119

TIDAL AND LONG-PERIOD EXCHANGES BETWEEN UPPER LAGUNA MADRE AND CORPUS CHRISTI BAY, TEXAS

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Abstract

Current-meter data and water level measurements from Upper Laguna Madre, Texas, are used to explain a north-to-south increase in both the multi-annual average salinity and the standard deviation about the average. Long-period exchanges, and to a lesser extent co-oscillating tidal motions, between Corpus Christi Bay and Upper Laguna Madre buffer salinity extremes arising from temporal variations in the local balance between precipitation and evaporation. The observed salinity distribution appears to reflect the penetration of meteorologically forced exchanges into Upper Laguna Madre.

Introduction

Laguna Madre of Texas is one of relatively few bar-built estuaries lying along the continental margin of the United States. These intracoastal bodies of water are characterized by large surface area to depth ratios, considerably reduced tidal action due to restricted access to the ocean, and relatively important wind effects. In the case of Laguna Madre, recent studies (Smith, 1978a) indicate that tidal ranges are on the order of a few centimeters in the northern extreme of the lagoon. Connection with the inner shelf waters of the northwestern Gulf of Mexico is poor, as exchanges must occur through approximately 35 km of shallow water and narrow channels (Fig. 1). Thus, co-oscillating tidal motions are nearly completely dampened.

On the other hand, the National Weather Service lists the International Airport at Corpus Christi as the third windiest in the country, with a scalar average windspeed of 23.5 km/hr. An investigation of exchange processes in this intracoastal lagoon must therefore extend over a long enough time period to reveal meteorological forcing occurring over time scales on the order of several days.

