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ABSTRACT

Hurricane Hilda crossed the Gulf of Mexico in the period 30 September to 4 October 1964, developing into a very severe hurricane in the central Gulf. Sea temperature data available prior to the storm indicated what was probably a typical late summer situation with some surface temperatures running above 30C. Beginning 5 October 1964, a 7-day cruise was conducted over the area where hurricane winds had been observed. Using the GUS III of the Galveston Biological Laboratory of the Bureau of Commercial Fisheries, four crossings of the hurricane path were made. Bathythermograph observations were taken regularly to 270 m and hydrographic casts to 125 m. The data on all four crossings indicated similar patterns. The observed temperature-depth structures after the storm indicated that the warm ocean surface layers were transported outward from the hurricane center, cooling and mixing as they moved; that these waters converged outside of the central storm area with the result that downwelling to some 80 to 100 m in depth took place there; and that cold waters upwelled along the hurricane path from depths of approximately 60 m. Sea surface temperatures decreased by more than 5C over an area of some 70 to 200 mi. A cyclonic current system was observed around the area of greatest hurricane intensity. It is estimated that the total heat loss from the ocean to the atmosphere in the area of hurricane force winds was 10.8×10^{18} cal with the transfer per unit area being 4500 cal cm^{-2}. The data collected on the GUS III cruise are the first systematic observations available immediately after a severe hurricane in deep water.

1. Introduction

There are several indications in the literature that areas of low sea surface temperature are found in the wakes of hurricanes [e.g., Fisher (1958) and Jordan (1964)]. These indications are based upon observations from merchant ships. On such a basis Jordan concluded that vertical mixing was a primary process in causing the observed drop in sea temperature. However, Fisher indicates that upwelling may be responsible. Hidaka and Akiba (1955) reported cold areas after hurricane passages and developed a linear theory based upon a stationary cyclonic wind system to explain them. Their theory indicates that there would be considerable upwelling in the center of a hurricane and that a cyclonic current would be formed around the area of low atmospheric pressure. Ichiye (1955) considers upwelling produced by a traveling cyclonic wind system.

Stevenson and Armstrong (1965), using data collected from the Texas A&M University research vessel HIDALGO, reported on shallow water ocean conditions associated with hurricane Carla in 1961. Their work emphasizes the apparent loss of heat from the ocean to the atmosphere. They also reproduced two deep water sections taken in the vicinity of hurricane Carla's path.

After hurricane Hilda crossed the Gulf of Mexico, the first opportunity arose for a systematic deep-water survey immediately after such a storm using standard oceanographic instrumentation. Some of the data are presented here. Additional information is available and may be obtained by writing the author. Several pertinent theoretical models have been developed by O'Brien and Reid (1967) and a portion of their work is submitted as a companion article to this one.

2. The Gulf of Mexico before hurricane Hilda

In order to completely describe the effects of hurricane Hilda upon the waters of the Gulf of Mexico, it would be desirable to have a full observational picture of these waters before the storm to compare with that obtained afterwards. However, until the time that regular synoptic observations are available for large ocean areas, obtaining a prior picture is largely a matter of luck. In the case of Hilda there were some prior data but the amount, particularly at subsurface depths, was minimal.

Probably the most useful prior data are of the type which to date have given almost the only information in other deep water hurricane situations, i.e., sea surface temperatures from merchant ships. Some of the Gulf is well traveled by such ships and the general character of the sea surface temperature distribution before Hilda was obtained by averaging over a 7-day period (Fig. 1). These data show that from the southeast to the northwest there was a wide band of water across the central Gulf having temperatures above 29C and being fairly

[1] Contribution from the Department of Oceanography, Texas A&M University, College Station, Tex.

uniform at about 29–30C. This is the band along which Hilda moved, as also shown in the figure. The level of sea surface temperature agrees with that of the climatic atlases which show the Gulf to be uniform at about 29C. The cooler water in the northeast Gulf in Fig. 1 is probably due to unusually cool weather in Florida in September (see, for example, *Weatherwise*, **17**, No. 6), and that off Yucatan is due to a regular upwelling found there[2].

Other data were obtained from the R/V ALAMINOS of Texas A&M University which crossed the Gulf just before the hurricane, being only one to three days ahead of the eye of the storm and crossing the path later followed by the storm (Fig. 2). Sea surface temperatures were obtained along this path from the ship's sea thermograph. For the deep water portion of the route, they showed a total temperature range of 28.7C to 29.3C, a little cooler than indicated by the merchant ship 7-day averages. Although the weather was unfavorable, three bathythermograph observations were obtained by the R/V ALAMINOS before Hilda. These were at approximately 26–27N and were near the locations of bathythermograph (BT) observations 26, 21 and 18, respectively, as shown in (Fig. 2), these latter observations being made after the storm

[2] J. D. Cochrane, personal communication.

