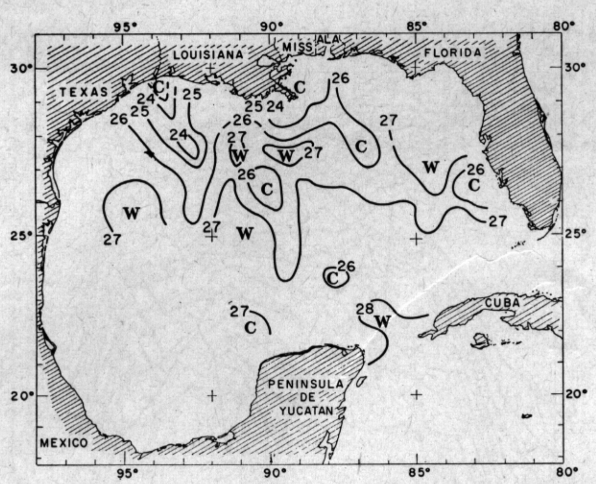


Fig. 10. Sea surface temperature two weeks after Hilda, 14–20 October.

mixed layer afterwards (the third, BT 57, appears to be one of the transitional ones between the upwelling character at the center and the mixed character further removed from the center), and there is heat loss above depths of 40 to 50 m and heat gained below those depths. Although these three locations show indications of vertical mixing, other temperature-depth observations made after Hilda on this section toward the center of the section have the rounded characteristic typical of upwelling as shown in Fig. 5.

The remaining three locations at which BTs were obtained both before and after Hilda were those in deep water indicated on Fig. 2 by the locations of BTs 26, 21, and 18. In Fig. 9, before and after observations were superimposed as before for each location. Additional observations made nearby after Hilda were also entered for each location. It should be noted from Fig. 2 that all of these positions were considerably to the right of the storm track. Reference to Figs. 2 and 5 shows BT 26 to be in the zone where surface convergence of warm water occurred, and where there was a resultant downwelling along with mixing caused by cooling at the surface, mechanical mixing, or both. BTs 21 and 18 are in the intermediate zone where some upwelling has probably occurred but where some of the original mixed layer remains. With this in mind, the before and after structures of Fig. 9 may be examined for these three BTs. The surface layer after Hilda is seen to be cooler in each case. The temperature decreases are of the order of 2 to 3C. Since the surface layer is isothermal, its cooling is the cooling which may have resulted from loss to the atmosphere, although mixing could account for a part of it. In the cases of BTs 26, 21, and 18, the mixed layer is deeper after Hilda than before. BT 16, however, shows a shallower mixed layer after Hilda which could be explained by upwelling occurring below 40 m depth since, in Figs. 2 and 5, BT 16 appears close to the major upwelling zone and definitely inside the transitional or 'ragged structure' zone.

Comparison of before and after BTs supports the concept of outward lateral transport of surface water, upwelling in the center of the hurricane, and cooling and mixing of the outward flowing water.

7. Duration of Gulf features observed after Hilda

Since there were no oceanographic cruises which provide data pertinent to the duration of the ocean features observed after hurricane Hilda, we fell back upon the always available, but difficult to use, sea surface temperatures from merchant vessels. These were obtained for the six weeks following the hurricane, and average charts were prepared for each of the 7-day periods beginning 1, 7, 14, 21, and 28 October and 4 November. The first three of these clearly showed the region of low sea surface temperature. The contours for the week beginning 14 October, approximately two weeks after Hilda crossed the northern Gulf and one week after the survey by the GUS III, are shown in Fig. 10. The numbers of observations in the critical positions are sufficient to provide a reasonable average temperature. Whereas the cold area was centered on the line of 92 deg longitude during the GUS III cruise (Fig. 4), it appears in Fig. 10 that the northern end of it has now moved to the west. The temperatures of the

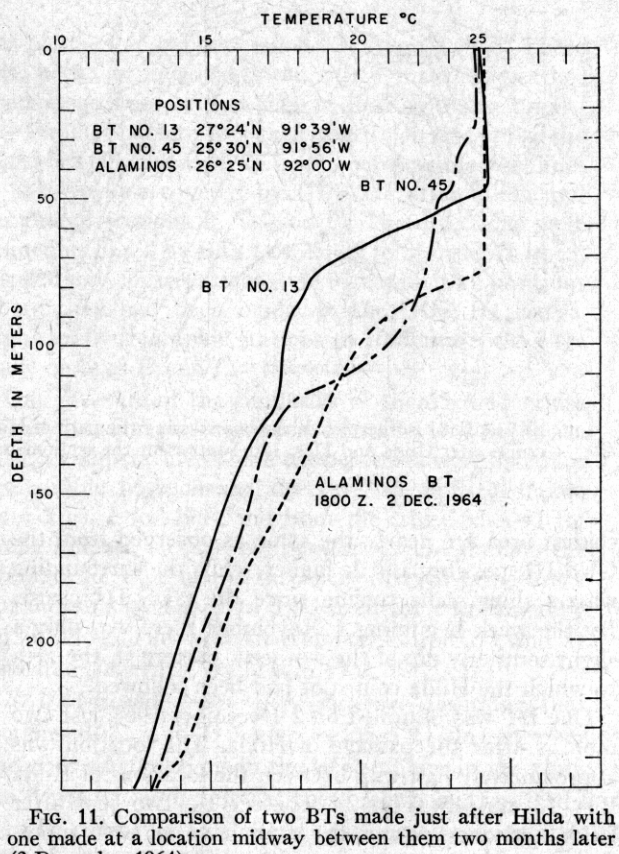


Fig. 11. Comparison of two BTs made just after Hilda with one made at a location midway between them two months later (2 December 1964).

