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Ecological Implications of Hydrography and Circulation to the Flower Garden Banks, Northwest Gulf of Mexico

Alexis Lugo-Fernández

A synthesis of historic and new physical oceanographic observations on the Louisiana–Texas shelf helps change the circulation paradigm around the Flower Garden Banks. The location of these banks near the shelf edge shields them from the direct influence of the Mississippi and Atchafalaya Rivers and summer hypoxic episodes but places them under direct influence of deepwater physical processes. These deepwater processes control temperature and salinity within ranges that are adequate for coral growth; however, summer temperatures can exceed thermal tolerance limits as evidenced by coral bleaching episodes. Currents near the Banks have longshore and significant offshore components. Loop Current (LC) rings and companion eddies (anticyclones and cyclones) with spatial scales of 30–150 km and residence times ~ 6 mo over the slope are the main driving force of shelf edge currents. This active eddy field induces significant and frequent cross-shelf water exchanges with the deep Gulf, which help regulate temperature, salinity, and larvae dispersal. The eddies also induce oxygen and nutrient enrichments near the mixed layer by sinking and rising water parcels that can help the reef biota. Four links between the Flower Garden Banks and the rest of the Gulf of Mexico are identified: the shelf edge current, LC rings and associated eddies, the mean westward surface wind drift in the Gulf, and alongshelf edge intrusions from the northeastern Gulf of Mexico. The coral reefs of the Flower Garden Banks can function as repositories and sources of reef biota.

The Flower Garden Banks (FGB) in the northwest Gulf of Mexico (Fig. 1) harbor the northernmost extension of typical Caribbean coral reefs and associated communities in North America. The two banks of the FGB, East and West (about 18 km apart), are in depths of 100 m, and their crests rise to within 17 m of the sea surface (Bright et al., 1985). The FGB are located near the edge of the Louisiana–Texas (LATEX) continental shelf, ~ 200 km off the Louisiana coastline. Earlier oceanographic studies around the FGB revealed the importance of physical processes to reef communities (McGrail, 1983). These initial results have remained as the paradigm for assessing the influence of physical processes on the FGB (Rezak et al., 1990). During the past decade, several major studies funded by Mineral Management Services [e.g., Gulf of Mexico Physical Oceanography Program (SAIC, 1989), GulfCet (Davis and Fargion, 1996), LATEX-A program (Nowlin et al., 1998)] yielded new data and insights on the regional oceanography of the northwestern Gulf. This new information warrants a revision of the physical oceanography of the FGB region.

Following is a synthesis of physical oceanographic observations around the FGB, a discussion of recent advances in the understanding of the circulation in this area, and its implications to these reefs. The information presented defines climatological conditions and does not reflect instantaneous conditions at any given time or point. These climatological conditions serve as useful background information in fields such as ecology. Environmental controls of biological communities on these banks of the northwestern Gulf include geological setting, currents, water temperature, river effects on salinity and turbidity, height of the bank, and depth of nepheloid layers (Rezak et al., 1990). Three aspects of the local oceanography related to regional environmental controls are reviewed: hydrography, circulation, and solar radiation. Hydrographic conditions affect the structure and composition of reef communities at the FGB by imposing environmental controls, such as temperature, salinity, and nutrients. The circulation and water exchange replenish nutrients and oxygen, remove wastes, control the suspended matter, and define the links between the FGB reefs and other Gulf of Mexico coral reefs. Solar radiation is a major factor controlling water temperature and imposes biological limitations because hermatipic corals depend on light through their symbiont, e.g., zooxanthella. This review addresses all environmental controls of biological communities in the northwestern Gulf as presented in Rezak et al. (1990), except geological setting.

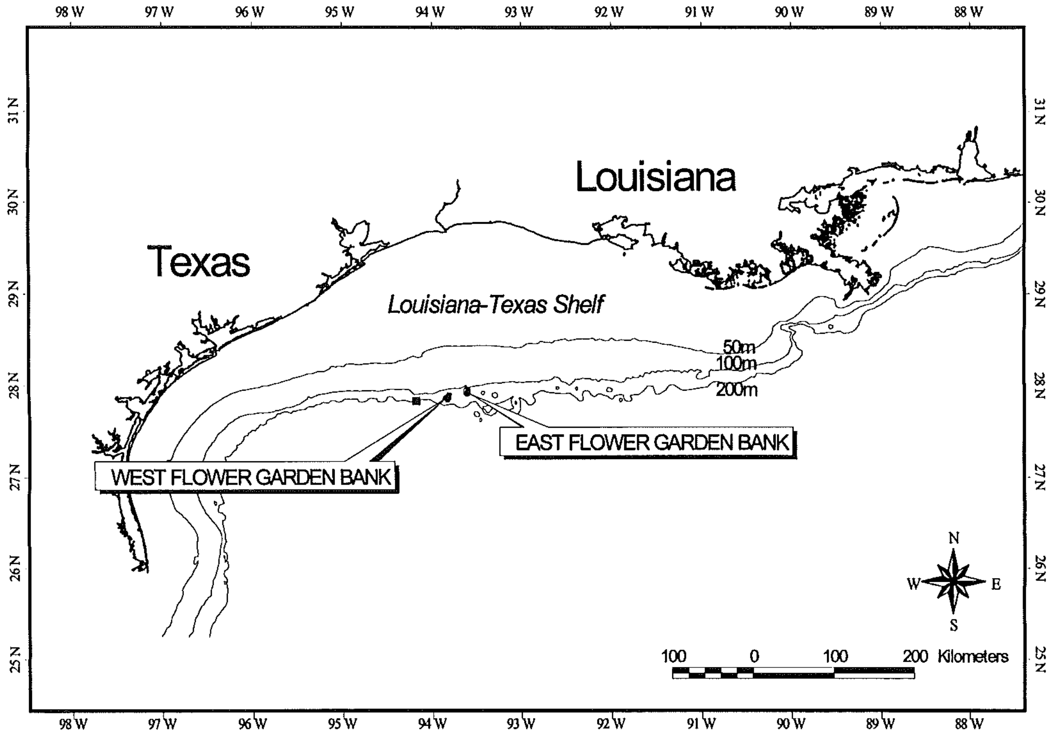

Fig. 1. The Louisiana–Texas shelf showing the location of the Flower Gardens Banks and mooring 8 (■) of the LATEX-A program.

Hydrography

Water temperature.—Water temperature near the FGB varies at several temporal scales. Interannual temperature variations are revealed by several temperature data sets collected in past years (McGrail, 1983; SAIC, 1989; Gittings et al., 1992b; CSA, 1996; Nowlin et al., 1998). Bottomley et al. (1990) summarized sea surface temperature (SST) data and showed that the climatological SST varies seasonally with an annual range of $\sim$ 9.3 C in the region near the FGB (30 yr of observations). A 7-yr mean temperature at 24 m depth over the West FGB (WFGB, Fig. 2) varied from a minimum in February (19–20 C) to a maximum in July/August (29–30 C) and yielded a range of 9–11 C, a pattern similar to the annual cycle of the SST. Temperature measurements near the shelf edge varied over a range of 10 C (SAIC, 1989). In the western Caribbean, the annual temperature range is $\sim$ 5 C and $\sim$ 8–10 C at the Florida Keys (Glynn, 1973; Jaap, 1984). The weekly and diurnal variations of local SST (11 yr of satellite data) were about 5–6 C in winter and about 2–3 C in summer (Gittings et al., 1992b).

SST gradients exhibited strong seasonal variations (SAIC, 1989; Nowlin et al., 1998). The cross-shelf gradient is very small in spring ($\Delta T < 1$ C). In summer, June to September, the Gulf of Mexico sea surface becomes isothermal (SST $\approx$ 30 C) and severely limits the use of satellite thermal data. In fall and winter the temperature contrast across the shelf is about 5 C. Near the shelf edge, distinct SST gradients or fronts are sometimes seen in satellite images from October to May. These fronts are associated with warm Loop Current (LC) rings and other causes (SAIC, 1989). About 5% of the time between November and May, eddy fronts were observed near the FGB, and shelf/slope fronts occurred 20% of the time (Vukovich and Hamilton, 1990).