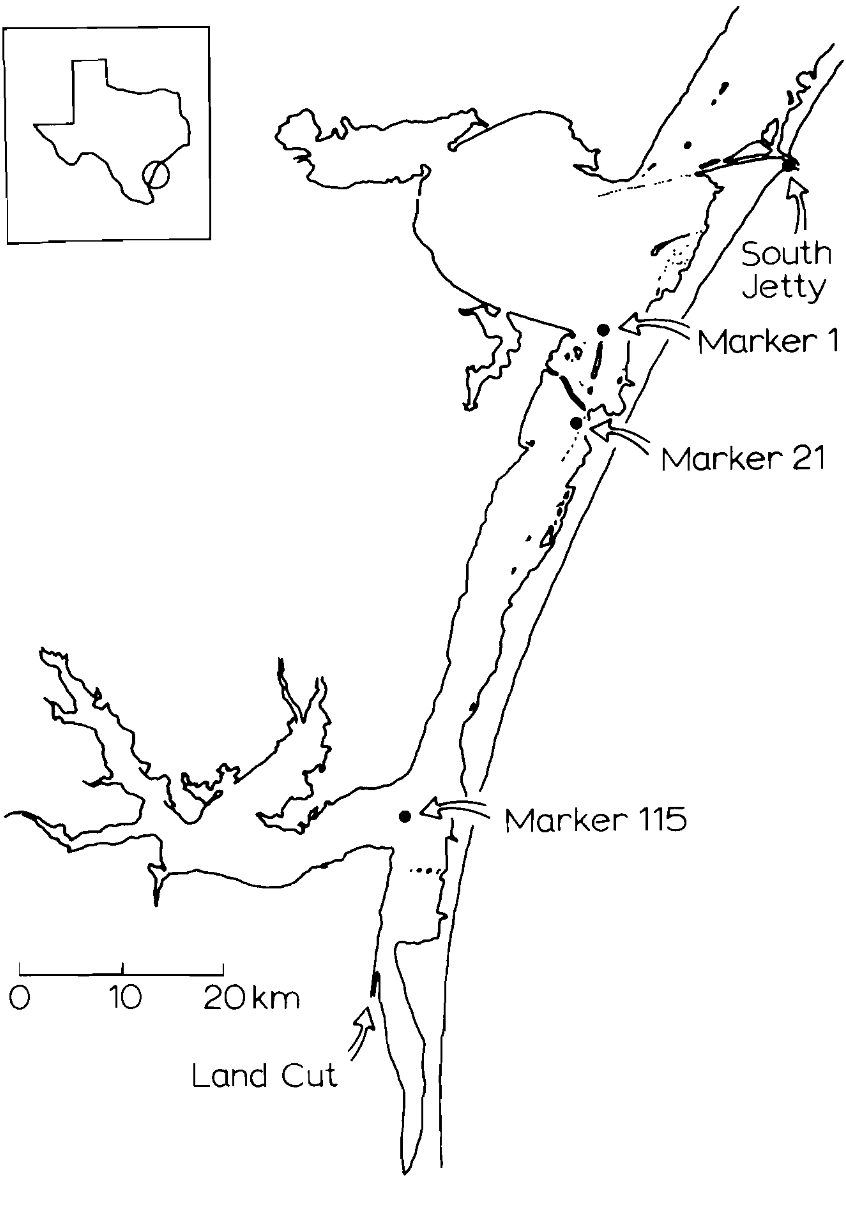

Figure 1. Map of Upper Laguna Madre, showing the current meter site at Marker 21. Insert shows the study area along the central Texas Gulf coast.

The coastal zone of South Texas is somewhat unusual because it lies in a region classified as transitional between subtropical humid and tropical semiarid (Critchfield 1974). Climatological maps published by the Coastal Management Program of the Texas General Land Office (1975) show a north-to-south increase of from 18 to 21 inches in the excess of annual potential evapotranspiration over precipitation between Corpus Christi Bay and Baffin Bay (Fig. 1). Under normal conditions, the relatively low rainfall amounts are insufficient to prevent hypersaline conditions, making Laguna Madre a negative estuary.

The completion of the Gulf Intracoastal Waterway through Laguna Madre in 1949 all but ended the reports of the exceptionally high salinities that had appeared in the earliest surveys. Gunter (1945) noted that "the average salinity of Upper Laguna Madre runs around 40-60 ppt when it is in good condition", but that salinities may increase to values nearly three times that of normal sea water. Such high salinities have not been reported during the past 30 years, but hypersaline conditions are still the rule.

More recently, Behrens (1966) has collected salinity data between Markers 1 and 115 over an approximately four-year period during the mid to late 1960's. The data are presumably representative of the present hydrographic state of Upper Laguna Madre. The salinity distribution reflects the buffering effects of increased exchanges along the intracoastal waterway. There may, however, be an additional effect of an increase in regional rainfall during this time.

Two features stand out in the data which are of particular interest here. First, though surface salinities appear to have been reduced somewhat from those recorded before the intracoastal waterway was dredged, values between 30 and 40 ppt are still found in years of normal rainfall. Values may get as high as 75 ppt under drought conditions. Second, on many surveys conducted along the intracoastal waterway between Corpus Christi Bay and Baffin Bay, salinities increased more or less regularly with increasing distance southward from Corpus Christi Bay. The observed salinity gradient presumably reflects a long-term balance between the local excess of evaporation over precipitation and the advective replacement of hypersaline water with Corpus Christi Bay water, which characteristically has salinities on the order of 30 ppt (Holland, et al. 1975).

The dependence of the salinity distribution on exchanges between Corpus Christi Bay and Upper Laguna Madre prompted an investigation of currents along the intracoastal waterway near Marker 21 (Fig. 1) in the northern extreme of the lagoon. The study was conducted during mid winter, at a time when frontal passages moving off the central Texas coast would produce temporarily dominant meteorological forcing in addition to the constant, if relatively minor, tidal motions. The purpose of this paper is to present results which describe both tidal and meteorologically forced exchanges. Correlation of current and salinity data is directed toward explaining the observed northerly directed salinity gradient reported by Behrens. Results therefore relate directly to the water quality (hypersalinity) of Upper Laguna Madre.

Observations

A General Oceanics Model 2010 inclinometer current meter was placed at the edge of the intracoastal waterway at Marker 21, approximately 2 km south of the Kennedy Causeway in Upper Laguna Madre (Fig. 1). Currents were recorded half-hourly between 9 January and 7 February 1976. Co-oscillating tidal and long-period variations in the current were constrained by the dredged channel, thus only the along-channel component was used in the analysis. Inclination angles were read to the nearest degree. This represents a precision of about ±0.5 cm/sec for the 10° to 50° inclination angles characteristic of this study.

