Performance of the Coastal Modeling System for Various Conditions in the Navigational Waters of the South Texas Coastal Bend

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Abstract: The Coastal Modeling System (CMS) hydrodynamic model was implemented for the South Texas Coastal Bend while taking advantage of a dense coastal observation network. The model was selected for its computational efficiency, ease of implementation and its emphasis on navigation channel performance. Model performance was evaluated based on accuracy in predicting water levels and currents at four locations. Average performance based on hourly water levels during 2010 falls below 2.6 cm for each location. Performances during periods which included several cold fronts are similar to the average yearly performances. Model performance during a two week period which included the passage of 2010 hurricane Alex and Tropical Depression 2 shows good performance as well, with water levels being within 2.8 cm of the measured values for each station. The research further shows that wind forcing affects the water levels at certain locations more than others and that the inclusion of a recent man made inlet, Packery Channel, only impacts the accuracy of the closest station to the inlet. CMS was further analyzed for its computational efficiency and the impact of grid resolution which have to be weighted to acquire a sufficient model. Based on this research CMS is a good selection for the real-time nowcasting of water levels in the South Texas Coastal Bend waterways.

Introduction

Accurate predictions of water levels and currents along the coast play an important role in maritime traffic assistance, fisheries, recreational activities and extreme

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weather event preparedness. The Texas Gulf Coast is home to many ports, population centers and ecological habitats making it an important location to have reliable coastal predictions.

Water levels and currents along the Texas coast are influenced by tides, but are also significantly driven by meteorological factors, especially strong wind. Winds are predominantly southeasterly with strong and periodic northerly winds from late fall to early spring accompanying frontal passages. Tidal predictions along the Texas coast do not meet the National Ocean Service (NOS) standard for water level predictive models that at least 90% of the predictions fall within 15 cm of the measurements (Hess, 2003). Since atmospheric forcings must be accounted for, other modeling techniques should be implemented such as statistical models or hydrodynamic models. The Texas coast is home to one of the densest coastal observation systems, the Texas Coastal Ocean Observation Network (TCOON). The network provides a dense, reliable, long–term set of historical observation data as well as real-time observations. The availability of a dense observation network provides the opportunity to have a heavily forced hydrodynamic model, using the observation stations' data.

Previously, there have been several hydrodynamic models implemented for the Corpus Christi Bay area (Figure 1a). Models tested for the area include the Estuary

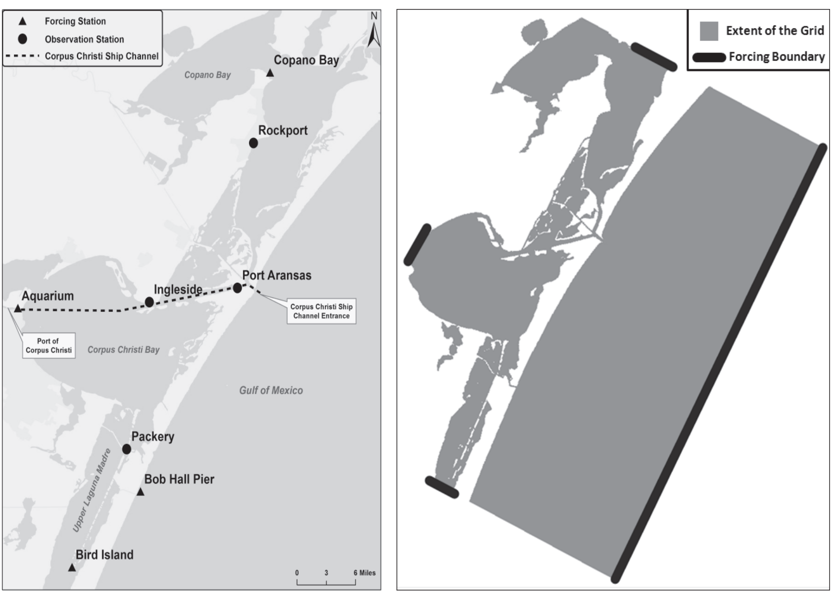

Figure 1(a). Study area map with locations of forcing stations and verification stations and (b). the model grid extent and location of water level forcing cells.

