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A Characterization of the Gulf of Mexico Waters in Winter [1]

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ABSTRACT

The results of a rapid survey of the Gulf of Mexico in the winter of 1962 are presented. Variations in the characteristics of the water in several core layers are described. Circulation has been examined on the basis of dynamic computations and G.E.K. measurements. In the eastern Gulf, water enters through Yucatan Strait and leaves through Florida Strait, flowing in an anticyclonic loop that extends well into the Gulf. In the western Gulf, circulation is anticyclonic around an elongated cell oriented NE–SW over the Gulf Basin. Sufficient similarities are seen in data obtained in other years to suggest that this pattern is typical of the circulation in winter. The complexity of the circulation pattern deduced from this survey is considerably less than that of patterns presented by others.

Introduction. During the winter of 1962, the R/V HIDALGO of Texas A and M University was engaged in a hydrographic survey to obtain data that might for the first time fully characterize the Gulf of Mexico waters during the winter. This cruise (62-H-3), which was executed as rapidly as the vessel's capability permitted—from 12 February through 31 March— systematically covered the entire Gulf of Mexico; Fig. 1 shows the stations numbered serially in the sequence of their occupation. At most stations the maximum sampling depth was near the bottom; Fig. 2 shows the general bathymetry of the Gulf.

This paper documents the findings that pertain to the waters above sill depth. The 1962 findings that pertain to the deep waters were presented earlier (McLellan and Nowlin 1963). The data in the present paper and the inferences therefrom are meant to be representative of conditions prevailing in the Gulf of Mexico during only February and March 1962 unless otherwise stated. This point is emphasized because of the temporal variability in
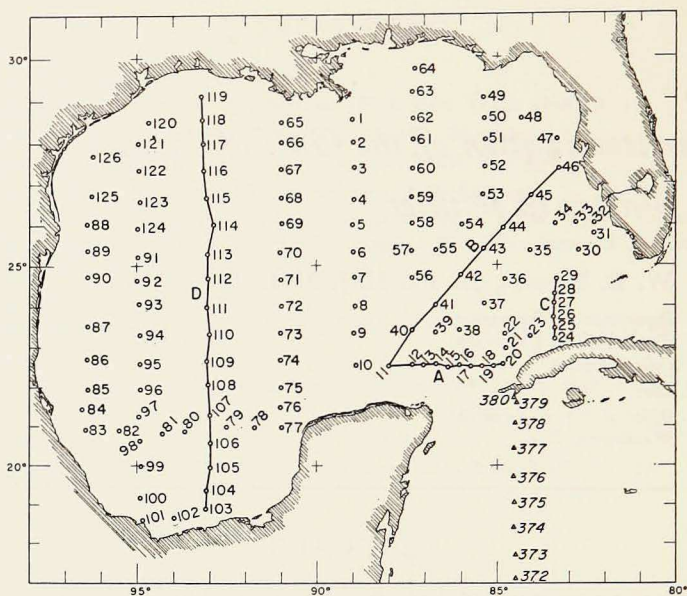
Figure 1. Stations occupied during HIDALGO 62-H-3, February-March 1962 (circles) and CRAW-FORD cruise 17, February-March 1958 (triangles). Lines indicate vertical sections discussed in text.
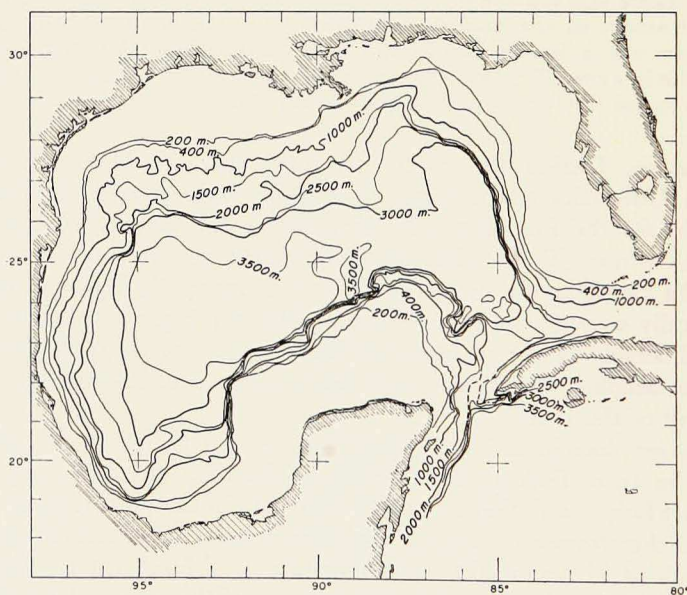

Figure 2. Bathymetry of Gulf of Mexico based on U.S. Coast and Geodetic Survey Chart 1007 and soundings on file at Department of Oceanography, Texas A & M University.
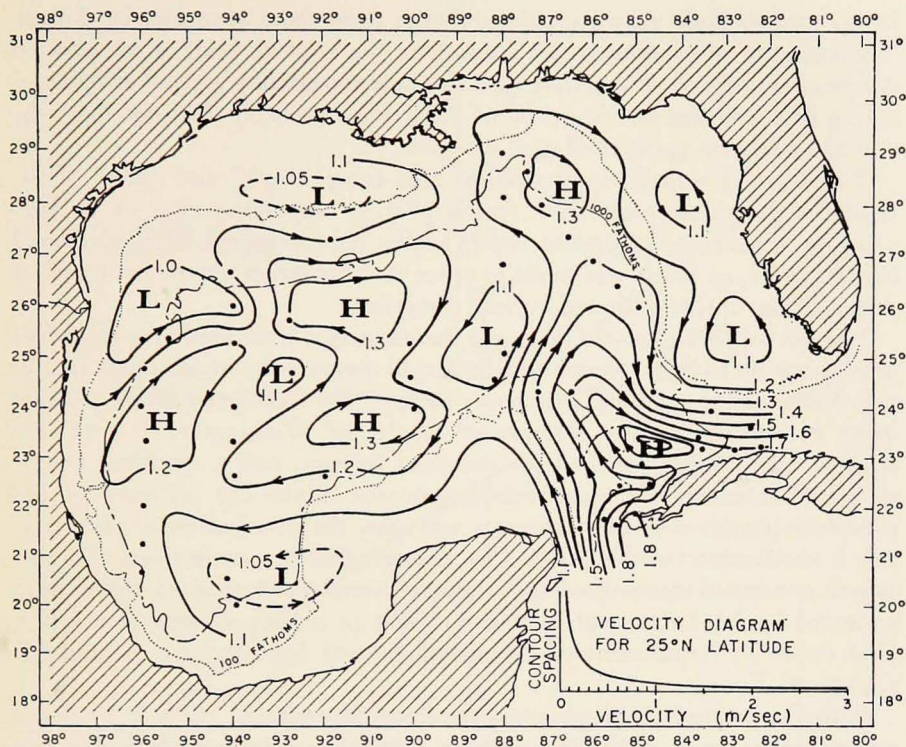
Figure 3. Dynamic topography of surface relative to 1000-db surface, ALASKA cruises 1-1 A, 2-1 B, and 3-1 C, 22 April–21 August 1951. After Austin 1955: fig. 2.

the strength and geographic distribution of circulation features in the Gulf shown by other studies, e.g., the work of Cochrane (1963, 1965) dealing with the Yucatan Current in and near the Yucatan Strait.

No sequence of serial observations covering the Gulf of Mexico has been made within a time period shorter than the duration of Cruise 62-H-3. The 124 hydrographic stations occupied during three cruises of the ALASKA between 22 April and 21 August 1951 constitute a sequence of observations that ranks second in most nearly approaching a synoptic survey of the entire Gulf. Combining data from these three cruises, Austin (1955) presented a pattern for the dynamic topography of the sea surface relative to the 1000-db surface (Fig. 3) and Collier et al. (1958) presented a similar pattern for the 500-db dynamic topography relative to 1000 db. These dynamic-height anomalies may be interpreted as indicating a very complicated circulation pattern within the central and western Gulf.

The averaged dynamic topographies presented by Duxbury (1962) are even more complicated, and, with the exception of the indicated loop current

in the eastern Gulf, they are quite different from those presented by Austin. The existence of semipermanent currents in the western Gulf of Mexico has not been established. We believe that dynamic topography arrived at by combining data collected over a period of many years probably does not show the typical circulation patterns of such a region.

The 62-H-3 cruise was planned so that every "high" and "low" of the Gulf circulation as inferred by Austin (Fig. 3) was intersected by at least one line of stations. In regions where earlier data indicated large horizontal current shear, an effort was made to space stations rather closely on transects perpendicular to the indicated current directions.

Nansen bottles and paired reversing thermometers were used at each hydrographic station to collect water samples and to measure the in situ temperatures and depths of the samples. The water samples were analyzed aboard ship by using a conductivity-type salinometer (Univ. of Washington, No. 12) for salinity, the Winkler method for dissolved oxygen, and a modified photoelectric colorimeter for phosphate-phosphorous. Since the accuracy of the phosphate-phosphorous measurements was low, the distribution of that variable is not discussed in this paper. The hydrographic data at observation depths as well as selected interpolated and computed variables at standard depths were presented by Mc Lellan and Nowlin in 1962 in an unpublished data report (Ref. 62-16 D, Department of Oceanography and Meteorology, A. and M. College of Texas).

Bathythermograms and geomagnetic electrokinetograph (G.E.K.) current measurements were made at one-hour intervals while underway between stations. The meteorological observations have also been presented in the data report cited above.

Characteristic T-S Relationship. Fig. 4 shows temperature versus salinity for all observations at temperatures lower than 17°C and for the near-surface layers at each of 17 stations in the regions of inflow and outflow. For the realm below 17°C (representing 849 data points) the plot shows a remarkable uniformity, indicating that the waters constitute essentially a single system. Comparison with historical data indicates no departures from this characteristic curve that could not be attributed to observational error.

If the data are examined on a regional basis, the interagreement between stations is even more remarkable. The salinity minima, which occur in the eastern Gulf at temperatures of approximately 6.3°C, are specific to the remnant of Subantarctic Intermediate Water. This feature appears to be eroded in the western Gulf to an extent that increases the minimum salinity some 0.02°/oo to 0.03°/oo and decreases the associated temperature some 0.1°C to 0.2°C. The width of the characteristic plot from 6°C to 13°C is occasioned by this mixing activity.

