McCarron, Connor; Knaapen, Michiel; Blanco, Belen; Dearnaley, Mike; Lewis, Richard; Leo, Maria de

Modelling the impacts of Hurricane Ike on the Texas coast using a fully coupled TELEMAC-TOMAWAC-SISYPHE model

Modelling the impacts of Hurricane Ike on the Texas coast using a fully coupled TELEMAC-TOMAWAC-SISYPHE model

Connor McCarron, Michiel Knaapen, Belen Blanco, Mike Dearnaley, Richard Lewis, Maria di Leo
HR Wallingford
Wallingford, United Kingdom
c.mccarron@hrwallingford.com

Hurricane Ike, a category 4 hurricane, made landfall near Galveston, Texas on the 13th of September 2008. A fully coupled TELEMAC-TOMAWAC-SISYPHE model was developed to predict sediment transport and associated morphodynamics resulting from the passage of Hurricane Ike. The predicted hydrodynamics were validated against observed tidal elevations, currents, waves and inundation. The predicted sediment transport pathways and resulting bed elevation change were compared with assessments of coastal impacts associated with Hurricane Ike. The model results show good agreement with observations and demonstrate the ability to predict hydrodynamics, sediment transport and morphodynamics associated with hurricanes using a fully coupled TELEMAC-TOMAWAC-SISYPHE model.

I. INTRODUCTION

Hurricane Ike, a category 4 hurricane, made landfall near Galveston, Texas, at 0700hrs UTC on the 13th of September, 2008. On landfall, the hurricane was downgraded to a strong category 2 but sustained winds of 175 km/h with maximum sustained wind swaths estimated at 180 km [1]. The track of the hurricane, its landfall at Galveston, and the sustained wind swaths are illustrated in Figure 1. Peak wind speeds were observed east of Galveston and extended east into Louisiana (Figure 1).

The development of a fully coupled TELEMAC, TOMAWAC and SISYPHE model used to predict sediment transport pathways and magnitudes as a result of Hurricane Ike along the coastline of Galveston, Texas is presented herein. The predicted hydrodynamics are compared with observations of tidal elevations and currents, waves and inundation recorded during the passage of Hurricane Ike. The predicted morphodynamics are compared with observations of coastal impacts as a result of Hurricane Ike.

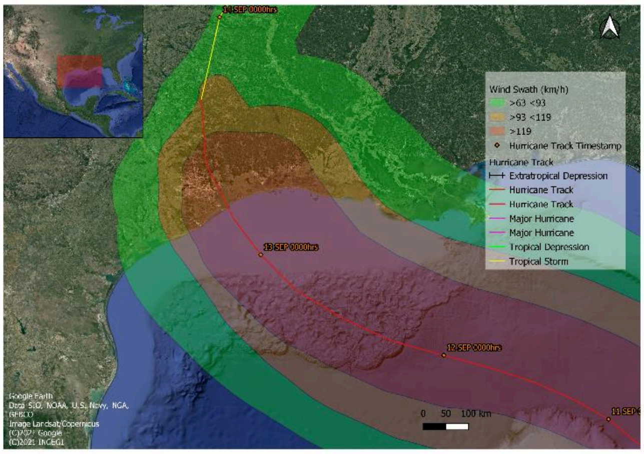

Figure 1 Storm track of Hurricane Ike from the National Hurricane Centre's HURDAT2 dataset illustrating the sustained wind swaths

II. THE MODEL

TELEMAC-2D (*v8p1r1*) was used to model the hydrodynamics associated with Hurricane Ike along the Galveston coastline. The model domain extended from Bay City, west of Galveston, Texas to Holly Beach on the Louisiana border, and extended up to 100 km offshore to a depth of 90 m MSL (Figure 2). The model grid comprised approximately 470,000 nodes and 930,000 elements which ranged in length from approximately 4 m in the nearshore to 7 km along the offshore boundary.

