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A Sequence of Current Patterns in the Gulf of Mexico

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The primary current in the Gulf of Mexico is in the form of a loop entering through the Yucatan Channel and eventually leaving through the Florida Straits. It usually transports more than 25 million m^3/sec of water at 50 to 200 cm/sec. Although it retains its basic characteristics along the line of flow, it is known to be highly variable in position. Little information on the exact nature of the variations is published. A series of eight cruises of about 2-weeks duration each was conducted by the author over a 30-month period in the different seasons. The primary current was crossed forty times. Five of these cruises supplemented by three others having somewhat differing objectives provided a series of eight cruises in one 16-month period beginning in July 1965. A reasonable sequence of current patterns for the primary current loop is indicated by the observations. The variations in pattern are compared with those indicated by data available from other time periods. The flow is well represented year-around by the topographies of the 22°C isothermal surfaces. This permits a simplified analysis and allows conclusions about the current systems to be drawn from cruises on which only limited data were collected. From July 1965 through December an eastward flow along the coast of Cuba strengthened and became the start of a 'spring intrusion' into the gulf. By August 1966 the intrusion had reached 760 km across the gulf, and a 'fall spreading' into the west gulf had begun. In July and August 1965 the northern end of the loop became a separate eddy, a detached exterior flow.

INTRODUCTION

Although the Gulf of Mexico is an adjacent sea, small compared with the three major oceans, it contains a current, the east gulf loop, which moves at about 50 to 200 cm/sec and usually transports more than 25 million m^3/sec of water. This is more than one-third of the transport of the Gulf Stream and is sufficient to refill the Gulf of Mexico basin in 30 months. This flow has large variations both in path and in volume. These variations may well have a significant effect on a part of the North Atlantic Ocean.

Beginning in May 1964 a series of eight cruises was conducted in the gulf with the objective of studying changes in the thermal structure throughout the year. Most cruises were limited to about 14 days of ship time. Five of the cruises fell within one 16-month period (July 1965 to November 1966) and may be used in sequence to indicate time changes in the primary circulation of the east gulf. Three cruises conducted (by Pequegnat, Nowlin and Reid, and Cochrane) during this same period provide additional data. Data from other time periods indicate that some of the features observed in the present sequence may occur repeatedly.

Since the initial objective of these cruises was to study the changes in the thermal structure, attention was focused on the upper 300 meters. It soon became apparent that the most important factor affecting local thermal structure was horizontal advection and that it would be necessary to know the changes in circulation pattern before any valid conclusions could be drawn about the thermal structure changes. In particular, when the major current in the gulf moved across a given location, the isotherms were found to change in depth by amounts of more than 125 meters with advective movements of 90 to 150 km. On the other hand, the structure of the current seldom changed significantly downstream along the path of flow.

In the earlier cruises of the present series, observations below depths of 300 meters were sacrificed in order to extend the area that could be covered within the available ship time. Some cruise results were based on bathythermograph data primarily. On two cruises an instrumented towed cable 267 meters in length was used with temperature sensors spaced 7.6 meters apart [*Leipper,* 1966]. After it was realized that movement of the current system was such a key factor in defining the geographical variation of the thermal structure, it was decided that the small amount of additional time required for deep observations would be very worth while. Thus, on the later cruises not only hourly temperature observations in the upper 300 meters but also hydrographic data to 1200 meters were obtained at regular distance intervals, normally about 65 km. The observational coverage of the current patterns was improved as insight was gained.

These results are presented not so much for their conclusiveness as for their potential use in future, more definitive studies, such as studies that may become possible during the Gulf Science Year proposed for 1970–1971.

Loop Current

Nowlin and McLellan [1967] and others have stated that the current bounding the eastern gulf loop is the main feature of the surface circulation in the Gulf of Mexico. This statement was further supported by the cruises described here. These cruises were planned to best observe, in the time available, the extent and character of the loop. However, for this study as for other time studies of ocean currents the words of *Stommel* [1965, p. 136] apply

> Very little is really known about such (ocean current) fluctuations. It takes years of careful and expensive observations to produce even a crude description of them . . . until this burdensome and not immediately rewarding task is undertaken, our information about the fluctuations of ocean currents will always be fragmentary.

In the present cruise series and others of the same type taken previously, about forty crossings were made of this strong current, most of the crossings running perpendicularly across the flow. The impression obtained from these crossings is that the loop current is always strong and that the current on each side of the loop is largely contained in a band 90 to 150 km in width. An isolated eddy, possibly broken off from the loop current and having many of its characteristics, has been observed. As the ship enters the band of strong current in the loop, the presence of the current becomes immediately apparent from the set of the ship, the angle of the wire in taking hydrographic stations, and the slope of the subsurface isotherms. At times there are also noticeable changes in sea state and changes in surface films and in amounts of other drifting materials.

