COMPARISON OF EFFECTS OF VARIOUS TROPICAL STORMS ON THE VERTICAL TEMPERATURE STRUCTURE OF THE OCEAN USING PICTORIAL REPRESENTATION

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THESIS

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Comparison of Effects of Various Tropical Storms on the Vertical Temperature Structure of the Ocean Using Pictorial Representation

by

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ABSTRACT

To make comparisons of the effects of tropical storms on the ocean's vertical temperature structure, temperature-depth cross-sections were constructed using bathythermograph data and data from published articles.

Upwelling, downwelling and mixing,caused by tropical storms in deep and shallow water,are analyzed and compared. For a slow-moving, intense and very intense tropical storm, upwelling, from a depth of 40 to 65 meters, is observed within the radius of hurricane-force winds. Downwelling as much as 20 meters occurs from 45 to 110 nmi from the path of the storm. This compares favorably with the theoretical results of O'Brien and Reid. A fast-moving, intense tropical storm has a similar effect on the vertical temperature structure if the thermocline is shallow, and upwelling, of a lessor degree than that caused by a slower-moving storm, can occur from a depth of 35 meters within the radius of hurricane-force winds. A very fast-moving, very intense tropical storm can cause upwelling from a depth of 30 meters if the thermocline is shallow.

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I. INTRODUCTION

Emphasis on the study of the effects on the sea surface and vertical temperature structure of the ocean by the passage of a tropical storm began in the mid 1950's. Evidence of marked cooling of the sea surface following the passage of tropical storms has been reported by several authors. These include Uda [1954], Fisher [1958], Jordan [1964], Leipper [1967], Stevenson and Armstrong [1965], Landis and Leipper [1968], and Hazelworth [1968].

The first systematic observational studies on the three-dimensional effect of a hurricane on the sea surface and vertical temperature structure were conducted by Leipper on the effects of hurricane Hilda, (1964). Further studies were conducted by Landis and Leipper, and Franceschini and El-Sayed on hurricanes Betsy (1965) and Inez (1966), respectively.

A theory for oceanic changes due to a stationary or slow-moving hurricane was developed by O'Brien and Reid [1967]; and O'Brien [1967, 1968]. Although somewhat limited by assumptions, the theory provides an explanation of some of the time-dependent non-linear processes involved. Basically, the initial ocean response to a hurricane is a development of an Ekman type flow which, in the Northern Hemisphere, leads to a divergence of the ocean surface layers away from the storm. The

outward flowing warm water converges near the outer edges of the wind circulation and leads, through downwelling, to the formation of a deep, still warm, well-mixed layer in the ocean. The mechanical effect of the wind and the convection brought about by heat loss from the sea surface to the atmosphere causes the mixing which occurs in the outward moving water. Near a coastline, the wind-induced motions are modified by the presence of a solid boundary, Franceschini and El-Sayed [1968].

To date, only Fisher [1958] and Hazelworth [1968] have concerned themselves with a comparison of the effect of more than one hurricane or typhoon. Both used sea surface temperature (SST) as the basic comparison parameter. The objective of this paper is to analyze and compare by use of selected numerical indices and pictorial representation, the effects on the vertical temperature structure of the ocean produced by hurricanes Carla (1961), Hilda (1964), Betsy (1965), Inez (1966) and typhoon Shirley (1965).

II. PROCESSING OF DATA

Leipper [1967], in his study of hurricane Hilda (1964), made observations and displayed vertical sections perpendicular to the hurricane's path. Comparison with data collected before the storm and with UNDISTURBED cross-sections (obtained during the next hurricane season prior to the passage of any storms and along the same cruise track lines) showed significant differences in temperature and salinity. These differences appeared to be the result of the storm's action on the ocean. The warm surface waters were displaced to either side of the hurricane's path and a core of cold water with a shallow thermocline appeared near the center of the wake, demonstrating active upwelling. The Hilda study and further studies by Leipper , prior to and following Betsy (1965)[1], indicated an area of downwelling outside the central upwelling region.

This investigation and pictorial comparison of the effect of various tropical storms on the vertical temperature structure of the ocean was initiated using the observations of Leipper [1967]. A method of pictorial representation to represent the areas of upwelling and downwelling of Hilda (1964), was selected as follows:

A. STEP ONE

The locations of all bathythermograph (BT) observations made AFTER Hilda and all BT observations made of the

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[1] To be published.

UNDISTURBED condition were plotted on the same chart of the Gulf of Mexico. The track of Hilda was superimposed over this data. Cross-sectional lines, perpendicular to the hurricane's track, were drawn with respect to the ship's track. For Hurricane Hilda, the placement of the cross-sectional lines was simplified because the AFTER and UNDISTURBED cruise tracks were made normal to the hurricane's track for both the first (AFTER) and second (UNDISTURBED) cruises. In the case of Betsy in the Gulf[2], the BEFORE and AFTER plots of BT stations were overlaid. Three of the AFTER lines had been made exactly along the BEFORE lines. The other two cross-sectional lines were drawn normal to the path of the hurricane through the area of greatest observational density except for cross-sections D-D'' and E-E''. All observations not falling directly on the cross-sectional lines were projected normal to the cross-sectional line. An example of the method of plotting the BT stations to the cross-sectional lines is shown in Figure 1, which corresponds to the study of Hilda.

B. STEP TWO

To further refine the pictorial representation of the UNDISTURBED and AFTER vertical temperature structure, each

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[2] Hurricane Betsy will hereafter be identified as Betsy in the Gulf or Betsy, the latter referring to hurricane Betsy in the Atlantic.

BT observation for the AFTER data was plotted with a vertical scale of 50 meters/inch. A horizontal scale of 60 nautical miles/inch was used to represent the distance from the path of the hurricane with the zero position representing the center of the hurricane path. Each BT observation was plotted at its respective distance from the center of the hurricane path and isotherms were connected between observations to form a temperature cross-section. A similar method was used to plot sections for the UNDISTURBED BT observations at their respective distances from the center of the hurricane's path.

C. STEP THREE

The plot of the UNDISTURBED isotherms was overlaid on the plot of the AFTER isotherms using the zero nautical mile position and the sea surface as the common points of allignment. With the vertical scales being the same, areas of upwelling, downwelling and mixing were readily discerned by comparing equal valued isotherms. To construct a pictorial representation of the effects of the hurricane for use in comparisons to other storms, the following procedure was used. With the AFTER plot overlaid on the UNDISTURBED plot, isotherms of the same value were compared starting from the surface. The lower stable isotherm was selected to serve as a reference for changes in the vertical temperature structure; that is, the isotherm was chosen as one which maintained the same depth within the area of upwelling both

in the AFTER and UNDISTURBED plot. Examination of the isotherms above this chosen lower reference isotherm showed that an isotherm for a 2°C greater temperature would adequately aid in representing depth changes due to the processes involved. In the case of Hilda, the lower and upper isotherms were 23°C and 25°C, respectively. Examination of the UNDISTURBED plot of isotherms indicated that the layer of water contained between these two isotherms, differing by 2°C, describes a layer with generally uniform thickness in the undisturbed water. In the case of Betsy (in the Gulf of Mexico) this index layer was best represented by the layer contained between the 26°C and 28°C isotherms. Henceforth, such layers contained between the two chosen isotherms will be referred to as the index layer.

D. STEP FOUR

The final construction of the figures used for Hilda and Betsy for pictorial representation was accomplished in the following manner. Dashed lines (----) were chosen to represent the UNDISTURBED or BEFORE condition. Solid lines (______) were chosen to represent the AFTER condition. When additional isotherms were needed to more clearly show the processes involved, a dash-dot line (-.-.) was chosen to represent the BEFORE or UNDISTURBED condition and a dotted line (.....) was chosen to represent the AFTER condition. Large dots occurring in any of the above lines

represent the location of BT stations as measured horizontally from the path of the hurricane and the depth of the isotherm as measured vertically from the surface. An example of this representation appears in Figure 2. The completed figures were then labeled and they represent simplified views of the temperature-depth cross-sections chosen for analysis and comparison.

To construct figures for analysis of tropical storms Betsy (1965), Shirley (1965), Carla (1961), and Inez (1966, results representing the BEFORE and AFTER isothermal structure were extracted from published articles by Landis and Leipper [1968], Wright [1969], Stevenson and Armstrong [1965], and Franceshini and El-Sayed [1968]. A search of literature showed that these articles contained suitable results for comparison. These results were presented in figures similar to those constructed in this study. The figures were modified so that the depth scale would be one inch per 50 meters and correspond to the depth scale used in the Hilda and Betsy (in the Gulf) analyses. The horizontal distance scale assumed the dimensions per inch created by the one to one enlargement of the published data. This enabled a direct comparison of changes in the thickness caused by upwelling, downwelling and mixing of the index layer. After the modification of the published figures, steps three and four were completed and the figures were used to compare the depth changes involved. To facilitate

ease in comparison, all depths are presented in meters, distances in nautical miles, and temperatures in degrees Celsius. The final pictorial representations used for comparison were not meant to give exact values of horizontal measurement such as the exact distances where upwelling or downwelling occurs on either side of the hurricane's path. The isotherms chosen were representative isotherms and show approximate distances to the most dominant features. The vertical pictorial representation indicates the change in depth and thickness of the index layer due to the effect of the hurricane on the vertical temperature structure. The isotherms for Hilda, and Betsy in the Gulf of Mexico, were plotted within ± one meter of their true depth on the BT graph or on the value on the NODC data printout. Therefore, the vertical scale represents the actual change in depth and thickness of the index layer. The accuracy of the vertical scale of Betsy , Carla, Shirley and Inez, was assumed to be the same since original data was not used to plot isotherms.

Section III explains in detail the construction of each temperature-depth cross-section. Analysis of a sample cross-section is included. Section IV is a comparison of the figures, and Section V is a comparison of the results of the pictorial analysis with the theoretical model proposed by O'Brien [1968].

III. ANALYSIS OF TROPICAL STORMS

Figures 1, 3 and 4 show the cruise track, cross-sections, and the extent of hurricane force winds of hurricanes Hilda (1964) and Betsy (1965) in the Gulf of Mexico. Figures 5, 6, 7 and 8 show the same information for tropical storms Betsy (1965), Shirley (1965),Carla (1961), and Inez (1966), respectively. Figures 9 through 14 are temperature-depth cross-sections of each tropical storm. Each cross-section was constructed normal to the path of that storm with the exception of cross-sections D-D" and E-E" of Betsy in the Gulf and A-A' of Shirley. Each temperature-depth cross-section was analyzed using the same procedures. The following is a sample analysis of Hilda (1964). The analysis examines two situations; first, a hurricane's effect on the vertical temperature structure in deep water, (cross-section A-A'); and second, the effect on the vertical temperature structure in shallow water (cross-section D-D'):

The path of hurricane Hilda, as it crossed the Gulf of Mexico from 30 September to 4 October 1964, is shown in Figure 1. When the hurricane was centered 250 nmi off shore in waters greater than 1,000 fathoms, she became more intense with winds up to 130 knots. The wind decreased to 105 knots as she moved toward the coast. The width of the zone having winds of hurricane force is shown in Figure 1. The average propagation speed was six to eight knots, and the width of the eye was approximately 35 nmi in the northern Gulf.

The data for the analysis was gathered in three ways. Some BEFORE data was collected by RV/ALAMINOS as it proceeded into port just ahead of the hurricane. Three bathythermograph (BT) observations were made near the locations of BT's 26, 21, and 18, respectively, as shown in Figure 1. Three additional BEFORE BT observations were obtained from the Bureau of Commercial Fisheries at locations near those indicated for BT's 57, 63, and 65 as shown in Figure 1. The remaining data was collected on cruise 65-A-11, conducted by the RV/ALAMINOS from 10-24 August 1965 and represents the UNDISTURBED condition taken eleven months later. Data was taken over the same paths used for observations of conditions after Hilda. The AFTER data was gathered using the 90-foot shrimp boat, GUS III, operated by the Galveston Biological Laboratory, Bureau of Commercial Fisheries. The observations after the storm were made using the same BT instruments used on the RV/ALAMINOS.

A. CROSS-SECTION A-A' (See Figure 1 for Location)

The UNDISTURBED and AFTER data are plotted in Figure 9a, with all stations projected to the baseline A-A', constructed normal to and centered around Hilda's path. UNDISTURBED data was selected for analysis from hydrographic stations two through eight and NODC data printouts of BT's 40 through 69, gathered on cruise 65-A-11. AFTER data was selected from photographs of BT's 25 through 41, gathered 5 days after Hilda by GUS III.

The UNDISTURBED condition was represented by the index layer contained between the 23°C and 25°C isotherms. The thickness of the index layer, 60 nmi either side of the path of Hilda, indicated a uniform, undisturbed layer approximately 10 meters thick, with the uppermost part of the index layer being 50 meters below the surface.

The AFTER condition was represented by the same pair of isotherms. As a result of the radial divergence of the surface water, colder water was upwelled from the index layer to the surface for a distance of 45 nmi to the left and 50 nmi to the right of Hilda's path as shown by the surfacing of the 25°C isotherm. A reduction of SST by 3°C in this area was observed by comparing the UNDISTURBED and AFTER BT readings. Beyond 60 nmi to the left and right of Hilda's path there were strong indications of downwelling, probably caused by convergence of the warm surface water displaced from the area of upwelling. In these areas the 25°C isotherm was depressed approximately 18 meters deeper than the observed UNDISTURBED position. At a distance greater than 120 nmi to the right of Hilda's path, steeply sloping isotherms were observed and are believed to be caused by horizontal advection toward the hurricane path, Leipper [1965].