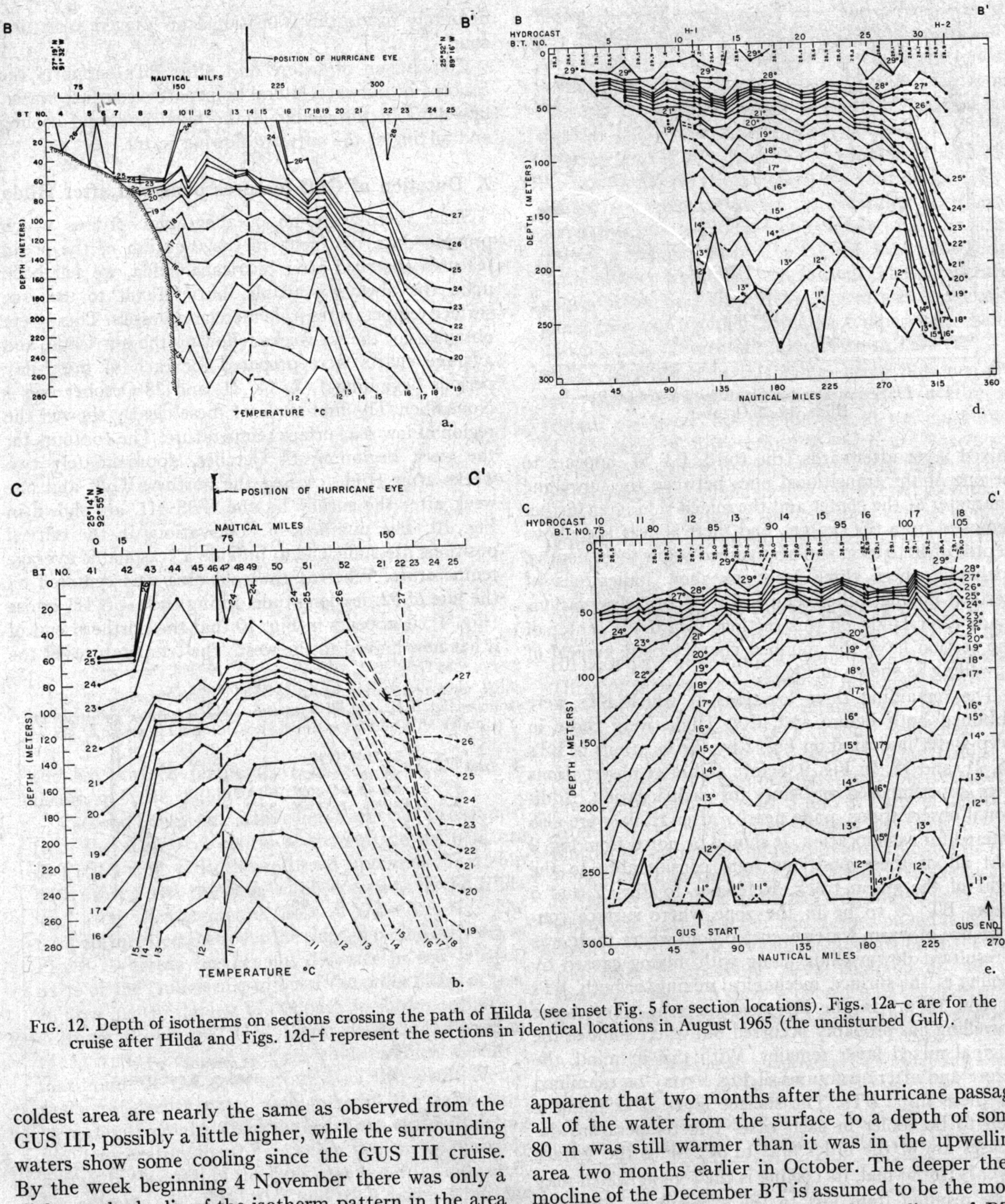
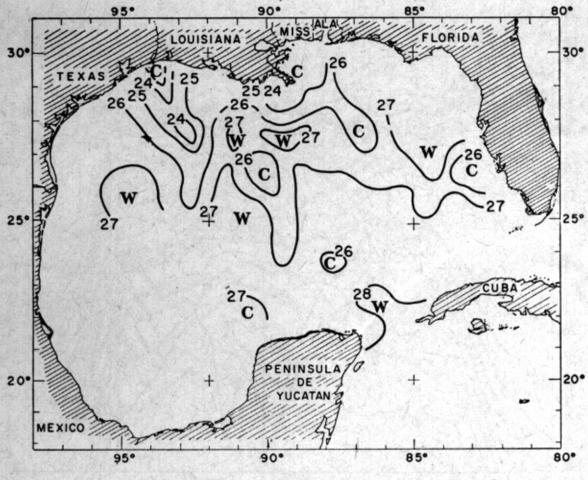


FIG. 12. Depth of isotherms on sections crossing the path of Hilda (see inset Fig. 5 for section locations). Figs. 12a–c are for the cruise after Hilda and Figs. 12d–f represent the sections in identical locations in August 1965 (the undisturbed Gulf).

coldest area are nearly the same as observed from the GUS III, possibly a little higher, while the surrounding waters show some cooling since the GUS III cruise. By the week beginning 4 November there was only a slight southerly dip of the isotherm pattern in the area to which the Hilda cold spot had been followed.

One BT was obtained on 2 December 1964 just two months after the passage of Hilda. The location was approximately half way between the locations of Hilda BTs 13 and 45 (Fig. 2). These BTs, two just after Hilda and one two months later, have all been superimposed upon the same coordinates in Fig. 11. It is apparent that two months after the hurricane passage all of the water from the surface to a depth of some 80 m was still warmer than it was in the upwelling area two months earlier in October. The deeper thermocline of the December BT is assumed to be the more normal one while the shallower thermoclines of BTs 13 and 45 are assumed to be due to upwelling caused by Hilda (Fig. 5). It is probable that, from October to December, the water upwelled in October gradually sank back to its normal position and the warmer surface waters outside of the upwelling area in October moved back horizontally toward the Hilda path, cooling from



