Observations and predictions of tides and storm surges along the Gulf of Mexico

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ABSTRACT: This paper shows that the subtidal energy on the Texas Coast and in Corpus Christi Bay is large due to meteorological events and that the water level anomaly can be larger than the astronomical tide itself. The relative importance of remote and local forcing on the subtidal response in Corpus Christi Bay was studied using water level and wind data observed during the winter and spring months from 1998 to 2000. The multiple coherence squared between the water level response inside the bay and the local and remote forcing was high ($MCS > 0.8$ for most locations), indicating that the local wind stress and water level on the coast are the primary forcing mechanisms inside the bay over the range of frequencies studied. The study further confirmed the importance of remote forcing for the water level response as predicted by the analytical model of Garvine (1985).

1. INTRODUCTION

The need for reliable water level forecasting is increasing with the trend toward deep-draft vessels, particularly for shallow water ports along the Gulf of Mexico (NOAA, 1999). Nine of the twelve largest U.S. ports are located along the Gulf of Mexico, and ports served by the Mobile Bay Entrance and Galveston Bay Entrance account for 46% of the total U.S. tonnage (NOAA, 1999). Although the astronomical tides in the Northern Gulf of Mexico are easily predicted by conventional harmonic analysis, it is difficult to accurately predict the total water level fluctuations because of frequent meteorological events, such as the passage of strong cold fronts. Our inability to accurately predict water level anomalies (difference between the observed water level and the tide prediction) can have severe consequences. In Galveston Bay there were over 1,240 ship groundings between 1986 and 1991, with a significant number of incidents involving petrochemicals.

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To improve navigation and safety in these waterways, NOAA has established the Physical Oceanographic Real-Time System (PORTS) which includes the near real-time monitoring and reporting of water levels and meteorological conditions via telephone or Internet (www.co-ops.nos.noaa.gov/). Other agencies are developing real-time forecasting models for estuarine hydrodynamics of oil spill response and for search and rescue operations along the Texas coast (hyper20.twdb.state.tx.us/bhydpage.html). Although both systems greatly reduce navigational and environmental hazards along the northern coast of the Gulf of Mexico, they rely on harmonic analysis for either the level prediction in the estuary itself or as a seaward boundary condition for an estuarine hydrodynamic model. Presently, they do not incorporate meteorological effects. This raises two questions:

1. What is the relative importance of the remote forcing (water level at the mouth of the estuary) to the local forcing (wind stress over the estuary) for subtidal water level, setup, and current response in the estuary?
2. To what extent can the remote forcing be predicted using a simple empirical model relating meteorological forecasts to water level anomaly?

Previously, Guannel et al. (2001) studied the entrance to Galveston Bay and confirmed the importance of the remote forcing on water levels inside the bay and the importance of the local forcing on the surface slope, consistent with the analytical model of Garvine (1985). In this paper, we look at observations in Corpus Christi Bay at one location on the open coast (014 Bob Hall Pier), and at four locations in Corpus Christi Bay (009 Port Aransas; 001 Naval Air Station; 008 Texas State Aquarium; and 011 White Point) as shown in Fig. 1. Data for these stations are provided by the Conrad Blucher Institute for Surveying and Science at Texas A&M University-Corpus Christi as part of the Texas Coastal Ocean Observation Network (TCOON) (Michaud et al., 1994). TCOON consists of over 40 stations with real-time access made available through the Internet and other media and has been in operation for over 10 years. All stations report water level, and many others report wind speed, direction, gust, air temperature, water temperature and barometric pressure. A subset of the archived data were used for this study from early December to the end of March for years 1998 to 2000, for a total of 318 days of data at hourly intervals. The choice of data was determined by data availability and by the intention to restrict the study to winter and spring months when cold front frequently passed over the study area. Tropical events and sea breeze activity associated with summer and fall months were excluded.

Fig. 2 shows observation for Port Aransas for $60 < Jd < 80$, 1998, during the passage of a strong cold front. The top panel shows the measured water level (solid) and that predicted by harmonic analysis (dashed). The figure indicates that the water level anomaly caused by the meteorological event is as large as the tide range itself.