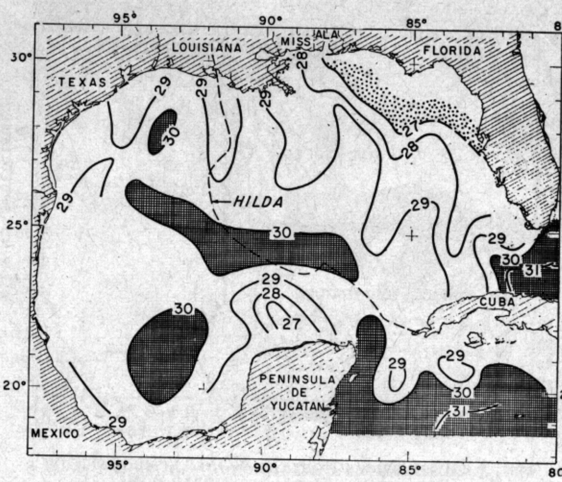


FIG. 1. Sea surface temperature before Hilda, 24–30 September, and hurricane path. Temperatures (°C) are based upon merchant ship data collected by the U. S. Weather Bureau, averaged by 1-deg quadrangles.

using the same BT instrument used on the R/V ALAMINOS.

There were several other sources of data which provided information on Gulf temperatures before Hilda. The NOMAD buoy in the center of the Gulf, at 25N, 90W, operated continuously. It was some 48 n mi from the hurricane path at the position indicated

