE DATA

The sea surface temperature reports used were those compiled by merchant vessels taking weather observations. The observations are made in a number of ways, using instruments whose accuracy is not fully known, by observers whose degree of training and whose diligence are also not known. Many of the observations are taken from the readings of the intake thermometers on the ships, and these may be located at varying depths beneath the sea surface, and errors may be introduced by the location of the instrument on the vessel itself.

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[1] Original paper was identified as Technical Paper No. 1, Hurricane Project, Contract No. Cwb-8731 (sponsored by U. S. Weather Bureau, National Hurricane Research Project), Department of Meteorology and Oceanography, College of Engineering, Research Division, New York University, New York, N. Y., July 1956.

[2] Numbers in brackets indicate references listed on pp. 45-46.

With these difficulties in mind, it was decided that a brief study of the reliability of the reports should be made. For this purpose, an area in the Gulf of Mexico was chosen where the temperature gradients were very small and where the number of ship reports was quite dense. The accompanying chart, figure I-1, shows the location of the region studied. All sea surface temperature reports in this area for the period August 23-26, 1955 were tabulated and analyzed. There were 245 reports, and figure I-2 is a histogram showing their distribution. The array is very nearly normal, although somewhat peaked, with the mode, the mean, and the median all falling at the value of 86° F. The standard deviation is 1.4°, indicating the very narrow spread of the bulk of the reports. This value of the standard deviation is strongly affected by the two observations of 79°, both of which can easily be spotted by an analyst as obviously incorrect. The data indicate that the ship reports are surprisingly accurate, particularly when one recalls that the observations were accumulated over many hundreds of square miles of sea surface over a 4-day period, and both the space and time variations of the temperature must have contributed somewhat to the size of the dispersion.

However, this degree of accuracy must be measured against what tolerances the analyst is allowed. As will be seen in the material to follow, since the temperature gradients are small, the tolerance in the analysis of the temperature field of subtropical waters is quite narrow, probably of the order of one or two degrees.

The next points of importance are the number and distribution of the reports. The total number of reports each day of the sea surface temperature in the subtropical regions from 10° N. to 40° N. latitude and 50° W. to 97° W. longitude is quite adequate, running between 250 and 450 observations. However, the distribution is very irregular. Most of the reports come from the shipping lanes, leaving large areas where only sparse data appear. In addition, quite understandably, ships have a strong tendency to avoid hurricanes, thus leading to a pronounced shortage of data in the very critical regions in the immediate vicinity of storms.

From the above discussion, it is seen that we are confronted with serious obstacles in the form of data of not quite adequate accuracy, poorly distributed, with a pronounced sparsity in the most critical regions. While these difficulties pose some trying problems, nonetheless, they are not entirely insurmountable, and the following descriptions of the results obtained will reveal interesting features which emerge in spite of the above inadequacies.

THE METHODS OF ANALYSIS

As a starting point for the investigation, it was decided to examine the hypothesis that the sea surface temperature field affected either the tracks of hurricanes or their intensity. From the work of earlier investigators, such as Jordan [6] and Riehl and Haggard [14], it is known that hurricane tracks tend to be governed by the direction and speed of the flow of the segment of the atmosphere in which they are embedded. In some cases, this flow is strong and fast and the hurricane moves rapidly in its direction with little meandering. In other cases, the flow is sluggish and ill-defined, and

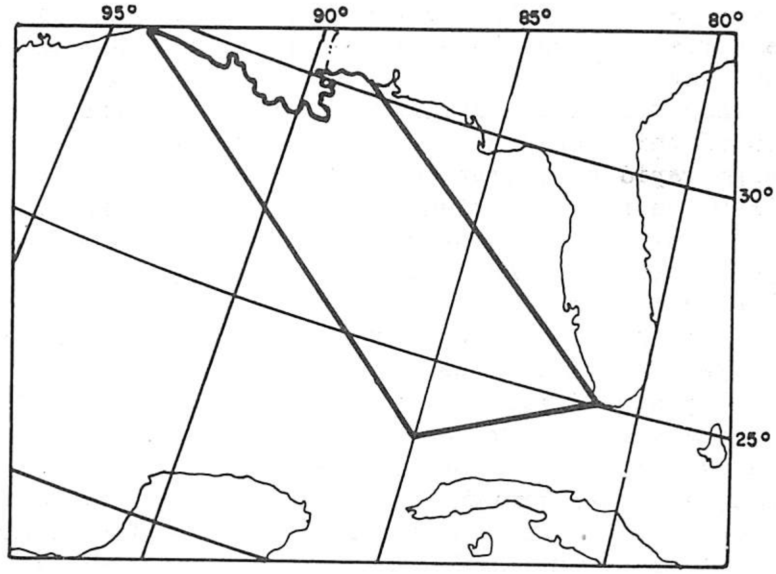

Figure I-1. Region where sea surface temperature reports were collected for August 23-26, 1955.

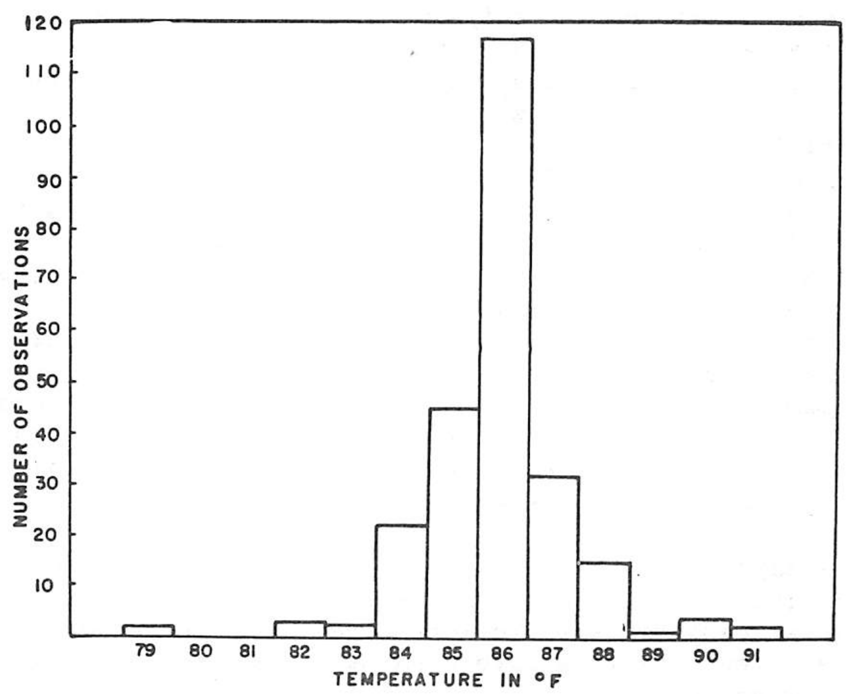

Figure I-2. Number of observations plotted against temperature for Aug. 23-26, 1955.

the hurricane moves slowly on a meandering path with frequent pronounced changes of direction. Certainly, if the track of a hurricane is to be influenced by the sea surface temperature field, the effect should be most strongly detected amongst this latter type. Thus the hurricanes studied were examined only while they were south of latitude 35° N., since, generally, once they move north of this latitude, they become grasped firmly by the westerlies and undergo rapid acceleration whilst losing many of their tropical characteristics. From the point of view of hurricane intensity, the sea surface temperatures fall very rapidly north of latitude 35° N. along the coast of the North American continent, and it is upon crossing into this abruptly colder water that one would expect to find a pronounced decrease in intensity. However, it is also in this region that a hurricane is most likely to receive an "impulse" from extratropical sources in the form of an approaching trough aloft or perhaps a surface cold front or both. This is not altogether a chance phenomenon, since when a hurricane recurves and begins to move northeastward, it is generally because it has become enmeshed in the southerly current ahead of an approaching trough aloft. In spite of these complications, it was possible to find at least one hurricane which moved into the colder northern waters without any pronounced extratropical "impulse" and its behavior will be examined later.

As a first step, the temperature data for each day of each hurricane were plotted for the area in the general vicinity of the storm. These data were then analyzed and the obviously incorrect reports were either corrected or eliminated. It should be stressed that only those ship reports were eliminated which were very definitely incorrect, and then only after the ship had been traced for as many days as possible so that its reports could be compared with those of neighboring ships whose observations were considered reliable. If there was any doubt as to the accuracy of any ship, its report was left in. Thus, the eliminations and corrections were relatively infrequent and did not amount to more than a few percent of the total data. Some examples of the plotted data with indications of those that were corrected or eliminated are given in the Appendix. All observations for any one 24-hour period were plotted on the same chart so that the maps would show the approximate temperature distribution for that day. Sea surface temperatures were found to change rather slowly, except in the immediate vicinity of a hurricane. Drawing charts meaned for a single day's temperature field did not introduce large errors, although it was found that there were enough important changes in the temperature fields, especially within a few hundred miles of a hurricane center, to made it impractical to average the field over a period longer than one day. It is this factor which may be the reason why monthly averages such as used by Riehl [13] revealed little relationship between the temperature fields and the behavior of the hurricanes.

The charts were analyzed in a careful manner, with strong emphasis on the continuity of the various features of each chart. In all honesty it must be pointed out, that at many times there were large areas of uncertainty in the analysis. However, few liberties have been taken, and the analyses follow the data as closely as possible.

Of the sixteen storms selected for study, the data on five (Alice Dec. 31-Jan. 5, 1955; Hurricane No. 5 Aug. 23-29, 1955; Edith Aug. 24-30, 1955; Gladys Sept., 3-6, 1955; and Hurricane No. 12 Oct. 10-14, 1955) were too sparse to be successfully analyzed. In figures I-3 through I-15, the sea surface temperature fields for the remaining eleven storms are reproduced. The following is a brief résumé of the behavior of each of the storms:

Dolly (Sept. 9-12, 1953, fig. I-3): This storm formed over warm water (about 82°-84° F.) near Hispaniola, and for the next three days followed a warm tongue of water northward. On the fourth day, September 12, the hurricane accelerated rapidly northeastward, possibly under the influence of a strong atmospheric flow in that direction, and was driven over considerably colder water northeast of Bermuda. At this time, according to Norton [10], the storm "lost force rapidly without apparent cause." It is very possible that the rapid collapse of this storm was due to the effect of the colder water upon the storm's intensity. There was no trough aloft in the vicinity, and, although there was colder air to the northeast of the hurricane, this may have also been associated with the cold sea waters.

Carol (Aug. 25-31, 1954, fig. I-4): Carol formed near the southern Bahamas over an area where the sea surface temperatures were of the order of 84° F. She then followed a belt of warm water northward for several days until the 27th of August when a tongue of cooler water pushing southward approached her track from the northeast. At this point Carol turned northwestward toward warmer water, and then continued to follow the warmest water toward the northeast along the coast. Aside from this odd change in path which occurred as the storm neared slightly colder water, another feature of considerable interest is the pool of decidedly cold water which formed behind the storm on the 29th and 30th. The appearance of cold water behind certain hurricanes during portions of their tracks will be found to occur in numerous other storms, and is apparently due to the upwelling of colder water.

Edna (Sept. 6-10, 1954, fig. I-5): Edna formed in a region of homogeneous temperatures ranging near 84° F. Between the 6th and 8th she moved over a broad region of 84° temperatures, and it was not until the 9th and 10th that she moved northward following a warm tongue between two slightly colder areas. By the 11th, she had accelerated rapidly and had moved far northward over much colder water. Unfortunately, she was overtaken by a trough aloft at this time and it was not possible to determine whether the colder water caused any weakening of the system.

Hazel (Oct. 6-15, 1954, figs. I-6 and I-7): The sea surface temperature field around Hazel was confused and irregular, and although there seem to be indications that she tended to follow warm water, the patterns are too indefinite to be certain.

Connie (Aug. 4-12, 1955, figs. I-8 and I-9): For the first few days of Connie's existence she traveled through areas where the data were too sparse for analysis; however, from the 6th on she headed steadily along or toward a tongue of warm water. Beginning on the 7th, and following Connie throughout the remainder of her carrer, an area of cold water formed immediately behind

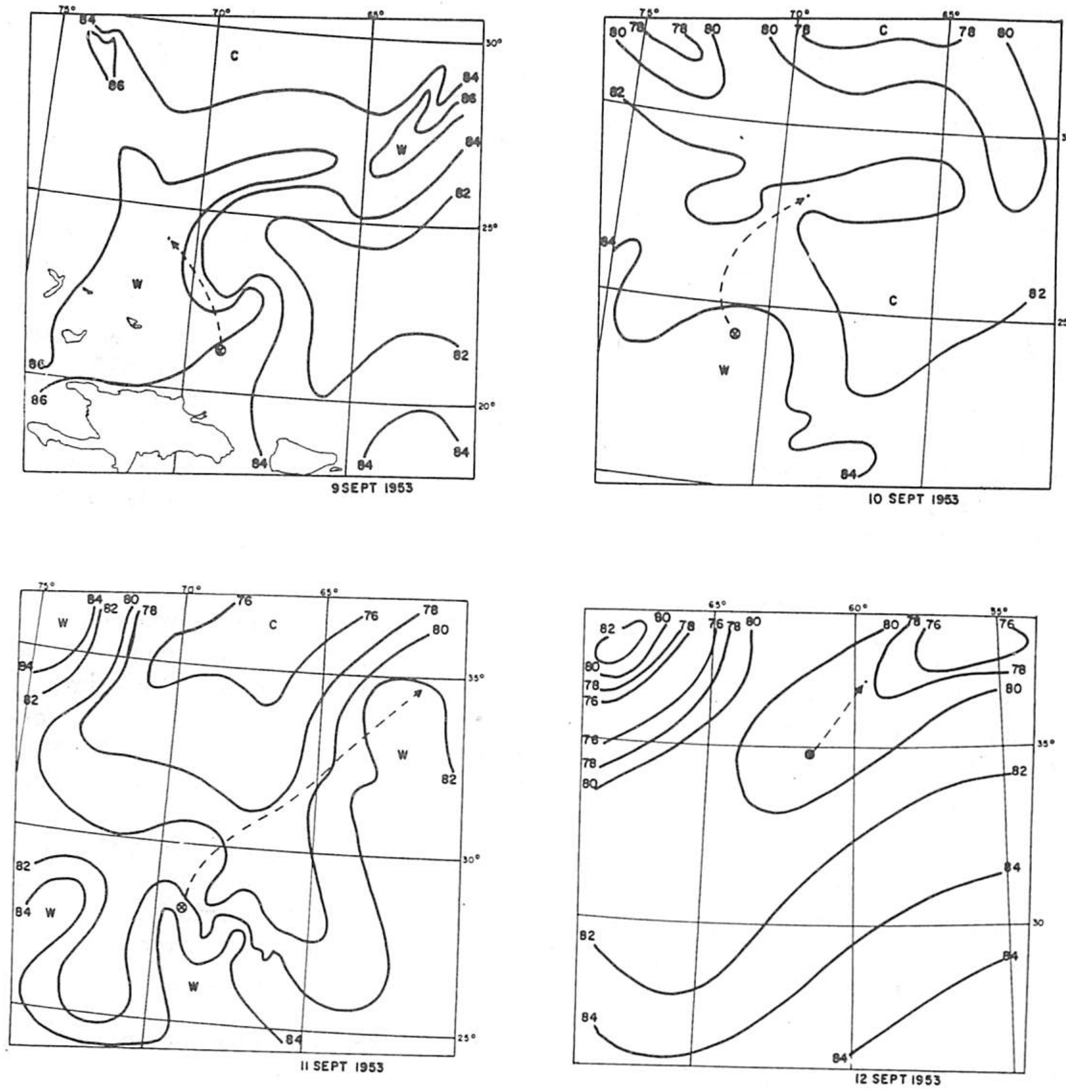

Figure I-3. Sea surface temperature field in the vicinity of hurricane Dolly, Sept. 9-12, 1953. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

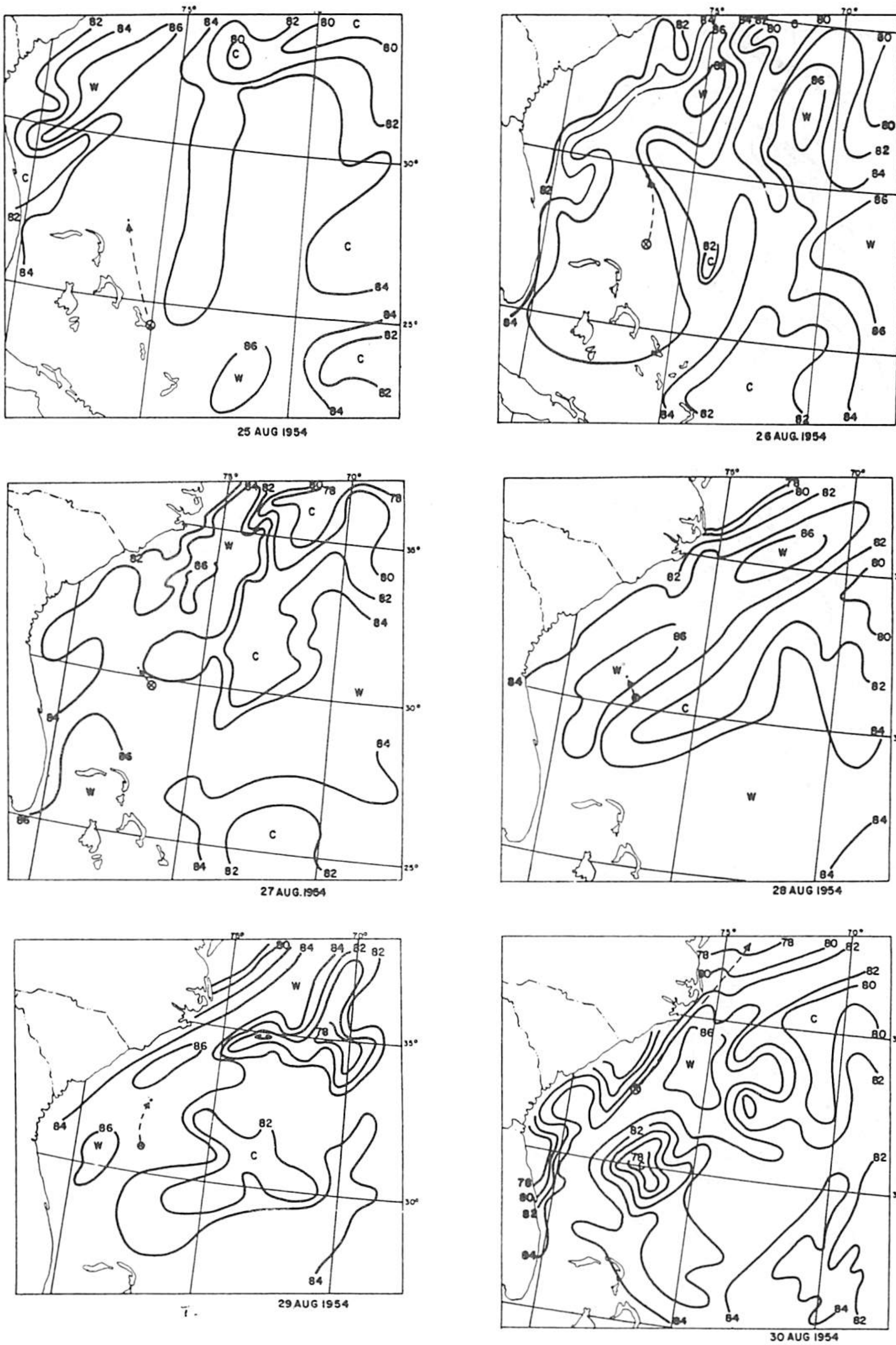

Figure I-4. Sea Surface temperature field in the vicinity of hurricane Carol, Aug. 25-30, 1954. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours. The data used in analyzing these charts are plotted in figure I-31.

