Local and Remote Forcing of Subtidal Water Level and Setup Fluctuations in Coastal and Estuarine Environments

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ABSTRACT: The relative importance of remote and local forcing on the subtidal response in Galveston Bay was studied using water level and wind data observed during the winter and spring months from 1997 to 2000. The study confirmed the importance of remote forcing through Eckman transport for the water level response and local forcing for the surface slope response. These two forcing mechanisms act independently since the estuary axis was oriented roughly orthogonal to the coastline. A neural network model was introduced which used the meteorological data to predict the water level anomaly which, when added to the harmonic tides, provided good estimates of the total water level at the bay entrance (remote forcing).

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 (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 which are addressed in this paper:

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?

The observations for this paper were taken at one location on the open coast near the entrance to Galveston Bay on Pleasure Pier (Station 021), Galveston Island, TX, and at three locations in Galveston Bay (Stations 521, 507 and 503) as shown in Figure 1. These hydro-meteorological stations are operated by the National Ocean Service as part of its National Water Level Observation Network. 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. For the first part of this paper, data were used from early December to the end of March from 1997 to 2000, for a total of 321 days of data at hourly intervals (Guannel, 2001). For the second part, a smaller data set of 270 days was used over roughly the same period (Tissot et al., 2001). 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. Extra-tropical events and sea breeze activity associated with summer and fall months were excluded.

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

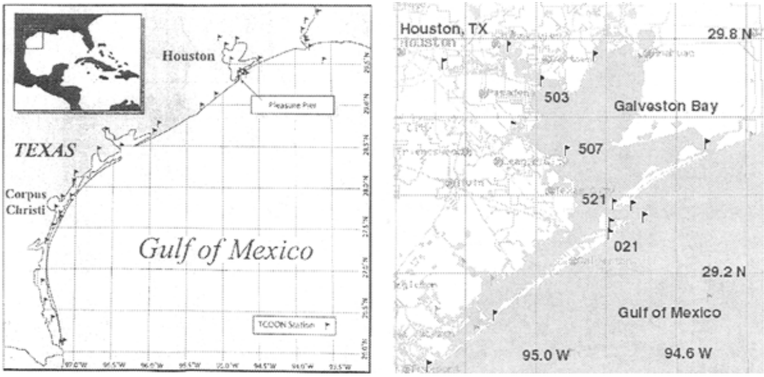

Figure 1: Overview of TCOON stations and detail study area.

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 coast, Garvine (1985) demonstrated that the local and remote forcing 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 the lagoonal estuary of 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 Galveston Bay which is a lagoonal estuary with its axis aligned perpendicular to the coast. 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 $n = 3$ TCOON stations used in Galveston Bay; η_0 is the observed coastal water level (Station 021) 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 either the water level gradient (setup) taken as the difference between Station 521 and 502 or the current fluctuations. H_{3j} and H_{4j} denote the transfer functions for the setup, and the currents are not included in this paper. Data were filtered using a Lanczos filter with a 36 hour cutoff to remove the tidal variability and high frequency wind fluctuations. The wind stress was estimated from the wind speed and direction following Wu (1980) and the motion was considered rectilinear (either shore-normal or shore-parallel) (Guannel, 2001).

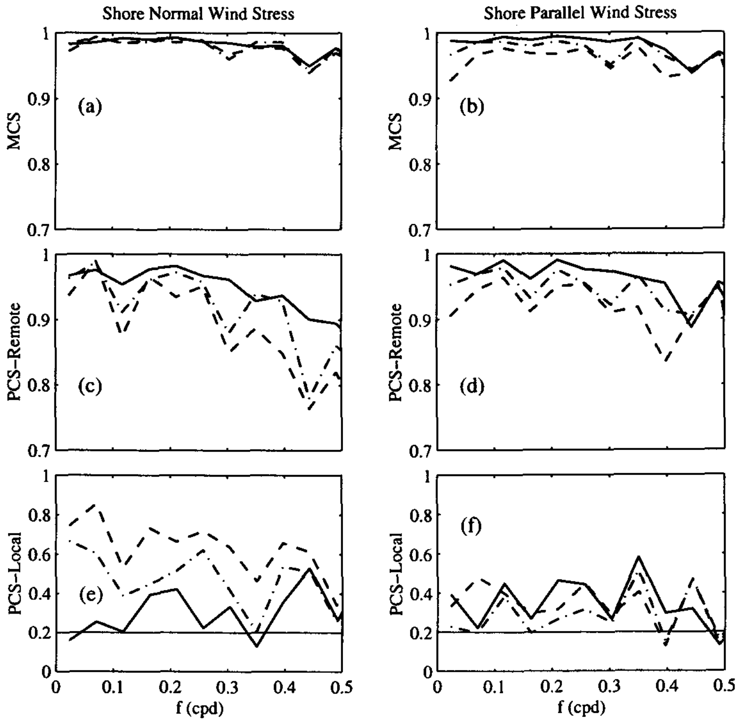

Figure 2: Water level response for shore normal wind stress (a, c, e) and shore parallel (b, d, f) for 521 (solid), 507 (dash-dot), 503 (dash). The 95% significance level is 0.20 computed with 30 DOF.