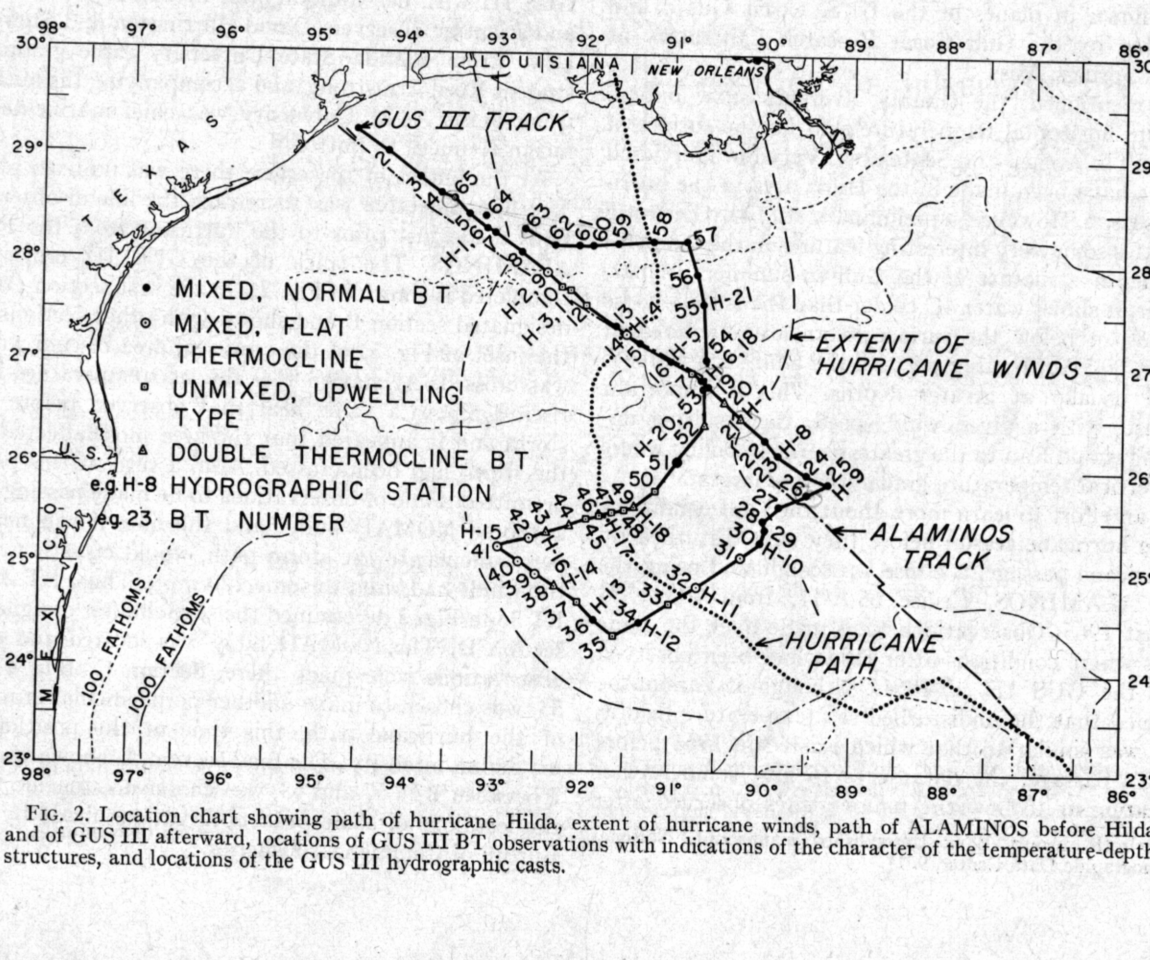


FIG. 2. Location chart showing path of hurricane Hilda, extent of hurricane winds, path of ALAMINOS before Hilda and of GUS III afterward, locations of GUS III BT observations with indications of the character of the temperature-depth structures, and locations of the GUS III hydrographic casts.

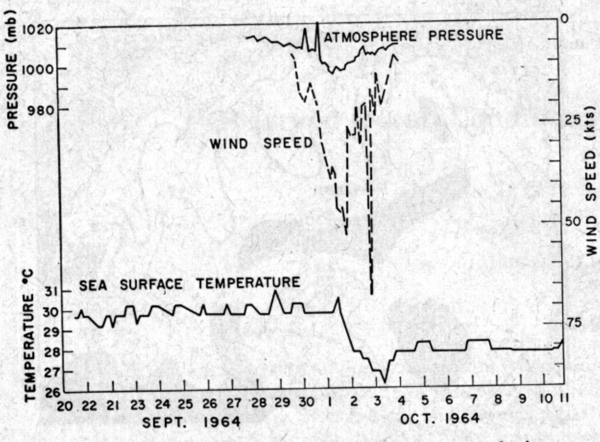


FIG. 3. Observations from the NOMAD buoy during Hilda. Buoy position was 25N, 90W.

by BT 30 in Fig. 2. The winds reached 57 kt according to the buoy records and the sea surface temperature dropped from 29.7 to 26.2C with the passage of the hurricane as shown in Fig. 3, and then recovered to 27.8C.

Data available in the shallow waters of the Gulf Coast area, to depths of some 40 fathoms, included monthly observations made by the Galveston Biological Laboratory of the Bureau of Commercial Fisheries and sea temperatures indicated by radiation thermometers flown in planes of the U. S. Coast Guard and collected by the Gulf Coast Research Laboratory at Ocean Springs, Miss.

As mentioned, the climatic averages show only a uniform horizontal temperature field for the surface of the Gulf in August and September. Very few individual cruises have been made in the Hilda area in the hurricane season. However, a preliminary study by Perlroth[3] indicates some very interesting features in the temperature-depth structure of the Gulf in summer. In particular, it shows water 4C colder than the surface to be only 30 m below the surface in an area centered at 25.5N, 90.5W. In other parts of the Gulf such water is found usually at greater depths. This is important because, with a given wind speed, the resulting upwelling would lead to the greatest surface cooling where the vertical temperature gradients were largest.

In an effort to learn more about the Gulf conditions in the hurricane season before they were disturbed by a hurricane passage, a cruise was conducted using the R/V ALAMINOS, Cruise 65-A-11, from 10 to 24 August 1965. Observations were made over the same paths where conditions after Hilda had been observed from the GUS III in 1964. Although it cannot be assumed that the undisturbed sea temperature field in 1965 was similar to that which existed in 1964 before Hilda's passage, the data serve to give some further indication as to how the temperatures observed after Hilda differ from those of the undisturbed Gulf in the same part of the year.

[3] Perlroth, Irving, 1966: Unpublished manuscript. National Oceanographic Data Center, 9–11.

3. Hurricane Hilda

The path of hurricane Hilda as it crossed the Gulf of Mexico is shown in Fig. 2. The most intense stage of the hurricane occurred when it was centered 250 mi offshore in waters over 1000 fathoms in depth. Thus, the effects of the storm upon the sea were quite likely similar to those which would result from storms in the larger ocean basins. Entering the Gulf on 30 September 1964 with winds less than 80 mph, the hurricane intensified to the 150 mph stage and the winds again decreased to less than 120 mph during the passage across the Gulf. The width of the zone having winds of hurricane speed is indicated in Fig. 2. The average propagation speed of the storm was 6–8 kt and the width of the eye was approximately 35 mi in the northern Gulf. By 4 October, hurricane Hilda had moved inland.

