# ATTACHMENT 9

# ERDC RISK BASED WAVE AND SURGE MODELING REPORT

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ERDC/CHL LR-XX-X
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# Comparison of Three Modeled Storm Surge Levels between Existing and With Project Conditions for Present Day and Future Sea Level Rise Condition for Freeport Harbor, Freeport, TX

***By Thomas Chris Massey and Jeffrey A. Melby***

**PURPOSE:** The U.S. Army Corps of Engineers Galveston District (SWG) is currently engaged in the Freeport Harbor Channel Improvement Project Post-Authorization Change Report (General Re-evaluation) and Environmental Assessment. This Coastal & Hydraulics Laboratory Letter Report provides an initial analysis for storm surge levels in Freeport Harbor, Freeport, TX (Figure 1) using existing and with project conditions for present day sea level conditions and a single future sea level rise value of 2.4 feet. Three different tropical storm conditions are considered for both water levels and both sets of structure conditions.


Figure 1: Brazoria Region Hurricane Flood Protection.

**INTRODUCTION:** This letter report summarizes the results from performing both without-project and with-project conditions storm surge and waves modeling for three proxy storms under present day sea level conditions as well as a future sea level rise condition of 2.4 feet for Freeport Harbor, TX. The numerical storm surge and wave modeling used was the USACE ERDC Coastal Storm Modeling System (CSTORM-MS). CSTORM-MS is a comprehensive methodology and system of highly-skilled and highly-resolved numerical models used to simulate coastal storm hydrodynamics. With physics-based modeling capabilities, CSTORM-MS integrates a suite of high-fidelity storm modeling tools to support a wide range of coastal engineering needs for simulating tropical and extratropical storms, wind, wave and water levels and for representing the coastal response (Figure 2). CSTORM-MS makes use of a graphical user interface (GUI) within the SurfaceWater Modeling System (SMS) to promote efficient configuration of models that are generally applicable to a wide range of modeling scenarios. For the FEMA numerical modeling study, the primary modeling emphasis was to produce accurate surge and waves in the coastal zone. Accordingly, the CSTORM-MS was applied with the following models:

- WAM for producing offshore deep-water waves mainly intended for providing boundary conditions to the nearshore steady-state wave model STWAVE
- ADCIRC model to simulate the surge and circulation response to the storms. The ADCIRC and STWAVE models were applied in a tightly- coupled mode using the CSTORM-MS coupling framework
- STWAVE to provide the nearshore wave conditions including local wind generated waves.

The CSTORM-MS coupling framework options used for the numerical modeling study tightly links the ADCIRC and STWAVE models in order to allow for dynamic interaction between surge and waves. The ADCIRC model provides the STWAVE model with updated water surface elevations along with wind fields and, in turn, the STWAVE model provides gradients of wave radiation stresses to ADCIRC. The execution of each model and the interchange of information between the models are controlled by the CSTORM-MS coupling framework. This type of coupling system is referred to as being tightly coupled. The information exchange between models takes place via computer memory to allow for fast and efficient sharing of information. Individual models, ADCIRC and STWAVE, in turn, can produce a file record of the input conditions that were supplied to them by the coupler. These records are useful for quality-control purposes and for performing additional simulations in non-coupled mode.