Seasonal variations of the subsurface temperature range decrease with depth. Temperatures at 13 and 24 m display the expected SST pattern, i.e., annual range of $\sim$ 10 C (20–30 C) and exhibit similar timing of minimum and maximum temperatures (CSA, 1996; Nowlin et al., 1998). At 30 m, the average low temperature is $\sim$ 1 C cooler than the SST and the average high temperature is $\sim$ 2–3 C cooler than SST. The maximum temperature occurs later (August or September) at depth. At 91 m deep, the annual range is $\sim$ 3 C; the average

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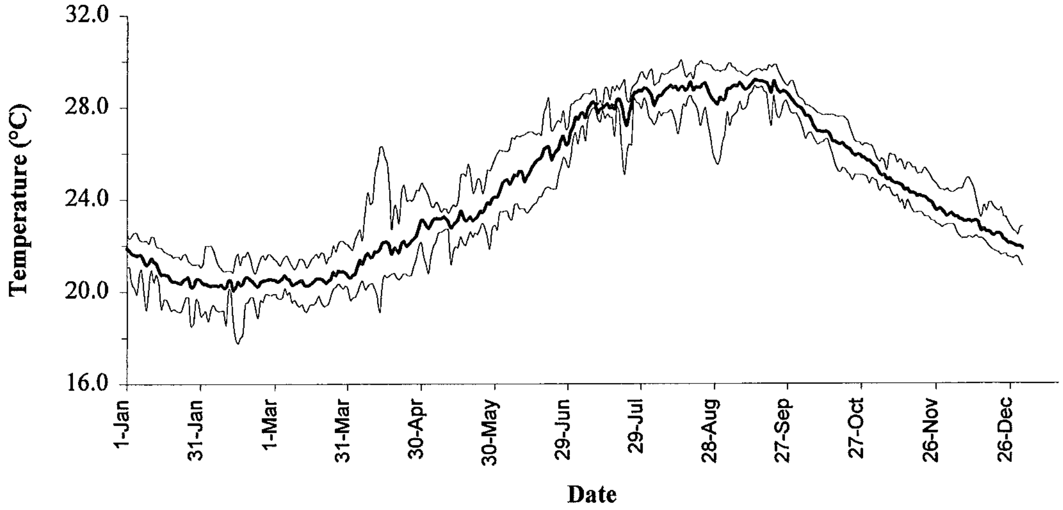

Fig. 2. The 7-yr average (heavy line) with maximum and minimum temperatures (thin lines) at the Flower Banks crests, displaying the typical annual cycle.

low, ~ 18 C, coincides with the SST minimum, and the high, ~ 21 C, occurs in fall to early winter (Robinson, 1973; Nowlin et al., 1998). Bottom offshore gradients vary seasonally (SAIC, 1989; Nowlin et al., 1998). Water temperature near the bottom at the shelf break is regulated at ~ 18 C by advection of warm water by Loop Current warm-core rings (Nowlin et al., 1998). Thus, an offshore gradient exists with warmer water near the coast. In summer, the horizontal gradient strengthens because of nearshore warming and the uniform bottom temperature near the FGB (McGrail, 1983).

Vertical temperature gradients separate a mixed layer, the thickness of which varies seasonally, from the deeper shelf waters. The minimum thickness (~ 20 m) occurs in April and increases to ~ 70 m in December/January (McGrail, 1983). Nowlin et al. (1998) observed a mixed layer in winter to about 100 m deep, created by surface cooling and mixing by strong winds. In summer, surface heating and light winds produce a shallower mixed layer.

Salinity.—The sea surface salinity (SSS) varies by seasons, vertically, and horizontally, reflecting changes in the general circulation and in river discharge. Following is a summary of a detailed analysis of seasonal salinity on the shelf conducted by Nowlin et al. (1998). The main offshore source of salty water is the Subtropical Underwater with a characteristic salinity of more than 36.2 at water depths of 50–100 m. Subtropical water is advected in from the core of LC warm rings and when these anticyclonic eddies interact with the shelf break near the FGB. In spring, the offshore SSS gradient increases in the offshore direction due to higher river discharge in nearshore areas. Near the shelf break, the SSS is more than 35, and increases to more than 36 near the bottom. Summer SSS is relatively low inshore and east of 95°W. West of this longitude, isohalines run offshore across the entire shelf and increase toward Texas. Near the FGB, the SSS is between 33 and 34, reflecting the Subtropical Underwater origin. Near the bottom, salinities increase in the offshore direction to 28.5°N. South of 28.5°N, salinity remains above 36. During fall, the average SSS is higher near the coast (29–30) and increases offshore to 36 or more. Bottom salinities are more than 36 near the shelf break. Early salinity measurements at the FGB varied between 31.5 and 36.5 from surface to bottom (McGrail, 1983). Measurements over 2 yr (1992–94) at LATEX program mooring 8, 30–48 km west of the FGB (Fig. 1), revealed a salinity range of 7 (30.4–37.4) at 13 m. At 100 m the range decreased to 1.2 (35.6–36.8) (Nowlin et al., 1998). Summarizing, at mooring 8, the 32-mo average salinity at 13 m is 35.5 with a range of 30.4–37.4; at 100 m, the mean salinity is 36.3 with a range of 35.6–36.8.

Low (~ 30–31) offshore salinities suggest a possibility of inshore waters reaching the FGB. This possibility was debated by Dodge and Lang (1983) and Rezak et al. (1990). However, McGrail (1983) indicated that low-salinity (30–31) water was confined to the near surface and would not affect the FGB's crests. In 1993, a year of above average river discharge, Nowlin et al. (1998) did not observe river water near the FGB.

CIRCULATION

Mean shelf circulation.—Cochrane and Kelly (1986) proposed a mean circulation for the LATEX shelf consisting of cyclonic nonsummer (September–May) flow and anticyclonic summer flow (June–August). The cyclonic cell consists of downshelf (Louisiana to Texas) nearshore flow and upshelf (Texas to Louisiana) flow near the shelf break. In summer, the nearshore flow clearly reverses, but the shelf edge current continues upshelf. This circulation is driven mainly by the annual cycle of the wind stress. The FGB are located within the year-round upshelf eastward mean flow along the shelf edge. Inner shelf to upper slope current measurements along 92°W by SAIC (1989) revealed a statistically significant mean current pattern consistent with Cochrane and Kelly's model. Near the shelf edge, the alongshelf component above 100 m was upshelf at ≤ 8 cm/sec. Below 100 m the flow was downshelf at 3–6 cm/sec. A surprising result in the SAIC (1989) data was the presence of a significant offshore flow at all depths over the outer shelf and upper slope. Monthly mean currents at 60 m over the East Bank flow upshelf, whereas the near-bottom mean currents tend to go offshore (McGrail, 1985).

The most comprehensive and recent data collected over the LATEX shelf (Rio Grande River to the Mississippi Delta) consist of 30 mo of current measurements and observations from several hydrographic cruises (Nowlin et al., 1998). Mean current patterns, stream functions, and current kinetic energy changes indicate a shelf divided at the 50-m isobath into inner and outer shelf provinces (Cho et al., 1998). In the inner shelf, alongshelf currents are directed downshelf most of the year, but reverse in summer (Fig. 3). Near the FGB (outer shelf), the mean over 30 mo of the 40-hr filtered alongshelf currents at 10 m are mostly upshelf at 4 cm/sec, but decrease to ± 1 cm/sec near the bottom. The 30-mo mean of the 40-hr filtered cross-shelf currents near the shelf edge are O(± 1 cm/sec). The 30-d filtered alongshelf and cross-shelf currents show no discernible patterns at annual time scales, i.e., downshelf vs upshelf. The 30-d filtered currents show alongshelf speeds of ~ 6 cm/sec at 10 m that decrease to ~ 1 cm/sec near the bottom; cross-shelf speeds decrease from ± 1.5 cm/sec at 10 m to ± 0.5 cm/sec near the bottom.

Fortnightly statistics of currents at 13 m (mooring 8, Fig. 1) during the LATEX-A program (DiMarco et al., 1997) showed that the mean flow was upshelf at 7.7 cm/sec; however, reversals do occur. At 13 m the largest upshelf flow was 74 cm/sec and the largest downshelf current was 55 cm/sec. At midwater (100 m) the up- and downshelf maximum speeds were similar at 69 and 66 cm/sec, respectively, with a mean speed of only 0.9 cm/sec directed downshelf. The mean offshore current at 100 m was only 0.6 cm/sec. The maximum offshore speed was 42 cm/sec and the maximum onshore speed was 38 cm/sec. Near the bottom (190 m), up- and downshelf maximum speeds decreased to 15 and 23 cm/sec, respectively, with a mean of 0.6 cm/sec headed downshelf. The highest offshore speed was 15 cm/sec and 11 cm/sec onshore, with a mean flow of 0.5 cm/sec directed onshore. These statistics indicate a large variability of currents at the shelf edge as well as large onshore–offshore flows (Nowlin et al., 1998).

Rose diagrams from mooring 8 (DiMarco et al., 1997) were sorted according to the downshelf (Fig. 4a) or upshelf regime (Fig. 4b). The 13-m roses were similar with eastward flows dominating. The westward flows were weaker and less frequent. The offshore component was more frequent (36% of time vs 26%) than onshore components during the upshelf regime. During the downshelf cycle, onshore components occurred 38% vs 27% for the offshore. Mid- and near-bottom level (100 and 190 m) current roses were nearly similar in both regimes. Comparing the occurrence of the alongshelf components, the upshelf flow was slightly more frequent. The onshore/offshore flows were significant. At the bottom level (190 m), currents were mainly directed offshore/onshore (occurrence frequency > 43%) with an upshelf flow occurring 19–22% of the time.

