The annual cycle of the Gulf Loop Current
Part I: Observations during a one-year time series

by George A. Maul[1]

ABSTRACT

The Gulf Loop Current is that portion of the Gulf Stream System which connects the Yucatan Current and the Florida Current in the eastern Gulf of Mexico. An experiment to test the annual cycle proposed by Leipper (1970) was conducted from August, 1972, through September, 1973. Twelve pathlines of the 22°C isotherm at 100 meters depth were made from Yucatan to the Florida Keys at 36-day intervals in conjunction with a satellite oceanography project. The sequence of pathlines shows an annual cycle of penetration into the eastern Gulf that is in phase with the historical annual cycle of current speeds and transports of the Gulf Stream, and is also reflected in tide gage sea-level records taken between Key West, Havana, and Progreso. The data suggest that an excess inflow of Yucatan Current water of $4 \times 10^6 m^3 s^{-1}$ over outflow of Florida Current water in the upper 500 meters is required to make the Loop Current grow; the outflow required to maintain static sea level conditions in the Gulf is postulated to be into the Caribbean Sea through the Yucatan Strait below this reference level. Separation of an anticyclonic eddy appears to be part of the annual cycle, which is shown to have great year-to-year variability.

1. Introduction

The portion of the Gulf Stream System in the eastern Gulf of Mexico is called the Gulf Loop Current. The flow from the Yucatan Strait penetrates northward into the Gulf to a varying degree before turning anticyclonically and exiting through the Straits of Florida. Leipper (1970) proposed an annual cycle of growth, spreading, and decay of this current system, based on data which were spaced at random intervals over two years. A sequence of current patterns designed to provide a proper time series of the Gulf Loop Current was observed in 1972-1973, and is the subject of this report.

The opportunity to observe the current at 36-day intervals for fourteen months came as part of a study in ocean color sensing from space. The Earth Resources Technology Satellite (now called LANDSAT-1) transited the study area every 18

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days. Surface observation cruises were conducted in synchronization with every second satellite overflight. Results of the investigation into the optical properties of the current and remote detection by LANDSAT were reported by Maul and Gordon (1975).

This paper is concerned with shipboard observations of the current. Later paper(s) will report the effects of observed transports through the Yucatan and Florida Straits on the heat and salt balance in the basin using concurrently observed hydrographic, sea level, meteorological, and river runoff data.

Since this paper is part of a journal dedicated to Dr. W. S. Richardson, it seems appropriate to make an acknowledgment at the outset. Bill and I had several useful conversations during the data collection stages of this work, and some of his own measurements were helpful in the analysis. It is almost impossible adequately to thank all the other persons involved, but Doctors C. Rooth, D. Hansen, D. Moore, and A. Leetmaa require a special note of gratitude.

2. Background of hydrographic observations

Early hydrographic work in the Gulf of Mexico has been summarized by Galtsoff (1954) who edited a complete overview of the biology, chemistry, geology, and physics of the area: in 1895, Lindenkohl published a map of the temperature field at 250 fm (457 m), in degrees Fahrenheit, on which the warm waters of the Caribbean could be seen flowing northward into the Gulf and penetrating deeply into the ambient thermal field; similarly the Gulf Stream, seen as a region of large horizontal temperature gradient, is shown flowing easterly and then northerly through the Straits of Florida. In an analysis of these data, Sweitzer, in 1898, reported that the circulation was a spreading of this inflow which resulted in an anticyclonic circulation around the entire Gulf basin. Parr, in 1935, reported the opposite conclusion using *Atlantis* data taken in 1933; he stated that the Gulf Stream takes the shortest path from Yucatan to the Straits of Florida. Leipper expressed this divergence of opinion as the state of knowledge in 1954 even after reviewing Dietrich's 1939 map of the salinity maximum core which, like Lindenkohl's, reflects deep penetration. Work done in the 1960's, notably by Leipper and others (Capurro and Reid, 1972), led Leipper to speculate that there was an annual cycle in the current patterns in the eastern Gulf.

Bottom topography in the eastern Gulf of Mexico is dominated by a broad shallow shelf extending north of the Yucatan Peninsula, the Campeche Bank, and another broad shallow shelf west of Florida, the west Florida Platform. The continental slopes are marked by steep escarpments along the west Florida area and northeast of Campeche. Sill depth in the Yucatan Strait is 2000 m, and in the Straits of Florida is approximately 800 m (see inset to Fig. 1). As the Yucatan Current flows along Campeche Bank, the bottom topography has been thought to control