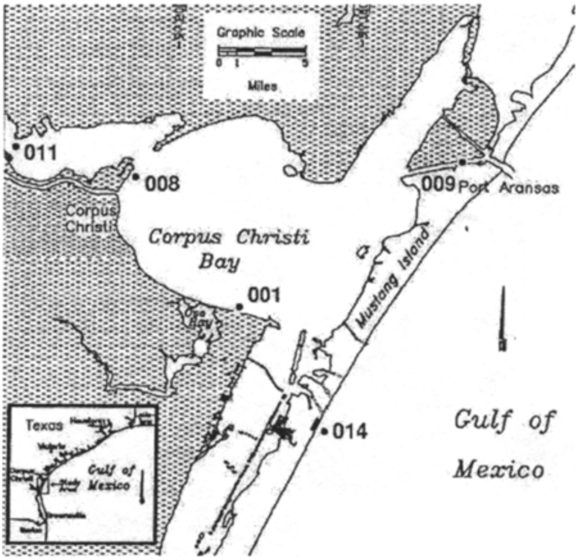

Figure 1: Corpus Christi Bay and gage locations.

Wind direction plays an important role in determining the magnitude and sign of the anomaly as was shown for Galveston Bay (Cox et al., 2002). The figure also indicates that the response of the system is on the order of only a few hours after the passage of the front.

Fig. 3 shows the power spectrum for the water levels in Corpus Christi Bay. The figure indicates the diurnal and semidiurnal tide components are damped from outside the bay (014) to the upper reaches of the bay (011). The figure also indicates that the subtidal energy is large and is not damped. Fig. 4 shows a portion of the filtered water level, η, water level setup , and wind stress. Data were filtered using a Lanczos filter with a 36 hour cutoff to remove the tidal variability and high frequency wind fluctuations, and the wind stress was estimated from the wind speed and direction following Wu (1980). The wind stress was considered rectilinear, either North-South and East-West or Shore Normal and Shore Parallel (Guannel, 2001). For this paper, winds recorded at 014 were used and assumed to be representative of the wind over the bay. The water level setup is simply calculated as the difference of the gages inside the bay, $\eta_{009} - \eta_{008}$ (solid) and $\eta_{009} - \eta_{001}$ (dash-dot). The top panel shows that the anomaly fluctuation can be as large as ± 0.2 m which is large compared to the rms of the meteorological tide at Port Aransas of 0.16 m. The figure also shows that there is a small lag on the order of several hours between the anomaly on the coast (014) and inside the bay (009). The three large positive anomalies in the upper panel ($Jd \simeq 15$,

$Jd \simeq 22$; and $Jd \simeq 28$) generally occur when there is a large component of wind stress from the east (dash-dot line in lower figure).

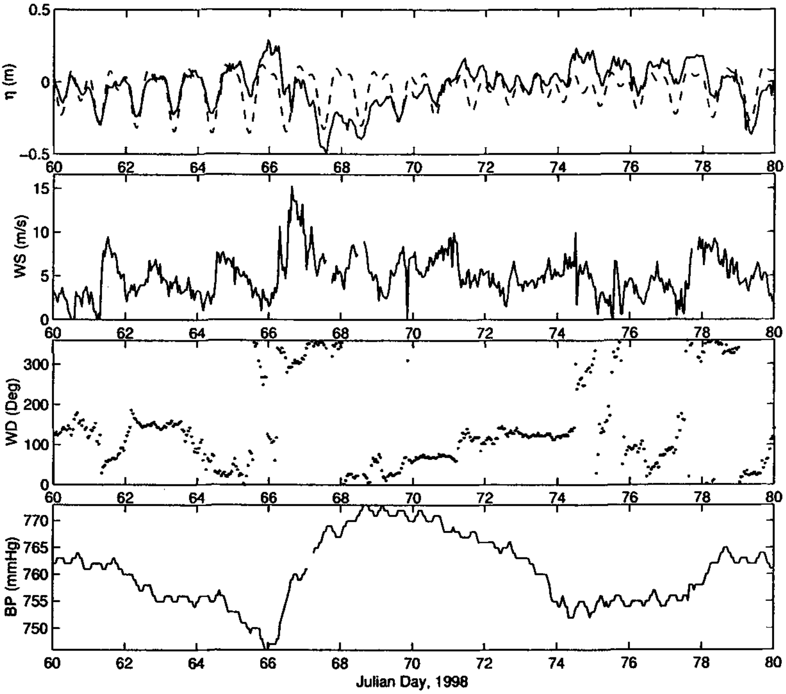

Figure 2: Observations for 009 Port Aransas Station in 1998. Top panel shows observed water level (solid) and predicted using harmonic analysis (dashed); second, third and fourth panels show observed wind speed, direction and barometric pressure. Wind and barometric pressure were measured at 014 and assumed constant over the study area.

