INTRACOASTAL TIDES OF UPPER LAGUNA MADRE, TEXAS[1]

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ABSTRACT

A 1-yr record of hourly water level measurements from Upper Laguna Madre, Texas, indicates water level variations occur primarily in response to estuarine-shelf exchanges in 3 forms. A dominant, semi-annual rise and fall of sea level is driven externally by thermohaline and dynamic processes in the Gulf of Mexico. Meteorologically forced variations in coastal sea level produce exchanges and thus intracoastal water level variations over time scales on the order of 1 to 2 weeks. Astronomical tides are relatively small perturbations superimposed onto the longer-period processes.

Water level data from Port Aransas, Texas, and Upper Laguna Madre are used to trace the movement and damping of tidal motions from the coast, through Corpus Christi Bay to the study site. Tidal crests move at approximately 4-5 km/hr, and the constituents are decreased to less than 25% of their amplitudes at the coast. Tidal motions in Upper Laguna Madre are primarily at diurnal periods, and K_1 and O_1 constituent amplitudes are both on the order of 2-3 cm. Comparison of tidal and non-tidal period water level variations indicates that tidal motions account for approximately 5% of the total observed variation in water level at this location.

INTRODUCTION

Laguna Madre, extending nearly 200 km along the South Texas Gulf coast, is a shallow, semi-enclosed coastal lagoon lying inside Padre Island. The width is generally between 2 and 3 km, and water depths are characteristically on the order of 1 m. Climatologically, the area is one in which the annual evaporation exceeds the precipitation, yet at times rainfall and freshwater run-off can be substantial. Partly for this reason, Laguna Madre has been the subject of considerable interest for many years. The resident plant and animal populations must be capable of tolerating a wide range of salinities between midsummer, when evaporation increases salinities to 60 parts/1000 or more (Behrens, 1966), and the fall months, when the annual precipitation curve is at a maximum and water may become decidedly brackish. Similarly, temperatures range annually from near freezing to as high as 40C in the shallow flats. In spite of these harsh environmental conditions, fish populations are abundant and the waters are heavily fished by sportsmen and commercial fishermen. Laguna Madre supports adult populations

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of fish the year around, in addition to serving as a nursery area for juvenile forms of fish and invertebrates.

The scientific interest and commercial value of the waters of Laguna Madre have stimulated studies over the past 30 years. Most of the published accounts deal with the biology or general ecology of the region. Hedgpeth (1947) included remarks dealing with the hydrography of Laguna Madre in a general study of the area. Some evidence for a wind-induced flushing of Laguna Madre waters is presented using salinity as a natural tracer. One phase of a 3-part ecological survey conducted by the Texas Game and Fish Commission was carried out in Laguna Madre north of the Land Cut (Simmons, 1957). This report is of a general nature and includes information relating to the local circulation and tides. Simmons notes that wind directions and water levels are interrelated, but no quantitative data are presented. Copeland, *et al.,* (1968) noted a similar relationship between winds and water levels in 3 short studies conducted in 1963.

The only purely hydrographic study of the area was that conducted by Collier and Hedgpeth (1950), which covered Texas intracoastal waters between Baffin Bay and Espiritu Santo Bay. A separate section was devoted to Laguna Madre, but the data presented were collected before the construction of the Intracoastal Waterway in 1949, and thus are largely of historical interest.

These previous studies provide a background for a more specific investigation of water level variations in Upper Laguna Madre. It has been shown qualitatively that tidal variations in water levels are small and often dominated by wind effects, but little quantitative information is available relating to tidal motions or the relative importance of tidal and long-period, nontidal processes. The purpose of this paper is to describe quantitatively the tidal and longer period water level variations, and thus to extend the results of previous studies of physical processes in Upper Laguna Madre.

THE OBSERVATIONS

Water level records were obtained from U.S. Army Corps of Engineers recorders located along the South Jetty of the Aransas Pass (Fig. 1) at Port Aransas, Texas, (27°50.25'N, 97°03.00'W), and at Marker 21 of the Gulf Intracoastal Waterway in Upper Laguna Madre (27°37.10'N, 97°14.32'W).

A 365-day time series of hourly observations over the period February 1, 1974 through January 31, 1975, provided the primary data base from which tidal and longer period water level variations were investigated. An overlapping 148.5-day water level record from the South Jetty in Port Aransas provided information on how tidal and longer period water level variations move into the study site from the northwestern Gulf of Mexico.