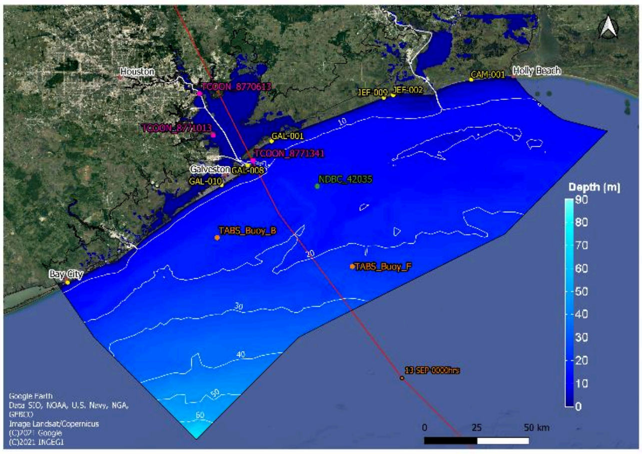

Figure 2 Model bathymetry including the locations of tidal level (pink), tidal current (orange), waves (green) and inundation (yellow) observations

A. Bathymetry

A subset of bathymetric data was extracted from the United States Army Corps of Engineers (USACE) ADCIRC model grid used in the Coastal Texas Protection and Restoration Feasibility Study [2] which covers the gulf facing beaches and inlets along the Texas coast, extending approximately 16.9 km offshore to a depth of approximately 10 m MSL. The USACE grid was extended beyond the 10 m depth contour using GEBCO bathymetry data [3]. The bathymetry employed in the model is shown in Figure 2.

B. Tidal boundary conditions

The model was forced with tidal elevations and currents using data extracted from the Hybrid Coordinate Ocean Model of the Gulf of Mexico (HYCOM + NCODA Gulf of Mexico 1/25° Reanalysis, GOMl0.04/expt_50.1). Hourly predictions of sea surface elevation (ssh), eastwards- and northward- velocities (u,v) were interpolated using a 2-dimensional linear interpolation and applied to the offshore nodes of the boundary of the model domain.

C. Wave boundary conditions

Wave boundary conditions were extracted from the European Centre for Medium Range Weather Forecast's (ECMWF) ERA5 wave reanalysis dataset which provides hourly wave spectra across a 0.5° (30 km) grid. Time-varying wave spectra from ERA5 output locations bordering the offshore boundary of the model domain were used to force the TOMAWAC model by interpolating the wave spectra along the offshore nodes of the model boundary.

D. Atmospheric conditions

Hourly atmospheric pressure (mean sea level) and 10 m wind speeds were also extracted from the ECMWF's ERA5 reanalysis dataset with a spatial resolution of 0.25°. The ERA5 wind speed and pressure fields were interpolated spatially on to the model mesh and used to account for wind stress in TELEMAC and wave generation in TOMAWAC.

E. River discharge

Within the model domain, the major rivers flowing into the Gulf of Mexico include the Neches, Sabine, Trinity, San Jacinto, and Brazos rivers, as well as the Buffalo and Chocolate Bayous (Figure 3). Extreme run-off events related to hurricanes have been shown to significantly affect flows in the bays [4]. River discharge data were obtained from the United States Geological Survey's National Water Information System (NWIS). NWIS stations closest to the model boundary which recorded discharge data were used to force the model. No discharge data were available for the Trinity or Brazos rivers during the passage of Hurricane Ike. These rivers were therefore not included in the model. Discharge from the remaining rivers were included and are shown in (Figure 3). The Buffalo Bayou and Neches River recorded the highest peak flood discharges during the passage of Hurricane Ike reaching 280 m^3/s and 580 m^3/s, respectively (Figure 3).

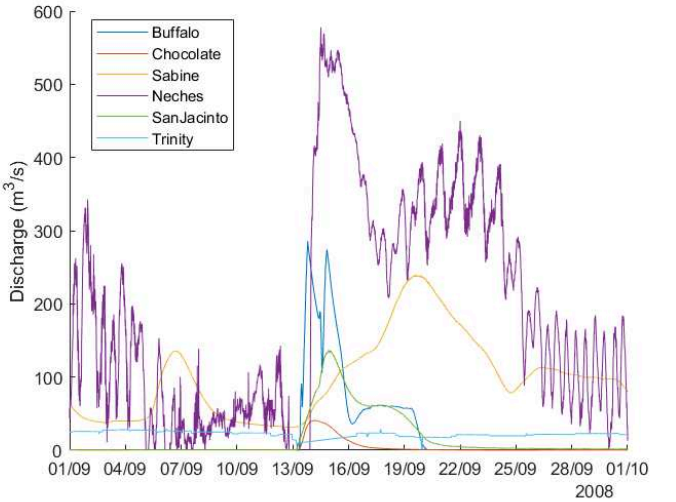

Figure 3 Discharge for the 6 largest rivers within the model domain entering the Gulf of Mexico during September 2008