Fig. 2a,b shows the multiple coherence squared (MCS) for the two input (η_0, τ_w), one output (η_j) system where j represents the three locations considered in the bay and where τ_w is computed using either the shore normal or shore parallel winds. For Fig. 2a, the MCS is high (> 0.95) 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, even for the interior point closest to the head of the estuary (503). Fig. 2b shows that the MCS is lower when considering the shore parallel winds, indicating the importance of the shore normal winds and that this importance increases as distance to the head increases. This is consistent with the analytical model of Garvine (1985). Fig. 2c shows the partial coherence squared (PCS) between η_0 (remote forcing) and η_j (response) with the local forcing shut down (Wong and Mose-Hall, 1998). The figure indicates that the PCS is high near the mouth (521) and decreases as one moves towards the head (507, 503). Overall, the PCS is high (> 0.90) indicating that the remote effect is primarily responsible for the water level, even in the case of the shore normal wind. Fig. 2e shows that the PCS is low and barely significant near the mouth (521) for $f < 0.4$ cpd. For $0.4 < f < 0.5$, there is a slight increase in PCS which would indicate the importance of the local effect, although the peak coherence is low. The importance of the local effect increases slightly as one moves towards the head. Fig. 2d,f show that for the shore parallel wind, the local wind is unimportant as expected since it blows perpendicular to the axis of the estuary.

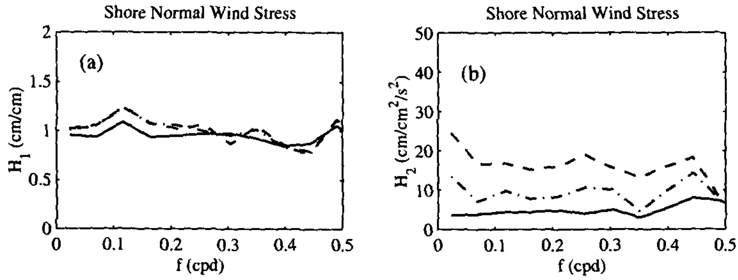

Figure 3: Transfer functions for 521 (solid), 507 (dash-dot), 503 (dash). Remote effect (H_1) (a) and Local effect (H_2) (b) considering shore normal wind stress.

Fig. 3 shows H_1 and H_2 for the remote and local effects considering the shore normal wind stress. Fig. 3a shows that H_1 is fairly constant across the subtidal frequency band and is approximately 1.0, indicating that the water level at the mouth is not amplified or attenuated, although there may be a small amplification at lower frequencies for 507 and 503. Fig. 3b also shows very little dependence of H_2 on frequency and indicates that the local effect, although small, increases as one moves toward the head. This increase is consistent with observed spectra (figure not shown), whereas the energy at the tidal frequencies is damped. That H_1 and H_2 are relatively constant with respect to frequency is in contrast with the work of Wong and Moses-Hall (1998).

Fig. 4 shows the analysis of the slope in the estuary, taken as the difference between the water level at 521 and 503. Both the shore normal (solid) and shore parallel (dash-dot) winds are considered. Fig. 4a shows that the MCS is high when considering only the shore normal wind and the remote effect, indicating that these two mechanisms are primarily responsible for the gradient in the estuary. The MCS for the slope is lower than for the water level response (Fig. 2a) which may be due to the noise induced when taking the difference of two large signals or other reasons. In any case, comparison of Fig. 4b and d for the shore normal wind stress shows that the local effect is dominant over the remote effect in producing the surface slope. In considering the shore parallel wind stress and surface slope, the MCS is significantly lower. The contribution of the remote effect remains about the same, and the local effect decreases significantly. The transfer functions H_3 and H_4 (Fig 4c, e) show the importance of local shore normal wind stress in producing the setup. This is consistent with the analytical model of Garvine (1985).