Water levels were recorded in analog form and read to the nearest 0.01 ft (3 mm) at hourly intervals relative to a datum plane 1 ft below mean sea level. High frequency noise in the water level records from both locations was effectively damped by the stilling well, and it is felt that values have a precision of approximately ±6 mm. Water levels were converted to cm above the datum before being analyzed.

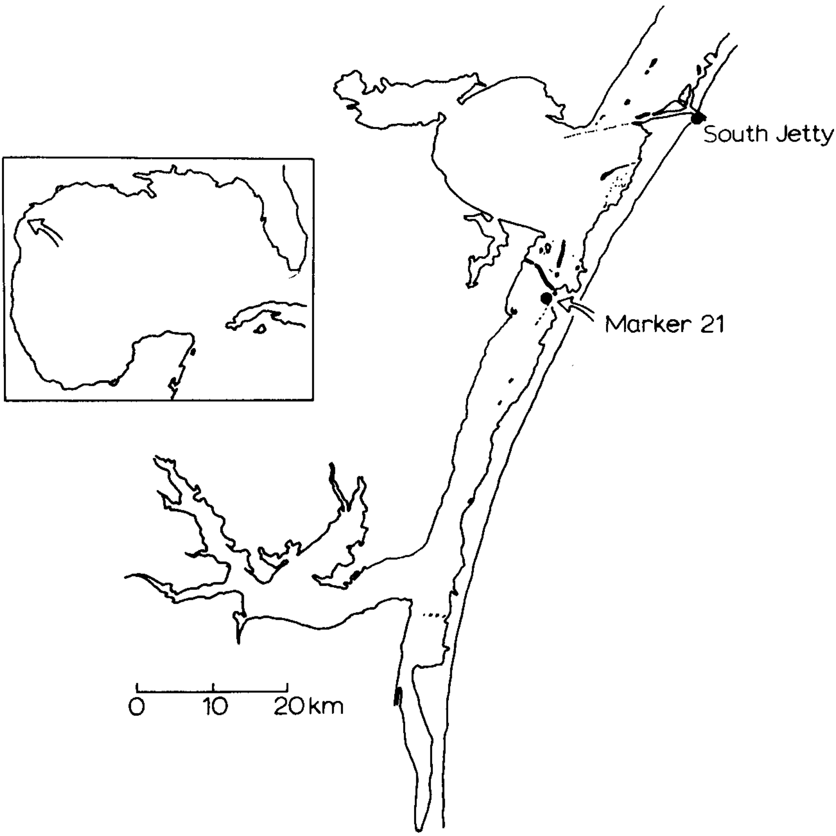

Figure 1. Locations of Marker 21 in Upper Laguna Madre, Texas, and the South Jetty at Port Aransas. Insert shows the study site in the northwestern Gulf of Mexico.

RESULTS

To put both tidal and longer period water level variations in Upper Laguna Madre in perspective, hourly values were plotted for the entire 365-day study period (Fig. 2). The results show largely in a qualitatively way the relative importance of water level variations occurring over time scales from a few hours to several months. Dominating the pattern in Fig. 2 is the very long period, semi-annual rise and fall of water level in the lagoon. High water occurs in late May and late October, while the semi-annual lows are found in late February and late July. The rise and fall in water level associated with these seasonal fluctuations is on the order of 50 cm.

Superimposed onto the very gradual rise and fall in sea level in Upper Laguna Madre are water level variations occurring over time scales on the order of 1 to 2