4. Cruise plans

As hurricane Hilda became a severe hurricane on 2 October, efforts were made to locate a research vessel which could be used to make a survey in the hurricane area immediately after the passage of the storm. The Bureau of Commercial Fisheries laboratory in Galveston, Texas, was able to provide the 90-ft shrimp vessel GUS III with her Captain, Jim McMurrey, the crew, and scientific observers David Harrington and Stewart Law. From Florida State University came graduate student Reed Armstrong, and accompanying the author from Texas A&M University was chief marine technician Kenneth S. Bottom.

At the outset of the cruise there was no fixed plan. The first objective was to retrace the line of observations made just prior to the hurricane from the R/V ALAMINOS. The track of the GUS III cruise as completed is shown in Fig. 2. On the first section (later designated section B and shown with other sections on the inset of Fig. 5) of the cruise an area of cold water was crossed. At station H-9 the sea temperature had risen again to a value near that observed before the storm and it appeared that the area most affected by the storm had been crossed. Also, a turn at this point permitted a line of observations to be made passing the anchored NOMAD buoy; and the line, if run nearly perpendicular to the storm path, would cross it where the winds had risen to some 120 mph. Thus, BT 25 to BT 35 in Fig. 2 determined the section later designated section D. The NOMAD buoy was located and ship observations were made there. Section C, BTs 41 to 53, was chosen to make another perpendicular crossing of the hurricane path, this time at the position of maximum intensity. The final section A, shown in Fig. 2 between BTs 57 and 63, was chosen to coincide with the locations of some prior observations made by the Bureau of Commercial Fisheries.

5. The Gulf after Hilda; indications of upwelling, mixing, heat loss and advection

Using the data collected after hurricane Hilda, the first questions one might try to answer would be those concerning the amounts of oceanic upwelling, advection, mixing and heat loss to the atmosphere. As previously mentioned, there is now no certain indication of these amounts in hurricane situations, different authors believing that different processes are most important and no author fitting the four processes into any one explanation or theory. The answer has not been obtained here but it is believed that a careful interpretation of the data allows considerable insight into the question of amounts and provides a concept of the manner in which the processes are related to each other and to the storm above.

The pattern of sea surface temperatures was one of the most marked features of the Gulf after hurricane Hilda. This pattern is shown in Fig. 4. There is no doubt but that the main features of the pattern as shown in the hurricane area truly did exist. Whereas previous information in similar deep sea situations has been based upon the erratic and undependable observations of ships of opportunity, the data after Hilda in the hurricane area were collected systematically from one ship, GUS III, using the most reliable instruments for sea surface temperature measurement. These included the bucket thermometer, the bathythermograph and reversing thermometers. The temperatures are accurate to within 0.2C.

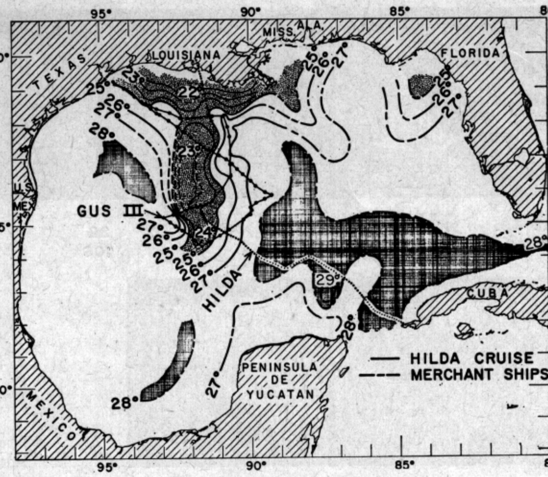


FIG. 4. Sea surface temperature after Hilda, 1–13 October, and hurricane path together with the track of GUS III.