and Lake Computer Model (ELCOM) and the TxBLEND model (Furnans, 2004). ELCOM is a 3-D finite volume model while TxBLEND is a 2-D, depth-averaged hydrodynamic and salinity transport model. TxBLEND is used by the Texas Water Development Board to model water circulation and salinity within seven major Texas bays (Schoenbaechler, 2011). Real-time predictions are also available online for four of the bays. Other mainstream models implemented for the region include; the Advanced Circulation model (ADCIRC) which was used to simulate storm surge in Corpus Christi Bay (Frey, 2010) and the Finite Volume Circulation Ocean Model (FVCOM) (Chen et al., 2003) which was applied to the area as part of a study to analyze the benefits of data assimilation in an embayment using a dense coastal observation network (Nevel, 2010). A recent comparison of FVCOM to two 3-D finite element models (SELFE and UTBEST-3D) was conducted for Corpus Christi Bay which focused on hydrodynamic and salinity transport (Negusse, 2012). A previous study for the Corpus Christi Bay area assessed the difference in computational time and accuracy for the prediction of water levels between a 2-D model, the Coastal Modeling System developed by the U.S. Army Corps of Engineers (USACE) and an established 3-D model, FVCOM (Reid et al., 2011). The model grids were set to the same area and similar resolutions with CMS having 12,000 cells and FVCOM 11,000 cells. While the accuracies for water level predictions were similar, the difference in computational time was substantial with respectively 2 hours and 17 hours for the 21 day test case from October 27 through November 16, 2002 using a desktop PC (2.66 GHz 64 bit quad-core processor, 8GB RAM).

The goal of this project was to implement a computationally efficient, heavily forced and accurate hydrodynamic model which can be used as a real-time forecasting tool to benefit navigation and coastal management in the South Texas Coastal Bend area (Figure 1a). The model was checked for performance by comparing the predictions to the actual water levels being measured at four tidal stations within the model area.
The main factors considered in implementing this model included: grid resolution, smoothing of the input water level data, adding wind data, selecting a consistent water level datum for all the water level observation stations and adding the Packery Channel to the grid. The comparisons were done using a 2010 yearly run as well as shorter runs for time periods which included extreme weather events such as cold fronts, a hurricane and a tropical depression.

South Texas Coastal Bend Area

The study area chosen for the hydrodynamic predictions was a portion of the South Texas Coastal Bend, a coastal area stretching from Copano Bay to the Upper Laguna Madre (Figure 1a). Corpus Christi Bay is the largest bay in the area and has the largest amount of maritime traffic running through its ship channel (a deep east-west channel) and the Intracoastal Waterway (a shallow northeast-southwest channel). Corpus Christi Bay is relatively shallow, averaging 4 meters in depth (Ward, 1997) and is home to the Port of Corpus Christi, the fifth largest U.S. port by tonnage (Bureau of Transportation Statistics). The main source of water for the area is the Gulf of Mexico and enters the bay mainly through the Corpus Christi Ship Channel.

The channel presents challenges for model implementation due to its sharp gradient and its asymmetrical shape. The asymmetrical shape is due to a sharp left turn that the channel makes approximately 2,000 meters from the Gulf entrance. The depth of the channel is approximately 14 meters and the width is 122 meters (Ward, 1997). Since the bay averages 4 meters in depth, the channel depth with the short cross-section presents a very sharp gradient that must be modeled with sufficient accuracy to properly quantify water exchanges between the Bay and the Gulf of Mexico.

A less significant source of water exchange between the Gulf of Mexico and Corpus Christi Bay is through the Packery Channel which is located approximately 18 miles southwest of the Corpus Christi ship channel entrance. This is a much smaller man-made channel which opened in 2006 and is used by fishing and recreational vessels. The Packery Channel is 37 meters wide, averages at 3 meters in depth (with respect to mean sea level) and stretches from the Gulf of Mexico to the Upper Laguna Madre across the barrier island (Williams, 2011).

Implementing the Hydrodynamic Model

CMS was chosen as the hydrodynamic model for this study. CMS is a 2-dimensional, structured grid model which is used to predict water levels, currents and sediment transport in coastal zones. Wave climate can also be modeled as part of CMS. The model was selected in large part for its computational efficiency, its ease of set-up and use compared to other hydrodynamic models and its design history with an emphasis on inlets and navigation channel performance (Buttolph, 2006). The model development's emphasis on coastal inlets and change in inlet morphology allows for flexibility in adjusting this model due to dredging, widening and extending of the local navigational channels which has been previously proposed (Port of Corpus Christi). CMS has also previously been applied to locations along the Texas coast including a portion of the study area (Reed, 2011). The model was implemented specifically to analyze its performance in predicting water levels and currents, excluding sediment transport analysis.