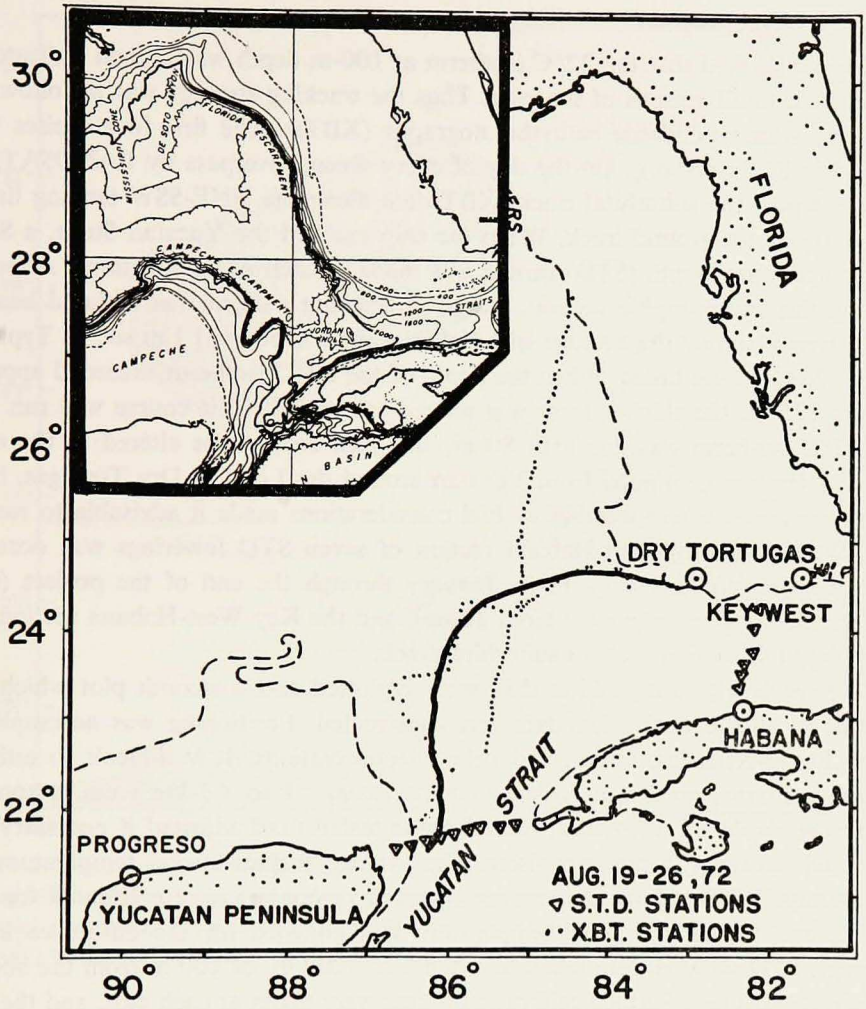

Figure 1. Example of the tracking technique is given in the main figure for August 1972. Dots are XBT drops and triangles are STD lowerings. The solid line is the pathline of the 22°C isotherm at 100 m depth. (Inset) Bottom topography in the eastern Gulf of Mexico. Contours are in meters and show the topography of the deep eastern basin surrounded by the Florida, Campeche, and Cuban Platforms.

the flow as far north as 23°30′N (Molinari and Cochrane, 1972). Above that latitude, the flow is no longer so constrained. After leaving the confines of the Campeche Bank, the Gulf Loop Current makes an anticyclonic turn in the deep water of the basin, and once again is channeled by the Florida Platform and the Cuban Platform into the Straits of Florida.

3. Observation program

Leipper showed that the 22°C isotherm at 100-m depth was a good indicator of the current in all seasons of the year. Thus the tracking strategy was to follow this isotherm with expendable bathythermographs (XBTs). The first four cruises were started in St. Petersburg. On the day of every second overpass by LANDSAT, the ship occupied the suborbital track; XBT data along the NNE-SSW tending line in Fig. 1 typify the ground track. When the ship reached the Yucatan Strait, a Salinity-Temperature-Depth (STD) profile was made at each of nine stations. After observing this hydrographic section, a zig-zag tracking pattern was initiated heading downstream, so that the average speed of the ship was boosted 1 m sec^{-1}. Typically hourly XBT's were taken. When the depth of the 22°C isotherm exceeded approximately 125 m, the ship's course was altered to the left. This course was run until the 22°C isotherm was less than 80 m, and then course was altered to the right. The pattern was continued from Yucatan around the Loop to Dry Tortugas, in all but a few cases, where weather or fuel considerations made it advisable to run for Key West. The Key West-Habana section of seven STD lowerings was occupied after a short refueling stop. From January through the end of the project (eight cruises), the cruises originated from Miami, and the Key West-Habana section was done first; this section is also a suborbital track.

After each trip, the position data were replotted and a smooth plot which is a best fit to all the navigation data was constructed. Positioning was accomplished using Loran-A, radar, visual, and celestial observations. It is difficult to estimate errors, but based on Loran-A/radar comparisons, ±1 to ±3 km seem reasonable. The expendable BT strip chart recorder was tested (and adjusted if necessary) before each cruise with a test canister. The average surface-bucket temperature and the average XBT-surface temperature (from the recorder) were calculated for each cruise, and the surface XBT temperature was adjusted for the difference in the average. STD stations were taken to a depth of 1000 m, or 100 m from the bottom, whichever was less. Surface calibration points were taken at each cast, and the lowering speed was about 50 m per minute. Station spacing was about 20 km, with no stations closer than 22 km (12 n mi) to foreign coasts.

4. Pathlines of the current

Conditions prior to the first cruise are summarized in Fig. 2. These data are compiled from Merrell (personal communication), Molinari and Yager (1977) and Brooks and Niiler (1975), and cover the period from 6 to 18 May, 1972. Areas where the 22°C isotherm is deeper than 125 m are stippled; the indicator isotherm is the heavy line outlining the main flow and the eddy. In this composite of their data, an anticyclonic eddy is in the process of separating as evidenced by the ridge in the topography of the 22°C isotherm extending northeast from Campeche Bank