Depth-of-isotherm sections were prepared from bathythermograph observations while the cruises were underway. Study of these sections in relation to other evidence of the presence of the strong current has led to the conclusion that the temperature data alone and in the upper 300 meters only gives a very good indication of current location. *Ichiye* [1962] found a good correlation between temperatures (at 100 and 200 meters) and dynamic heights referred to the 1000-meter reference in the gulf. On this basis he suggested synoptic surveys be made with the bathythermograph. Depths of isotherms in the Gulf Stream area have been utilized systematically by *Fuglister and Worthington* [1951] and others. However, deeper stations were obtained in most cases of the present series, and a more complete description of the current can be developed. This more complete description will not be undertaken here since the simple temperature indications of current locations are sufficient to show the changes being discussed.

On a pattern of the topography of an isothermal surface, northern hemisphere flow is assumed to be along the isotherms with the greater depths of the isothermal surface being on the right-hand side of the current as the observer faces downstream and the lesser depths being on his left. The speed of the current is assumed to be proportional to the slope of the isothermal surface. In other words, it is assumed that the topography of the isothermal surface, insofar as the loop current in the gulf is concerned, is interpreted in the same way in which charts representing geostrophic flow are interpreted. No attempt is made to infer or compute the actual current speed from the relative slopes of the isothermal surfaces, although speed has been computed in selected locations by using the geostrophic assumption and the hydrographic data. In the present study attention will be focused on the variation in position of the current. A study of variations in its speed will make another investigation, as will the detailed study of the mixing that occurs as the narrow band of current moves through the Gulf of Mexico. Meantime it can be stated that there is a notable similarity among all the temperature sections representing crossings of this current, even though some of the sections were made just as the current enters through the Yucatan Straits and others were observed after it had wandered distances of some 1700 km in the gulf and was about to leave through the Florida Straits.

Temperature-Depth Sections

To show the nature of isothermal slopes associated with crossings of the current, an east–west section north of the Yucatan Strait is reproduced as Figure 1. The slope downward to the east centered near the 165-km abscissa represents northerly flow, and the slope at the right-hand boundary represents southerly flow. The location of this section is shown in Figure 8 between stations 16 and 23.

Figure 1 represents February, the coldest month of the year in the gulf. For comparison, a temperature section along a line in nearly the same location is reproduced for the warmest month, August, of the same year, see Figure 2. Figure 10 shows the location of this section between stations 28 and 37.

The 22° isotherm is darkened in Figures 1 and 2. It is apparent that the slopes of this particular isotherm in both the warmest and the coldest months are typical of the field of isotherms. The total range in depth of the 22° surface in these sections is nearly the same in summer and winter, being 195 meters in summer and 193 meters in winter. Further, its depth from summer to winter does not change notably. In summer in this example it ranged from 25 to 220 meters and in winter from 7 to 200 meters. It is interesting to see that the greatest depth differences in Figures 1 and 2 are in the southerly flow in winter and in the northerly flow in summer.