F. Bed composition

A spatially varying grain size distribution and bed friction was employed in the model. The bed comprised 5 separate grain classes ranging from medium silt to medium sand: 30 µm (medium silt); 70 µm (coarse silt); 125 µm (very fine sand); 0.25 mm (fine sand); and 0.5 mm (medium sand). The mean grain size calculated from the employed sediment fractions is illustrated in Figure 4. These sediment classes were derived from an assessment of available sediment data collected between 1899 and 2015 by various sources including: the Texas General Land Office's coastal sediment database (TxSeD); the USGS's usSEABED database; the Bureau of Ocean Energy Management's Marine Mineral Information System; core logs collated by the University of Texas Institute for Geophysics; and shear strength maps of shallow water sediments in the Gulf of Mexico compiled by Texas A&M University's Offshore Technology Research Centre. The bed composition in the model was corrected to account for areas likely to be non-erodible:

- structures such as groynes, jetties and sea walls;
- areas where the clay content exceeded 40%;
- areas where maximum velocities exceeded 1.5 m/s.

III. Observational Data

During the passage of Hurricane Ike, water levels, tidal currents and winds were recorded by a number of buoys maintained by the Texas Automated System (TABS), as well as tide gauges on the Texas Coastal Ocean Observation Network (TCOON) hosted by the National Oceanic and Atmospheric Administration (NOAA). Within the model domain, waves were recorded by one National Data Buoy Centre wave buoy (NDBC 42035). This buoy became adrift on the 12th of September passing through the eye of the hurricane and recorded a maximum significant wave height of 6 m at 0450 UTC on the 13th of September. The location of these buoys and tide gauges are shown in Figure 2 and the data recorded by each is indicated in Table 1.

Table 1 Observations available from buoys which successfully recorded data during the passage of Hurricane Ike

Station ID	Tidal Elevations	Tidal Currents	Waves	Winds
NDBC 42035			X	X
TABS Buoy B		X		X
TABS Buoy F		X		
TCOON 8770613	X			X
TCOON 8771013	X			X
TCOON 8771341	X			X

The coastal inundation which occurred as a result of the storm surge driven by Hurricane Ike was recorded by a number of temporary USGS rapid deployment gauges [5] which are also shown in Figure 2.

The tidal, wave, wind and inundation observations recorded at these locations were used to validate the hydrodynamics predicted by the model during the passage of Hurricane Ike.

IV. Model Calibration

The hurricane model is based on a model that was calibrated for normal conditions. For January 2018, the model results were compared to measured values in 8 locations; one for waves; three for water level elevation and four for flow velocities.

The model uses a spatially and temporally varying wind for waves and currents and spatially varying bed friction using the Nikuradse coefficient. There were remarkably few changes from the default setting required. For the waves, Yan's formula was used for the wind generation, but otherwise default settings produced the best results. For the currents, the method of characteristics and the wave equation were used to minimise the computational requirements. No upwind discretisation for the water depth and free surface gradient compatibility of 0.7 were needed to stabilise the water levels. For the sediments the active layer thickness was reduced to 1m, to allow for some bed composition changes. Soulsby van Rijn was used for bedload transport (5) and for the reference concentration formula (4).

The skill of the model to predict the hydrodynamics observed during Hurricane Ike is quantified by the mean error (ME), mean absolute error (MAE), root mean square error (RMSE) and the Willmott (1981) skill score (1):

$$\mathrm{WS} = 1 - \frac{\sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}(|M_i - \langle O\rangle| + |O_i - \langle O\rangle|)^2} \quad (1)$$

in which M and O are the measured and observed values, respectively, and angled brackets denote an average. A perfect fit has a value of 1 and predicting a constant equal to the mean of the measured data has a value of 0. The model is deemed adequate with values between 0.55 and 0.65, sufficient between 0.65 and 0.75, good between 0.75 and 0.85, and very good for values >0.85.

The calibration results (Table 2) show that the model is very good for the waves and water levels, good to very good for currents near the inlets where tidal currents dominate (g6010 and Sn0101) and sufficient for the offshore locations where the wind driven ocean currents dominate.

