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Low-Frequency Circulation on the Texas-Louisiana Continental Shelf

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For the Texas-Louisiana coast west of 92.5°W, long series of data from near Freeport, Texas, together with shorter series from other locations show strong response of coastal current to wind stress in agreement with coastal jet concepts. We infer from coastal winds, scattered current measurements, and distributions of sea-surface salinity and geopotential that a cyclonic gyre elongated along the shelf is the dominant feature of the prevailing shelf circulation. The inshore limb of the gyre is the coastal jet driven by wind with a west or southward (downcoast) component which prevails along much of the coast except in July–August. Because the coast is concave, the shoreward prevailing wind results in a convergence of coastal currents, which marks the downcoast extent of the gyre. Corresponding to the convergence is a seaward flow which forms the southwest limb of the gyre. A prevailing countercurrent (north or eastward flow) along the shelf break includes the outer limb of the gyre. The eastern, shoreward-flowing limb of the gyre corresponds to divergence along the coast centered near 92.5°W. The convergence at the western or southern end of the gyre migrates seasonally with the direction of the prevailing wind, reaching south of the Rio Grande mouth in fall and the Cameron offing in July. The gyre is normally absent in July, but reappears in August–September when a downcoast wind component develops.

1. INTRODUCTION

Although a large body of information on the waters and currents of the Texas-Louisiana Shelf has accumulated in the last 40 years (see, for example, *Angelovic* [1976]) and important investigations of the coastal currents at a few locations on the shelf have been made, a coherent picture of the prevailing, low-frequency circulation on the shelf has in our opinion not yet been achieved. We attempt here to provide at least a coherent sketch of the circulation.

The Texas-Louisiana Continental Shelf (Figure 1) includes the shelf region from the Rio Grande to the Mississippi Delta. The shelf break lies in depths from about 75 to 100 m. The coast is arcuate, concave to the southeast. Off the Rio Grande the shelf is narrow, about 85 km in width; it widens to about 200 km off Cameron, Louisiana; and then nearly disappears at the Mississippi Delta. In its wide central portion, the shelf is fairly flat. Near the delta there is a submarine canyon. A number of reefs lie along the outer edge of the shelf. In contrast to the shelf, the topography of the continental slope is quite complex.

The Texas-Louisiana Shelf is considerably shallower, and, over much of its length, wider than the shelf off the Pacific coast of the United States. It is comparable in depth to the West Florida Shelf and the shelf off the Atlantic coast of the United States. Unlike the latter shelves, however, the Texas-Louisiana Shelf does not have a huge current lying at or near its break.

A considerable body of data from many locations shows that the alongshore component of current is strongly coherent with the alongshore component of wind stress. *Winant* [1980], for example, reviews the evidence for wind-driven coastal currents. The response mechanism of coastal currents to wind is discussed, for example, by *Csanady* [1982]. In the upper layers at some distance from a coast, the component of wind stress parallel to the coast induces a transport normal to the coast (Ekman transport). Because of the coastal boundary such transport leads to upwelling or downwelling near the coast. To compensate for the cross-shelf transport in the upper layers, a transport in the opposite direction must occur in the deeper layers, an "adjustment drift." This drift is deflected by the Coriolis force (to the right in the northern hemisphere). The alongshore component of the deflected drift reaches equilibrium when its Coriolis force is balanced by the cross-shelf slope of an appropriate isobaric surface, that is, when geostrophic balance is achieved. *Chew* [1964] seems to have been the first to consider such a response of current, and therefore sea level, to alongshore winds in the Gulf of Mexico coastal regions.

Wind is a primary cause of currents along much of the Texas-Louisiana coast. Strong coherence between alongshore stress and alongshore current has been found for coastal locations by *Smith* [1978, 1979], *Kelly et al.* ([1982], for example]. *Crout et al.* [1984], and *Lewis and Reid* [1985]. Along that coast, however, *Chuang and Wiseman* [1983] have found indications that there is at least one region, one with extensive shallow water off Eugene Island, Louisiana (Figure 1), where at least in winter the relation to alongshore stress is very weak. Studying sea level, which is clearly linked to alongshore current according to the model outlined above, they have shown that its only strong relationship off Eugene Island is to the cross-shelf wind-stress component.

In the following we discuss the responses of current to wind along the Texas-Louisiana coast as they vary through the year. West of 92.5°W, approximately, current is influenced primarily by the alongshore component of wind stress; east of 92.5°W, however, such influence is apparently much weaker. We separate our discussion of responses along the coast accordingly. Finding patterns of convergence and divergence in the annual progressions of coastal currents, we consider indications of cross-shelf flow. We also note the available information about current near the continental shelf break. We conclude by presenting evidence that the coastal, cross-shelf,

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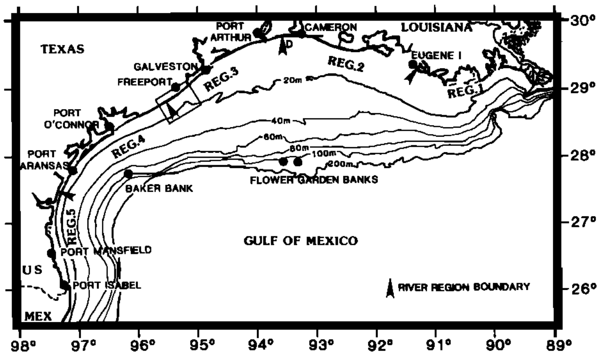

Fig. 1. Map of the Texas-Louisiana Continental Shelf showing locations discussed in text.

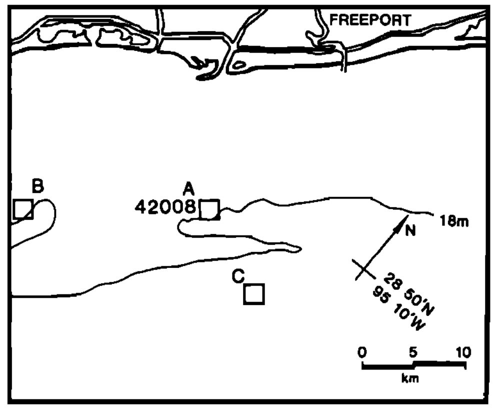

Fig. 2. Map of the Bryan Mound Strategic Petroleum Reserve Brine Disposal study region off Freeport, Texas, showing positions of current meter moorings. Wind measurements were made at NDBC Station 42008. See Figure 1 for the location of region.

and shelf-break currents form a coherent system which prevails over the shelf during much of the year.

2. Coastal Currents in Response to Wind Stress

2.1. *Currents and Wind Stress off Freeport, Texas*

In order to establish firmly the relationship between wind stress and coastal currents, we turn to the longest series of current and nearby wind measurements in a Texas-Louisiana coastal region of which we are aware, measurements taken off Freeport, Texas, between early 1978 and September 1984. Table 1 and Figure 2 give their locations. The oceanographic and some of the meteorological data were collected by the Texas A&M University Environmental Engineering Division of the Department of Civil Engineering for the U.S. Department of Energy Strategic Petroleum Reserves Office. The National Oceanic and Atmospheric Administration Data Buoy Center (NDBC) took most of the meteorological measurements. Summaries of the data are given in *Kelly et al.* [1980, 1981, 1982, 1983*a*, 1984*b*, and 1985*a*].

Wind data obtained for more than six years at NDBC Station 42008, located on a platform off Freeport, Texas (Table 1, Figure 2), permit us to characterize the prevailing wind regime in terms of the monthly mean wind stresses (vector means). We calculate the stress τ from wind speed U by use of the relation $\tau = \rho_A C_D U^2$, where the air density ρ_A is 1.3 kg m^{-3} and $C_D = (0.8 + 0.065U) \times 10^{-3}$ [*Wu*, 1980]. The monthly means are shown in Figure 3. Also included in the figure are similarly computed monthly means for the Galveston airport based on hourly observations taken in the period 1951–1960 [*U.S. Department of Commerce*, 1973]. The similarity of the two annual progressions lends support to the less extensive information for Station 42008. The mean stress at Station 42008 has a component from the east in all months; from May through August, there is a component from the south; and, for the remainder of the year, a component from the north.

Currents were measured at three locations off Freeport, Texas (Figure 2, Table 1). ENDECO model 105 current meters which record on film were used until August 1979. ENDECO model 174 meters which record on magnetic tape were then phased in over a period of about 3 months and used until the end of operations in 1984. Moorings A and B were in water of 18-m depth and mooring C in water of 22-m depth. Current meters were placed always at two and, usually, at three depths on the moorings, at 3.7 m below the sea surface and 1.8 m above the bottom, and, usually, at mid-depth. We call the currents measured at the near-surface and near-bottom depths, surface and bottom currents, respectively. Gaps of as much as a month occur in the series, but they are very rare.

Since alongshore and cross-shelf directions are so evidently important to our discussion we now introduce the following coordinate system: the x axis is parallel to the coastline or to an isobath and the y axis is directed toward land, thus determining the positive x axis to be directed to the right of an observer facing toward land (the upcoast direction). For the Freeport offing the positive x-axis is directed 55° clockwise from north.