Surface salinities from nineteen stations between Marker 1, at the southern end of Corpus Christi Bay, and Marker 115, at the entrance to Baffin Bay, were collected at approximately monthly intervals by Behrens (1966) and made available for further analysis in this study. Surface salinities were measured with a Goldberg refractometer salinometer. The refractometers are temperature compensated, and the precision is on the order of ±0.5 ppt.

Water level records were obtained from Army Corps of Engineers tide gages at Markers 21 and 115 (Fig. 1), at the northern and southern extremes of Upper Laguna Madre, respectively. Water levels were read to the nearest 0.01 foot (3 mm) relative to a datum plane one foot below mean sea level, and converted to centimeters before analysis.

Results

An overview of temporal variations in the current during the study period is provided by a time plot of the along-channel components (Fig. 2). During the 33 days the current meter was in place, a series of current reversals was recorded, occurring over a wide range of time scales, as water was exchanged between Corpus Christi Bay and Upper Laguna Madre by both tidal and meteorological forcing. Negative values, by

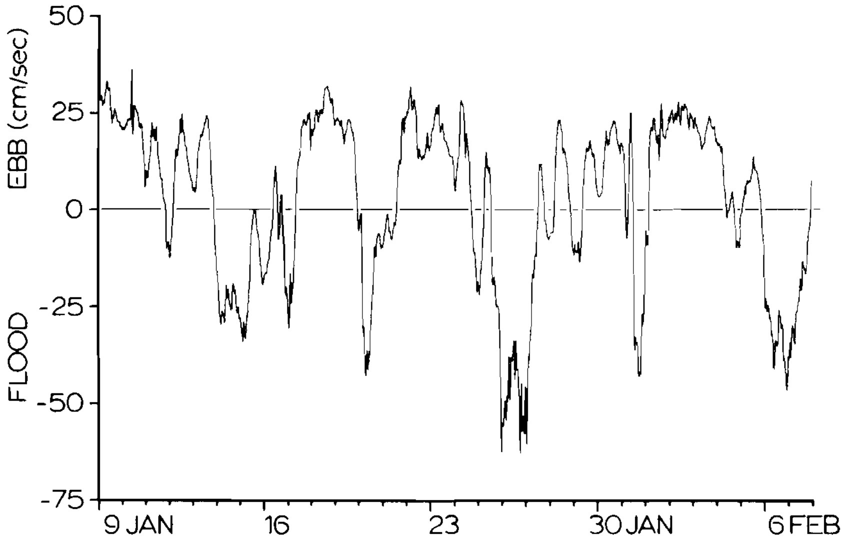

Figure 2. Half-hourly recording current meter data from Marker 21, 9 January through 7 February, 1976. Along-channel components are in cm/sec; positive values indicate flow from Upper Laguna Madre into Corpus Christi Bay.

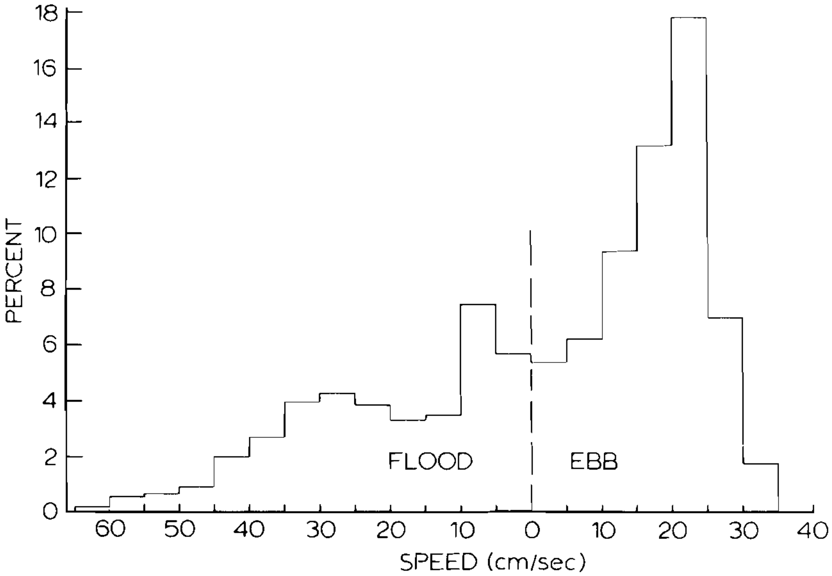

Figure 3. Histogram of along-channel current components past Marker 21, 9 January through 7 February, 1976.