A duration analysis of mooring 8 data at 13 and 100 m (DiMarco et al., 1997) indicates that flows of 0–10 cm/sec lasted longest with spans of 117–184 hr. Flows of 10–20 cm/sec spanned 50–73 hr, and flows of 20–30 cm/sec lasted 41–46 hr at maximum. The average duration for all speed ranges was ≤ 14 hr and ≤ 7 hr for higher speeds. All the above current statistics apply best to the West Bank because its distance from the mooring is nearly equal to the longshore correlation scale, ~ 35 km (Li et al., 1996).

The LATEX-A shelf program findings can be summarized as follows: (1) they showed the existence of large interannual and intraseasonal

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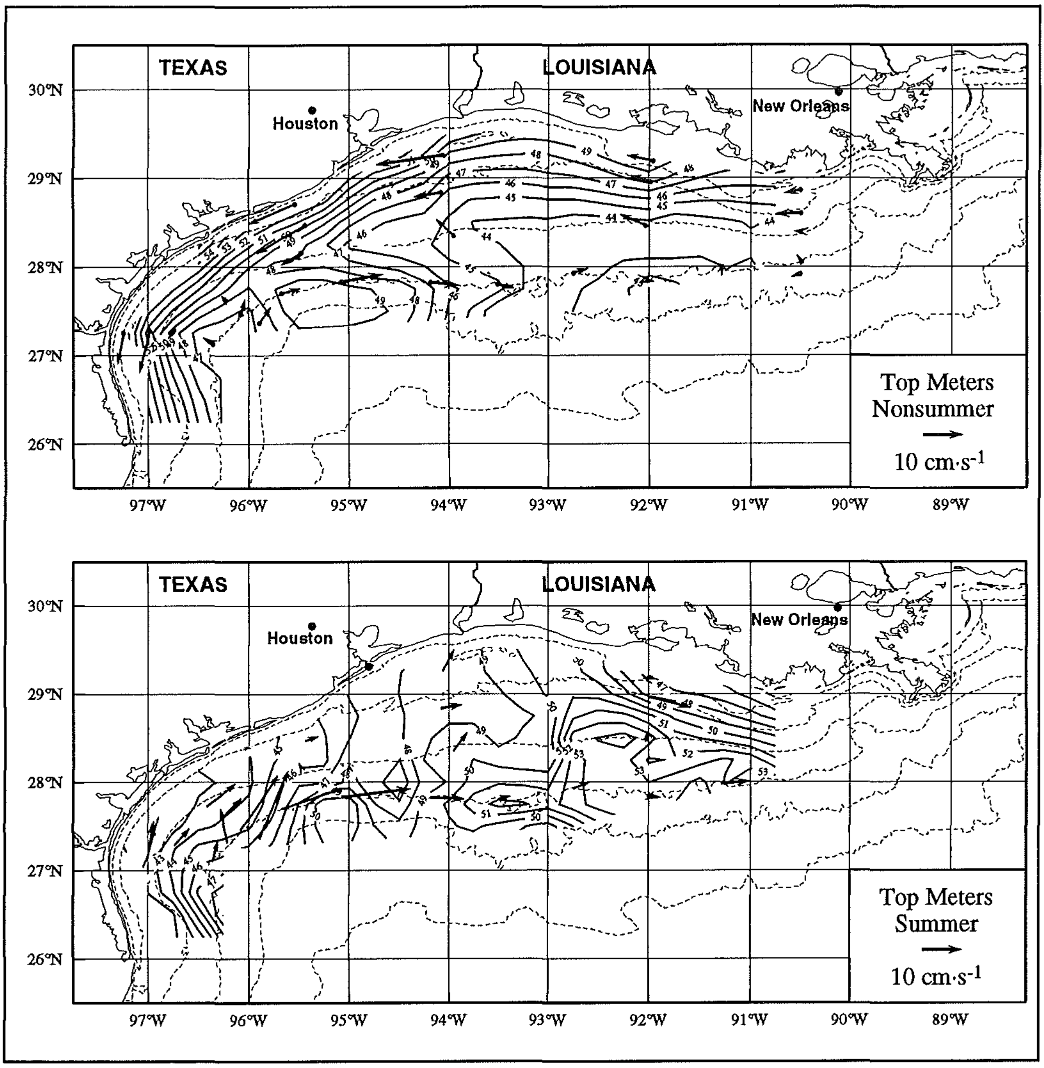

Fig. 3. Mean surface geopotential anomaly relative to 200 db showing the nonsummer and summer circulation pattern in the Louisiana–Texas shelf. Arrows represent 10-m average currents for nonsummer (September–May) and summer (June–August) during April 1992 through November 1994. Geopotential anomaly contours range from 43 to 54 dynamic cm in both panels. From Nowlin et al. (1998).

variability of currents (Fig. 5); (2) cross-isobath currents were frequent and strong (Fig. 6); and (3) the net mean eastward current at the shelf edge was caused by eddies (Nowlin et al., 1998). These findings confirm Oey's (1995) numerical model results that the shelf edge current is affected by LC eddies and eddy-driven intrusions and resulting patterns of convergences and divergences. The shelf edge current, while agreeing with Cochrane and Kelly's model, results primarily from interactions between LC rings, eddies, and the shelf break (Berger et al., 1996; Nowlin et al., 1998) rather than being driven by a cyclonic circulation cell.

Eddies.—Systematic observations in the Gulf of Mexico revealed a complex and rich field of LC rings and eddies (SAIC, 1989; Berger et al., 1996). The large LC warm rings or anticyclones, 200–400 km in diameter, (Fig. 7) are usually shed at 9- and 14-mo intervals (Vukovich, 1995) and travel mainly in a southwest direction at 2–6 km/d (Elliot, 1982; Cooper et al., 1990). However, some LC rings travel along the upper slope off Louisiana. A ring's life span is about one year, so usually two or more LC rings reside in the western Gulf. Smaller eddies, cyclones or cold core eddies, and anticyclones of ~ 100 km in diameter over the

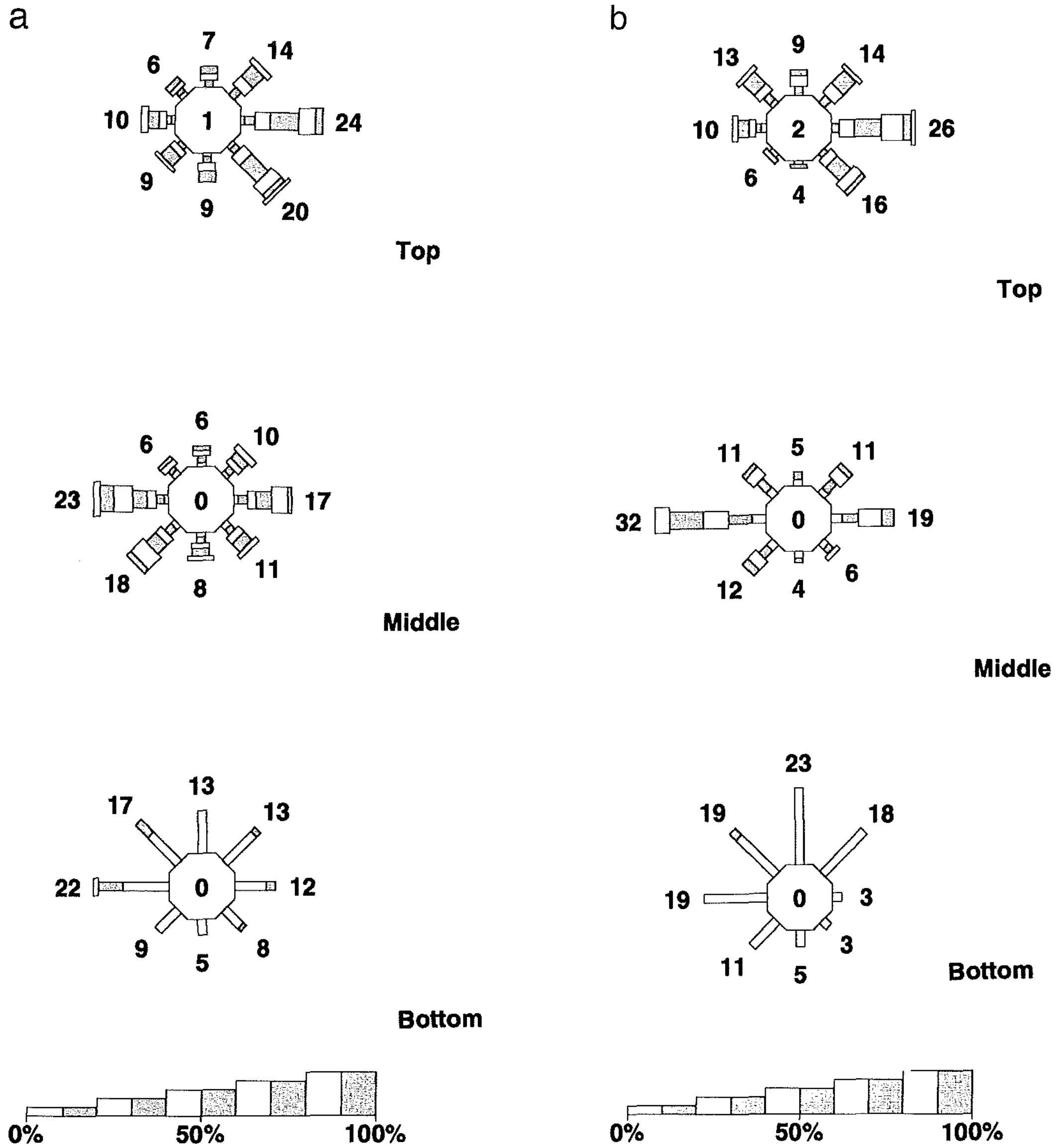

Fig. 4. Current roses corresponding to the downshelf (a) and upshelf (b) current regimes at mooring 8 from the LATEX-A program.