Table 2 Error statistics analysis between model prediction and observations for January 2018

Forcing	Station ID	ME	MAE	RMSE	Skill Score
Elevation (m)	TCOON 8772471	-0.03	0.09	0.11	0.92
Elevation (m)	TCOON 8771013	-0.31	0.34	0.43	0.89
Elevation (m)	TCOON 8771341	-0.09	0.10	0.13	0.89
Currents (m/s)	g6010	0.01	0.10	0.13	0.92
Currents (m/s)	Sn0101	-0.06	0.10	0.11	0.72
Currents (m/s)	NDBC 42050	-0.01	0.08	0.10	0.41
Currents (m/s)	NDBC 42051	0.01	0.05	0.06	0.56
Waves (m)	NDBC 42035	-0.02	0.11	0.15	0.95

Units of the ME, MAE and RMSE are in m for elevations and waves, and m/s for tidal currents

V. Model Validation

Validation of the model was completed by first comparing the predicted tidal elevations, currents and waves with observations from the buoys and tide gauges which successfully recorded data during the passage of Hurricane Ike. The predicted inundation as a result of Hurricane Ike was then compared with observations of inundation from the USGS rapid deployment gauges.

A. Tidal elevations, currents and waves

The error statistics for the model are presented in Table 2. The model performs well when compared with observations with skill scores ranging from 0.67 to 0.98 (Table 2). The results are even better than for the calibration period.

Table 3 Error statistics analysis between model prediction and observations during Hurricane Ike

Forcing	Station ID	ME	MAE	RMSE	Skill Score
Elevation (m)	TCOON 8770613	0.05	0.12	0.15	0.96
Elevation (m)	TCOON 8771013	0.02	0.11	0.17	0.98
Elevation (m)	TCOON 8771341	0.02	0.09	0.13	0.98

Forcing	Station ID	ME	MAE	RMSE	Skill Score
Currents (m/s)	TABS Buoy B	-0.12	0.16	0.20	0.67
Currents (m/s)	TABS Buoy F	-0.09	0.12	0.18	0.72
Waves (m)	NDBC 42035	-0.15	0.24	0.34	0.96

Units of the ME, MAE and RMSE are in m for elevations and waves, and m/s for tidal currents

Predicted and observed tidal elevations at TCOON station 8771013 are shown in Figure 4. The skill score of the predicted tidal elevations were deemed to be very good (> 0.85). The model slightly overpredicted water elevations as indicated by a ME of between 0.02 m and 0.05m (Table 3). The model accurately resolved the phase and magnitude of the tidal elevations pre-, post-, and at the peak of Hurricane Ike (Figure 4).

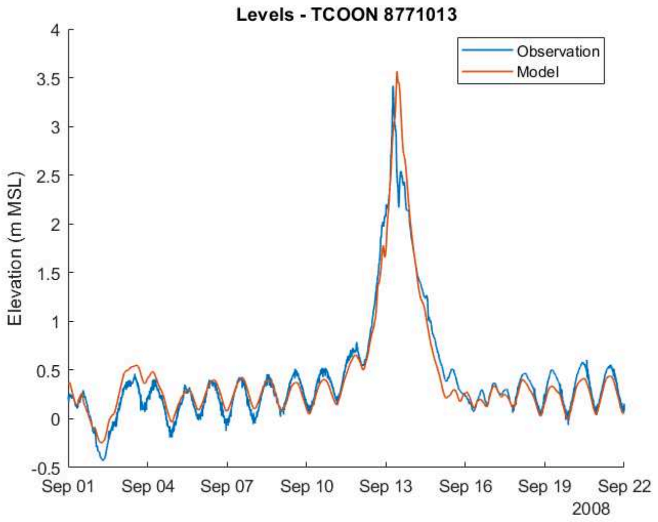

Figure 4 Modelled and observed elevations at TCOON station 8771013

Predicted and observed tidal current magnitudes and directions at TABS buoy B are shown in Figure 5. The model predicted the phase of the tidal currents well both pre-Ike and during the peak of the Hurricane, however, the predicted tidal currents were lower than observed and there was a noticeable phase shift between the predicted and observed tidal currents post-Ike (Figure 5). This was reflected by the skill score which was deemed to be sufficient (0.65 – 0.75) (Table 2). The model predicts larger tidal currents during the landfall of Hurricane Ike then observed (Figure 5), however, previous studies have noted that the TABS buoys do not resolve current speeds greater than 1 m/s well [6]. Therefore, it is likely that the skill score for current speeds at TABS Buoys B and F are underestimated. The lower predicted current speeds compared with observations is possibly related to the hourly temporal resolution of the boundary forcing which may act to alias peak current flows.