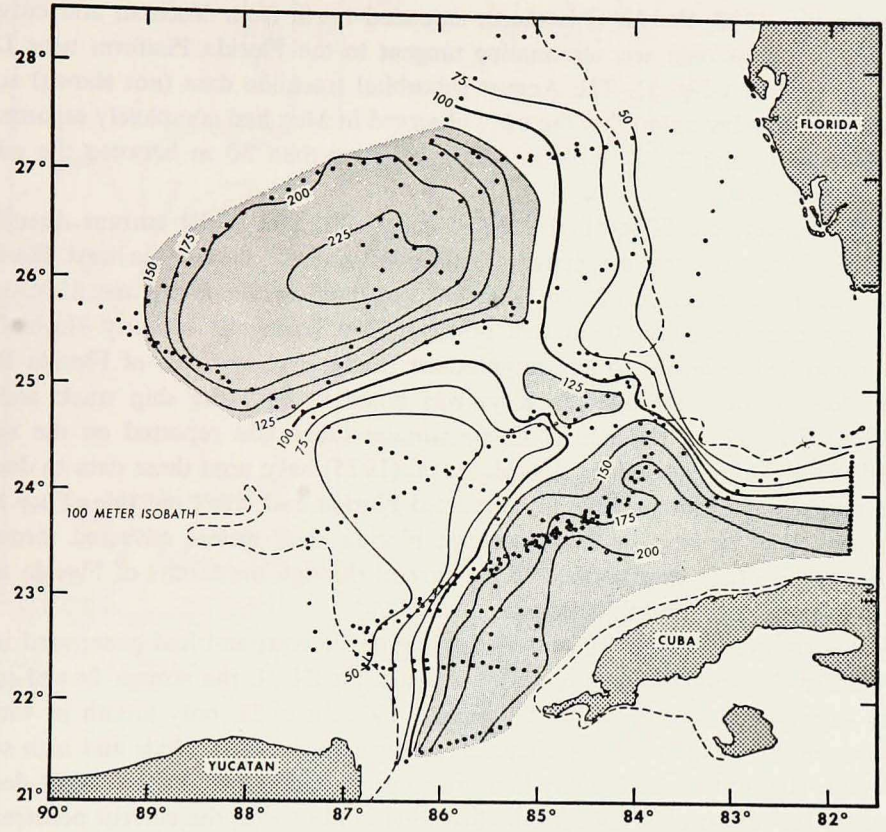

Figure 2. Depth of the 22°C isotherm in the project area, composited from data taken 6-18 May, 1972. The eddy was actively separating from the main flow, and this figure required spatial smoothing, but it does illustrate the relation of the indicator (100-m depth contour heavy) to the thermal field.

to the Florida Platform. The tracking technique would show very short radii of curvature in the zone where the separation was taking place; conversely the eddy could be missed entirely if it were not for the suborbital trackline (cf., Fig. 1). Recirculation in the eddy is already quite extensive as evidenced by the closure of the isopleths. The process of eddy separation cannot be discussed with the pathlines of the 22°C isotherm except to confirm that this did indeed occur. This eddy was observed as late as December, 1972, in the suborbital trackline near the west Florida Platform.

Pathlines of the 22°C isotherm at 100 m depth are given in Fig. 3. Dates of each survey are labeled on the appropriate pathline. The shortest tracking time was three days and the longest six days, so that near synopticity was accomplished. Hydrographic station transects of the straits added two to three days to each cruise.

In August, 1972, the 22°C isotherm extended north from Yucatan and curved in a gentle anticyclonic arc, terminating tangent to the Florida Platform near Dry Tortugas (see also Fig. 1). The August suborbital trackline data (not shown) supports the earlier discussion that the eddy observed in May had completely separated, as evidenced by the 22°C isotherm being shallower than 30 m between the eddy and the main flow.

By September, conditions had changed markedly. The initial current direction had a significant easterly component and flowed directly toward the west Florida shelf. There was evidence of Loop Current water on the shelf, and the 22°C isotherm apparently went aground well north of Dry Tortugas. By early November the current had reformed to its southernmost extent, and evidence of Florida Bay water flowing south through the Keys was noted in both the ship track and a LANDSAT image. A red tide of *Gymnodinium breve* was reported on the west Florida shelf during September. Murphy *et al.* (1975) have used these data to document partially the source of the first reported Florida east coast red tide. They hypothesized that the organisms in the west Florida shelf waters advected through the Keys where they were carried by the current through the Straits of Florida and into the coastal region north of Miami.

By December, 1972, the current had swung to the west and had penetrated into the Gulf to the same latitude as during August. At 24°N, the stream flowed in a sharp anticyclonic turn to the east. January, 1973, was the only month in which transects of the Straits were not obtained, because 25 m sec^{-1} winds and high seas forced the ship to turn back. Only four crossings were obtained, but sufficient detail permitted the observation that, for the first time in the series, the current penetrated north of Dry Tortugas (25°N).

The "spring intrusion" (Leipper, 1970) continued from February through June when the current extended to 27°N. As the current penetrated deeper into the Gulf, it also swung farther to the west. North of 24°N, the isobaths curve sharply to the west, in a region of deeper water where topographic influence becomes unlikely.

The northward penetration to almost 29°N in July, 1973, coupled with a marked cyclonic curvature off the west Florida shelf at 26°N led to the expectation of an eddy separating by the following cruise. The intrusion at 26°N from the east was not a sampling artifact; the R. V. *Bellows* obtained concurrent hydrographic station data across the shelf and out into the main current throughout this area. The furthest western extent of the current also occurred in July. A vast area of green, high chlorophyll-content water was encountered along the western boundary opposite the 26°N intrusion from the east (Ednoff, 1974).

By August, 1973, the current system extended almost to the Mississippi Delta. The eddy had not separated. Very low salinity water (24‰) was recorded by a simultaneous cruise of the R. V. *Bellows* and the R. V. *Virginia Key* all along the current edge off the Florida Shelf. Surface salinities were less than 30‰ along the