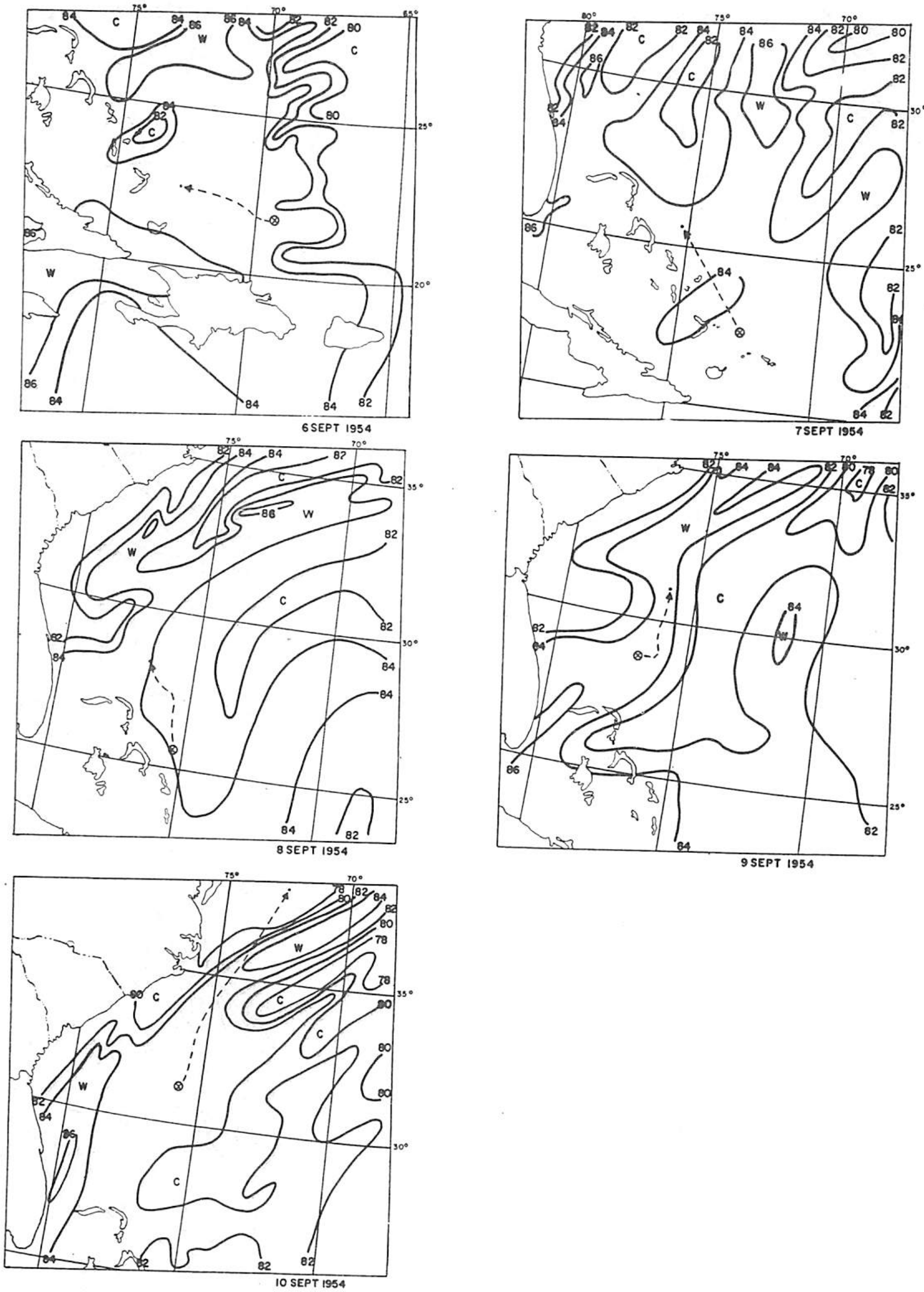

Figure I-5. Sea surface temperature field in the vicinity of hurricane Edna, Sept. 6-10, 1954. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

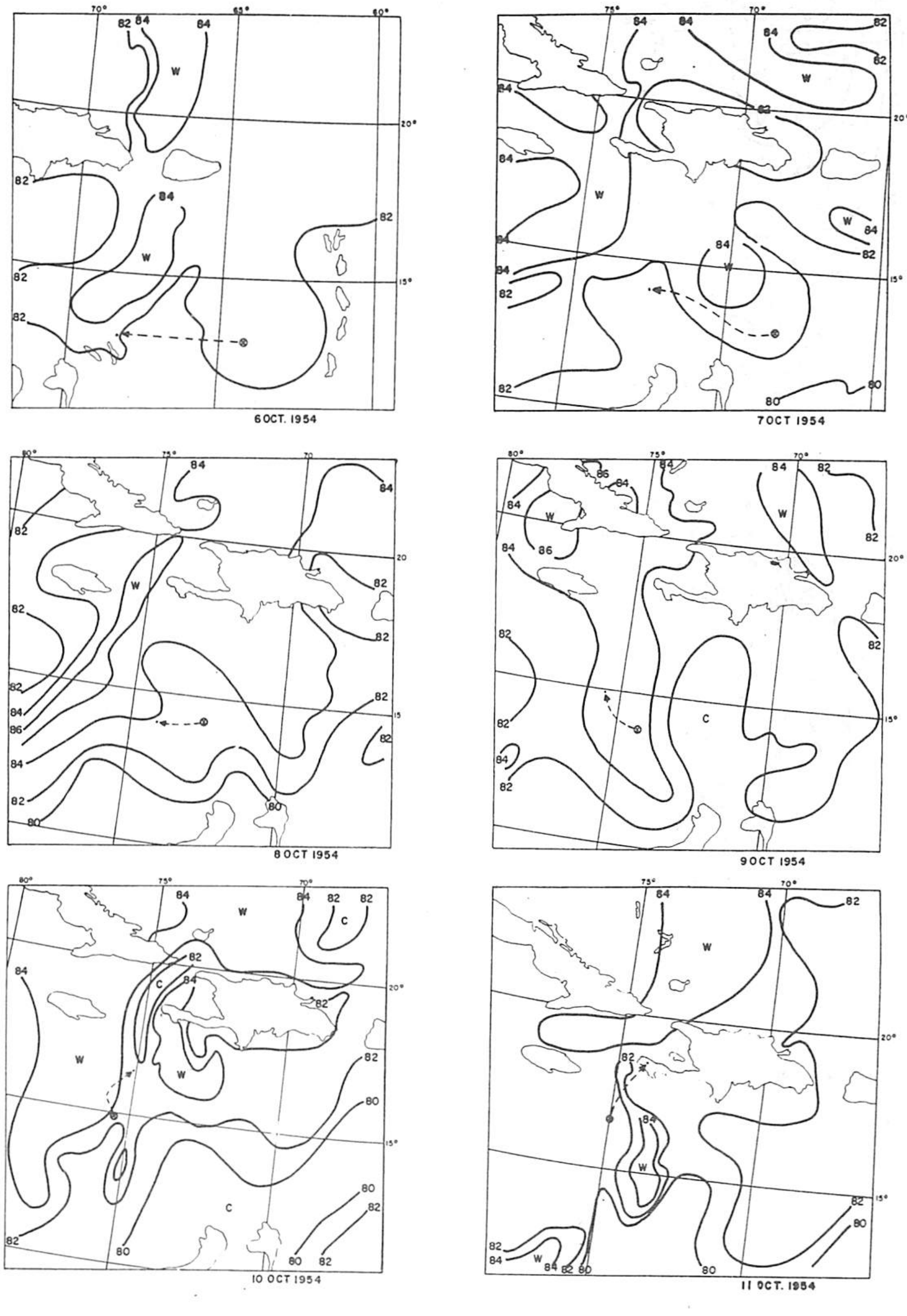

Figure I-6. Sea surface temperature field in the vicinity of hurricane Hazel, Oct. 6-11, 1954. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours. (See also Fig. I-7.)

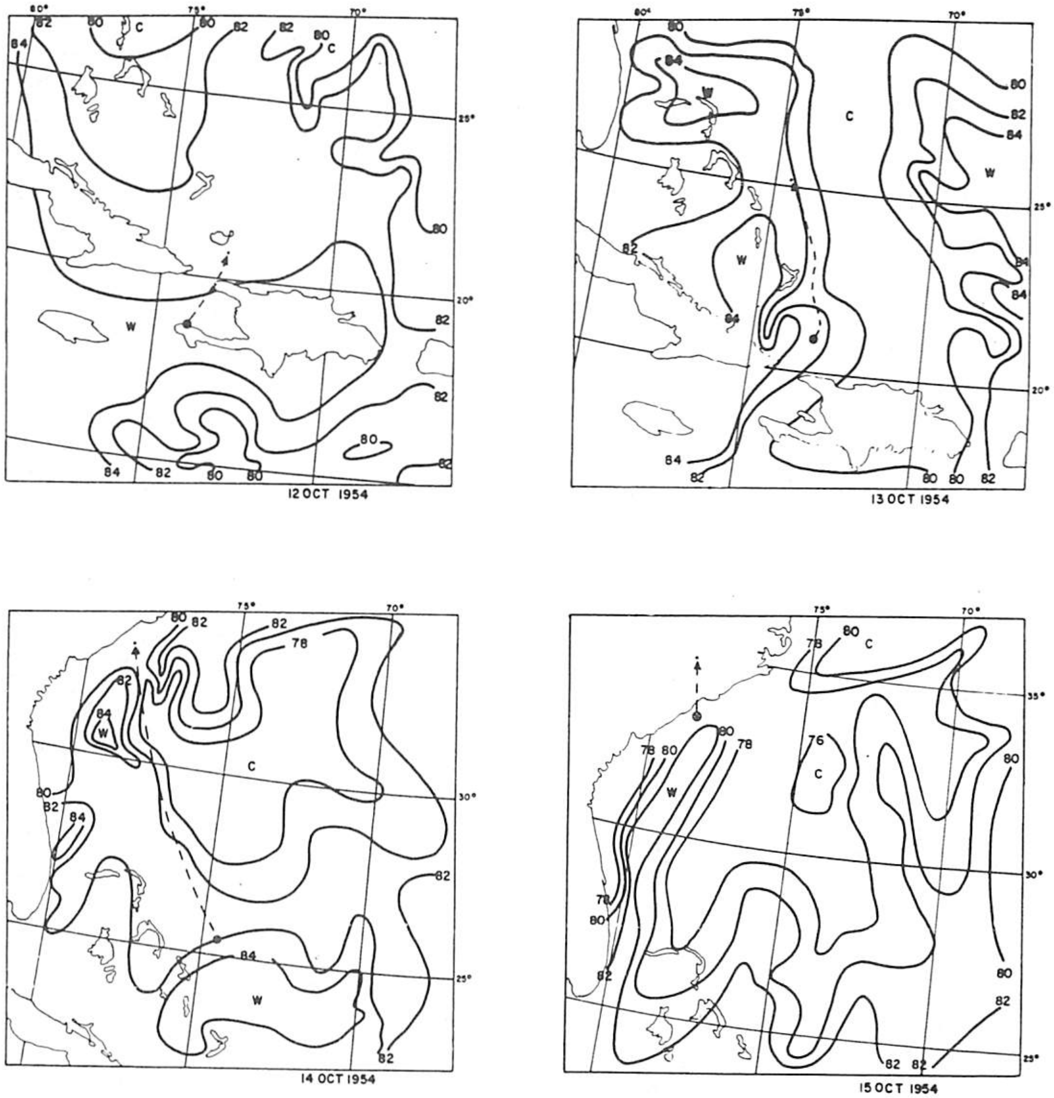

Figure I-7. Sea surface temperature field in the vicinity of hurricane Hazel Oct. 12-15, 1954.

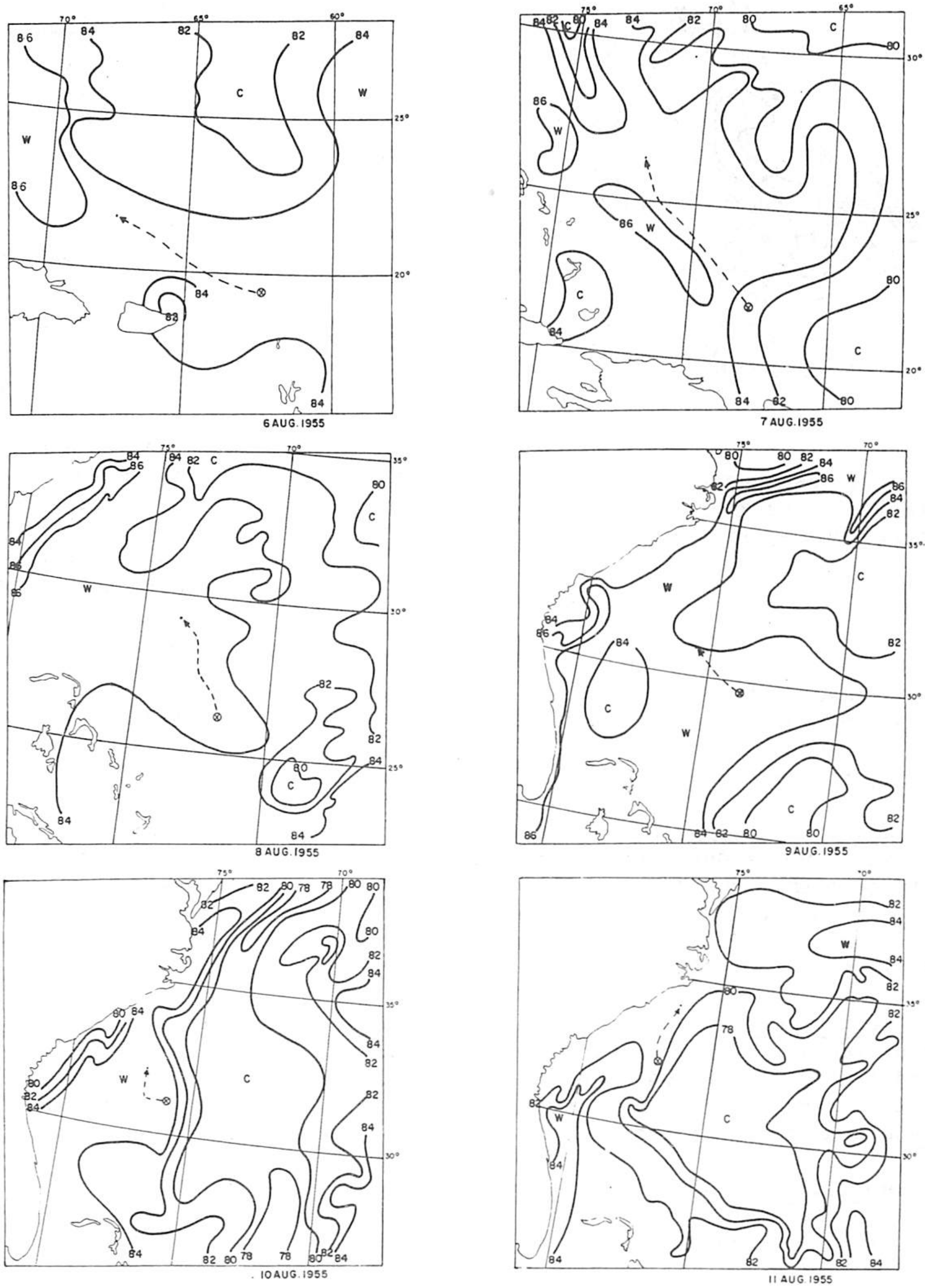

Figure I-8. Sea surface temperature field in the vicinity of hurricane Connie, Aug. 6-11, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours. The data used in analyzing these charts are plotted in figure I-32. (See also fig. I-9.)