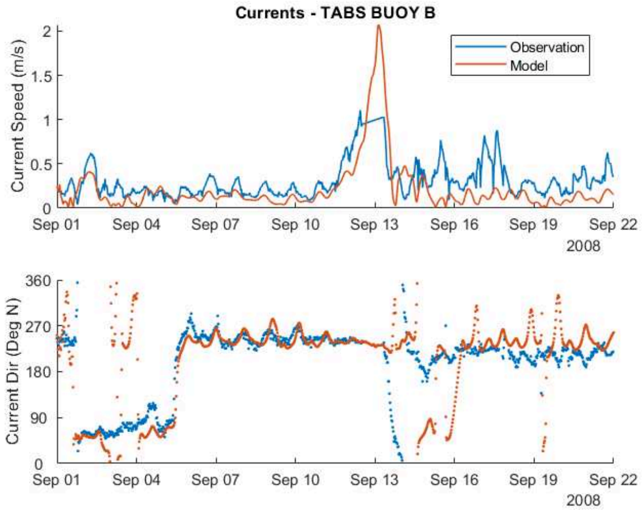

Figure 5 Modelled and observed currents at TABS buoy B

Predicted and observed significant wave heights and directions at for NDBC buoy 42035 are shown in Figure 6. The model accurately predicted the wave heights and directions during the passage of Hurricane Ike (Figure 6) which is reflected by a skill score of 0.96, deemed as very good (Table 2).

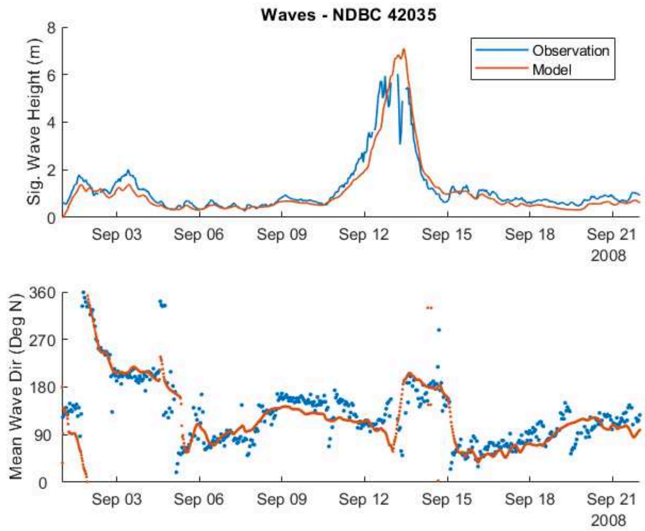

Figure 6 Modelled and observed waves at NDBC buoy 42035

B. Inundation

The inundation predicted by the model was compared with observations at 7 USGS rapid deployment gauges along the coastline within the model domain (Figure 2). The error statistics for the model are presented in Table 3 and the predicted inundation at GAL-010 is compared with the observed inundation in Figure 7. The model predicted the inundation observed at each of the USGS stations well with skill scores between 0.80 and 0.97, except for station MAT-008 where the skill score was 0.49 (Table 3). The poorer skill score at this station is attributed to its proximity to the model boundary, and the short duration of inundation observed at the station. The model skill is very good considering there is likely large variability in the permeability of the surfaces (i.e. roads, paths, etc.) close to the locations of the rapid deployment gauges which the model does differentiate.