The model grid was constructed through the Surface-Water Modeling System interface, using NOAA's coastline data to define land boundaries and a digital elevation model to represent bathymetry (Taylor, 2008). The grid was set to a UTM, zone 14 projection with vertical measurement in meters. Packery Channel had to be separately added to the grid because the bathymetry data used for this project was taken before the channel's completion in 2006. A uniform Manning's n of .025 was used to define the area's sandy/muddy seafloor. The grid's forcings were set using TCOON's wind and water level data from four observation stations with locations described below. The water level data was downloaded with reference to each station datum and further adjusted to each station's mean sea level for the 2010 yearly datasets.

The model water levels were forced from four opposite sides of the grid; the Gulf of Mexico using the Bob Hall Pier observation station, the Upper Laguna Madre on the south end of the model using the Bird Island station, the western side of Corpus Christi Bay using the Aquarium station and the northern end of the model was forced using the northern Aransas Bay Copano station (Figure 1b). The Port Aransas station's wind measurements were used to force the model throughout the grid.

The verification stations used for the model analysis include: Port Aransas located at the entrance of the Corpus Christi ship channel, Ingleside located along the channel inside Corpus Christi Bay, Rockport located at the northern end of the model area and Packery located at the southern end of the model area in the Upper Laguna Madre (Figure 1a). The station used for current analysis is located near Port Aransas, close to the ship channel entrance.

The grid resolution was progressively adjusted based on model performance through various iterations, aiming at determining the coarsest resolution which can be used without significantly impacting model performance. The final resolution chosen was 800 by 584 cells, totaling 467200 cells. Each cell is approximately 100x100m. This decision was made by determining the smallest number of cells which can be used for the channel cross-section to represent the channel's sharp gradient without greatly impacting the results and keeping computational efficiency. The final grid consists of at least four cells along each cross section of the channel (Figure 2).

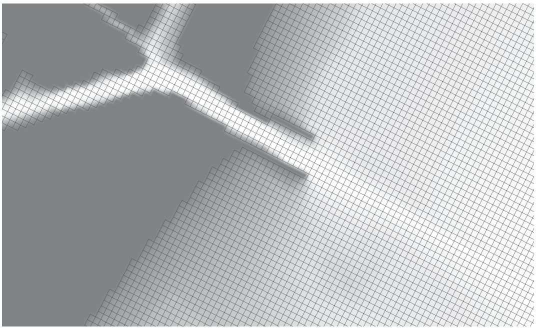

Figure 2. View of the rectangular model grid for the entrance of the ship channel.

Results and Discussion

The model's performance was evaluated by comparing the modeled water level and current predictions to actual measurements at stations located inside the model area. Stations used as forcing time series are excluded from the model assessment. The four existing observation stations within the modeling area were used to analyze the water level predictions. A fifth observation station inside the Corpus Christi ship channel near Port Aransas was used to analyze the currents. The analysis was conducted over a full 2010 yearly dataset.

The overall 2010 mean absolute error showed all the stations falling below 2.6 cm for water level predictions. The lowest mean absolute error of 1.6 cm occurred at the Rockport station and the highest mean absolute error of 2.5 cm occurred at the Port Aransas station. The yearly average predictions do not present a noticeable bias, the slight biases that were computed, average themselves out amongst the four stations (Table 1). Using Pearson's correlation; the correlation coefficients for all the stations fall above .98 for the yearly average. The model was further analyzed for a period of time which included hurricane Alex and tropical depression 2 from late June to mid July 2010. The mean absolute error increases for all the stations when compared to the yearly average. The most notable change occurs at Rockport with a 1 cm increase and Ingleside with a .6 cm increase in the mean absolute error. The correlation coefficients during this period fall above .97 for all four stations (Table 1).