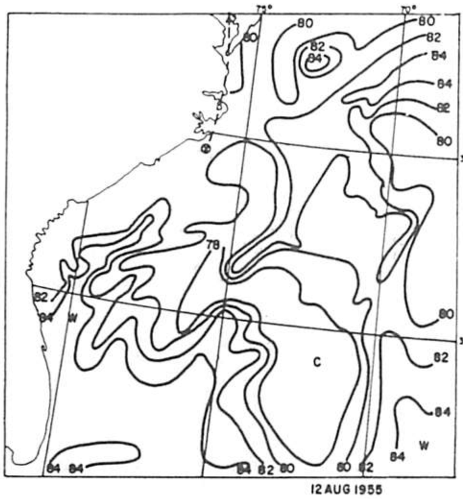

Figure I-9. Sea surface temperature field in the vicinity of hurricane Connie, Aug. 12, 1955.

the hurricane. This cold water was undoubtedly due to upwelling similar to that which occurred behind Carol (1954). Another interesting feature in the temperature field is the cold water which appeared ahead of Connie on the 8th and 9th, just at the time when she altered her track as if to avoid this area and follow the warmer water to the west. This phenomenon will be observed to occur in several other cases.

Diane (Aug. 11-16, 1955, fig. I-10): Diane formed on the 11th of August in a warm pocket surrounded by a belt of colder water to the north, and with the cold water which had formed behind Connie to her west. On succeeding days she moved first northward to the edge of the cold water, then westward still skirting the edge. On the 14th she was virtually surrounded by cooler water and was apparently carried by steering currents westward over progressively colder water for the next few days. During this time, Diane appears to have weakened steadily. On the 16th, data in the immediate vicinity of the storm center were too sparse for any conclusions to be drawn, although there were indications that the water temperatures were somewhat cooler than those experienced by Connie as she reached the coast.

Flora (Sept. 3-9, 1955, fig. I-11): Even though Flora formed in a portion of the Atlantic where data were sparse, there were still enough reports available to note that she definitely followed a track extending along the warmest water. On the 9th, she underwent an acceleration which thrust her northeastward over much colder water, whereupon she diminished in intensity, behaving similarly to Dolly (1953) in this respect.

Hilda (Sept. 12-15, 1955, fig. I-12): Hilda formed over a region where the temperatures were unusually high, approximately 85° to 86° F. For the remainder of her life, she moved westward following an area of very warm water until she crossed the Yucatan Peninsula. Data became too sparse for accurate analysis when she emerged on the west side of the peninsula.

Ione (Sept. 13-18, 1955, fig. I-13): Although the temperature patterns were complex, particularly in the later stages, Ione, as many of the other storms previously discussed, tended to remain near an area of warmest water.

Janet (Sept. 22-27, 1955, fig. I-14): Janet moved westward across the Caribbean Sea over water of homogeneous temperatures, although she exhibited a definite tendency to stay near the warmest waters. During the later portions of her track, she gave some evidence of creating slightly cooler water in her wake.

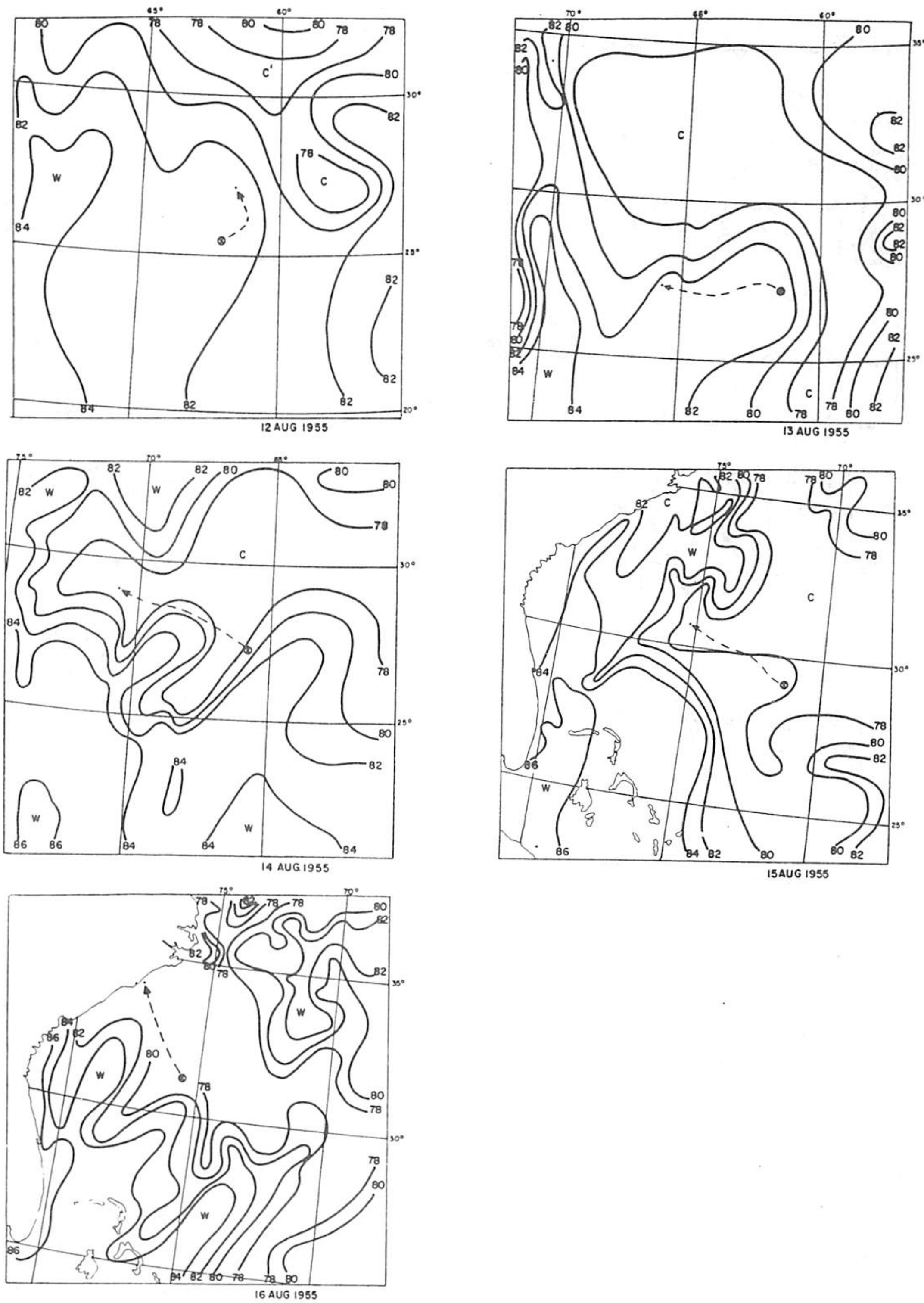

Figure I-10. Sea surface temperature field in the vicinity of hurricane Diane, Aug. 12-16, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours. The data used in analyzing these charts are plotted in figure I-33.

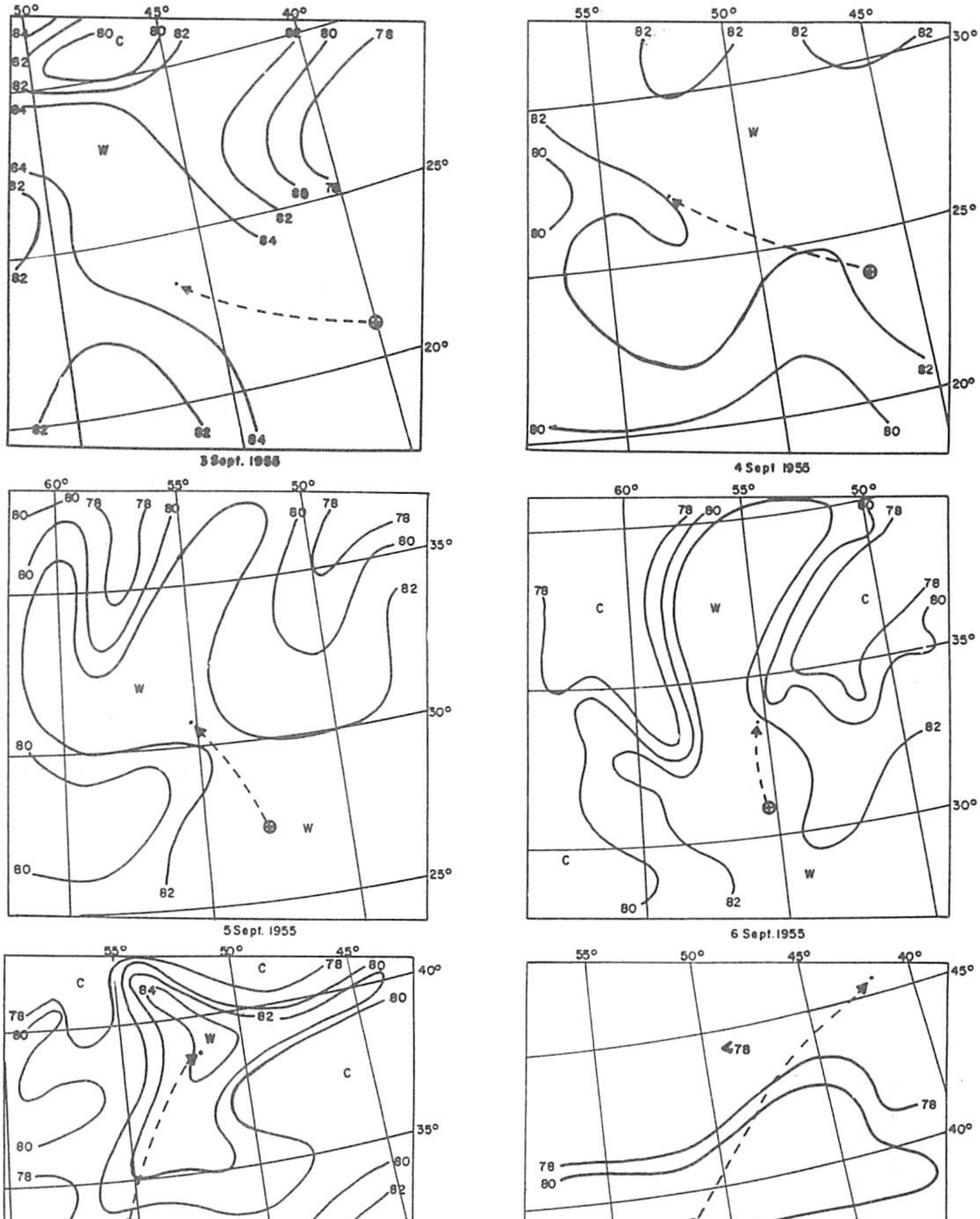

Figure I-11. Sea surface temperature field in the vicinity of hurricane Flora, Sept. 3-8, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

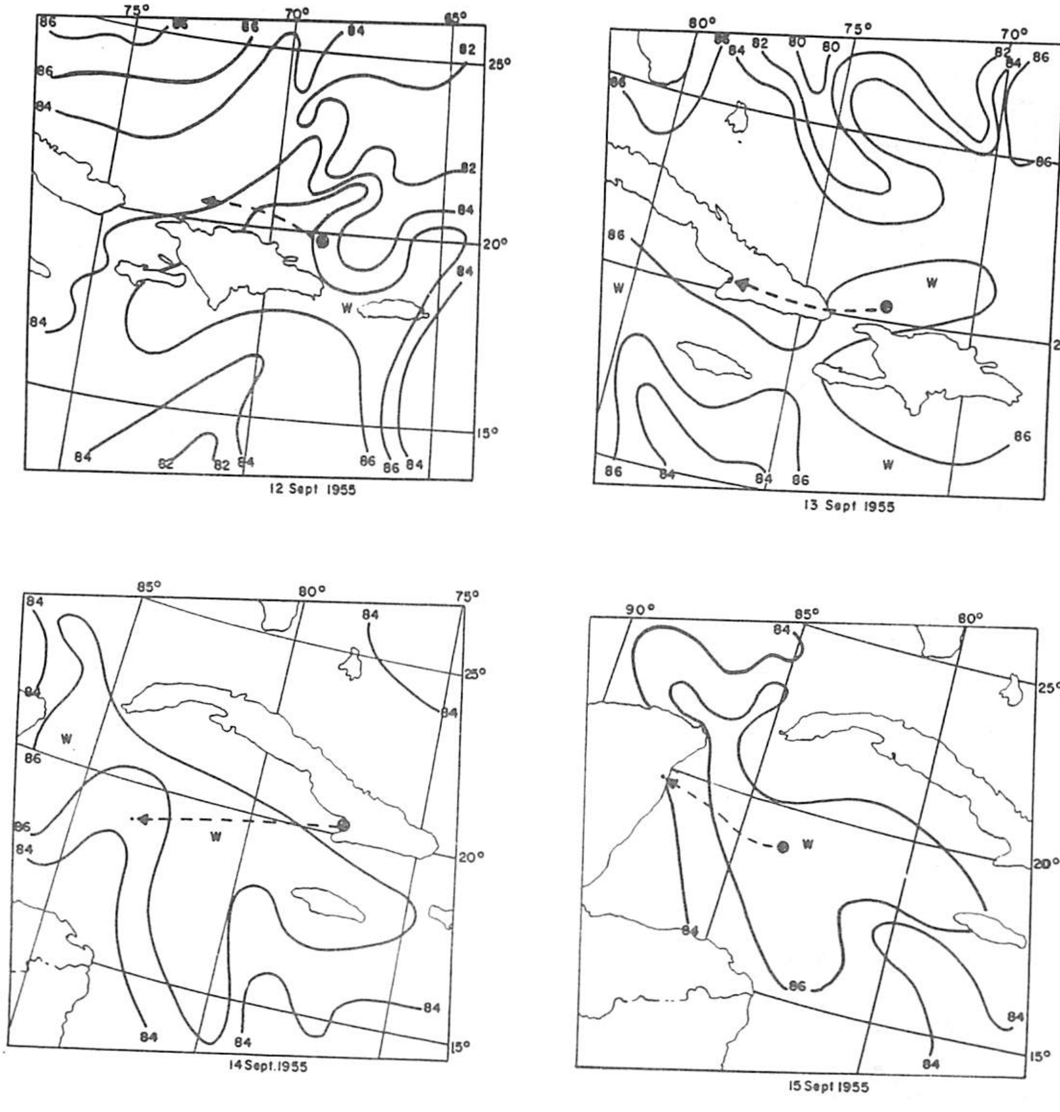

Figure I-12. Sea surface temperature field in the vicinity of hurricane Hilda, Sept. 12-15, 1955. Position of hurricane at 1230 GMT, is shown by circled X, with path for following 24 hours.