The strong association usually noted between alongshore stress and alongshore current, both surface and bottom, may be detected by visual comparison of time series of the quantities. More objective indications of relationships between wind and current are obtained by cross-spectral analysis (*Jenkins and Watts* [1968], for example) in the form of coherence-squared and phase relationships. We consider all four combinations of current components with wind components. Be-

TABLE 1. Dates of Operation and Positions of Current-Meter Moorings and Meteorological Measurements

Measurement Facility	Dates of Nearly Continuous Operation	Position
	Off Freeport, Texas	
Current-meter mooring A	June 1978–August 1981	28°47′03.0″N, 95°18′46.8″W
Current-meter mooring B	May 1979–August 1981	28°41′57.5″N, 95°25′42.4″W
Current-meter mooring C	September 1979–November 1984	28°43′53.9″N, 95°25′42.4″W
NDBC station 42008	December 1977–August 1984	28°47′04.2″N, 95°18′42.6″W
	Off Cameron, Louisiana	
Current-meter mooring D	January 1981–September 1985	29°39′54.0″N, 93°28′43.8″W

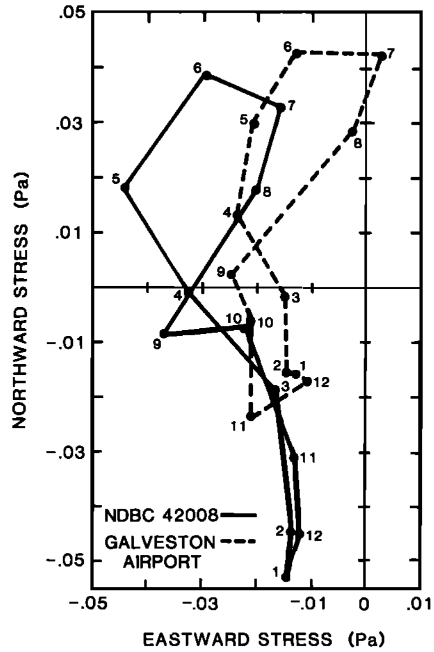

Fig. 3. Monthly mean wind stresses for NDBC Station 42008 off Freeport, Texas (see Figure 2), based on all available data from October 1978 through August 1984 (September, October, and November 1982 missing). A vector from the origin to the appropriate point on curve represents the monthly mean stress. Also shown are the monthly mean stresses for the Galveston, Texas, airport.

cause spectral relationships are slightly blurred by noise in the surface layers, bottom currents are presented although surface current records were also analyzed. Since 1981 has nearly complete records of wind and current, we applied the analysis to data from that year. Only subinertial frequencies or, more precisely, those below 0.5 cycles per day (cpd) were considered.

Figure 4*a* gives the phase and coherence-squared between alongshore wind stress and bottom current (both the alongshore and cross-shelf components). Current is considered to be the dependent variable. Figure 4*b* gives the same quantities in relation to cross-shelf wind stress. The coherence spectra for alongshore wind stress (Figure 4*a* and corresponding curves for surface current, which are not shown) indicate the following:

1. The coherences with alongshore current, both surface and bottom, are significant through much of the frequency range considered.

2. The phase from the alongshore stress to the alongshore bottom current increases from roughly 0° at low frequency to roughly 90° near 0.5 cpd, indicating frictional response at low frequency and inertial response at high frequency [see *Lewis and Reid*, 1985]; for surface current the corresponding phase is not clearly marked, perhaps because of the higher noise level in the upper layers.

3. The coherence with cross-shelf bottom current is significant through much of the frequency range considered although not so high, usually, as the coherence with alongshore bottom current; the coherence with alongshore surface current (not shown), on the other hand, falls below the 95% significance level.

4. The phase angle from stress to cross-shelf bottom current increases from near zero at low frequencies to about 90° near 0.2 cpd and higher frequencies; the generally positive phase implies, for the coordinate system used, that alongshore stress elicits a bottom cross-shelf current to its left.

The coherence of cross-shelf stress with both bottom current components (Figure 4*b*) is below the 95% significance level through most of the frequency range. The same is true of coherence of cross-shelf stress with both surface current components (not shown).

The responses of current to local wind indicated by cross-spectral analysis agree in most respects with the model given in the Introduction. Alongshore stress drives currents effectively, cross-shelf stress does not. (Cross-shelf wind induces Ekman transport with a net alongshore direction and so does not produce a jet.) Alongshore wind stress is coherent with cross-shelf bottom current and the phase indicates flow to the left of the stress, that is, in the expected direction of an adjustment drift [*Csanady*, 1982]. The one disagreement with the model is the lack of cross-shelf surface current in response to alongshore wind. Since some such response is necessary if an adjustment drift is to form, it seems likely that the response is masked by noise in the upper layers. An important source of relatively low-frequency noise appears to be baroclinic mo-

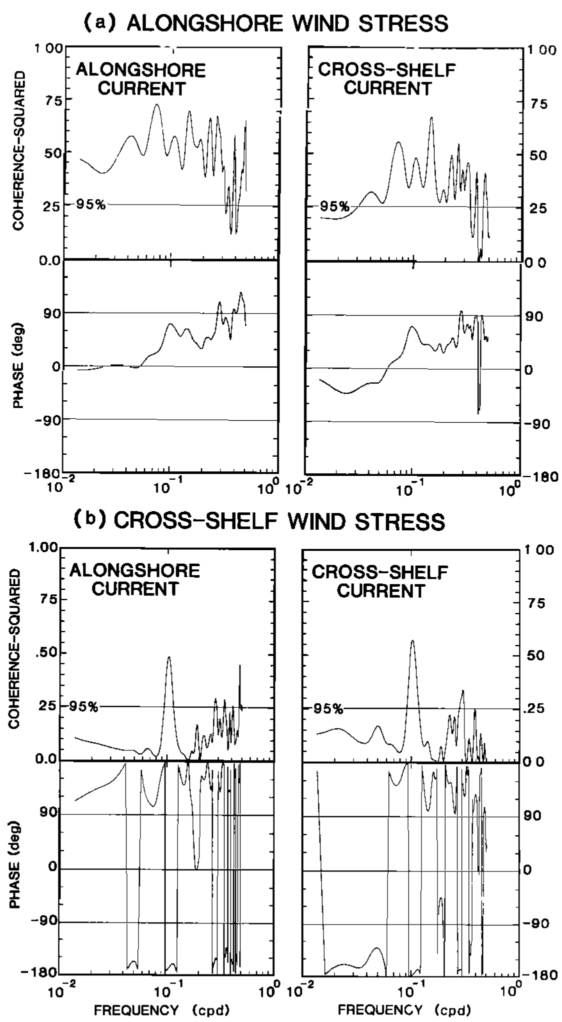

Fig. 4. Coherence spectra for wind stress at NDBC Station 42008 and bottom current at Mooring C off Freeport, Texas, in 1981: (*a*) for the alongshore wind stress; (*b*) for cross-shelf wind stress. The analysis is based on 6-hourly, 40-hr low pass filtered data and has 22 degrees of freedom. Positive phase indicates that the current lags the wind. With 22 degrees of freedom and coherence-squared of 0.7, the 95% confidence limits for phase are ±13° [*Jenkins and Watts*, 1968]. The 95% significance levels for coherence-squared are entered in the figure.

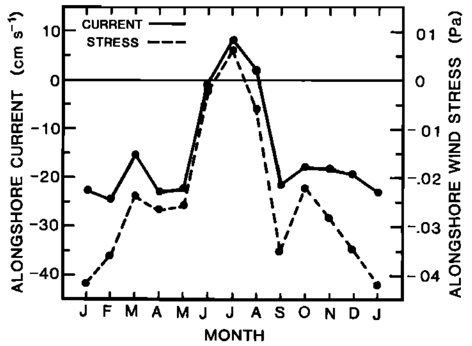

Fig. 5. Monthly mean alongshore components of wind stress at NDBC Station 42008 together with monthly mean alongshore components of surface current (3.7 m below sea surface) at moorings A, B or C off Freeport, Texas. (See text in regard to moorings used in computing mean.) The positive alongshore direction is 55° clockwise from the north.

tions in the vicinity of the front separating fresher coastal water from saltier offshore water.

Turning now to longer time scales, we present the annual progressions of the alongshore components of current and wind stress. Because near-surface conditions over the shelf are best known, we consider the surface current. Figure 5 shows the annual progressions in terms of the monthly means. Both sets of means are based on hourly values of three-hour low-passed data obtained between August 1978 and September 1984. The current data are from mooring A for the period August 1978 to August 1979, and mooring C for the remainder of the time unless it was out of service during a substantial part of a month; in that case the data are from mooring A or, if mooring B operated for a larger part of the month, from mooring B. We believe this procedure to be justified because the values of coherence-squared in alongshore current among moorings A, B, and C are very high.

Standard errors of estimate of the monthly means are given in Table 2. The standard error is taken as $S(\bar{X}_i)/(n-1)^{1/2}$, where $S(\bar{X}_i)$ is the unbiased estimate of standard deviation of the means for individual years and n is the number of years of observation, in most cases 6 years. The magnitude of the errors is relatively large as might be expected because of the small number of years. However, the differences between means for May and June and for August and September are quite significant. Both quantities exhibit positive (upcoast) values in July, nearly zero values in June and August, and negative (downcoast) values during the rest of the year. The magnitude of the downcoast values is larger than that of the upcoast value for July. In view of the strong coherence between the alongshore components of current and stress, the similarity of the two annual progressions is to be expected. The 6 years of paired current and wind data, the longest series for the coastal regions of the Gulf of Mexico of which we are aware, provide a strong basis for the simple annual progressions we have described above.