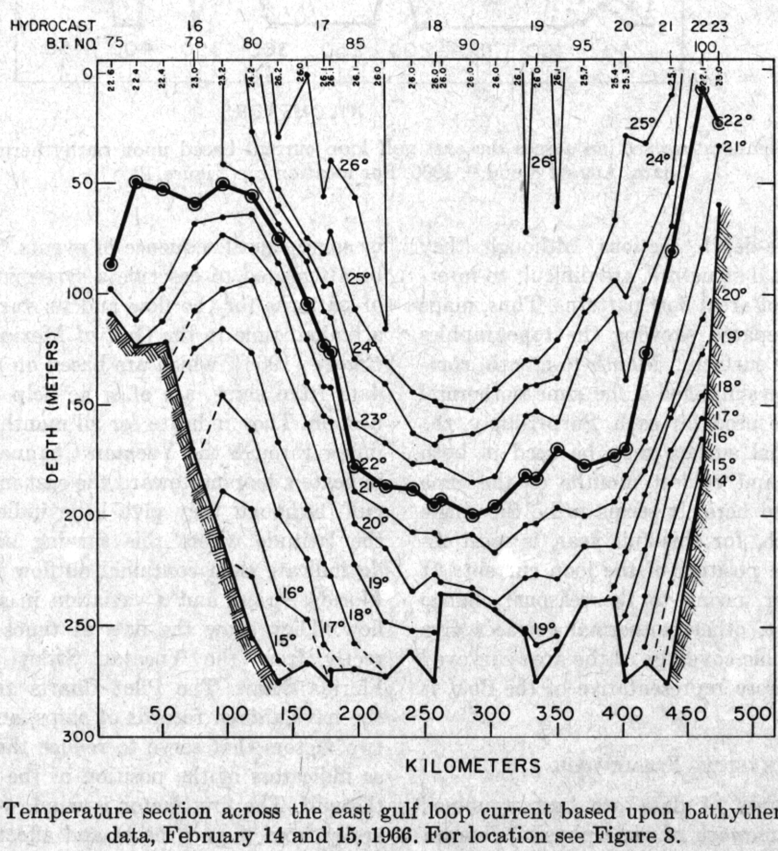


Fig. 1. Temperature section across the east gulf loop current based upon bathythermograph data, February 14 and 15, 1966. For location see Figure 8.

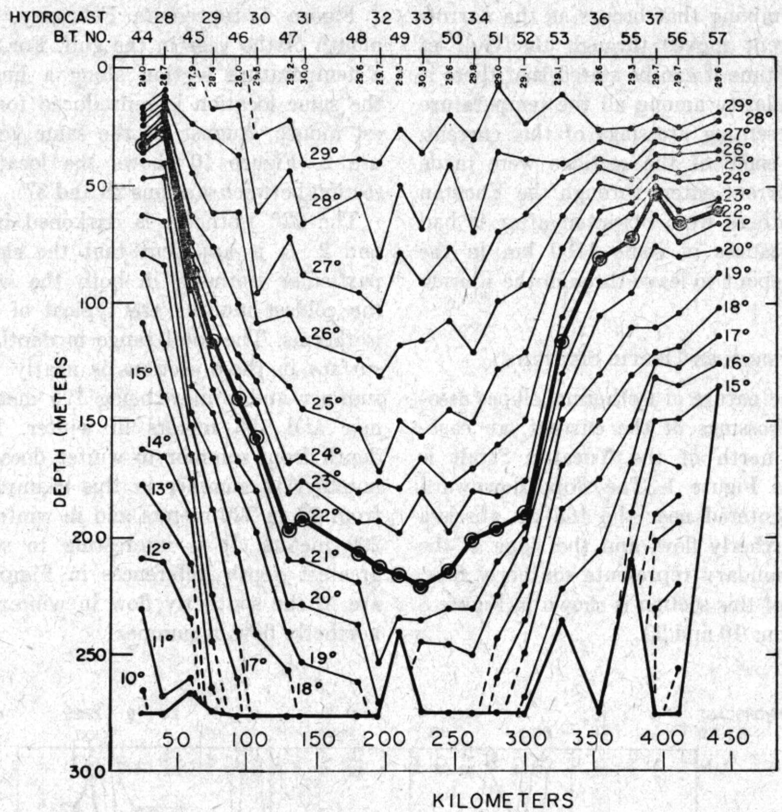


Fig. 2. Temperature section across the east gulf loop current based upon bathythermograph data, August 8 and 9, 1966. For location see Figure 10.

Temperature-depth sections, although they do show thermal structure, are difficult to interpret in terms of areal flow patterns. Thus, maps have been prepared showing the topographies of isothermal surfaces. Month-to-month comparisons can be simplified if the same isothermal surface can be used for each. Surprisingly, the 22°C isothermal surface may be used in both the warmest and coldest months of the time period involved here. It seems to be the single isotherm which, for this full year, is most indicative of the position of the loop current. At times, however, owing to the seasonal change of temperature, other isothermal surfaces give better geographic coverage of the area surveyed and may be more representative of the flow at that one time.

Physical Framework

Large amounts of data are best examined within the framework of some physical concept or some logical sequence of events. Thus, it will be attempted to describe a systematic sequence of patterns for the flow and its variations over a limited time in the Gulf of Mexico. The *Pilot Charts* [1966], which are based on navigational data from ships, are of some help in this connection. They indicate for all months the strong inflow through the Yucatan Channel. They also indicate a looping toward the east in the eastern gulf, although they give little indication as to the latitude where this turning occurs. They do indicate then continual outflow through the Florida Straits and a variation in speed of the flow. They show the flow at times coming directly from the Yucatan Strait toward the Florida Strait. The Pilot Charts are based on the navigational records of ships, and there are two factors that serve to reduce their accuracy as indicators of the position of the loop within the gulf. The first factor is wind, which is generally from the southeast and affects nearly all observations. Second, ships crossing the gulf are usually interested only in net drift between their point of origin and their final destination. Since the main features of the gulf are the loop current and isolated eddies, a crossing ship will be set first in one direction and then by an almost equal amount in the other direction, with the net drift being negligible. The navigational records may thus not always indicate major features of flow, and at times, because of wind drift, they may indicate flow where none existed.