The path of coldest surface water is centered to the west or to the left of the path of the storm. This

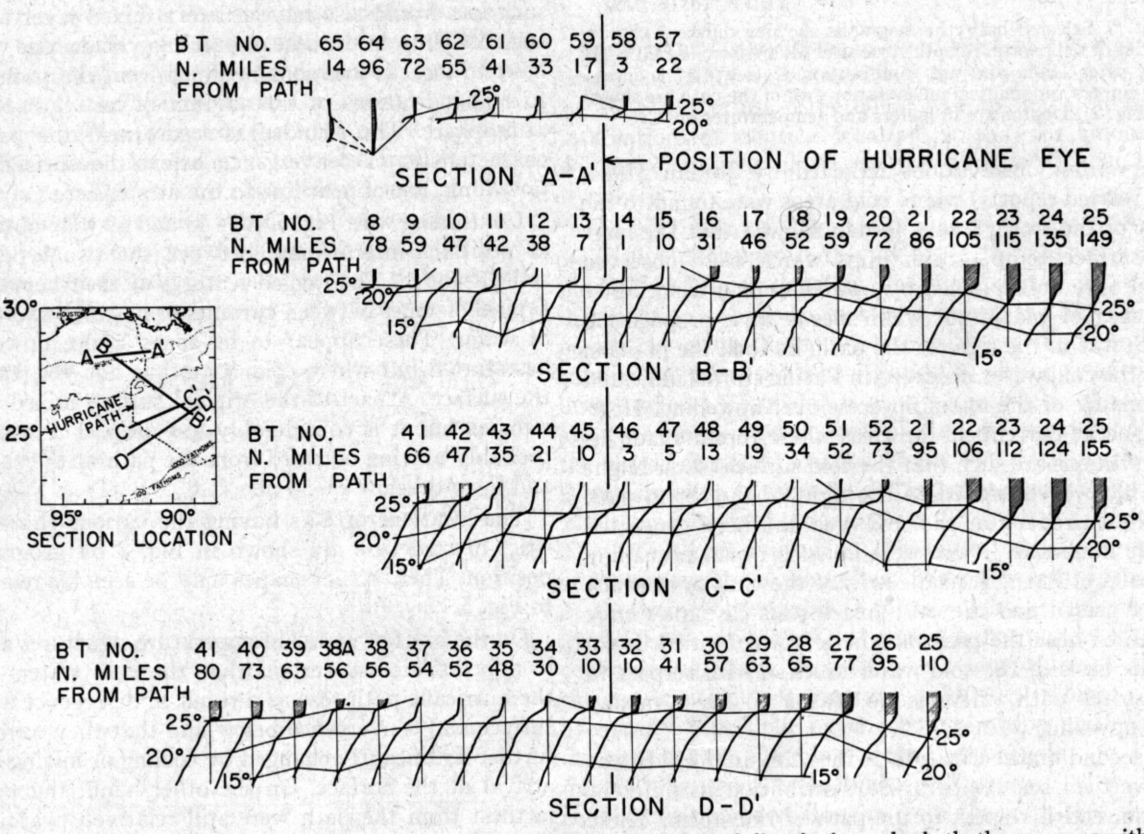
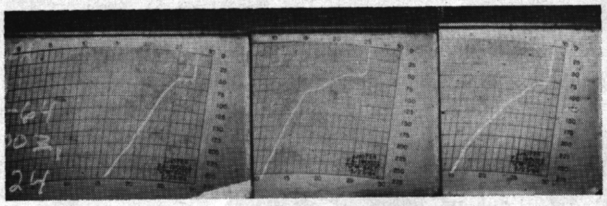
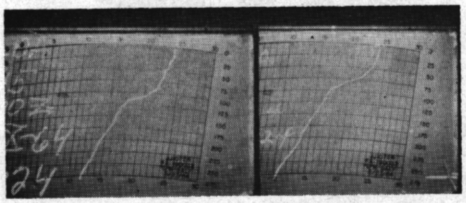


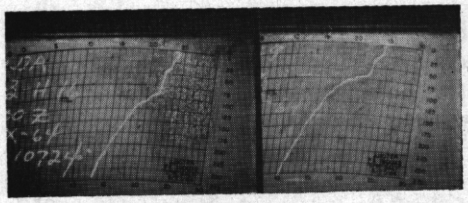
FIG. 5. Copies of BT traces along sections crossing the path of Hilda. Traced directly from the bathythermograms with no allowance for difference of grids. Portions of the structure warmer than 25C are shaded. BT numbers and the number of nautical miles of each from the path of Hilda are shown. Section locations are shown in the inset. Observations are projected on to straight sections.