B. CROSS-SECTION D-D'

The BEFORE and AFTER data are plotted in Figure 9d, with all stations projected to baseline D-D', which is normal to and centered to the far left of Hilda's path. BEFORE data was selected from BT's 10, 5 and 2, obtained by the Bureau

of Commercial Fisheries in 40 fathoms of water. AFTER data was selected from photographs of BT's 57 through 65, gathered nine days after Hilda by GUS III. This represents an area where Hilda reached shallow water and the wind-induced motions were modified by the presence of a coastline.

The BEFORE condition was represented by the index layer defined by the 23°C and 25°C isotherms. The thickness of the index layer from 120 nmi to the left and 30 nmi to the right of Hilda's path represents a uniform, undisturbed layer averaging 10 meters thick, with the uppermost part of the index layer being about 40 meters below the surface.

The AFTER condition was represented by the same pair of isotherms. As a result of the radial divergence of the surface water, colder water was upwelled from the index layer to the surface for a distance of 20 nmi to 40 nmi to the left of Hilda's path as shown by the surfacing of the 25°C isotherm. A reduction of SST in this area of 5°C was indicated by comparing BEFORE and AFTER BT's. Seventy nautical miles to the left of Hilda's path there were strong indications of downwelling, probably caused by convergence of warm surface water displaced from the area of upwelling. In this area, the 25°C isotherm is depressed approximately 10 meters deeper than the observed BEFORE position. From 110 nmi to the left and 10 nmi to the right of Hilda's path, large areas of mixing were indicated by the equal distribution of the index layer above and below the BEFORE data position.

The data obtained from the analysis of all of the temperature-depth cross-sections prepared in this way is summarized in Table 1.

IV. COMPARISON OF FIGURES

The comparison of figures is considered in two parts: hurricane effects in deep water and hurricane effects in shallow water. In each part, comparisons are made of upwelling, downwelling, mixing, sea-surface temperature decrease, and the extent of winds of hurricane force.

A. EFFECTS IN DEEP WATER:

1. Upwelling

As a result of radial divergence of the surface water in all directions, sub-surface water is usually upwelled to compensate for the initial loss at the surface. O'Brien [1970] shows that the upwelling is a result of the influence of the radial component of wind stress. The component of wind stress was viewed as a steady state component by O'Brien, which enabled him to adequately describe the ocean dynamics under the core of the hurricane.

Table 1 shows the comparison of the various cyclonic disturbances. In each case, the area immediately beneath the path of the hurricane was upwelled from a depth of at least 40 meters to the surface. This is demonstrated by the surfacing of the upper portion of the chosen index layer. Currents have also had an effect on the observed location of the upwelled water. This is demonstrated in cross-sections C-C", D-D", and E-E" of Betsy (in the Gulf). In the upwelled area, the chosen lower isotherm has remained essentially stable. This

indicates that water is brought in from below the mixed surface layer probably causing a decrease in thickness of the index layer in areas near the outer limits of the hurricane force winds. Most cross-sections studied exhibited upwelling beneath the path of the storm and were offset to the left of the path of the storm as shown in cross-sections A-A', B-B', C-C', D-D' of Hilda; B-B'', C-C'', D-D'', F-F'' of Betsy (in the Gulf); A-A' of Shirley; A-A' of Carla; and A-A' of Inez. The upwelling effect is a lasting effect, with indications, in at least the Hilda case, that it may last for up to twenty days.

2. Downwelling

As a result of the radial divergence of the surface waters from the storm centers, still warm water displaced from the upwelled area converges near the outer area of the wind stress component. Leipper in his study of Hilda, and Betsy (in the Gulf of Mexico) found that downwelling was significant outside the upwelled area. Table 1 shows that an area of downwelling occurs near the outer edge of hurricane force winds which would agree with the onset of downwelling as described in theory by O'Brien [1967]. The mechanisms involved in downwelling are not as simple as those occurring directly beneath the hurricane and downwelling cannot be treated with the simple dynamic steady-state model used for upwelling. A common effect in the downwelled areas was a decrease in the thickness of the index layer and an increase in the depth of the index layer.

3. Mixing

As a result of the radial divergence of the surface water from the upwelled area and the combined effect of wind stress and turbulence in the diverging surface water, areas of deep, well-mixed waters are often encountered inside the storm area, and usually in concurrence with areas of maximum downwelling. An area of mixing is easily recognized by equal displacement of the upper and lower isotherm, thickening the BEFORE or UNDISTRUBED index layer. Mixing was not a common occurrence in deep water, but will be discussed in greater detail under EFFECTS IN SHALLOW WATER.

4. Sea Surface Temperature

A decrease in sea surface temperature was observed in the wake of each hurricane, and has been noted by many authors. The amount of decrease of sea surface temperatures is dependent upon the conditions existing prior to passage, the speed of passage, and the intensity of the cyclonic disturbance. The total decrease in the SST can not always be attributed to the effect of upwelling, but may be the result of heat loss to the hurricane, if no upwelling occurred.

B. EFFECTS IN SHALLOW WATER:

1. Upwelling

Three cross-sections demonstrate that the decrease in ocean depth and the presence of a coastline apparently alter the effects of a hurricane. Cross-section D-D' of Hilda; cross-section G-G" of Betsy (in the Gulf),

and cross-section A-A' of Inez each show similar features. Upwelling is mostly confined beneath or slightly offset to the left of the hurricane centers. Also, these areas exhibit extensive upwelling.

2. Downwelling

Downwelling, as a result of the divergence of the warm water from the upwelled area, is not as clearly defined as in the deep water case. The extent of downwelling is less, being only several meters, as compared to observed effects in deep water. Areas where extensive downwelling was noted, such as cross-section A-A' of Carla, were possibly associated with areas of convergence of an induced current with an already present current in an opposite direction.

3. Mixing

The mixing in the areas of upwelling and downwelling is more common in shallow water as evidenced by cross-sections D-D' of Hilda, G-G" of Betsy (in the Gulf) and A-A' of Inez. The extensive mixing exhibited in the case of Betsy is probably a result of the effect of the geographical coastal boundary and the effect of the outflow of the Mississippi River.

4. Sea Surface Temperature

The presence of a coastal boundary and the added complication of the outflow of a major river makes SST analysis difficult. The outflow of the Mississippi River places a warm, less saline tongue of water over the area

where Betsy had immediately passed. This tongue of water soon masks any effects of Betsy on the SST.

V. COMPARISON WITH THEORY

O'Brien and Reid [1967] developed a theoretical decription of upwelling induced in a stratified, rotating, two-layered ocean by momentum transfer from an intense stationary, axially-symmetric atmospheric vortex. The dynamic internal response of the ocean was assumed to be axially-symmetric. Transfer of momentum between the air and the sea and between the upper and lower layers was allowed.

O'Brien and Reid found that the results predicted by the model agree qualitatively with the following observations taken in the Gulf of Mexico after hurricane Hilda, 1967. Intense upwelling was confined within the radius of hurricane-force winds. The displaced warm, central waters produced some downwelling outside the upwelled region. The maximum upwelling occurred at approximately 16 nmi from the hurricane path, which is an expected response to the maximum value of surface wind stress. The displaced warmer waters accounted for downwelling and thickening of the upper layer between 45 and 100 nmi from the hurricane path. A shallow mixed layer less than 25 meters deep was observed along the hurricane path and a deeper mixed layer (60-80 meters) along the edges of the cross-section.

O'Brien [1967] continued the study with a second model that included mixing. He found that the velocities of the two models are essentially the same and mixing had little influence on the dynamic response of the system but that the

dynamic response does influence mixing. Mixing tends to lower the temperature and increase the salinity of the surface layer of the ocean over a broad region. Comparing the theoretical results to Hilda observations, O'Brien noted that in observations the mixing and upwelling were not symmetric about the hurricane path. He concluded that this may be due to the observed asymmetry of the wind stress distributions in a moving cyclone. The latter was not incorporated in the model.

In a later study, O'Brien [1968], two important limitations to the above models were relaxed. They were; first, a specifically defined tropical storm was used to drive the ocean; and the second, this tropical storm was constrained to be stationary and symmetric. He relaxed these limitations to some extent and varied the initial layer depth from 30-150 meters (previous model 100 meters), the radius of maximum winds from 5-110 nmi (previous model 16 nmi), and varying the speed of the storm from three to eight knots.

The relationships used by O'Brien were:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} = fv - \epsilon\frac{\partial P_a}{\partial x} + T_x^S/\rho h - T_x^I/\rho h \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} = -fu - \epsilon\frac{\partial P_a}{\partial y} + T_y^S/\rho h - T_y^I/\rho h \qquad (2)$$

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \qquad (3)$$

where:

ρ is the density of the ocean
f is the Coriolis parameter
g is the acceleration of gravity

P_a is the pressure at a radius in the hurricane
h is the thickness of surface layer of the ocean
t is the independent temporal coordinate
u is the radial velocity in the ocean
v is the tangential velocity in the ocean
ϵ is the density contrast

T^S_x, T^S_y are the wind stress components at sea surface

T^I_x, T^I_y are the components of internal shearing stress at interface between layers.

The results were:

1. Cold wakes associated with upwelling occur sooner if the tropical storm acts on a shallow layer than if it acts on a deep layer.

2. As the tropical storm intensifies, upwelling is enhanced.

3. As the tropical storm intensifies, the extent of maximum upwelling becomes independent of the effective thermocline depth. For weak tropical storms, the extent of upwelling is highly dependent on the undisturbed thermocline depth.

4. A slowly-moving tropical storm, even though not too intense, would tend to produce upwelling in its wake. A fast-moving storm might not produce much upwelling if the thermocline is deep, simply because there is too much water to move in a short time and the rate of momentum transfer to the ocean would be too slow.

O'Brien's [1968] model for the response of the ocean to a slow-moving tropical storm was used for comparison with the data contained in Table 1, taken from Figures 9 through 14. Actual comparison with theory can only be made with slow-moving, intense, and very intense tropical storms, when the speed of propagation falls within the three to eight knot range used in the development of theory. However,

conclusions reached by O'Brien can be extended to apply to faster propagating and more intense tropical storms, since speed and intensity were independent variables, and variations of these showed some specific tendencies; that is, that a tropical storm's increase in propagation speed lessens the amount and extent of upwelling, but an increase in intensity increases the amount and extent of upwelling.

The comparison between results from theoretical model and conclusions drawn from observations of the present study is considered in three parts: first: slow-moving, intense tropical storms (Hilda, Betsy),and a very intense tropical storm, (Carla). Second: a fast-moving, intense tropical storm (Betsy in the Gulf); and third: very fast-moving, very intense tropical storm (Shirley). Observations from tropical storm Inez and cross-sections D-D' of Hilda and G-G" of Betsy (in the Gulf), were not compared to results from theory, since the nearness of the coastline and the shallow depth of water imposed boundary conditions not used in theory.

A. SLOW-MOVING, INTENSE AND VERY INTENSE TROPICAL STORM

O'Brien and Reid and O'Brien have shown from numerical studies that the upwelled isotherm may decrease in depth from its original position as much as 80 to 90 meters and that the downwelling isotherm may increase in depth as much as 10 to 20 meters. Maximum upwelling occurs within the area of hurricane-force winds and maximum downwelling occurs 45 to 100 nmi from the path of the tropical storm.

Comparison of cross-sections A-A', B-B' and C-C' of Hilda and cross section A-A'' and B-B'' of Betsy to show the expected variations. As the intensity of the winds of Hilda decreased, the depth to which upwelling occurred (Sec. C-C') also decreased. An examination of cross-section A-A' of Carla shows that the greater intensity of this hurricane resulted in upwelling from a deeper depth than in Hilda. This is as intuition and theory would predict.

B. FAST-MOVING, INTENSE TROPICAL STORM

Theory predicts that as the propagation speed increases, the amount and extent of upwelling and downwelling decreases for a given thermocline depth. Theory also predicts that as the depth of thermocline decreases, the amount and the extent of upwelling increases for a given speed of propagation. Hurricane Betsy in the Gulf of Mexico was of the same intensity as Hilda, but the depth of the thermocline was shallower. Examination of cross-sections C-C'', D-D'', E-E'', and F-F'', shows extensive upwelling and downwelling, but for a shallower depth than that of slower-moving hurricanes Hilda and Carla. This agrees with what theory predicts. Comparison of the extent of upwelling and downwelling with that predicted for a slow-moving tropical storm of the same intensity shows agreement in cross-sections D-D'' and F-F''. Cross-section C-C'' and E-E'' do not show this agreement, and is possibly due to the effect of the eddy described by Wunderly [1970].

C. VERY FAST-MOVING, VERY INTENSE TROPICAL STORM

This case has not been examined theoretically, but conclusions from theory of slower and less intense storms and observations imply that even with a very high speed of propagation, the high intensity of typhoon winds would cause a significant influence on the vertical temperature structure. Cross-section A-A' of Shirley shows that Shirley, a storm of these characteristics, did affect the vertical temperature structure and caused water to be upwelled from 30 meters to the surface.

VI. CONCLUSIONS

Previous studies of upwelling, downwelling and mixing caused by a tropical storm indicate the effects to be governed by several parameters. They are:

1. Initial depth of the thermocline
2. Propagation speed of the hurricane
3. Intensity of the hurricane
4. Depth of water
5. Nearness of shallow water and coastal boundaries

Comparison of tropical storms Hilda, Betsy, Carla, Inez and Shirley show that:

1. Observational data for slow-moving, intense tropical storms is relatively consistent from storm to storm, and agrees qualitatively with the theory of O'Brien, and O'Brien and Reid.