Finally, in regard to measurements in the Freeport offing, we note that the current usually turns counterclockwise with depth. This veering, which is described in more detail in *Kelly et al.* [1985*a*], particularly between mid-depth (11 m) and the very near bottom (0.5 m above the bottom) current meters, is large. For the period from fall 1981 through spring 1984, excluding the June–August seasons, the mean veering angle was 52°. Veering which clearly persists over such long periods evidently results from bottom stress. It must be borne in mind when we discuss the application of geopotential to surface currents in section 4.

2.2. *Monthly Means of Wind Stress and Current From Cameron, Louisiana, West*

For convenience we separate the further discussion of currents in response to wind into a section on the coastal ocean from Cameron west and a section on that east of Cameron. In the first (western) region, the response of currents to alongshore wind stress is usually quite strong and current data are numerous. In the second (eastern) region, there is a coastal section where the seaward extent of very shallow water adjacent to the coast is exceptionally large. In such places, according to *Chuang and Wiseman* [1983], the response of current to strong alongshore wind stress is quite weak. Current data for the second region are scanty.

Off Cameron, current meters were maintained at 3.7 m below the sea surface and 1.8 m above the bottom at mooring D (Table 1) from February 1981 to October 1985 by the Environmental Engineering Division of the Department of Civil Engineering at Texas A&M University. The mooring was in water of 9.5 m depth. Winds were measured at least at one of two neighboring NDBC stations from February 1978 to January 1985. The sources of wind data used for the Cameron offing are given in Table 3. The wind and current data have been discussed by *Kelly et al.* [1983*b*, 1984*c*, 1985*b*]. The positive alongshore direction is taken as 86° clockwise from north.

Representations of the annual progressions of alongshore wind stress and alongshore surface current are shown by monthly means in Figure 6. The means are based on data from the period from February 1981 to January 1985. Similar to the results for Freeport (Figure 5), the means for the current are positive (upcoast) only in July and those for stress are very nearly zero although not positive in July. The two sets of means are clearly correlated. Both the stress and current means are smaller than their counterparts for Freeport.

To broaden our view of the annual progression of wind-driven current along the coast west of Cameron, we present information on the wind stress for a number of locations, consider a simple model for coastal current in order to find the consequences of the wind-stress information, and, finally, examine the fragmentary information based on available

TABLE 2. Standard Errors of Estimate for Monthly Means of the Alongshore Components of Surface Current and Wind Stress off Freeport, Texas

Month	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Current, cm s^{-1}	2.0	4.3	6.5	8.3	5.1	6.2	2.8	3.2	9.8	8.6	4.7	3.2
Wind Stress, Pa.	0.005	0.008	0.007	0.012	0.003	0.005	0.005	0.010	0.011	0.011	0.010	0.004

TABLE 3. Locations for Which Monthly Mean Wind Stresses are Computed and the Sources of Wind Information

Location	Sources of Wind Information
Port Isabel, Texas, Offing	Wind observations taken at Brownsville Airport in 1951–1960 [*U.S. Department of Commerce, Climatography of United States, 82-41*]
Port Aransas, Texas, Offing	Wind observations taken at Corpus Christi Airport in 1951–1960 [*U.S. Department of Commerce, Climatography of United States, 82-41*]
Freeport, Texas, Offing	Wind records taken at NDBC buoy 42008 at 28°47.1'N, 95°18.7'W in August 1978 and from October 1978 to September 1983 [*Kelly et al.* 1980, 1981, 1982, 1983*a*, 1984*b*, 1985*a*]
Cameron, Louisiana, Offing	Wind records taken at NDBC buoys 42010 at 29°39.5'N, 93°23.3'W, 42011 at 29°40.3'N, 93°28.1'W, and the Texas A&M University Meteorological Station, College Station, Texas (to fill small gaps) [*Kelly et al.* 1983*b*, 1984*c*, and 1985*b*]
Offing of Louisiana Coast, 92°W to the Mississippi Delta	Wind observations taken at New Orleans Airport in 1951–1960 [*U.S. Department of Commerce, Climatography of United States, 82-16*] and wind observations from ocean area of five-degree quadrangle 25°–30°N, 90°–95°W [*U.S. Department of Commerce*, 1973], equally weighted

direct measurements of current. Table 3 gives the sources of information on wind stress used here. The stress is computed as in section 2.1. Figure 7 shows the monthly means (vectors) for Brownsville, Galveston, and the 5° quadrangle 25°–30°N, 90°–95°W in the Gulf of Mexico (Figure 1). As in Figure 3 for Galveston and the Freeport offing, lines connecting the means for the months in succession give the annual progressions. For all the locations, these lines form a "figure 8" and the chronological progression has the same sense. The similarity in the form of these annual progressions and those found for Freeport and Port Aransas, Texas (latter not shown), strengthens our confidence in the determinations we have made.

Monthly mean alongshore components of stress are of course our primary interest because of their importance to coastal currents. Monthly means for five inshore locations are shown in Figure 8. Figure 8*a* presents graphs for locations in the west, while Figure 8*b* is for locations farther east. The annual progression differs considerably among the locations because of geographical variation in both the frequency distributions of wind and coastal orientation. There is, however, a long section of the coast where much smaller differences are found, the section from the offing of Port Aransas, Texas, to that of Cameron, Louisiana. All three of the progressions for that section of coast exhibit a downcoast sense in fall and winter and an upcoast sense in July (or a very small downcoast value off Cameron). The Port Aransas component, however, has an upcoast sense in April, May, and June, while the other stations still show a downcoast sense.

To determine the effect of alongshore stress on alongshore current on a monthly mean basis, we assume steady conditions for alongshore forces integrated in the vertical, that is, a balance between the alongshore components of wind stress τ and bottom stress [*Csanady*, 1982]. Expressing the latter as a linear function of vertical-mean velocity u [*Csanady*, 1979; *Scott and Csanady*, 1976], we obtain

$$0 = \tau - \rho r u \qquad (1)$$

where ρ is the density of the ocean water and r the bottom resistance coefficient.

To simplify the picture of wind-driven currents along the coast west of 92.5°W, one may envisage a uniform wind stress field over the northwest Gulf of Mexico. The wind always blows toward the concave coast, but its direction varies seasonally so that the point where the wind is normal to the coast begins an upcoast migration from south of Port Isabel in fall to arrive in the vicinity of Cameron in July. Then, from July to September or October, the point rapidly returns to the south. Clearly, the point represents a convergence in alongshore stress. We use the term convergence to indicate a point toward which flow is directed from either side. Under the assumptions of equation (1), such a convergence in stress indicates a convergence in alongshore current. Essentially the same idea has been applied to the Texas coast by a number of investigators, including *Hunter et al.* [1974] and McGrail [in *Rezak et al.*, 1983].

Returning to the actual alongshore wind stresses for coastal locations (Figure 8), one sees a downcoast sense off Port Isabel in September, November, and possibly October, if the small positive value for that month represents only an irregularity due to the years considered in the sample (Table 3). The convergence, consequently, lies south of Port Isabel in those months. From December through March, the stress component off Port Isabel is upcoast while that off Port Aransas is downcoast; thus a convergence in coastal current lies between the locations. From March through June the stress components for Port Aransas and Freeport similarly imply a current convergence between those locations. In July the stress off Freeport is upcoast while off Cameron it is about zero: the convergence lies off Cameron, approximately. In August the stress and current convergences begin a rapid downcoast migration as the alongshore stresses for Freeport, Port Aransas, and Port Isabel indicate. The monthly mean currents off Freeport (Figure 5) provide a confirmation of the migration for at least one location.

Leipper [1954] apparently was the first to note the convergence in currents off the Texas coast. Ship's drift information (U.S. Navy Hydrographic Office Pilot Charts) provided the evidence for a convergence. *Watson and Behrens* [1970] and *Hunter et al.* [1974] found evidence of the convergence on the

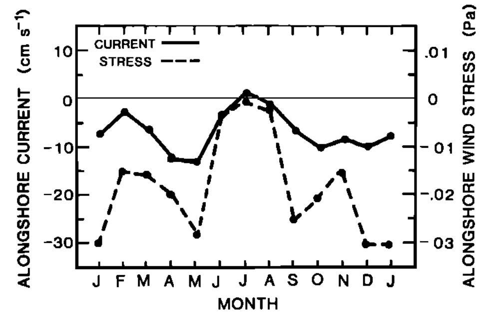

Fig. 6. Monthly mean alongshore components of wind stress for the Cameron, Louisiana, offing (sources of wind data listed in Table 3) together with monthly mean alongshore components of surface current (3.7 m below sea surface) at mooring D. The positive alongshore direction is 86° clockwise from north.