In Fig. 4 the characteristics of waters below 4.4°C are shown in an insert.
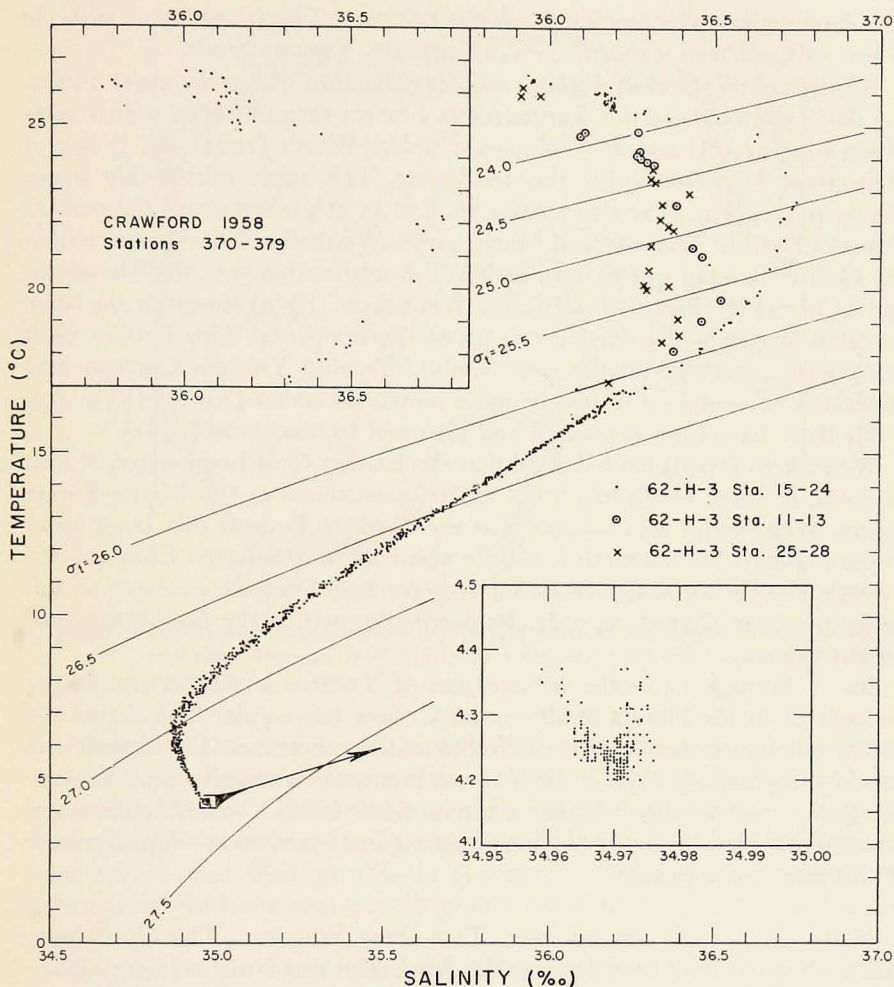
Figure 4. Temperature versus salinity, HIDALGO 62-H-3, for all observations with temperature less than 17°C and for the near-surface waters at 17 stations in the regions of inflow and out-flow. For temperatures greater than 17°C, T-S relations plotted for 10 CRAWFORD stations occupied in the Caribbean. See Fig. 1 for station locations.

The pressure effect leads to an increase in in situ temperature with depth below 2000 m, although potential temperature appears to decrease slowly to at least 3000 m (Mc Lellan and Nowlin 1963). Similarly, the salinity of the deep water was shown to increase slightly, though continuously, with depth.

The T-S curve from 4.5°C to 17°C is similar in form to that found in the Caribbean (Wüst 1964: fig. 3); but there, especially in the east, the salinity

minimum appears as a much more distinct feature. This is consistent with the inflow of Caribbean water to the Gulf through Yucatan Strait.

All stations off the shelf display a salinity maximum within the upper 200 m. For Sts. 15 through 24 this feature traces a rather smooth curve, with a maximum near 22.5°C and 36.75°/oo—not unlike Wüst's (1964: fig. 3) case of Subtropical Underwater for the Caribbean. This same relationship shows clearly (insert, Fig. 4) at CRAWFORD Sts. 370 to 379 taken across the western Cayman Basin in February and March 1958. We shall call the feature within the Gulf containing waters with such a T-S relationship (i.e., that shown for Sts. 15 to 24) the Eastern Gulf Loop. Wennekens (1959) has given the name Yucatan Water to that having this set of characteristics. This Eastern Gulf Loop water, bounded on the west by the inflowing Yucatan Current, may sometimes be contained in two or more individual eddies (Austin 1955: figs. 3–6); these have been delineated and discussed by Cochrane (1961).

Wennekens (1959) has indicated that the Eastern Gulf Loop water, at least at times, is found in Florida Strait as far downstream as the Miami-Bimini region. Wenneken's data indicate that the northern limit of this Loop water in the southern Florida Strait is usually about midway between Cuba and the western Florida Keys. On cruise 62-H-3 we found definite evidence of this water in section C at St. 24 only. Its distribution within the Gulf is discussed further below.

Sts. 11 through 13 in the western part of Yucatan section A and Sts. 25 through 28 in the Florida Strait section C show less regular T-S curves and display salinity maxima at lower salinities and temperatures. This feature was noted by Cochrane (1963) for the Yucatan Strait, and his suggestion (Cochrane 1965) that part of the Yucatan Current flows inside Cozumel Island and Arrowsmith Bank invites speculation that vigorous vertical mixing may occur in this part of the passage.

Water Masses and Stratification. THE DEEP WATERS. The Gulf waters below sill depth have been discussed by McLellan and Nowlin (1963). Comparing potential temperatures computed from the 62-H-3 data with those reported for the Cayman Basin, we have estimated the maximum controlling sill depth to be between 1650 and 1900 m. There were no discernible horizontal variations in either salinity or potential temperature, although small vertical gradients in these two parameters were observed to the bottom.

REMNANT OF SUBANTARCTIC INTERMEDIATE WATER. Wüst (1964) has reviewed his earlier (1936) findings concerning the distinctive water mass that is formed near the Polar Front in the South Atlantic (48° to 52°S). To this he gave the name Subantarctic Intermediate Water, although it is sometimes referred to in the literature as Antarctic Intermediate Water. The mechanism of formation is not well understood, but these waters sink and spread out northward. Wüst (1964: fig. 17) illustrated the paths of spreading
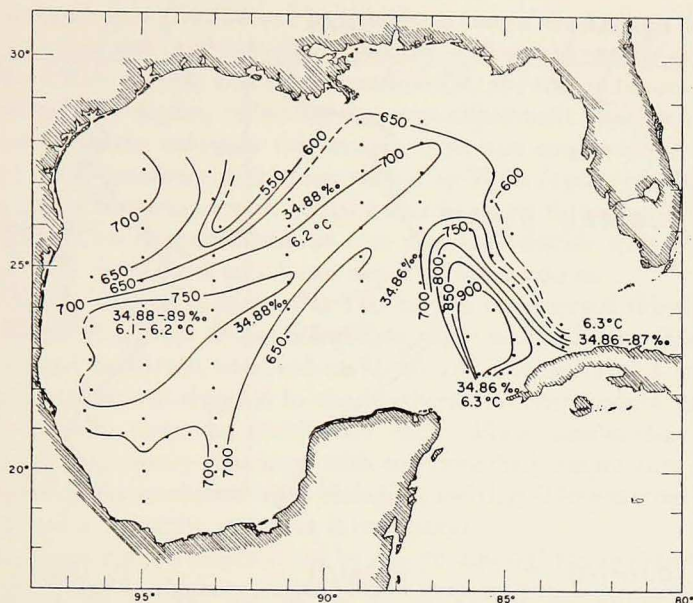
Figure 5. Depth (50-m intervals) of core layer in Subantarctic Intermediate Water remnant (salinity minimum), HIDALGO 62-H-3. Selected values of salinity and temperature at the core are shown.

and indicated a marked tongue extending northwestward along the northern coast of South America. This tongue enters the Caribbean through those passages of the Lesser Antilles that have sufficient sill depth and then spreads out in the Caribbean as shown by Wüst (plates XVI and XVII). Salinities in this core may be less than 34.7 °/oo in the eastern Caribbean, but mixing that accompanies the horizontal spreading raises the salinity to 34.85 °/oo at Yucatan Strait.

Fig. 5 shows the depth of the salinity minimum as observed in the Gulf; it also shows representative salinities and temperatures. Prior to contouring, the depths at each station were selected from smoothed curves of observed salinity versus depth. From the following discussion of currents it will be recognized that the depths are related to the circulation, being greater than 900 m in the center of the Eastern Gulf Loop and close to 500 m in the northern central Gulf.

On the basis of minimum salinity, Wüst (1964) has constructed a table for estimating the percentage composition of the Subantarctic component in the core. This would indicate that at Yucatan (34.86 °/oo) there is already less than 5 °/o and in the western Gulf (34.88–34.89 °/oo) only some 1 °/o or 2 °/o. For this reason Wüst has, in personal discussion, rightly questioned the labeling of this water as Subantarctic Intermediate Water. In our opinion the origin
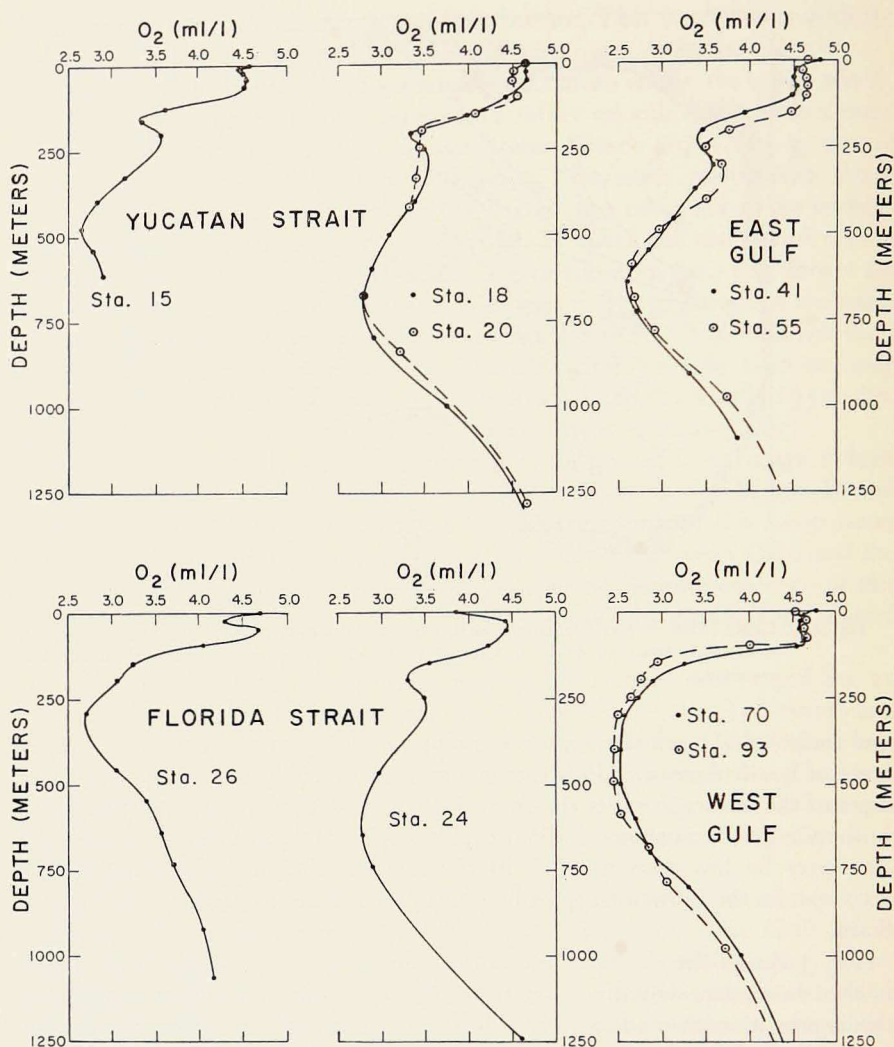
Figure 6. Dissolved-oxygen concentration versus depth at selected stations on HIDALGO 62-H-3.

of this distinctive feature in the Gulf is clear, and we choose to label it a remnant of this well-defined water mass.