2. Observations show that an increase in propagation speed, while maintaining the same intensity, results in less upwelling.

3. Observations show that a decrease in intensity, while maintaining the same propagation speed, decreases upwelling.

4. Observations show that the presence of a coastal boundary and the shallow depth of water results in extensive mixing. This lends support to the validity of the assumptions of Franceschini and El-Sayed concerning hurricane Inez.

5. The simple-index layer method of comparison is a useful method for comparing the effects on the vertical temperature structure caused by a tropical storm.

6. A search of literature shows that observational data suitable for this type of study is extremely scarce considering the number of hurricanes observed each year.

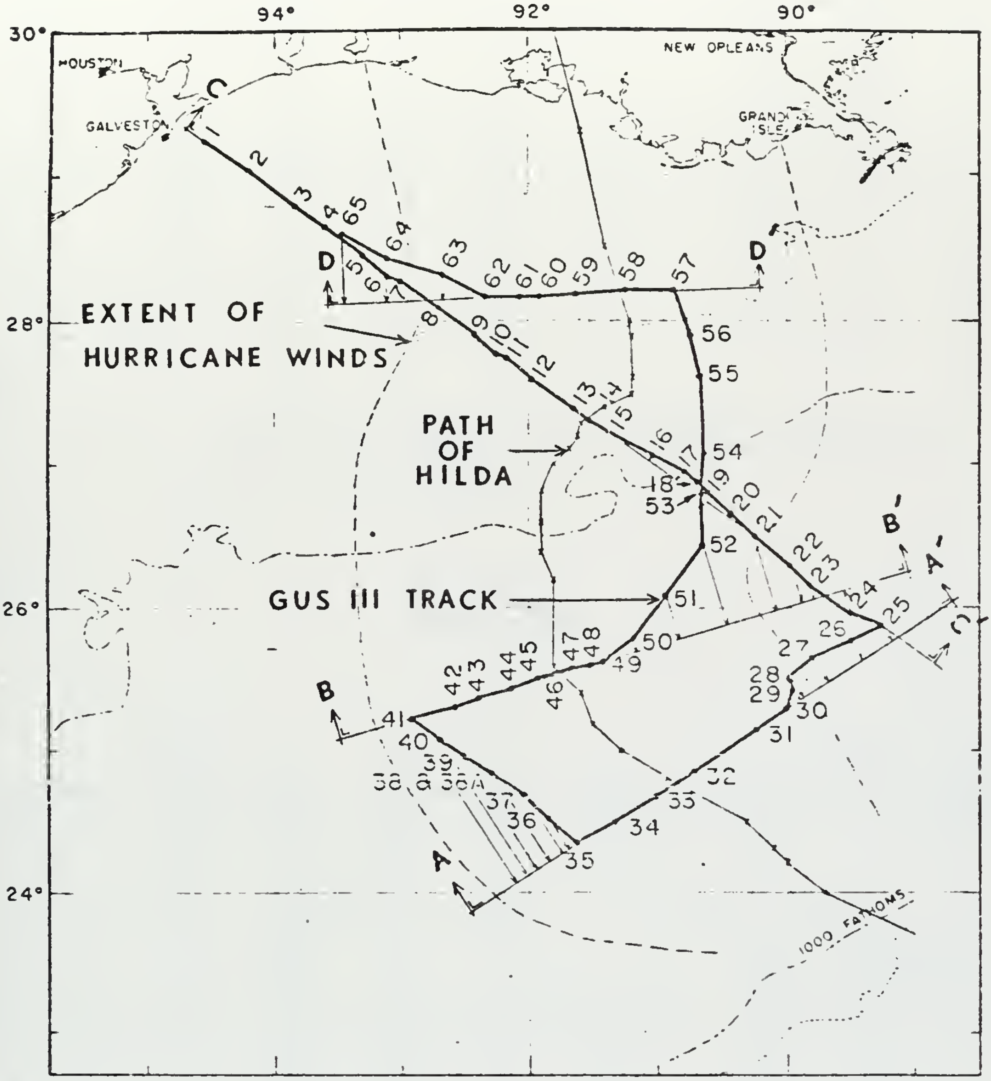
VII. RECOMMENDATIONS

It is recommended that:

1. Procedures be set up to take aircraft expendable bathythermographs (XBT's), prior to, and after severe tropical storms. Tracks normal to the projected path of tropical storms could be predicted with a fair degree of confidence at times, and XBT drops made. The ready availability of data gathered this way would simplify and enhance the study of the effects of tropical storms on the vertical temperature structure of the ocean.

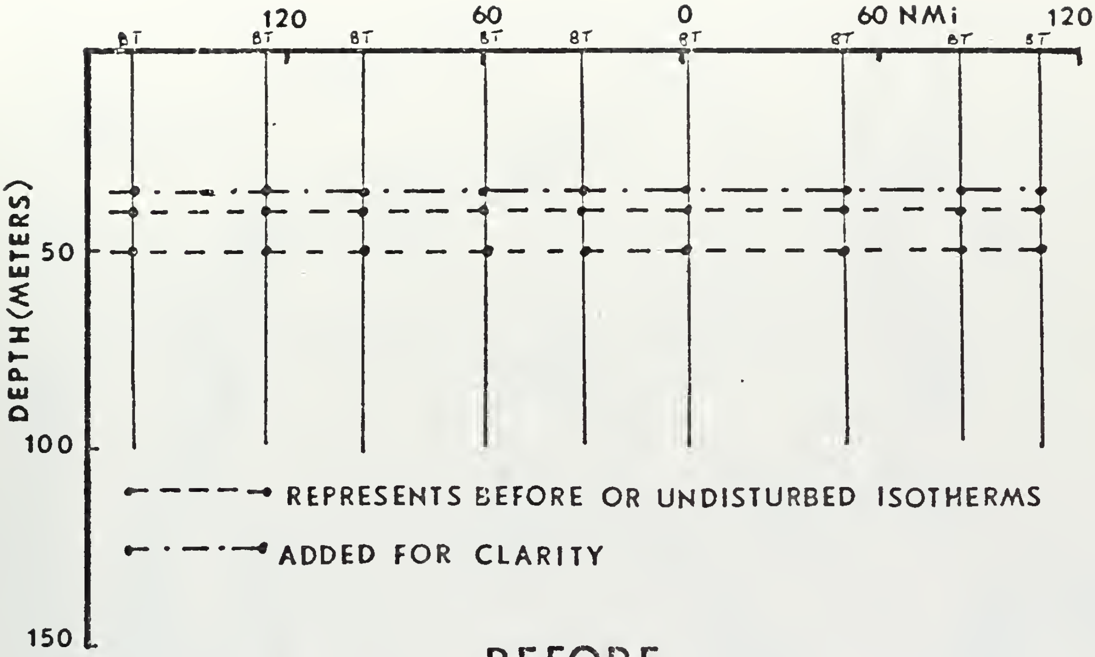
2. A computer study based on the model proposed by O'Brien [1968] should be conducted, incorporating the effects of evaporation, precipitation, sensible and turbulent heat transfer, and radiation exchanges with the atmosphere. The propagation speed of the tropical storm should be extended beyond the present value of eight knots.

APPENDIX A

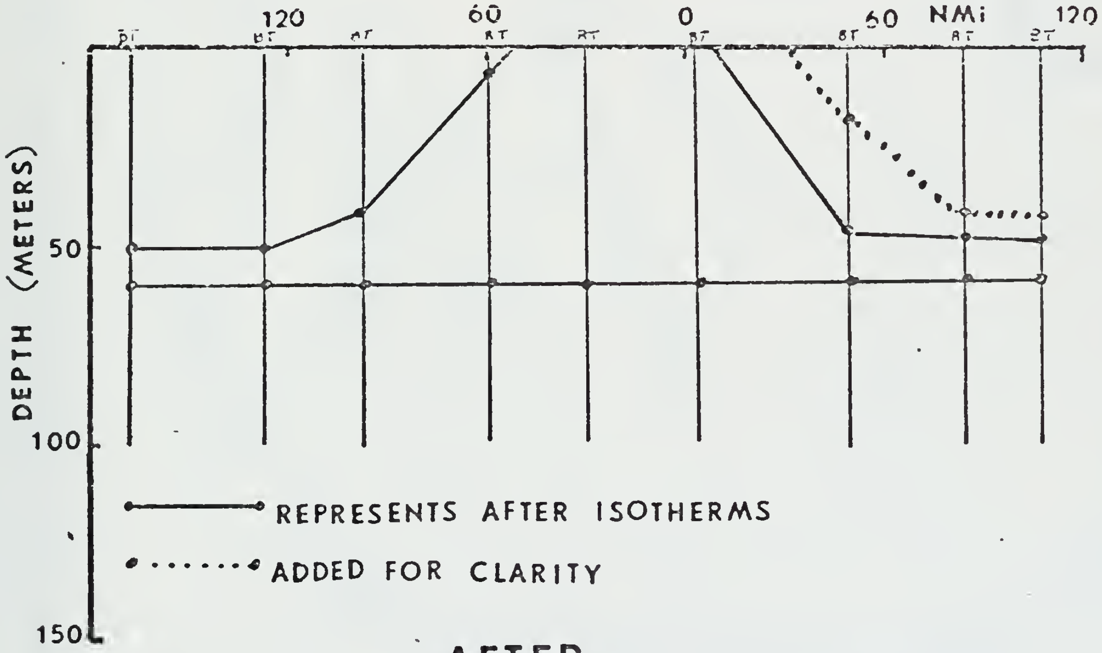


CRUISE HILDA TRACK
SECTIONS AND B.T. NOS.
GUS III, OCT, 1964

Fig. 1. Cruise track used by GUS III for AFTER Hilda(1964). This figure represents the method of selection of cross-sectional lines A-A' through D-D' and the method of projection.



BEFORE



AFTER

Fig. 2. An example of the construction of the figures used for analysis.

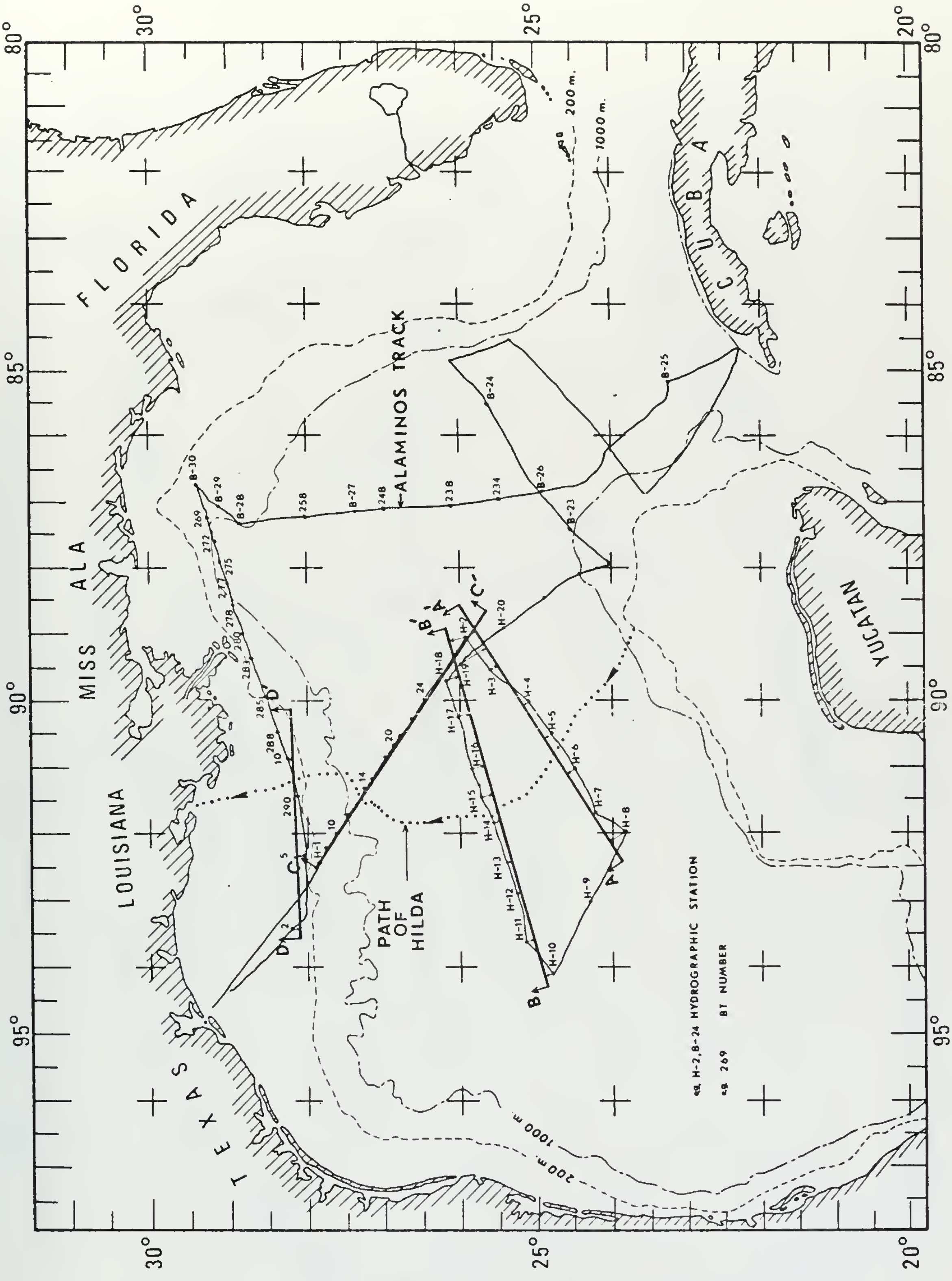


Fig. 3. Cruise Track Used by R/V ALAMINOS for UNDISTURBED Hilda (1964) and BEFORE Betsy (1965) in the Gulf of Mexico, (after Leipper [1967]).