northern slope in the Gulf (water depths 200–2,000 m) have been detected (SAIC, 1989; Hamilton, 1992). Still smaller eddies (cyclones and anticyclones) on the order of 30–50 km diameter commonly reside over this slope (Fig. 8) (Berger et al., 1996). Anticyclones have strong topographic signals and, from fall to spring, surface thermal signals; therefore, monitoring and tracking can be performed with remote sensing (thermal or altimetry satellites) techniques. The tracking of cyclones, however, necessitates the use of satellite altimetry because cyclones often lack a surface thermal expression.

The 100-km cyclones move onto (off) the slope when on the western (eastern) side of a large LC anticyclone. These cyclones displace isotherms ~ 150 m vertically, which is comparable to displacements found in LC rings (Hamilton, 1992). The residence time of these eddies over the slope can be up to 6 mo (Hamilton, 1992; Berger et al., 1996). The smaller eddies can mask the currents induced by larger eddies at the shelf edge at subtidal frequen-

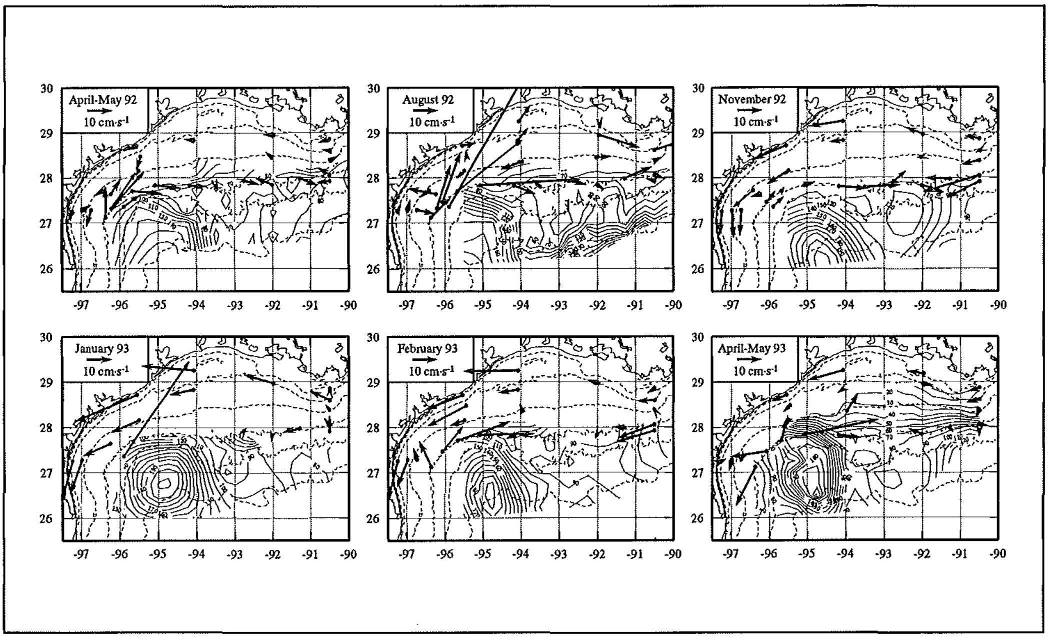

Fig. 5. Vectors of average currents at 10 m over the panel period plus preceding 14 d. Depth contours of the 20 C isotherm over the slope range from 70 to 210 m. From Nowlin et al. (1998).

cies. Presence and interactions of all eddy scales appear to be an important factor for LC ring paths (Berger et al., 1996).

Interaction of counter-rotating eddies is a mechanism for water exchange between the shelf and upper slope (Fig. 9) (Berger et al., 1996). Sahl et al. (1993) discussed hydrographic and nutrient data to show that the alongshelf component of the shelf break current can induce Ekman upwelling, creating high nutrient concentrations at depths of ~ 50 m or near the base of the mixed layer. Onshore flux of warm-core eddy water having low concentrations of particles brings fewer materials across the shelf edge, but offshore flux by cyclones and between counter-rotating eddies results in the seaward flux of particles. Because most cross-shelf water exchange occurs in the upper water column and because nutrient concentrations increase with depth, exchange of nutrients by cross-shelf transports may not be affected (Sahl et al., 1997). A cyclone–anticyclone pair (Fig. 9) affects productivity over the upper slope by two mechanisms: raising cold, nutrient-rich water to the photic zone and removing nutrient-rich water from the shelf between these eddies, mainly in the western Gulf (Fargion et al., 1996). Thus, eddies appear to be a driving force of shelf break currents and affect the water mass properties, heat, and particle transports at the shelf edge. Shelf edge currents so induced are not seasonal currents, but intermittent flows with time scales of weeks (Berger et al., 1996).

Water transport.—Mass transport is important because it replenishes the nutrient and oxygen supply to the reef communities. The alongshelf transport near the FGB averages about 0.4 Sv (1 Sv = 10^6 m^3/sec) in summer and decreases to about 0.2 Sv in nonsummer periods; the record mean transport is less than 0.1 Sv. Cross-shelf transports are 0.2 Sv in summer, 0.1 Sv in nonsummer periods, and a mean of 0.1 Sv (Bender and Reid, unpublished). These transport estimates agree with those by Oey (1995).

Daily currents.—Tidally driven currents have been analyzed in more spatial detail by the LATEX-A program because of the extensive mooring array design that provided current data over the entire shelf (DiMarco and Reid, 1998). The data showed that, near the FGB, the tides contribute ~ 10% of the current energy available in the 8- to 40-hr band. The root mean squared current amplitude of all tidal constituents analyzed near the FGB was only about 3 cm/sec. The strongest tidal current was the K1 component, and near the FGB it equals the O1 component with a current amplitude of nearly 1–2 cm/sec. Diurnal tidal currents exhibit strong vertical shear and clock-