	Packery	Ingleside	Port Aransas	Rockport
Full 2010 Analysis				
MAE (m)	0.020	0.021	0.025	0.016
RMSE(m)	0.143	0.146	0.157	0.128
Bias (m)	-0.003	0.004	0.006	-0.006
Correlation	0.984	0.988	0.988	0.993
Tropical Storm Analysis (June 28 - July 14, 2010)				
MAE (m)	0.022	0.027	0.027	0.026
RMSE(m)	0.147	0.166	0.165	0.160
Bias (m)	-0.008	-0.009	-0.011	-0.023
Correlation	0.977	0.971	0.980	0.982
Cold Front Analysis (January 1 - March 31, 2010)				
MAE (m)	0.022	0.024	0.028	0.013
RMSE(m)	0.149	0.155	0.169	0.115
Bias (m)	0.005	0.020	0.015	0.001
Correlation	0.969	0.989	0.984	0.990
Cold Front Analysis (November 1 - December 31, 2010)				
MAE (m)	0.022	0.014	0.025	0.013
RMSE(m)	0.147	0.118	0.158	0.115
Bias (m)	0.000	0.005	0.009	0.008
Correlation	0.967	0.992	0.987	0.994

Table 1. CMS water level performance analysis for the 4 verification stations.

To analyze the importance of wind forcings, model results were compared for two cases; one with and the other without wind forcing. The model was run for both cases for the January 1-15, 2010 period during which wind speeds varied from 0 m/s to 14 m/s with variable wind direction. The results show that the inclusion of winds does not significantly impact model performance except during strong wind events, particularly the passage of cold fronts. Port Aransas, Rockport and Ingleside stations only had fractional decreases in performance when the winds were excluded. The mean absolute error for water levels at the Packery station increased by about 1 cm. The larger impact of excluding wind forcing in the model at this station is likely due to the coarse resolution used to represent Packery channel which effects the accuracy of flow through the channel. The error at this station is significantly higher during northerly winds; this subject is further discussed in the context of cold front passages. The lack of impact of including the wind on model performance at the other stations is likely due to a combination of the stations being along the ship channel and the lag between wind forcing along the coast and changes in water levels. As the model is forced by water level measurements, the impact of wind forcing is at least in part already included in the forcing.

The ability of the model to predict current velocity was evaluated using a current station located along the ship channel in Port Aransas for May 1-22, 2010 (Figure 3). Current comparison is not a direct one because CMS is a two-dimensional model predicting average currents throughout the water column while verification was obtained from Acoustic Doppler Current Profiler (ADCP) measurements for the center of the channel at mid depth. The results show that the phase of the predicted current velocity along the x-direction is synchronized with the actual measurements and the mean absolute difference between depth averaged and mid-depth measured currents is .18 m/s. The apparent respective over-prediction and under-prediction during ebb and flow could be due to differences between average and mid depth currents. The influence of grid resolution on model currents is discussed later in this

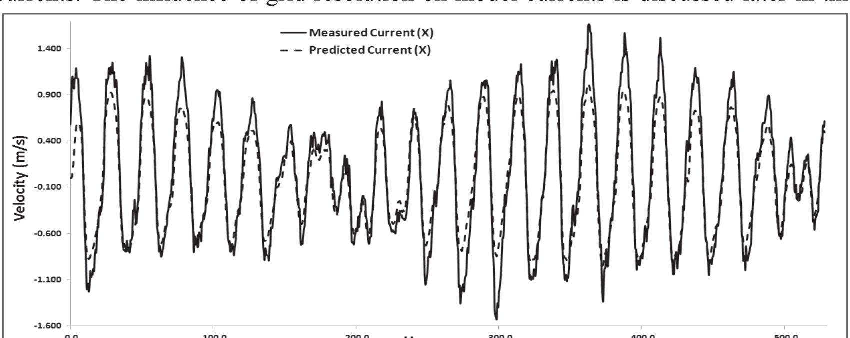

Figure 3. Along channel current assessment at Port Aransas station (May 1- 22, 2010)

section. Currents were further assessed qualitatively by looking at current patterns particularly at the ship channel inlet where large current velocity gradients and eddy formations are expected (Figure 4).