definition, indicate flow into Upper Laguna Madre. The half-hourly measurements have been smoothed by a 3-weight moving filter to remove some of the very high frequency fluctuations that were not of interest here. The time plot contains a slight but distinct diurnal tidal variation, but the dominant features are the long-period reversals, irregularly spaced in time, but occurring generally over time scales on the order of a week. The strongest currents coming into Upper Laguna Madre from Corpus Christi Bay are those associated with frontal passages, when southerly directed windstress piles water against the south shore of Corpus Christi Bay.

Figure 3 is a histogram of the 1,592 along-channel component current speeds recorded at Marker 21. A small frequency maximum occurs for flood currents of between 25 and 30 cm/sec. A second, and somewhat higher peak is found for flood current speeds of between 5 and 10 cm/sec. By far the most common situation over this time period, as indicated by the histogram, is an outflowing current of slow to moderate speeds. Highest frequencies are found for ebb currents with speeds between 20 and 25 cm/sec. Frequencies drop off quickly with increasing current speed, and no ebb current speeds over 40 cm/sec were recorded over this time interval.

An indication of the advective transport associated with the co-oscillating ebb and flood currents is provided by plotting the cumulative net displacements past Marker 21 (Fig. 4). This is computed just like a progressive vector diagram, however since the calculations involve the scalar along-channel current components, the cumulative displacements can be plotted against time, rather than in x-y coordinates.

Figure 4 shows three principal periods of outflow, occurring at intervals on the order of two weeks. The outflow is followed by a period of inflow, however the net result is a movement of water out of Upper Laguna Madre and into Corpus Christi Bay. These major reversals can be attributed to the variations in surface windstress which accompany the passage of cold fronts.

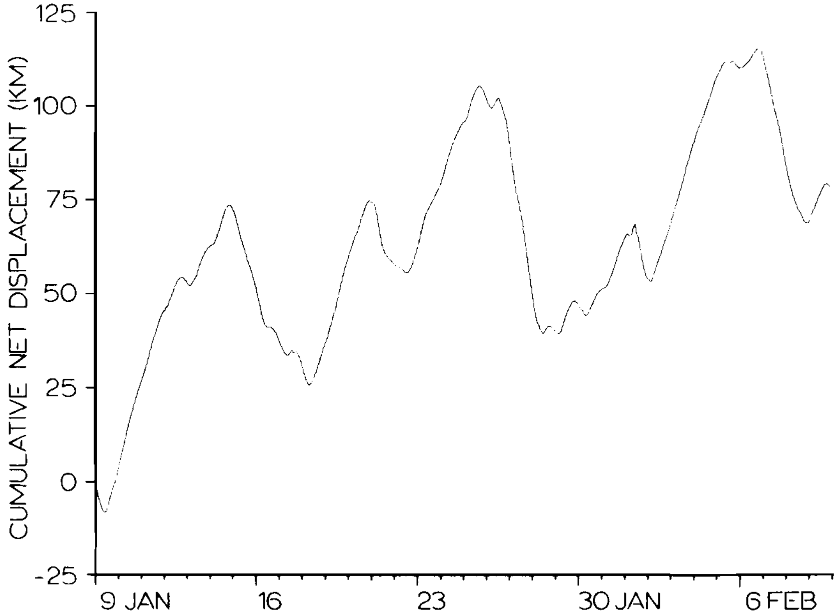

Figure 4. Cumulative net displacement, in kilometers, past Marker 21, 9 January to 7 February, 1976. Positive values indicate flow from Upper Laguna Madre into Corpus Christi Bay.