Also useful in providing a foundation upon which to establish a preliminary sequence of flow patterns in the east gulf are the data collected from the *Atlantis* and the *Mabel Taylor* in the 1930's, the work of *Austin* [1955], and the oceanographic studies conducted by Cochrane, Collier, Duxbury, and Ichiye, as reported along with their own work, for example, by *Nowlin and McLellan* [1967]. The emphasis in these reports was on the loop current and its variability, although there was not sufficient time coverage to describe such variation completely or to determine the relationship of the loop current to other currents in the gulf. The cruises discussed in the present paper are less extensive in their coverage of the total gulf area and the full depths of the ocean than some of the above studies. The present cruises do, however, add toward time continuity and, since they were planned to define the features of the primary current system, they may be used to extend considerably the previous results, particularly as regards time changes.

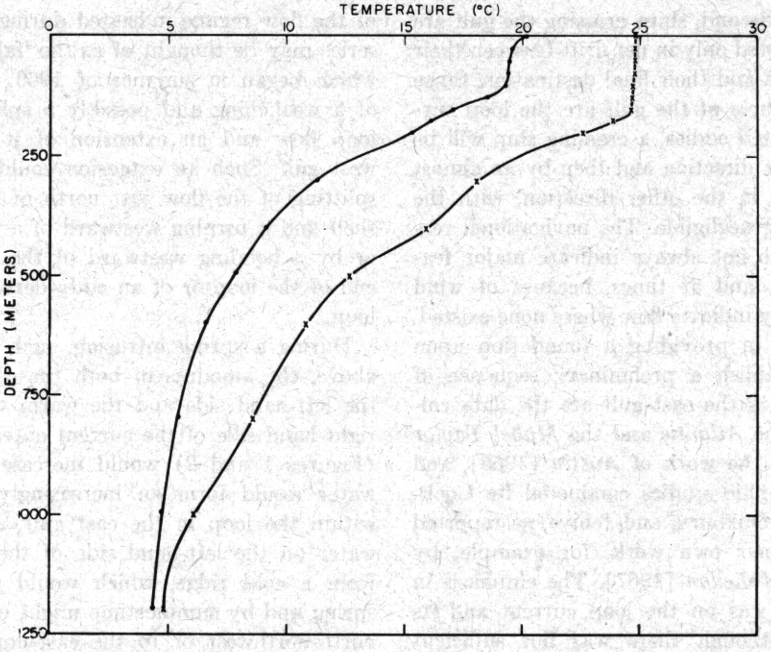
Cochrane [1965] has described an annual variation in the speed of the Yucatan inflow based on Pilot Chart data, GEK (geomagnetic electrokinetograph) observations, and the slopes of isotherms. He finds a maximum of nearly 67 km/day in May and June and a minimum of approximately 45 km/day in October and November. It appears, as will be discussed later (Figures 14 and 15), that the current regime in the gulf during 1965 and 1966 can be considered in two parts related to this variation in inflow speed. The first portion, which appeared to develop during the period of maximum flow, may be called the 'spring intrusion.' It consists of the formation of a small loop close to Cuba in winter 1965 and its continual growth and extension further into the gulf during spring and into summer. The second portion of the flow regime indicated during the present series may be thought of as the 'fall spreading,' which began in summer of 1966. It consisted of a weakening and possibly a splitting of the loop flow and an extension of it toward the west gulf. Such an extension could occur by a splitting of the flow just north of the Yucatan shelf and a turning westward of a portion of it or by a bending westward of the entire north end of the loop or of an eddy derived from the loop.

During a spring intrusion, such as described above, the amounts of both the cold water on the left-hand side and the warm water on the right-hand side of the current entering the gulf (Figures 1 and 2) would increase. The warm water would form an increasingly large mass within the loop in the east gulf, and the cold water on the left-hand side of the flow would form a cold ridge, which would grow in the spring and by summertime might extend to the north-northwest or to the east-northeast from Yucatan completely across the Gulf of Mexico. The cold ridge might serve to isolate the west gulf from the east gulf in early summer. It seemed to shift slightly westward and become broader by late summer in 1966.