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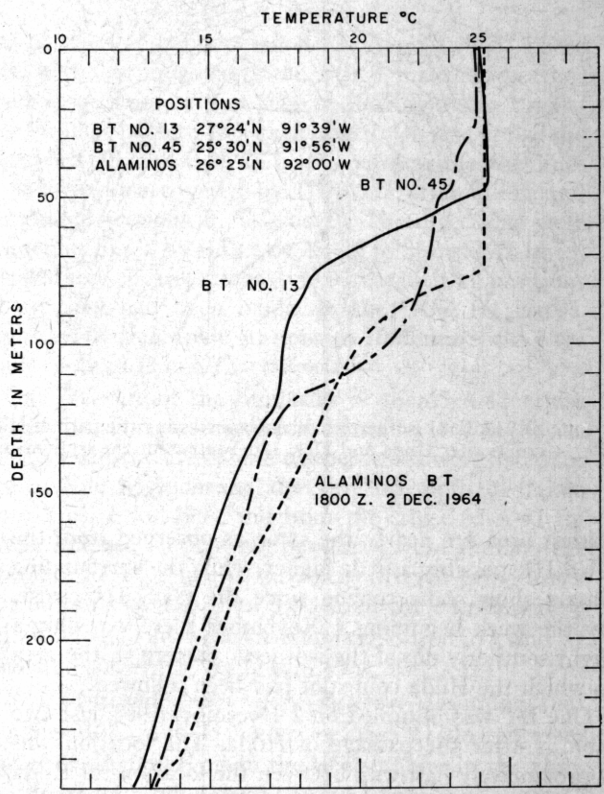

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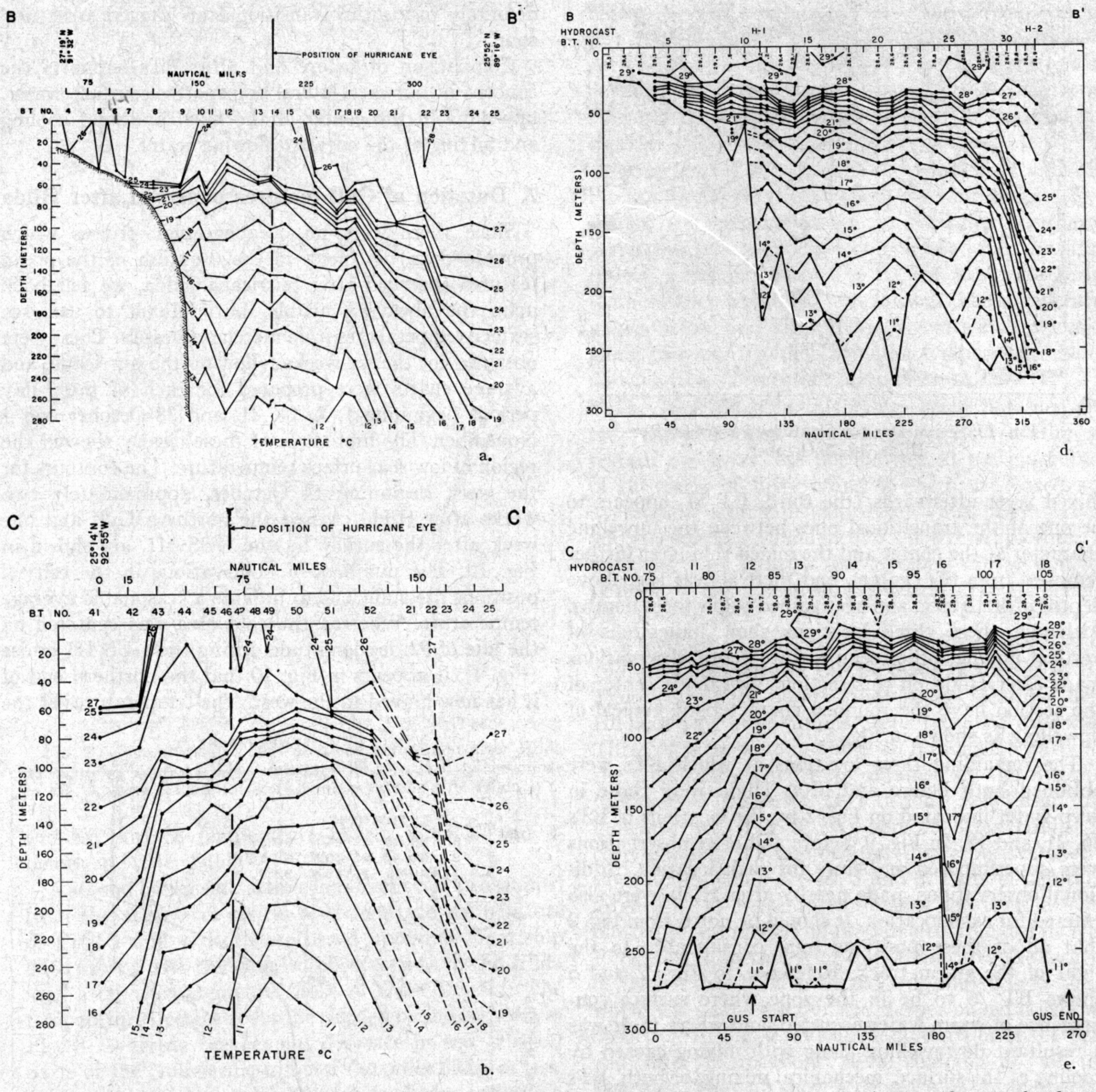

FIG. 12. Depth of isotherms on sections crossing the path of Hilda (see inset Fig. 5 for section locations). Figs. 12a–c are for the cruise after Hilda and Figs. 12d–f represent the sections in identical locations in August 1965 (the undisturbed Gulf).

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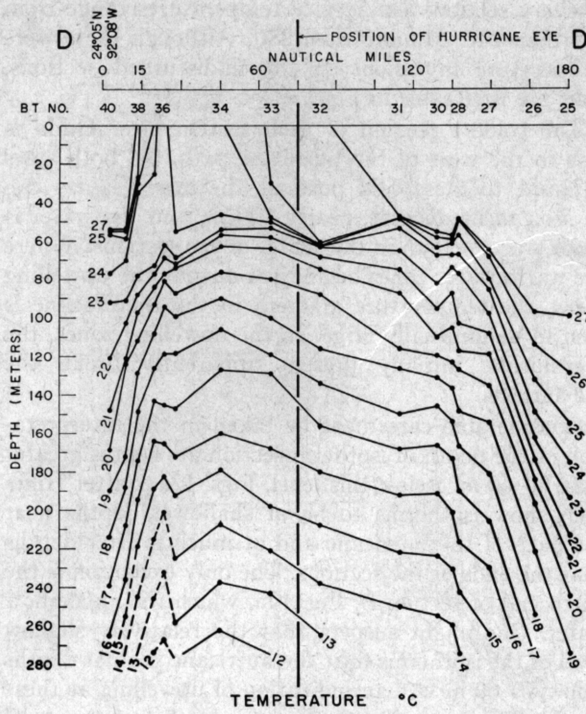