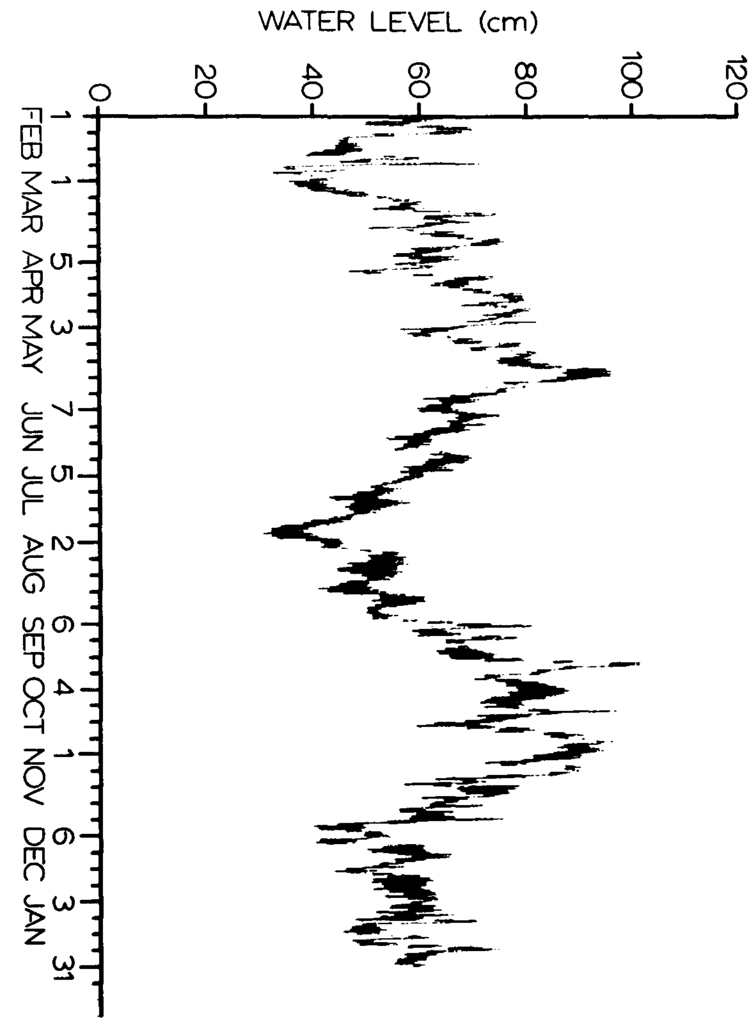

Figure 2. Time plot of hourly water levels, in cm, relative to a datum 1 ft below mean sea level, from Marker 21, February 1, 1974 through January 31, 1975.

weeks. The rise and fall of water level over these time intervals is quite variable, but generally on the order of 10-20 cm.

Diurnal and perhaps semi-diurnal astronomical tides appear as little more than high frequency and relatively insignificant noise on the longer period variations. There is some indication of a cycling in and out of phase of tidal constituents, significantly altering the relative importance of tidal period water level variations and those occurring over longer time scales.

The relative importance of water level variations occurring over a wide range of time scales was investigated quantitatively by computing an energy density spectrum from the year-long water level record. Fig. 3 is an energy density spectrum computed from 2-hourly water levels from Marker 21 recorded between February 1, 1974 and January 31, 1975. The computer program used for the calculations (Fee, 1969) involves a fast-Fourier transform technique after the linear trend has been removed from the data.

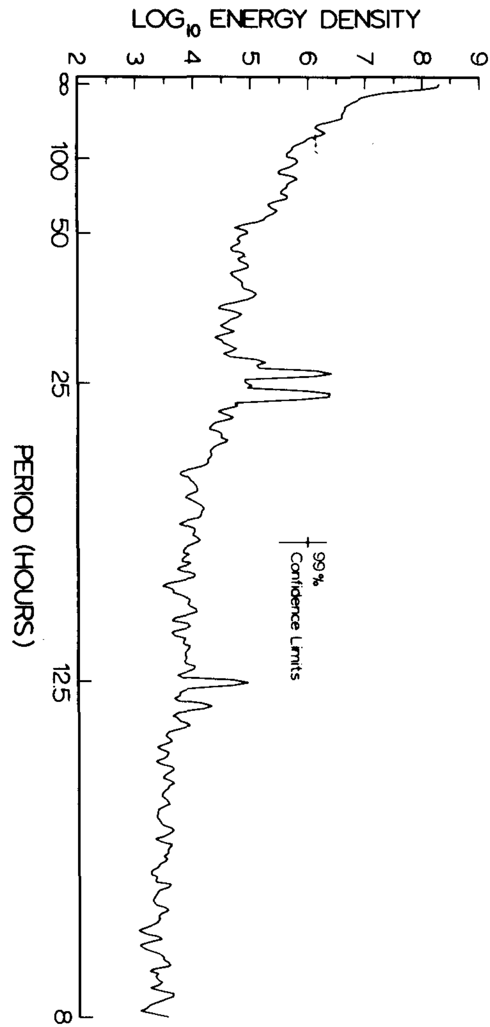

Figure 3. Relative energy density spectrum of 2-hourly water levels from Marker 21, February 1, 1974 through January 31, 1975. Vertical axis is in cm^2/cph. Spectral resolution is 0.000385 cph.