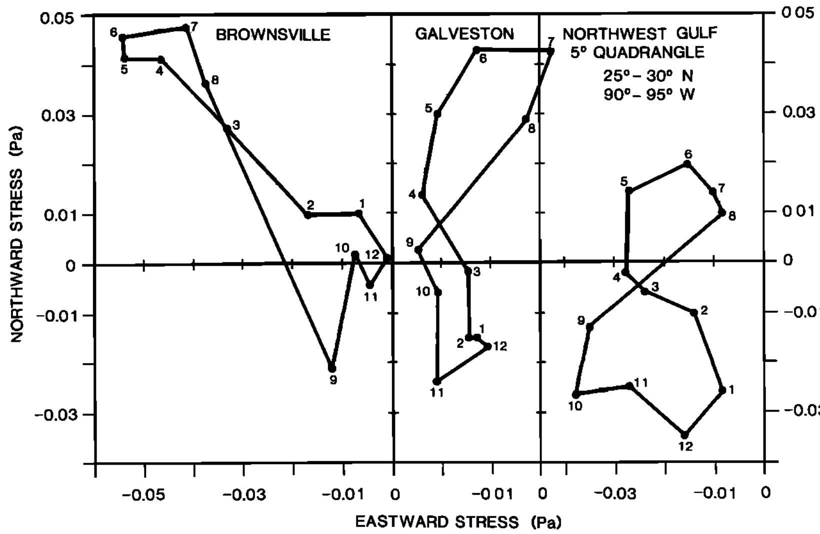

Fig. 7. Monthly mean wind stress for Brownsville, Texas; Galveston, Texas; and the 5° quandrangle 25°–30°N, 90°–95°W. The sources of wind data are listed in Table 3.

shelf and its migration in drift bottle studies and recognized that it is related to the wind.

The region of similar annual progression in alongshore wind stress from the Port Aransas to the Cameron offing (Figure 8*b*) has, if equation 1 is correct, a single current regime with downcoast flow prevailing except for a period of upcoast flow in spring and summer. Off Port Aransas the period is long, but off Freeport and Cameron it is limited to July. To determine whether this regime, which we shall call the Freeport regime, holds along the coast from Port Aransas to Cameron, we have collected all readily available current meter data. Table 4 lists the mean alongshore velocities for the shallowest meter at moorings for which data are available, except the values for the Freeport and Cameron offings which have been presented in Figures 5 and 6. The time intervals over which the means extend are those given in the source materials. Because the exceptional month in the Freeport regime is July, means are separated into groups for time intervals which include July and which do not. All of the means for the non-July intervals are negative, indicating downcoast flow. Seven out of the eleven means for intervals including July are positive, indicating upcoast flow. The negative means in the latter group are either very small or for intervals including a large proportion of time not in July. We believe that the Freeport regime is strongly supported.

It should be noted, however, that the current meter information does not permit complete testing of the prevailing relationship between wind stress and current. In particular, we lack direct confirmation by current meter data for prevailing upcoast flow implied for the coastal region south of Port Aransas, Texas, by mean wind stresses for March through June (Figure 8). For that region we know only of *Smith*'s [1980] measurements off Port Mansfield, Texas (Figure 1), taken between 28 June and 10 August 1977, and thus not in the period of interest. Still, there are drift bottle determinations of currents reported by *Hunter et al.* [1974] which show upcoast surface flow prevailing in April 1970 and 1973 (but not 1972), in May 1971 (the only May sampled), and in July 1970 (the only July sampled). There were no June determinations. Thus upcoast flow appears to be present when it is implied by mean upcoast wind stress.

The earliest recognition of the Freeport regime of which we are aware is in an unpublished manuscript by D. L. Harrington. The manuscript, to our knowledge circulated first in 1971, is entitled "Oceanographic Observations on the Northwest Continental Shelf of the Gulf of Mexico 1963–1965". On the basis of drift bottle studies, he stated that "(1) currents between September and April for the most part are alongshore westward along the Louisiana and southwestward along the Texas coast; (2) the reversal of the system usually starts around May or June when currents become irregular and obliquely offshore; (3) by July, currents are stronger northeasterly or easterly; this reversal usually prevails for a short period of time and by mid-August, the flow has returned to westward." Drift bottle studies by *Kimsey and Temple* [1963, 1964], *Watson and Behrens* [1970], *Hunter et al.* [1974] and *Hill et al.* [1975] lead to similar conclusions.

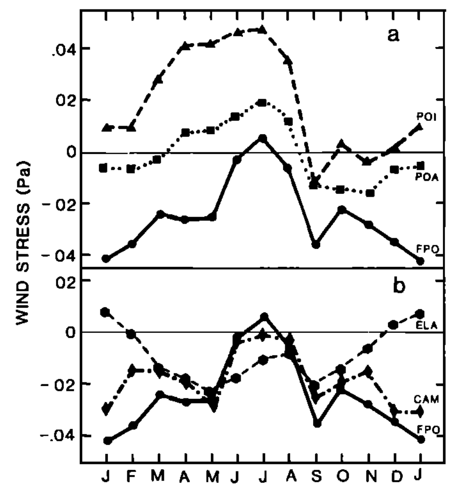

Fig. 8. Monthly mean alongshore components of wind stress for the waters (*a*) off Port Isabel, Texas (POI), Port Aransas, Texas (POA), and Freeport, Texas (FPO); and (*b*) off the latter (FPO), Cameron, Louisiana (CAM), and the Louisiana coast between 92° W and the Mississippi Delta (ELA). The sources of wind data are listed in Table 3.

TABLE 4. Mean Alongshore Component of Current Measured along the Texas-Louisiana Coast (at Shallowest Current Meter Used Throughout Deployment)

Location	Measurement Period	Mooring Depth (m)	Meter Depth (m)	Alongshore Component[a] (cm s^{-1})	Reference
	Measurement Periods Including July				
Off Port Aransas, Texas					
27°47′N, 96°58′W	13 Jul 73–20 Aug 73	18	4	−9	*Smith* [1975]
	18 Jun 74–20 Aug 74	18	4	−0.4	*Smith* [1978]
	28 Jun 77–10 Aug 77	18	8	3	*Smith* [1980]
Off Port O'Connor, Texas					
28°24′N, 96°02′W	28 Jun 77–10 Aug 77	20	10	2	*Smith* [1980]
Off Galveston, Texas					
28°52′N, 94°42′W	26 Jul 78–30 Aug 78	20	4	2	*Danek and Tomlinson* [1981]
Off Port Arthur, Texas					
29°33′N, 94°12′W	1 Jul 83–31 Jul 83	10	4	−4	*Kelly et al.* [1984*a*]
29°33′N, 94°08′W	15 May 78–11 Jul 78	9	7	1	*Waddell and Hamilton* [1981]
	12 Jul 78–13 Sep 78	9	7	−2	*Waddell and Hamilton* [1981]
29°36′N, 94°00′W	15 May 78–11 Jul 78	9	3	8	*Waddell and Hamilton* [1981]
	12 Jul 78–13 Sep 78	9	3	−6[b]	*Waddell and Hamilton* [1981]
Off Cameron, Louisiana					
29°42′N, 93°28′W[c]	7 Jun 78–6 Aug 78	9	6	0.4	*Crout et al.* [1984]
	Measurement Periods not Including July				
Off Port Aransas, Texas					
27°47′N, 96°58′W	5 Feb 73–13 Mar 73	18	4	−15	*Smith* [1975]
	21 Nov 73–19 Jan 74	18	4	−4	*Smith* [1978]
	4 Nov 75–17 Dec 75	14	10	−9	*Smith* [1977]
	15 Dec 76–26 Jan 77	33	10	−11	*Smith* [1979*a*]
	9 Mar 77–26 Apr 77	15	5	−14	*Smith* [1980]
Off Galveston, Texas					
28°52′N, 94°42′W	14 Feb 79–20 Mar 79	20	4	−12	*Danek and Tomlinson* [1981]
Off Port Arthur, Texas					
29°33′N, 94°12′W	2 Jun 83–30 Jun 83	10	4	−12	*Kelly et al.* [1984*a*]
	1 Aug 83–31 Aug 83	10	4	−3	*Kelly et al.* [1984*a*]
	1 Sep 83–22 Sep 83	10	4	−8	*Kelly et al.* [1984*a*]
29°33′N, 94°08′W	2 Dec 77–28 Feb 78	9	7	−6	*Waddell and Hamilton* [1981]
	10 Mar 78–14 May 78	9	7	−6	*Waddell and Hamilton* [1981]
29°36′N, 94°00′W	2 Dec 77–28 Feb 78	9	7	−5	*Waddell and Hamilton* [1981]
	10 Mar 78–14 May 78	9	7	−5	*Waddell and Hamilton* [1981]
29°39′N, 93°38′W	20 Oct 77–1 Dec 77	9	7	−5	*Waddell and Hamilton* [1981]
	2 Dec 77–18 Feb 78	9	7	−7	*Waddell and Hamilton* [1981]
	1 Mar 78–14 May 78	9	7	−3	*Waddell and Hamilton* [1981]
Off Cameron, Texas					
29°42′N, 93°28′W	2 Dec 77–18 Feb 78	7	5	−4	*Waddell and Hamilton* [1981]
	1 Mar 78–14 May 78	7	5	−6	*Waddell and Hamilton* [1981]
29°42′N, 93°28′W	8 Oct 78–7 Dec 78	9	6	−7	*Crout et al.* [1984]
	7 Nov 78–6 Jan 79	9	6	−9	*Crout et al.* [1984]
	7 Dec 78–5 Feb 79	9	6	−8	*Crout et al.* [1984]
	6 Jan 79–7 Mar 79	9	6	−5	*Crout et al.* [1984]
	5 Feb 79–6 Apr 79	9	6	−5	*Crout et al.* [1984]

ENDECO current meter type 105 was used for all measurements except those reported in *Kelly et al.* [1984*a*] which were ENDECO type 174 and in *Crout et al.* [1984] which were Grundy 9021.