DISSOLVED OXYGEN DISTRIBUTION. Fig. 6 shows typical oxygen-depth curves for depths from the surface to 1250 m. Surface values were found to be generally at or near saturation for the particular temperature and salinity. The most persistent feature is a continuous layer of minimum dissolved-oxygen content. This shows up at depths of about 700 m on the right-hand side of the

main Yucatan inflow (Sts. 18 and 20), in the center of the Eastern Gulf Loop (Sts. 41 and 55), and in the southerly portion of the outflow (St. 24). To the left of the inflow (St. 15) and of the outflow (St. 26) the minimum occurs at considerably lesser depths, reflecting the mass adjustment associated with the circulation. Extreme values in this oxygen-minimum core were in the range 2.5 to 2.7 ml/l, consistent with those shown by Wüst (1964: plate XV), and they are clearly continuous with the core that he traces through the Caribbean (plate XIX). This oxygen-minimum core does not coincide with the salinity-minimum core but occurs at a lesser depth of some 200 m.

A secondary oxygen minimum at 150 to 300 m, observed throughout the Eastern Gulf Loop, was almost completely suppressed at St. 26. The shallow maximum and minimum observed at St. 26 are illustrative of a number of such regional features observed in the northern and northeastern part of the survey, especially over the continental shelf. These near-surface maxima, which are not necessarily associated with corresponding temperature or salinity extrema, are likely associated with biological activity. They are not presently explained and are worthy of future investigation.

In the western Gulf (represented by Sts. 70 and 93) the oxygen-minimum layer is considerably thicker, and the lower extreme values (typically 2.4 ml/l or less) indicate a considerable residence time for this water.

The oxygen content in vertical profile along section D (approximately 93°W) is shown in Fig. 7. The maximum vertical gradient of dissolved oxygen occurs between depths of 75 m and 150 m across the section, corresponding to the top of the thermocline (Fig. 15). The depth variations in the oxygen-minimum layer appear to be related to the circulation, and below this the configuration of oxygen isopleths generally conforms to the isotherms and isosteres (see Figs. 15 and 18). The very low value observed in the minimum layer at St. 105 (1.67 ml/l) suggests the possibility of a permanent eddy in Campeche Bay.

Below 1200 m there are very distinct regional variations in the dissolved oxygen (McLellan and Nowlin 1963). Nowlin (unpublished data), when repeating the stations occupied along 93° and 95°W (excepting 109, 112, 119, 120, and 121) in the winter of 1964, obtained data that confirm an apparent structure in the deep water and the reported inverse relationship between oxygen and phosphate-phosphorous. No explanation has been tendered to date that can be uniquely confirmed with existing data. The observations in 1962 and 1964 show regions of high and low oxygen in roughly the same locations, yet they show local changes that are larger than those that can be attributed to measurement uncertainty. The implication is that the deep waters are not completely stationary.

TROPICAL SALINITY MAXIMUM. Another distinct layer in the water structure of the Gulf, which shows up as a subsurface salinity maximum, has been referred to above. Wüst (1964) has traced this layer through the Caribbean
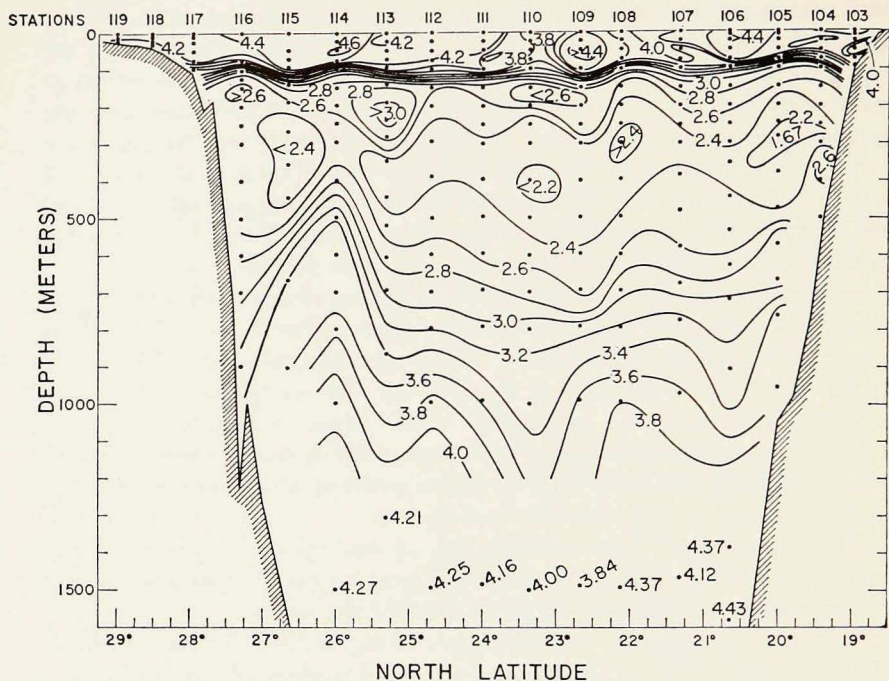
Figure 7. Dissolved-oxygen concentration along vertical section D, 22–27 March 1962, HIDALGO 62-H-3. Upper 1250 m at interval of 0.2 ml/l. Observation positions indicated by dots. Vertical exaggeration 555:1.

and has given it the name Subtropical Underwater. According to Wüst, it originates at the surface-salinity maxima in the North and South Atlantic (cf. Defant 1961: plate 5), where their maximum surface expression is found at 20° to 25°N, 30° to 50°W and approximately 15°S, 30°W; westward these maxima spread out as intermediate layers. Although the core of the South Atlantic component extends along the northern coast of South America, Cochrane's (1965) presentation of data from the EQUACHEQUE Expedition makes it clear that the maximum salinities encountered offshore from northern Brazil are already too low for the South Atlantic to be considered a source for the Subtropical Underwater in the Caribbean. We may point then to the tropical North Atlantic as the source region for this layer in the Caribbean and the Gulf of Mexico.

Salinity values at the subsurface maxima are shown in Fig. 8a. The maximum salinity in this layer, about 36.75°/oo, is confined to the Eastern Gulf Loop and is in agreement with Wüst (1964: plate XIII). In the western part of the Yucatan Current, the salinity appears to be decreased by vertical mixing, as discussed above. As a consequence, the salinity maxima throughout most of
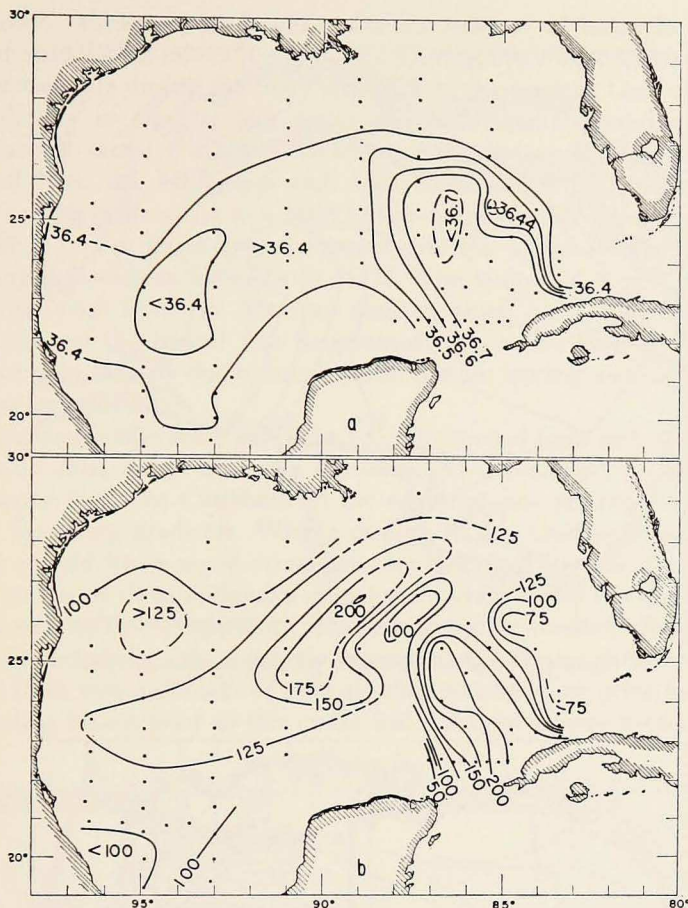
Figure 8. Core of salinity maximum, HIDALGO 62-H-3: (a) salinity (0.1°/oo intervals); (b) depth (25-m intervals). Locations of maxima indicated by dots.

the Gulf are lower than those in the Eastern Gulf Loop. As shown in Fig. 8b, the average depth of this layer is about 150 m, which is in general agreement with the depths at which the layer is found in the Caribbean.

THE SURFACE LAYERS. The observed surface salinities are depicted in Fig. 9; surface salinities taken underway were used to augment station data in constructing this figure. In the Yucatan area and the Eastern Gulf Loop, the values 35.9°/oo to 36.2°/oo are typical of the Caribbean during the winter.

Franceschini (1961) studied the hydrologic balance of the Gulf of Mexico for the year October 1958 through September 1959, using meteorological observations from stations around the region as well as observed river discharge rates. He showed the Gulf to be an area where evaporation generally exceeds
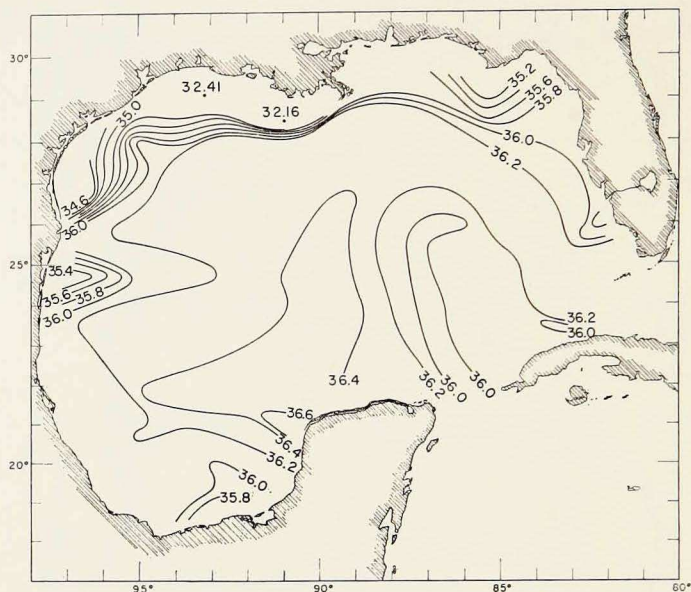
Figure 9. Surface salinities (parts per mil), HIDALGO 62-H-3.
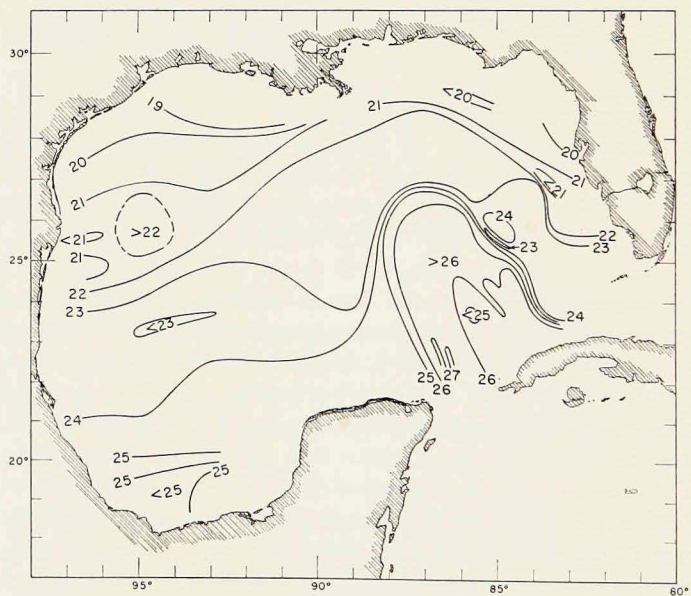

Figure 10. Surface temperatures (degrees Celsius), HIDALGO 62-H-3.

precipitation. However, he found a distinct seasonal variation in computed values of evaporation minus precipitation. During the winter season of 1958–1959, particularly during February and March, the western Gulf experienced a net addition of fresh surface water. In summertime, therefore, salinities considerably in excess of those shown here are expected, and have been observed.