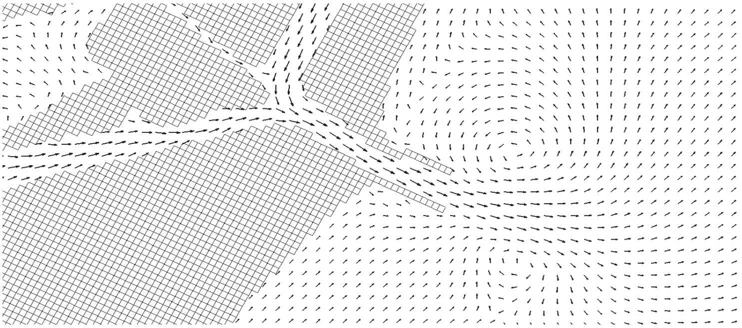

Figure 4. Eddy formations occurring around Port Aransas jetties on May 12, 2010 with higher current speeds (~.9 m/s) occurring inside the ship channel during ebb

To analyze the performance during cold front passages, two periods in 2010 were assessed. The first period was January through March which included two strong cold fronts and the second period was November through December which included three cold fronts. The tropical storm analysis presented a slight negative bias while the cold front passages presented a slight positive bias (Figures 5 and 6). The negative bias difference is assumed to be due to the sudden increase in water levels during storm events with the model under-predicting and the positive bias difference due to a sudden decrease in water levels during cold fronts with the model over-predicting. The most noticeable error occurs during cold front passages at the Packery station (Figure 6). The model under predicts by 0.10m or more during 18 events in 2010 with 15 of these events having wind directions between 315° and 15°. The MAE during the 18 events is at .12 m with average winds of 12.4 m/s compared to the .02m annual MAE with average winds of 5.2 m/s. Given that this discrepancy is only observed at the Packery Channel station and mostly for strong northerly winds, it is hypothesized that either the grid resolution needs to be increased for the channel to better model the area or that there are inaccuracies in the manually added bathymetry for the area.

To analyze the effects of including the Packery ship channel in the model, two separate runs were conducted; one included the channel using average depth values and the other identified the channel as land which existed before the dredging of the channel. Both scenarios were run for the period of January 1-15, 2010. The results show that adding the channel has no effect on the analysis stations except for the Packery station which is located alongside the Laguna Madre side of the channel. When the channel is included, the mean absolute error is at 2.6 cm for the 15 day case and when the channel is removed, model error increases to 3.8 cm. The results identify the importance of having the channel to better predict the water levels at the Packery station and in the southern end of the model area.

As grid resolution is one of the main drivers of computational time, additional analysis was conducted to assess its impact. This part of the study was conducted for the May 1-22, 2010 case. The study area was modeled with a higher-resolution grid consisting of 1,051,200 cells versus 467,000 for the original grid and increasing the number of cross channel cells from a minimum of 4 to a minimum of 7. The increased resolution only influenced the results at the Port Aransas station with the accuracy increasing from .04m to .02m in MAE, this 50% increase is substantial and shows the importance of representing the channel's steep gradient with a higher resolution grid. The downside to the higher resolution grid is the need to reduce the time step from 3 seconds to 1 second and the significant decrease in computational efficiency. Both models ran using the same desktop PC with the regular grid completing in 20 hours and the high resolution grid completing in 134 hours (i.e. from about 1 hour of computation time per day of simulation to about 6 hours). This increase time was deemed too costly computationally for the present real-time application running on a PC. Reasonable computational time is however subjective and constantly changing due to the ever increasing performance of affordable desktops. The future goal for this project is to implement a new feature of CMS, a telescoping grid option which allows for more flexibility in grid resolution (Reed, 2011). The telescoping grid will allow for an increase in resolution in the ship channel area without significantly increasing the run time which should benefit the prediction accuracy at Port Aransas while keeping the model computationally efficient.