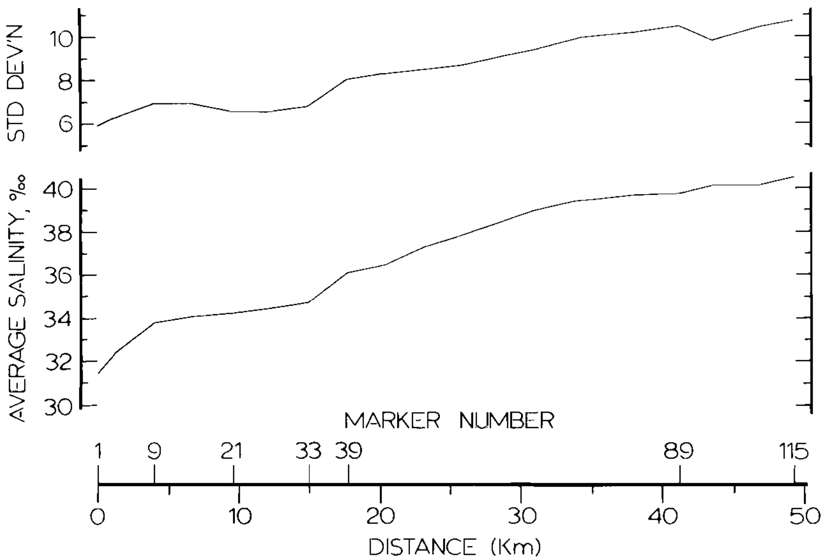

Figure 5. Average salinities and standard deviations between Marker 1 and Marker 115 in Upper Laguna Madre. See Figure 1 for station locations. Values computed from 31 synoptic surveys between December, 1964, and September, 1968.

TABLE I. Coherence between along-channel current components recorded at Marker 21 and the 025°-205° component of the windstress, 9 January to 7 February, 1976. Spectral resolution is 0.005 cph.

Period (hours)	*Frequency (cph)*	*Coherence*
	0.000	0.946
200	0.005	0.940
100	0.010	0.886
67	0.015	0.826
50	0.020	0.871
40	0.025	0.821
33	0.030	0.813
29	0.035	0.515
25	0.040	0.416
22	0.045	0.214

Table I shows coherences computed from the along-channel components of the surface windstress and the along-channel components of current recorded at Marker 21. Windstress was calculated according to the technique suggested by Wu (1969) from winds measured at the National Park Service Ranger Headquarters, approximately twenty kilometers from the study site. High coherence values appear for time scales in excess of about a day and a half. The three major current reversals therefore seem to be wind-driven and a direct effect of frontal passages.

The resultant current computed from the ebb and flood measurements indicates a net outflow of approximately 2.5 cm/sec into Corpus Christi Bay. This result corresponds quite well with field observations of water levels made while installing and recovering the current meter. Spoil islands along the intercoastal waterway, inundated at the start of the study, were exposed by early February, indicating a slow lowering of water levels, and thus a net outflow. Seasonal variations in sea level along the northwestern rim of the Gulf of Mexico include a semi-annual low, occurring in mid-winter (Whitaker 1971). The resulting effects on intracoastal water levels have been discussed for Upper Laguna Madre in particular by Smith (1978a).

The time series of along-channel current components provides an opportunity to isolate and quantitize the co-oscilating tidal component of the current. A 29-day time series of hourly along-channel current components was used to compute the harmonic constants of the principle tidal constituents (Dennis and Long 1971). The amplitudes of the co-oscillating tidal constituents were, in turn, used to calculate the associated tidal excursion along the intracoastal waterway. One must assume that the along-channel motion associated with each tidal constituent varies sinusoidally according to the expression

$$u(t) = U \sin(2\pi\, t/T),$$

where U is the amplitude of the tidal constituent in question, T is its period, and t is time. One may then integrate through one-half tidal cycle ($\frac{1}{2}T$) to obtain the along-channel tidal excursion, s, associated with either the flood or ebb tide:

$$(\tfrac{1}{2}T) = UT/\pi,$$

where s will be in kilometers if U is in km/hr and T is in hours. Tidal excursions provide a good estimate of the horizontal extent of the co-oscillating tidal flow past the point of measurement.