Runoff from the Mississippi and Atchafalaya and from smaller rivers to the east and west gives rise to a band of low-salinity water along the northern shore. Most of this water flows westward over the Texas Shelf and shows its freshening influence as far south as 26°N. The tongue of fresher water protruding eastward from the Mexican coast at about 25°N may have been a continuation of the coastal flow augmented by the Rio Grande River or it may have been entirely due to local runoff. Station spacing was inadequate for a positive interpretation.

The surface-temperature field (Fig. 10), constructed from bathythermograph and station data, shows mainly a latitudinal variation, with an intrusion of warm water from the Caribbean in the southeast, the periphery of which is marked by strong gradients. Winter cooling in the Gulf generally proceeds stepwise as cold fronts move across the central United States and out over the Gulf, but few of these outbreaks extend completely across the Gulf. Some of the apparent surface-temperature structure is due to weather changes during the survey period, e.g., the southerly extension of isotherms in the west, which resulted from two outbreaks of cold air that occurred just prior to sampling. The cooling season prior to this cruise had not been severe; a comparison of
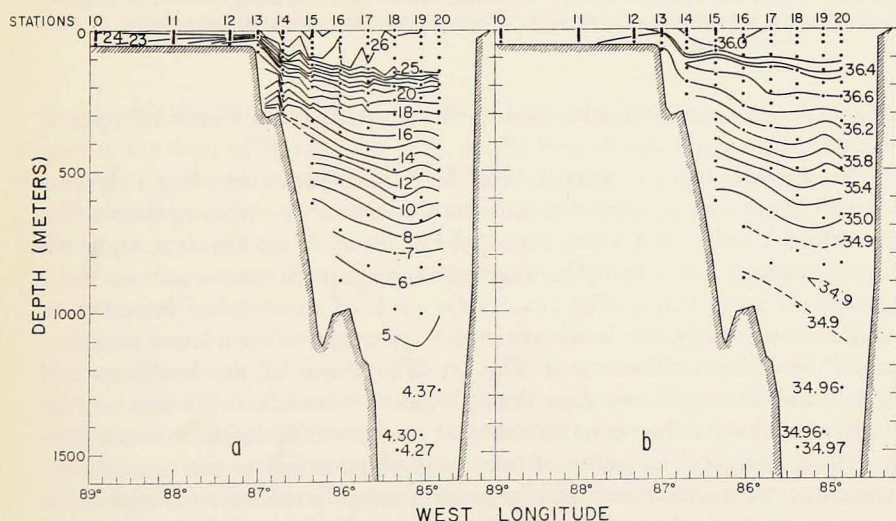

Figure 11. (a) Temperature (degrees Celsius) and (b) salinity (parts per mil) along section A, HIDALGO 62-H-3, 16–18 February 1962. Sampling positions indicated by dots. Vertical exaggeration 340:1.
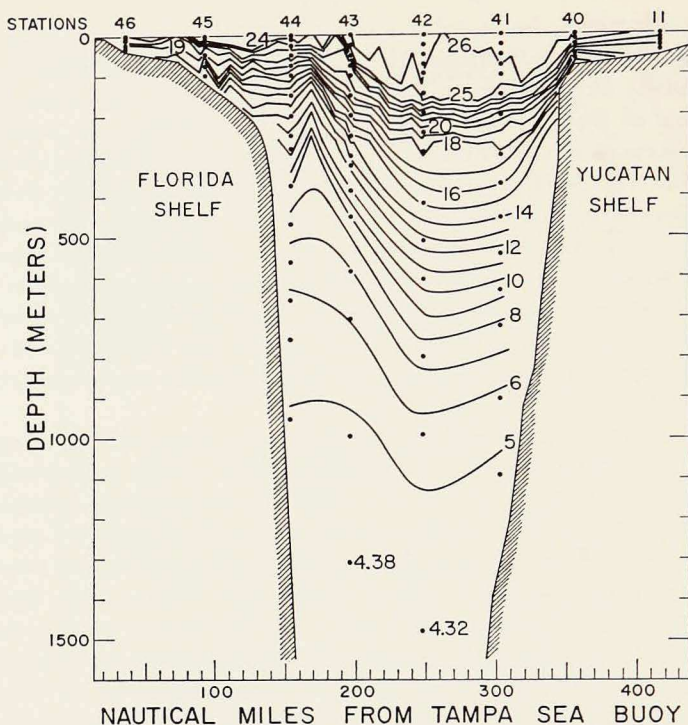
Figure 12. Temperature (degrees Celsius), section B, HIDALGO 62-H-3. St. 11 occupied 16 February 1962; Sts. 40 through 46, 25–27 February 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

the 1962 temperature data with those collected during the winter of 1964 is presented below.

TEMPERATURE AND SALINITY IN THE VERTICAL SECTIONS. Fig. 11 shows the temperature and salinity distributions in section A—the east-west line just north of Yucatan Strait (see Fig. 1). In addition to station data, temperature observations from bathythermograph lowerings between stations have been used in constructing Fig. 11a, as for each of the vertical temperature sections. Consequently, the isotherms in the upper 275 m show more structure than do the isolines elsewhere in Fig. 11. The slopes of the isotherms and isohalines indicate northward flow through most of the section; in the western part some northward flow is indicated to at least 1000 m depth or to the bottom. (Here, as in the discussion of vertical sections to follow, we use the distributions of temperature and salinity to infer roughly the currents within the upper 1000 m, with the tacit implication that such flow is relative to an assumed reference level at greater depth.) Southward flow is suggested between Sts. 18 and 19. The thermal structure indicates that there is a marked intensi-
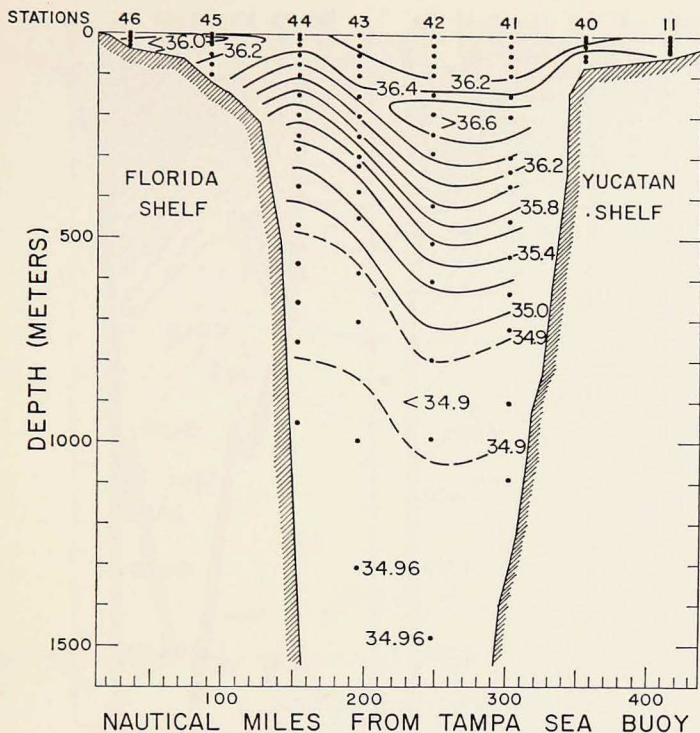
Figure 13. Salinity (parts per mil), section B, Hɪᴅᴀʟɢᴏ 62-H-3. St. 11 occupied 16 February; Sts. 40 through 46, 25–27 February 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

fication of the Yucatan Current along its westward flank, with a maximum just to the west of St. 14. East of St. 14 the flow slackens and again increases to another maximum near St. 15. Cochrane (1963, 1965) has shown this sort of banded structure to be a consistent feature of the Yucatan Current. Note that, as a consequence of the current structure, waters over the shallow Yucatan Shelf are of considerably lower temperature and higher salinity than elsewhere at comparable depths.

Figs. 12 and 13 show, respectively, temperature and salinity distributions in section B—from the western Florida Shelf to the Yucatan Shelf. The subsurface salinity minimum at shallow depths over the Florida Shelf is a feature observed in much of this region. The configuration of isolines shows the two crossings of the major current loop. Bathythermograph data, again used in Fig. 12, give evidence of a strong flow, with a northwestward component just northeast of St. 40 and a strong southeastward flow in the region of St. 43. Thermal data indicate a region of strong horizontal shear between Sts. 43 and 44, as do the G.E.K. current measurements presented below.
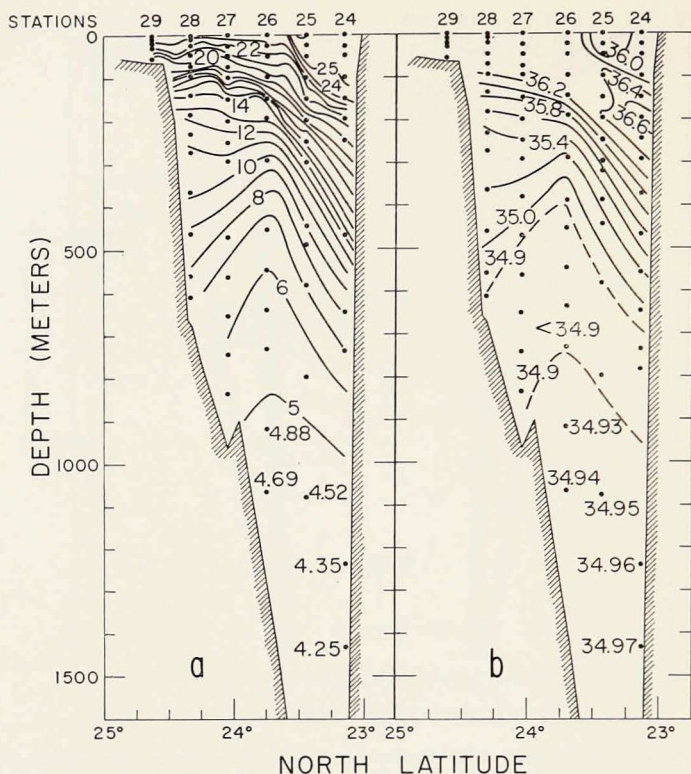
Figure 14. (a) Temperature (degrees Celsius) and (b) salinity (parts per mil), section C, Hidalgo 62-H-3, 19–20 February 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

Temperature and salinity for section C are shown in Fig. 14. The slopes of isolines indicate a strong eastward surface current close to the southern end of the section and some eastward flow reaching to at least 1000-m depth. The flow appears to be reversed (based on the slope of isolines in the deeper waters) in the northern half of the section.