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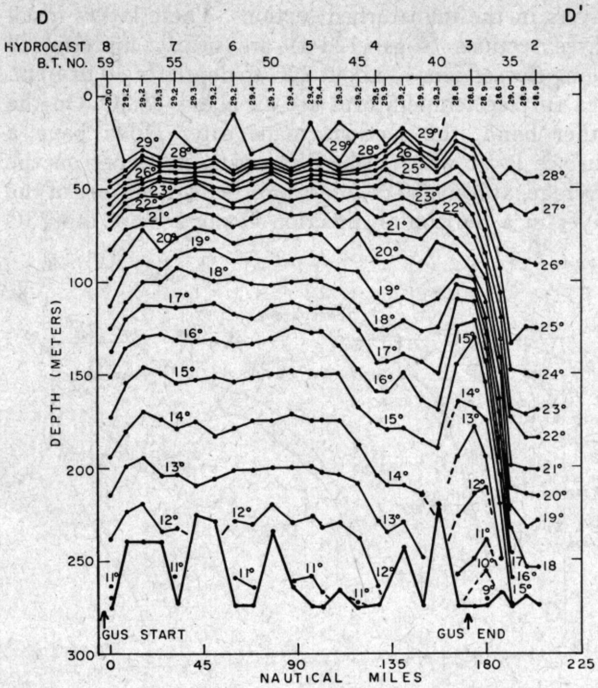


f.

FIG. 12. (*Continued*).

some 28C in October to the observed value in December of 25C as they returned or after they returned.

The geostrophic current observed after Hilda in Fig. 7 would be expected to last only so long as the internal distribution of mass remained unaltered. This distribution is indicated by the sea temperatures so the current probably disappeared within a few weeks if surface temperatures are indicative (Fig. 10). It is quite possible that it would have persisted longer if it had not been for the fact that the northern end of it extended into shallow water. In this circumstance bottom interference and friction probably broke up the flow relatively rapidly.

8. Comparisons of GUS III data with the undisturbed Gulf in other years

a. General. Since there was only a limited amount of oceanographic data available to determine undisturbed conditions existing prior to the passage of hurricane Hilda, considerable effort was devoted to attempts to better define these conditions using observations from other years. In the hurricane season there was very little other than surface data from prior years, with only a single line of observations running north to south across the area in 1959 being available.

In order to obtain more information on the undisturbed conditions in the summer over the area where the effects of Hilda had been observed, cruise 65-A-11 was planned and conducted 10–24 August 1965. There had been no hurricanes or other marked weather phenomena prior to that time in 1965 so that a typical late summer pattern was anticipated. On this cruise the ALAMINOS repeated as nearly as possible the lines of observations covered by GUS III after Hilda and designated sections B, D, and C. These sections were defined in Fig. 2 by BTs 1 to 25, 25 to 35, and 41 to 53, respectively. Observations were repeated at all positions where they had been made on the GUS III cruise. Eighteen hydrographic stations to 1000 m depths were made on lines D and C.

One measure of the similarity of the 65-A-11 cruise to the situation existing before Hilda in 1964 is the sea surface temperature. These temperatures were listed for comparable positions on the three sections as taken from Figs. 1 for 1964 and from the cruise 65-A-11 for 1965. The sea surface temperatures were similar, the averages for each of the three legs in 1965 being lower but differing by less than 0.8C from the corresponding leg in 1964. The western ends of sections C and D appeared somewhat warmer in 1964.

b. Undisturbed temperature sections. Assuming that sections B, C, and D for cruise 65-A-11 do represent undisturbed conditions in the late summer in the Gulf, the depth of isotherms for these sections, Figs. 12d-f may be compared to those for the same sections after Hilda in 1964 in Figs. 12a–c. First, attention may be almost undisturbed by upwelling during passage of the storm but that, at distances greater than 65 n mi from the path, surface waters converged and downwelled to some 100 m and waters below 50–60 m in depth may have moved in horizontally toward the storm path.

c. Density sections. Although temperature change is the most noticeable and best known effect of upwelling, the redistribution of mass as indicated by the field of density is more significant in the oceanographic process. Since salinity observations were made to depths of 125 m on the Hilda cruise, it is possible to compute density and to represent it by means of Sigma-*t*, a density anomaly at atmospheric pressure as shown in Figs. 14a–e. The density anomaly band of value 24.0 to 24.5, which is shaded in the figures, shows at depths of 40 m and below in the undisturbed data, whereas it rises so that it does not appear at all near the storm path after Hilda and it descends on the eastward ends of the sections to depths of greater than 100 m. This is evidence of both upwelling near the hurricane path and downwelling at greater distance from it.

If the size of the area of upwelling were to be judged by the extent of surface water having an anomaly greater than 24.5, for example, the area would be seen to be greatest on section C where the winds were at a maximum and to be of considerably less extent on sections B and D where the winds were not so strong. As judged by the density distribution, the depth of the surface mixed layer can be seen to be a minimum near the hurricane path and to deepen outward. On section C, this mixed layer depth as indicated by density computations was less than 28 m near the path since density at the second depth of observation at stations 16, 17 and 18 (at depths indicated by points in the figure), was greater than the density at the surface. The temperature data indicate that there is no mixed layer at all at some locations near the path.

d. Salinity observations. The situation after hurricane Hilda may also be compared to the undisturbed Gulf by means of salinity observations as shown in Figs. 15a and b. Fig. 15a shows comparisons at positions along the section designated as section C and the positions are indicated in Fig. 12e by hydrocast numbers. Fig. 15b is on section D with positions shown in Fig. 12f, the easternmost comparison being interpolated between hydrocasts 3 and 2 of Fig. 12f. Since water samples were required for salinity determinations, values were obtained only for specific depths as indicated by the points along the curves in Fig. 15. Thus, the layer of low salinity water indicated for the undisturbed Gulf (cruise 65-A-11) may have been very thin. Its thickness could not be defined since the only data were at the surface and at 25 m. In any case, wherever relatively low surface salinities were observed for the undisturbed Gulf, they did not appear in the observations after Hilda. This might be ascribed to mixing within the water column. It appears, however, that both vertical and horizontal advection are involved. In the midportions of these sections where upwelling from 60 m depth has been shown to occur, the salinity changes in the upper 50 m could be explained by upwelling of water from this depth after the surface waters had been transported horizontally away from the storm center (see the undisturbed station H-14 comparison of Fig. 15a and those of stations H-7 and H-4 of Fig. 15b).