TABLE II. Tidal current constituent amplitudes (cm/sec) and tidal excursions (m).

	Constituent			
	0_1	K_1	M_2	S_2
Period (hours)	25.82	23.93	12.42	12.00
Amplitude (cm/sec)	1.0	0.8	0.1	0.2
Excursion (m)	291	226	14	30

Table II gives the results of a harmonic analysis of the along-channel current components, and the associated tidal excursion between two successive slack waters. It becomes immediately apparent that tidal motions do not play a significant role in exchanges between Corpus Christi Bay and Upper Laguna Madre. Even when the K_1 and O_1 constituents are in phase and additive, the total tidal excursion is only on the order of 0.5 km. Furthermore, it is questionable that the tidal excursions are physically realistic, since the ± 0.5 cm/sec precision of the raw current measurements used in the computations are of the same order of magnitude as the resulting amplitudes.

Salinity measurements made at nineteen locations along the intracoastal waterway between Markers 1 and 115 (Fig. 1) were provided by Dr. E. W. Behrens. Data from 31 synoptic surveys carried out between 16 December, 1964, and 27 September, 1968, were used to compute long-term averages and standard deviations of salinity along the axis of the intracoastal waterway (Fig. 5). The results are useful both for understanding the hydrography of Upper Laguna Madra and for inferring the penetration of tidal and meteorologically forced exchanges between Upper Laguna Madre and Corpus Christi Bay. These exchanges have the effect of buffering local salinity extremes caused by alternate excessive evaporation and occasionally heavy rainfall in the shallow water of the lagoon. The portion of Upper Laguna Madre experiencing a more or less regular renewal of water from Corpus Christi Bay can be identified by salinity values more like those of the bay, and by a smaller standard deviation about the average. Conversely, that part of the lagoon lying beyond the limit of normal exchanges with the bay should be identifiable by both higher average salinities and larger standard deviations.

Figure 5 does in fact show an increase in both the average salinity and the standard deviation with increasing distance from Corpus Christi Bay. The increase is more or less gradual, however, with the possible exception of the slight jump in both variables between Markers 33 and 39. This occurs approximately 17 km south of Marker 1, thus it is definitely too far into Upper Laguna Madre to be related to tidal exchanges. The difference in standard deviations at these two locations was not found to be statistically significant at the 95% confidence level, using the F-Test with 30 degrees of freedom. Nevertheless, the possibility remains that this increase marks the normal limit of penetration of water into Upper Laguna Madre in response to meteorological forcing. The sharp increase in average salinity and, to a lesser extent the standard deviation, between Markers 1 and 9, on the other hand, may reflect the limit of the periodic incursion of the diurnal tides.

The apparent dominance of long-period processes in flushing Upper Laguna Madre prompted the analysis of some water level data collected at the northern and southern extremes of Upper Laguna Madre. An 88-day period from 31 March to 26 June, 1974, was selected to compare hour-by-hour variations in water levels recorded simultaneously at Markers 21 and 115. The coherence spectrum from these two time series (not shown) indicates high coherences only over time scales in excess of approximately 300 hours (12.5 days), though the spectral resolution makes it difficult to accurately resolve time scales in the very long period portion of the spectrum. Nevertheless, it would appear that the frontal effects recorded at Marker 21 (Fig. 2) and occurring over time scales of about a week are not felt at Marker 115. Thus, the dominant exchanges affecting Upper Laguna Madre as a whole would seem to be those driven externally by the semi-annual rise and fall of sea level along the northwestern rim of the Gulf of Mexico.

TABLE III. Coherence and phase relationships of low-frequency water level variations at Markers 21 and 115, 31 March through 26 June, 1974. The last column gives the angular lead of water level variations at Marker 21. Number in parentheses gives the corresponding time lead, in hours.