Figs. 15 and 16 show temperature and salinity in section D (93°W). In this section the tropical salinity maximum is only a weak feature. The striking feature of the salinity distribution in the near-surface layers is the occurrence of low-salinity waters, resulting from continental drainage, over the inshore portions of the shelves at each end of the section. The finer-scale temperature structure in the upper layers suggests that the flow between the northern shelf and 26°N may not be a simple current structure, although a generally westward flow appears to exist to a considerable depth between Sts. 114 and 116. Between Sts. 114 and 112 there is indication of a strong eastward flow based on the configurations of isotherms and isohalines below the thermocline.
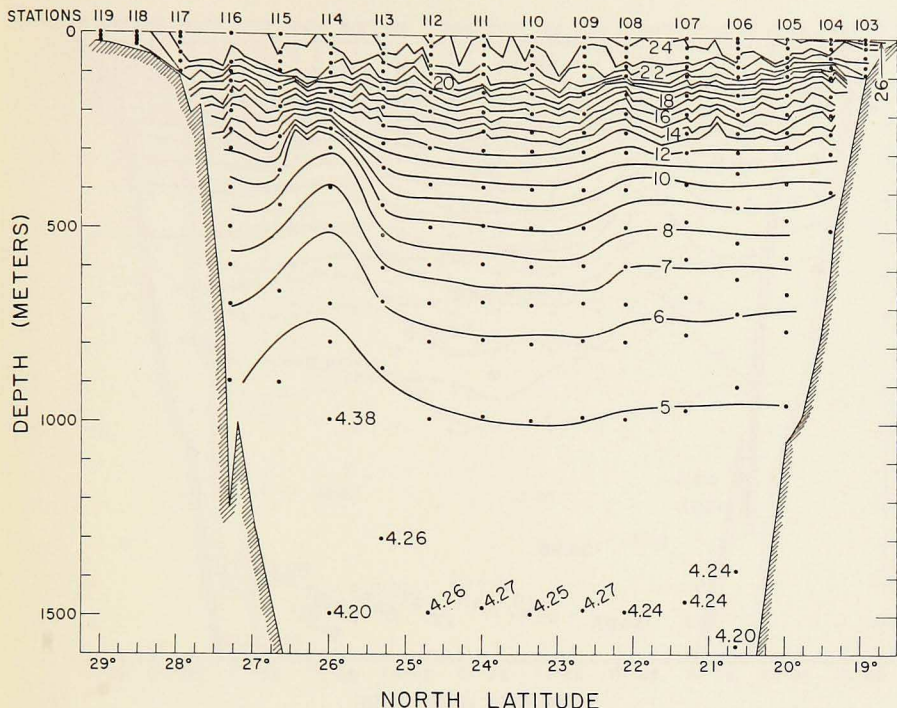
Figure 15. Temperature (degrees Celsius), section D, HIDALGO 62-H-3, 22–27 March 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

The temperature pattern in Fig. 15 may be compared with that in Fig. 17, which was taken along approximately the same longitude in late January and February 1964. The most striking difference is in the extent of development of the mixed surface layer. The thermocline lay almost 100 m deeper in 1964 than in 1962, and the waters above it were cooler and more uniform.

Again in 1964 there was evidence (24° to 25°N) of an eastward flow extending to a considerable depth south of the Texas Shelf. However, the current seems to have been centered some 60 nautical miles (110 km) farther south in 1964 than in 1962. A westward flow near 22°N is indicated for both years. Although these features were less well developed in 1964 than in 1962, and although the eastward flow near 25°N was not in the same location during both years, it is tempting to suggest that there is a regularity in the circulation pattern of the western Gulf.

Density (σ_t) for section D is shown in Fig. 18. The features discussed in connection with the temperature and salinity fields are apparent. In the thermocline the maximum stability was typically $1.5-2 \times 10^{-5} m^{-1}$, with an extreme value of about $3.5 \times 10^{-5} m^{-1}$ at St. 105. Below the thermocline, stability
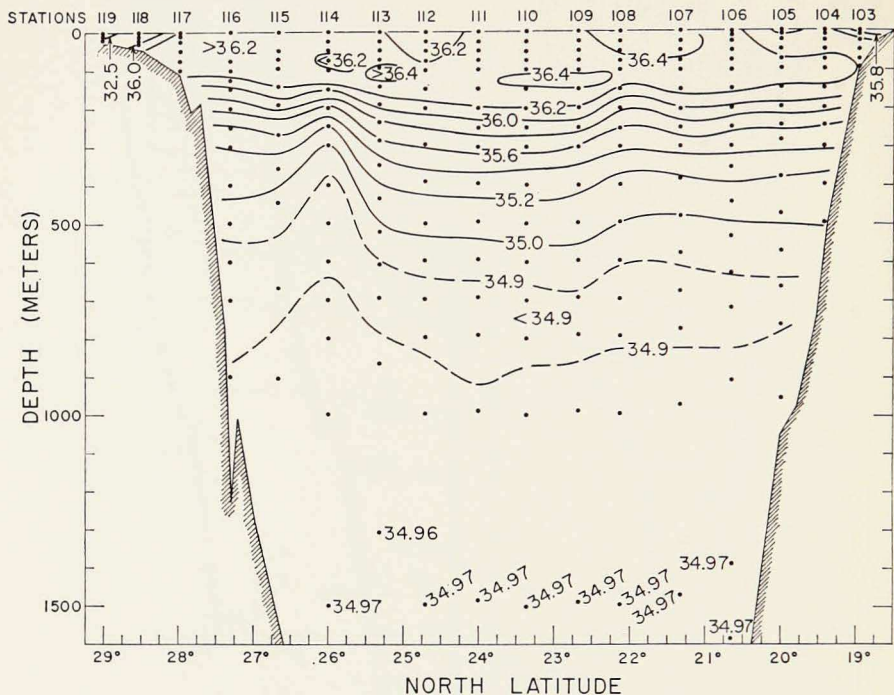
Figure 16. Salinity (parts per mil), section D, HIDALGO 62-H-3, 22–27 March 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

decreased monotonically with increasing depth, having values of about 10^{-6}m^{-1} at 500 m and 5×10^{-8}m^{-1} at 1000 m. Below sill depth the stability has been shown (McLellan and Nowlin 1963) to decrease even further to average values of 1.3×10^{-8}m^{-1} at 2000 m, 8×10^{-9}m^{-1} at 2500 m, and 2×10^{-9}m^{-1} at 3000 m. These lowest values may already be less than the uncertainty introduced into stability computations by the uncertainties in values of the thermodynamic coefficients, and they may only indicate slight positive to neutral stability in the basin waters.

LOW-SALINITY WATERS OVER THE TEXAS-LOUISIANA SHELF. Fig. 19 shows the salinity distributions in north-south vertical sections over the outer shelf of the northwestern Gulf. Waters of salinity less than $35\,^{\circ}/_{\circ\circ}$ were observed as far west of the Mississippi River as St. 126. Apparently such water, formed by the mixing of river discharge and near-shore waters, is confined to a band along shore some 40 to 60 nautical miles (75 to 110 km) wide. Lower salinities were observed at the near-shore locations closest to the Mississippi, which points to this river as the chief source and indicates a general westward
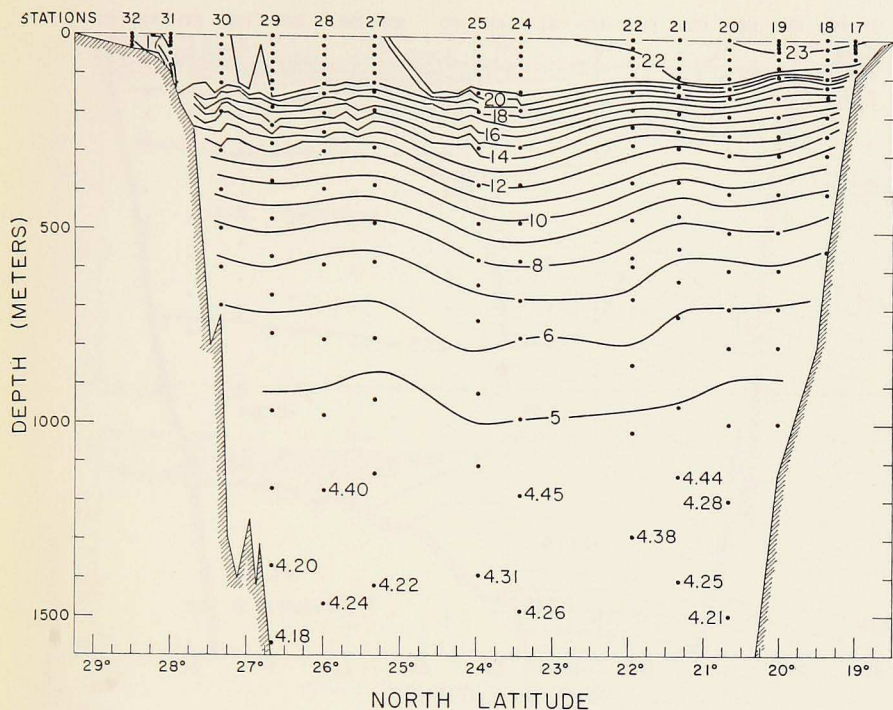
Figure 17. Temperature (degrees Celsius) along 93°W (approximately section D), Sts. 17 through 21, 24–25 January 1964, ALAMINOS 64-A-2; Sts. 22 through 32, 27 February–2 March 1964, ALAMINOS 64-A-3. Sampling positions indicated by dots. Vertical exaggeration 555:1.

spreading. The configurations of isohalines over the outer Texas Shelf, reflected in the density distribution (Fig. 18), indicate a strong westward flow associated with this low-salinity water.

A similar situation was observed in January 1966 (Nowlin, unpublished data taken on ALAMINOS cruise 66-A-1), when a band some 30 nautical miles (55 km) in width containing salinities of less than 35°/oo lay along the coast from Southwest Pass on the Mississippi Delta to at least 95°20′W (the western limit of the survey). During this latter survey the coastal waters (at the 12-m isobath) had salinities of approximately 30°/oo over this region, with the exception of the immediate vicinity of Southwest Pass, where salinities approaching 22°/oo were observed.