TABLE 4 ERROR STATISTICS ANALYSIS BETWEEN INUNDATION PREDICTED BY THE MODEL AND OBSERVATIONS

Station ID	ME (m)	MAE (m)	RMSE (m)	Skill Score
CAM-001	0.11	0.18	0.40	0.88
GAL-001	0.06	0.07	0.27	0.91
GAL-008	-0.04	0.09	0.25	0.92
GAL-010	0.01	0.07	0.16	0.97
JEF-002	0.27	0.30	0.53	0.80
JEF-009	0.03	0.20	0.44	0.85
MAT-008	0.00	0.01	0.01	0.49

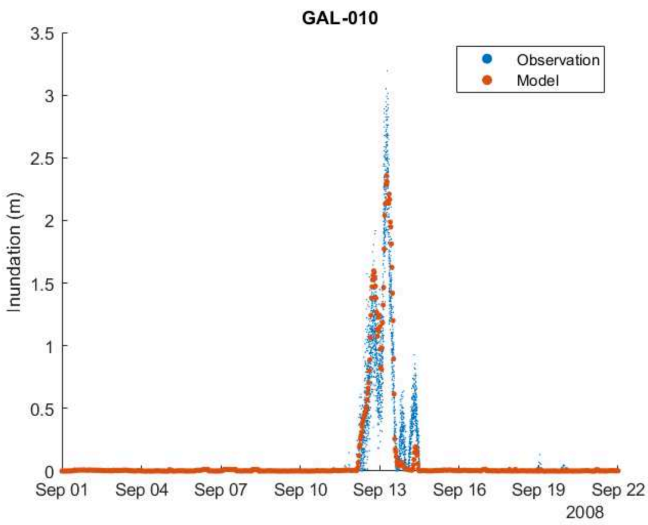

Figure 7 Modelled and observed tidal inundation at GAL-010

VI. RESULTS

A. Sediment Transport

The sediment transported predicted during the landfall of Hurricane Ike is shown in Figure 8. Sediment was predicted to be transported dominantly onshore east of the Galveston bay entrance channel across Bolivar Peninsula into Galveston bay, along the coastline of the McFaddin National Wildlife Refuge, and into Sabine Lake and the surrounding areas (Figure 8). West of the Galveston entrance channel the direction of sediment transport veers alongshore with little onshore sediment transported predicted (Figure 8).

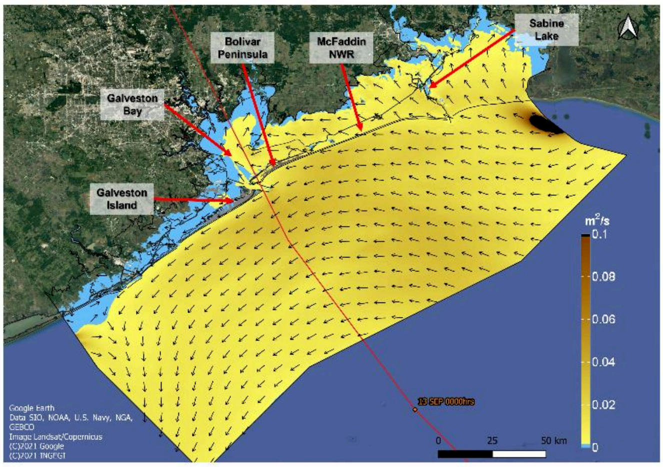

Figure 8 Predicted sediment transport rates during the landfall of Hurricane Ike on the 13th of September 2008 at 0700hrs

B. Erosion/Deposition

The patterns of erosion and deposition predicted as a result of Hurricane Ike are shown in Figure 9. The impacts of Hurricane Ike were predicted to occur dominantly along the coastline to the east of the Galveston entrance channel with lesser impacts predicted along the coastline to the west (Figure 9). Doran et al. [7] relate the difference in the impacts observed east and west of the entrance channel to the location of the hurricane track. The eye of the Hurricane travelled over the Galveston entrance channel (Figure 1), which resulted in onshore winds to the east, and offshore winds to the west of the entrance. These offshore winds reduced the height of the storm surge and dampened the waves to the west of Galveston. Conversely, the onshore Hurricane wind eastward of the Galveston entrance increased the storm surge and waves on that side [7].