Fig. 3 shows a rather uniform decrease in energy density levels with decreasing period. The exponential decrease is interrupted first by the spectral peaks occurring at the O_1 and K_1 tidal constituent periods. Energy density values rise nearly 2 orders of magnitude above surrounding levels in that part of the spectrum. The M_2 and S_2 semi-diurnal constituents produce spectral peaks of lesser importance at periods of approximately 12.4 and 12.0 hrs. The spectrum has been plotted only to a period of 8 hrs, as no statistically significant spectral peaks were computed at shorter periodicities.

To investigate the possibility that water level variations observed in Upper Laguna Madre move in from the northwestern Gulf of Mexico through the Aransas Pass at Port Aransas (Fig. 1), a coherence-squared spectrum was computed from water level records obtained simultaneously over a 148.5-day period from the South Jetty at Port Aransas and Marker 21 in Upper Laguna Madre. Results are shown in Fig. 4. Three significant features stand out in the spectrum. Highest coherence-squared values occur at periods longer than about 50 hrs, resulting from long-period variations in meteorological, thermohaline and dynamic forces. These forces drive water against or away from the coast at Port Aransas, forcing a slow filling or draining of the intracoastal bays. The estuarine-shelf exchanges eventually affect the study site, approximately 35 km from the coast along the Corpus Christi Ship Channel and through Corpus Christi Bay.

Coherence-squared values drop off abruptly and remain low between periods of approximately 50 and 30 hrs, then rise sharply at the diurnal tidal periodicities. Both the O_1 and K_1 tidal constituents can be identified in the spectrum by slightly higher coherence-squared values.

The semi-diurnal motions are statistically significant at the M_2 period only, with a coherence-squared value of over 0.65 at a period of 12.5 hrs. The immediate decrease in coherence suggests that the S_2 constituent does not move in from the Gulf to the study site. The spectral peak in Fig. 3 may therefore be a result of local wind effects.

Table 1 gives the phase lag of water level variations at diurnal and semi-diurnal periods recorded at Marker 21 relative to those recorded at the coast at Port Aransas. At the diurnal periods, between 23.3 and 27.0 hrs, phase lags of between 122° and 132° are computed. These are equivalent to time lags of between 8.5 and 9.3 hrs. With a distance of approximately 35 km from the coast to the study site, this corresponds to a speed of propagation of the tidal wave crest of about 4 km/hr. At semi-diurnal periods of between 12.3 and 12.7 hrs, the phase lag is between 204° and 206°, corresponding to a time lag of between 7.0 and 7.2 hrs and a speed of propagation of approximately 5 km/hr.

Twenty-nine day blocks of hourly water levels were used to compute the harmonic constants of the principal tidal constituents with a computer program described by Dennis and Long (1971). Tidal constituent amplitudes, in cm, and local phase angles are shown on harmonic dials for the K_1 and O_1 partial tides in Fig. 5. Points for the O_1 tidal constituent are fairly tightly clustered, with phase angles