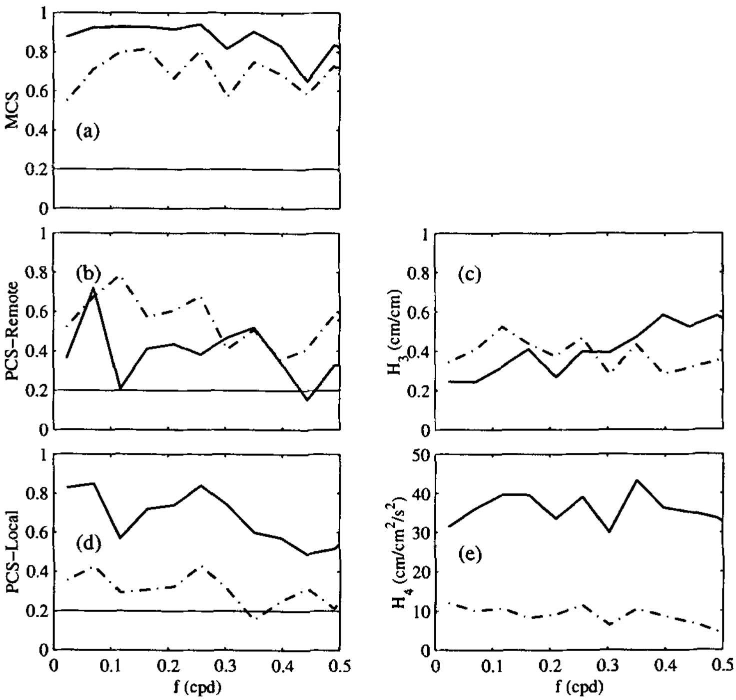

Figure 4: Coherence and transfer functions for setup with shore-normal (solid) and shore-parallel (dash-dot) winds: MCS (a), PCS remote effect (b), transfer function remote effect(c) PCS local effect (d) and transfer function local effect (e).

3. Neural Network Model to Predict Remote Forcing

The previous section shows the dominance of the remote forcing in determining the water levels inside the bay. The transfer functions between water levels outside the bay and inside the estuary can be determined using standard spectral techniques. Therefore, to predict water levels inside the estuary, it is necessary to know the water levels outside the bay due to the remote effect, transfer function, and phase. This section briefly outlines a neural network model that uses historical wind speed and direction, barometric pressure, and known response to predict the water level anomaly outside the bay for given marine (meteorological) forecasts. The predictions are limited to the range of 1 to 30 hours which are typically used for navigation, oil spill response, and search and rescue. Prediction beyond 30 hours degrades with the uncertainty of the meteorological forecast.

Neural networks have been recently applied to coastal engineering to predict monthly water levels (Vaziri, 1997), hourly tides (Tsai and Lee, 1999), coastal structure response (Mase et al., 1995; van Gent and van den Booraard, 1998), and runoff and drainage (Proano et al., 1998). Whereas Tsai and Lee (1999) used neural networks for one-hour predictions of tidal variations in the absence of significant meteorological events, the present model relies on harmonic analysis to predict the tidal fluctuations and neural networks to predict the anomaly.

The neural network model was trained using a back-propagation algorithm and all computations were performed within the MATLAB 5.3/version 3 of the Neural Network Toolbox. A simple neural network structure based on one hidden layer and one output layer was found to be optimal in forecasting the anomaly. Logsig and tansig transfer functions were used for the hidden and output layers, respectively, while the input decks were scaled to a [-1,1] range. The optimal structure of the input deck depended on the extent of the forecast and the inclusion of forecasted winds. With forecasted winds, optimum input decks could be kept relatively small. For this work, an input deck including time series of 5 previous hourly measurements of water anomalies, east-west wind speed squared, and north-south wind speed squared, and 20 hourly measurements of the barometric pressure complemented the forecasted wind. The neural network was trained over one data set (1997, 1998, or 1999) and evaluated over the two other data sets not included in the training.

Fig. 5 shows observed water levels for the entrance to Galveston Bay (021) during the passage of a cold front in 1999. Fig. 5a shows the limitations of conventional harmonic analysis for the Gulf of Mexico when meteorological effects are not included. Fig. 5b shows the 9-hour predictions of the neural network model trained with 1997 data. The model works surprisingly well considering that winds at only one point were used. Since historical marine forecasts were not readily available at the time of the study, the wind forecasts were derived from observations subjected to a random filter with a Gaussian distribution (Tissot, et al., 2001). The variance of the distribution was increased as the extent of the forecast increased to simulate the uncertainty in the forecast. Fig. 5c shows a detail of the model prediction and shows that the prediction for 1999 is not sensitive to the either 1997 or 1998 training periods because there were a large number of fronts during the training periods.