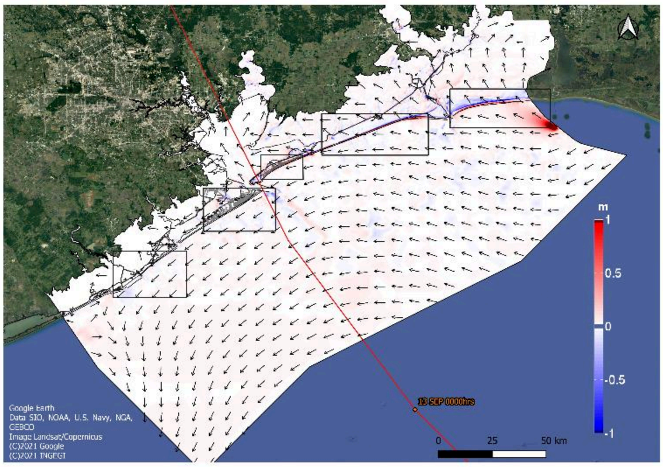

Figure 9 Bed elevation change predicted during the passage of Hurricane Ike. The black boxes indicate the areas assessed for coastal impacts by Doran et al. [7]

Along Galveston Island, the impacts of Hurricane Ike were confined to the beaches west of the Galveston Island seawall where the shoreline was eroded landward [7]. The Galveston Island seawall acted to protect the city of Galveston, however, beach erosion was observed in front of the seawall and to a section on the eastward section of the Island not protected by the seawall [7]. The model correctly predicted shoreline erosion to the west of the sea wall indicated by band of red west of the seawall and blue to the north of it; the erosion of the unprotected section of the coastline at the eastern end of Galveston Island; and the protection of Galveston City by the seawall and some beach lowering in front of the seawall (Figure 10).

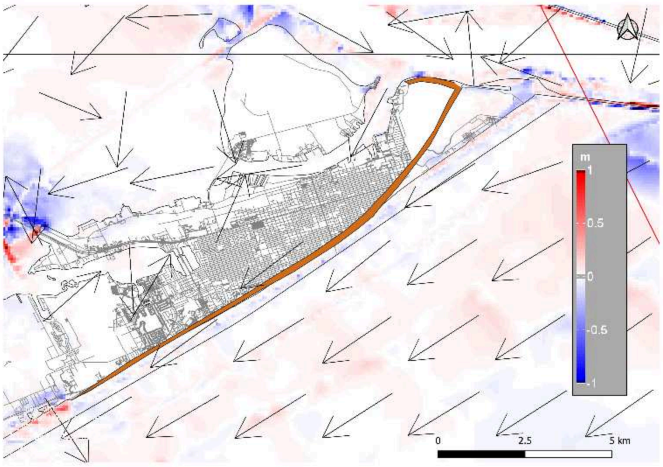

Figure 10 Predicted bed elevation change across the Galveston Island assessment area. The orange polygon shows the location of the seawall protecting Galveston City

Bolivar Peninsula experienced significant impacts due to the landfall of Hurricane Ike close to the Galveston entrance channels and the combined force of the storm surge, onshore winds and associated waves [7]. The combination of 5 m storm surge and waves, with low-lying dunes (approx. 2 m elevation) providing little protection, resulted in sand being eroded from the beach and dunes and transported onshore which was subsequently deposited across Bolivar Peninsula [7]. The erosion of the beach and dunes and subsequent deposition of the sediment onshore is reflected well by the model (Figure 11).

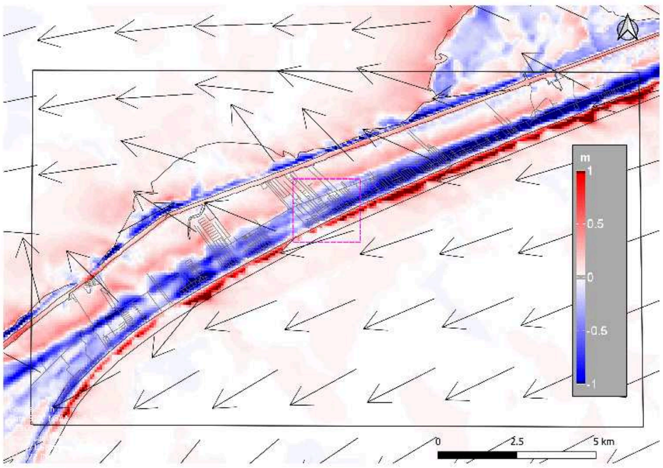

Figure 11 Predicted bed elevation change across the Bolivar Peninsula assessment area. The pink dashed box indicates the area of topographic change assessed from pre- and post-Ike LIDAR by Doran et al. [7] at Chrystal beach

Doran et al. [7] completed an assessment of topographic change at Crystal Beach, Bolivar Peninsula using lidar data collected in September 2005 and September 2008. The observed topographic change is compared with the model prediction in Figure 9. Bed lowering of up to 1 m was observed along the coast at Crystal Beach which was predicted by the model, however, the model did over predict the landward extent of erosion (Figure 9). This is attributed to the reduced resolution of the model mesh in this area compared to the resolution of the lidar data and the presence of small scale hard layers such as building foundations and roads - which may act like revetments - not represented in the model.