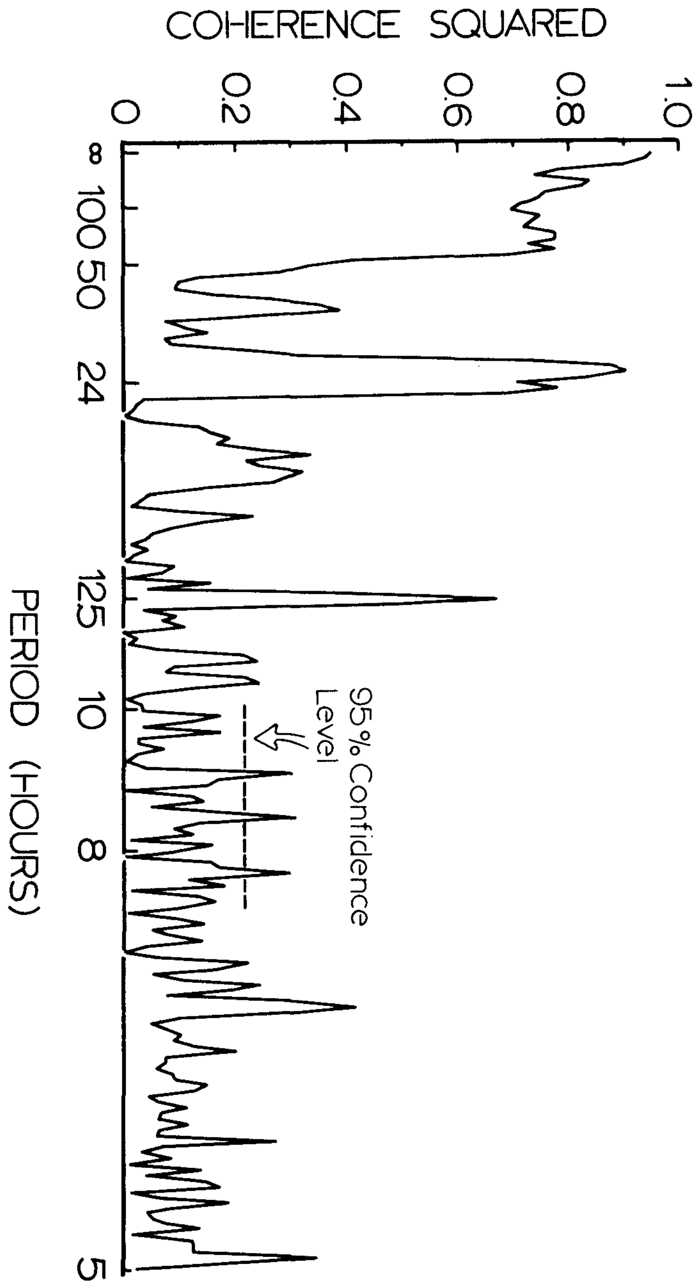

Figure 4. Coherence-squared spectrum for South Jetty and Marker 21 water level data, January 30 through June 27, 1974. Spectral resolution is 0.0001 cph.

TABLE 1

Phase Lags of Diurnal and Semi-diurnal Period Water Level Variations at Marker 21, Relative to Those at Port Aransas, January 30 to June 27, 1974.

Period (Hrs)	Phase Lag at Marker 21 (Degrees)	Corresponding Time Lag (Hrs)
27.0	124	9.3
26.3	125	9.1
25.6	125	8.8
25.0	122	8.5
24.4	125	8.5
23.8	130	8.6
23.3	132	8.5
12.7	204	7.2
12.5	205	7.2
12.3	206	7.0

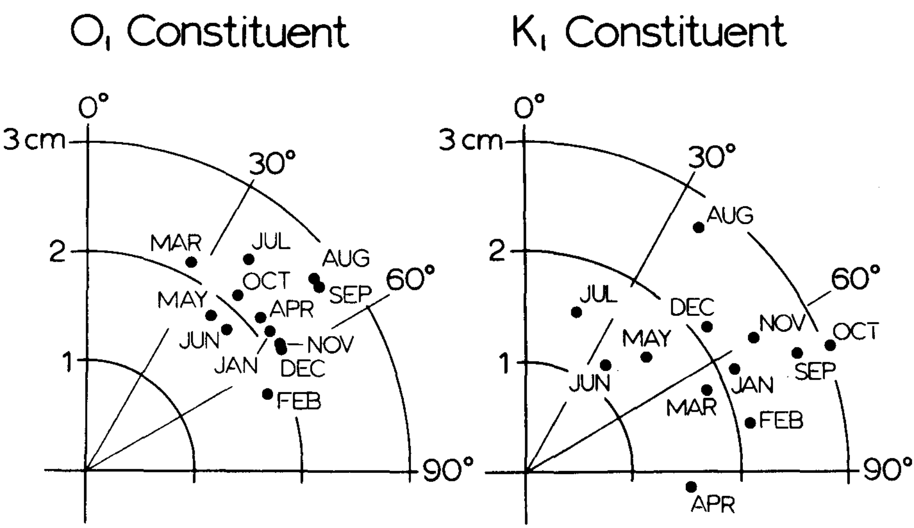

Figure 5. Harmonic dials of amplitudes, in cm, and local phase angles of the O_1 and K_1 partial tides for Marker 21, February, 1974 through January, 1975. Harmonic constants computed from 29-day records, starting on the first day of the indicated month.

generally between 30° and 60°, and amplitudes between 1.8 and 2.8 cm. For comparison, O_1 constituent amplitudes computed from South Jetty water level data are approximately 12 cm (Smith, 1974). There is no well-defined seasonal variation in amplitude, however, phase angles computed for the fall and winter months are somewhat larger than those computed for the spring and summer months.