[a]Positive values indicate upcoast flow (into the northeast quadrant).

[b]Note that measurement period extends into August and September.

[c]Position of center mooring in an array of five closely spaced moorings [*Crout et al.*, 1984].

2.3. *Circulation East of Cameron*

Although neither wind nor current information exists for the coastal waters east of Cameron in the amounts available for the waters west of Cameron, we can point out a few aspects of the circulation there. As already noted, a region of extensive shallow coastal water is found between about 91.0° and 92.5°W along the Louisiana coast. Starting from the west, we note that the seaward extent of shallow coastal water increases markedly near 92.5°W. According to *Chuang and Wiseman*'s [1983] results, a large increase in the bottom resistance coefficient r toward the east is to be expected there. As the coefficient increases, the vertical-mean current u required to balance a given alongshore stress decreases. Thus even a constant alongshore stress at the coast may produce alongshore divergence in the current. To learn more about such divergence, we differentiate equation 1 with respect to upcoast distance obtaining under the assumption of no change in depth or density along the upcoast direction

$$\frac{\partial u}{\partial x} = \frac{1}{\rho r}\left(\frac{\partial \tau}{\partial x} - \frac{\tau}{r}\frac{\partial r}{\partial x}\right) \tag{2}$$

Besides the obvious consequences that divergence in wind stress along the coast implies current divergence of the same sign, the assumption of balance (equation (1)) implies that, for the downcoast wind stress which prevails through most of the year (Figure 8), an alongshore rate of change in r results in divergence of the same sign.

TABLE 5. Alongshore Divergence $\partial u/\partial x$ According to Equation (2) for Coastal Segments East and West of Cameron, Louisiana

300 km Segment (Δx) Extending Downcoast	τ, Pa	$\Delta\tau$, Pa	r, $\mathrm{ms^{-1}}$	Δr, $\mathrm{ms^{-1}}$	$\frac{1}{\rho r}\frac{\Delta\tau}{\Delta x}$, $\mathrm{s^{-1}}$	$-\frac{\tau}{\rho r^2}\frac{\Delta r}{\Delta x}$, $\mathrm{s^{-1}}$	$\frac{\partial u}{\partial x}$, $\mathrm{s^{-1}}$
From Galveston (west)	−0.02	−0.04	0.0003	0	-4×10^{-7}	0	-4×10^{-7}
From Eugene Island (east)	−0.02	0.03	0.0005	0.0005	10^{-7}	10^{-7}	2×10^{-7}

$\rho = 1000\ \mathrm{kg\,m^{-3}}$.

In order to compare the divergences (positive or negative) for coastal segments east and west of Galveston, Texas, we have prepared Table 5. The estimates of τ and its alongshore changes are based on the values in Figure 8. The values of r are based on *Chuang and Wiseman*'s [1983] work which indicates values of roughly 0.0001 m $\mathrm{s^{-1}}$ and 0.001 m $\mathrm{s^{-1}}$ for the offings of Galveston and Eugene Island, Louisiana, respectively. Since the largest increase in seaward extent of shallow depth occurs near 92.5°W, that is, in the segment east of Galveston, it seems likely that much of the change in r is found in that segment. We take this change Δr to be 0.0005 m $\mathrm{s^{-1}}$ in order to estimate its effect on $\partial u/\partial x$ conservatively. For the coastal segment east of Galveston, the table shows that the eastward increase in r leads, in the case of downcoast wind stress, to a positive divergence. The eastward increase in wind stress east of Galveston also implies a positive contribution to divergence. The magnitude of divergence in the east is comparable to that of the convergence in the west.

The only combined current meter and wind data we have found for the offing east of Cameron are the measurements in the Mississippi Bight (the shelf region east of 91°W) reported by *Daddio* [1977]. The alongshore component shows poor correlation between alongshore wind stress and wind. From the information given in the report, we infer that the mean alongshore current at 28°55′N, 89°47′W between January 29, 1974, and February 28, 1974, was 4 cm $\mathrm{s^{-1}}$ upcoast at a depth of 6 m on a mooring anchored in 33 m of water. Since the climatological mean stress for the Louisiana coast between 92°W and the Mississippi River is also directed upcoast, some measure of agreement is indicated.

3. CIRCULATION AS INDICATED BY SEA-SURFACE SALINITY

Sea-surface salinity viewed as a tracer provides confirmation for some aspects of the coastal current we have studied by means of current, wind, and sea level measurements; it also reveals aspects of the circulation along the coast and over the entire shelf which available measurements of other types do not show. The best coverage of salinity (and temperature) on the shelf is provided by a series of observations taken in 1964. During 1963, 1964, and 1965, the U.S. Fish and Wildlife service made monthly monitoring surveys of the waters of the Texas-Louisiana Shelf aboard the GUS III [*Temple et al.*, 1977]. Figure 9 shows the sea-surface salinity distributions based on observation from alternate months. The salinities were determined by titration of samples. A band of low-salinity water lay along the coast from September through June. Along most of the coast, salinity reached a minimum in May. The lowest salinities were found off the Mississippi River mouths. The main trend in salinity along the coast was an increase toward the west and south although a secondary low appeared in almost all months along the coast from about Cameron to Galveston. The band began to recede upcoast in June and had disappeared by August although brackish water remained along the coast from the delta to about 92°W and in a region extending seaward over the shelf. In September, a coastal band of brackish water reappeared along the coast with salinities nearly as low as in May. Similar features are found in corresponding months of the 1963 and 1965 cruises. It should be noted that the 1963–1965 period was one of relative small river discharge, as *Dinnel and Wiseman* [1986] note.

For the inner shelf, say the inner third of the shelf, river discharge is a far more important influence on salinity than is evaporation or precipitation (rainfall). Dinnel and Wiseman estimate that for the entire Texas-Louisiana Shelf, out to the 200 m isobath, the evaporation rate is 138 cm $\mathrm{yr^{-1}}$ (loss) and the precipitation rate is 95 cm $\mathrm{yr^{-1}}$ (gain). River discharge, as estimated by Dinnel and Wiseman, corresponds to a mean fresh water flux for the inner third of the shelf of 1070 cm $\mathrm{yr^{-1}}$. Their mean discharge volume is derived on the conservative assumption that only 53% of the Mississippi discharge reaches the Texas-Louisiana Shelf.

The dominant role played by Mississippi-Atchafalaya discharge is indicated in Table 6 which gives the monthly and annual mean discharges of the rivers within each of five regions of equal length along the Texas-Louisiana coast (Figure 1). The Mississippi-Atchafalaya mean discharge is more than 15 times the combined mean discharge of all of the other rivers.

Figure 10 shows the annual progression of monthly mean discharges for the Mississippi-Atchafalaya system, based on a convenient seven-year sample. The progression has a strong maximum (spring flood) peaked in April and a rather flat minimum in October. Spring maxima appear also for the rivers in coastal regions 2, 3, and 4 (Table 6) although they occur in March or May instead of April.

The slow downcoast change in coastal sea-surface salinity that is found in all of the months shown in Figure 9 except July cannot result simply from the local river discharges which vary widely. Only downcoast advection of Mississippi-Atchafalaya water can explain the very gradual changing.

The very low salinity in the coastal tongue during May 1964 is in accord with the April maximum in discharge from the Mississippi-Atchafalaya system. In the main the advection which would produce the coastal brackish band is in agreement with the currents as observed (Table 4, Figures 5 and 6) and as inferred from alongshore wind stress (Figure 8). However, the salinity distribution makes clear that water is somehow advected downcoast past the region of extensive shallow water off the coastal segment from 91° to 92.5°W. There, as noted above, a wind-driven coastal jet is not present, at least in winter, according to *Chuang and Wiseman*'s [1983] analysis.