At the ends of the sections as mentioned in the discussion of temperature changes, horizontal advection seems to have played a dominant role. Of particular interest in Fig. 15 are the high salinity values at a depth of 130 m for the station at the west end of section C (Fig. 15a), and for the stations at the two ends of section D (Fig. 15b). These values are comparable to values at similar depths found on the extensions of the

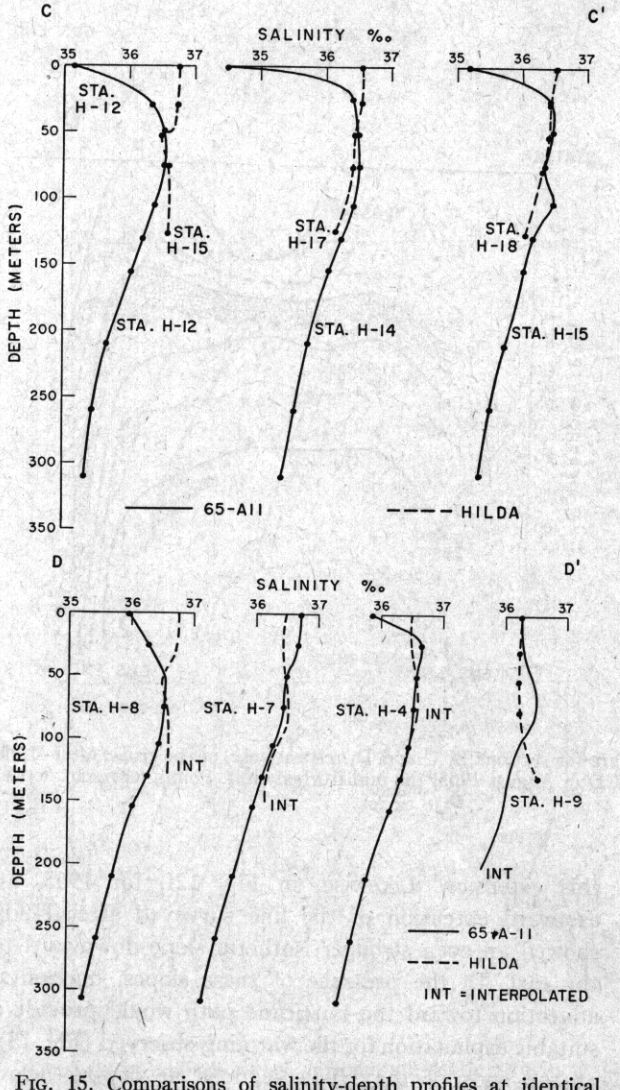
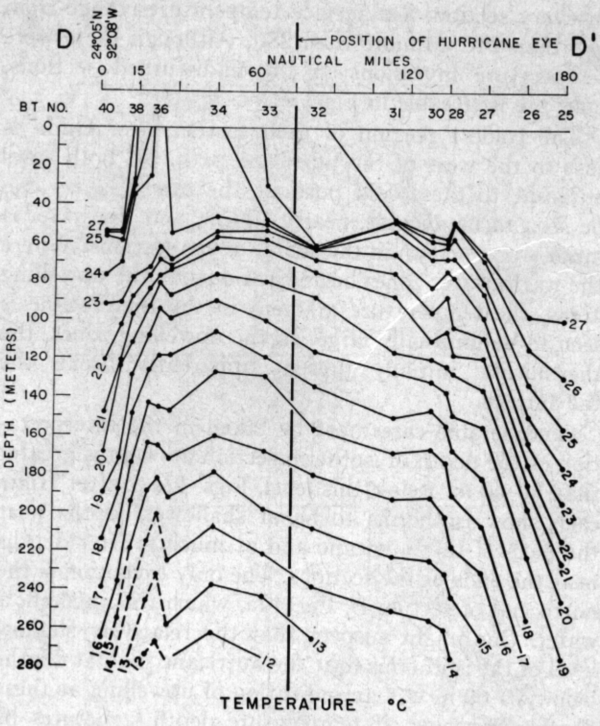


FIG. 15. Comparisons of salinity-depth profiles at identical locations for the undisturbed Gulf, 1965, and the GUS III cruise after Hilda. Fig. 15a represents locations on section C and 15b on section D. Locations may be compared to hydrocast number locations of Figs. 12e and f for 65-A-11 (undisturbed Gulf).



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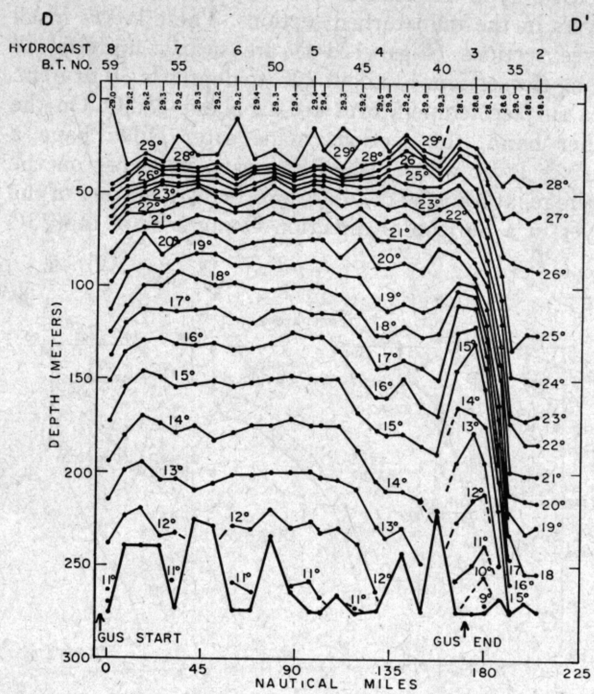

f.

FIG. 12. (*Continued*).