The root-mean-square error (normalized by the root-mean-square of the observed water level), E, is shown as a function of the extent of the forecast in Fig. 6. The horizontal dashed line $E \simeq 0.8$ shows the large error associated with the harmonic analysis which is independent of the meteorological forecast (Fig. 5a). A simple method to reduce the error is shown by the light solid line. This method assumes that the present anomaly at $t = t_0$ will be the same at a time $t = t_o + t_{forecast}$. This "adjusted water level" works well for $t < 3$ hours, but the error increases rapidly as the extent of the forecast increases. This is because the water level responds within a matter of hours to the shift in wind direction. The dashed line shows that the error of the neural network model is lower than either the adjusted water level or harmonic prediction. The error increases with the extent of the simulated forecast.

4. Summary and Conclusions

The first part of this paper was concerned with the relative importance of local and remote forcing for water levels and surface slopes for a shallow estuary on the northern Gulf of Mexico. The principle axis of the estuary was normal to the coast, and the analysis consisted of studying the two input (local and remote forcing), one output (water level or setup) system. Shore normal and shore parallel winds were considered separately. The conclusions of the present analysis are consistent with the analytical model of Garvine (1985) in that the remote forcing dominated the water level response at subtidal frequencies considered and the local shore normal wind stress dominated the surface slope. This means that the subtidal water level in the bay can be predicted simply if the remote forcing, transfer function, and phase are known. The importance of the local wind on the water level inside the bay is minor, although it does have an effect on the surface slope and possibly residual currents.

The second part of the paper showed that this remote forcing can be predicted using a point measurement of the wind speed and direction with a neural network model. Optimization of the model (number of neurons, additional input, etc.) and utilization of marine forecasts are left for future work.

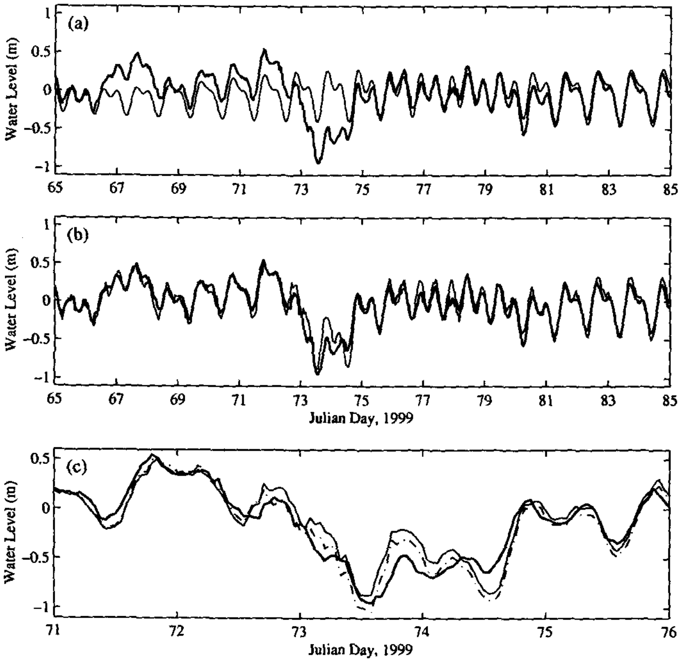

Figure 5: Water level observations (heavy line) and harmonic predictions (light) (a); and observations (heavy), and NN model trained in 1997 (light) (b) for $65 < Jd < 85$, 1999, Station 021. Detail (c) for $71 < Jd < 76$ including NN model trained in 1998 (dash-dot).

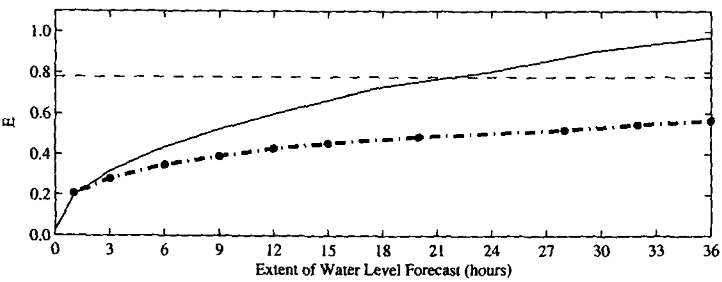

Figure 6: Error estimates, E, between observed water level and predictions as a function of the extent of the forecasts. Predictions by unadjusted tide harmonics (light dashed), adjusted tide harmonics (light solid), and NN model (dash-dot).

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