In sharp contrast, the January and February 1964 data taken along 93° and 95°W on ALAMINOS cruises 64-A-2 and 64-A-3 show no surface salinities lower than 36.5°/oo beyond the closest station to the shore (35 nautical miles; 65 km).
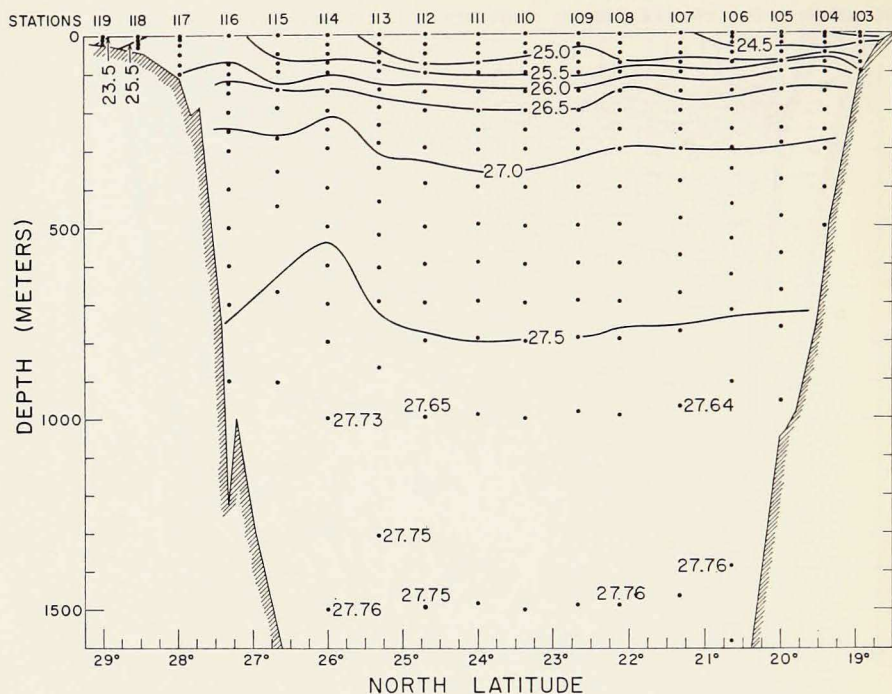
Figure 18. σ_t along section D, HIDALGO 62-H-3, 22–27 March 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

Currents and Transports. GROSS FEATURES. Circulation patterns at the time of the 1962 cruise may be inferred from G.E.K. surface-current measurements and from observed distributions of physical properties. In order to draw inferences about the current and transport regimes, we have tacitly assumed geostrophic flow and relied on dynamic calculations, even though there may be strong arguments against applying such an assumption to a confined region such as the Gulf.

The dynamic topography of the sea surface relative to the 1000-db surface (Fig. 20) pictures the current that bounds the Eastern Gulf Loop as the main feature of the surface circulation. In contrast to the findings of Austin (1955), only one major eddy is shown. This may have been a result of station spacing, or else the Cuban Eddy, a semipermanent feature centered 60 to 80 nautical miles (110 to 150 km) north of the western tip of Cuba (Cochrane 1961), may have been the only major eddy present. The other principal feature shown in Fig. 20 is the elongated cell oriented northeast-southwest over the central and western Gulf. We assume that this feature is closed westward, but we chose not to show the closure in Fig. 20. That these two anticyclonic circula-
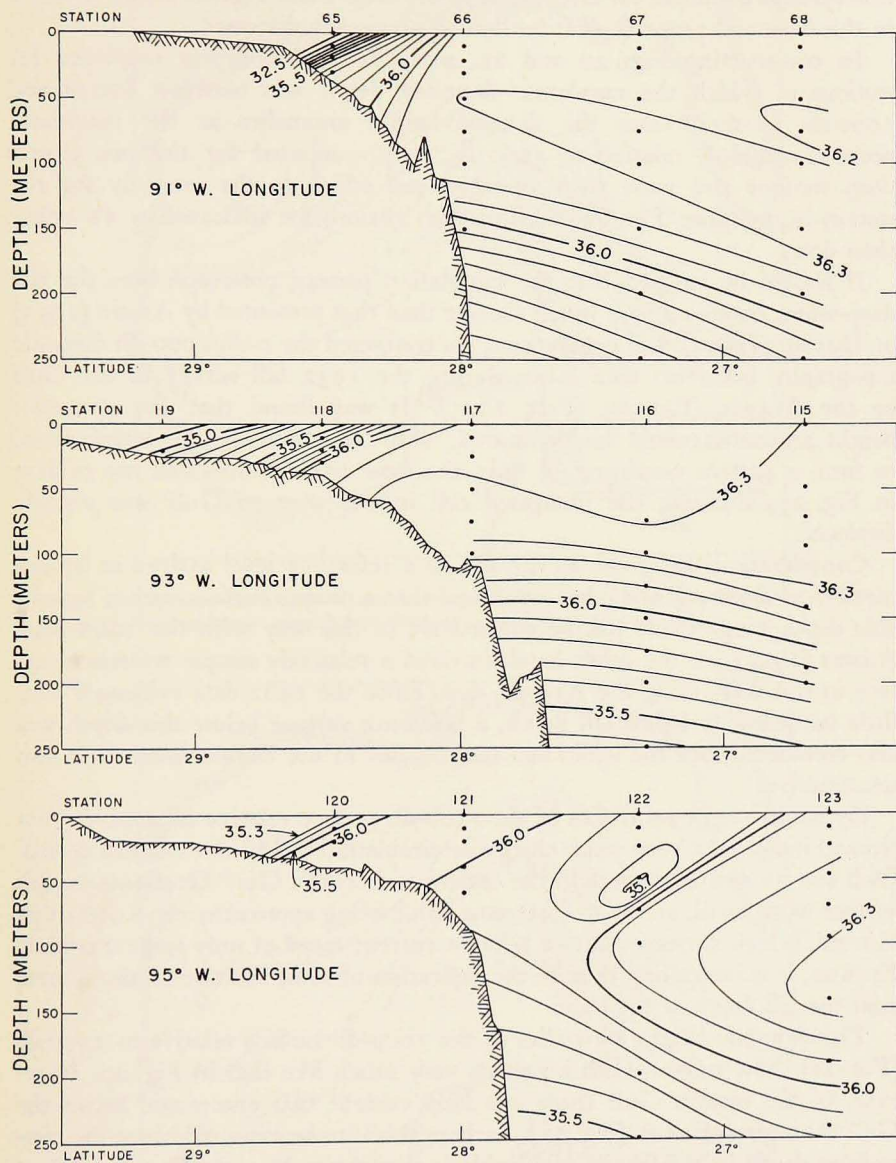
Figure 19. Vertical sections of salinity (parts per mil) over outer Texas Shelf, HIDALGO 62-H-3. Data from section along 91°W collected 7–8 March 1962; data along 93° and 95°W collected 26–30 March 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.

tion systems dominate the circulation in the deep-water regions is also reflected in the mass and property distributions as previously discussed.

In constructing Figs. 20 and 22, some extrapolation was employed for stations at which the maximum sampling depth was between 800 m and 1000 m. In these cases the dynamic-height anomalies at the maximum pressure sampled, relative to 1000 db, were computed for the two closest deep stations and were then averaged and added to the anomaly for the station in question. The locations of such stations are indicated by x's rather than dots.

It should be stressed that the circulation pattern presented here for the deep-water regions is very much simpler than that presented by Austin (1955) or Duxbury (1961). For comparison, we computed the 0-db/1000-db dynamic topography based on data taken during the 1932 fall survey of the Gulf by the Mabel Taylor (Parr 1935). It was found that the dynamic-height anomalies could be contoured, with no strain of the imagination, to form a pattern consisting of only the same two features that are evident in Fig. 20, although the elongated cell in the western Gulf was slightly displaced.

Consideration was given to the use of a reference level arrived at by the method of Defant (1961), but we found that a unique surface with a reasonable depth range could not be constructed in this way with the 1962 data. Adams (1954), on the other hand, inferred a relatively simple reference surface in this way, using the Alaska data. Since the 1962 data evidenced very little baroclinicity below sill depth, a reference surface below this depth was also considered, but the additional stations lost in the computation made this unattractive.

Dynamic-height anomalies of the 1500-db surface relative to 2000 db (not shown) indicated a very weak clockwise circulation cell in the western central Gulf and no distinct pattern in the eastern and central Gulf. Gradients on this surface were small, an isolated extreme value being approximately 0.0002 dyn m/n mi, which corresponds to a relative current speed of only some 2 cm/sec. Even so, it is interesting to note the indication of some relative motion at and near the sill depth of the basin.

The dynamic-height anomalies of the 1000-db surface relative to 1500 db (Fig. 21) show motion with a pattern very much like that in Fig. 20. However, in the eastern Gulf there is a loop current that enters and leaves the Gulf through section A (Fig. 21). Perhaps this is to be expected, since the controlling depth in the Straits of Florida is thought to be some 800 m (Defant 1961). This pattern may be partially closed in the Yucatan Strait south of section A. Relative speeds indicated in Fig. 21 are mostly less than 10 cm/sec. The 1000-db surface may then be taken as a reference for computing geostrophic current speeds in the upper layers of the Gulf without introducing errors of much more than 10 cm/sec.
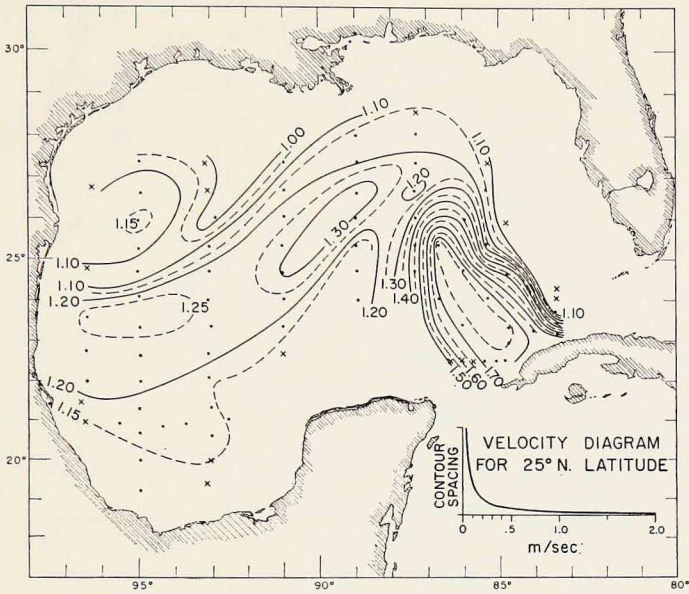
Figure 20. Dynamic topography of surface relative to the 1000-db surface, HIDALGO 62-H-3; x's indicate some extrapolation. Contour interval, 0.05 dynamic meters.
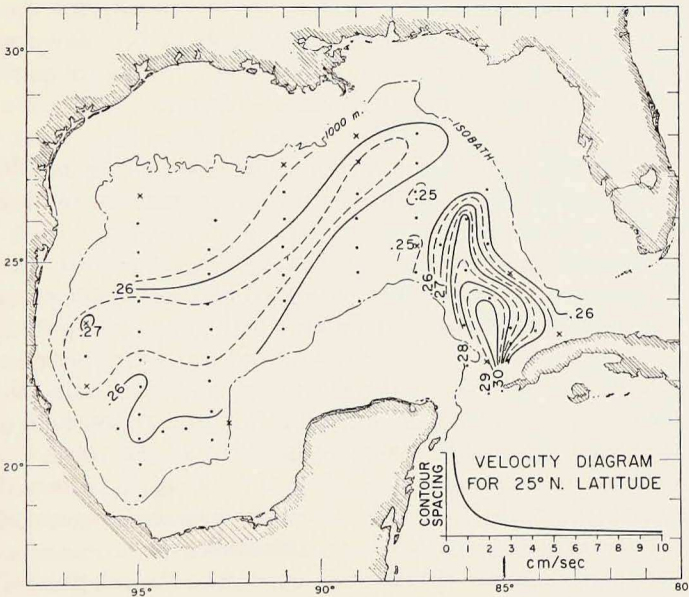