The drastically changed salinity pattern of July 1964 (Figure 9) is in agreement with the "Freeport regime" of currents which has upcoast flow in that month. The salinity pattern

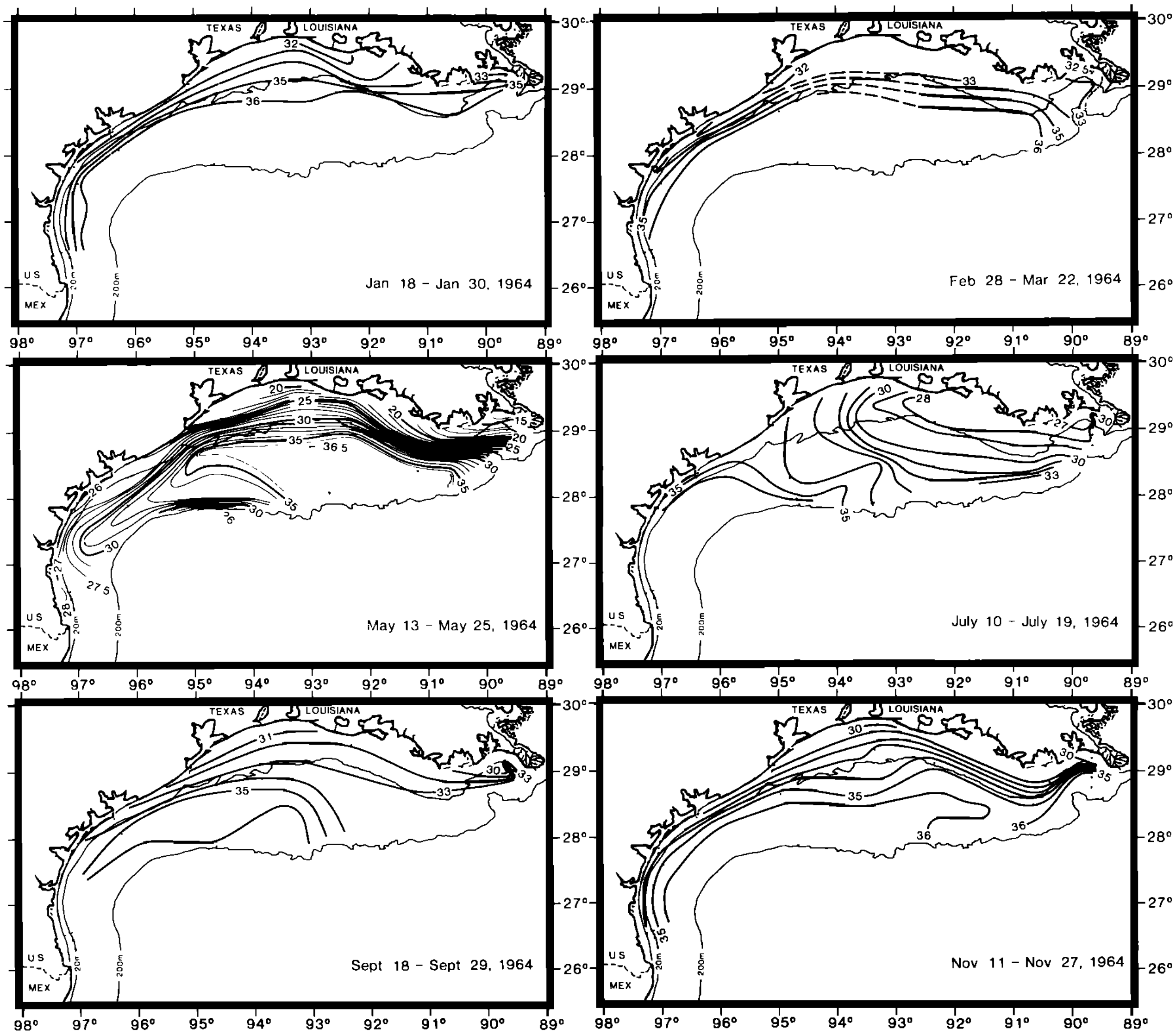

Fig. 9. Sea-surface salinity (10^{-3}) for M/V Gus III cruises in alternative months of 1964, prepared by J. Schmitz [*Kelly et al.*, 1980].

was similarly changed in July of 1963 and 1965. The absence of brackish water on the coast west of about 92.5°W results from the upcoast currents and from upwelling implied by the upcoast wind stress in July and, for the south, in earlier months also.

The reestablishment of the coastal brackish band in September is somewhat more difficult to explain. Examination of the discharge data (Table 6) does not reveal an autumnal maximum in any coastal region large enough to replace the band. On the other hand, current information, as already noted, does show a return to prevailing downcoast flow in September. Wind stress information also implies such flow. The main source of the brackish water which by September again forms a coastal band appears to be the extensive region of low-salinity water which lies off eastern Louisiana in July (Figure 9) and August. The wind stress off Port Isabel (Figure

TABLE 6. Mean River Discharge Rates for Regions Along the Texas-Louisiana Coast ($m^3 s^{-1}$) Based on Water Years 1977–1983

Region	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
1	20425	20508	26325	34137	30723	27100	17140	13320	11994	11193	12003	20359	20436
2	217	248	374	208	173	102	63	59	101	25	56	242	156
3	910	1291	1056	1370	1483	1336	672	473	483	328	454	727	882
4	173	201	137	238	337	315	142	88	268	120	200	158	198
5	45	42	27	55	82	138	61	17	46	104	67	70	63

Location of river regions shown in Figure 1. The regions include the following rivers along with smaller streams: region 1, Mississippi, Atchafalaya; region 2, Vermilion, Calcasieu; region 3, Sabine, Neches, Trinity, San Jacinto, Brazos, San Bernard; region 4, Colorado, Tres Palacios, LaVaca, Navidad, Guadalupe, San Antonio, Mission, Aransas; region 5, Nueces, Rio Grande.

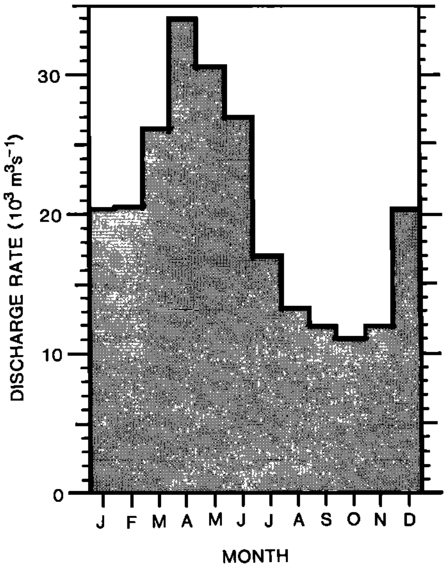

Fig. 10. Monthly mean discharge rates for the Mississippi-Atchafalaya River system based on the water years 1977–1983.

8) implies that downcoast flow extends south of there in September.

Evidence that the main coastal features of the M/V GUS III sea-surface salinity distributions west of Galveston are not peculiar to the GUS III cruises is presented in Figure 11 which shows the monthly means of salinities observed at tide gauges located at Galveston, Port Aransas, and Port Isabel, Texas. Fairly long records are available [*U.S. Department of Commerce*, 1973] for these locations. Figure 11 indicates a moderately regular increase in the mean salinity from Galveston downcoast to Port Isabel. The annual progressions for the three locations are similar: each progression has a minimum in October and a maximum in August. In May, Galveston and Port Aransas have minima and Port Isabel shows a change from constant to rapidly increasing salinity. The May minima result from the Mississippi-Atchafalaya spring flood and downcoast advection. The conditions off Port Isabel are consonant with the increased upwelling and upcoast advection which the local alongshore wind stress implies for April and May (Figure 8). The minimum which all of the tidal stations exhibit in October (Figure 11) corresponds to the reestablishment of downcoast mean flow and the coastal low-salinity band which, according to wind data (Figure 8) and GUS III sea-surface salinities (Figure 9), begins in September.

An important feature of the sea-surface salinity, particularly marked in May, is the seaward extension of the coastal brackish band out from the coast of south Texas, which the map for May 1964 in Figure 9 illustrates. The feature is found in all of the M/V GUS III cruises for that month (1963, 1964, and 1965). The observations of *Smith et al.* [1979] in May 1977 off south Texas also strongly suggest the presence of this feature. It is in agreement with the convergence which we inferred above from the wind stress field along the coast and appears to show flow out from the coast. Although we have no direct evidence of such flow, it is difficult to explain the salinity pattern by any other mechanism.

Not only does the brackish water extend out from the coast, it also is present along the shelf break (Figure 9) in May 1964, west of about 93°W, apparently indicating that the seaward flow of brackish water turns to head northeast or eastward along the shelf break.

4. SHELF CIRCULATION

4.1. *Countercurrent Near the Shelf Break*

Further evidence of flow to the northeast or east along the shelf break is provided by the mass distributions observed near the break and by current measurements made on the outer shelf near the break. The more abundant type of evidence for a prevailing current running counter to the coastal current except in July and early August is embodied in vertical sections crossing the shelf. *McLellan* [1960] is the first of whom we are aware to point out that in such sections off Texas, the isopycnals over the inner continental slope and outer shelf slope down in the seaward direction and that this implies, if the currents are quasigeostrophic, northward or eastward flow, or, more precisely, an upward increase in such flow. We refer to the current near the break running counter to the coastal current as the countercurrent.

This feature is clearly indicated in many bathythermograph sections across the shelf (for example, see *Etter and Cochrane* [1975]) which show a shallow dome of cool water over the outer shelf; the inner portion of the dome is related to the coastal current. Figure 12 shows the vertical sections of thermosteric anomaly ($\Delta_{S,T}$; *Pond and Pickard* [1983]) for the May and July 1964 GUS III cruises. The May section, which

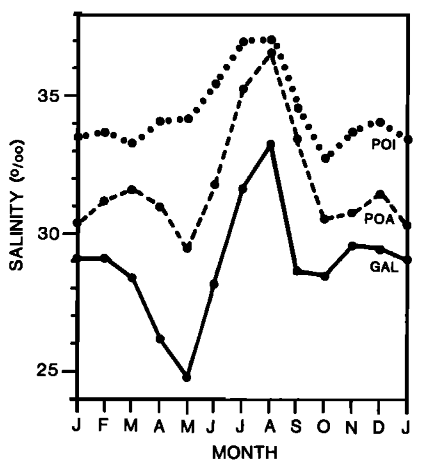

Fig. 11. Monthly mean sea-surface salinity for Galveston (GAL), Port Aransas (POA) and Port Isabel (POI), Texas, based on samples taken at tidal stations [*U.S. Department of Commerce*, 1973]. Observations at Galveston are for the years 1957–1971, those at Port Aransas for 1958-1971, and those at Port Isabel for 1944–1967.