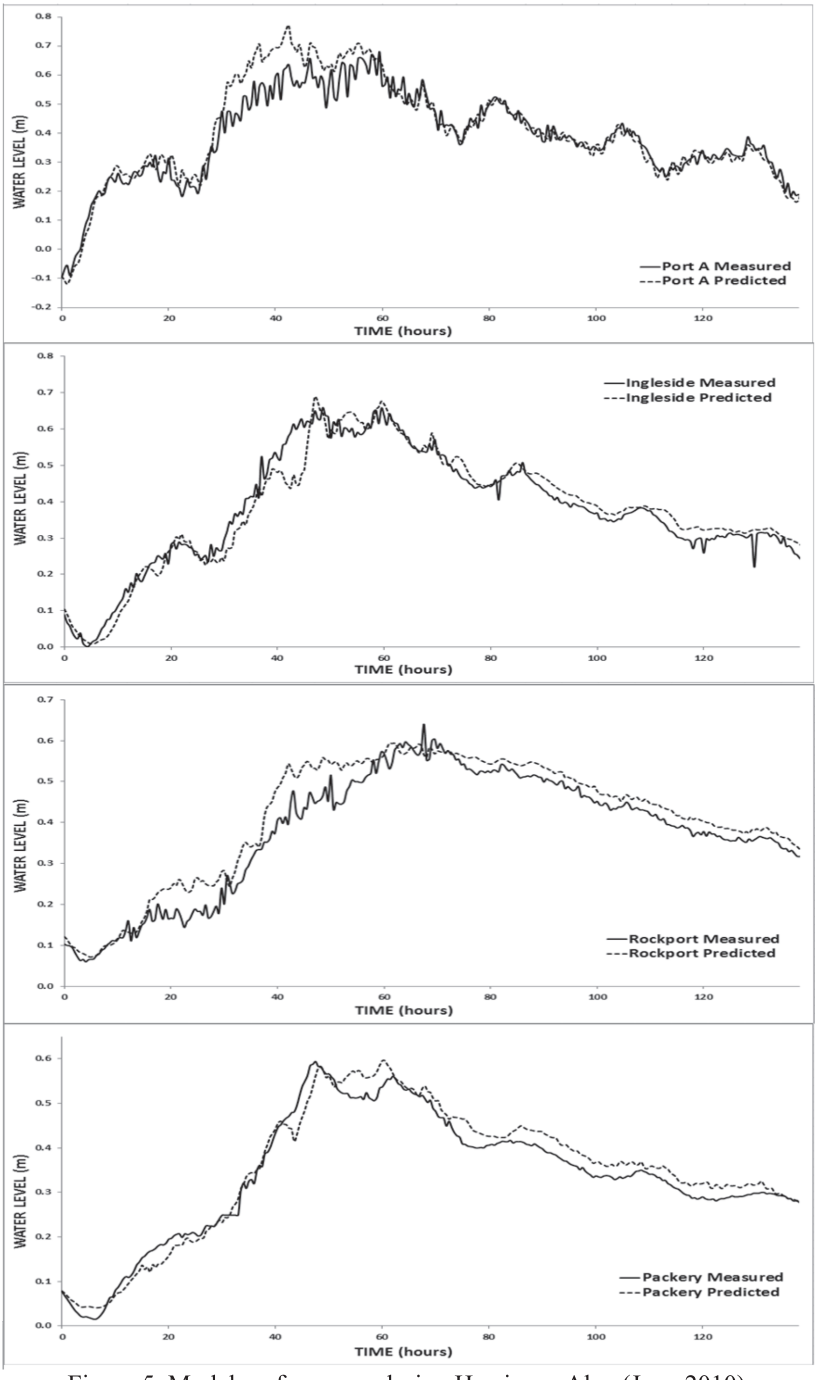

Figure 5. Model performance during Hurricane Alex (June 2010)