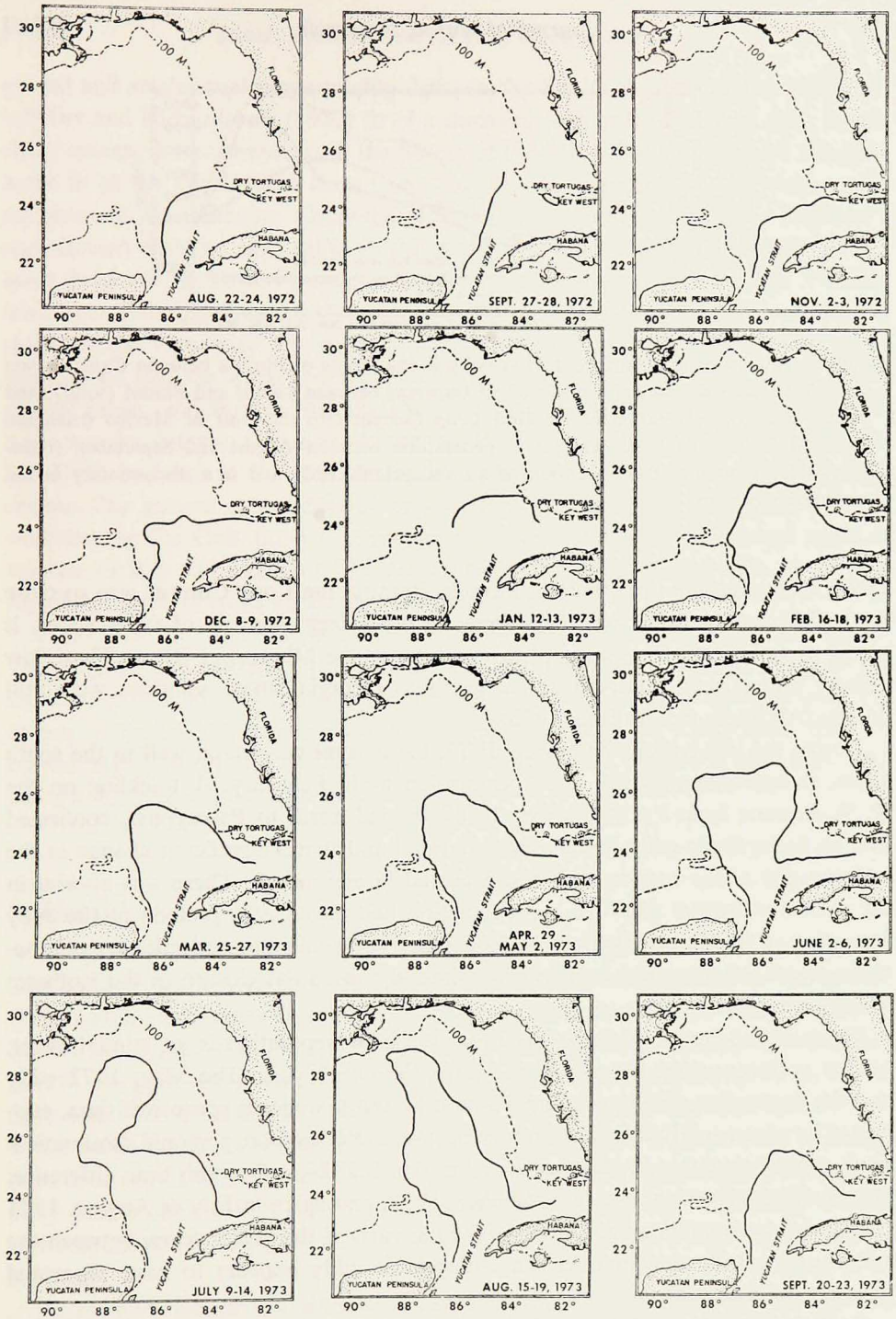

Figure 3a thru 1. Pathlines of the 22°C isotherm at 100-m depth for the period August, 1972 to September, 1973. Dashed line is the 100 m isobath. Actual dates of each survey from Yucatan to Dry Tortugas, but excluding the time required for the STD sections, are given on the lower right of each figure.

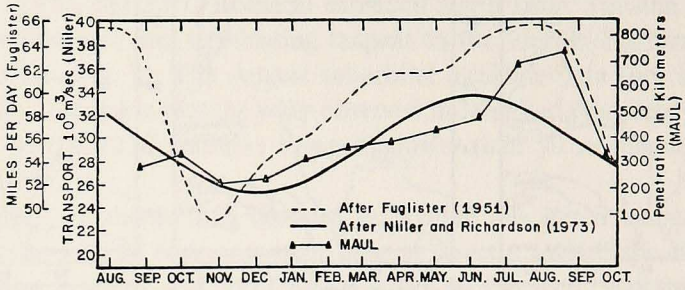

Figure 4. Annual cycle of surface drift velocity in the Straits of Florida between Cape Florida and 30°N (dashed), annual cycle in direct transport between Miami and Bimini (solid), and annual cycle of penetration of the Gulf Loop Current into the Gulf of Mexico (triangles) during 1972-73. The large decrease in penetration between August and September (right-hand side) represents the separation of an anticyclonic eddy and is a discontinuity in the penetration pattern.

cyclonic boundary in the Straits of Florida. Because the Loop Current was so close to the Mississippi Delta and there were no other large sources of fresh water, it seems probable that the source of this water was the Mississippi River. These low salinity waters were observed as far north as Georgia where salinities were still 34.5‰ (Atkinson and Wallace, 1975).

During the last cruise, September, 1973, the current was found well to the south again, at approximately the same penetration as in February. A trackline on the R. V. *Bowers*, from Ft. Myers west to 87°W and north to Pascagoula, confirmed that an anticyclonic eddy had indeed separated and that a significant change in the hydrography of the eastern Gulf had occurred in one month. There was no hint in the extensive August data that a recirculation had begun as a prelude to the eddy formation, although observations by Cochrane (Personal communication), made between the April-May and June cruises, showed substantial closure in the isotherm field in this area.

These data support the hypothesis that the eddy separation is an annual event, but by no means does it occur at the same time each year. The May, 1972 eddy and the September, 1973 event are 16 months apart, whereas spacecraft data, supported by concurrently obtained buoy tracks (W. S. Richardson, personal communication), suggest that an eddy had separated in April, 1974, a 7-month time difference. Other eddies have separated in November, 1970, and again in July or August, 1971 (J. Brucks, personal communication). Thus in each of the last 5 years, between the vernal and autumnal equinoxes, an anticyclonic eddy appears to have separated from the main current.

In Fig. 4, the northward penetration of the 22°C isotherm into the Gulf is compared with historical data. The dashed line is Fuglister's (1951) harmonic fit of

annual and semiannual terms to ship drifts in the Straits of Florida. The solid line is Niiler and Richardson's (1973) fit of a sinusoid, with an annual term only, to the direct transport measurements in the Straits of Florida. The light line with triangles is the fit of the arc distance from Cabo San Antonio (western tip of Cuba) to the pathlines of the indicator. Cochrane (1965) did an analysis similar to Fuglister's and showed that the ship drifts in the western Yucatan Strait are essentially the same as in the Straits of Florida, except that the maximum drift through Yucatan leads that through Florida by 1 month. Niiler and Richardson's curve shows the same general feature of low transports in winter and high transports in summer. They noted that the week-to-week fluctuations in the current were as much as the annual range, and further that the transports lag the annual cycle of wind stress curl over the Atlantic Ocean by 4 months. Maul (1974) reported that the slope of the 17°C isotherm in the Yucatan Strait lagged the penetration by three to four cruises. The general agreement between the three curves in Fig. 4 suggests that the variations in the Gulf Loop Current are well correlated with the annual cycle of current velocity and transport. The annual cycle of current velocity is in phase with the annual cycle of trade wind stress (Fuglister, 1951).