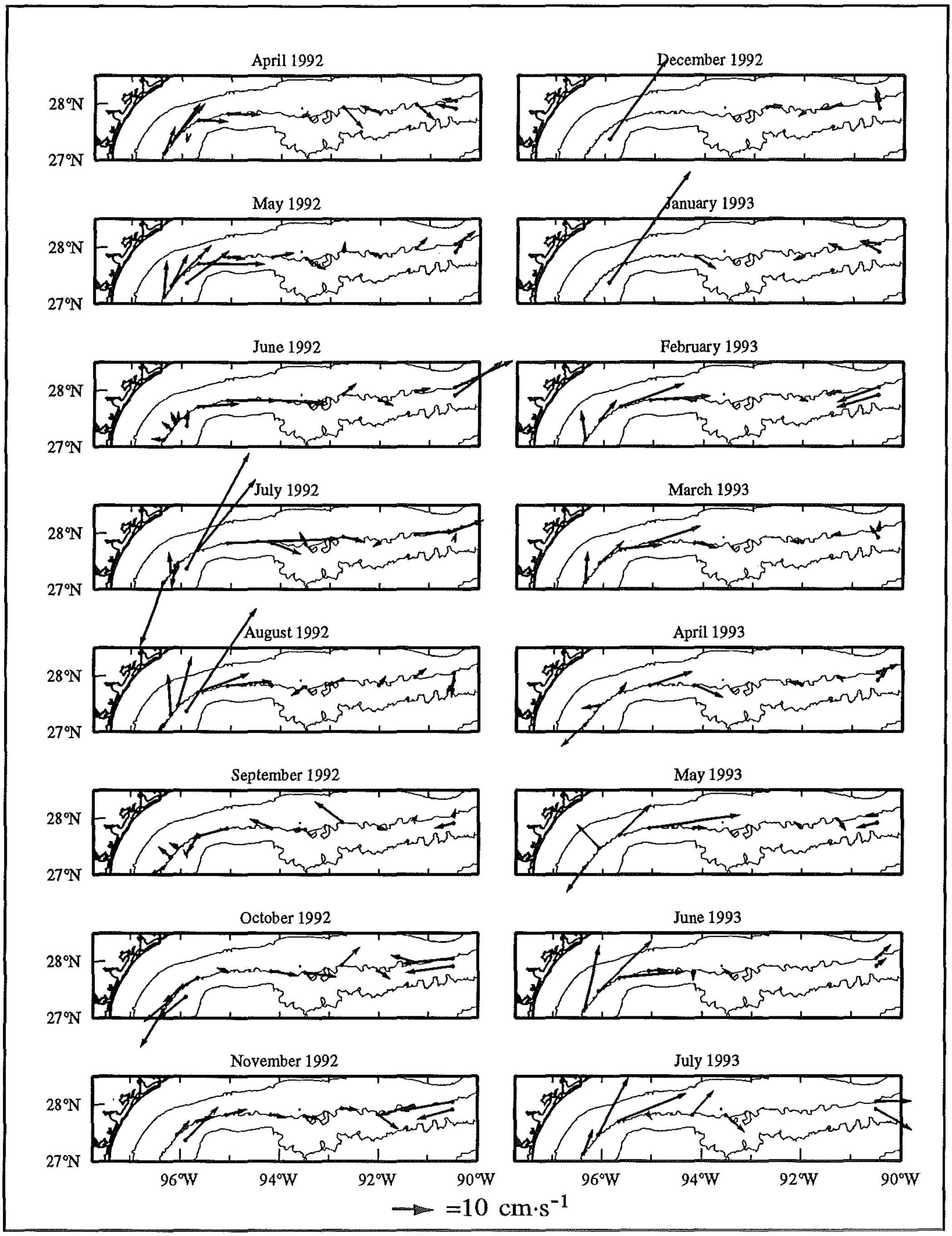

Fig. 6. Forty-hour, low-passed, 10-m monthly mean vectors showing the influence of eddies at the shelf edge. The observation period is from April 1992 to July 1993. From Nowlin et al. (1998).

wise rotation. The M2 component dominates the currents at semidiurnal periods. Near the FGB, the amplitude of this component is 1–2 cm/sec and vertically sheared. The semidiurnal currents rotate clockwise. The M2 component differs from the diurnal components in its current phase change across the shelf (western sites lag those on the east) due to anticlockwise motion of M2 component around the Gulf of Mexico. Estimates of tidal currents

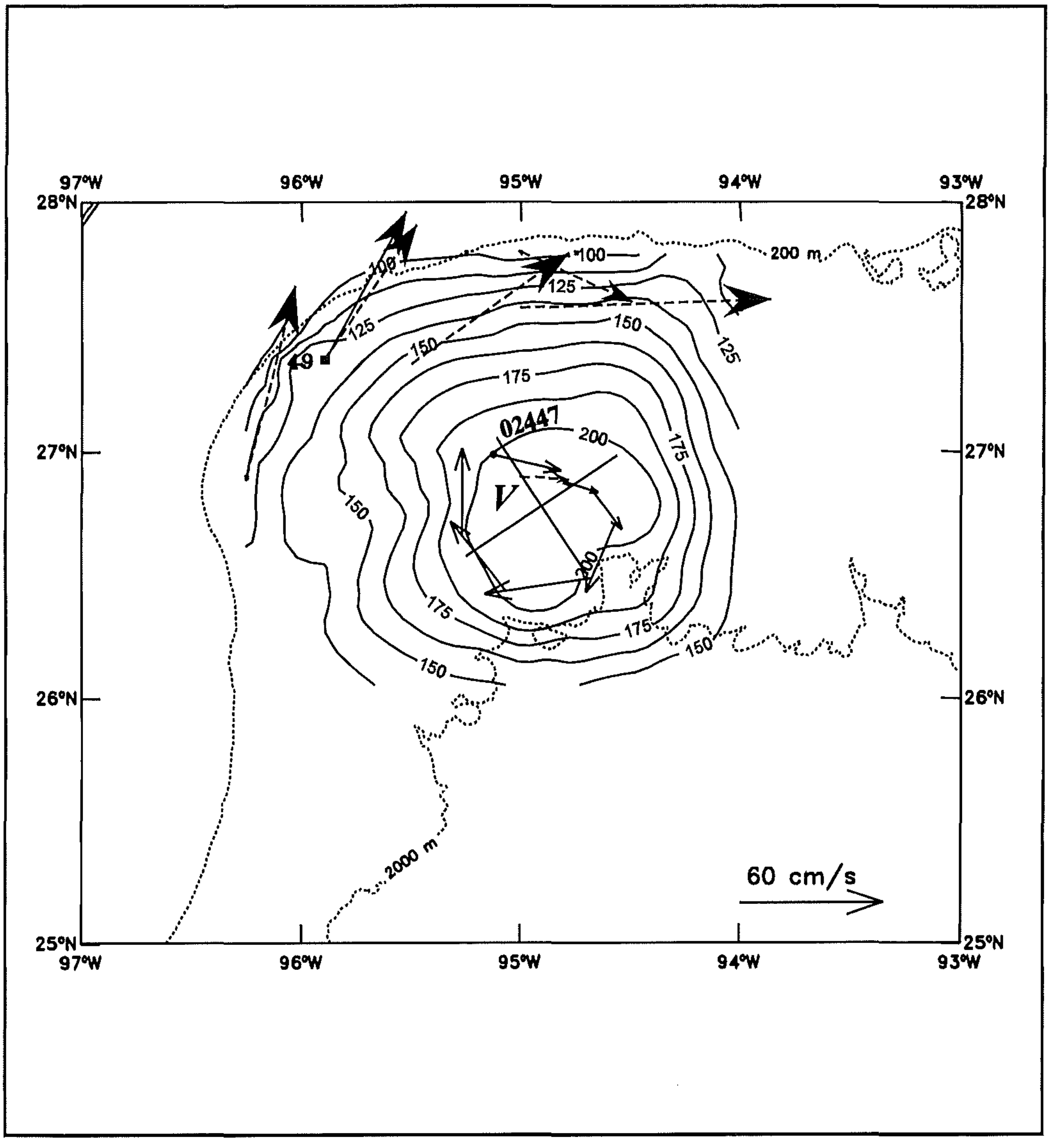

Fig. 7. Topography of the 20 C isotherm based on LATEX-C data for Eddy V. Arrows near the center are daily mean currents derived from Drifter 02447. Solid and dashed arrows from the squares represent daily low-passed current averages at 12 and 100 m on 5 Jan. 1993 from LATEX-A measurements. From Berger et al. (1996).

from shorter records at the FGB are 1–5 cm/sec for the M2 component. Currents of the K1 component are 2–5 cm/sec with a maximum of 9 cm/sec (McGrail, 1983).

Inertial motions with periods of 22–28 hr were observed over the LATEX shelf (Chen et al., 1996; Nowlin et al., 1998). These inertial currents rotate clockwise, persist for 3–5 d, and have amplitudes of 20–30 cm/sec (Chen et al., 1996), accounting for ~ 50% of the energy in the 8–40-hr band (Nowlin et al., 1998). The current amplitudes of inertial oscillations decayed with depth, and their vertical phase differences depended on the water column stratification (McGrail, 1983). Inertial motions were maximized at the shelf edge and decayed both onshore and offshore. Strong meteorological events, e.g., hurricanes and extratropical cyclones, generated strong (current amplitudes > 60 cm/sec) inertial motions.