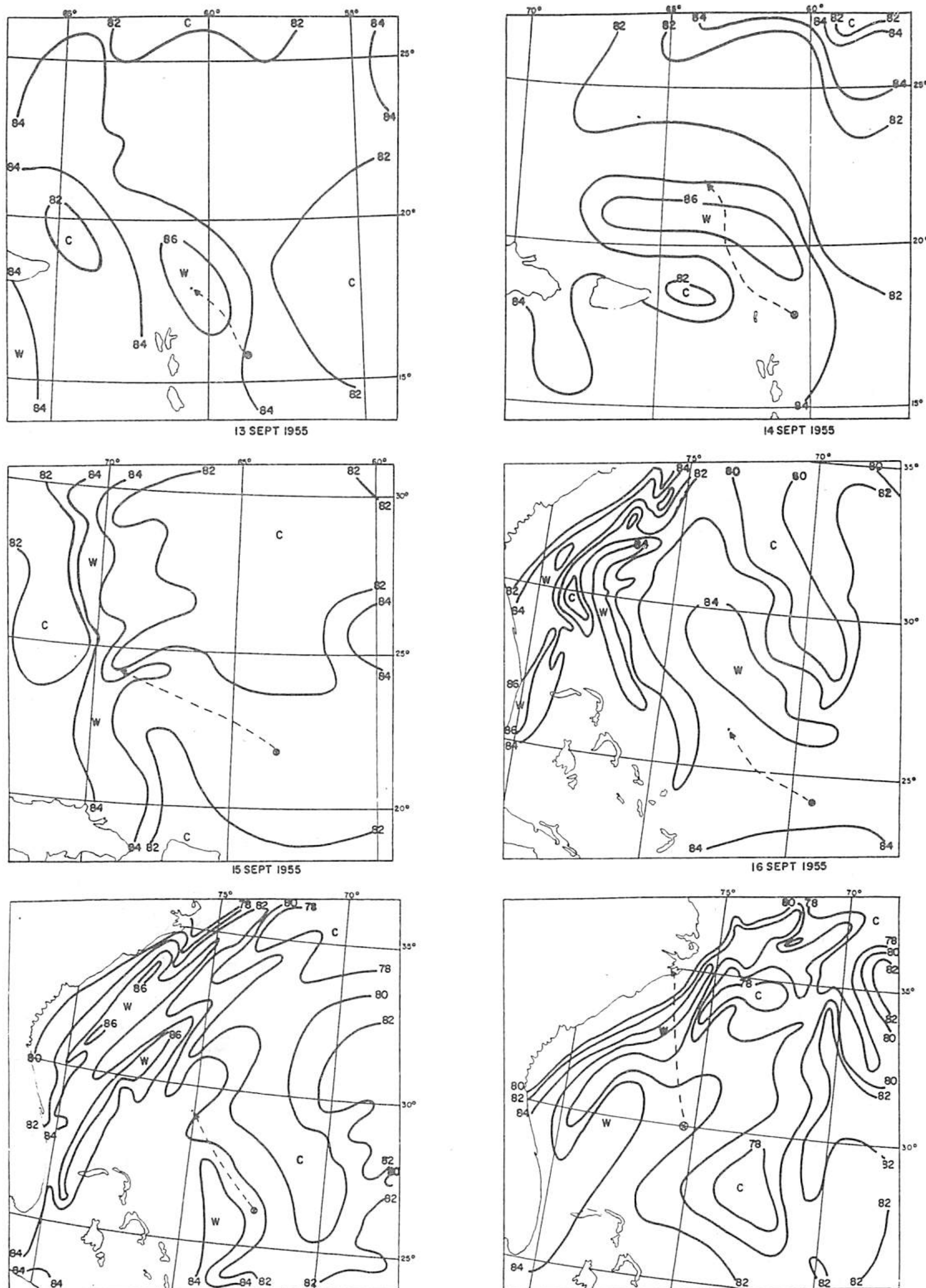

Figure I-13. Sea surface temperature field in the vicinity of hurricane Ione, Sept. 13-18, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

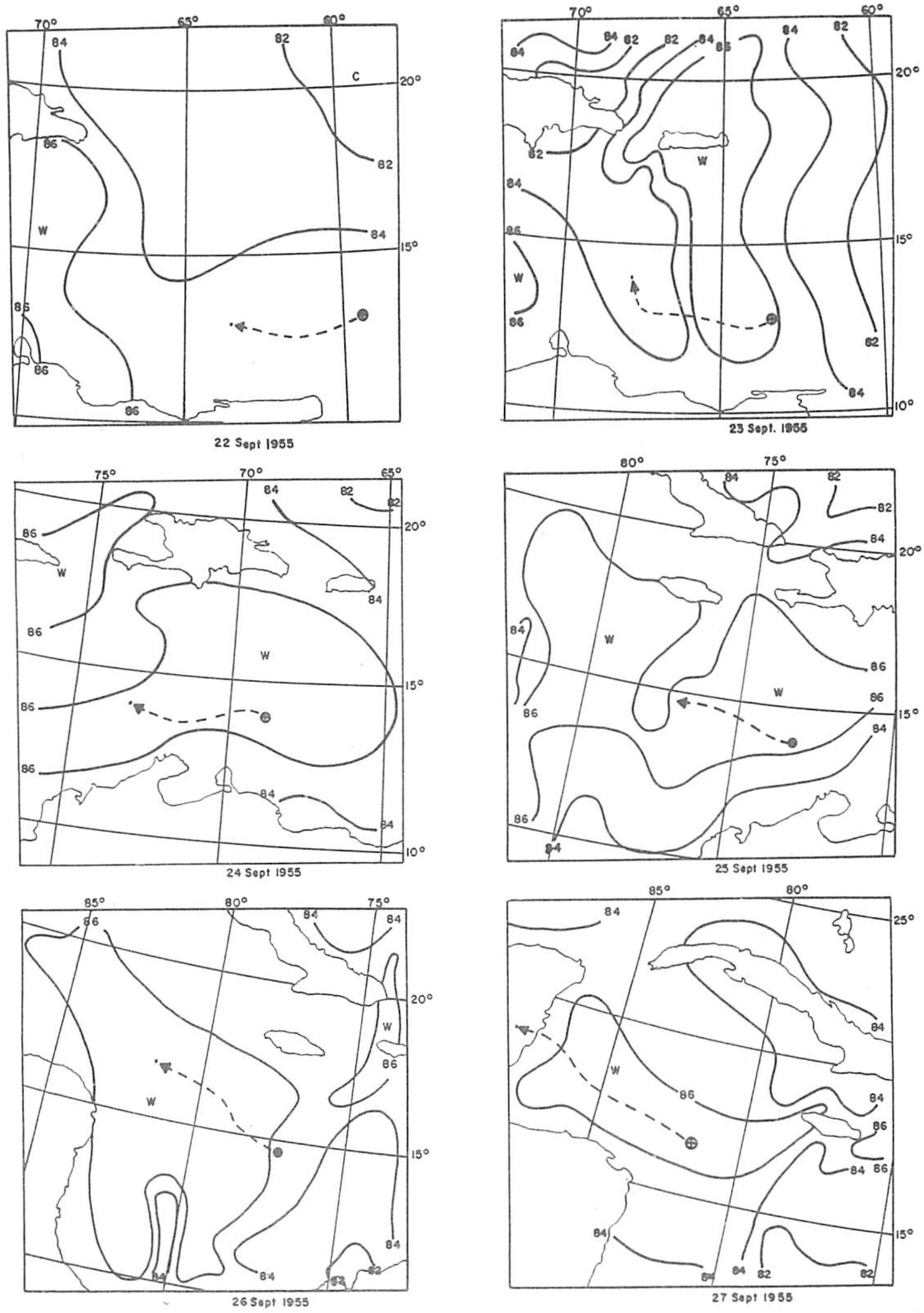

Figure I-14. Sea surface temperature field in the vicinity of hurricane Janet, Sept. 22-27, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

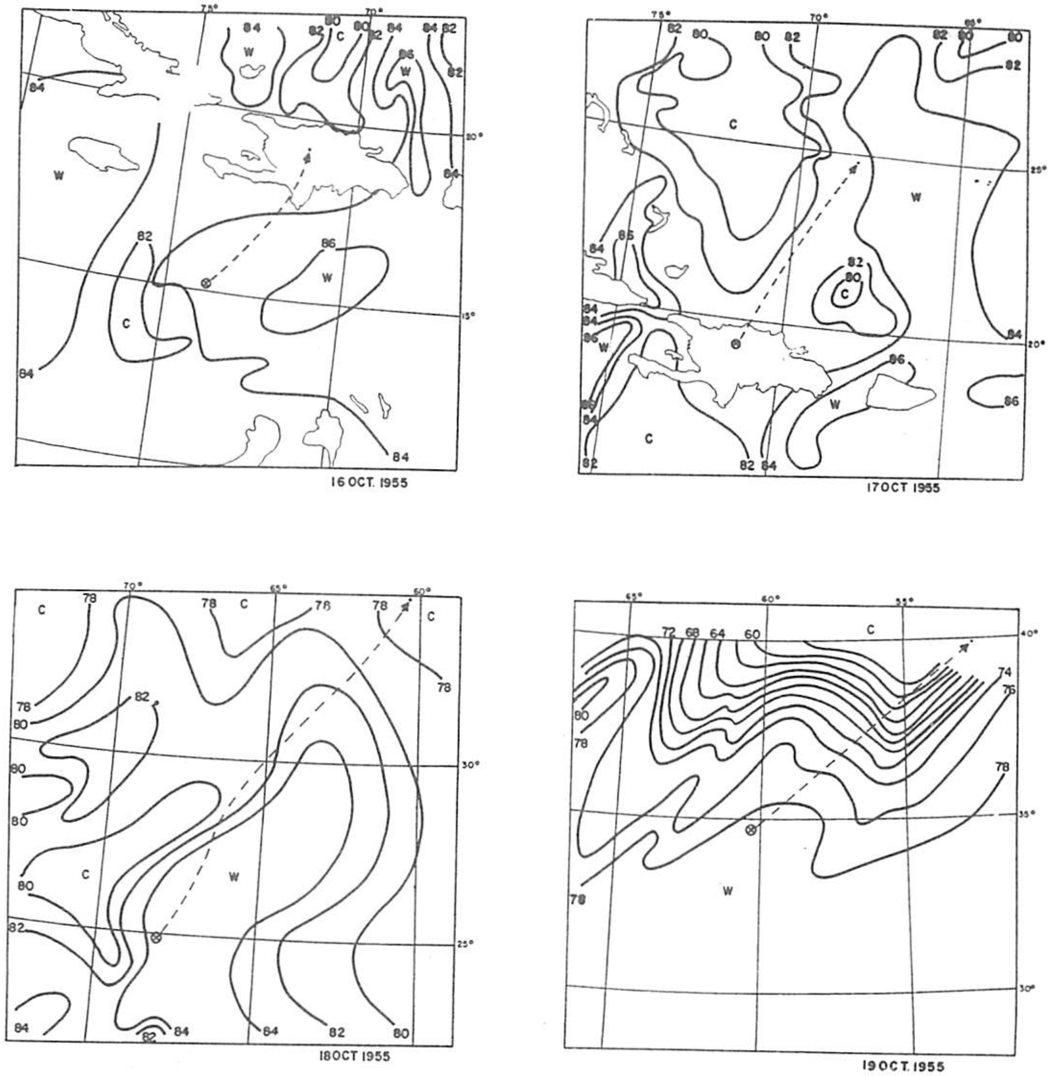

Figure I-15. Sea surface temperature field in the vicinity of hurricane Katie, Oct. 16-19, 1955. Position of hurricane at 1230 GMT is shown by circled X, with path for following 24 hours.

Katie (Oct. 16-19, 1955, fig. I-15): Katie formed in the Caribbean near an area where temperatures were very high, particularly for that season (about 85° to 86°). She moved northeastward, generally remaining near the warmest water until late on the 18th when she accelerated rapidly, moved over water well below 80° in temperature, and weakened pronouncedly.

Before drawing any conclusions from the previous data, it is perhaps better to examine them from a different point of view. Since the previous analyses were to a certain extent unavoidably subjective, it was decided to study the data from a purely objective approach. Thus, the mean sea surface temperature field was constructed relative to the path that the storm was going to take in the next 24 hours. A line was drawn from the 1230 GMT position of the storm on each day to its position 24 hours later. An overlay was then placed on the map, centered on the 1230 GMT position of the hurricane and oriented according to the direction of the line. All temperature reports for that entire day were then plotted on the overlay, and this was repeated, using the same overlay for all of the days of each hurricane's existence for which there were satisfactory data. Thus a chart was obtained representing all reports of the sea surface temperature field surrounding the hurricane for most of its life, oriented according to the path the hurricane was going to take in the next 24 hours. The temperatures were then smoothed and meaned in the following fashion. A grid was constructed consisting of the intersections of lines spaced a distance equal to 1-1/2 degrees of latitude apart. This grid was placed over the overlay centered on the position of the hurricane. At each grid point, the average of all temperatures within a square 3° of latitude in size centered on the grid point was computed and plotted. By this process of overlapping and averaging, a smoothed mean temperature field around the hurricane was described. This system has the advantage of almost pure objectivity, but suffers from the disadvantage that accompanies any process of smoothing, that is, there is a tendency to blur the subtle features of the field, and these subtleties may be the very factors we are seeking. However, this method serves as an excellent complement to the less objective but more sensitive analysis previously described.

The mean sea surface temperature fields around each of the hurricanes studied are shown in figures I-16 through I-30. Evidence of a tendency to move along the path of warmest water can be found in the charts for Dolly (1953), Carol, Connie, Flora, Hilda, Ione, Janet, and, to a small degree, for Hazel. Edna and Katie appear to show little evidence of this, although in the day-by-day analyses, figures I-5 and I-15, they seem to show a definite tendency to follow the warmest water. The formation of a cold pool of water behind the hurricanes can be seen clearly in the charts for Carol, Connie, Diane, Flora, and Ione.

Two of the storms, Connie and Diane, seemed, from the advisories, to have undergone first a period of intensification, and then a period of weakening. They were therefore additionally broken into two separate time periods covering these two phases for each storm. The results for Connie are shown in figures I-21 and I-22. It can be seen that during the period of intensification the sea surface temperatures near the center of the storm and ahead of it were several degrees warmer than during the period of weakening. In the case of Diane, figures I-24 and I-25 show slightly warmer water ahead of the storm in its early phases, with definitely cooler water ahead of it during the period when Diane weakened.

Utilizing a suggestion made by Mr. Cecil Gentry, the data were examined from a third point of view in order to study the possibility that there might be a relationship between pronounced changes of direction of the track of a hurricane and the temperature field in the area. The sixteen hurricanes were studied and each major change of direction (that is, each angular turn of at least 30°) was noted. Then the position to which the hurricane would have moved in the next 24 hours, had it not turned, but maintained its speed and direction, was found by simple extrapolation. The temperature of this point, at the time the turn began, was compared with the temperature, at that same time, of the point to which the hurricane actually moved in the next 24 hours. Thus, if the hurricane was influenced so that it would turn toward the warmest water, the temperature at the point found by pure extrapolation should be lower than the temperature at the point at which the hurricane was actually going to arrive in 24 hours. All changes of direction were examined wherever the temperature data were sufficiently well defined to allow reasonably accurate estimates to be made. Table 1 gives the dates and times of the turns which were used, along with the temperatures found at the extrapolated position compared to the actual position.

Table 1. - Comparison of sea surface temperatures at the extrapolated and actual positions of storms.

Storm	Date	Time (GMT)	Temperatures (° F.) Extrapolated	Actual
Dolly	Sept. 10, 1953	1230	82	83
Carol	Aug. 29, 1954	1230	84	85
Edna	Sept. 9, 1954	1230	82	84
Hazel	Oct. 9, 1954	1230	83	84
Alice	Jan. 4, 1955	0030	82	83
Connie	Aug. 10, 1955	2200	83	84
Diane	Aug. 12, 1955	2200	79	82
Flora	Sept. 5, 1955	1000	81	82
Flora	Sept. 6, 1955	1600	80	82

Although the temperature differences were generally quite small, in each case the storm turned toward warmer water. The points toward which the storm went averaged 1.4° F. warmer than the points away from which the storm turned. When Student's "t" test is applied to the above data, the difference between the mean temperatures of the extrapolated points as compared to the actual points is found to be significant at the 95 percent level of confidence. Thus, if we can accept the temperature data listed above as accurate, there is a high degree of probability that hurricanes which make pronounced changes of

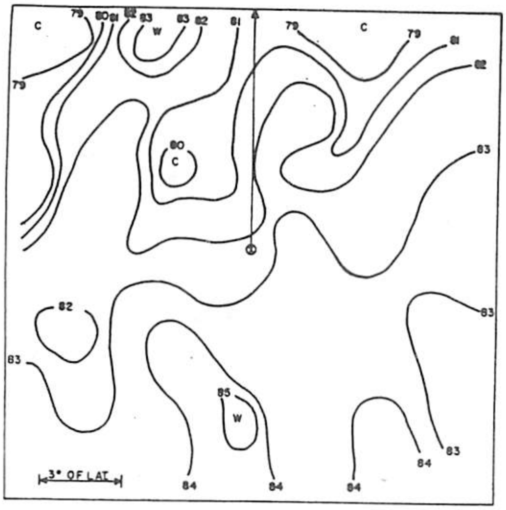

Figure I-16. Mean sea surface temperature pattern surrounding Dolly (1953) oriented according to her future direction of movement.

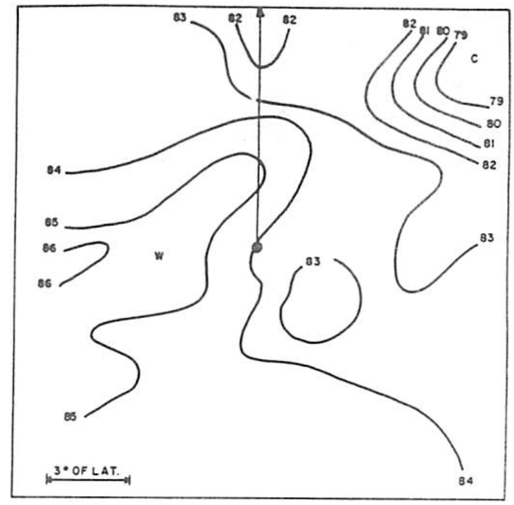

Figure I-17. Mean sea surface temperature pattern surrounding Carol (1954) oriented according to her future direction of movement.

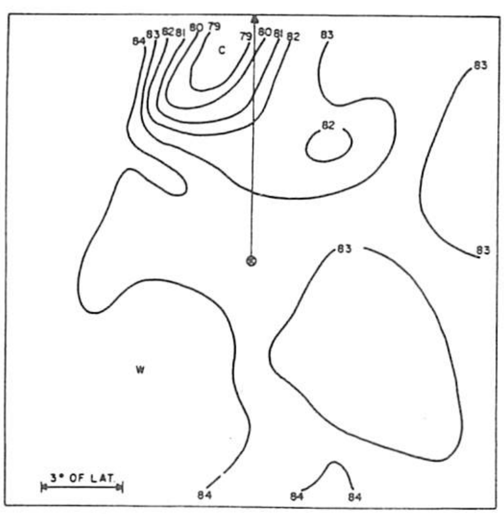

Figure I-18. Mean sea surface temperature pattern surrounding Edna (1954) oriented according to her future direction of movement.