These data form the basis upon which Liepper's suggestion has been investigated. The pathlines indicate that: (a) there is an annual cycle of growth and decay of the Gulf Loop Current, (b) a major exchange of heat, salt, and momentum from the current into the Gulf is made through the separation of an anticyclonic eddy or current ring, and (c) the circulation in the eastern Gulf of Mexico is associated with the annual cycle of mass transport.

5. Discussion

Comparing pathlines of the 22°C isotherm with historical data averaged by months gives some indication of the variability of this current's cycle. Robinson's (1973) atlas clearly shows that the minimum penetration of the Loop occurs in March and April, whereas the maxima are in August and September. Whitaker's (1971) averages show that the minimum is in November and the maxima are in May and October. Leipper found minima in August, 1965 and November, 1965 and a maximum in August-October, 1966. From Fig. 3 it is seen that the minimum here occurred in October-November and the maximum in July-August. This summary points out the high degree of temporal variability in the Gulf Loop Current and emphasizes that the data obtained in this study are not a final description of the cycle.

Simple dynamic models of the Gulf Loop Current such as those by Ichiye (1962) and Reid (1972) suggest that the penetration of the Yucatan Current into the Gulf depends on the flow direction. Their potential vorticity-conserving model in natural

coordinates for a two-layer ocean with the lower layer at rest, is given by

$$\frac{KV - \frac{\partial V}{\partial n} + f}{D} = \text{constant} \tag{1}$$

where K is curvature, V is velocity along a streamline, $\overleftarrow{n}$ is the coordinate normal to the velocity vector, positive to the left facing downstream, f is the Coriolis parameter and D is the depth of the upper layer. In the pathlines given in an earlier section, D is a constant 100 m. If it is assumed that the velocity core is a streamline whose neighboring streamlines are nearly equidistant, $\partial V/\partial n$ is also constant. For that case, the work of Ichiye and Reid gives

$$V = \tfrac{1}{2} p^2 \beta \tag{2}$$

where p is the penetration of the streamline into the Gulf, and β is the meridional variation of f. Reid (1972) was careful to point out that the model only holds in deep water, that is north of Campeche Bank, and that V is an average value for the upper layer. Applying equation (2) north of Campeche during those months when bottom topography controls the flow, and at the latitude of Cabo San Antonio at other times, the velocity range is 44 to 303 cm sec^{-1} (excluding August, 1973). Forty-four cm sec^{-1} is a reasonable value for the average surface value, but 303 cm sec^{-1} is beyond the range of observations. This suggests that a geostrophic deep-water potential vorticity-conserving model is not an adequate explanation.

From Fig. 3, it can also be seen that the bottom topography of Campeche Bank did not control the current during August, September, October-November, and December, 1972, or September, 1973. During the February, March, April-May, June, and July, 1973 cruises, the 22°C pathline closely followed the 100 m isobath from the Yucatan Strait almost to 24°N. This supports Cochrane's (1965) contention that the Yucatan Current is farther to the west during periods when surface velocities are higher and these are also the months when the indicator hugs Campeche Bank. Thus, when the current is strongest in spring and summer (Molinari and Cochrane did their analysis on data observed in May 1962, 1965, and 1966), and is farther to the west, the velocity near the bottom may be sufficient for equation (1) to describe the dynamics coarsely.

Another interesting kinematic result is summarized in Fig. 5. The northern terminus of the Straits of Florida hydrographic section was near Cosgrove Lighthouse (halfway between Key West and the Dry Tortugas). The horizontal distance between Cosgrove Lighthouse and the 22°C isotherm at 100 m depth is plotted against the northward penetration of the pathline into the Gulf (measured from Cabo San Antonio). The farther north the current penetrates into the Gulf, the farther south

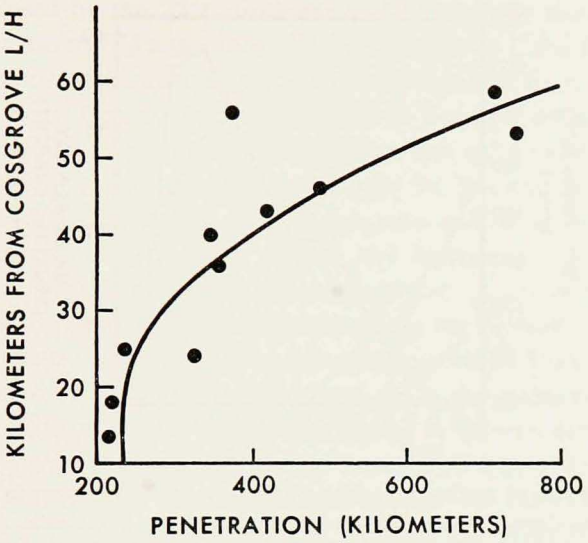

Figure 5. Distance that the 22°C isotherm at 100-m depth was found from Cosgrove Lighthouse (northern terminus of the Straits of Florida transects) versus distance from Cabo San Antonio to the northern penetration of the current into the Gulf of Mexico. The heavy line is the least-squares fit to the data. The point at 55 and 400 km represents a case where the indicator was near 100 m for three STD stations, but was chosen to be the first crossing from north to south for consistency.

it was found in the Straits of Florida. Paskausky and Reid's (1972) numerical model also shows that the current flows close to Cuba when the penetration of the Loop Current is greater, but there are no analytic models incorporating bottom topography to which these observations can be applied.