Extreme events.—Tropical cyclones are extreme events that affect the FGB and their associated reef communities. In July 1979 three tropical

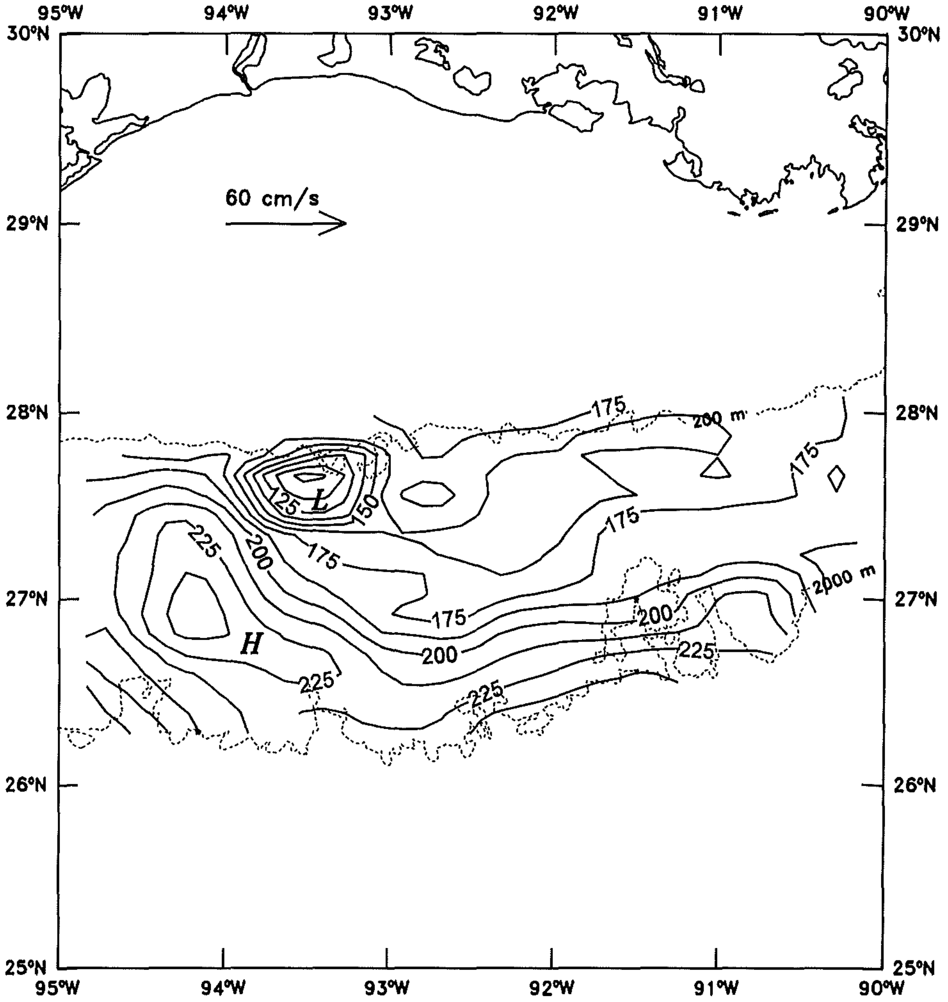

Fig. 8. Topography of the 15 C isotherm from GulfCet data on 2 Sept. 1993. Notice the cold ring (L) near the 200-m isobath centered around 93.5°W. Also notice the warm ring (H) centered around 27°N and 94°W. From Berger et al. (1996).

storms (Bob, Claudette, and Elena) passed near the FGB (McGrail, 1983). More recently in August 1992, Hurricane Andrew crossed the LATEX shelf between 90° and 92°W or ~ 350 km east of the FGB (Nowlin et al., 1998). Observed hurricane effects consisted of an acceleration of the flow, reversal of currents from upshelf to downshelf, generation of inertial os-

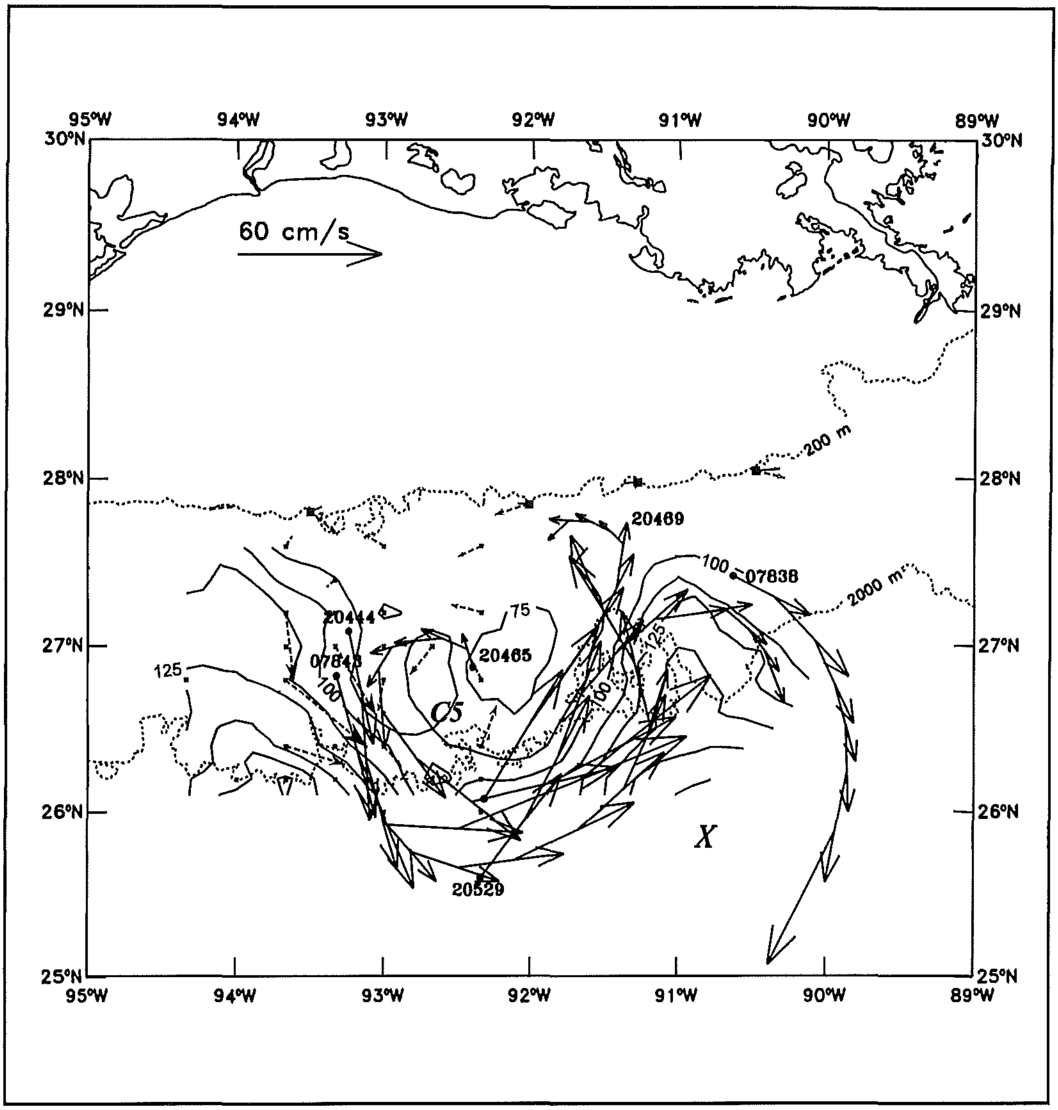

Fig. 9. Topography of the 20 C isotherm in December 1993 showing a cyclone (C5)–anticyclone (X) pair with very strong currents (long vectors) in between. Arrows are daily mean current from Sculp drifters 20444, 20465, 20469, and 20529 from 15 Dec. 1993 and from LATEX-A drifters 07838 and 07843 starting on 20 Dec. 1993. Solid and dashed arrows from the squares represent daily low-passed current averages at 12 and 100 m on 21 Dec. 1993 from LATEX-A measurements. Arrows from crosses represent 25–100 smoothed AXCP current profiles. From Berger et al. (1996).

cillations and strong near-bottom currents (> 20 cm/sec) (McGrail, 1983; Bright et al., 1985). Storm-generated surface waves in the Gulf attained large wave heights (H ~ 5–9 m) and long periods (T ~ 10–16 sec) (McGrail, 1983; Nowlin et al., 1998). These hurricane waves induced significant motions—orbital speeds of 0.7–1.4 m/sec estimated with linear wave theory near the FGB. These speeds are sufficient to initiate movement of coarse sands and finer sediments. After Hurricane Andrew, SST decreased 1–2 C at various points on the shelf and near the FGB (Breaker et al., 1994). The SST decrease is caused by entrainment mixing at the thermocline base combined with latent and sensible heat exchange (Shay et al., 1992).

Orography.—The vertical and horizontal dimensions of the FGB are such that orographic effects on the currents need to be considered. Initial calculations showed flow divergence and lateral deflection around the FGB with small vertical displacements (~ 10 m) of water parcels at the point of divergence. These effects are caused by rotation, friction, and water column stratification. On the lee side of the bank, data suggest the presence of waves and vertical displacement of the isotherms. Upper water column isotherms are depressed, but near-bottom isotherms rise when compared with upstream conditions. The biological implications for the reef community are that near-bottom water does not rise over the FGB and top reef organisms are mostly immersed in clear, warm water year-round and subjected to patterns that resemble near-surface conditions (McGrail, 1983).

SOLAR RADIATION

Solar radiation is crucial to hermatypic corals because of their symbiotic relationship with zooxanthella algae, which are important for calcification and nutrient recycling (Muscatine, 1973). High inputs of solar radiation has been linked to coral bleaching episodes (Brown, 1997). McGrail (1985) examined light transmission around the FGB and discovered a near-bottom nepheloid layer. The nepheloid layer, defined by ≤ 60% transmissivity, was always confined to within 20 m of the bottom and was caused by high concentrations of resuspended soft sediments. The upper 80 m had transmissivities exceeding 60%.