Figure 21. Dynamic topography of the 1000-db surface relative to the 1500-db surface, HIDALGO 62-H-3. Contour interval, 0.005 dynamic meters.
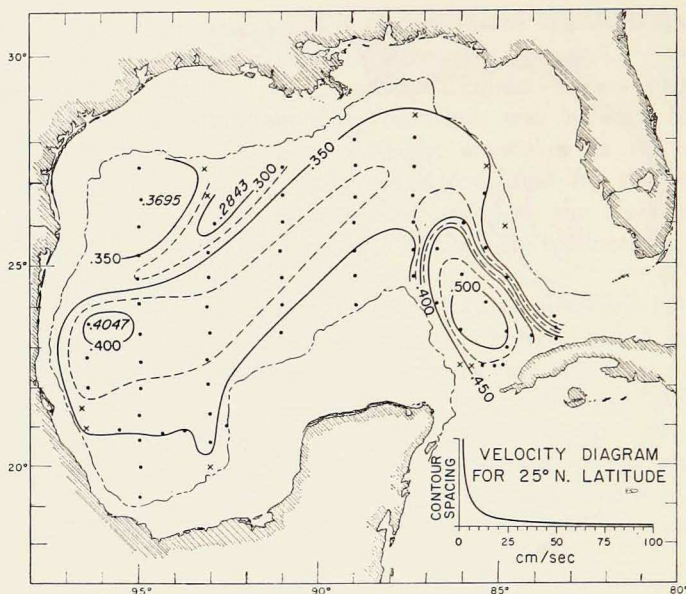
Figure 22. Dynamic topography of the 500-db surface relative to the 1000-db surface, HIDALGO 62-H-3; x's indicate some extrapolation. Contour interval, 0.025 dynamic meters.

Fig. 22 presents the contours of dynamic-height anomaly for the 500-db surface relative to 1000 db. There was considerable motion down to 500 m and the circulation patterns at the sea surface and at 500 db were quite similar.

Figure 23 shows surface currents as inferred from a G.E.K. No corrections other than those for magnetic-field intensity have been made to these values. Unfortunately no G.E.K. data were obtained along 89°W, which seems to be a region of transition between the flow regimes of the eastern and western Gulf.

The G.E.K. measurements are in general agreement with the major features of the computed surface-current pattern. The cores of the currents that bound the Eastern Gulf Loop are clearly seen in Fig. 23. Along the northern boundary of the anticyclonic ridge in the western central Gulf, the core of the northeastward flow is seen, as are the shear zone to its north and the southwestward flow along the outer shelf. The G.E.K. observations show no strong currents along the position of the southern boundary of this ridge, which may be a broad diffuse flow as indicated in Figs. 20 and 22. Many smaller-scale features appear in the G.E.K. data, but these are presumably averaged out or are otherwise not seen in the dynamic topographies.

The geostrophic transport field for the upper 1000 m relative to 1000 db is presented in Fig. 24. For each station, from 1000 m to the surface, the dynamic-height anomaly relative to 1000 db was vertically integrated with
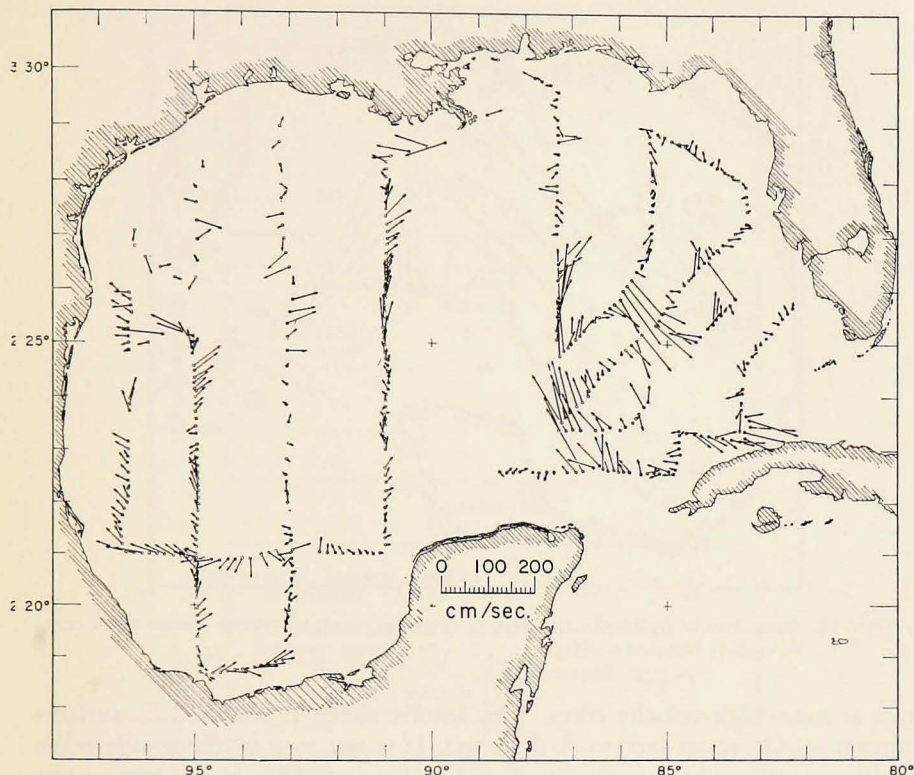
Figure 23. G. E. K. surface-current observations, HIDALGO 62-H-3.

respect to elevation to obtain the transport potential. Before contouring this scalar field, the minimum value was subtracted from every value and the residual at each station was divided by the value of the Coriolis parameter at 24° latitude. Of course, the field is very similar in appearance to the dynamic topography presented in Fig. 20.

For further discussion, the Gulf of Mexico is divided into eastern and western subregions.

EASTERN GULF. The Yucatan Current, which bounds the Eastern Gulf Loop on the west, appears to turn clockwise in the eastern central Gulf and then issue into the Straits of Florida, where it is known as the Florida Current. We refer to this current in the turn-around region as the Loop Current. The geographical extent of the Eastern Gulf Loop water seems well defined by dynamic computations, by salinity values at the salinity maxima, and by the characteristic T-S relationship of all stations on the Cuban side of the main current.

Cochrane (1963) presented G.E.K. data that indicate that the Yucatan Current in the region of the Yucatan Strait is kinematically banded, showing
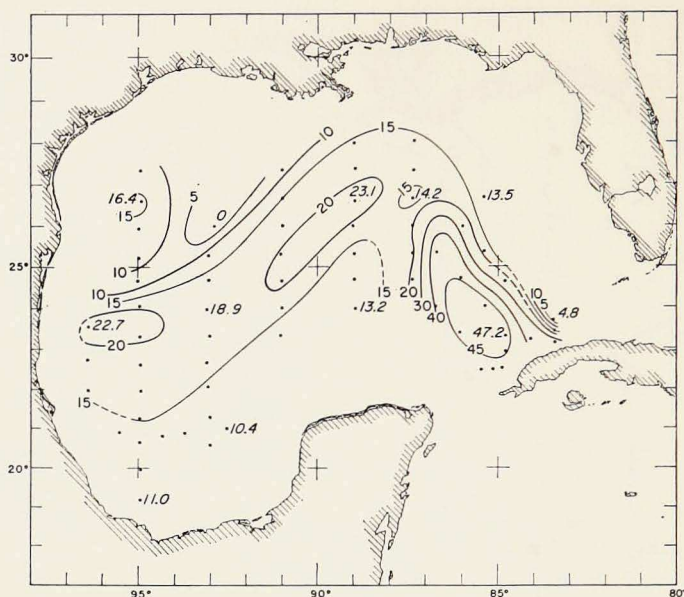
Figure 24. Streamlines of geostrophic transport, in $10^6 \text{m}^3/\text{sec}$, in upper 1000 db relative to the 1000-db surface, Hidalgo 62-H-3.

two or more high-velocity cores. This feature shows in the G.E.K. surface-current profile across section A (Fig. 25). It is not seen in the profile taken along 23°22′N, which is also presented in Fig. 25. This is not inconsistent with the results of Cochrane, which show a weakening of this intercore shear zone in the downstream direction. Surface-velocity components in the direction 330° are shown, since this was judged to be the orientation of the current axis during the period of observation. This banding is also evident in the temperature profile (Fig. 11a) along section A. Referring to the G.E.K. surface velocities for section A in Fig. 23, it it seen that in the Yucatan Current between the two apparent high-velocity cores there is a considerable component of velocity directed toward the Yucatan Shelf.

The waters at the positions of the two cores in the current are different. At St. 13 and in the high-velocity core just west of St. 14, water of the type that characterizes the eastern Yucatan Shelf (Fig. 4) was found. At St. 15, within the secondary current core, the waters showed the salinity maximum and smooth T-S relationship characteristic of the waters within the Eastern Gulf Loop.

At section A, the main core, with axial velocity components of approximately 150 cm/sec, was situated approximately over the 300-m isobath (Fig. 25). Cochrane (1965) found a sharp core situated approximately over the 200-m isobath when the surface currents were the strongest (average maximum
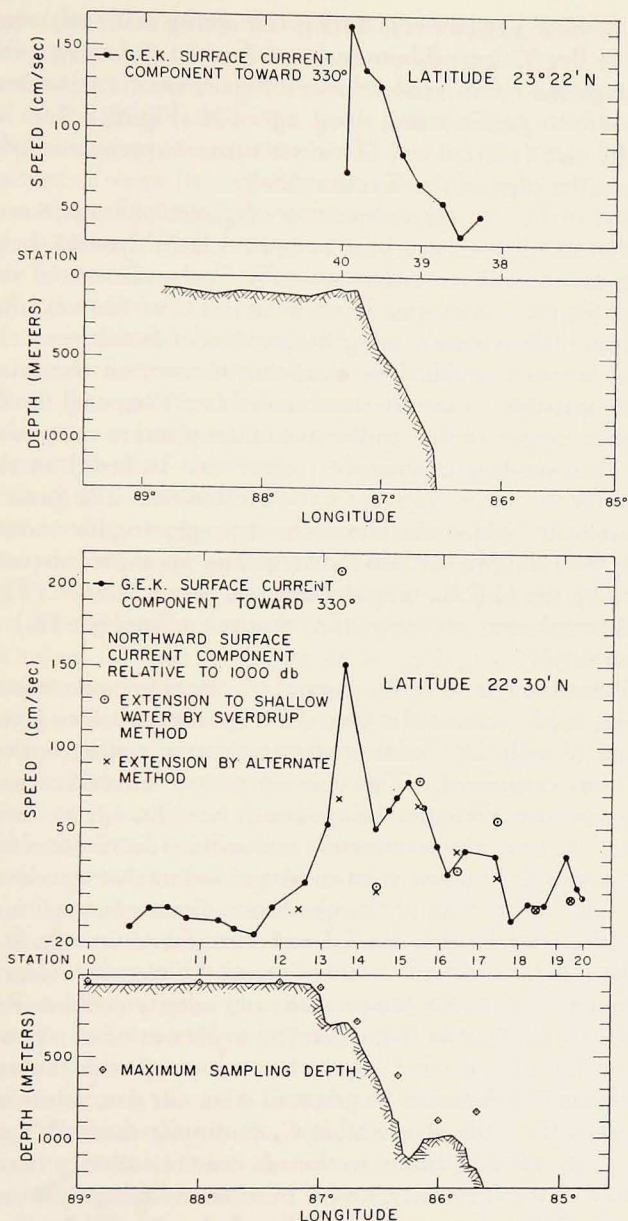
Figure 25. Two upper panels: G. E. K. surface-current components toward 330° and depth profile along a section at 23°22′N. Two lower panels: depth profile and surface currents along section A (22°30′N). Shown are: G. E. K. surface-current components toward 330° and geostrophic surface current normal to section A; the maximum sampling depths for hydrographic data on which geostrophic computations were based. All data from both sections collected during HIDALGO 62-H-3. For positions of stations, see Fig. 1.

velocity component of 177 cm/sec), during late spring and early summer. A more diffuse core lies farther offshore in late fall when the current reaches its minimum (average maximum axial-velocity component of 127 cm/sec).