Period (hours)	*Frequency (cph)*	*Coherence*	*Phase Lead (degrees)*
	0.00000	0.935	4.0 (15.0)
600	0.00167	0.915	9.0 (18.3)
300	0.00334	0.816	21.9 (28.5)
200	0.00500	0.433	51.4 (18.0)
150	0.00667	0.346	43.3 (19.4)

The phase angles computed for the long-period variations in water level at these two locations are listed in Table III. It is noteworthy that there is only a slight phase lead computed for variations recorded at Marker 21. Near-zero phase angles indicate that water levels rise nearly uniformly along the entire length of Upper Laguna Madre. A 180° phase angle, on the other hand, would indicate a back-and-forth sloshing of water within Upper Laguna Madre, and thus little net exchange with Corpus Christi Bay.

It is of interest to note the time interval required for long-period water level variations to propagate the length of Upper Laguna Madre between Markers 21 and 115 (approximately 40 km). The phase angles computed from the 88-day water level records mentioned above indicate that, for the very long period motions, water level variations at Marker 21 are followed approximately 15-20 hours later by variations at Marker 115 (see Table III). It is not known, however, the extent to which they have been damped. This time lag is about four times as long as one would predict using the shallow-water equation with a characteristic water depth of 0.5 m. The discrepancy may reflect the resistance to wave-like motions provided by the spoil islands along the waterway, or the sometimes dense seagrass beds in the area.

Discussion

The current and water level data presented in this study underline the relative importance of long-period motions arising from synoptic scale wind systems or external dynamic and thermohaline forcing originating in the northwestern Gulf of Mexico. The results of the harmonic analyses suggest that tidal processes are of negligible importance. In this sense, Laguna Madre nicely reflects the characteristics normally associated with bar-build estuaries.

The classification of Upper Laguna Madre as a negative estuary has been well supported by measurements of hypersalinity over the past 35 years. The dredging of the intracoastal waterway led to a reduction of the high salinities that had been reported as recently as the mid 1940's, but readings in excess of 40 ppt are still not uncommon. Thus, the calculated net outflow over the 33-day current study is somewhat surprising. A net outflow is more logically associated with substantial river run-off into, and eventually through a positive estuary. The net outflow is, however, consistent with the semi-annual rise and fall of coastal sea level characteristic of the northwestern Gulf. An earlier study of exchanges between Corpus Christi Bay and the inner shelf waters off Port Aransas, Texas (Smith 1978b) showed a net outflow during a 30-day period in July-August, 1976. Results obtained in this study further underline the necessity of conducting a current sutdy over a sufficiently long interval of time to identify exchange processes, well in excess of the tidal ebb and flow, which may dominate the circulation patterns of coastal lagoons.

It should be noted that the observed increase in salinity with increasing distance from Corpus Christi Bay (Fig. 5), while apparently a real and at least semi-permanent feature of the hydrography of Upper Laguna Madre, may be accentuated by the southward increase in the difference between local precipitation and potential evapotranspiration. Thus, even if the flushing of Upper Laguna Madre by exchanges with Corpus Christi Bay were spatially uniform along the axis of the waterway, it is likely that the average salinity would increase southward, given the climatology of the region. The similar increase in the standard deviation, however, clearly indicates a spatial variation (southerly decrease) in the buffering effects of co-oscillating, long-period current variations and the importance of exchanges with Corpus Christi Bay in determining the local variation in salinity at any point along the waterway.

Although the cumulative displacement past Marker 21 (Fig. 4) cannot strictly be equated with transport in either direction along the intracoastal waterway, it is of interest to note that, for the three major outflow-inflow sequences recorded during the study, the displacements calculated in this way are all on the order of 50-75 kilometers. Figure 1 shows that this is equivalent to the length of Upper Laguna Madre between Markers 1 and 115. One might tentatively conclude that the wind-driven exchanges associated with the winter cold fronts, at least, penetrate a significant distance into Upper Laguna Madre, and it is possible that Corpus Christi Bay water moves all the way down to the entrance to Baffin Bay (Marker 115). Relatively minor displacements occur throughout the record.

The pattern that emerges is one of continual back-and-forth motions of varying degrees, with the magnitude of the horizontal transport in either direction related in a roughly inverse way to the frequency with which it occurs. If this is true, then one would expect that during the summer months, and in the absence of frontal effects, relatively mild meteorological forcing would be available to supplement tidal exchanges.

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