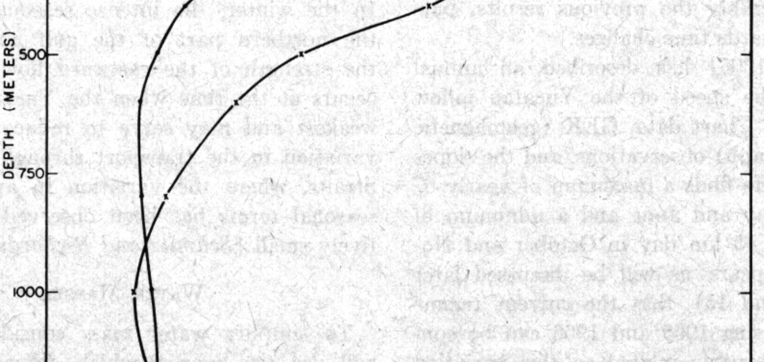
The simple sequence of flows described here indicates that the driving force for the circulation of the Gulf of Mexico, particularly in the spring, is the current entering through the Yucatan Strait. This has long been suspected. In the winter, the intense seasonal cooling in the northern part of the gulf contributes to the strength of the eastward flow there. This occurs at the time when the Yucatan inflow is weakest and may serve to reduce any annual variation in the transport through the Florida Straits, where the variation in aperiodic and seasonal terms has been observed to be relatively small [*Schmitz and Richardson*, 1968].

Water Masses

To simplify water mass considerations, we will use two masses which differ only above 17°C. One, called the 'eastern gulf loop water' by *Nowlin and McLellan* [1967], will be called the 'right-hand' water. It is the water on the right of the loop flow as one faces downstream. The other water mass will be 'left-hand' water, because it is the water found on the left of the stream. The transition zone is the region of

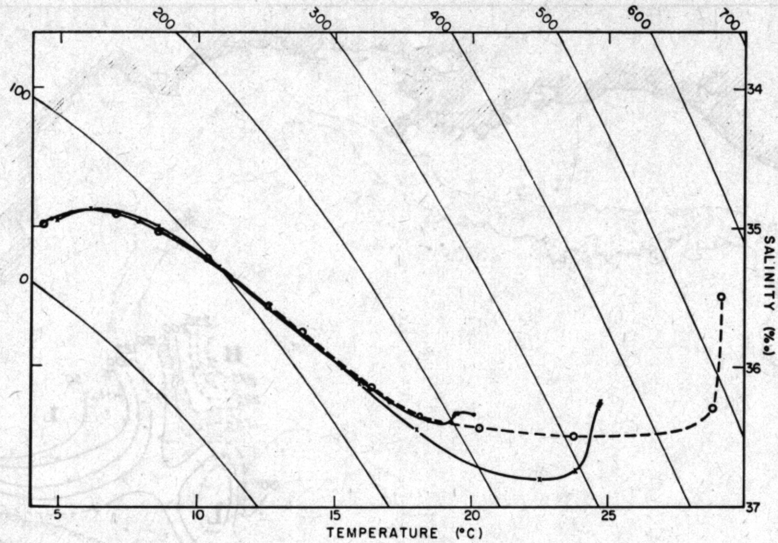


(a)



(b)

Fig. 3. Comparative characteristics of water on the right-hand and the left-hand side of an observer facing downstream in the east gulf loop current. The left-hand water is the colder, lower-salinity water. (*Top*) Temperature-depth; (*bottom*) salinity-depth; (*opposite*) temperature-salinity relationship.



(c)

flow. Figure 3 shows the temperature and salinity characteristics of these two water masses as illustrated by two stations from the February 1966 cruise (locations in Figure 8). Stations 32 and 39 represent right-hand and left-hand water, respectively.

Although the primary emphasis in this paper is on the use of data representing the upper 300 meters of the gulf, values in Figure 3 have been plotted to the full depths of observations made, in other words, to nearly 1200 meters. It is apparent, however, that the observations at shallow depths do illustrate striking features of the temperature and salinity structures and temperature-salinity relationships. For example, at 200 meters the temperature of the right-hand water is 7°C higher and the salinity 0.80‰ higher than that of the left-hand water. These higher values over a considerable depth range are characteristic of the right-hand water.