The volume of water necessary to make the Loop grow can be estimated from the length of pathlines. Assuming a mean depth (z) of 500 m for the current, pathline measurements show that 64,000 km^3 of resident Gulf water must be displaced by Yucatan water in the six months that the Loop grows. The excess transport of Yucatan water into the Gulf in this period averages 4.1×10^6 m^3 sec^{-1}. As an independent check on this value, sea-level records were studied. Cochrane (1965) showed that there is a good correlation between the monthly sea-level difference between Habana and Progreso and the average ship drift in the western Yucatan Strait; the data in Fig. 4 show a correlation between surface velocity and transport. For an upper layer flow which is in geostrophic balance in the crossstream direction, the sea-level difference across the stream is a measure of the average surface current. A transport estimate may be made by multiplying this average surface current by a mean depth for the upper layer flow, which is taken to be 500 m in this case. Marmer's (1954) mean monthly sea-level data are used. The stations are Habana (1947-1950), Key West (1930-1948), and Progreso (1947-1950). Trans-

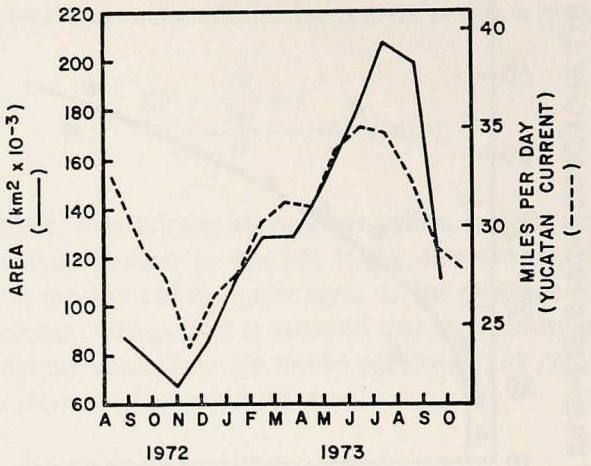

Figure 6. Annual cycle of surface area, enclosed by the 22°C isotherm in the Gulf and the Key West-Habana-Cabo San Antonio-Isla Contoy boundary, is the solid line. Dashed line is the annual cycle of surface velocities as estimated by Cochrane (1965) for the Yucatan Current from ship drift reports.

port difference between the Habana-Progreso (T_{H-P}) and the Habana-Key West (T_{H-K}) sections is then given by

$$T_{H-P} - T_{H-K} = \frac{gz}{f}(h_K - h_P) + C \tag{3}$$

where g is gravity, z is the mean depth of the current, h_K is the monthly sea level at Key West, h_P is at Progreso, and $C = (\bar{h}_K - \bar{h}_P)gz/f$, where the overbars denote mean annual sea level. Progreso and Key West are on the same side of the current, and it is assumed that the annual mean sea level along the coast is approximately the same, therefore $C = 0$. During the period that the Loop is growing, the difference $h_K - h_P = 4.88$ cm. The transport difference calculated from equation 3 is 3.8×10^6 m^3 sec^{-1} during this period.

By two independent methods, it is shown that there must be an excess inflow of Yucatan water. Jacobs (1951) estimated that evaporation exceeds precipitation in the Gulf by 35 cm per year. This would account for only $0.02 \times 10^6 \times$ m^3 sec^{-1} excess of inflow. Sea level in the Gulf does not rise 34.5 m in six months as implied by excess inflow, and the transports inferred from sea level records require that very little Gulf of Mexico water exits the Straits of Florida. This implies that Hansen and Zetler's (1972) and Schlitz's (1973) direct measurements of a net south drift at the bottom of the Yucatan Strait may have detected the major source of discharge during some phase of the growth cycle. Schlitz's estimate of the southward transport through the Yucatan Strait, based on April, 1970 data, is 4×10^6 m^3 sec^{-1} which is in excellent agreement with this discussion.

The area enclosed by the 22°C isotherm at 100-m depth along the line from Cosgrove Lighthouse to Habana, along the Cuban coast to Cabo San Antonio and across to Isla Contoy, was estimated using a polar planimeter from Fig. 3. The area enclosed by the Loop Current defines a volume of Yucatan water, and its annual cycle should be related to volume transports. As a first estimate, the transports are assumed proportional to current velocities through the Yucatan Strait, as estimated from Cochrane's ship drift studies. The comparative results are plotted in Fig. 6. The sharp decrease in area between August and September, 1973 is due to the separation of the anticyclonic eddy discussed earlier. A clear correlation exists between area and current velocities, with little phase lag between transport and the area covered by the current system. The numerical models of Wert and Reid (1972) and Paskausky and Reid (1972) attempted to relate the penetration of the Gulf Loop Current to changes in the vorticity distribution or velocity field of the Yucatan Current, but they kept the volume transport constant; Ichiye (1972) used changes in the Yucatan velocity in a rotating tank model, but did not relate the velocities to the penetration. There are no established relationships between velocity or vorticity fields in the Yucatan Current and transport, nor are there any models (except indirectly Reid (1972) or Ichiye (1962)) which use changes in transport to drive the circulation in the Gulf of Mexico.

6. Evidence of fine-scale features

The subject of oceanic eddies is increasing in importance, and is the focus of several recent multi-national studies. Besides the large eddies of May, 1972 and September, 1973 described above, a large range of smaller eddy features were observed during the year of observations. These are collectively called fine-scale features, and are discussed below.

Cochrane (1965) noted that the surface velocity field of the Yucatan Current had double maxima. It was also noted by Pillsbury in 1890 in this area and by Stommel (1966) in other portions of the Gulf Stream. It appears distinctly in Cochrane's geomagnetic-electrokinetograph profiles north of the Strait. Cochrane postulated that it occurs when the cyclonic edge of the Yucatan Current is found against the Mexican coast, and the main flow is bifurcated by Isla Cozumel; one branch passes between the island and the mainland, and the other branch passes to the east of this topographic wedge.