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b. Undisturbed temperature sections. Assuming that sections B, C, and D for cruise 65-A-11 do represent undisturbed conditions in the late summer in the Gulf, the depth of isotherms for these sections, Figs. 12d-f may be compared to those for the same sections after Hilda in 1964 in Figs. 12a–c. First, attention may be focused upon the mixed or nearly isothermal surface layers in the undisturbed sections. These layers in all three sections (Figs. 12d–f) are nearly uniform all along the sections at about 29C to depths of 30 to 40 m. Sea surface temperatures are all above 28.5C. On the other hand, the sections made after Hilda have a surface layer which, where it exists, is deeper on the average, at some 60 m total, and the temperature of the layer in a horizontal direction changes more than 3C

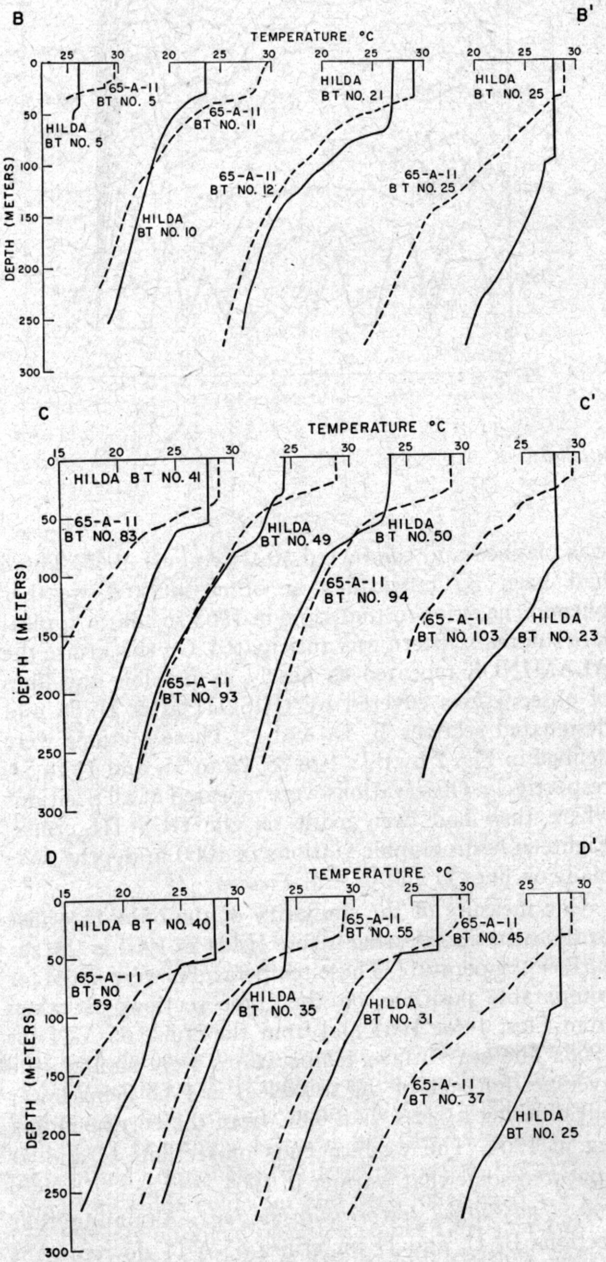

FIG. 13. Comparisons of temperature-depth structures at identical locations for the undisturbed Gulf, 1965, and the GUS III cruise after Hilda. Figs. 13 a–c are along sections B, C and D, respectively. Locations may be identified on Fig. 2 and Fig. 5.

in every section. Sea surface temperatures range from less than 24C to more than 28C. Although there were temperature inversions in the undisturbed sections, none are noticeable in Figs. 12a–c.

The coldest portion of each section after Hilda is just to the west of the hurricane path. On both sides adjacent to these cold portions the mixed layers can be seen to be deepest, nearly 100 m, and the water is much warmer than in the center of the sections. Where the warm water zones begin, just outside the upwelling areas, the temperature gradient in the thermocline is seen to be unusually large. In the upwelling zones, the thermocline initially present apparently broke the the surface.

Considerable care must be taken in the interpretation of the depth of isotherm section at depths greater than 50–60 m. Below this level, Figs. 12a–c after Hilda each show isotherms to be at shallower depths near the path of the hurricane and at much greater depths near the ends of the sections. The only exception is the north end of section B, Fig. 12a, which was in shallow water. One might suspect that the relatively shallow level of the isotherms near the hurricane path at depths below 50–60 m was an indication of upwelling at these depths. However, if temperature depth structures be compared for identical locations using observations of the undisturbed Gulf in 1965 and those after Hilda as in Figs. 13a–c, this does not appear to be the case. In this figure, looking at the comparisons for the central portions of the sections (Hilda BTs 10, 21, 49, 50, 35 and 31), it appears that the temperatures below 50–60 m after Hilda are not greatly different from the undisturbed ones of 1965. As a matter of fact, four of these central BTs indicate warmer water after Hilda at depths below 50–60 m than they did in the undisturbed observations. Since the observations were made in different years, the differences are probably not large enough to be significant. However, it is clear that no noticeable upwelling is indicated at these depths. If, indeed, the relatively shallow isotherms at depths below 50–60 m in Figs. 12a–c had been the result of upwelling, there would have been an indicated cooling at these depths of more than 7 or 8C when the observations after Hilda were compared to those of the undisturbed Gulf.

When attention is focused in Figs. 12a–c upon the portion of the sections most removed from the hurricane path, i.e., upon the ends of the sections, it appears that, below 50–60 m, isotherms were found at much greater depths after Hilda than they are in the undisturbed Gulf. This is shown in the comparisons of undisturbed BTs with Hilda BTs 25, 41, 23, 40 and 25 in Figs. 13a–c. In each of these locations the water at depths greater than 50-60 m is seen to be much warmer after Hilda than in the undisturbed conditions. This indicates either downwelling or horizontal advection