2. Local and Remote Forcing

A number of remote mechanisms can cause water level fluctuations at the mouth of an estuary, including winds blowing parallel to the coast and the associated Eckman transport. Local winds act directly on the the bay through the surface wind stress. Garvine (1985) used scaling arguments and a simple analytical model to show that subtidal variations of water levels inside the estuary are dominated by the remote effects because the length scale of the estuary is short compared to the subtidal wavelength. The depth-averaged current is a response to the conservation of mass. The surface slope was shown to be dominated by the local wind. In considering the orientation of the estuary to the coast, Garvine (1985) demonstrated that the local and remote forcing

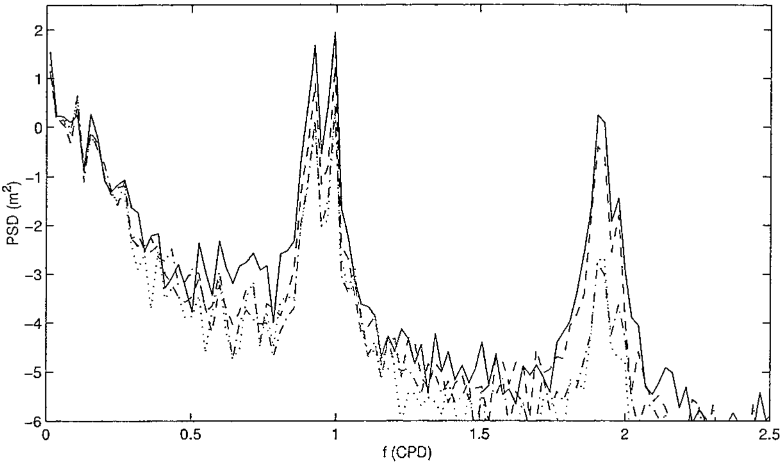

Figure 3: Power spectrum of water level for η_0 (014, solid), η_1 (009,dashed), η_2 (001, dash-dot), η_3 (008, dotted).

should have either a combined or opposite effect if the estuary is aligned parallel to the coast, and the two mechanisms should be independent if the estuary is perpendicular to the coast. Smith (1977) found that for Corpus Christi Bay there was evidence of local forcing dominance at shorter time scales (60 to 100 hours) and remote forcing dominance at lower frequencies on the bay volumes. Using a month-long set of water level and current observations, Wong and Moses-Hall (1998) confirmed the importance of the remote forcing on water levels for Delaware Bay, but found that the local wind effect dominates the current fluctuations, particularly the current structure.

The analysis method used by Wong and Moses-Hall considers the multiple and partial coherence of a two input, one output system. This method is applied here to Corpus Christi Bay which is a lagoonal estuary. In the frequency domain, the water level response η at any location in the estuary can be written

$$\eta_j = H_{1j}\,\eta_0 + H_{2j}\,\tau_{wj} + \epsilon_{\eta j} \quad j = 1, 2, ..., n \tag{1}$$

where η_j represents the water level at the j-th estuary station with $j = 1, 2, ..., n$ representing the $n = 4$ TCOON stations used in Corpus Christi Bay; η_0 is the observed coastal water level (Station 014) representing the remote effects; τ_{wj} is the local wind stress; and $\epsilon_{\eta j}$ represents the noise that is not coherent with either η_0 or τ_w. H_{1j} and H_{2j} are complex quantities representing the transfer functions between the remote (H_1) and local (H_2) forcing and response of the estuary. A similar equation can be written for the water level gradient (setup) or currents in the bay.