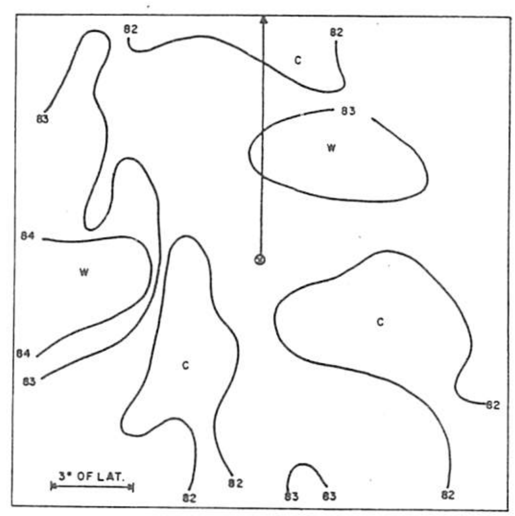

Figure I-19. Mean sea surface temperature pattern surrounding Hazel (1954) oriented according to her future direction of movement.

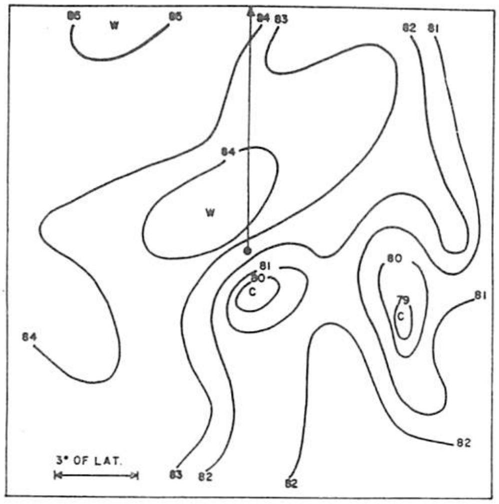

Figure I-20. Mean sea surface temperature pattern surrounding Connie (1955) oriented according to her future direction of movement.

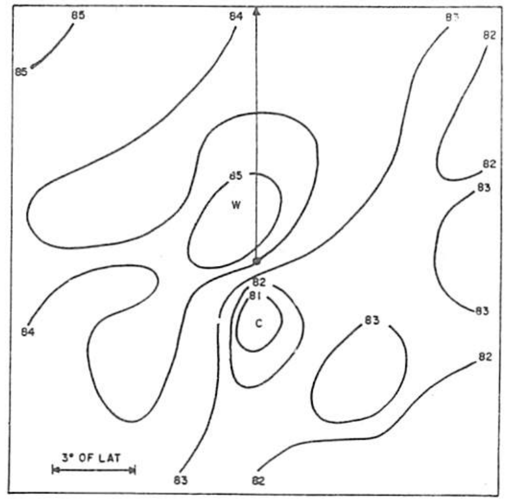

Figure I-21. Mean sea surface temperature pattern surrounding Connie during period of formation and steady intensity, Aug. 4-8, 1955, oriented as in fig. I-20.

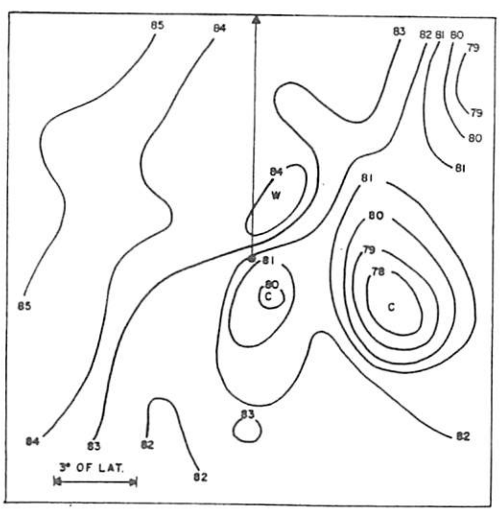

Figure I-22. Mean sea surface temperature pattern surrounding Connie during period of weakening Aug. 9-11, 1955, oriented as in fig. I-20.

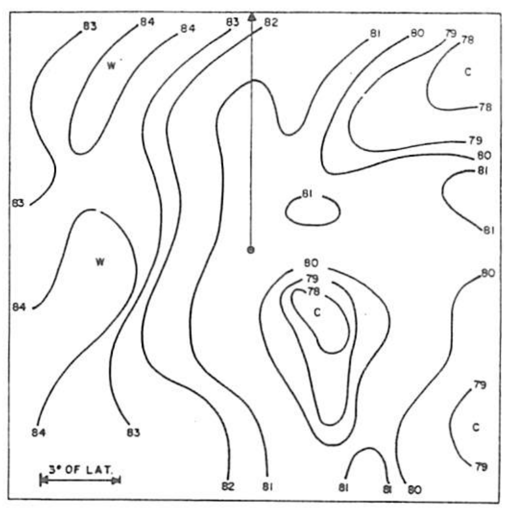

Figure I-23. Mean sea surface temperature pattern surrounding Diane (1955) oriented according to her future direction of movement.

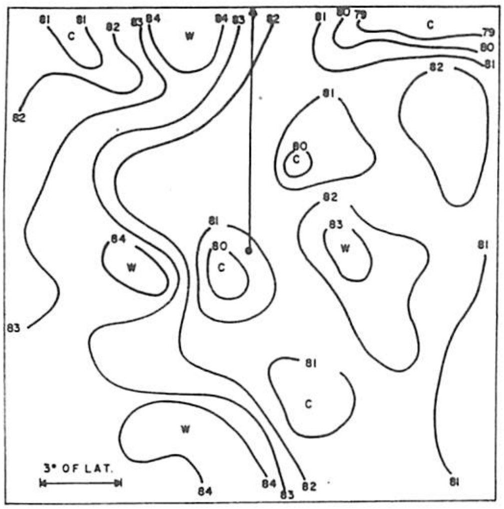

Figure I-24. Mean sea surface temperature pattern surrounding Diane during period of formation, Aug. 11-13, 1955, oriented according to her future direction of movement.

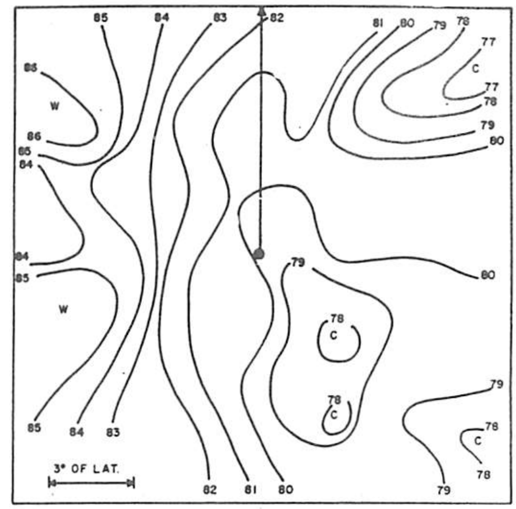

Figure I-25. Mean sea surface temperature pattern surrounding Diane during period of weakening, Aug. 14-16, 1955, oriented as in figure I-23.

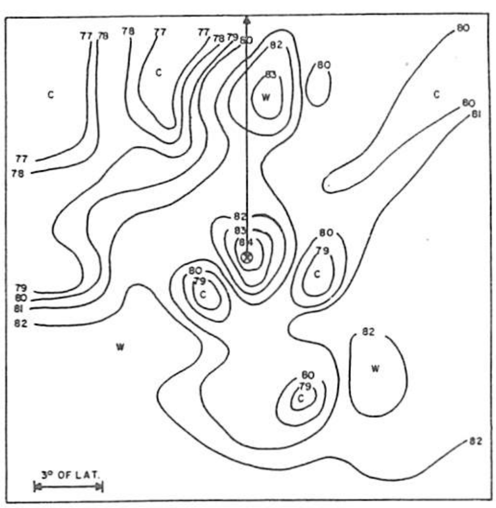

Figure I-26. Mean sea surface temperature pattern surrounding Flora (1955) oriented according to her future direction of movement.

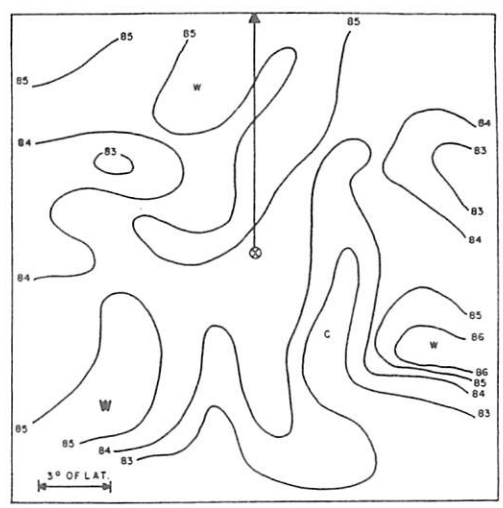

Figure I-27. Mean sea surface temperature pattern surrounding Hilda (1955) oriented according to her future direction of movement.

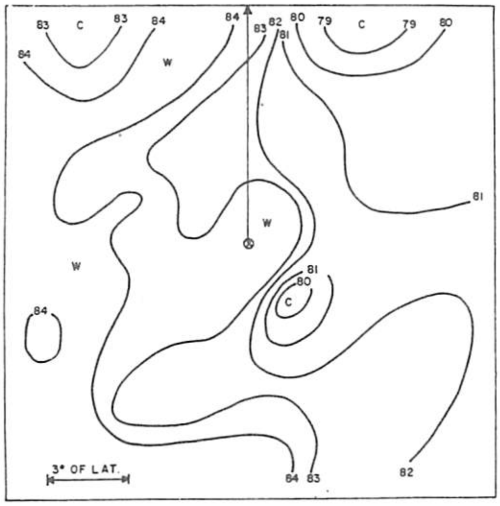

Figure I-28. Mean sea surface temperature pattern surrounding Ione (1955) oriented according to her future direction of movement.

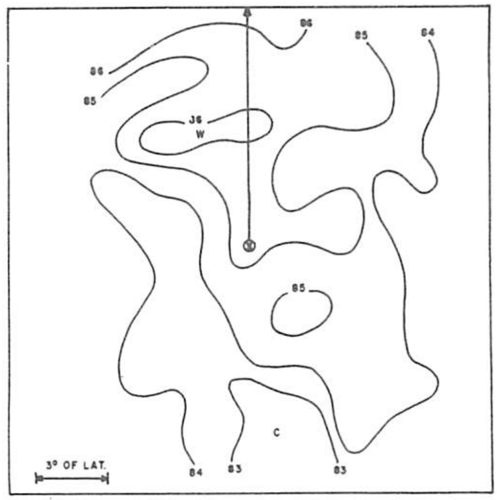

Figure I-29. Mean sea surface temperature pattern surrounding Janet (1955) oriented according to her future direction of movement.

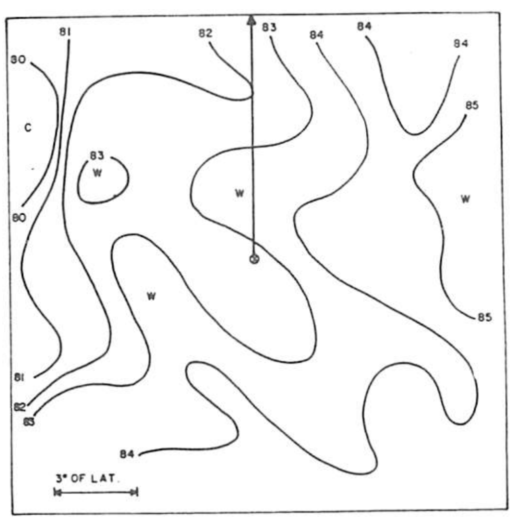

Figure I-30. Mean sea surface temperature pattern surrounding Katie (1955) oriented according to her future direction of movement.

direction turn toward warmer water. It must be stressed, however, that although every care was taken in the analysis of the temperature fields near these turns, and those cases were omitted where the data were felt to be too scarce for reasonably accurate estimates to be made, nonetheless, the sparsity of the data and their inherent inaccuracy combined with the small number of cases examined requires that one accept this result with caution. It should also be noted that all of the turns examined occurred when the hurricanes were moving slowly (less than 10 knots), so that these conclusions should not be applied to fast-moving systems obviously embedded in strong steering currents.

In addition to the above investigations, an attempt was made to study the sea surface temperatures in the areas where each of the hurricanes formed. Unfortunately, many of the storms developed in regions where the data were scarce, and in many cases there was some uncertainty concerning the exact time and place of formation. However, it was apparent that most of the storms formed in areas where the sea surface temperatures were at least 83° F. and very possibly higher. Since these temperatures are reached over very large areas most of the time during the warm season, this information is not particularly useful. What is more significant, perhaps, is that it was found that this condition was not satisfied over sizeable areas of the Atlantic and the Caribbean during certain periods. Thus, if an easterly wave is seen to be traversing one of these cold areas (frequently below 80° F.), it is probably unlikely that a hurricane will form until the water temperatures beneath the easterly wave increase.

CONCLUSIONS

The largest portion of the work in this study has centered around attempts to prove the hypothesis that during the part of a hurricane's life when it is moving slowly in the belt of the easterlies, and before it has accelerated under the influence of the more rapid westerlies, it will tend to follow the track over warmest water. The charts showing the daily temperature fields around each hurricane clearly support this hypothesis. However, because of the subjectivity of this form of analysis, it is wisest to summarize this section of the report by stating that there was nothing which forced rejection of the hypothesis, and there was considerable evidence in its favor.

The second portion of the analysis, the meaned temperature fields, was, on the other hand, nearly entirely objectively performed. Although this form of analysis tended to smooth out the details of the temperature distribution, nevertheless, the results again showed nothing which forced rejection of the hypothesis, and very defintely offered support for its acceptance.

The third approach, which attempted to relate definite changes in the path of a hurricane to its surrounding sea surface temperature field, again suffered from the subjectivity involved in reading small temperature differences in a poorly delineated field. However, the results, which would carry only small weight by themselves, can be said to add strength to the argument in favor of the hypothesis when viewed against the background furnished by the other material.

Thus, it is highly probable that, under the conditions specified, hurricanes tend to follow the warmest water. In addition to this observation, it will be recalled that several hurricanes (i.e., Dolly 1953, Diane 1955, Flora 1955, and Katie 1955) moved over colder water, apparently under the influence of strong steering currents. Diane weakened at this time, and Dolly, Flora, and Katie virtually lost their tropical characteristics and became relatively minor cyclones. There is, therefore, a strong suggestion that a hurricane will weaken and even dissipate if it moves over cold water (i.e., water whose temperature is below 79° F., although this figure varies with the season and situation).

Another phenomenon which should not be overlooked, is the creation of marked pools of cold water behind some hurricanes during parts of their lives. This has also been noted to occur off the coast of Japan (Suda [15]) and has been attributed to divergence of the surface waters by Hidaka and Akiba [4]. The phenomenon apparently occurs only where the top layers of the ocean are not isothermally stratified, and then the up-welling induced by the divergence can be clearly detected by the abrupt appearance of cold water behind the hurricane. For our purposes, this process has some interesting implications. For example, if a hurricane is truly affected by the sea surface temperatures, then those hurricanes which are bringing cold water to the surface cannot remain stationary without weakening. In addition, the cooling caused by the passage of a previous storm might have a pronounced effect on a following storm. This appears to be what actually happened in the cases of Connie and Diane. Diane weakened when she moved over the area of cold water left by the recent passage of Connie.

As a final note, some thought should be given to the mechanism by which the warm sea surface temperatures extend their influence into the atmosphere above the ocean. Palmén [11] has left little doubt that the hurricane is essentially a manifestation of the release of the latent energy of instability within the tropical air masses. The sea adds to this energy by the upward transport of both sensible heat and latent heat. Over the warmer areas of the ocean, this transport can be seen to be very great. In general, over these regions the air temperatures are lower than the sea temperatures, and the dew points are even lower. Since the winds are far from calm, the effects of turbulence must be quite large, and the upward turbulent transport of heat and water vapor must also be large. It may be possible that a direct investigation of the distribution of latent instability within the air masses around the hurricane might reveal relationships which are more definite than those we seem to have found by observing the distribution of the sea surface temperature field.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. Jerome Spar and to Mr. Cecil Gentry for their many helpful suggestions. He wishes to thank Mr. Abram Bernstein for his careful analysis of the data, Mr. David Spiegler for his plotting, and Miss Joan Cipley for the drafting of the figures.

APPENDIX

The data appearing in figures I-31 - I-33 represent the temperatures actually reported by the ships. In many cases it was possible to trace a ship for several days and arrive at a satisfactory correction favor to the data. These cases are indicated in figures I-31-33 by underscoring the temperature. In cases when the data from a ship were so erratic that no satisfactory correction factor could be determined, or when a ship with temperatures obviously too high or too low could not be traced sufficiently to determine an accurate correction factor, an "X" appears as an exponent to the plotted temperature to indicate that the data were inaccurate. On some of the maps, for instance, there are several high (or low) readings in an area. When several of these readings were made by a single ship for which an accurate correction was not available, the "X" exponent was used.

The map sections which appear in figures I-3-15 are relatively small portions of the analyzed areas, and the positions of some of the isotherms near the boundaries of the sections were determined by data in adjacent areas. In some cases where data were sparse and there were no weather phenomena which appeared to cause radical changes in the temperatures, the last report obtainable in those areas was used to indicate the temperature field. In other cases where data were very sparse the analysis was based on continuity with either the preceding or the following chart.