Fig. 7 is a computer enhanced LANDSAT image of the Yucatan Strait. This is a negative print, and thus dark tones represent areas of high radiance. The water outside the current is seen to be of lower radiance than that in the current; the radiance is dominated by a higher sea state or different glitter pattern in the current. Here the western edge of the current can be seen leaving the coast northwest of Cozumel. In the wake of the island is a spacecraft observation of an oceanic von

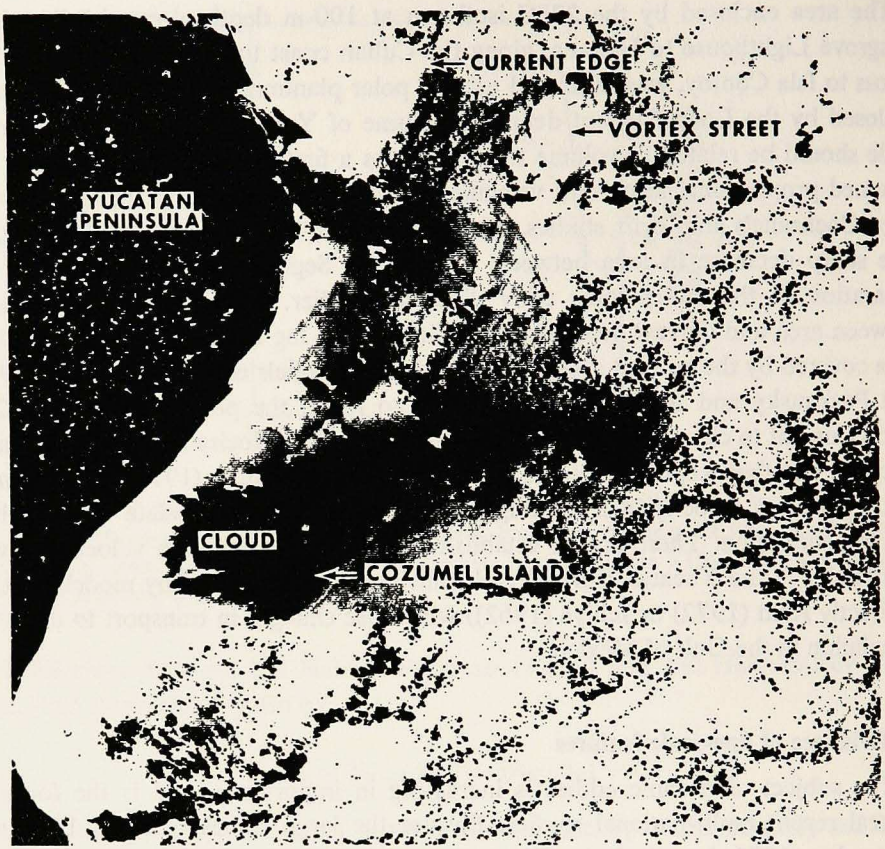

Figure 7. Negative print (ID 1029-15413) of computer-contrast-stretched MSS-5 (0.6-0.7 μm) LANDSAT image of Yucatan and Cozumel, Mexico, observed on 21 August, 1972. The Yucatan Current's cyclonic edge can be seen emerging from between the island and the mainland. In the lee of Cozumel is a vortex pattern which causes a disturbance in the surface velocity profile well downstream. Horizontal distance across image is 135 km.

Karman vortex street; this is the oceanographic analog to similar observations in the atmosphere, photographed by Gemini and Apollo astronauts in the cloud cover over the Guadeloupe Islands in the equatorial Pacific Ocean. Fig. 7 was imaged on 21 August, 1972. The August, 1972 pathline was observed at this time, and the current's edge and the vortex street are confirmed to be ocean features.

Surface current velocities were determined by the geostrophic method from the hydrographic transect of Yucatan Strait on 21-22 August, 1972; station location is given in Fig. 1. Station spacing was very nearly 18 km, and the north component of the surface speeds relative to 700 db, from Yucatan to Cuba, were: 103, 145, 80, 119, 73, 88, 62, and 35 cm sec^{-1}. The low value of 80 cm sec^{-1}, bracketed by higher values of 145 and 119 cm sec^{-1}, is in the middle of the vortex zone

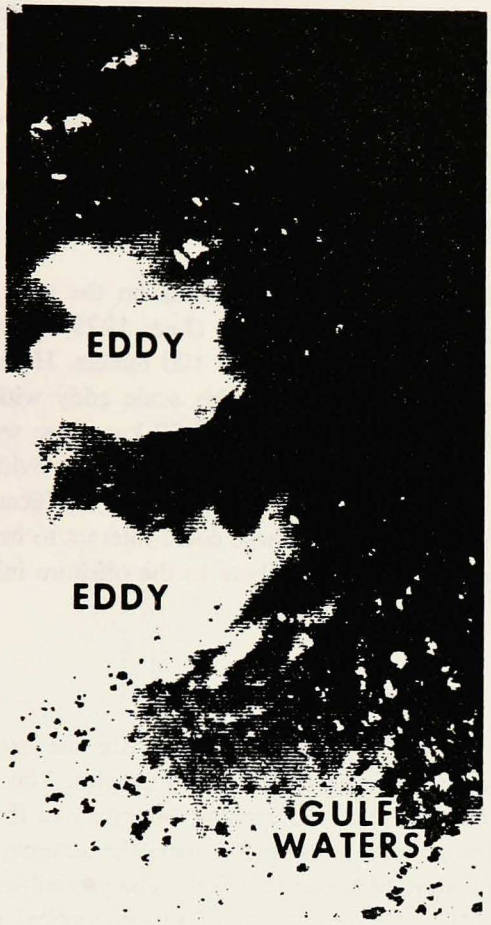

Figure 8. Negative print of computer enhanced LANDSAT MSS-4 (0.5-0.6 μm) image (ID 1153-15292) of detached eddies on the west Florida shelf observed on 22 December, 1972. Details of the boundary of these 20-km diameter Gulf Loop Current eddies show significant irregularity and nonsymmetry. Horizontal distance across the image is 45 km.

shown in Fig. 7. This cross correlation of hydrographic and satellite data is offered as evidence that the observed double maxima is caused by topographic-induced vortex generation, and explains one type of fine-scale structure as eddies imbedded in the main flow of the Yucatan Current.