Major features of the temperature-salinity relationships are compared for right-hand and left-hand water in Figure 3*c*. As mentioned, the two are quite similar below 17°C. However, the depth of water represented by a given point on this portion of the *T-S* curve is considerably (150–300 meters in this example) less in the left-hand water than in the right. This difference is attributed to uplifting of the left-hand water as it passes across the relatively shallow Yucatan bank upon entering the gulf. At higher temperatures the right-hand waters have a characteristic S shape with a maximum salinity near 22°C and a minimum at the highest temperature. By contrast, the left-hand water deviates from the S curve toward a straight line at a salinity of less than 36.5‰. (Data from a summer station at the same location are used to extend this curve to higher temperatures than were present in February.) West gulf waters at temperatures between 17° and 24°C appear to be a mixture of these right- and left-hand masses [*Birchett*, 1967; *Leipper*, 1967].

1965–1966 Sequence of Current Patterns

With this background, attention will now be focused on what appears to be a related sequence of patterns of the major current in the east Gulf of Mexico, as illustrated by the series of eight cruises between July 1965 and October 1966. Gradients in the topography of the 22°C isothermal surface will be taken as indicative of the position of this strong current. To facilitate comparison of current positions on the different charts, the portion of the topography lying between 150 and 200 meters in depth will be shaded on all charts. At these depths the 22° isotherm seems to have remained in the current at all times of the year in the 1965–1966 period. On a crossing of the full normal current of the loop, the depth of this isotherm changes by more than 100 meters.

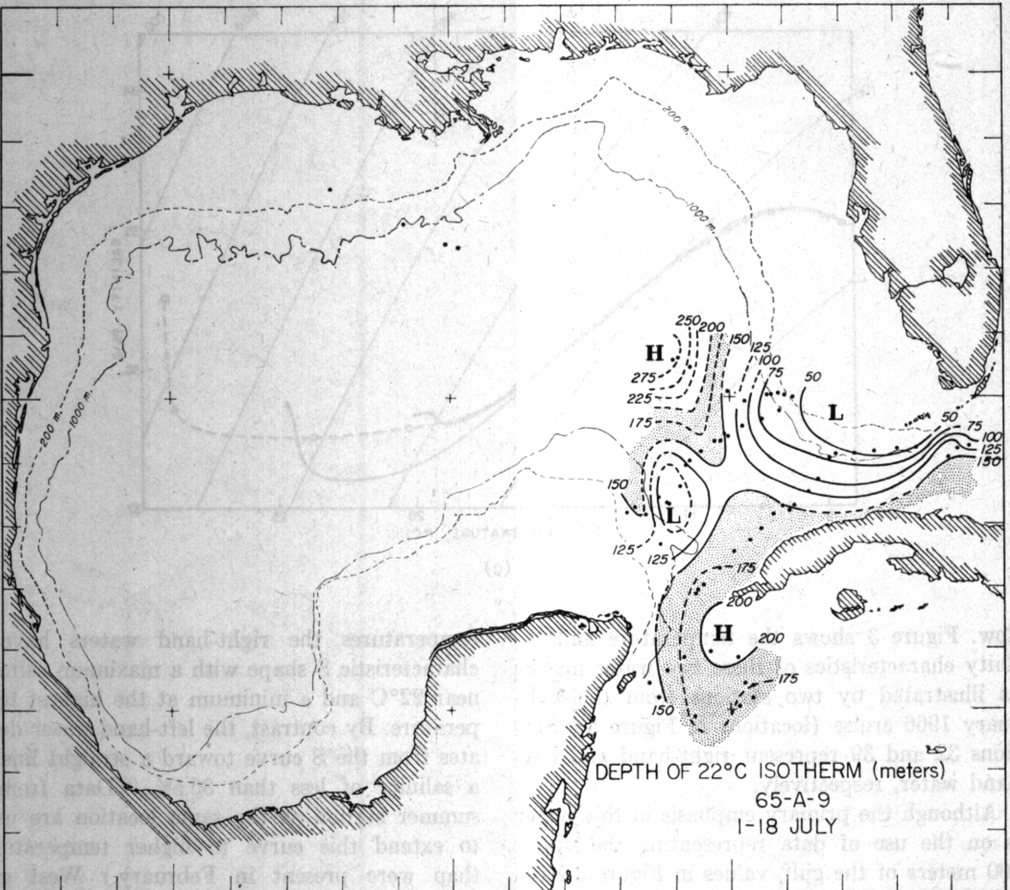


Fig. 4. Topography of the 22°C isothermal surface, July 1 to 18, 1965. (*Alaminos* cruise 65-A-9; chief scientist Pequegnat.) Dots indicate locations at which observations were made. Shaded area is location of current as indicated by the 150- to 200-meter gradient of the 22°C surface.