The harmonic dial for the K_1 constituent shows a pattern that is similar though somewhat more spread out. Amplitudes are between about 1 and 3 cm, and local phase angles fall between approximately 30° and 90°. There is some indication that higher amplitudes are characteristic of the fall and winter months. K_1 constituent amplitudes at Port Aransas are approximately 12 cm (Smith, 1974), suggesting that diurnal period tidal constituent amplitudes at the study site have been damped to less than 25% of their amplitudes at the coast.

The relative importance of tidal and non-tidal water level variations at Marker 21 was investigated by numerically filtering the 365-day water level record to remove tidal periodicities. The "D39" Doodson-Warburg type filter described by Groves (1955) was chosen for this part of the analysis. The variance of the water level data was computed both before and after filtering. Ninety-five percent of the total variance remained in the filtered water level data, indicating that tidal-period processes contribute a small fraction of the variation in water level at this location. In contrast to this, variance in water level records from the South Jetty at Port Aransas appears to be approximately equally distributed between tidal and nontidal periodicities.

DISCUSSION

Aside from set-up and set-down effects produced locally by surface windstress, intracoastal water level variations occur primarily in response to the estuarine-shelf exchanges driven by variations in coastal water levels. The high coherence-squared values in Fig. 4, along with the computed phase angles, clearly demonstrate that both tidal and the longer period water level variations recorded at Marker 21 in Upper Laguna Madre appear first at the South Jetty at Port Aransas. Fig. 4 also shows that highest coherences are found in the very long period part of the spectrum. Thus, it is not surprising that the dominant feature of water level variations in Upper Laguna Madre is the semi-annual rise and fall of sea level characteristic of coastal locations along the northwestern rim of the Gulf of Mexico.

The causes of the semi-annual variations in coastal sea level have been suggested by Marmer (1954), Whitaker (1971), and Sturges and Blaha (1976), and appear to include both thermohaline and dynamic forcing. The spring run-off is primarily responsible for the relatively high coastal water levels in May. Seasonal warming and cooling produce a maximum expansion and contraction of shelf waters in September-October and January-February, respectively. Sturges and Blaha (1976) have recently suggested that the July minimum may be related to temporary storage of water in a large anticyclonic gyre in the western Gulf of Mexico maintained by the curl of the windstress. It is apparent from Fig. 2 that these sometimes distant processes, acting on the waters of the Texas shelf and in the waters of the open Gulf, have a profound and dominant, if indirect effect on water levels in Upper Laguna Madre.

Similarly, the water level variations occurring in Upper Laguna Madre over time scales on the order of 1 to 2 weeks can be attributed to the slow exchange of water between intracoastal areas and the inner continental shelf in response to meteorological forcing. Smith (1977) has shown statistically significant relationships exist between variations in the regional pressure field over the central Texas shelf and variations in the volume of Corpus Christi Bay. Results suggest that bay-shelf exchanges are driven both by the cross-shelf component of the wind, producing a set-up and set-down of coastal water levels over time scales on the order of 4-6 days, and by the longshore component of the wind, producing a cross-shelf Ekman transport in the surface layer over longer time scales. Again, these estuarine-shelf exchanges have a significant local effect on water levels recorded in Upper Laguna Madre. The approximately weekly or biweekly addition or removal of volumes of water sufficient to raise or lower the water level by 5-10 cm must constitute an effective flushing mechanism.

The sympathetic tidal motions in Upper Laguna Madre provide a relatively small but nevertheless dependable mechanism for exchanging water with Corpus Christi Bay and eventually with the Gulf of Mexico. The low amplitudes of the individual tidal constituents in the study area (Fig. 5) are a direct result of the 35 km of shallow bays and constricting channels through which tidal motions must propagate. All of the principal tidal constituents' amplitudes are less than approximately 3 cm. While individual tidal constituents are geometrically additive, they periodically cycle in and out of phase, and one must still think of tides at the study site as being on the order of a few centimeters. Price (1971) has stated that the range of the daily astronomical tide in the northern Laguna Madre is 1.0 ft, but this appears to be about an order of magnitude too high.

The numerical filtering of the water level data to remove tidal-period variations demonstrates clearly that non-tidal forcing is of primary importance in Upper Laguna Madre. These aperiodic variations are as unpredictable as the meteorological events that cause them, however, they must be considered in any discussion of water level variations in this area.

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