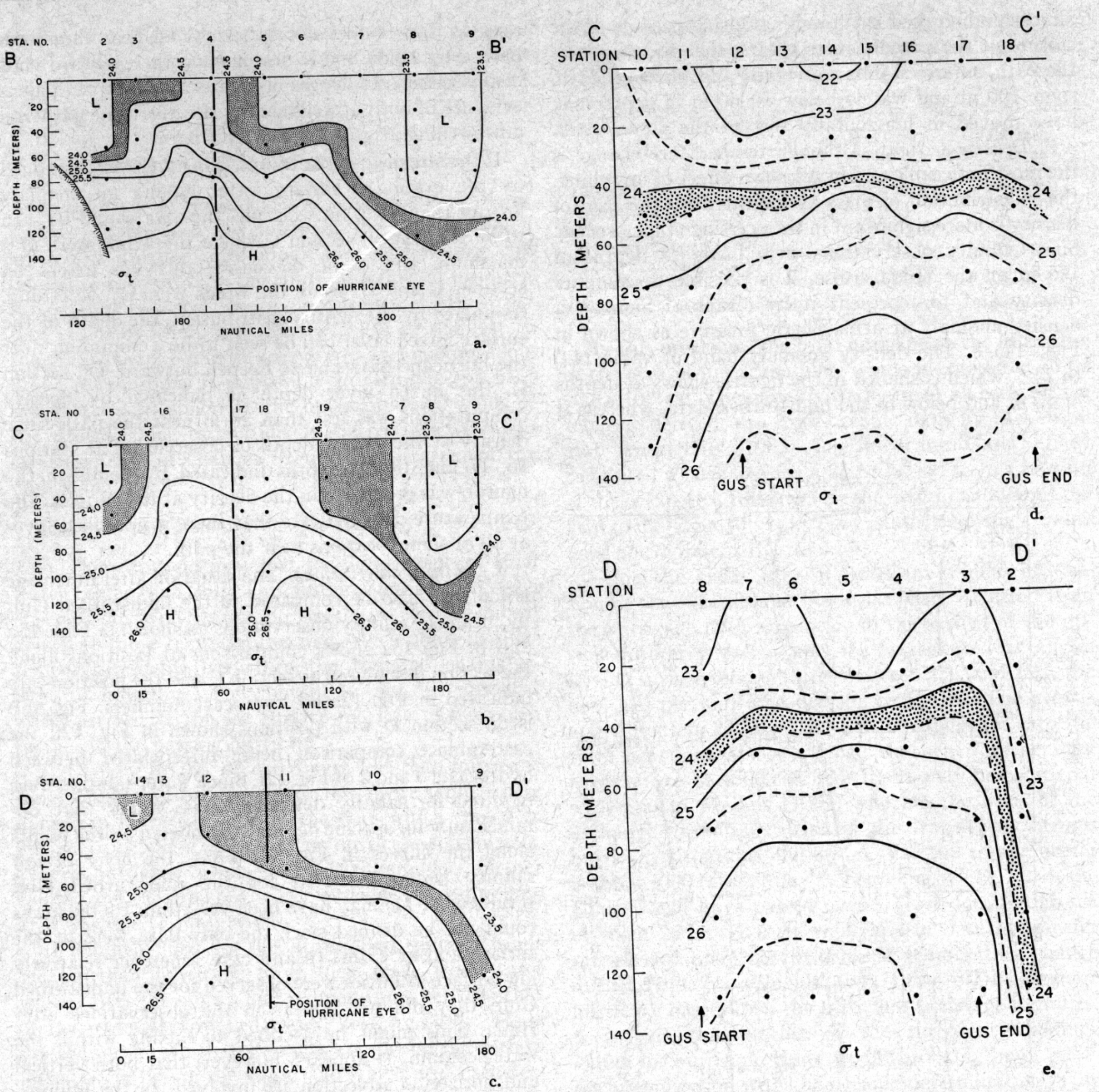

FIG. 14. Depth of lines of equal value of Sigma-*t*. Figs. 14a–c are for sections B, C and D, respectively, of the cruise after Hilda while 14d and e represent sections in the same locations as C and D in August 1965, the undisturbed Gulf. Points represent depths of observations.

of warm water or both. The depth of the isothermal layer at the surface compared with the usual smaller Gulf layer depths indicates that downwelling must be the important factor here. At greater depths, horizontal advection must be dominant. In Figs. 12e and f for 1965, the section lines surveyed after Hilda in 1964 end where the arrows 'Gus end' and 'Gus start' appear. In Fig. 12e, the section in 1965 was extended to the westward beyond the end of the Hilda section and it reveals isotherms sloping steeply downward to the west on this extension. Likewise, in Fig. 12f, for 1965, an eastward extension of the line surveyed after Hilda showed an even stronger isotherm slope downward to the east. In the presence of these slopes, horizontal advection toward the hurricane path would provide a suitable explanation for the warming observed (Fig. 13), at the ends of the Hilda sections at depths below 50–60 m.

Thus, it appears that at depths below 50–60 m the waters near the hurricane path may have remained almost undisturbed by upwelling during passage of the storm but that, at distances greater than 65 n mi from the path, surface waters converged and downwelled to some 100 m and waters below 50–60 m in depth may have moved in horizontally toward the storm path.

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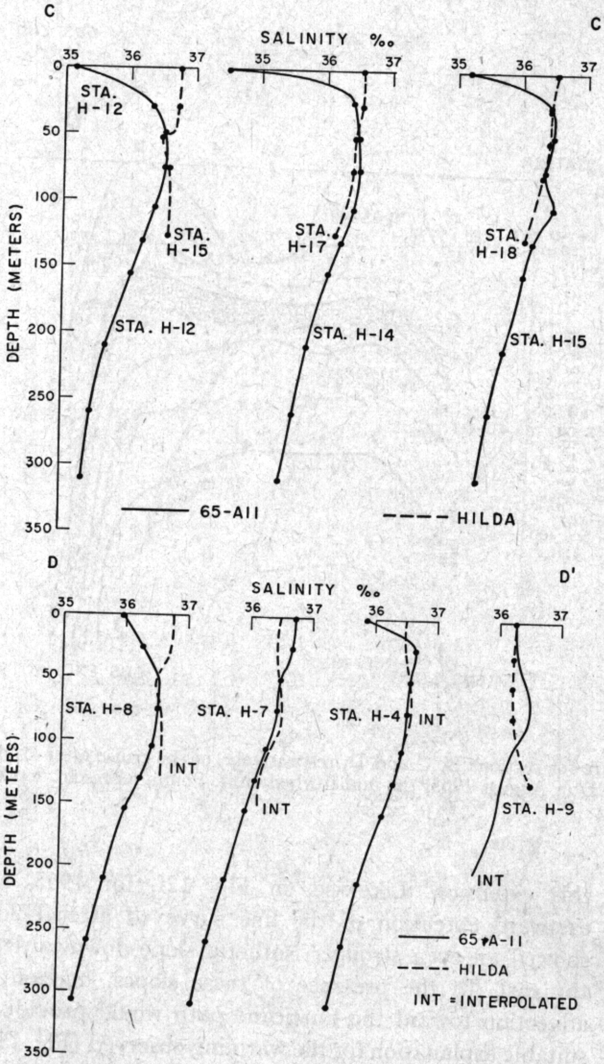

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At the ends of the sections as mentioned in the discussion of temperature changes, horizontal advection seems to have played a dominant role. Of particular interest in Fig. 15 are the high salinity values at a depth of 130 m for the station at the west end of section C (Fig. 15a), and for the stations at the two ends of section D (Fig. 15b). These values are comparable to values at similar depths found on the extensions of the sections for the undisturbed Gulf and their presence after Hilda supports the concept that water was moving toward the storm center at this depth in these locations.