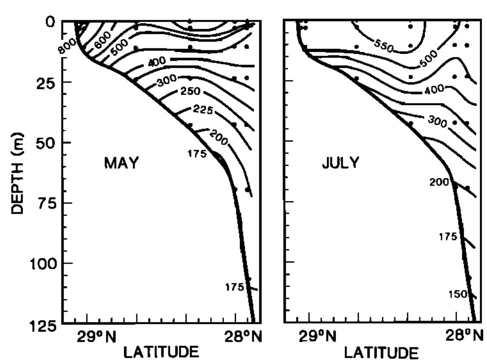

Fig. 12. Mean thermosteric anomaly ($\Delta_{S,T}$, 10^{-8} m^3 kg^{-1}) along M/V GUS III line of stations off San Luis Pass for May and July, based on data taken in 1963, 1964, and 1965. Location of the line is shown in the first map of Figure 13.

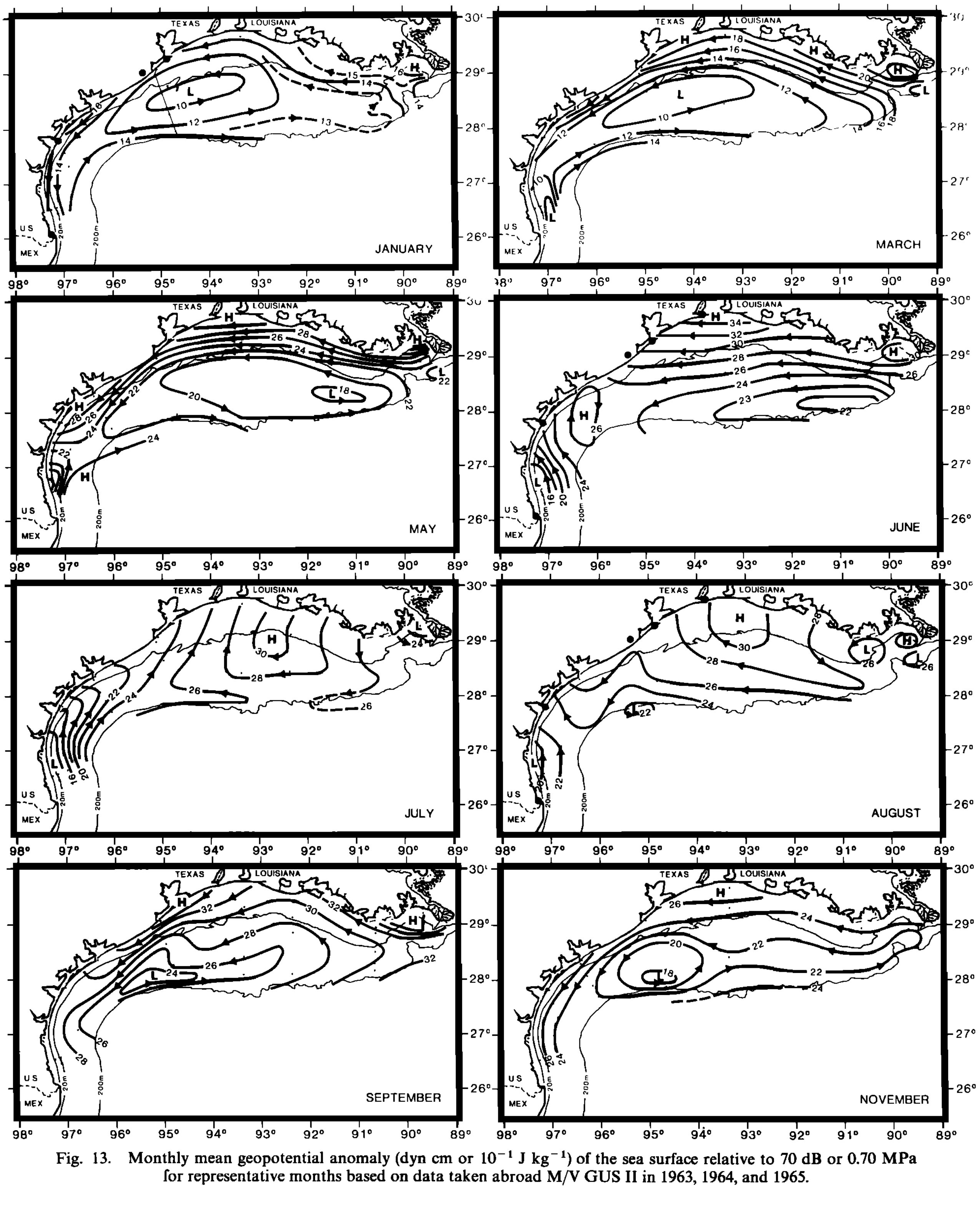

Fig. 13. Monthly mean geopotential anomaly (dyn cm or 10^{-1} J kg^{-1}) of the sea surface relative to 70 dB or 0.70 MPa for representative months based on data taken abroad M/V GUS II in 1963, 1964, and 1965.

is typical of months other than June, July and August, shows the dome, and so the countercurrent, clearly. The July section has only an ambiguous dome-like feature near 25 m depth over the continental slope, the main feature of the section being the upward tilt of the isopleths toward shore, which evidently represents upcoast flow (as well as upwelling). *Rezak et al.* [1983] discuss sections on the Texas Shelf which show the doming feature, although they note other sections in non-summer months which do not show it. W. J. Wiseman, Jr., (personal communication) also has encountered the dome in hydrographic sections which crossed the eastern Louisiana section of the shelf in some non-summer months of 1982. The region below the dome is similar to the "cold pool" found in the Middle Atlantic Bight [for example, *Houghton et al.* 1982].

Current measurements lend further support to a flow counter to the coastal current prevailing near the shelf break. *Rezak et al.* [1983] report measurements from current meters moored on and near the Flower Garden Banks (Figure 1) in

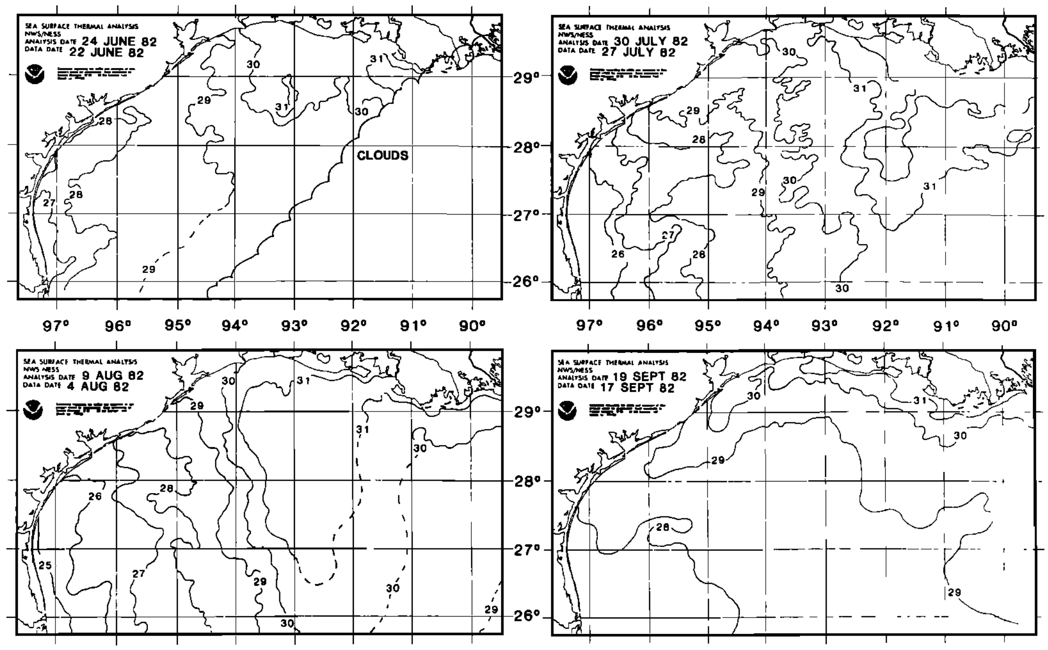

Fig. 14. Sea-surface temperature based on IR imagery (supplied by NOAA/NWS/NESS) for days in June, July, August, and September 1982.