Maul, Norris, and Johnson (1974) observed eddies which appeared to be embedded in the core of the current, north of Campeche Bank. These eddies were 10-30 km in diameter and were interpreted to be shear instabilities as distinguished from the von Karman vortex street observed in Fig. 7. These data cannot dismiss the possibility that the eddies in mid-Gulf are generated by Isla Cozumel. If these

eddies were shear instability features, then one could expect to find them in other areas of the stream as Stommel (1966) reported. If Cozumel was the only source of disturbance vorticity, then these eddies have been advected 600 km downstream and may be found farther. The latter seems unreasonable because of Cochrane's (1965) report that velocity profiles well upstream of Cozumel do not often exhibit these features. This may be dependent on the season of the year because the current does not always flow as close to the Mexican coast as it seems to in midsummer.

In Fig. 8, a LANDSAT image of two eddies on the west Florida Platform is shown. These appear to be spin-off eddies (Lee, 1975) which have drifted into shallow waters where the depth is less than 100 meters. Here is another example (*cf.*, Austin, 1971) of the interaction of this scale eddy with the coastal water. Austin noted that several eddies of the 20- to-50 km range were observed around the perimeter of the current in a survey in 1970. This is evidence that these features drift onto the shelf where they must exchange significant quantities of salt, heat, and momentum. Eddies such as these could interact to bring cyst stages of *G. breve* into the euphotic zone and contribute to the offshore initiation of a destructive plankton bloom.

7. Summary

This research was initially undertaken to evaluate the use of an ocean-color-sensing satellite for observing currents in the subtropics. The Gulf of Mexico was chosen as a test site because there the cyclonic boundary of the Gulf Loop Current cannot be detected by infrared techniques during the summer, and this current is the major circulation feature of the eastern Gulf. The ground-truth pathlines (Fig. 9) provided measurements of the seasonality of several optical properties across the current as well as a history of the flow itself for comparison with satellite data and for basic oceanography.

This unambiguous time series of the Gulf Loop Current based on ship observations shows that Leipper's (1970) proposition is correct in that there is an annual cycle of growth and decay, but that year-by-year variability in the patterns is significant. An anticyclonic eddy separation appears to have occurred at least once each year in the last five years.

Evidence for turbulence embedded in the core of the Gulf Loop Current is obtained from comparing velocity profiles across the Yucatan Strait with satellite imagery. Two sources of turbulence are tentatively identified: shear instability and topographic influence.

The annual cycle of growth, eddy separation, and decay of the 1972-1973 data is in phase with the annual cycle of transport of the Gulf Stream System. During the period that the Gulf Loop Current is growing, resident Gulf of Mexico waters

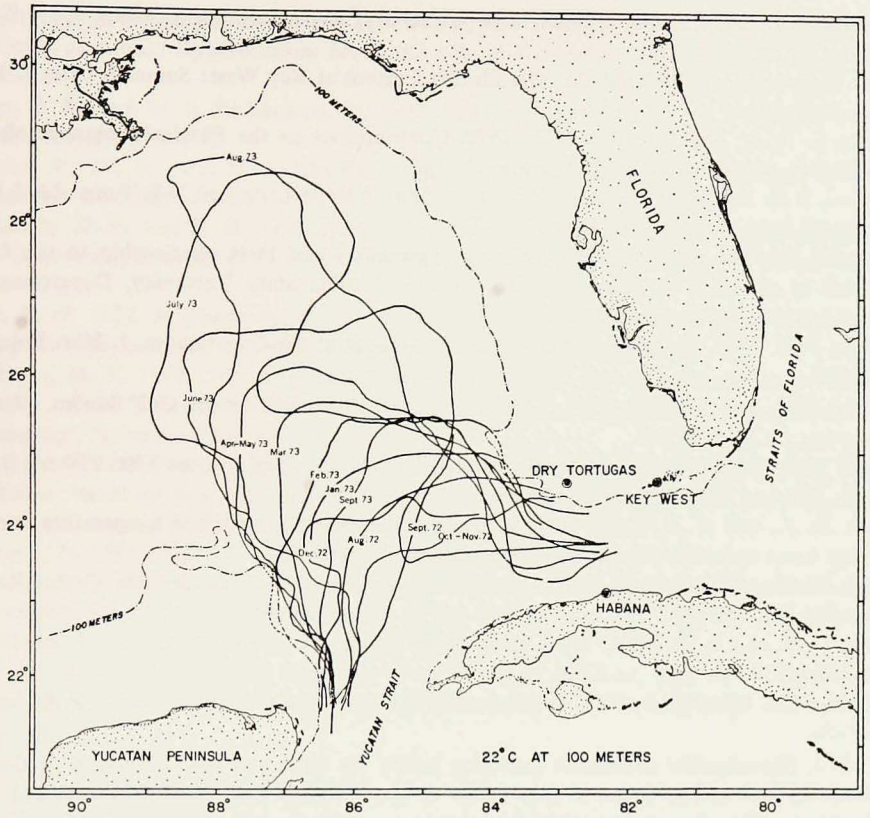

Figure 9. Compilation of pathlines of the 22°C isotherm at 100-m depth from August, 1972 through September, 1973 (see also Fig. 3). Where the indicator isotherm intersected the bottom topography, a dashed line is used to estimate its position from the other thermal data. Where the cruise started in 1 month and ended in another, both months are indicated. 100 m isobath is indicated by a dash-dot line and represents very closely the shelf break and escarpment zone.

must be displaced; this requires that 4×10^6 m^3 sec^{-1} more Yucatan water enters the basin in the upper layers than leaves through the Straits of Florida. The southward outflow appears to be near the bottom of the Yucatan Strait during part of the growth phase. Details of the balance of mass and salt were presented by the author at the second CICAR Symposium (July, 1976) and will be reported in Part II of this series of papers.

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