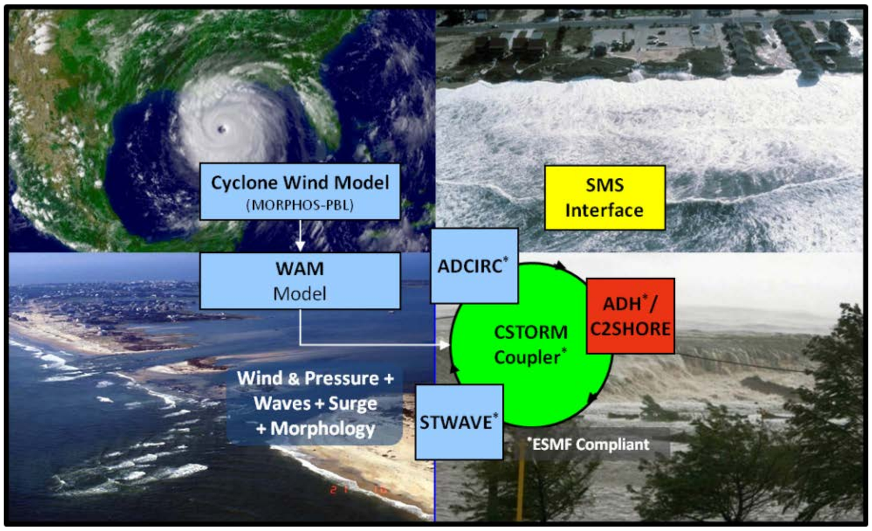
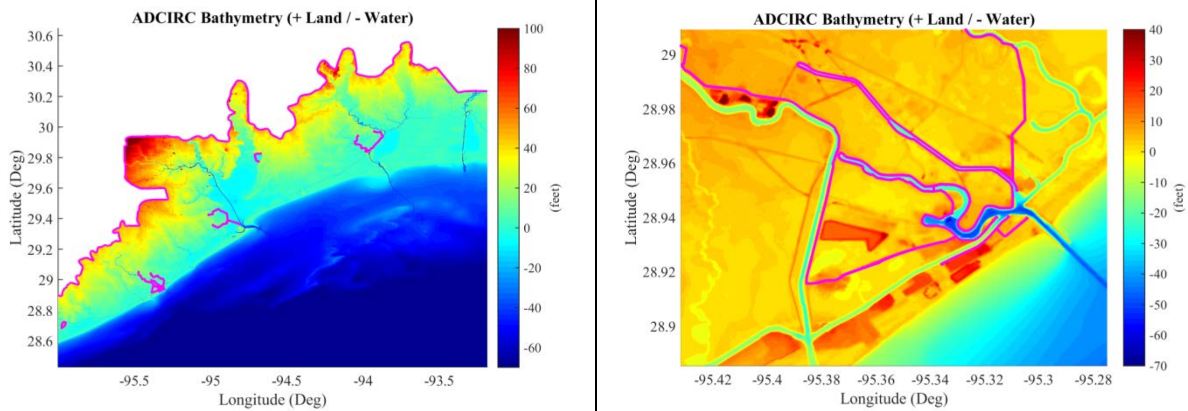



Figure 2: Schematic of CSTORM-MS workflow.

The study summarized herein took advantage of previous modeling conducted for the FEMA Region VI National Flood Insurance Program (NFIP) Risk MAP study reported in FEMA (2011). The climate modeling and the hydrodynamic modeling of offshore waves using the WAM wave model that was conducted for the FEMA study was used for the present study. However, new coupled modeling using the CSTORM-MS framework for the two-way coupling between the hydrodynamic surge/circulation model ADCIRC and the near shore wave model STWAVE was conducted to improve some of the prior modeling and to model the future sea level rise scenario in a consistent manner. Within the FEMA study, synthetic tropical storms were originally defined in an efficient sample from a joint probability model of tropical storm parameters. This joint probability model was generated from historical storm parameters found in the HURDAT database. The ADCIRC and STWAVE model bathymetry and topography used in this study is the same used in the FEMA study (2011), where it is noted that all elevations are referenced to NAVD88, see Figure 3. However, for the purpose of comparing with-project and without-project conditions, the ADCIRC and STWAVE models were both updated. In case of ADCIRC, additional mesh resolution was added around the with-project areas in order to represent project conditions accurately within the model. Once refinement occurred, two new ADCIRC meshes were created, on that represents present day (without-project) conditions and another that represents with-project conditions. A new STWAVE grid was created for the with-project condition to represent the removal of the wave barrier and to update the bathymetry where the bend easing and channel widening/deepening are to take place.




(a) (b)

Figure 3: ADCIRC bathymetry referenced to NAVD88 feet for northern Texas shown in (a) and a detailed view of the Freeport Harbor region in (b).