B.T. NO. 41 51 22
MILES 66 52 106



B.T. NO. 45 48
MILES 10 13



B.T. NO. 43 49
MILES 35 19

FIG. 6. Selected bathythermographs showing different characteristics of temperature-depth structure. All are from the GUS III cruise after Hilda and are from section C (see Fig. 5, inset). BT numbers and nautical miles east or west of the path are shown (see Fig. 2). Depths are in meters and temperatures in °C.

differs from observations reported by Jordan (1964, and related reports) where cold areas were found to the right of the storm track. Jordan showed that the large sea surface temperature drops which were observed could only be explained by upwelling or mixing. Since the area of maximum wind speeds in a propagating storm was to the right of the path, he took the position that the cold water observed in Pacific storms indicated dominance of the mixing process over upwelling. However, ocean currents in the areas where Jordan made his observations are such that the cold surface water might well have been carried to the right of the storm path by the current after the cold area had been generated in the hurricane. There were no such broad prevailing currents of strength in the area of the Gulf over which Hilda passed and the cold area in this case may have remained near the position where it was formed. If so, on the basis of the cold water location with respect to the storm path, there is no reason to favor mixing over upwelling.

A second marked feature of the Gulf after Hilda was the vertical sea temperature distribution in different locations with respect to the path of the storm. These are shown in Fig. 5 where all of the temperature-depth structures as obtained by BT observations are copied in their respective order determined by their distance from the hurricane path. In addition, certain observations have been selected from section C and photographed to show the character of the structure at various distances from the storm path, as shown in Fig. 6. BTs 41, 51 and 22 represent observations at greatest distances from the path. They are characterized by deep, well-mixed surface layers warmer than 25C, underlain by thermoclines having unusually steep gradients. Such structures represent either cooling at the surface with resultant convective mixing, or mechanical mixing, or both. They also may represent convergence at the surface with forced downwelling. In the area of hurricane force winds, it is only from these waters that heat losses to the atmosphere are indicated. For a discussion of temperature-depth structure and related causal phenomena see La Fond (1962).

In Fig. 6, BTs 45 and 48 represent locations near the path of the storm. These temperature-depth structures are characterized by having no mixed layer but rather a rounded structure near the surface. No significant surface mixing of any type could have occurred in these locations since this would have resulted in a surface isothermal layer. There was apparently no important loss of heat to the atmosphere after the water reached the surface since convection resulting from such loss would also have led to a mixed layer at the surface. Thus, in the case of hurricane Hilda, one would have to look at locations removed from the path area to find indications of the amount of heat lost to the atmosphere. The rounded structure near the path is characteristic of convergence below the surface and upwelling, not of heat loss to the atmosphere.

Continuing with Fig. 6, BTs 43 and 49 were obtained at positions intermediate between the two types described above. The ragged features of their curves are typical of zones between currents or between two types of water. These appear to be zones where upwelling has started but where cold water has not yet reached the surface. A part of the original surface mixed layer remains but it is considerably less deep. The water is probably moving outward from the path at the surface and inward below 25–50 m.

The locations of BTs having the various characteristics of structure are shown in Fig. 2 by geographic position. Their actual shapes may be seen by referring to Fig. 5.

On the basis of vertical temperature structures alone, it appears almost certain that the cold waters near the hurricane path rose as a result of divergence at the surface and convergence below and that they were not further significantly changed by cooling or mixing after arrival at the surface. On the other hand; the waters farthest from the path were still relatively warm but it appears that they had either been mixed by surface cooling or by mechanical mixing or both and that there had been convergence at the surface. Since it may be assumed that the normal undisturbed summer situation in the Gulf consists of a well-mixed surface layer, it is postulated that the hurricane winds moved this layer outward from the center, cooling it and mixing it as it moved. Then cold water rose from below to replace the surface layer as it was transported away from the hurricane path and the warm layer moving outward led to surface convergence and downwelling at a distance from the path. The manner in which the stress of the wind acting on the ocean surface could bring this about is discussed by O'Brien and Reid (1967).

A final feature of the Gulf based upon observations made after Hilda is the ocean current pattern in the area of the storm. This was forcibly brought to attention by the set of the GUS III between BTs 41 and 52 as shown in Fig. 2. This section was meant to be a straight line and only after good navigational positions were determined was it found that the vessel had been carried far to the north of the heading which was being followed. (Not enough is known about the prevailing currents in this area in summer to ascertain whether or not the current was set up by the hurricane. However, it is clear that any such prevailing current would have been intensified in the presence of the cold upwelled water.) From BT 52 to BT 57 the heading was directly north. Here again was a set of the vessel, this time to the west. Because of these indications the dynamic topography of the sea surface referred to 250 m was computed where depth and data were sufficient. The results (Fig. 7) show part of a cyclonic current of approximately one knot around the area of coldest water. (The *T-S* relationship determined from the top 125 m where salinities were obtained was used to infer salinities to 250 m, which were required for the computation.) An interesting check on the calculated flow was a rise in the isotherms along section B, indicated in Fig. 5 at BTs 18 and 19, where the flow would have