January, May, and June 1980. The prevailing current direction was toward the east-southeast. Continental Shelf Associates operated a current meter array moored near Baker Bank off the central Texas coast (Figure 1) for CONOCO, Inc. from March 1978 through most of March 1980 with a few relatively short gaps. The data from the shallowest meter (12 m depth) of the array, which was moored in water 73 m deep, show that the resultant current over the entire period was directed approximately along the isobaths toward the east-northeast, that is, counter to the coastal current prevailing in nonsummer months (Cortis Cooper of CONOCO, Inc.; personal communication). W. J. Wiseman, Jr. (personal communication) in current measurements on the outer shelf between 92° and 93°W during July and August 1983 found eastward flow. In view of the unusual persistence of downcoast currents near the coast into August 1983 [*Kelly et al.* 1984*a*, *b*, *c*], Wiseman's measurements represent a countercurrent over the outer shelf. Thus evidence that a countercurrent prevails near the shelf break is provided both by hydrographic data and direct measurements of current.

The countercurrent near the continental shelf break seems to have prevailing connections with the downcoast current which dominates the inner shelf except during summer. As we have pointed out, convergence along the coast in the south and divergence in the east suggest cross-shelf flow in those regions, and the sea surface salinity patterns in the south provide fairly convincing evidence of such a connection there.

4.2. *Prevailing Circulation on the Shelf*

For a representation of the shelf circulation encompassed by a single type of information, we present in Figure 13 geopotential anomaly distributions which we have obtained from the GUS III data for various months. Since our objective is to depict the prevailing currents, monthly mean geopotential anomalies were computed from monthly mean temperatures and salinities for the data from GUS III cruises. Observations were made at predesignated stations in most of the months of 1963, 1964, and 1965. (Note that the values for any given time may differ greatly from the corresponding monthly means.) The geopotential anomaly was computed from mean thermosteric anomalies at a station and from extrapolations of means to the bottom along a station line (Figure 13). The integration over pressures greater than that for the bottom depth at a station was made along the bottom at the station line from a pressure of 70 dB or 0.70 MPa. The method is essentially that of *Montgomery* [1941]. *Csanady* [1979] argues that such a calculation produces a valid picture of coastal geostrophic currents provided that along-isobath variations in density (or specific volume) are small, as they usually are on the Texas-Louisiana Shelf. Although the near-bottom currents close to the coast clearly deviate from geostrophy, as the persistent, large veering with depth noted above indicates, geostrophic currents provide a first approximation to the actual flows.

In the maps of geopotential anomaly, an elongated cyclone (low) is indicated over much of the shelf for all months except July and August. The cyclone implies flow away from the coast in the south and toward the coast in the east. The coastward flow in the east corresponds to the divergence of coastal current inferred in section 2.3 above. The seaward flow in the south or west corresponds to the convergence of coastal current inferred from the alongshore wind stresses (Figure 8). From February through July, a second low is present off the coast in the south, a ridge separating it from the larger elongated low. The ridge migrates seasonally and, consequently, also the seaward flow indicated by its upcoast side. The migration is very similar to that of the convergence implied by the monthly mean wind stresses.

The westward extent of the cyclone becomes smaller in June and an anticyclonic region develops replacing the ridge. By July the anticyclone has grown so large that the original cyclone is virtually gone. In August the anticyclone is still larger. Abruptly in September (or late August) with the onset of downcoast winds, a large cyclonic region is reestablished over much of the shelf. Freeport data [*Kelly et al.*, 1982, 1983*a*, 1984*b*, and 1985*a*] indicate that the downcoast winds and currents become dominant in mid-August.

The center of the cyclonic gyre moves seasonally according to the GUS III data (Figure 13). In September when the gyre is abruptly reestablished, its center is far to the west and somewhat south on the shelf near 95°W. Through its seasonal cycle the center moves steadily east reaching about 90.5°W in June. Thus the center and the ridge to the west of the cyclonic gyre (and the coastal convergence) migrate in the same direction during the seasonal cycle. The "cold pool" of the Mid-Atlantic Bight, the structure of which the deeper parts of the cyclone's center resemble, also moves seasonally [*Houghton et al.*, 1982].

A noteworthy aspect of the monthly mean geopotential distributions (Figure 13) is that they imply in all months except July and August a westward or downcoast flow along the coastal segment between 91° and 92.5°W. Such flow is also indicated by the brackish coastal band in the nonsummer months. Further the flow is usually in agreement with the alongshore wind stress component (Figure 8) which is downcoast off the Louisiana coast except in winter, when it has small upcoast values.

The anticyclone in July coincides roughly with the region of low-salinity surface water (Figure 9). Since the stability at the bottom of this brackish layer is high, the temperature of the layer becomes high. The density is consequently low and results in the high geopotential.

During months other than July there is a high of geopotential anomaly (usually not closed) in the Mississippi Bight (between 91°W and the Mississippi Delta), a circulation separate from the main cyclonic feature on the shelf.

A quite independent corroboration of some of the features which are indicated by the geopotential distributions is provided by sea-surface temperatures distribution. R. Barazotto of NOAA/NWS/NESS supplied distributions on satellite infrared imagery to us. The imagery for June through September 1982 seemed to us to illustrate a particularly interesting phase in the annual cycle and was rather free of clouds. We selected a map for one day of each month in the period on the basis of clarity and present these in Figure 14. The June map indicates that upwelling is present off the south Texas coast, extending as far northeast as Matagorda Bay. By the July map time, the contrast in temperature between east and west has increased markedly and the warm region in the east has extended farther offshore. On the August day, the warm region has moved somewhat westward reaching approximately the position of the July high center for geopotential. In September, the warm region is pressed against the coast and has extended southwestward along the coast as is usual for the brackish coastal water.

5. Concluding Remarks

We have attempted to describe the prevailing low-frequency circulation on the Texas-Louisiana Continental Shelf on the basis of several types of information. Because some of the information is quite extensive and because the different kinds of information lead to a coherent picture, we believe our description to be fairly reliable.

Since current measurements are available for only a scattered few locations along the Texas-Louisiana coast, the link which we have established between wind stress and coastal current plays an important role in the description of the circulation prevailing on the Texas-Louisiana Shelf. As for most coastal regions, cross-spectral analysis indicates strong coherence between alongshore wind stress and coastal current in the region west of 92.5°W. Among the data analyzed are a 6-year series taken off Freeport, Texas, and a 5-year series taken off Cameron, Louisiana. These and other such analyses leave little doubt that alongshore wind stress provides a major driving mechanism for coastal currents. On the other hand, between 92.5° and 91.0°W, approximately, where the seaward extent of coastal shallow water reaches its maximum for the coast west of the Mississippi delta, the response of alongshore current to alongshore wind is weak, according to *Chuang and Wiseman*'s [1983] study of sea-level/wind coherences off Eugene Island, Louisiana.

A feature of the shelf circulation which encompasses a large part of the picture we have developed is the cyclonic gyre prevailing over much of the shelf except during July and August. The downcoast currents dominating much of the coast except during the latter months constitute the coastal or inner limb of the gyre. The countercurrent near the shelf break includes the outer limb of the gyre; note that some of the countercurrent appears to extend south and east beyond the gyre. Flow directed offshore forms the gyre's southwestern limb and the shoreward flow off the Louisiana coast forms its eastern limb. The geopotential anomaly maps in Figure 13 show the gyre in various stages of its annual progression.

When in July the upcoast component of prevailing winds has reached eastward almost to the Cameron, Louisiana, offing, the prevailing cyclonic gyre has disappeared from the shelf, being replaced by an anticyclone centered off Louisiana. In late August or September after an abrupt change in prevailing wind direction, downcoast wind stress dominates most of the Texas-Louisiana coast, the cyclonic gyre is reestablished and reaches its maximum southward extent beyond the Rio Grande. Once established, the eastern side of the gyre remains in place until July. The western side of the gyre, in contrast, begins to contract eastward in March or April, as prevailing upcoast winds migrate northward and eastward. By June the westward extent of the gyre is greatly reduced. By July the gyre is gone. The long wind and current records for the Freeport and Cameron offings provide local verification of the progression of coastal currents which form a part of the system (Figures 5 and 6, respectively). Figure 8 shows the alongshore wind-stress components on which much of our picture of the coastal progression is based.

Convergence at a change in direction of alongshore wind stress and consequent offshore-directed flow correspond to the southwestern limb of the gyre. The eastern limb with flow directed onshore corresponds to divergence in the alongshore current due to a change in bottom frictional resistance r as well as to wind-stress divergence.

The distribution of sea-surface salinity along the Texas coast, particularly a coastal band of brackish, sea-surface water, exhibits a characteristic seasonal progression (Figures 10 and 11) which can be explained on the basis of the annual march of discharge from the Mississippi-Atchafalaya River system and the annual march of coastal currents established in this study. Both sea-surface salinity and the geopotential anomalies indicate that westward flow of Mississippi River water occurs between the river mouths and 92.5°W, that is, that westward flow occurs in that sector despite the apparent inefficacy of wind driving in the region where the seaward extent of very shallow coastal water is exceptionally large.

Clearly the picture of circulation we have developed is largely qualitative. Further quantification can probably be carried out most efficiently in connection with mathematical modelling. More detailed study of some topics raised in this study seems quite feasible on the basis of existing data: we are now preparing papers on the differing responses of current to wind along the coast and on the shelf waters. Applications of the picture to problems of plankton dispersion and sediment transport seem promising to us; *Shaw et al.* [1985] have used it in studying transport of fish larvae and *Rezak et al.* [1983] have considered some of its geological implications.

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Dedication. This work is dedicated to Robert O. Reid of Texas A&M University as a token of our high regard for him as a teacher, scientist, and friend.

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