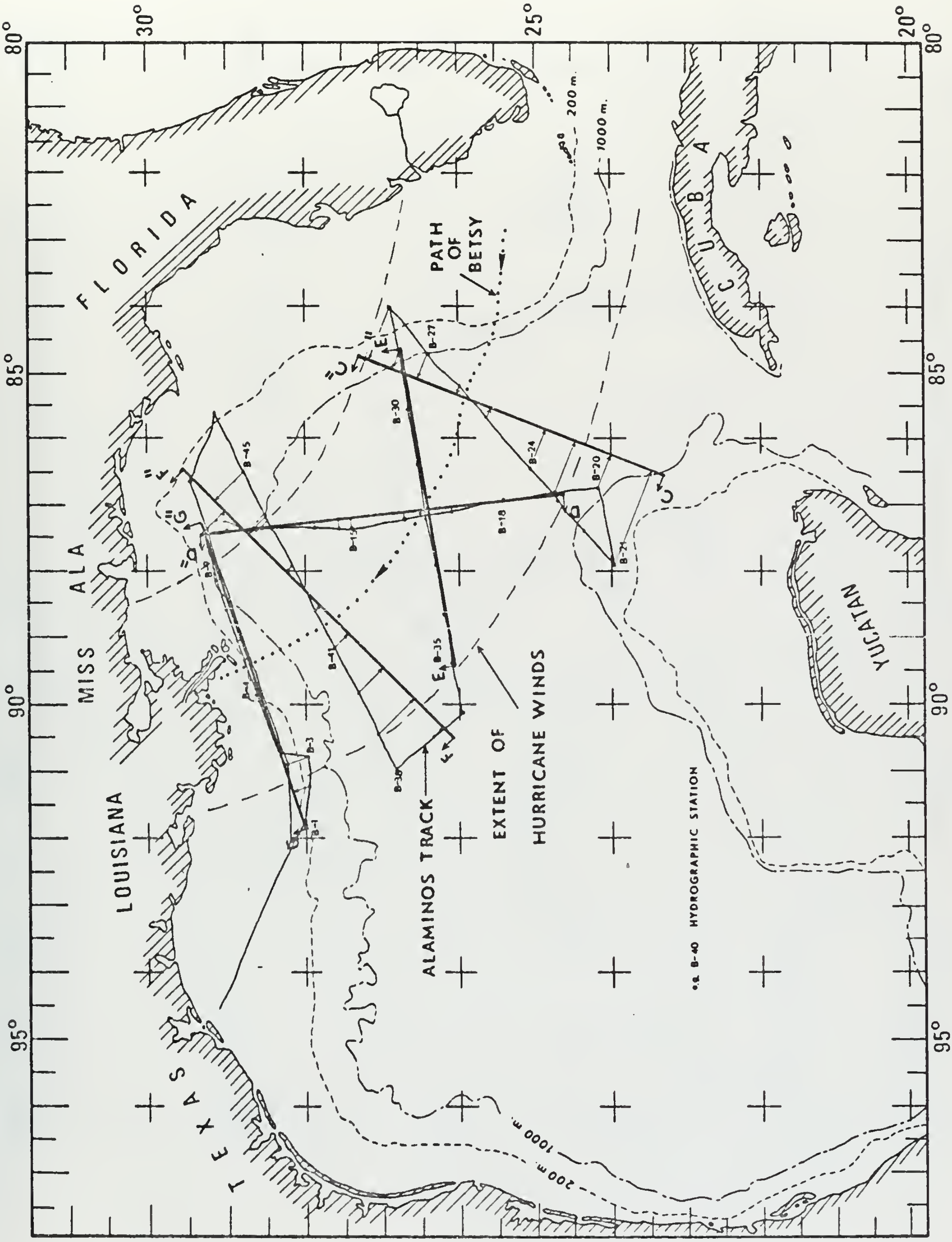


Fig. 4. Cruise Track Used by R/V ALAMINOS for AFTER Betsy (1965), and Location of Cross-sections C-C" through G-G", (after Leipper [1968]).

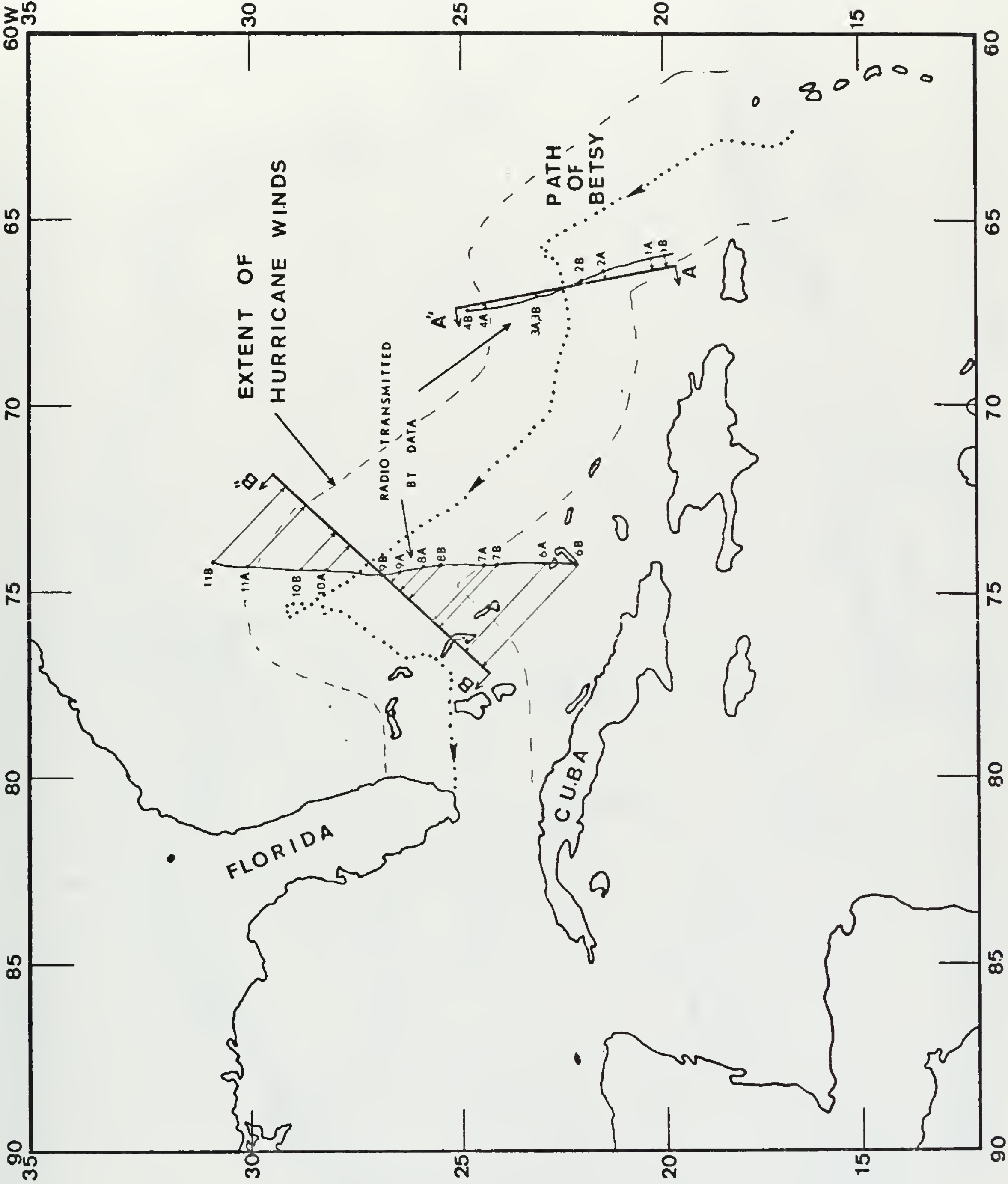


Fig. 5. Position of Cross-sections A-A" and B-B" across the Track of Betsy (1965) with Location of Radio-Transmitted BT's, (after Landis and Leipper [1968]).

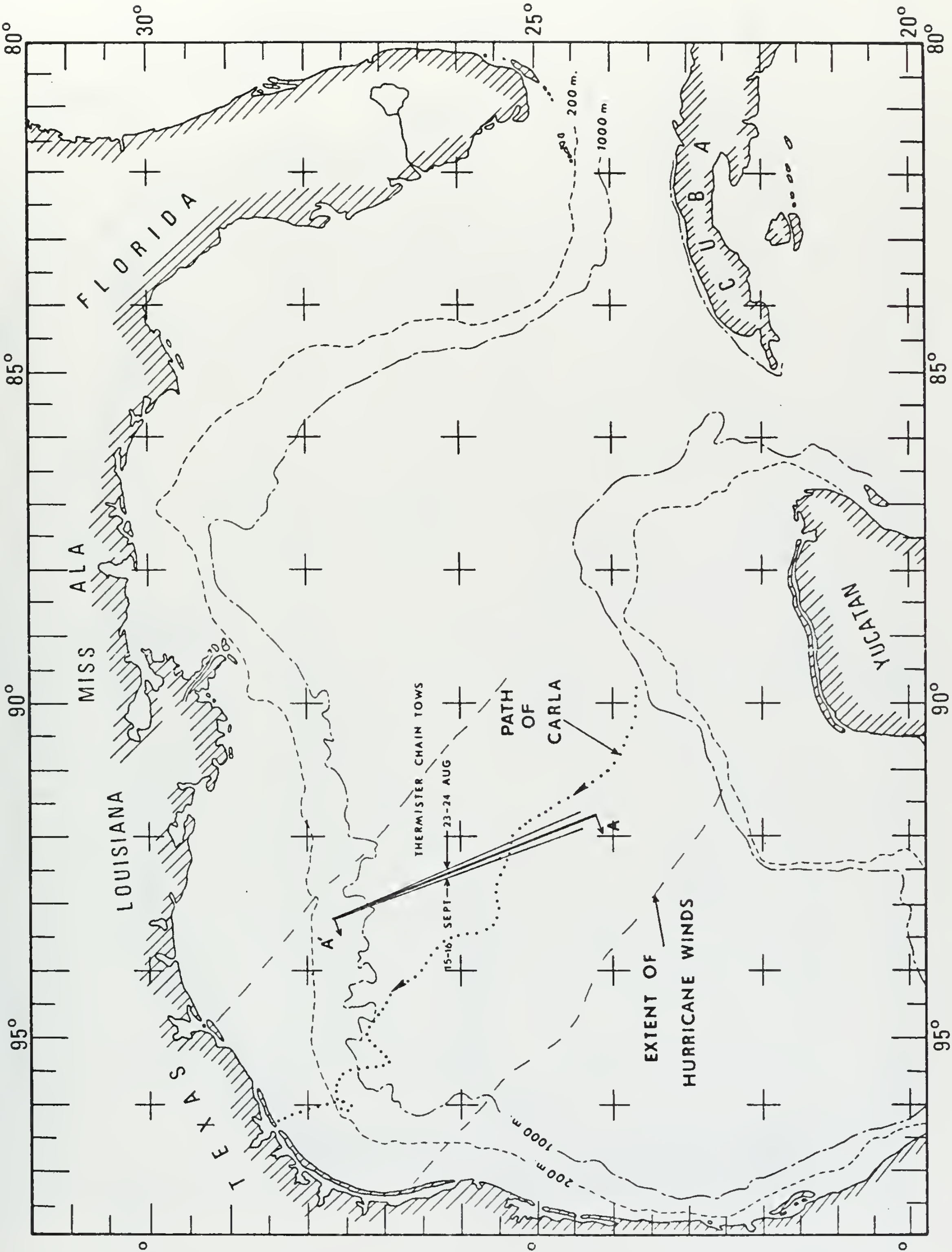


Fig. 6. Cruise Track Used by R/V HIDALGO for Thermistor-Chain Tows of BEFORE and AFTER Carla (1961) and Location of Cross-section A-A', (after Stevenson and Armstrong [1965]).