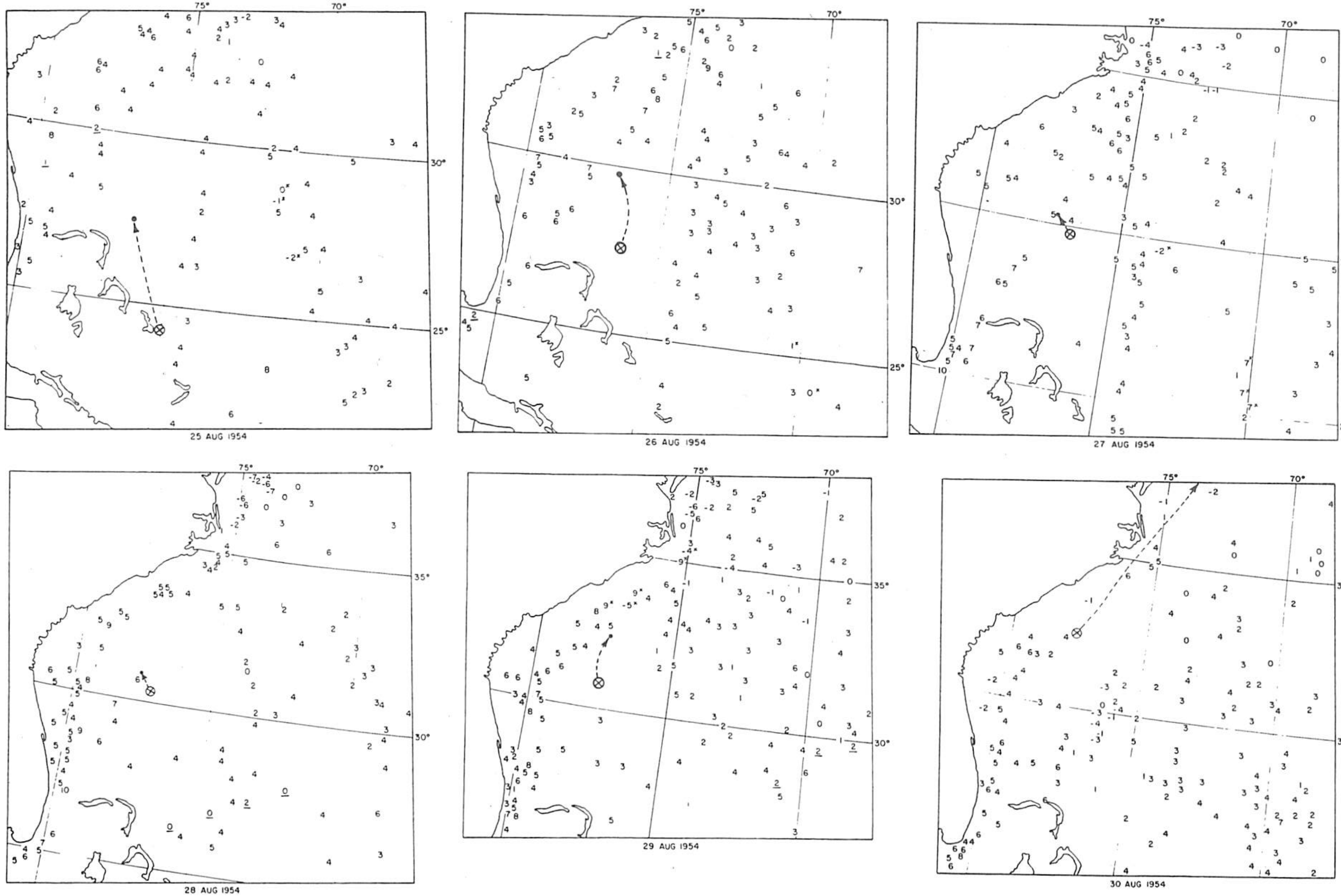

Figure I-31. Sea surface temperatures (80°F. subtracted from actual temperature) used in analyzing the charts given in figure I-4, hurricane Carol, Aug. 25-30, 1954. Underscore indicates correction factor has been applied. Exponent x indicates data are considered inaccurate.

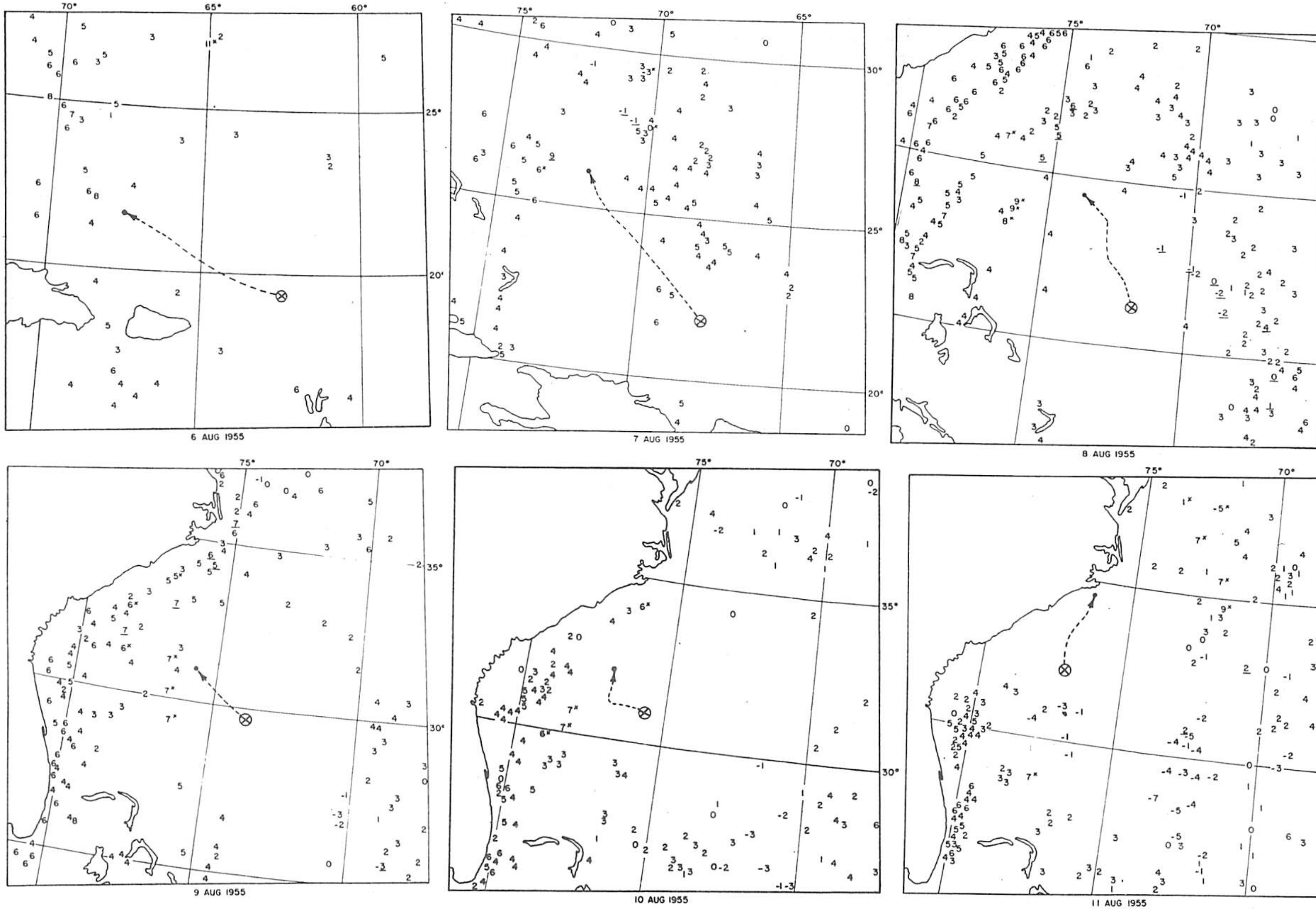

Figure I-32. Sea surface temperatures (80°F. subtracted from actual temperatures) used in analyzing the charts given in figure I-8, hurricane Connie, Aug. 6-11, 1955. Underscore indicates correction factor has been applied. Exponent x indicates data are considered inaccurate.

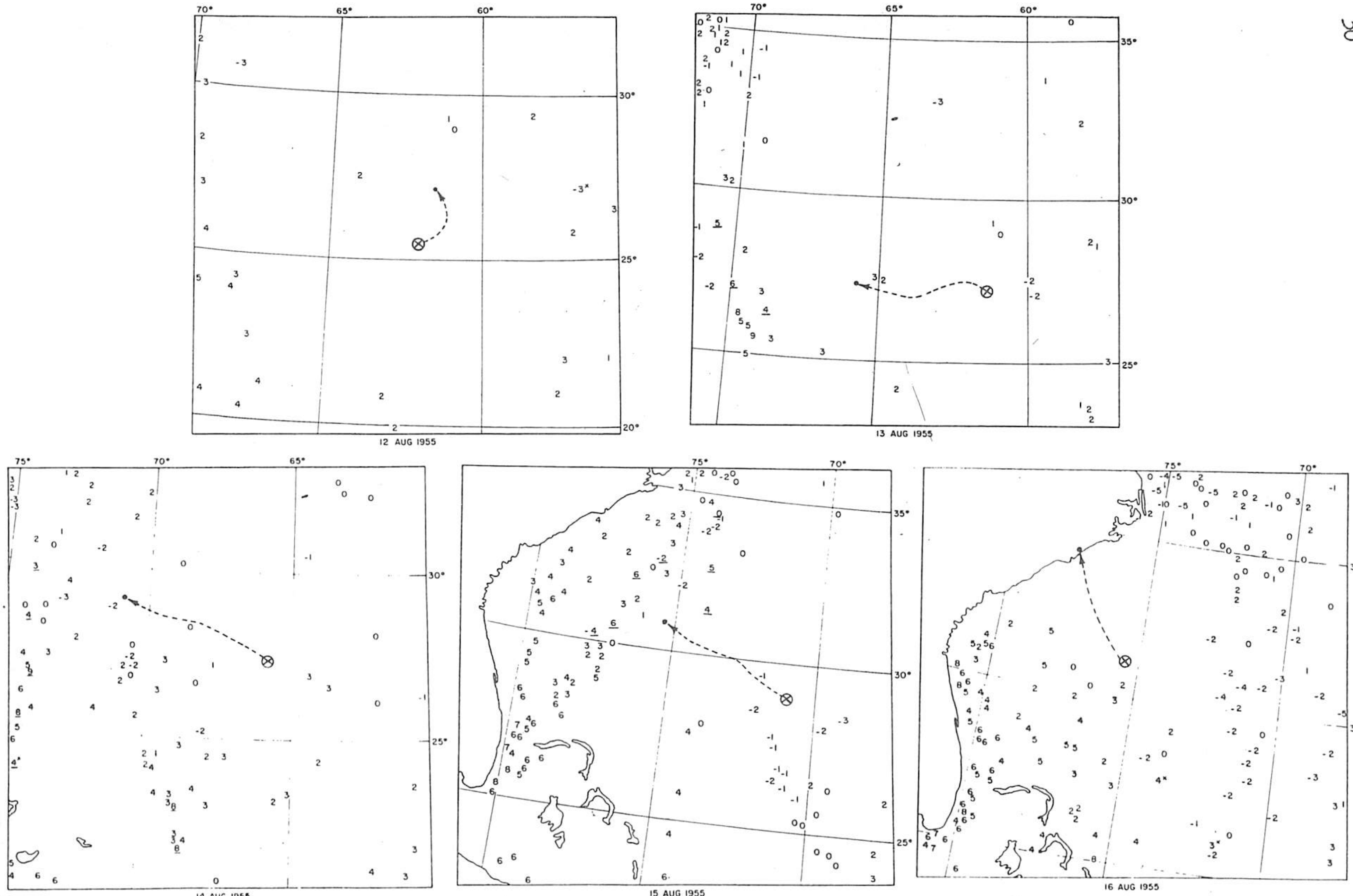

Figure I-33. Sea surface temperatures (80°F. subtracted from actual temperature) used in analyzing the charts given in figure I-10, hurricane Diane, Aug. 12-16, 1955. Underscore indicates correction factor has been applied. Exponent x indicates data are considered inaccurate.

PART II. - THE EXCHANGE OF ENERGY BETWEEN THE SEA AND THE ATMOSPHERE IN RELATION TO HURRICANE BEHAVIOR[1]

[Manuscript received April 9, 1957]

INTRODUCTION

In Part I of this report, the behavior of hurricanes in relation to the sea surface temperature fields was examined. It was found that there was detectable evidence which pointed to dependence of these storms upon the warmth of the sea surface in the vicinity of the storm. Because of the inherent difficulties in attempting to construct synoptic charts of the sea surface temperature field near a hurricane, it was impossible to determine with any great degree of accuracy the exact nature of this relationship. However, it was evident that there was a marked tendency for the storms to form only over very warm water, to follow tracks which lay over the warmest water, and to dissipate when driven over colder water.

If such a relationship is assumed actually to exist, the next question which arises must deal with the possible physical processes which may be involved. A hurricane can be viewed as a thermodynamic system which converts other forms of energy into kinetic energy at a great rate. If this were not so, the dissipation of the storm's kinetic energy by viscous stresses would quickly destroy the system. Since the storm must have a continuing supply of energy in one form or another, since it is safe to assume that a large portion of this energy may be obtained by a flux from the sea to the atmosphere in the areas around the storm, and since this flux would be strongly dependent upon the temperature of the sea surface, it is quite reasonable to examine this relationship in the hope that it may provide the physical hypothesis needed to corroborate the dependence of hurricane behavior upon the sea surface temperature field.

It has generally been assumed that the computation of this flux on a synoptic basis is not possible (Sutcliffe [16]). However, the problem is gradually becoming of greater importance, particularly since the problems of numerical prediction point more and more to the growing necessity for the inclusion of such influences in the dynamical equations utilized. Thus it seems that some effort must be made to determine if such computations can indeed be made, and if, despite the crudities involved, these computations will render useful information.

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[1] Original manuscript was identified as Technical Paper No. 2, Final Report, Hurricane Project, Contract No. Cwb-8948 (sponsored by U. S. Weather Bureau, National Hurricane Research Project) Department of Meteorology and Oceanography, College of Engineering, Research Division, New York University, New York, N. Y., January 1957.

THE NATURE OF THE COMPUTATIONS

Any flux of energy from the sea to the air must consist largely of the turbulent transfer of heat in two forms - latent heat and sensible heat. The problem of the interaction between the interface of sea and air has received considerable attention, both from a theoretical approach and an empirical approach. Sutton [17], Sverdrup [19], Montgomery [9], and many others have derived semi-theoretical equations which deal with the evaporation of moisture from a water surface into the air above, and there is no need to dwell on these approaches in this report. On the other hand, Jacobs [5] and Marciano and Harbeck [8] have treated the problem in an empirical manner which is much more applicable to the matter at hand.

Most of the theoretical research has pointed toward evaporation equations similar to the following general form:

$$E = k(e_w - e_a)\, W_a \tag{1}$$

where: E = evaporation.

e_w = vapor pressure of saturated air at the temperature of the water surface.

e_a = vapor pressure of the air at anemometer level.

W_a = wind speed at anemometer level.

k = a constant dependent on certain parameters in the physical conditions surrounding the point of measurement.

Thus, Jacobs [5] selects an equation of this form and by the use of climatological data succeeds in computing a value for k. To accomplish this, he first computes the total energy available for heating the air and for evaporation of moisture into the air for several oceanic areas by the use of the heat balance equation. He then uses Bowen's [2] ratio to break this total amount of energy into the parts used for heating and for evaporation. Then, by the use of climatological data based on the reports of merchant vessels, he recomputes the value of the energy used for evaporation by turbulent processes as a function of k in equation (1). Thus he is able to solve for k.

Marciano and Harbeck [8] treat this same problem from a very different point of view. At Lake Hefner, Oklahoma, they made detailed observations of the actual rate of evaporation based on the known rate of inflow and outflow from this large lake. The daily values of the actual evaporation were compared with computed values based on detailed observations obtained by instruments distributed over and around the lake. Several of the theoretical equations previously mentioned were then tested. While two of these (Sutton [18] and Sverdrup [19]) were found to give good results, an empirical equation of the form given above proved to be the best fit to the data. In addition, an attempt was made to compute the evaporation from the lake by utilizing data consisting of standard airways observations taken at an airport 13 miles away. Only a relatively minor change in the constant in equation (1) was found necessary in order to compute correctly the evaporation at the lake. In the use of this equation for the computation of evaporation at Lake Hefner, the data were averaged over a 3-hour period (as contrasted to Jacobs' data meaned over a year). The authors concluded: "Although boundary layer problems are still imperfectly understood, a complete and detailed knowledge of them does not appear necessary for the determination of evaporation for periods of a day or more" and further: "The empirical equation developed from the water budget data is, on the other hand, not entirely empirical, but embodies some of the principles of mass transfer theory. Though further tests of this equation should be made, it is now believed possible, despite gaps in our knowledge, to compute daily evaporation from a water surface with reasonable accuracy."

The value of the constant, k, computed by Jacobs is about 45 percent larger than those obtained at Lake Hefner. (There is some confusion as to the precise ratio since the units used at Lake Hefner are not clearly indicated. However, this estimate is probably correct.) In view of the wide disparity between the approaches used in each of the above experiments, this difference in the results may be considered quite small. In our case, since we are interested in the distribution of this energy flux around a hurricane rather than its absolute value, the precise value of k is not critical at this stage of the research. The question of whether or not k is a true constant is, however, of great importance to us. As the matter now stands, little is known about the spatial or temporal variations of k. We are taking a very definite calculated risk in assuming that the distribution of energy flux about a hurricane can be safely determined by assuming k to be a true constant. However, from the previous studies, it can be seen that the constant has shown a considerable degree of stability despite large changes in the nature of the data inserted in equation (1), and it therefore appears that the assumption of a constant k, while questionable, may furnish us with a modus operandi for a preliminary investigation, provided caution is taken in framing the conclusions which are drawn from the results.