The individual cruises of the sequence to be discussed are presented in Figures 4 through 11. The positions of the 200- and 1000-meter bottom contours and the positions of temperature observations are indicated on the charts. It will be noted that, on most legs of the cruises, observations extended across the deep basin of the east gulf and that the charts do represent the regions of major transport there. Caution is required since it is believed that the highest current velocities occur at times in depths as shallow as 200 meters.

The first chart of the sequence, Figure 4, represents a cruise July 1–18, 1965, in which temperature observations were only incidental to other work. However, the 22° topography based on the limited temperature data obtained on this cruise does show, as will be better understood after other charts in the sequence have been examined, that the loop current does not extend as a strong entity into the gulf but its extension is limited by a neck formed at 24°N, where the 22° surface has risen to less than 150 meters. North of this position a clockwise eddy is indicated with the 22° surface sinking to more than 250 meters. Also, a weak flow to the east immediately along the coast of Cuba is indicated by the greater depth of the isothermal surface near the coast than offshore.

Figure 5 is drawn from two consecutive cruises. This chart shows clearly the separation of a major eddy from the Yucatan inflow and its associated loop. (The flow in such an eddy may be considered an 'exterior detached' flow, one which is probably decaying.) The 22° surface now has risen to less than 50 meters, forming a cold ridge between the eddy and the current near the Cuban coast. Other data such as navigational determinations of ship drift and GEK direct current measurements confirm this pattern of separation [*Cochrane*, 1966]. The current eastward near the coast of Cuba now appears to have intensified, as indicated by the closer spacing of contour lines and the greater total change in topography across the current. A broad cold ridge shown as a region of low indicated by L in the figure extends from Yucatan to Galveston. (Shallowest depths of the isothermal surface are always indicated on the charts by L and greatest by H. The flow would thus be counterclockwise around lows and clockwise around highs.) The cold ridge serves to separate the east from the west gulf. A high of 125 meters is indicated in the west gulf by the westernmost observations.

Figure 6 represents observations made only a few weeks after the time of the previous cruise in the same area. It is the situation existing immediately after the passage of Hurricane Betsy, which occurred between the two cruises. It does not cover the east gulf loop but only the area where the detached eddy was observed before the hurricane. It was a cruise planned specifically to study the effects of the hurricane and not to follow the loop current. An analysis of observations after Hurricane Hilda [*Leipper*,

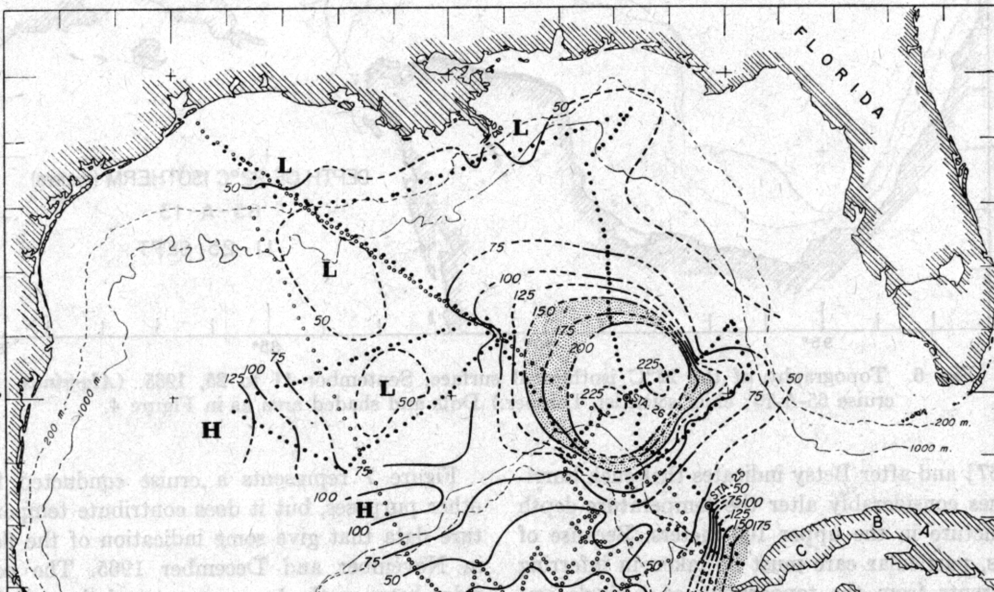


Fig. 5. Topography of the 22°C isothermal surface, August 10 to 24, 1965 and August 31 to September 8, 1965. (*Alaminos* cruises 65-A-11 and 65-A-12; chief scientists Leipper (black dots), Cochrane (open circles).) Dots and shaded area as in Figure 4.