9. Heat lost from the ocean to the hurricane

On the basis of the analysis of oceanic observations, concepts have been developed of the way in which advection, mixing, upwelling, and downwelling are related to each other in the Hilda situation. It has been stated that observed ocean temperature-depth structure indicates where heat has been lost or not lost to the atmosphere. Using these concepts and making some broad assumptions it is possible to estimate the heat lost to the atmosphere in the hurricane force winds of the storm. The estimation is based strictly upon measurements of changes in the heat content of the underlying ocean.

The following assumptions are made:

1) There was no heat lost to the atmosphere from water colder than 25C. This assumption is based upon observations which show no significant surface mixed layers at these temperatures and which show in their temperature-depth structure the rounded characteristics of upwelling. The concept is that the upwelled water arrived at the sea surface too late to be cooled further in the passing hurricane.

2) Cooling to 28C occurred with less than hurricane force winds and occurred over the entire Gulf. There appear to be broad areas of the Gulf which cooled to 28C in areas where there were no hurricane force winds. Where hurricane winds did exist there was further cooling and the drop below 28C outside of the upwelling area was due to these winds.

3) All heat loss to the atmosphere during winds greater than hurricane force took place from water which, after the storm, had temperatures between that of the warmest upwelled water, 25C, and 28C. These are the waters which apparently comprised the surface mixed layer before the storm and which are characterized after the hurricane by the deeper well-mixed layer at the surface indicating great surface cooling and convection. They surround the upwelled waters in the storm center.

Using these assumptions, the heat apparently lost to the atmosphere during hurricane force winds can be computed if the volume of the 25C to 28C water is determined. This volume was computed by first approximating with two rectangles on Fig. 4 the surface area of water in the 25 to 28C temperature range around the hurricane path. One rectangle was west of the hurricane path and one was east of it. Next, the mean depth of this water was estimated from the temperature sections of Fig. 12 for both the western and the eastern rectangles.

The selected dimensions, the computed average temperatures after Hilda, and the associated heat deficits below 28C water were as follows:

	Western volume	Eastern volume
Width	30 n mi	100 n mi
Length	310 n mi	310 n mi
Depth	65 m	80 m
Average temperature	27.3C	26.9C
Total heat deficit from water of 28C	1.4×10^{18} cal	9.4×10^{18} cal

By this procedure the total heat loss to the hurricane in the area of hurricane force winds is computed to be 10.8×10^{18} cal. The only known figure at all comparable was one derived also from oceanic data by Stevenson and Armstrong (1965) for hurricane Carla. They computed a heat loss for a 24-hr period from a portion of the ocean area traversed by that storm and found the loss to be 2.5×10^{17} cal. They state that their value does not represent the total loss.

Using the entire area of hurricane winds, i.e., assuming that heat loss to the atmosphere occurred from the hurricane path area prior to the arrival of the upwelled water as well as from the two selected rectangles having surface temperatures between 25C and 28C, the heat loss per unit area may be computed. The area is approximately 225 by 310 n mi. Dividing this into the total heat loss, 10.8×10^{18} cal, the heat loss per cm^2 turns out to be 4500 cal. This figure may be compared with that of Malkus (1962) who, on the basis of the exchange formulas, calculates the transfer in various hurricane situations and states that the total transfer is about 3000 cal cm^{-2} day^{-1}. Traveling at 7 kt, hurricane Hilda would have passed over a given location at sea in about 26 hr. Thus, it would appear that the transfer rates based upon observed ocean temperature change during Hilda were higher than those of the average hurricane based upon the turbulent exchange formulas. A specific computation of the turbulent exchange values for hurricane Hilda would probably be of interest in connection with the oceanic determination made here.

The larger heat deficit in the eastern rectangle is interesting. A somewhat larger transfer would be expected here because of the direction of storm propagation. However, since the hurricane moved at 6–8 kt, the winds on the eastern sector should only have been 12–16 kt higher than those on the western. This does not seem enough to explain the difference in calculated deficits. It is quite likely that water advection associated with the hurricane winds is partly responsible.

It will be recognized from the nature of the assumptions and of the computations that the identification of the heat loss figures arrived at here to the hurricane force winds of Hilda is open to a number of questions. The most uncertain part of the computation may be the size of surface area selected. Once this is determined, however, the heat content below that surface is well established since it can be computed from the temperature sections. The choice of 28C after the storm as the upper limit of water cooled by hurricane force winds is another critical element in the computation.

In spite of the uncertainties, the values of heat exchange presented have value for two reasons. First, they are completely independent of the turbulent exchange computations and second, their uncertainties are no greater than those of the exchange formulas when these formulas are applied to hurricane wind situations.

10. Summary

An attempt has been made to describe the changes brought about in the Gulf of Mexico by the passage of severe hurricane Hilda in 1964. Data available included a few observations prior to the passage of the storm, a small amount of pertinent historical data, and the observations from a systematic survey of the area over which the storm had passed conducted immediately after the storm and repeated a year later in the hurricane season before any hurricane weather had disturbed the normal summer Gulf conditions. The observations indicate upwelling along the path of the storm from some 60 m in depth, outward transport of the warm surface layers, cooling and mixing of these layers as they move outward, and convergence and downwelling of the outward moving water around the hurricane area. The description presented may be useful in planning future surveys of similar situations, in estimating energy budgets involving exchange with the hurricane, and in providing assumptions upon which theoretical developments may be based.

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