On the basis of the successful use of ordinary synoptic data at Lake Hefner, it was felt that the use of standard synoptic weather observations from ships in the general vicinity of a hurricane might be satisfactorily used in these computations provided the data were carefully applied. Since ship observations were the basis for Jacobs' results, it was felt that there might be less risk of distortion of the results if the constants he computed were used.

Jacobs' final equation for the energy (gm. cal. cm.$^{-2}$ day^{-1}) removed from the sea by evaporation (or returned by condensation) is as follows:

$$Q_e = 145.4(e_w - e_a)\, W_a \qquad (2)$$

By the use of Bowen's ratio his equation for the transfer of sensible heat (gm. cal. cm.$^{-2}$ day^{-1}) between sea and air is

$$Q_c = .01 \frac{(t_w - t_a)}{(e_w - e_a)} Q_e \qquad (3)$$

The sum of (2) and (3) is the total eddy transfer of heat:

$$Q_a = 145.4[(e_w - e_a) + .01\,(t_w - t_a)]\, W_a \qquad (4)$$

where the following units are used:

e_w and e_a: inches.

W_a: knots.

t_w (the sea temperature): degrees F.

t_a (the air temperature): degrees F.

THE DATA AND THEIR ANALYSIS

Ideally, each of the measurements which go into equation (4) should be made simultaneously and meaned over some relatively short time interval (of the order of minutes, perhaps). A shipboard weather observation only roughly approximates this condition. In addition, the observations should be repeated many times a day at the same locality in order to integrate the energy transport at that point for a 24-hour period. Needless to say, this condition is far from satisfied over the vast expanses of ocean around a hurricane. In order to approximate these requirements, for a single day in the life of a hurricane all ship observations within a circular area 900 miles in diameter around its 0930 GMT position were plotted (0930 GMT was chosen since the observations are made at 0030, 0630, 1230, and 1830 GMT). As a first approach, the observations were run through equation (4) just as they were received and the results were then plotted at the appropriate position. These data were then mechanically smoothed by systematically running a circle of 3° latitude in diameter over the field and at chosen grid points the mean of all observations within the circle centered at each grid point was plotted. The size of the circle and the spacing of the grid points were chosen so that the field used to compute the average value for any grid point overlapped the field used for each of the neighboring grid points. Thus the energy transport from individual ship reports was objectively computed and objectively smoothed.

If a sizable number of storms was to be studied so that statistical criteria could be applied to the results, this method would certainly be one of the better approaches. However, since this project was of limited scope, and could thus be only exploratory in nature, another method of computing the eddy energy transport was decided upon. It was noted that many of the ship reports had to be ignored because the data for the computation were incompletely reported (one or more elements missing). Because of this, a certain amount of information concerning meteorological conditions in the areas around the hurricane was being overlooked. Since scarcity of data is one of the more severe problems that is encountered in any study of oceanic weather systems, it was decided that another approach should be used, an approach wherein this additional information could be utilized. Thus, separate maps were drawn of each of the various elements used in the computation as reported by ships traversing the area in a single day. In this manner, the average daily values of dewpoint, sea temperature, wind, and sea-air temperature difference were drawn. Next, at grid points 1-1/2° of latitude apart distributed about the hurricane, the necessary readings were made and the computations of energy transport were effected. At any point in the field where any one of the elements needed was not sufficiently clearly delineated, the computation was omitted, and these areas appear blank on the figures showing the results. As an indication of the amount of data which was available, an average of between 75 and 150 observations was utilized in each daily computation.

There are a number of questionable points in this approach. Firstly, an element of subjectivity is introduced into the analysis. However, since the final result is based on the independent analyses of several different charts, the introduction of any consistent bias is relatively unlikely. Secondly, areas near the hurricane center are difficult to analyze since the data are sparse and some of the elements (wind in particular) vary greatly with distance. Thus, no extended attempt was made to measure the energy transport within an area 3° in latitude about the storm center. Actually, this should not seriously affect the results since in this part of the storm the gradients of vapor pressure and temperature between sea and air tend to become minimized and, despite the great turbulence, the energy flux must become quite small. In addition, Riehl [12] has shown, by a simple computation, that even a small hurricane must draw from surface air extending at least to the limits of a circle 8° in latitude about the center in order to support its cloud and precipitation area in a steady state. For these reasons, omitting the central area of each hurricane and examining the energy transport in the surrounding areas seems justifiable.

A third point of question arises out of the problem of dealing with a moving system by meaning fixed observations taken over a 24-hour period. In retrospect, it might have been advisable to have examined the possibilities of plotting each observation relative to the position of the storm center at the time the observation was made. This would have led to many complications, and since most of the elements being analyzed (with the possible exception of the wind field) were not strongly affected by the storm's movement, especially since the area nearest the storm had been omitted, it was felt that this effect might be safely ignored.

THE RESULTS OF THE ANALYSIS

The computations were performed on 25 days in the histories of five hurricanes. The analyses of the energy transport for each day of each storm are shown in figures II-1 through II-5. In general, it will be noted that the flux of energy is, with a few rare but important exceptions, upward from sea to atmosphere. There is always a maximum value near the hurricane itself due largely to the increase of wind speed near the storm, and as one views the picture on a large scale it is immediately evident that the hurricane is a mechanism which massively siphons energy from the sea. As for the individual storms themselves, the following comments can be made:

Carol (Aug. 25-30, 1954, fig. II-1): In the early stages, during the 25th and 26th, when the storm was relatively weak, it traversed areas of relatively weak energy flux, and in the later stages, on the 28th and 29th, it became much more intense and traversed areas of much greater transport. Part of this increase may have been due merely to the increase in intensity of the

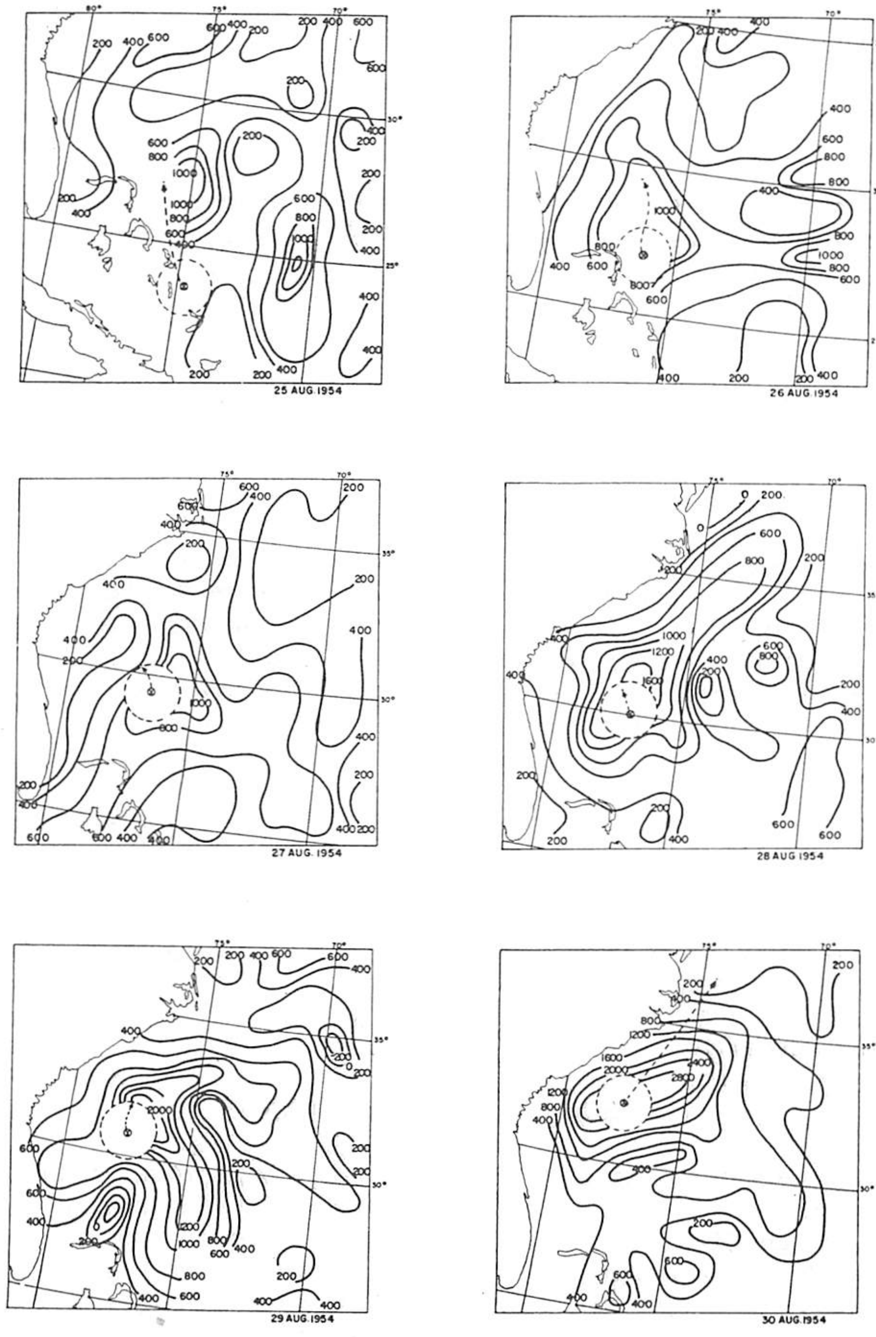


Figure II-1. Total eddy transport of heat (latent and sensible) from ocean to atmosphere in the vicinity of hurricane Carol, Aug. 25-30, 1954. Position of hurricane at 0930 GMT is shown by circled X, with path for following 24 hours. Units are gram calories per square centimeter per day.

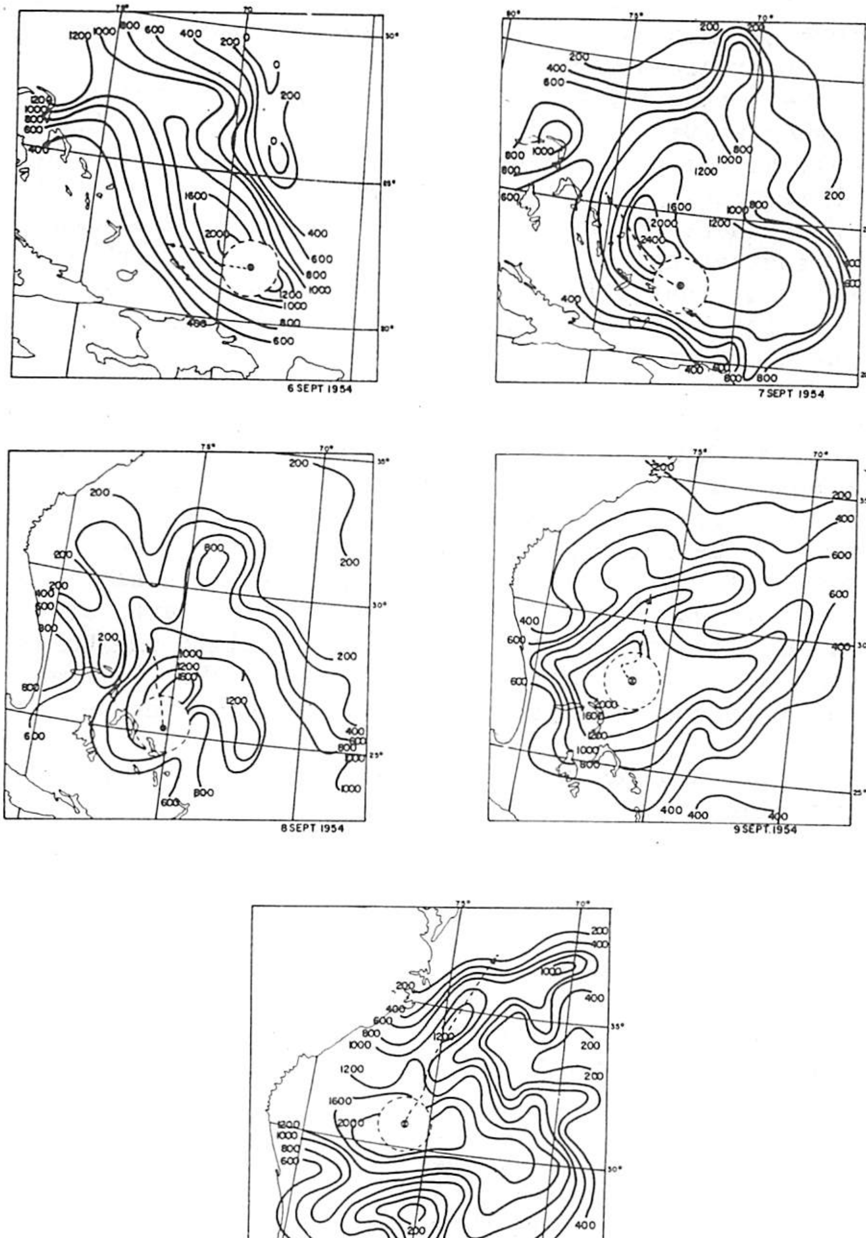


Figure II-2. Total eddy transport of heat (latent and sensible) from ocean to atmosphere in the vicinity of hurricane Edna, Sept. 6-10, 1954. Position of hurricane at 0930 GMT is shown by circled X, with path for following 24 hours. Units are gram calories per square centimeter per day.

storm itself, although there are some indications that the reverse possibility may be true, since certain areas showed increased fluxes before the direct effects of the storm reached them. On the 27th, low values of energy flux appeared across the northern quadrant and the storm decelerated, turning toward somewhat higher values to its north-northwest. On the 28th and 29th, a tongue of markedly higher values appeared to its northeast and the storm veered in that direction. On the 30th, the hurricane accelerated rapidly, apparently now grasped by the westerlies, and moved north of Cape Hatteras over a region of increasingly lower energy fluxes. The hurricane advisories indicated weakening at that time. The effects of the cool water which formed behind Carol (see fig. I-4) can be seen in the areas of low energy flux which appear behind the storm on nearly all days.

Edna (Sept. 6-10, 1954, fig. II-2): During most of the period studied, a tongue of high energy fluxes extended out ahead of Edna. With the exception of the 6th, the hurricane showed a marked tendency to seek out and move along these areas. In most cases, the tongue of maximum values extended far enough ahead of the storm to be out of the area of the storm's direct influence, and thus its presence could not be attributed to the storm itself. On the 6th, the track of the storm was about 45° to the west of the axis of the tongue of maximum energy flux. An attempt has been made by Malkin and Holzworth [7] to compute the steering effects on this storm at this time. Interestingly, they found that steering tended to indicate movement more to the west than Edna actually took, although the differences were small. It is possible that the deviation to the northward was a result of the energy distribution ahead of the storm at that time.

Connie (Aug. 6-10, 1955, fig. II-3): The data surrounding this storm were unfortunately sparse, particularly in the regions nearest the hurricane. There is detectable, however, a tendency to seek tongues of largest energy flux. The effects of the cold water churned up by the hurricane can be seen clearly on the 9th and 10th. The positive flux began to decrease behind the storm, and on the 10th the direction of the flux in one area actually reversed itself (i.e., there was a loss of energy from the atmosphere to the sea.)

Diane (Aug. 14-16, 1955, fig. II-4): Unfortunately, Diane formed over a portion of the ocean in which there were very few reports, and its early life could not be studied. However, for the short period during which the data were usable, it can be seen that Diane skirted along the southern edge of a region of very low energy flux (in fact, the flux was negative on the 14th). This was the region where the sea temperature field showed very low surface temperatures (see fig. I-10). The general scale of the flux seems to be lower than that found in the other storms, and Diane was notably a weaker system.

Ione (Sept. 13-18, 1955, fig. II-5): Ione was first picked up as a "tropical disturbance" on the 13th. At that time she was headed toward an area of higher energy flux. Upon reaching this region on the 14th, Ione became a full-blown hurricane, and, interestingly, under the influence of Ione, the energy transport in this area increased markedly. From that time onward, Ione showed the characteristic tendency to stay near, and head for, regions of higher transport.