A plot showing the existing ADCIRC weir structures (in green) and with project plan lines overlaid are shown in Figure 4. With-project conditions included removal of the wave barrier to allow for bend easing, and deepening and widening the channel around the Dow Thumb area. Comparisons of ADCIRC mesh configurations for with and without-project conditions in the Freeport Harbor area are shown in Figure 5. The first row of Figure 5 shows the bathymetry color contour plots and the levee representations as black lines for the existing without-project conditions. Similarly the second row of Figure 5 shows the with-project updated bathymetry and levee structure representations as magenta lines. The last row shows the bathymetry change contour plots made between with and without project conditions.

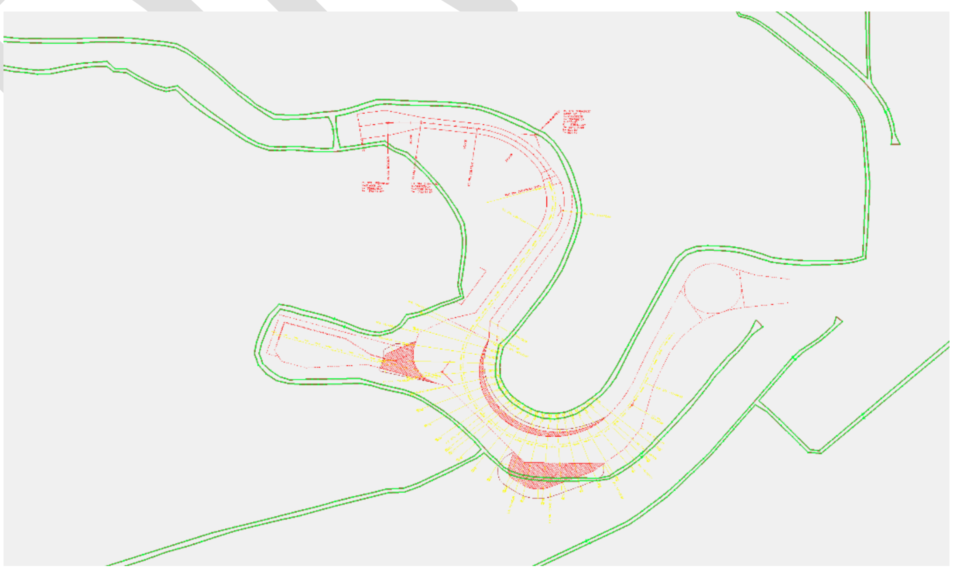


Figure 4: An image of the existing ADCIRC mesh weir structures in the Freeport area are shown in green and project plans are overlaid and are shown in red and yellow.