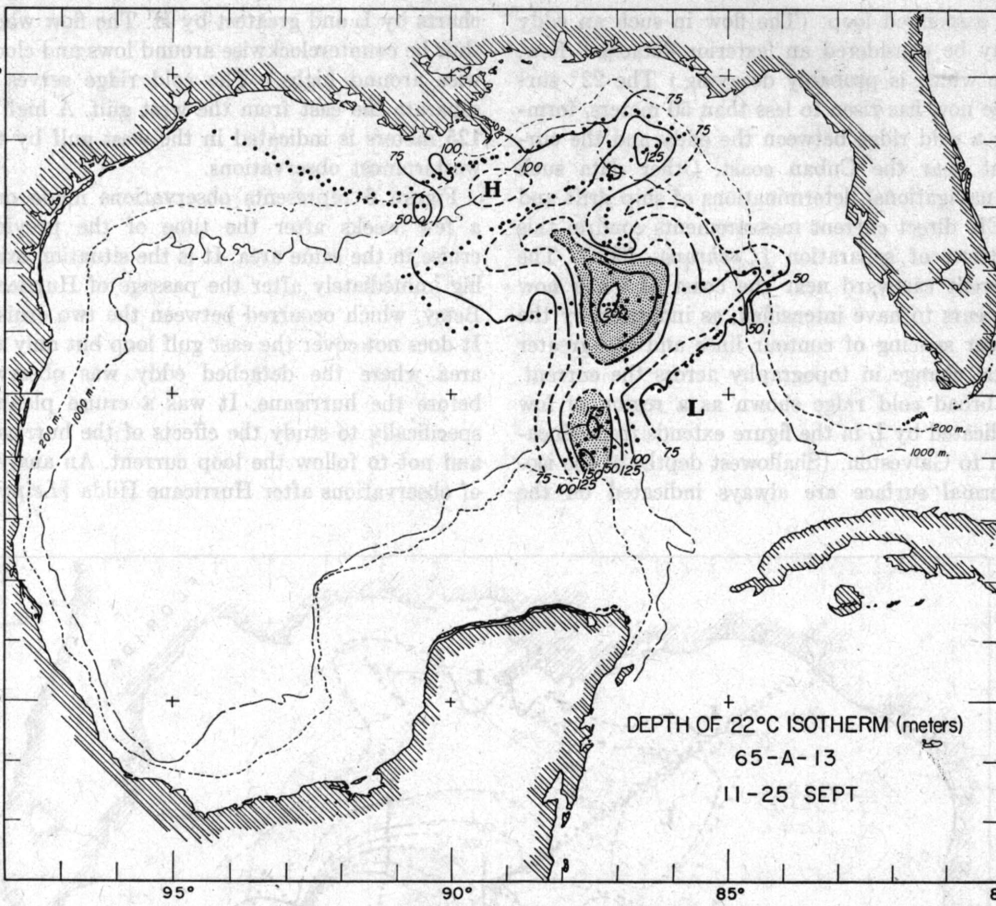


Fig. 6. Topography of the 22°C isothermal surface, September 11 to 25, 1965. (*Alaminos* cruise 65-A-13; chief scientist, Leipper.) Dots and shaded area as in Figure 4.

1967] and after Betsy indicates that such hurricanes considerably alter the temperature-depth structure in the upper 100 meters. Because of this, particular care must be taken in inferring currents from the topography of a single isothermal surface. However, comparison of the flow indicated in Figure 6 with flows at the surface, 100 and 300 meters, computed by the dynamic heights method referred to 1000 meters shows the pattern of Figure 6 to be truly indicative of the pattern of current. The indication of most interest in connection with the present study is that the strong isolated eddy of Figure 5 appears to have been considerably altered and possibly broken up. This change is not attributed to the effects of Hurricane Betsy because of the depth to which the change seems to have occurred.

Figure 7 represents a cruise conducted for other purposes, but it does contribute temperature data that give some indication of the flow in November and December 1965. The cold ridge between the loop current and the remains of the detached eddy appears at about 25.5°N and is still at a depth of some 50 meters. The Cuban Current indicated in August, Figure 5, now seems definitely to have left the coast and to be making a loop about 260 km north of the tip of Cuba. (This distance to the northern extent of the loop is taken to be the distance from the Yucatan Channel to the northernmost position of the 150-meter contour within the loop on the topographic chart. This custom will be used in making other measurements of the extent of the intrusion of the loop.) The northern eddy having a 175-meter maximum is prob-