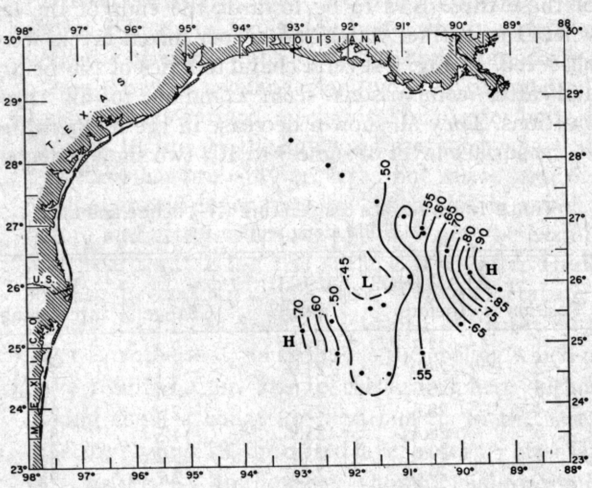


FIG. 7. Dynamic topography of the sea surface referred to 250 m, cruise of the GUS III after Hilda, 1964 (in dynamic meters). The degree to which the hurricane is responsible for the indicated circulation is uncertain.

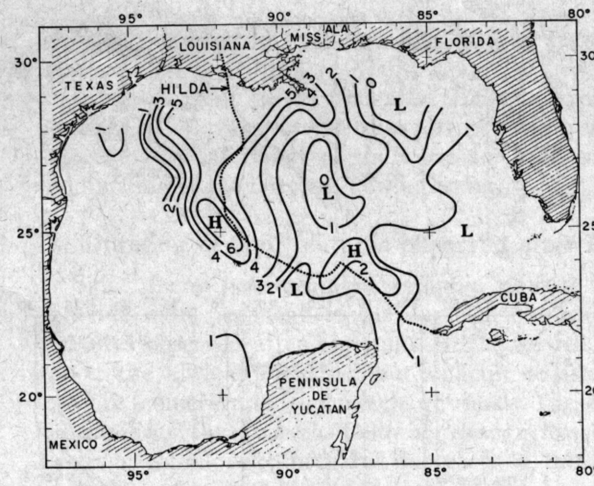


FIG. 8. Sea surface temperature decrease (°C) from before to after Hilda.

been strongly upslope and probably would have created a mechanical upwelling. This rise in isotherms is more clearly indicated on the depth of isotherm section B (Fig. 12a).

6. Directly observed changes in the Gulf before and after Hilda

Earlier, the observations made in the Gulf before the passage of Hilda were described. A major objective of the GUS III cruise after Hilda was to make similar observations at identical locations so that the amount of change brought about by the hurricane could be described.

The only location where continual observations were maintained throughout the period of the passage was the NOMAD buoy location. The significant changes at this location are shown in Fig. 3. When the hurricane passed closest to the bouy (48 n mi) it was apparently gaining in intensity. BTs 30 and 29, obtained at the buoy site and 7.5 mi NNE of it, respectively, $8\frac{3}{4}$ days after the storm passage, were of the type found outside the upwelling area, i.e., they had a well-mixed surface layer extending to some 60 m depth as shown in Fig. 5. The temperature of the layer was 27.2C for BT 30 and 27.4C for BT 29, while 27.8C was indicated by the buoy at the surface at the same time. The lowest temperature at the buoy, observed 3 October, might be explained in one of two ways. First, it is possible that rapid surface cooling could have dropped the temperature at the surface creating a temporary instability which was eventually wiped out by convective mixing and some associated later warming at the surface due to the mixing. The second possibility is that upwelled water could have extended this far from the path and then receded toward the path or downward as the winds decreased after the storm. The NOMAD temperatures agree within one degree with the values indicated on