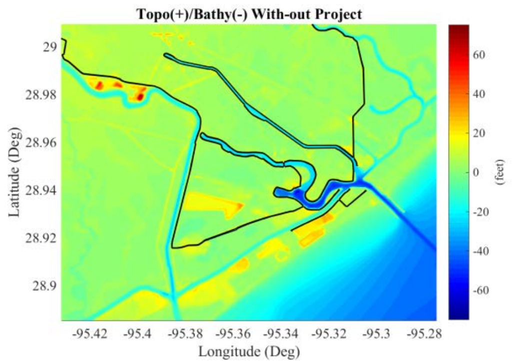
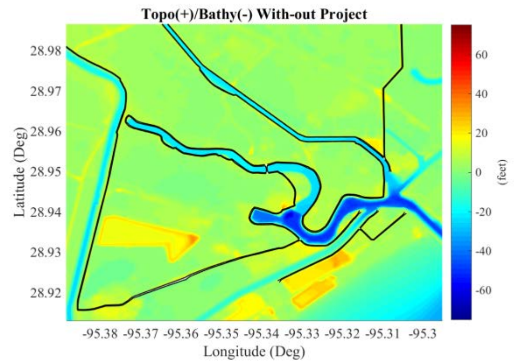
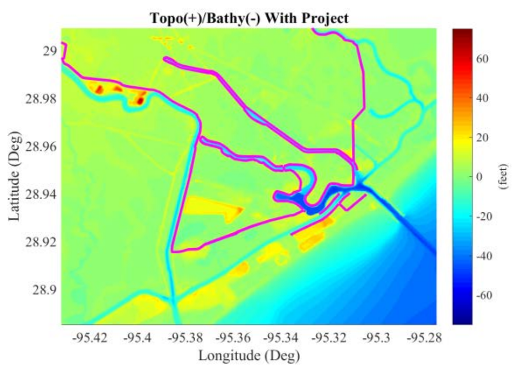
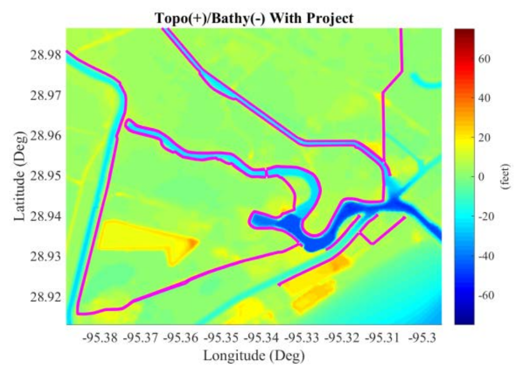
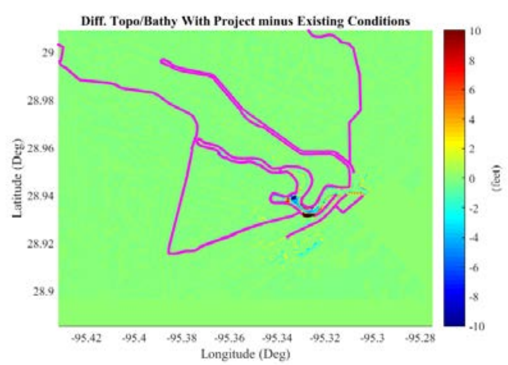
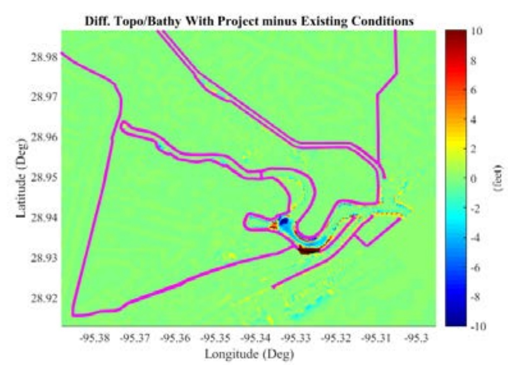
| | Visual Bounding Box 1 | Visual Bounding Box 2 (Zoom) |
|---|---|---|
| **Without-Project** |   (a) |   (b) |
| **With Project** |   (c) |   (d) |
| **Bathymetry Difference (With Project – Without Project)** |   (e) |   (f) |

Figure 5: ADCIRC bathymetry and levee structure representations for both without and with-project conditions along with a difference plot showing changes in bathymetry values.

**METHODOLOGY:** Nearly all the ADCIRC model parameters as described in the FEMA (2011) report were kept the same. However, some changes were made to account for changes in the ADCIRC model since the FEMA study and to improve upon results. In particular, the lower limit for the bottom drag friction coefficient was changed from a value of 0.0 in the FEMA report to a value of 0.0023. A Garrett wind drag formula was applied with an upper limit to the wind drag coefficient of 0.002. Finally, some of the ADCIRC model runs used a form of slope limiting applied to the computed sea surface elevation calculations in order to improve model stability over localized areas in the model domain. The implementation of slope limiting in the ADCIRC model has changed since the 2011 study. Every attempt was made to match as closely as possible the original slope limiting areas used in the FEMA study. Figure 6 shows the locations where slope limiting was allowed to occur. A default slope limiting value of 100 was defined everywhere in the model domain and only selected locations along the coastline had a value of 0.00002 assigned to them. These locations closely resemble locations from the original FEMA work. The value of 100 prevents slope limiting from being used in that area while the much smaller value of 0.00002 allows slope limiting to be turned on, whenever the magnitude of the gradient of surface elevations is greater than 0.00002.