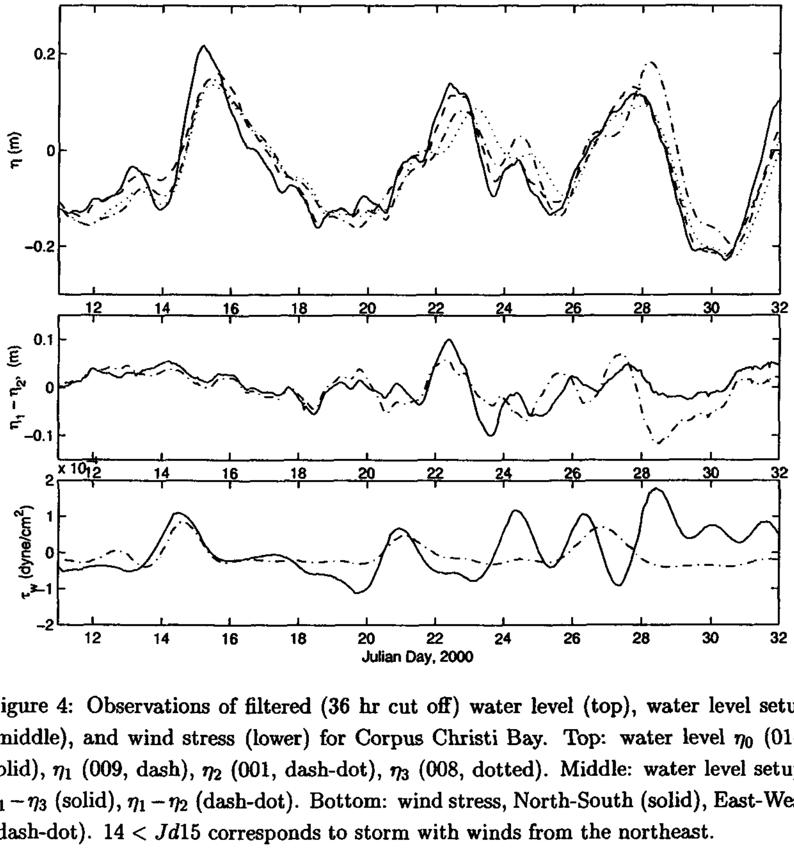

Figure 4: Observations of filtered (36 hr cut off) water level (top), water level setup (middle), and wind stress (lower) for Corpus Christi Bay. Top: water level η_0 (014, solid), η_1 (009, dash), η_2 (001, dash-dot), η_3 (008, dotted). Middle: water level setup, $\eta_1 - \eta_3$ (solid), $\eta_1 - \eta_2$ (dash-dot). Bottom: wind stress, North-South (solid), East-West (dash-dot). $14 < Jd15$ corresponds to storm with winds from the northeast.

Fig. 5a,b shows the multiple coherence squared (MCS) for the two input (η_0, τ_w), one output (η_j) system where j represents the four locations considered in the bay and where τ_w is computed using either the shore normal or shore parallel winds. For Fig. 5a,b the MCS is high (> 0.8) for most of the locations indicating that the estuary response is primarily a function of these two mechanisms. Other mechanisms such as river discharge are less important for the data considered here, with the possible exception of the Station 011. Overall, the MCS is lower in Corpus Christi Bay, however, compared to the previous study at Galveston Bay (Guannel et al, 2001), indicating that the assumption of rectilinear winds may not be as suitable as in the earlier location.

Fig. 5c shows the partial coherence squared (PCS) between η_0 (remote forcing) and η_j (response) with the local forcing shut down (Wong and Moses-Hall, 1998). The figure indicates that the PCS is high near the mouth (009) and decreases slightly the head (008, 001) and more so at the far reaches of the bay (011). Overall, the PCS is high (> 0.6) indicating that the remote effect is primarily responsible for the water level. Fig. 5e shows that the PCS is low and only slightly above the 95% significant level (0.2).

Fig. 6a-f shows similar results considering the local forcing as either North-South or East-West directed. The only curve which is significantly different than the corresponding curve in Fig. 5 is that for the station at the furthest reach of the bay (011). For this station, the MCS appears to be highest considering the East-West directed wind stress which is consistent with the analytical model of Garvine (1985).