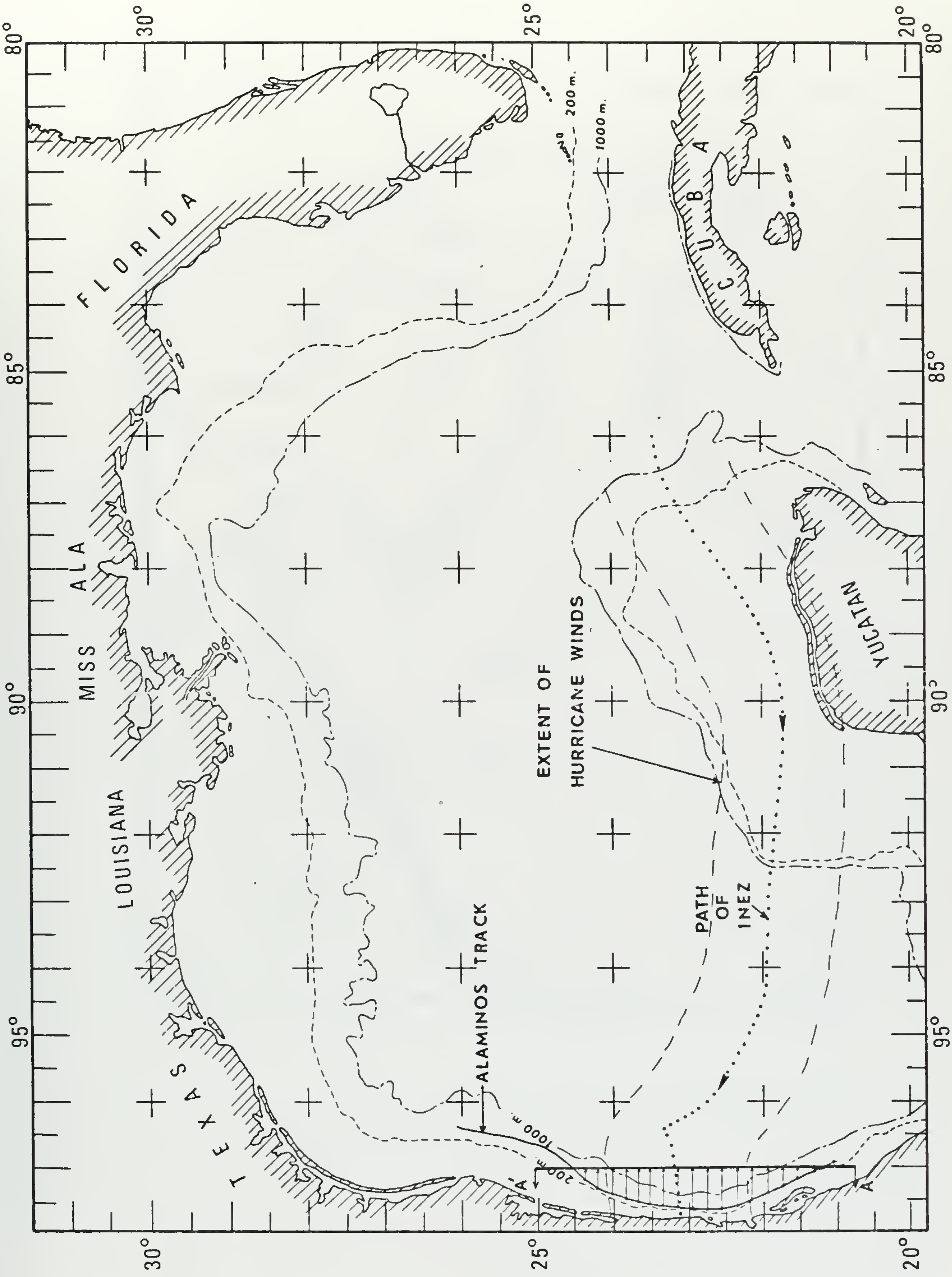


Fig. 7. Cruise Track used by R/V ALAMINOS for BEFORE and AFTER Inez (1966) and Location of Cross-section A-A', (after Franceschini and El-Sayed [1968]).

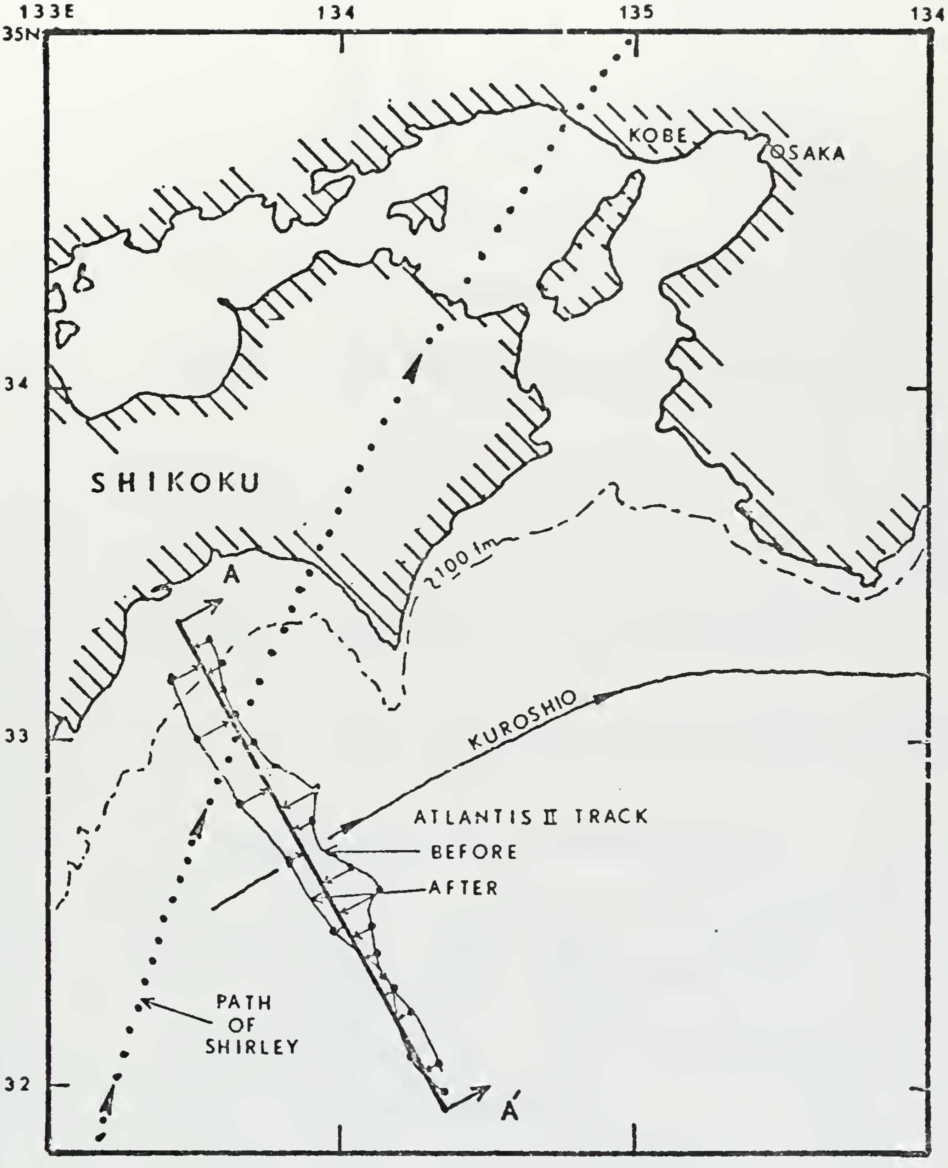


Fig. 8. Cruise Track Used by R/V ATLANTIS II for BEFORE and AFTER Shirley (1965) and Location of Cross-section A-A', (after Wright [1969]).

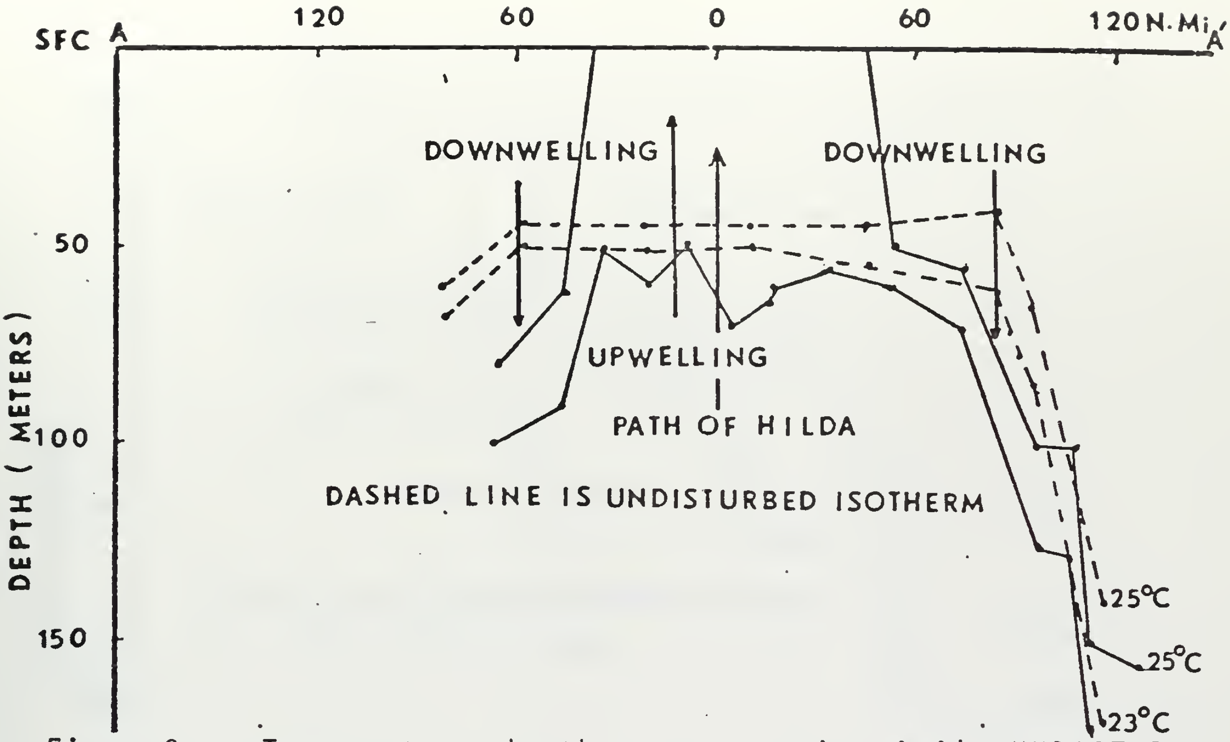


Fig. 9a. Temperature-depth cross-section A-A', UNDISTURBED and AFTER Hilda (1964). (See Fig. 1 for location.)

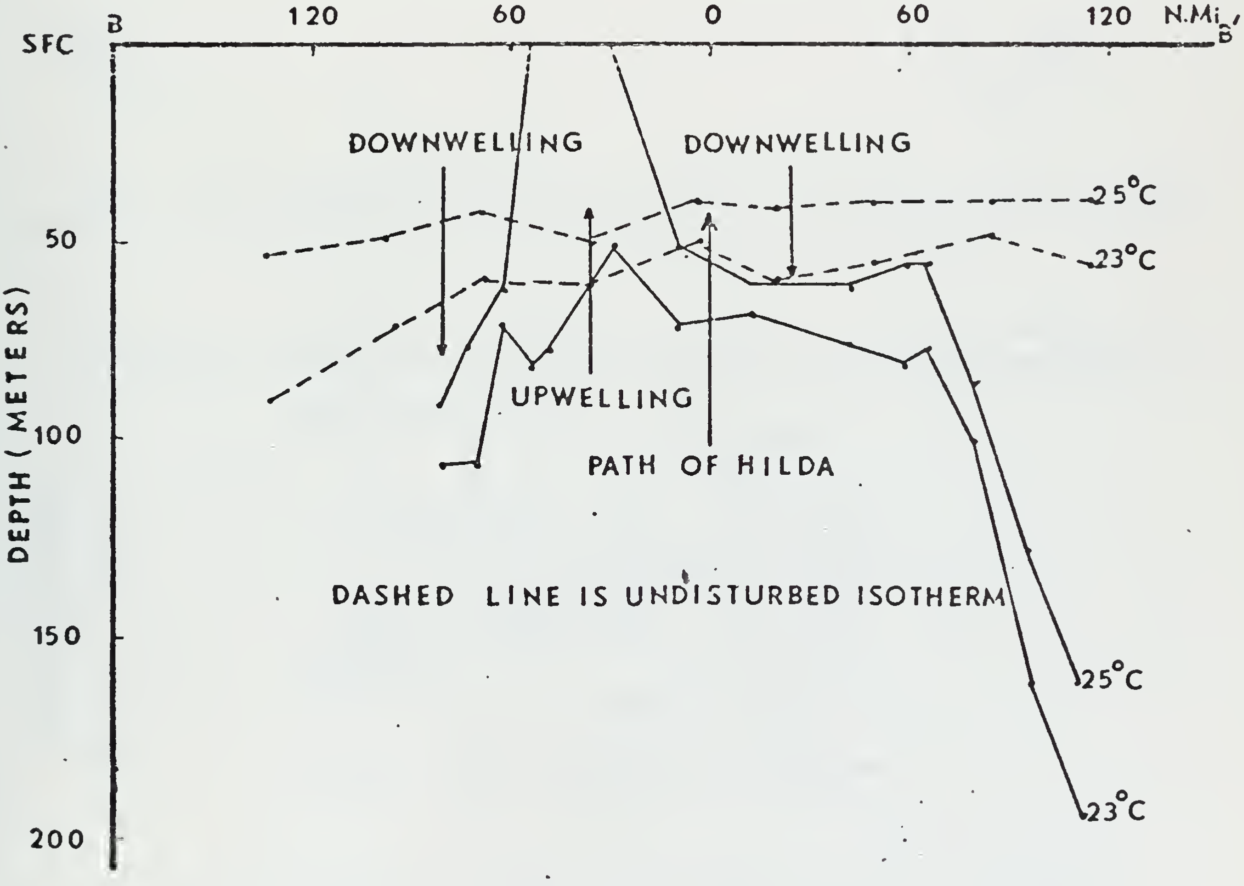


Fig. 9b. Temperature-depth cross-section B-B', UNDISTURBED and AFTER Hilda (1964). (See Fig. 1 for location.)