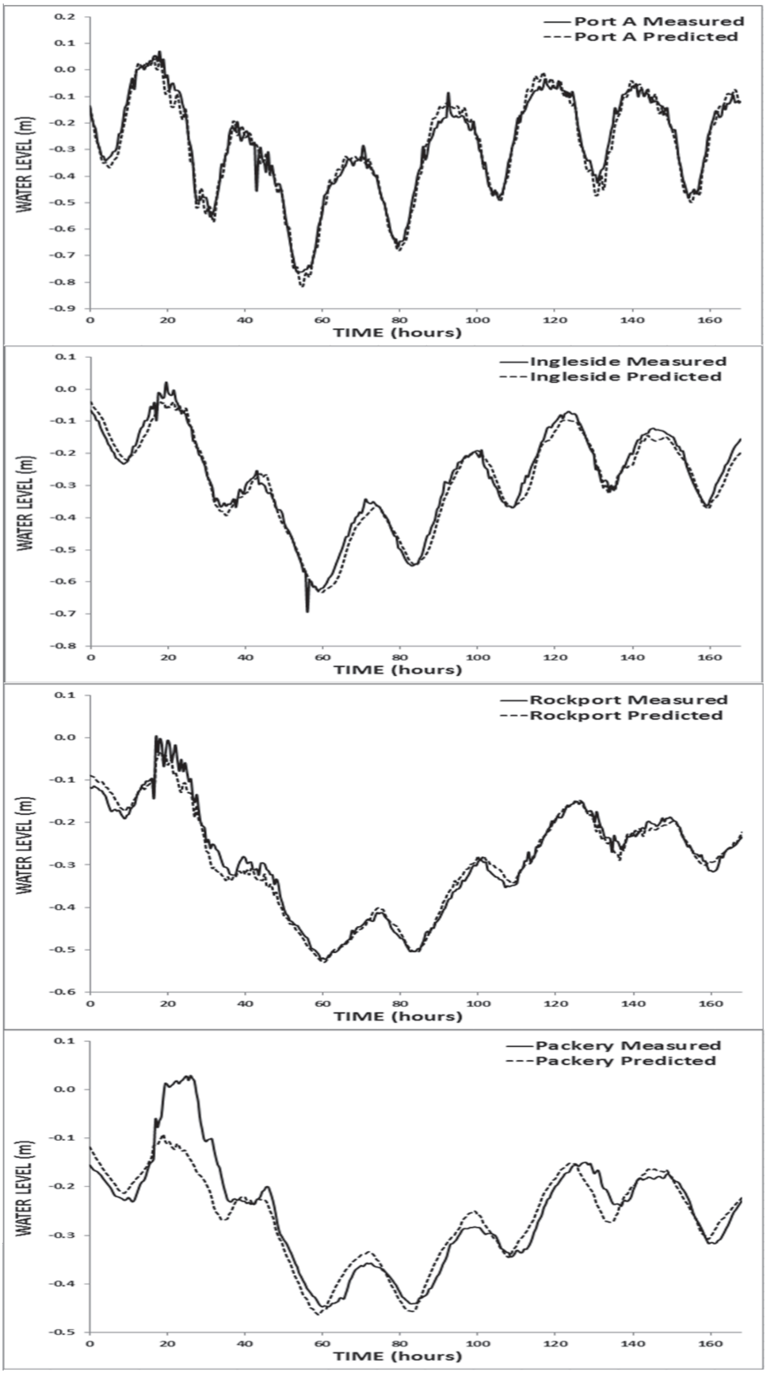

Figure 6. Model performance during cold front passage (March 20-26, 2010)

For proper assessment of model performance it is important to reference water levels using compatible datums. Official datums for the project stations are based on different time periods, e.g. Rockport tidal datums are computed based on a 2002-2006 special epoch while Bob Hall Pier datums are computed based on data collected from 1986 to 2001. Rates of sea level rise in the Coastal Bend range from 3mm/yr to 9mm/yr for the time period of 1996 to 2009 depending on location. A difference of even 5 years in the time period used for datum computations will result in significant differences. To avoid differences due to datum mismatches, all project water level data were referenced to stations' mean sea level computed for year 2010. Using the stations' official tidal datums instead would lead to significant decreases in performance. For example, mean absolute errors would increase to 6.2 cm and 6.9 cm at the Rockport and Packery stations.

Conclusion:

The Coastal Modeling System was implemented and tested for the South Texas Coastal Bend region. The model was analyzed for various conditions such as storm events and frontal passages. The 2010 yearly analysis shows that the model implementation was successful with all stations having a small mean absolute error at no more than 2.5 cm and no significant bias. Small increases in mean absolute error are observed during cold front passages and storm passages, up to an average of 2.8 cm for water levels at the Port Aransas station and maximum errors above 10 cm on a few cold front occasions for the southeast portion of the bay at the Packery station.

The research also shows that the inclusion of the recently dredged Packery channel only affects the Packery observation station and does not significantly affect the stations in the rest of the model area. Furthermore, the analysis shows that wind does not play a significant role for the prediction of water levels for stations along the ship channel, likely due to the fact that wind information is already factored in the water level measurements due to the lag occurring between the winds and the water level measurements. High winds have a stronger influence at the Packery Channel station where a higher resolution grid is required to model the water flow.

Given the good nowcasting performance the model will be tested in forecasting mode by predicting water levels at the forcing locations using Artificial Neural Network predictions. The model will then be analyzed to see how far in time predictions can satisfy the National Ocean Service criteria of having 90% of the predictions fall within 15 cm of the measurements.

Acknowledgements:

Support for this work from the NOAA Environmental Cooperative science Center (ECSC) is gratefully acknowledged. The authors would like to express their appreciation for the advice and feedback from Alex Sanchez, and for the encouragements and insights provided by Nicholas C. Kraus at the Coastal and Hydraulics Laboratory, Engineer Research and Development Center, U.S. Army Corps of Engineers. The authors also thank the three reviewers and the proceedings' editor for their contribution to improving this work.

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