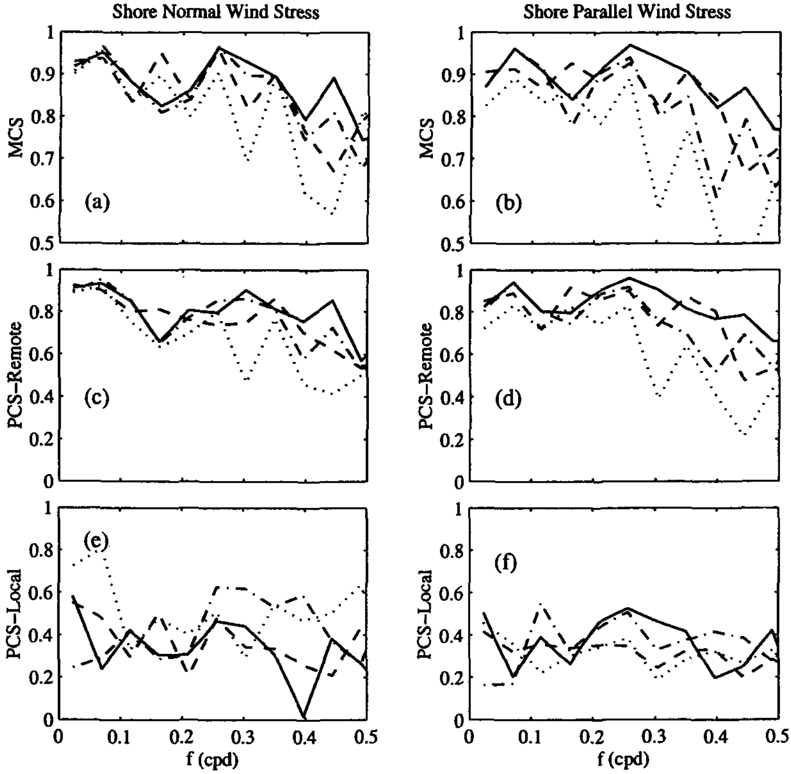

Figure 5: Water level response for shore normal wind stress (a, c, e) and shore parallel (b, d, f) for 009 (solid), 001 (dash-dot), 008 (dash), and 011 (dotted). The 95% significance level is 0.20 computed with 30 DOF.

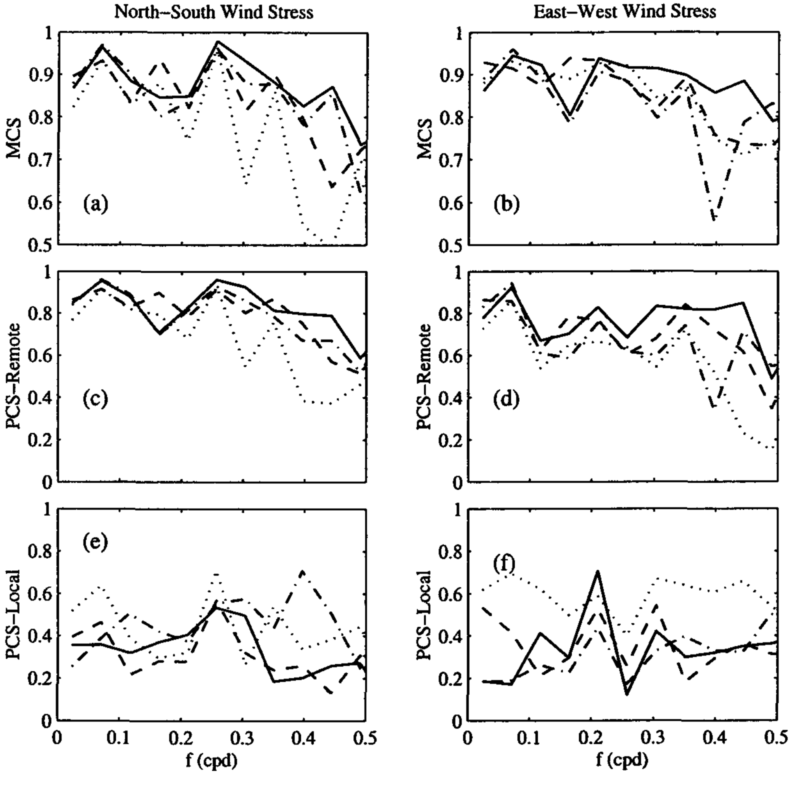

Figure 6: Water level response for shore normal wind stress (a, c, e) and shore parallel (b, d, f) for 009 (solid), 001 (dash-dot), 008 (dash), and 011 (dotted). The 95% significance level is 0.20 computed with 30 DOF.

4. Summary and Conclusions

This paper shows that the subtidal energy on the Texas Coast and in Corpus Christi Bay is large due to meteorological events and that the water level anomaly can be larger than the astronomical tide itself. The relative importance of remote and local forcing on the subtidal response in Corpus Christi Bay was studied using water level and wind data observed during the winter and spring months from 1998 to 2000. The multiple coherence squared between the water level response inside the bay and the local and remote forcing was high ($MCS > 0.8$ for most locations), indicating that the local wind stress and water level on the coast are the primary forcing mechanisms inside the bay over the range of frequencies studied. The study further confirmed the importance of remote forcing for the water level response as predicted by the analytical model of Garvine (1985).

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