Optical measurements at 92°W (SAIC, 1989) showed that, near the shelf edge, suspended particle concentrations varied between 0.15 and 2.47 mg/liter and averaged 1.25 mg/liter over a 2-yr period. Measurement of suspended particulate matter (SPM) during the LATEX-A program revealed large interannual and seasonal variations related mainly to the river discharge variability (Nowlin et al., 1998). Seasonally, the maximum averaged suspended particulate matter occurs in fall, minimum SPM in summer, and intermediate SPM in spring. SPM and other observations suggest that this shelf is divided west–east at about 93°–94°W (Nowlin et al., 1998). In both sectors, the maximum SPM concentrations (≲ 20 mg/liter) occurred inshore of the 50-m isobath. SPM concentrations near the FGB were < 1 mg/liter on almost every cruise. These data revealed that in south Texas there is frequent offshore SPM transport. This offshore transport is related to the presence of offshore LC ring–eddy pairs. Ring–cyclone pairs create alternating areas of onshore–offshore SPM transport that extend near the FGB and down to midwater over the shelf edge. The SPM values reported by SAIC (1989) and Nowlin et al. (1998) are at least one-half to one order of magnitude less than those found in near-shore turbid waters. SAIC (1989) found the photic zone to cover the upper ~ 65 m of the water column. Based on the optical properties at the shelf edge, the water type was deep oceanic, blue water, which allows deep penetration of photosynthetically active radiation. Through optical observations, they detected deep Gulf water intrusion onto the shelf. The penetration of ultraviolet (UV) radiation near the shelf edge varied seasonally. The depth of the 1% level increased from 37 m in winter to an estimated 67 m in July. Thus, reef biota at the crests of the FGB (17 m) receive ~ 10–20% of the surface UV radiation. Vertical radiation attenuation in this region is due primarily to yellow substances, suspended particles, and water properties. The yellow substances are from the Mississippi and Atchafalaya River outflows and are an indirect effect of both rivers because their plumes never reach the FGB (SAIC, 1989).

DISCUSSION AND CONCLUSIONS

Because the FGB lie ~ 200 km off the Louisiana coastline, they are not directly influenced (direct impact by the river plume) by the Mississippi and Atchafalaya Rivers runoff (Rezak et al., 1990). Direct runoff effects would include large volumes of low-salinity water, large nutrient and sediment loads, and pollutants. Although surface sediment plumes of Mississippi or Atchafalaya River origin have not been observed near the FGB (Walker, 1996), low-salinity (30–31) water has made it to the FGB during periods of high river discharge (Dodge and Lang, 1983; Nowlin et al., 1998). But this water does not penetrate deep enough to affect the corals (McGrail, 1983). Water of low salinity (~ 21) down to 11 m and of less salinity to 26 m have been observed in squirts (Walker et al., 1996). Such low salinities could be harmful to the FGB; however, these features are short lived and seldom reach the FGB, so their effects are very small. The location also places the FGB reefs outside the hypoxic areas in summer (Rabalais et al., 1994). Frequent and direct riverine influence would be deleterious to the development of coral reef communities at the FGB.

The elevation of the FGB places their crests within the mixed layer; thus, coral reef communities at their crests experience temperatures well within the accepted range (16–30 C) of coral growth (Stoddart, 1969) and a seasonally modulated annual temperature range of ~ 11 C. Communities near the surrounding seafloor (100 m) experience cooler temperatures and ~ 2 C annual temperature variation. The mixed-layer temperature range is twice that experienced by Caribbean coral reefs, but similar to that of Florida reefs (Glynn, 1973). Coral bleaching episodes at the FGB during summer high temperatures (≥ 30 C) have been documented (Gittings et al., 1992b; CSA, 1996). These bleachings and subsequent recoveries suggest that these corals live near their thermal tolerance limit and have adapted to the annual temperature range in this region through acclimatization (Brown, 1997). Although solar radiation has been shown to induce coral bleaching (Brown, 1997) the radiation levels at the FGB tops are not enough to cause these episodes. It is noteworthy that SST has been identified as a control of coral growth in the FGB (Dodge and Lang, 1983).

The tops of the FGB experience higher salinities (~ 37) and larger salinity fluctuations (~ 7) than near-seafloor communities with a range of only ~ 1.2. These values, though, are within the accepted normal salinity range for corals (23–37) (Kleypas, 1997). Observations of low-salinity waters (~ 30) near the FGB (Cochrane and Kelly, 1986; Nowlin et al., 1998) have been explained as the return flow of inner-shelf freshwater (Cochrane and Kelly, 1986). Data from ARGOS-tracked drifters (P. P. Niiler, W. R. Johnson, and N. Baturin, unpubl. data) show that this water comes from south Texas and Mexico, is pushed offshore, and returns eastward via the shelf edge (Fig. 10). Walker et al. (1997) identified two other paths by which shelf water could reach the FGB. Water from off the Texas shelf moves eastward near the shelf edge and reaches the vicinity of the FGB. The second route is a cyclonic circulation between in the LATEX shelf (Walker et al., 1997: fig. 2). But again, the influence of low-salinity water is not deleterious. Salinity and temperature data suggest that LC eddies interact with the shelf edge by advecting warm, salty water onto the outer shelf and moving cooler, fresher shelf water offshore (Nowlin et al., 1998).

Freshwater intrusions onto the outer shelf preceded recurrent episodes of discolored waters mostly in July at the FGB when short-lived planktonic blooms (e.g., *Trichodesmium*) occur over and around the FGB (G. Rinn, pers. comm.). Furthermore, green discolorations at the FGB have, on occasion, been associated with sudden brief spells of cooler waters (temperature drops from 29 to 24 C). *Trichodesmium* blooms usually occur when seawater temperature is at 28–29 C preceding the August–September temperature peak.

The FGB lie in the LATEX outer shelf province (Nowlin et al., 1998), influenced mainly by deepwater physical processes and indirectly influenced by river runoff. Near the shelf edge, LC eddies and cyclones affect oxygen availability by sinking or rising water parcels. The sea surface near the FGB is 90–110% oxygen-saturated year around. Oxygen decreases from surface saturation (90–110%) to 4–6 ml/liter at 30 m, and at depths > 100 m it is ≤ 3 ml/liter (CSA, 1996; Nowlin et al., 1998). LC anticyclones depress water parcels (~ 50 m), increasing the oxygen concentration by ~ 2 ml/liter between 70 and 100 m. Above 70 m the oxygen concentration is about the same. Cyclones raise deepwater parcels (~ 30 m), decreasing the oxygen by 0.4 to 1.2 ml/liter between 30 and 70 m (Nowlin et al., 1998). Cyclone- and anticyclone-induced changes should not affect the FGB corals at the crest because these changes occur below 20 m, or deeper than the crest. Should a change occur, the resulting oxygen decline would be only 20%.

Nutrient concentrations (nitrate, phosphate, silicate), like oxygen, are affected by eddies. The nutrient concentrations change opposite to those of oxygen because they increase with depth on the shelf, but most significantly over the upper slope (Nowlin et al., 1998). Changes in nutrient concentrations caused by anticyclones and cyclones were assessed by comparing inside to outside concentrations. Anticyclones cause large nutrient changes: nitrate decreases ≤ 15 μmol/liter (from ~ 15 outside to 0 inside), phosphate ~ 1 μmol/liter (from ~ 1 outside to 0 inside), and silicate ~ 4 μmol/liter (from 5 outside to 1 inside). Cyclones cause smaller nutrient increases: nitrate ≤ 5 μmol/liter (from 15 outside to 20 inside), phosphate ~ 0.1 μmol/liter (from 0.6 outside to 0.7 inside); silicate by ~ 1 μmol/liter (from 5 outside to 6 inside) (Nowlin et al., 1998). The vertical displacements inside cyclones do not reach the FGB crest, except for silicate, so only the seafloor communities near the FGB could benefit by these enrichments. The silicate enrichment near the surface, though, should benefit all reef organisms that use it.