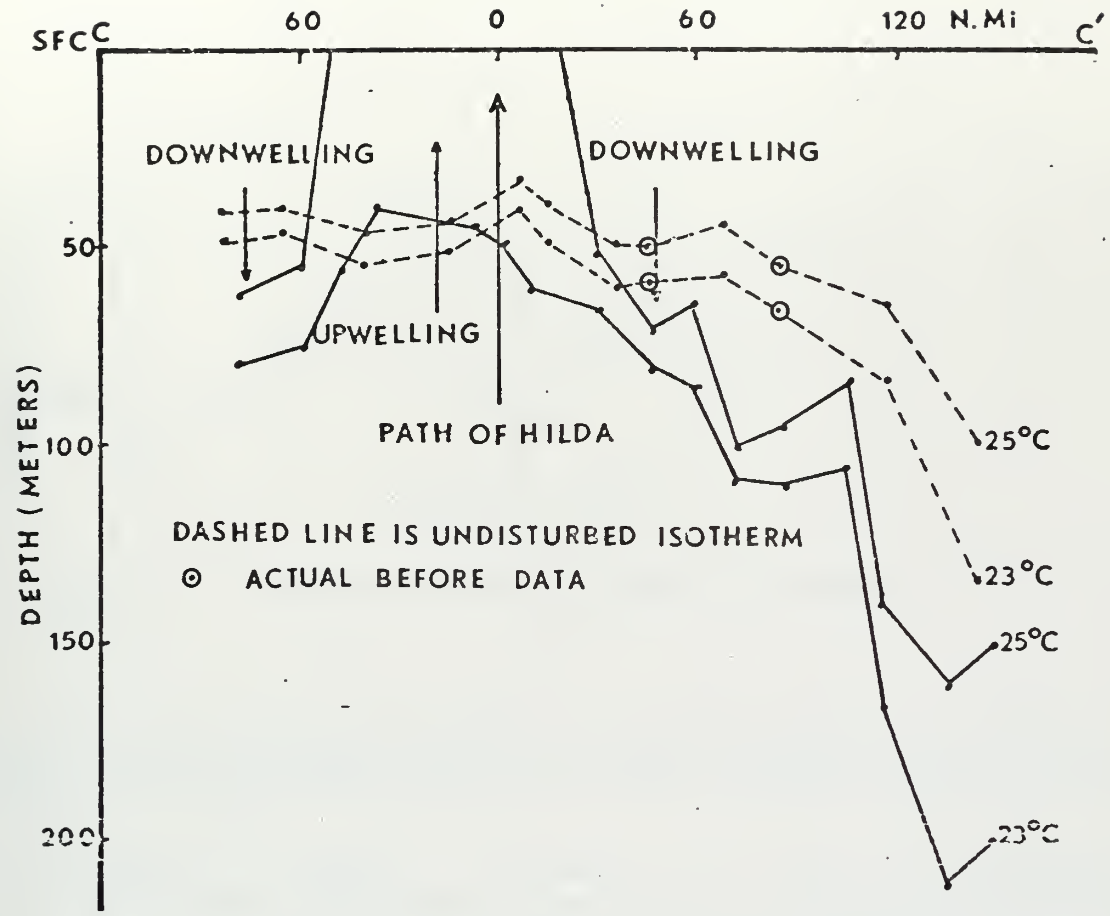


Fig. 9c. Temperature-depth cross-section C-C',UNDISTURBED and AFTER Hilda(1964). (See Fig. 1 for location.)

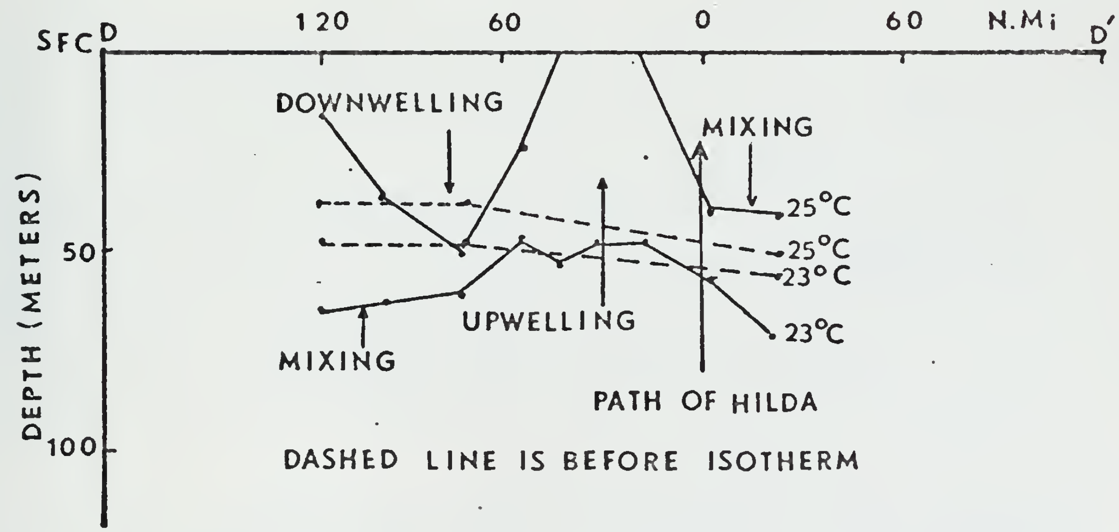


Fig. 9d. Temperature-depth cross-section D-D', BEFORE and AFTER Hilda(1964). (See Fig. 1 for location.)

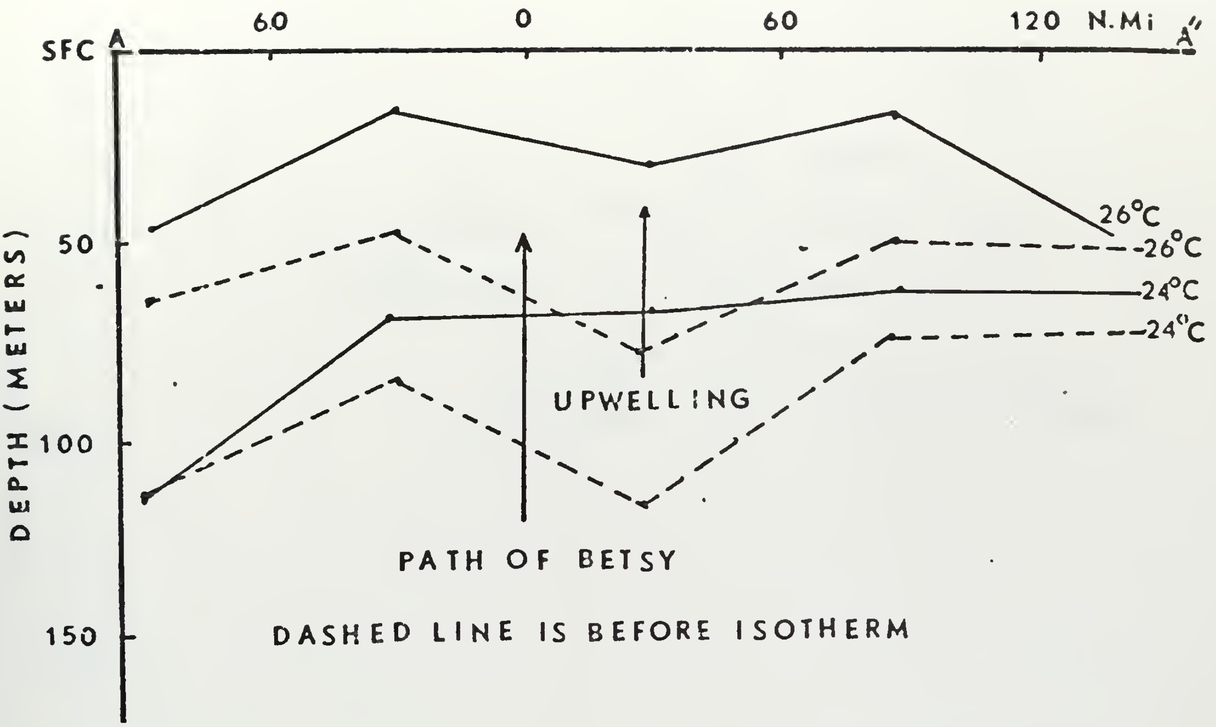


Fig. 10a. Temperature-depth cross-section A-A'', BEFORE and AFTER Betsy(1965) based on radio transmitted data. (See Fig. 5 for location.)

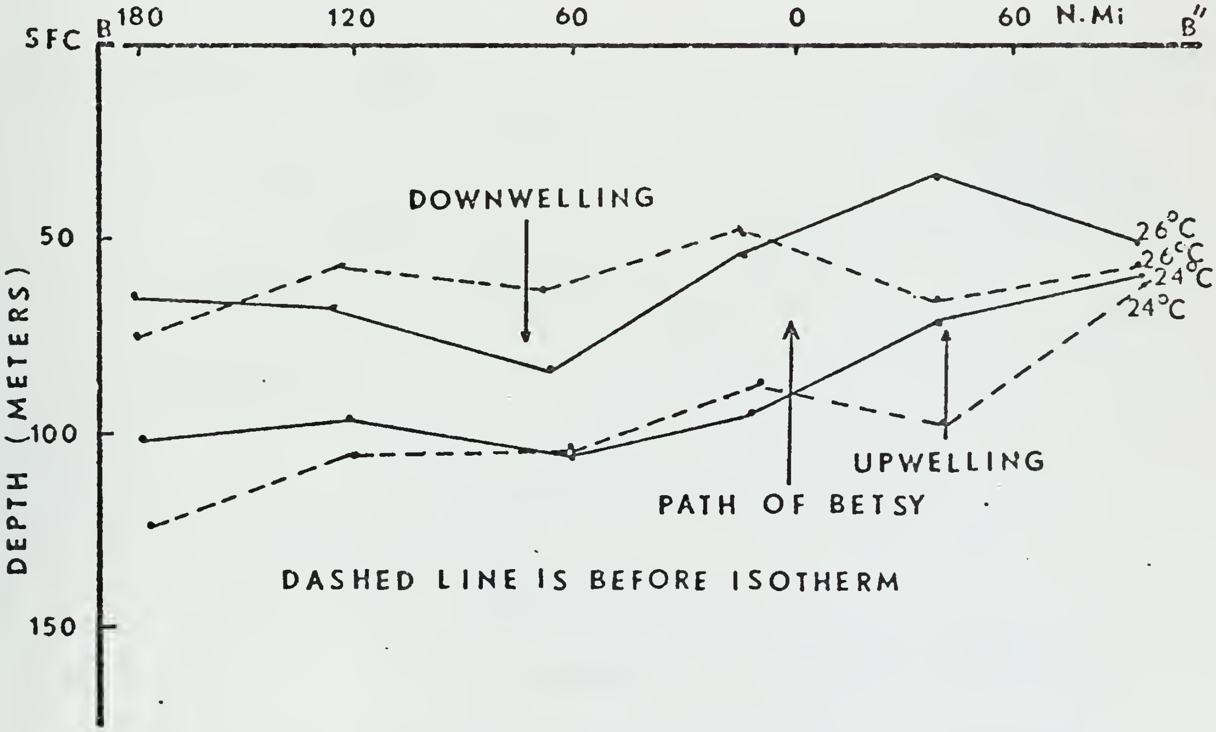


Fig. 10b. Temperature-depth cross-section B-B'', BEFORE and AFTER Betsy(1965) based on radio transmitted data. (See Fig. 5 for location.)

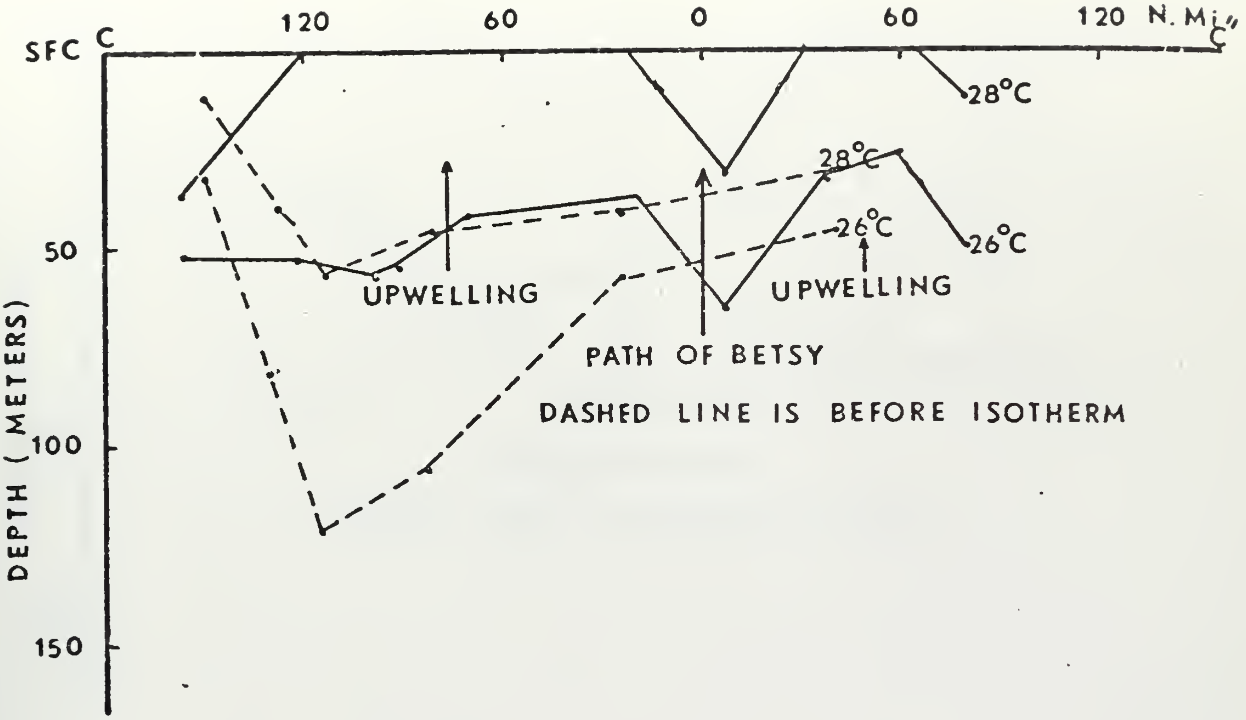


Fig. 11a. Temperature-depth cross-section C-C'', BEFORE and AFTER Betsy(1965) in the Gulf of Mexico. (See Fig. 4 for location.)