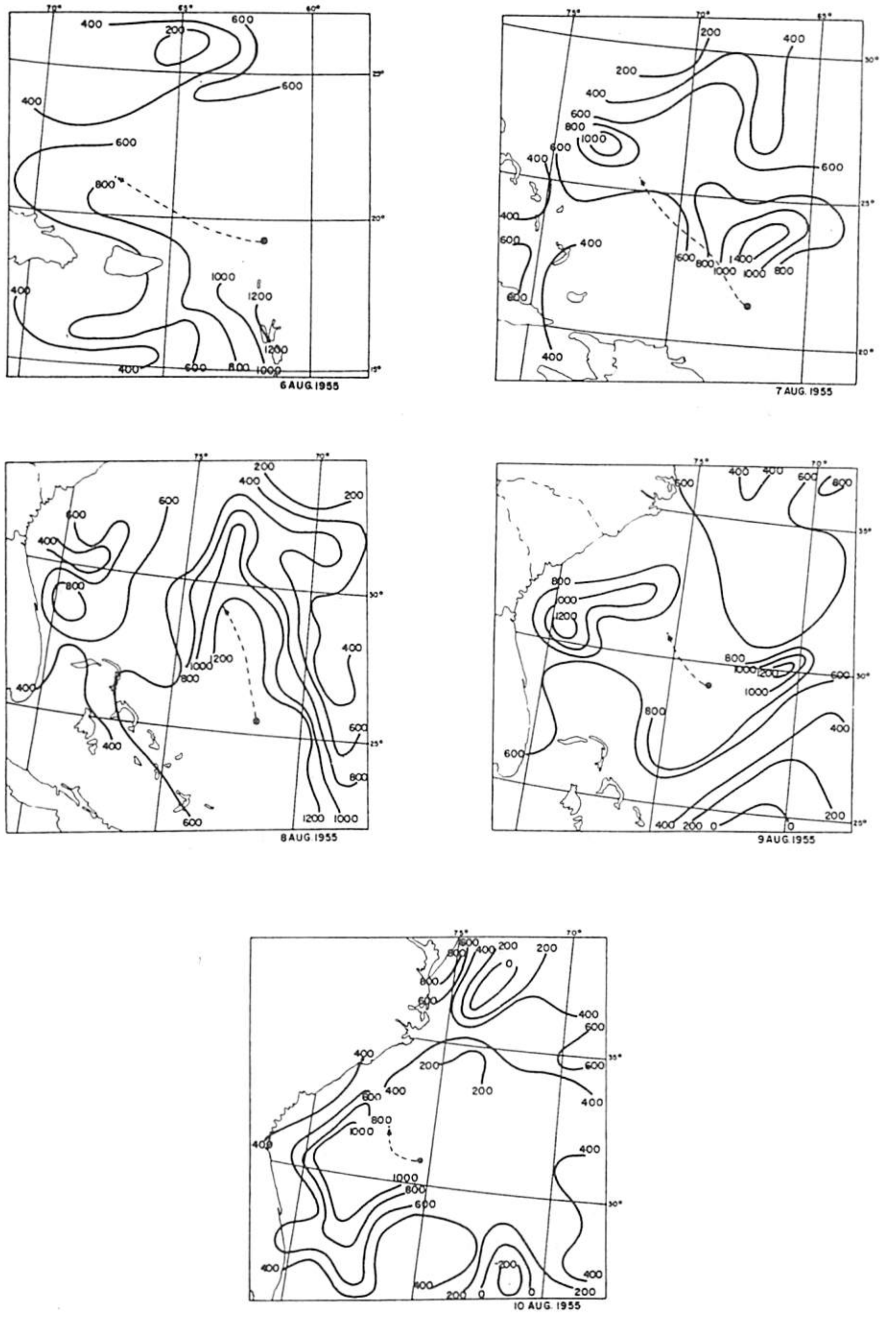


Figure II-3. Total eddy transport of heat (latent and sensible) from ocean to atmosphere in the vicinity of hurricane Connie, Aug. 6-10, 1955. Position of hurricane at 0930 GMT is shown by circled X, with path for following 24 hours. Units are gram calories per square centimeter per day.

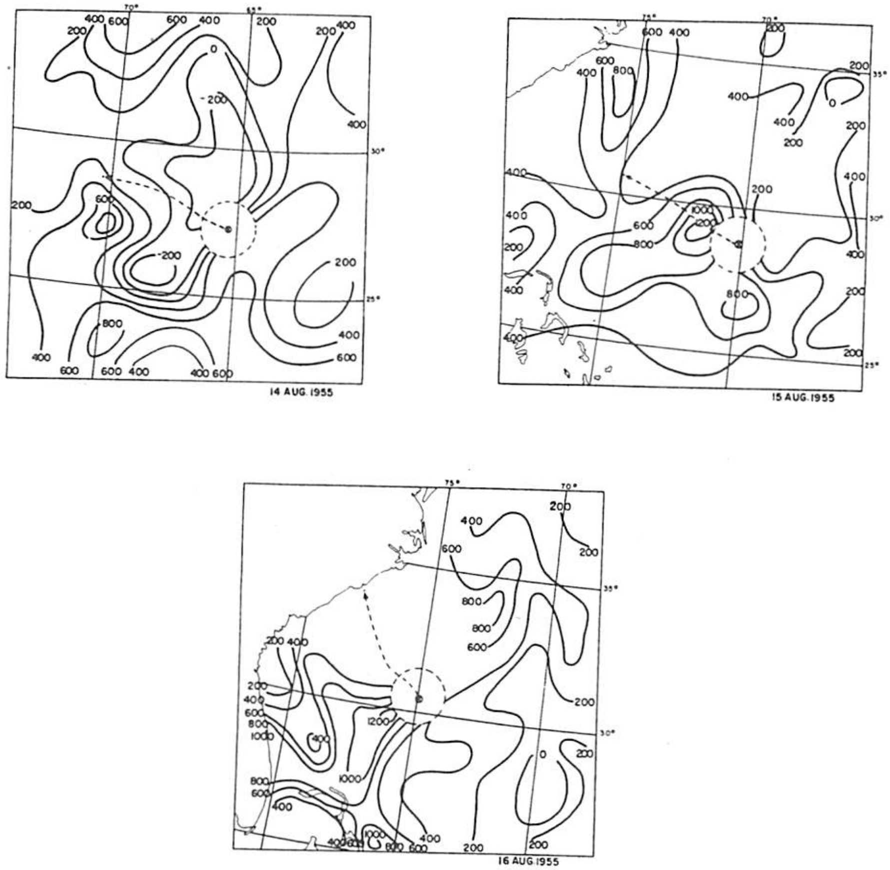


Figure II-4. Total eddy transport of heat (latent and sensible) from ocean to atmosphere in the vicinity of hurricane Diane, Aug. 14-16, 1955. Position of hurricane at 0930 GMT is shown by circled X, with path for following 24 hours. Units are gram calories per square centimeter per day.

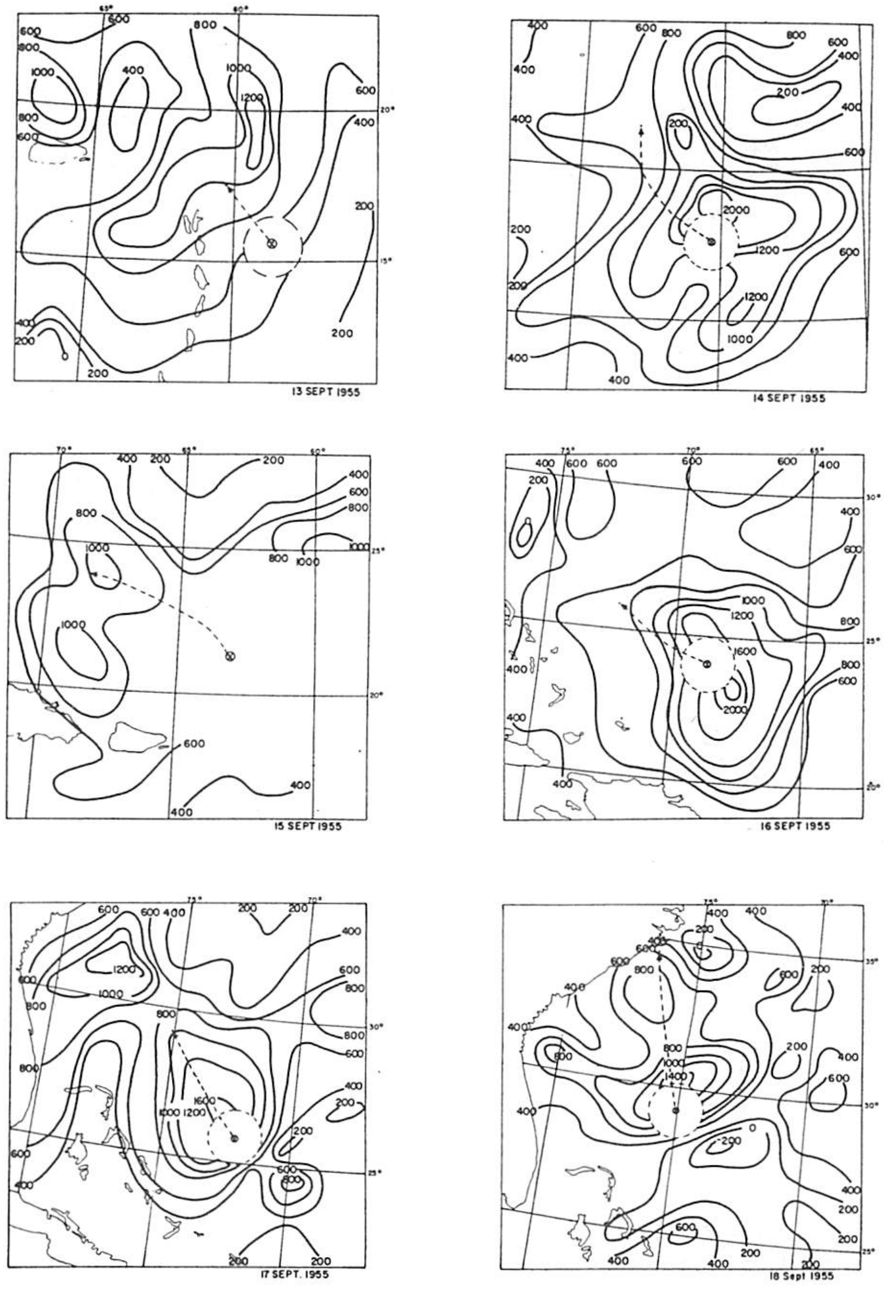
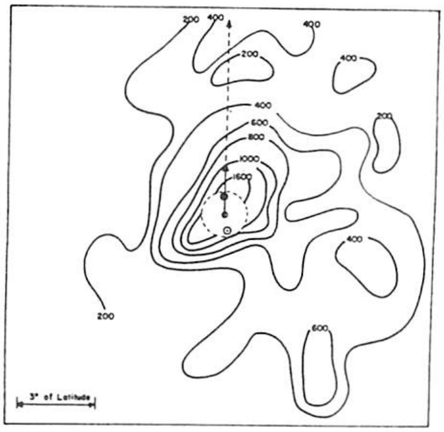
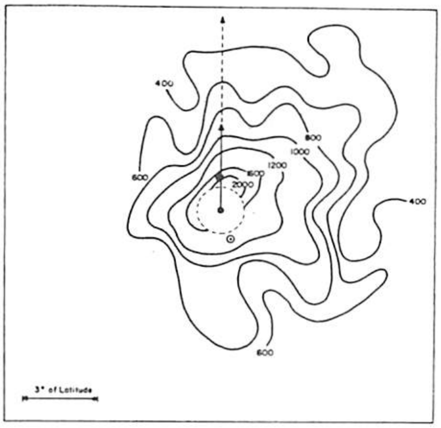


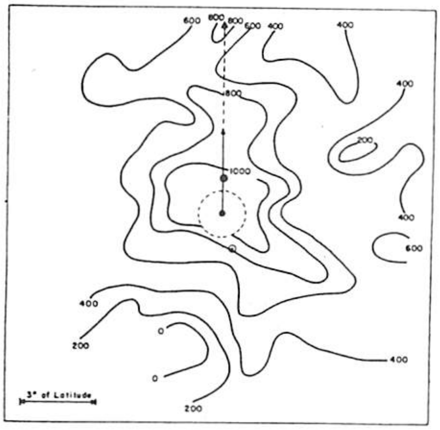
Figure II-5. Total eddy transport of heat (latent and sensible) from ocean to atmosphere in the vicinity of hurricane Ione, Sept. 13-18, 1955. Position of hurricane at 0930 GMT is shown by circled X, with path for following 24 hours. Units are gram calories per square centimeter per day.



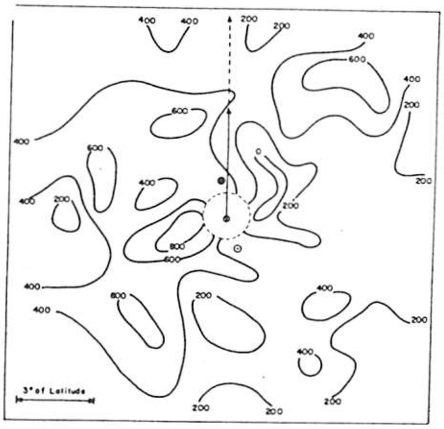
(a) Hurricane Carol
25-30 August 1954



(b) Hurricane Edna
6-10 September 1954



(c) Hurricane Connie
6-10 August 1955

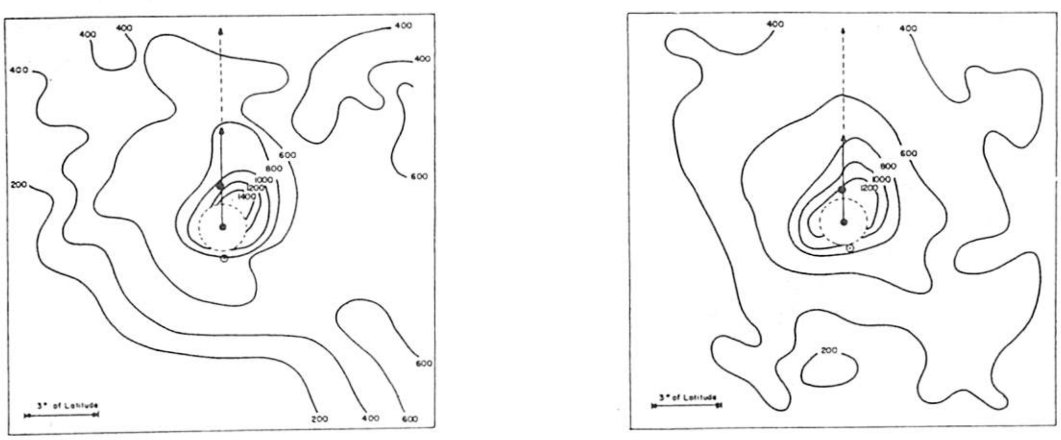


(d) Hurricane Diane
14-16 August 1955

Figure II-6. Mean eddy transport of heat (gm cal/sq cm/day) from ocean to atmosphere for hurricanes Carol, Edna, Connie, and Diane, oriented according to the direction toward which the storm moved in the following 24 hours. Solid arrow indicates mean 24-hour movement (0930 to 0930 GMT); open circle indicates mean 0030 GMT position; closed circle, mean 1830 GMT position.

These same data were reviewed in another fashion in the hope that any trends present might be brought out more clearly. As was stated earlier, the computations had been made at grid points around the storm. This pattern of grid points was always centered on the 0930 GMT position of the storm and oriented so that the columns were parallel to a line drawn between the present position of the storm and its position 24 hours later. Thus it was a simple matter to mean the value of energy flux around each storm for the period studied by simply meaning the values at corresponding grid points. In this manner we arrived at figures II-6 and II-7 (a), which show the mean energy flux for each of the storms oriented according to the path the storm was going to take in the next 24 hours. Figure II-7(b) is the mean for all storms combined, a total of 25 days. On each of the charts, the solid arrow represents the displacement of the storm in the next 24 hours. The circles near the center of the storm represent its mean 0030 GMT and 1830 GMT positions. These data are included so that one may judge the area that was influenced by the immediate presence of the storm circulation itself.

In each case (with the possible exception of Diane) the patterns show a strong flux near the storm center and also over the areas where the storm's influence must have been felt during the period for which the data are meaned. However, when we look ahead of each storm into the regions beyond its displacement in the next 24 hours, we are examining areas where the storm's direct influence was probably not felt. It will be noted that even in these areas there is a tendency for larger values to be found ahead of the storm. Diane, which was the weakest of the group, showed the lowest mean values. Carol and Edna, two of the strongest of the group, showed the highest values.



(a) Hurricane Ione
(13-18 September 1955)

(b) 25 days studied for
the five hurricanes.

Figure II-7. (a) Mean eddy transport of heat (gm cal/sq cm/day) from ocean to atmosphere for hurricane Ione. (b) Mean data for the 25 days studied for all storms. (Analysis and units same as in fig. II-6.)

CONCLUSIONS

The entire approach to this research has been that of an exploratory operation. In an attempt to understand some of the mechanics of hurricane development and behavior a rather radical technique has been tried. This method of calculating the eddy energy flux from the sea to the atmosphere is certainly open to question and criticism. The constants used in the computations, their stability, the type of data inserted in the equations, and the very equations themselves are all not yet securely founded on a sound scientific basis. However, the problem is one of importance, and it was felt that an attempt must be made at its solution despite the handicaps mentioned.

The results obtained suggest that this approach is not fruitless. Certainly, the values of energy flux and their distribution about the hurricanes seem to be reasonable and physically sensible. There is considerable evidence that the hurricane responds to the eddy energy flux (or whatever part of it we are measuring by these methods) in a logical manner. Where the fluxes are weak, the storms weaken; where the fluxes seem to be strongest the storms strengthen. There is evident a tendency for each storm to remain near or move along regions where the replenishment of the supply of energy is greatest. It is interesting to speculate somewhat further on some of the possibilities suggested by these relationships. For example, in several of the hurricanes cold water was brought to the surface by the action of the storm (see Part I). The presence of this cold water resulted in a reduction of the energy flux in these regions, and it can be seen that a hurricane which had become stationary over such a region might slowly cut off an important portion of its energy supply and thus weaken or dissipate. Therefore, knowledge of the possible nature of the energy flux and changes of the flux near a hurricane may be of some immediate use to a forecaster.

It seems that this technique, crude as it is, can be of value in understanding hurricane behavior, and on the basis of this incomplete preliminary investigation, it might be well worthwhile to extend this study to as many more storms as possible. There is a wide range of varying oceanic conditions in the hurricane areas and in easterly waves which have not been touched upon, and which should certainly be investigated.

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