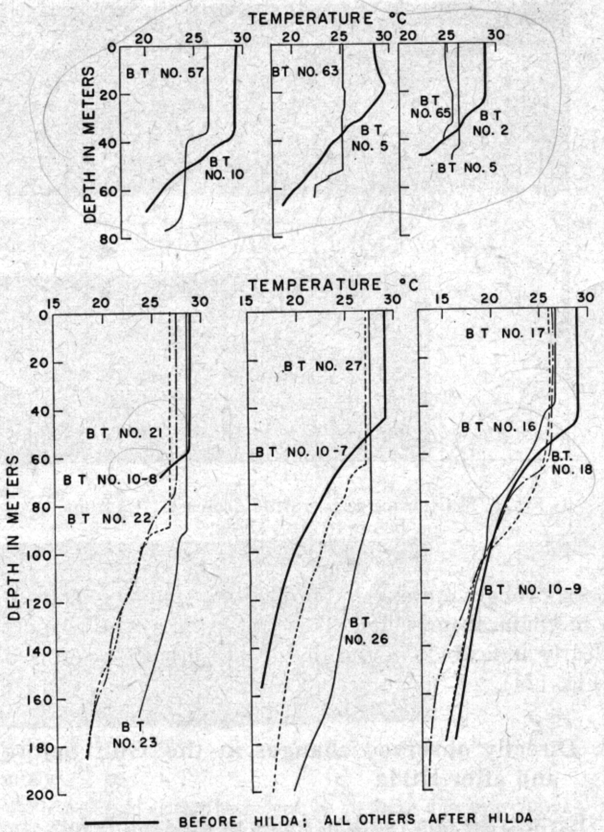


FIG. 9. Comparisons of BTs obtained before and after Hilda at identical locations. Locations may be identified by reference to Fig. 2, using BT numbers of the observations after Hilda.

the sea surface temperature charts, Figs. 1 and 4, before and after Hilda.

A second before and after comparison can be obtained from the successive charts of sea surface temperature of Figs. 1 and 4. Both are based upon merchant ship data except that the detailed observations in the Hilda area after the storm are those of the GUS III. The temperature decrease over the elapsed period is shown in Fig. 8. Whereas the general decrease in less affected parts of the Gulf seems to be of the order of 1C or less, an area just to the left of the path is shown to have a decrease of over 6C. This largest decrease occurred at the latitude where the average winds of Hilda were at a maximum. If the cold surface was the result of upwelling of deeper water, as is thought, the water must have come from depths of the order of 60 m, considering the temperature-depth structure which is probably normal in this part of the Gulf in summer (as indicated, for example, by BTs 10-7 and 10-9 taken from the ALAMINOS before Hilda given in Fig. 9). The area of greatest surface cooling is near but does not coincide with the area of minimum mixed layer depth indicated by Perlroth[4] from scanty historical data.

Another area of larger change is that NNW of the Yucatan Strait where a change greater than 2C is indicated. The winds were less than 90 mph in this case. The maximum cooling zone is to the right of the path but this is an area where the wind drift and the northward current through the Yucatan Strait could have moved the cold area to its observed position after creation of the cold area by the hurricane.

Along the leg B indicated between BTs 1 and 25 in Fig. 2, the ALAMINOS obtained a continuous trace of sea surface temperature on the recording sea thermograph just before Hilda. Immediately after the storm, the leg was repeated by the GUS III and sea surface temperatures were again measured. The temperature values before and after the storm at similar locations along this leg, together with the temperature changes and the time differentials, are shown in Table 1.

The data listed in this table, being obtained from only two ships and with reliable instrumentation and trained observers, are not subject to the inaccuracies of the parts of Figs. 1 and 4 which are based upon averages of merchant ship data. Thus, they serve to add considerable confidence to the overall picture. The positions were equally spaced along the section with position 1 being nearest Galveston and 10 being at BT 26 (Fig. 2).

A final set of observations from which direct before and after comparisons can be made is the set of BTs. There were such observations in six locations before Hilda where observations were repeated afterwards. Three of these were in about 40 fathoms of water near the Gulf coast. They were obtained by the Bureau of Commercial Fisheries at locations very near those indicated for BTs 57, 63 and 65 after Hilda. The corresponding BT numbers for the respective observations before Hilda are 10, 5 and 2. Pairs of before and after BTs at these three shallow locations are each plotted superimposed on the same coordinates in Fig. 9. Reference to section A of Fig. 5 indicates the locations of these three BTs to be towards the ends of the leg where the warmer water and deeper mixed layers were observed. In Fig. 9 several characteristics of the before and after comparisons seem common to all three locations. They all show a decrease in the temperature of the surface layer of some 3 to 4C, two show a deeper

TABLE 1. Sea surface temperature (°C) before and after Hilda along section B.

Position	ALAMINOS (before)	GUS III (after)	Change	Days intervening
1	27.3	25.0	−2.3	6½
2	28.0	24.9	−3.1	7
3	28.0	25.0	−3.0	7½
4	28.3	25.5	−2.8	7¾
5*	28.4	23.9	−4.5	8
6	29.0	23.8	−5.2	8½
7	29.0	26.3	−2.7	9¼
8	29.3	26.4	−2.9	9½
9	28.7	27.4	−1.3	9¾
10	28.7	27.5	−1.2	10¼

* Position where eye of Hilda passed.

[4] *Loc. cit.*