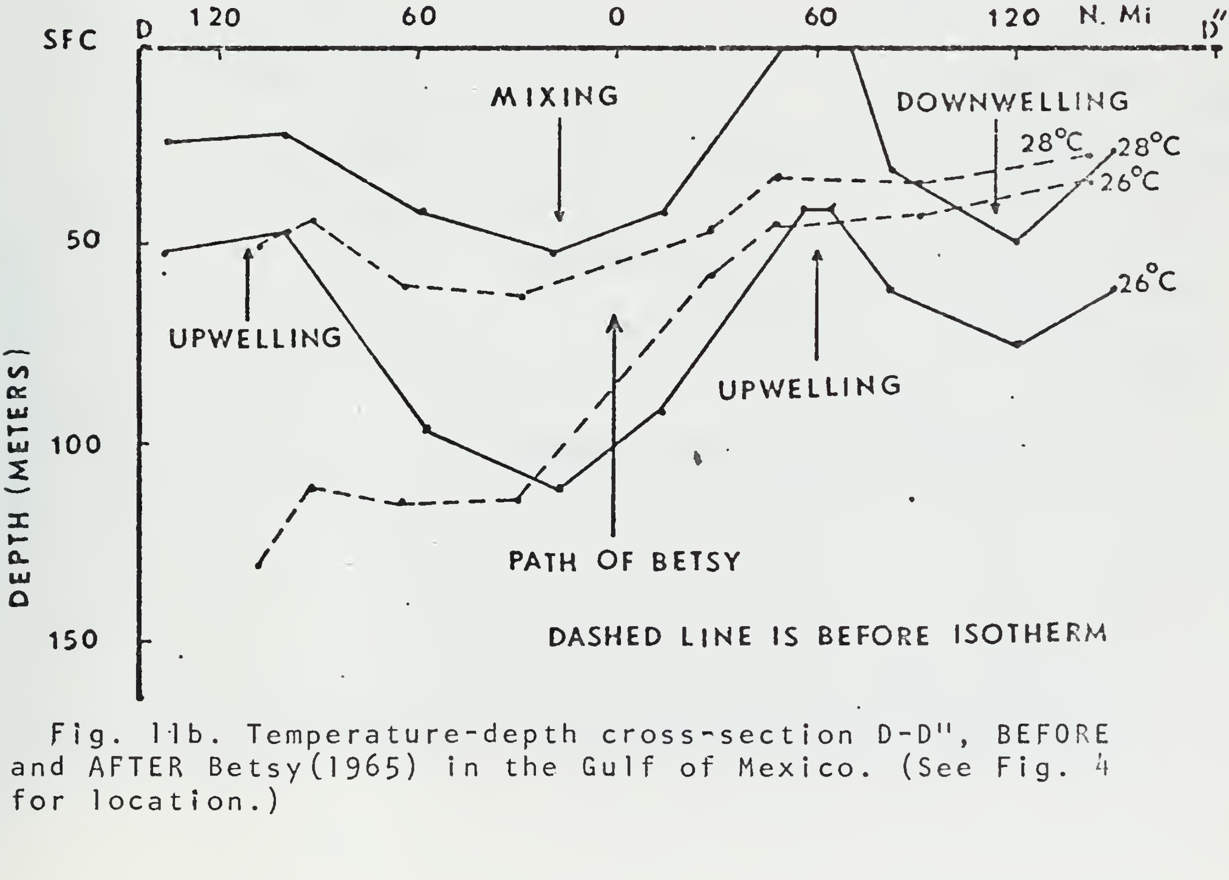


Fig. 11b. Temperature-depth cross-section D-D'', BEFORE and AFTER Betsy(1965) in the Gulf of Mexico. (See Fig. 4 for location.)

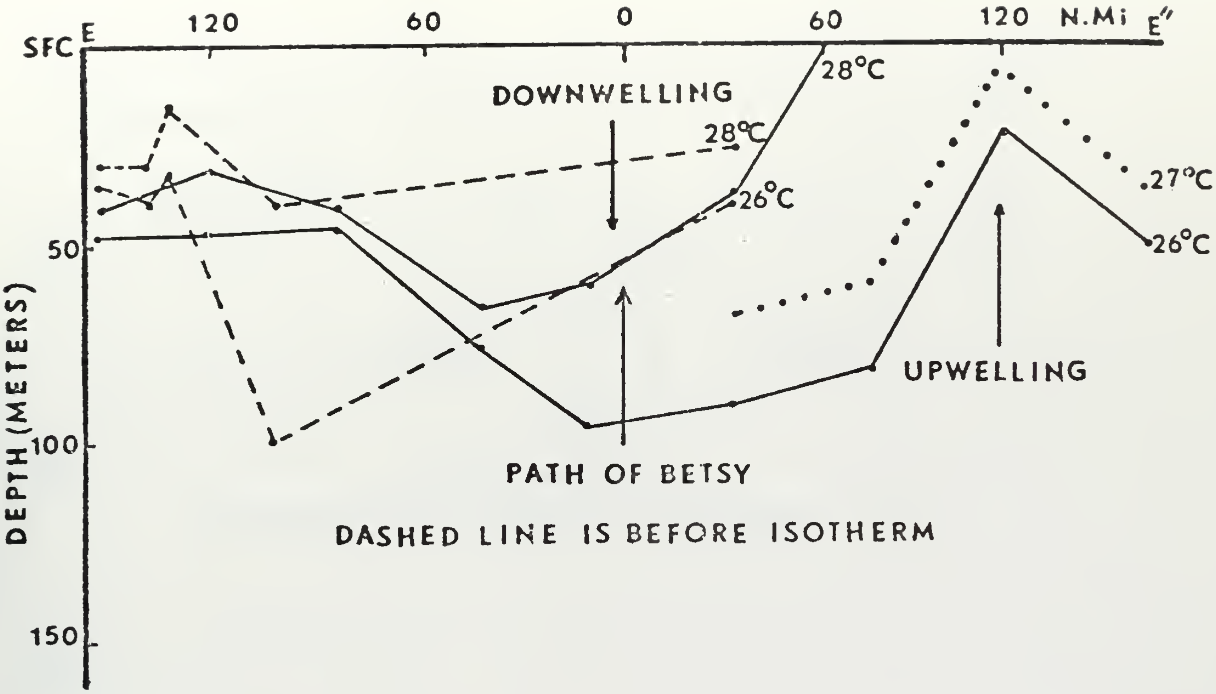


Fig. 11c. Temperature-depth cross-section E-E'', BEFORE and AFTER Betsy(1965) in the Gulf of Mexico. (See Fig. 4 for location.)

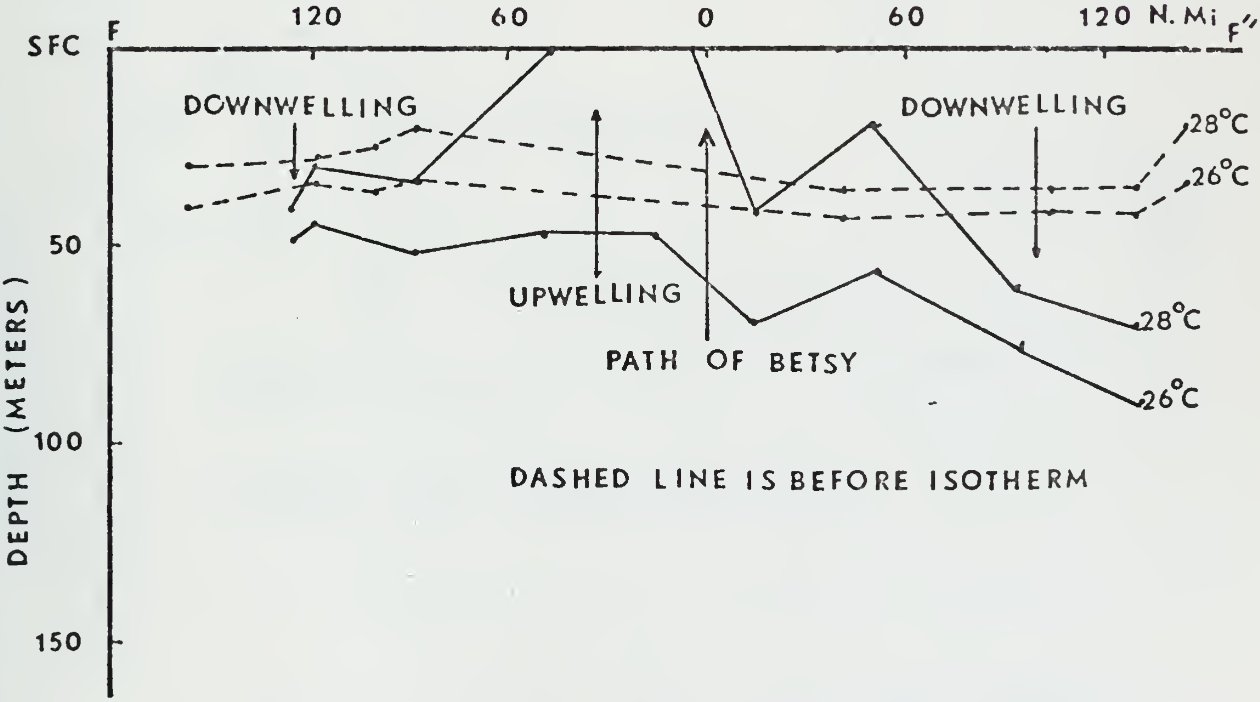


Fig. 11d. Temperature-depth cross-section F-F'', BEFORE and AFTER Betsy(1965) in the Gulf of Mexico. (See Fig. 4 for location.)

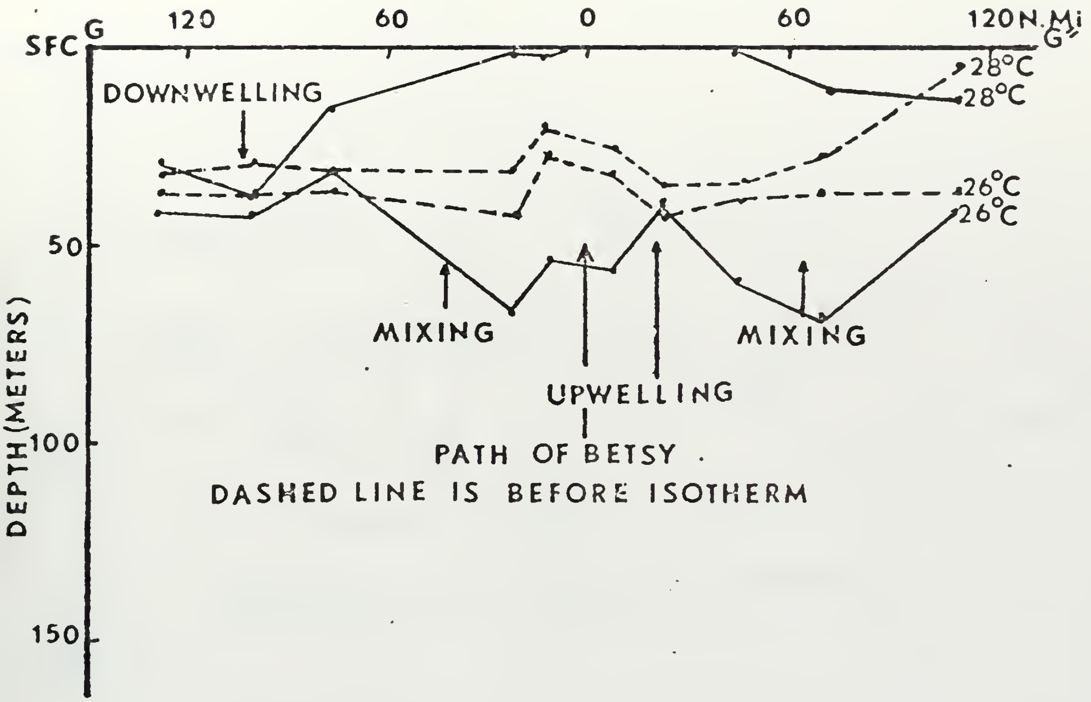


Fig. 11e. Temperature-depth cross-section G-G'', BEFORE and AFTER Betsy(1965) in the Gulf of Mexico. (See Fig. 4 for location.)