Eddies near the FGB affect zooplankton availability to corals. LC anticyclones have low concentrations of zooplankton (Biggs, 1992), so when they induce shelfward water transport, they effectively decrease zooplankton availability. Cyclones are richer in zooplankton (Biggs

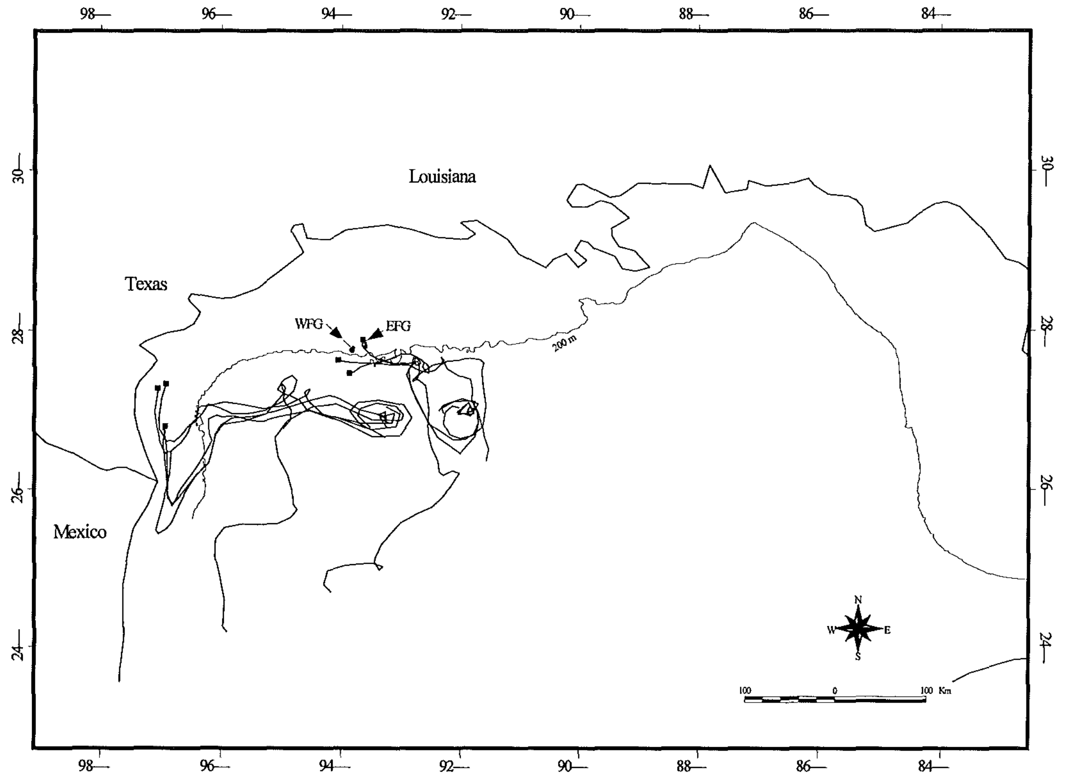

Fig. 10. Trajectories of Argos-tracked drifters over LATEX shelf released in February 1994 and 1995 during the Sculp program. Solid squares mark the start of each trajectory.

et al., 1991), and onshelf transport should enrich the shelf waters. However, the main mechanism for cross-shelf transport is flow between counter-rotating eddies. Squirts transport midshelf water offshore with higher particle and nutrient content, increasing their availability to the corals. If the counter-rotating eddies transport surface slope water onshelf, particles and nutrients will be reduced.

This review suggests four possible circulation links between the FGB and other coral reefs within the Gulf of Mexico. These possible links have scientific and reef management implications. First, the western boundary current, or Texas current, which may be present most of the year (Sturges, 1993), can bring coral larvae and nutrients from Mexico, linking these two reef communities (Fig. 10). Bright et al. (1991) estimated travel times of 4–9 wk for larvae from Mexican reefs reaching near the FGB. The shelf edge current flows mostly eastward during spawning (after the August full moon; Gittings et al., 1992a) and should induce a net eastward transport of water and materials, but most importantly of larvae. According to estimates of current duration, the alongshelf displacements calculated (50–66 km) are sufficient to ensure larva exchanges between the West and East FGB given their small separation. The occurrence of hermatypic corals on oil and gas platforms east of the FGB suggests eastward transport of coral larvae (Bright et al., 1991; Scarborough-Bull and Kendall, 1994). Two additional mechanisms linking the FGB to other Gulf of Mexico reefs are LC eddies that travel westward and prevailing surface currents directed westward (U.S. Navy, 1986) in the northern Gulf. Both of these processes can advect material or larvae from the Caribbean Sea and from coral reefs in the Yucatan peninsula. Biggs (1992) found zooplankton and phytoplankton, albeit low values, of Caribbean origin inside warm-core eddies in the western Gulf. This observation supports a potential link between the FGB and the Caribbean through LC rings. These LC rings and large eddies can influence the shelf edge for ~ 2 mo (estimated with a propagation speed of 4 km/d and ~ 200 km diameter), allowing enough time for advected materials to reach the FGB. This time compares favorably with residence times of 6 mo for cyclones over the

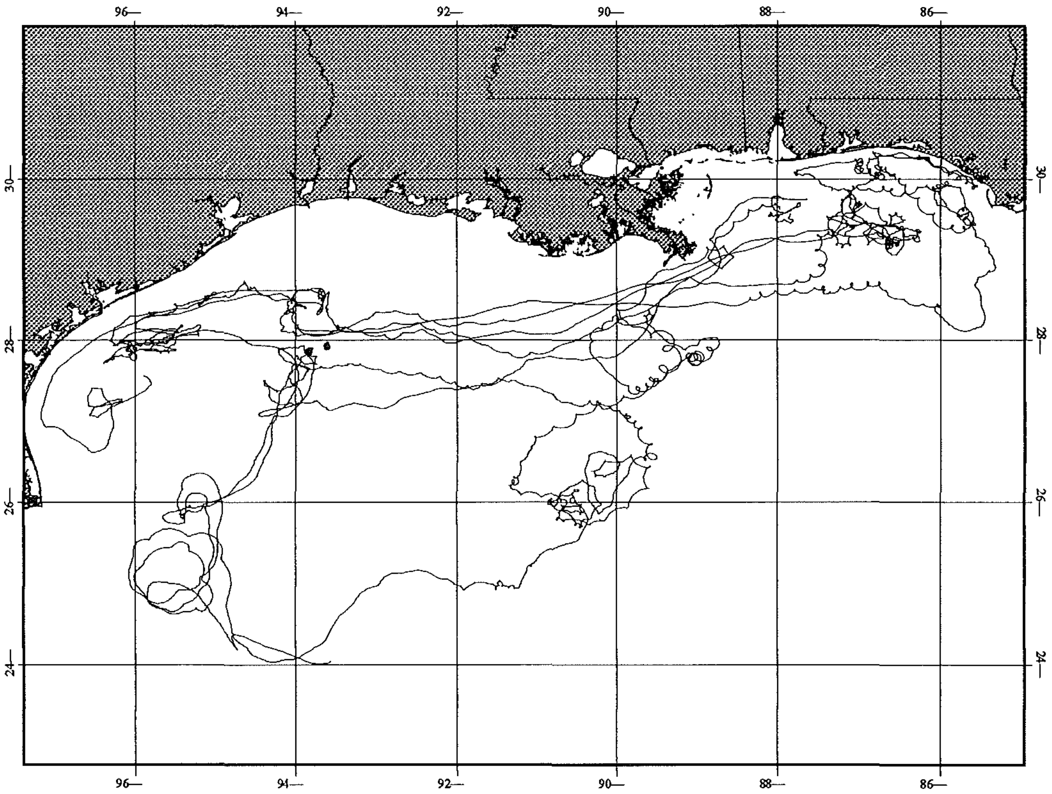

Fig. 11. Trajectories of Argos-tracked drifters released in the northeastern Gulf of Mexico in November 1995 during the Inner Shelf Study, passing within 10 miles the West and East Flower Garden Banks.

slope (Hamilton, 1992). Historic drift card releases in the Caribbean, Yucatan Channel, and eastern Gulf have landed in Texas and Louisiana, suggesting a link between the southern and northern Gulf of Mexico reefs (Parker et al., 1979; unpubl. data). Another potential link with the FGB was recently observed through ARGOS-tracked drifters released in the northeastern Gulf of Mexico. Under certain conditions, these drifters bypassed the Mississippi Delta and made it to the FGB in ~ 1 mo (Fig. 11) (W. R. Johnson, pers. comm.). In contrast, the FGB may act as a source of larvae for the Florida Keys, but this eastward flow is not common because of the predominantly westward surface currents (U.S. Navy, 1986). Although such eastward flows from the FGB have been observed with cards and satellite-tracked drifters, this path might prove deleterious for coral larvae because they might pass too close to the large river runoff dominating the inner shelf. Satellite-tracked drifter data (P. P. Niiler et al., unpubl. data) show 22 of 300 drifters passing within 6 km of the FGB over a 1-yr period. Although most tracks show net offshore motions, some had eastward displacements, but none reached the Florida area during the observation period. Card drifters, however, reached Florida. At the same time, the FGB's position placed them under the influence of deepwater physical processes, such as LC rings and associated eddies. Deep-water processes regulate the winter minimum temperature that allows reef growth, but in summer these same processes help temperatures reach levels that may induce coral bleaching. Deep-water processes also regulate salinity and nutrient levels that enhance coral growth. In this sense and also because of their latitudinal location, the FGB can be classified as near-marginal reefs. The circulation around the FGB suggests that larvae are easily exchanged between both banks and that these reefs are linked to the Caribbean Sea, the Yucatan Peninsula, and the eastern Gulf of Mexico. Variable circulation processes in the region suggest that the FGB could also act as repositories for coral reef biota.

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