In the downstream profile taken along 23°22'N (Fig. 25) there was only one high-velocity core (160 cm/sec). This was situated approximately over the 100-m isobath at the edge of the Yucatan Shelf.

Also presented in Fig. 25 are components of geostrophic surface velocities normal to section A. These have been computed from dynamic-height anomalies relative to 1000 db for adjacent station pairs. Since the maximum sampling depths for stations west of St. 18 were less than 1000 m, the section was extended into shallow water, using the method of Sverdrup et al. (1942: 451). A simpler alternate method of extending the section was tried and is presented for comparison. In the alternate analysis we computed the dynamic-height anomaly of the sea surface to the maximum pressure sampled. To this we added the dynamic-height anomaly (relative to 1000 db) at that same pressure surface for the deeper adjacent station to the east. The banded nature of the surface-velocity field is also shown in these geostrophic computations.

Downstream from the two sections shown in Fig. 25, the maximum current speeds indicated by the G.E.K. ranged from 100 to 200 cm/sec. The largest values were observed approximately 160 nautical miles (300 km) north of section A, near St. 56.

At section C, eastward between Sts. 24 and 26, the volume transport relative to 1000 db (Fig. 24) is $30.0 \times 10^6 \mathrm{m^3/sec}$. (The transport values given in the text were computed with the Coriolis parameter corresponding to the average latitude of stations considered.) This flow is greatly intensified southward, with maximum surface velocities being found near St. 25, as seen in the G.E.K. observations or in the temperature and salinity distribution for section C (Fig. 14). Much of the outflow must consist of waters that are characteristic of the interior Gulf rather than of the Caribbean, since waters with a salinity maximum typical of the Eastern Gulf Loop were found at only St. 24.

In the northern part of section C some flow to the west is evidenced in the G.E.K. observations and in the temperature and salinity profiles. Relative to 500 db, the westward inflow in the upper 500 m between Sts. 26 and 28 was just over one million $\mathrm{m^3/sec}$—not large when compared with the outflow.

No good estimate of inflow can be prepared from our data across section A. However, based on the outflow at section C, continuity demands that the net inflow in the upper 1000 m across section A must be some $30 \times 10^6 \mathrm{m^3/sec}$. The gross inflow in the Yucatan Current must be even larger, since, relative to 1000 m, somewhat over one million $\mathrm{m^3/sec}$ is transported southward over section A between Sts. 18 and 20. Most of this southward transport takes place at depths greater than 500 m.

Apparently about $10 \times 10^6 \mathrm{m^3/sec}$ of this inflow branches westward from the Yucatan Current in the region of the northern Yucatan Shelf. The transport

in the upper 1000 m of the Loop Current is approximately $24 \times 10^6 \mathrm{m}^3/\mathrm{sec}$ between Sts. 55 and 57. Along the northeastern boundary of the Eastern Gulf Loop the transport in the Loop Current increases in a downstream direction as additional waters from outside the Loop join the flow.

In addition to the currents that bound the Eastern Gulf Loop, some 5 to $10 \times 10^6 \mathrm{m}^3/\mathrm{sec}$ of water having characteristics typical of the Eastern Gulf Loop circulate as an anticyclonic gyre within the Gulf.

WESTERN GULF. The connection between the Yucatan Current and the circulation in the western Gulf is not clear from the present study. It seems possible that part of the Yucatan Current may leave the main stream and flow across, or along the northern edge of, the Yucatan Shelf to join the broad slow flow that forms the southern flank of the anticyclonic ridge in the western central Gulf. (At 91°W, the computed westward transport between Sts. 71 and 73 was $9.5 \times 10^6 \mathrm{m}^3/\mathrm{sec}$.) The sampling pattern did not allow delineation of the western end of this ridge. However, a well-developed current was observed along its northern flank.

For this northern region, geostrophic current speeds at a number of levels relative to 1000 db were computed. From 24°20′N, 95°W downstream to 25°30′N, 93°W, the maximum axial-velocity components were approximately 50 cm/sec. The geostrophic speeds in the core then seemed to decrease downstream to values of some 30 cm/sec at 27°20′N, 91°W. By comparison, the G.E.K. measurements gave a maximum speed of approximately 70 cm/sec at all three of the stream crossings made over this distance. Dynamic computations gave larger speeds at 100 m than at the surface. Along 93°W, the downstream component was almost 70 cm/sec at 100 m. Speeds decreased below 100 m but were still of the order of 20 cm/sec at 500 m. The indications are that the stream widened in a downstream direction from 95° to 91°W; apparently water was being entrained along the northern edge of this flow from a parallel counterflow located over the shelf edge.

In the southwestward counterflow, geostrophic current speeds at the surface and at 100 m were both about 30 cm/sec as measured at 93°W. Surface G.E.K. measurements gave 50 cm/sec at this longitude and showed a current shear between these two flows of more than 100 cm/sec in a distance of 35 nautical miles (65 km).

As discussed above, the 1964 data show the eastward flow between 24° and 25°N at 93°W. According to the 1964 data, the dynamic topographies of the 0-, 100-, and 500-db surfaces relative to 1000 db (not shown) indicate a strong shear zone, with possible westward flow between this feature and the edge of the Texas Shelf. There was no evidence of either low-salinity water or a strong westward flow over the outer shelf at that time.

Based on vertical sections of temperature, salinity, and σ_t presented by McLellan (1960), strong eastward flow was present in February of 1959 at 93°30′W between 26° and 27°30′N. This 1959 section extended to within

40 nautical miles (75 km) of the northern Gulf Coast, and no low-salinity waters were encountered over the outer shelf. Correspondingly, at that time there was no evidence of a westward flow over the shelf. In March of 1958, however, McLellan found that waters having salinity of less than 35 °/oo extended to 80 nautical miles (150 km) offshore along 94°30'W. Indicated were a strong westward flow along the shelf edge, a narrow shear zone, and a broad eastward flow extending south to about 24°N.

The available evidence points to the existence of the eastward or northeastward current as a semipermanent feature during the winter season, although its position and width is certainly variable. The westward flow over the outer shelf does not appear to be permanent; it may depend on the occurrence of low-salinity water over the outer Texas-Louisiana shelf. As discussed above, a broad southwestward flow that appeared to be centered at 22°N on section D (93°W) was found during the winters of 1962 and 1964. Such a flow was also evidenced in the winters of 1958 and 1959 (McLellan 1960); in 1958 from 20° to 23°N at 94°30'W, and in 1959 near 23°N at 93°30'W.

REFERENCES

Adams, R. M.
  1954. Depth of the motionless layer in the Gulf of Mexico. The A. & M. College of Texas, Dept. of Oceanogr., Unpubl. Tech. Rept. No. 11; 6 pp.

Austin, G. B., Jr.
  1955. Some recent oceanographic surveys of the Gulf of Mexico. Trans. Amer. geophys. Un., *36* (5): 885–892.

Cochrane, J. D.
  1961. Investigations of the Yucatan Current. *In* Unpubl. Rept. of Dept. of Oceanogr. & Meteorol., The A. & M. College of Texas, Ref. 61–15 F: 4–7.
  1963. Yucatan Current. *In* Unpubl. Rept. of Dept. of Oceanogr. & Meteorol., The A. & M. College of Texas, Ref. 63–18 A: 6–11.
  1965. The Yucatan Current and Equatorial Currents of the western Atlantic. *In* Unpubl. Rept. of Dept. of Oceanogr. & Meteorol., Texas A & M University, Ref. 65–17 T: 6–27.

Collier, Albert, K. H. Drummond, and G. B. Austin, Jr.
  1958. Gulf of Mexico physical and chemical data from Alaska cruises, with a note on some aspects of the physical oceanography of the Gulf of Mexico. Spec. Sci. Rep. Fish and Wildl. Serv., Fish. 249; 417 pp.

DEFANT, ALBERT
    1961. Physical Oceanography, Vol. 1. Pergamon Press, London. 729 pp.
DUXBURY, A. C.
    1962. Averaged dynamic topographies of the Gulf of Mexico. Limnol. Oceanogr., 7 (3):
        428–431.
FRANCESCHINI, G. A.
    1961. Hydrologic balance of the Gulf of Mexico. Unpubl. doctoral dissertation. The A. &
        M. College of Texas. 58 pp.
McLELLAN, H. J.
    1960. The waters of the Gulf of Mexico as observed in 1958 and 1959. The A. & M.
        College of Texas, Dept. Oceanogr. & Meteorol., Ref. 60-14 T; 17 pp.
McLELLAN, H. J., and W. D. NOWLIN
    1963. Some features of the deep water in the Gulf of Mexico. J. Mar. Res., 21 (3): 233–
        245.
PARR, A. E.
    1935. Report on hydrographic observations in the Gulf of Mexico and the adjacent straits
        made during the Yale oceanographic expedition on the 'Mabel Taylor' in 1932.
        Bull. Bingham oceanogr. Coll., 5 (1): 93 pp.
SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING
    1942. The oceans; their physics, chemistry, and general biology. Prentice-Hall, Engle-
        wood Cliffs, New Jersey. 1087 pp.
WENNEKENS, M. P.
    1959. Water mass properties of the Straits of Florida and related waters. Bull. Mar. Sci.
        Gulf Carib., 9 (1): 1–52.
WÜST, GEORG
    1936. Schichtung and Zirkulation des Atlantischen Ozeans. Die Stratosphäre. Wiss. Er-
        gebn. Dtsch. Atlant. Exped. METEOR, 6 (1) with Atlas, Berlin.
    1964. Stratification and circulation in the Antillean-Caribbean basins, Pt. 1. Columbia
        Univ. Press, New York. 201 pp.