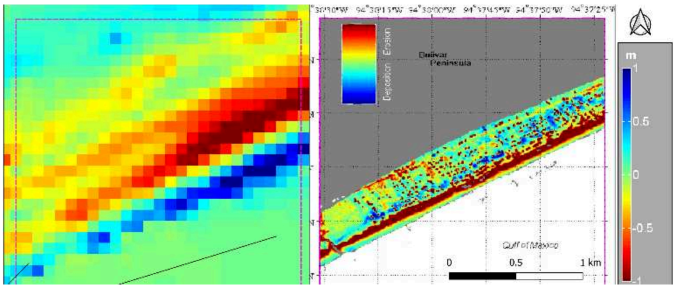

Figure 12 Comparison of the bed elevation change predicted by the model (left) and the bed elevation changed at Crystal Beach, Bolivar Peninsula assessed by Doran et al. [7] (right)

VII. Discussion and Conclusions

The model presented herein was developed to predict sediment transport pathways and magnitudes, and resulting coastal impacts along the coastline of Galveston, Texas arising from the passage of Hurricane Ike. The predicted hydrodynamics were calibrated and validated against observations of tidal elevations, currents, waves and inundation which show good agreement.

The validation of the hydrodynamics predicted by the model illustrates that predicted tidal elevations, waves and inundation were in good agreement with observations. Discrepancies between the predicted and observed tidal current speeds and directions are attributed to the applied boundary forcing and issues with TABS instrumentation [6].

The predicted sediment transport pathways and morphodynamics were compared with observations of coastal impacts associated with Hurricane Ike. Although no observational data (i.e. channel surveys or infill) were available with which to assess the validity of the predicted sediment transport rates, model predictions of bed elevation change are in line with observed bed elevation change from pre- and post-Ike LIDAR data. The predicted sediment transport pathways also reflect that assessed by Doran et al. [7].

The lack of a detailed map of small scale hard structures, such as roads and buildings is the main source of the model errors.

The results of this work demonstrate the ability to predict hydrodynamics, sediment transport and morphodynamics associated with hurricanes using a fully coupled TELEMAC-TOMAWAC-SISYPHE model.

ACKNOWLEDGEMENT

The authors thank the USGS, NDBC, NOAA, TCOON, NHC, ECMWF, HYCOM, the Texas General Land Office, the Bureau of Ocean Energy Management's Marine Mineral Information System, the University of Texas Institute for Geophysics, Texas A&M University's Offshore Technology Research Centre, and the USACE for making the data used herein publicly available.

REFERENCES

[1] Berg, R. (2009). Tropical cyclone report Hurricane Ike: National Oceanic and Atmospheric Administration National Hurricane Centre Report AL092008.

[2] USACE (2020). Appendix D: Engineering Design, Cost Estimates and Cost Risk Analysis for the Coastal Texas Protection and Restoration Feasibility Study.

[3] GEBCO Compilation Group (2019) GEBCO 2019 Grid (doi:10.5285/836f016a-33be-6ddc-e053-6c86abc0788e).

[4] Du, J., & Park, K. (2019). Estuarine salinity recovery from an extrem precipitation event: Hurricane Harvey in Galveston Bay. Science of the Total Environment, 1049-1059.

[5] East, J.W., Turco, M.J., and Mason, R.R., Jr., (2008). Monitoring inland storm surge and flooding from Hurricane Ike in Texas and Louisiana, September 2008: U.S. Geological Survey Open-File Report 2008–1365 [https://pubs.usgs.gov/of/2008/1365/].

[6] Hope, M.E., et al. (2013). Hindcast and validation of Hurricane Ike (2008) waves, forerunner, and storm surge. J. Geophys. Res. Oceans, 118, 4424–4460.

[7] Doran, K.S., Plant, N.G., Stockdown, H.F., Sallenger, A.H., Serafin, K.A. (2009). Hurricane Ike: Observations and analysis of coastal Change. USGS Open-File Report 2009-1061.