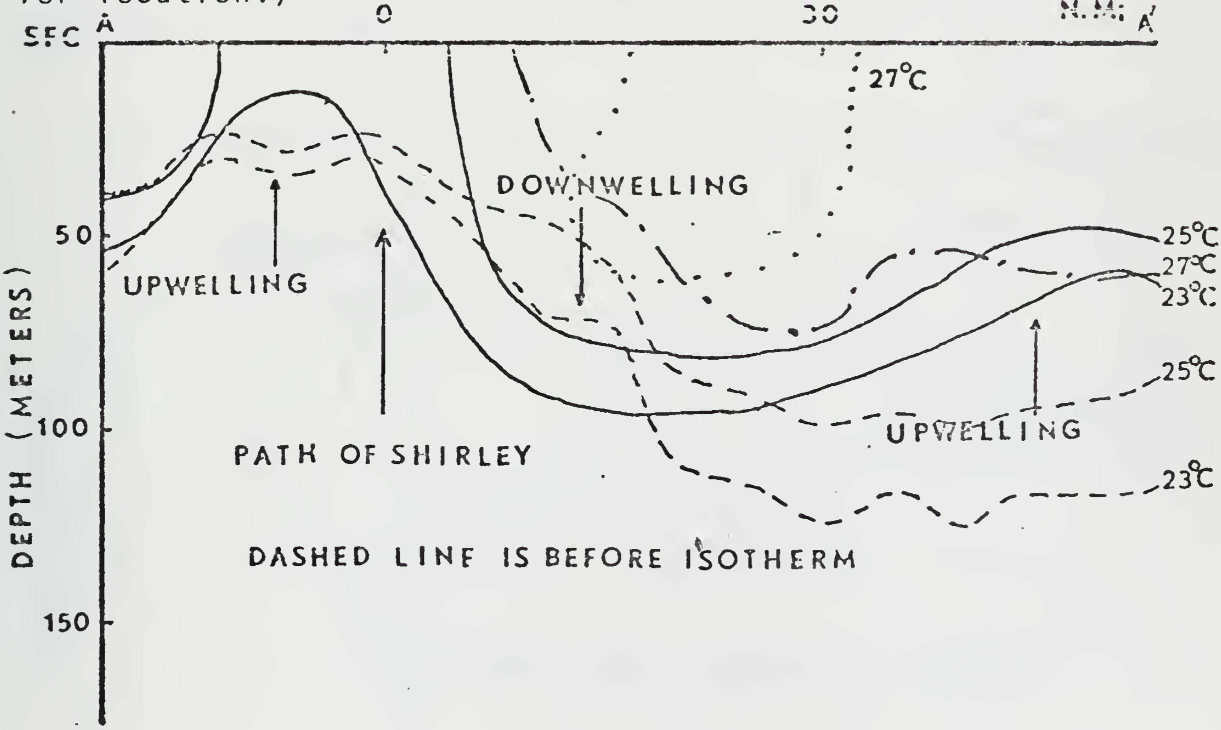


Fig. 12. Temperature-depth cross-section A-A'', BEFORE and AFTER Shirley(1965). (See Fig. 6 for location.)

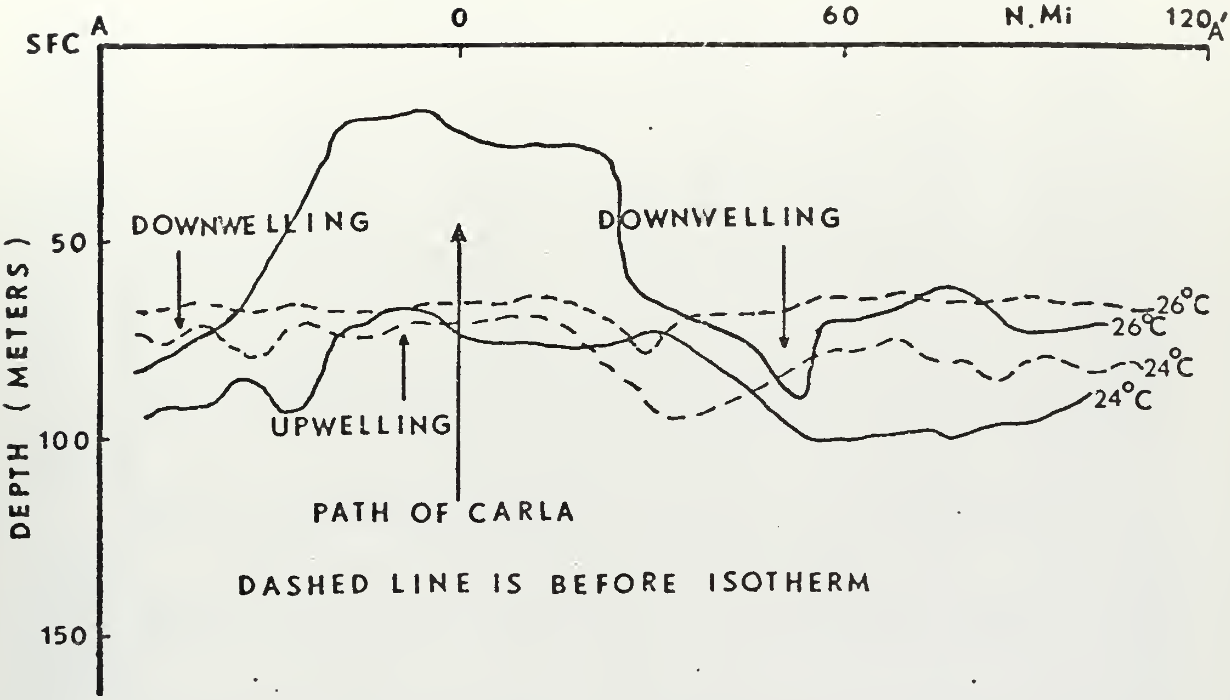


Fig. 13. Temperature-depth cross-section A-A', BEFORE and AFTER Carla(1961) based on towed thermister chain data. (See Fig. 7 for location.)

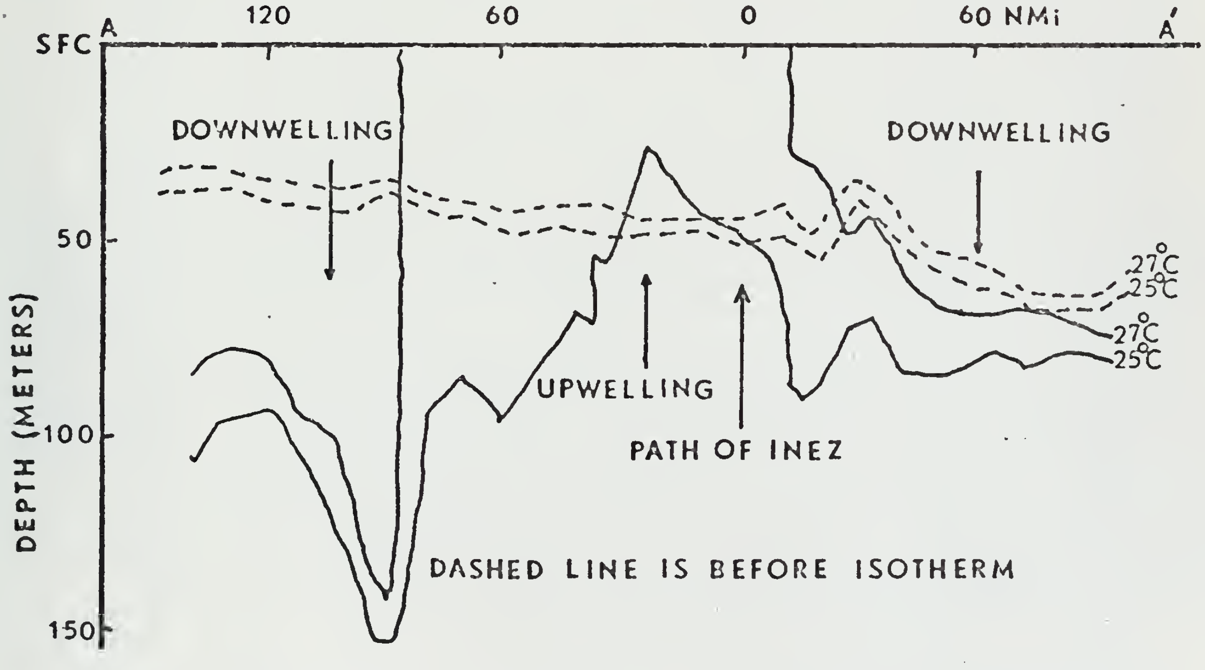


Fig. 14. Temperature-depth cross-section A-A', BEFORE and AFTER Inez(1966). (See Fig. 8 for location.)

HURRICANE/ TYPHOON	MAXIMUM SEA SURFACE TEMPERATURE (°C)	CHANGE IN THICKNESS/DEPTH OF THE INDEX LAYER (M)						IN UPWELLED AREA, THE VERTICAL DISPLACEMENT OF THE BOTTOM OF THE INDEX LAYER		PROPAGATION SPEED OF HURRICANE (KNOTS)	MAXIMUM FORCE OF WINDS (KNOTS)	EXTENT OF HURRICANE WINDS (NMI)		TIME DATA WAS GATHERED (DAY)		DEPTH OF WATER (METERS)	DISTANCE FROM PATH TO MAX. DOWNWELLING	
Cross-Section		DOWNWELLING LEFT		UPWELLING		DOWNWELLING RIGHT												
		Before	After	Before	After	Before	After	Before	After			Left	Right	Before	After		Left	Right
Hilda(1964)																		
A-A'	3°C	8/45	15/70	10/50	65/SURF	15/45	10/60	60	65	6 - 8	130	70	85	+11mon	+5	1000	65	80
B-B'	5°C	30/50	20/95	12/50	55/SURF	20/40/	10/60	60	65	6 - 8	120	70	80	+11mon	+7	1000	75	30
C-C'	5°C	8/40	20/65	8/45	45/SURF	10/50	8/70	55	50	6 - 8	110	80	85	+11mon	+3	100- 1000	70	50
D-D'	5°C	10/35	50/65*	8/40	50/SURF	6/50	35/40*	50	50	6 - 8	100	80	80	UKN	+9	100	70	*
Betsy(1965)																		
A-A''	1.8°C	NOT OBS		35/65	40/30	NOT OBS		110	70	3 - 4	130	85	85	-(1-15)	+(3-25)	1000	NOT OBS	
B-B''	3°C	40/65	20/80	35/65	35/35	NOT OBS		90	85	5 - 6	130	85	85	-(4-15)	+(5-20)	1000	60	NOT OBS
C-C''	3°C	NOT OBS		40/45 15/30	45/SURF 35/SURF	NOT OBS		120 40	55 25	12-14	130	85	90	-19	+8	1000	NOT OBS	
D-D''	3°C	30/65	50/45*	10/35	40/SURF	8/28	25/48	44	40	12-14	120	90	90	-17	+6	1000	18	120
E-E''	3°C	25/30	40/55	NO DATA	20/SURF	NO DATA		NO DATA		12-14	120	90	90	-(18-23)	+10	1000	ON PATH	
F-F''	3°C	8/30	12/40	10/30	45/SURF	8/35	15/60	35	45	12-14	110	90	90	-(16-23)	+11	1000	85	90
G-G''	3°C	8/30	8/38	8/30	5/SURF*	32/ 5	27/14	45	50	12-14	105	90	90	-15	+(3-4)	200- 1000	110	110
Shirley(1965)																		
A-A'	3°C	NO DATA		8/30 20/90	15/SURF 15/45	20/45	15/75	35 115	15 60	25-30	150	UKN		-7	+2	500	NOT OBS	20
Carla(1961)																		
A-A'	1.5°C	6/70	15/80	5/65	50/25	15/75	10/90	70	70	6 - 8	150	90	90	-17	+5	200- 2000	50	50
Inez(1966)																		
A-A'	3°C	10/35	10/140	10/40	50/SURF	8/55	15/65	50	45	6 - 8	110	60	60	-2	+2	200	60	60
THEORY	DECREASE	DECREASE/INCREASE UP TO 20		INCREASE/DECREASE UP TO 80-90		DECREASE/INCREASE UP TO 20		DECREASE IN DEPTH		3 - 8	75	5-100	5-100	NOT DEFINED		INFINITE	45-100	45-100

Table 1. Characteristics of the Tropical Storms, the Results of Analysis and the Predictions of Theory.

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William Revesz, Jr.

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13. ABSTRACT

To make comparisons of the effects of tropical storms on the ocean's vertical temperature structure, temperature-depth cross-sections were constructed using bathythermograph data and data from published articles.

Upwelling, downwelling and mixing, caused by tropical storms in deep and shallow water, are analyzed and compared. For a slow-moving, intense and very intense tropical storm, upwelling, from a depth of 40 to 65 meters, is observed within the radius of hurricane-force winds. Downwelling as much as 20 meters occurs from 45 to 110 nmi from the path of the storm. This compares favorably with the theoretical results of O'Brien and Reid. A fast-moving, intense tropical storm has a similar effect on the vertical temperature structure if the thermocline is shallow, and upwelling, of a lessor degree than that caused by a slower-moving storm, can occur from a depth of 35 meters within the radius of hurricane-force winds. A very fast-moving, very intense tropical storm can cause upwelling from a depth of 30 meters if the thermocline is shallow.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hurricanes						
Typhoon						
Upwelling						
Air-Sea Interactions						

Thesis 130324
R365 Revesz
c.1 Comparison of effects
of various tropical
storms on the vertical
temperature structure
of the ocean using pic-
torial representation.