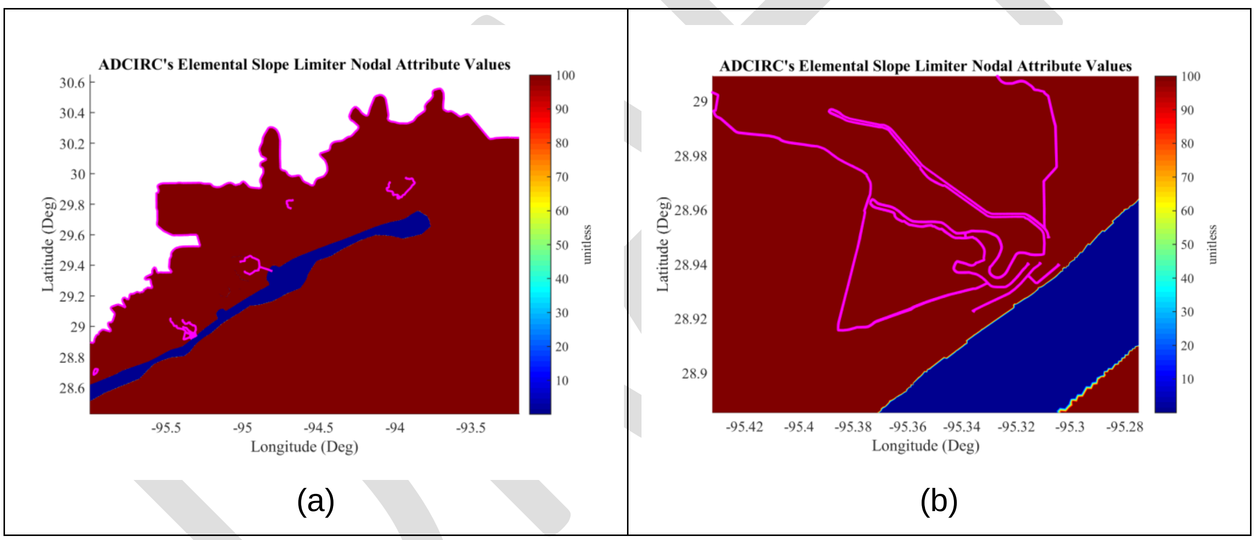
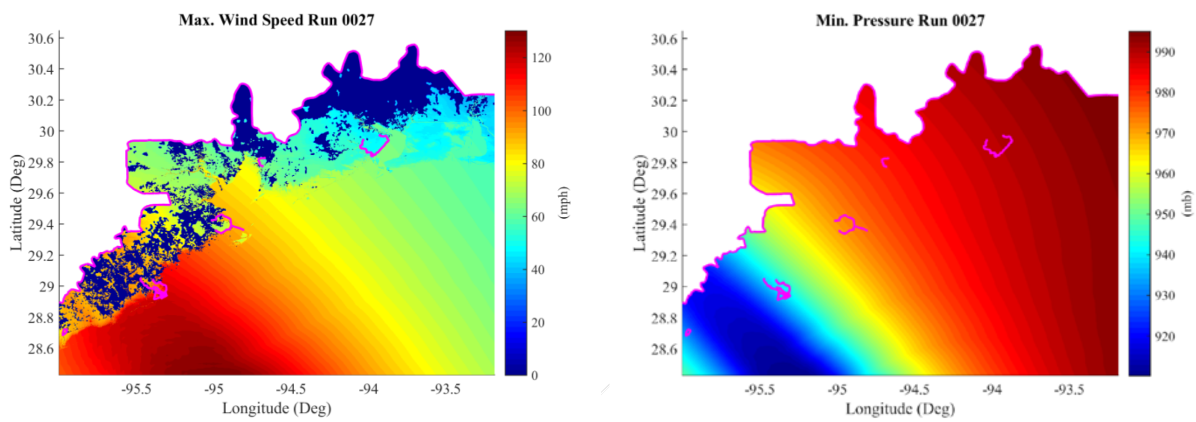



Figure 6: Contour map showing ADCIRC's nodal attribute value for triggering elemental slope limiting.

The storms available from the FEMA study that are germane to this study are the 223 North Texas ADCIRC and STWAVE simulations. We note that STWAVE does not include wave diffraction so waves are not expected to be transformed from the jettied inlet through the Freeport channel correctly. The STWAVE NE grid covers the Freeport Harbor area and has a spatial resolution of 200 meters. While this resolution is too coarse to resolve many details within the Freeport channel, the wave height and period resulting from local wind wave generation appear to be reasonably well predicted. It is expected that the primary wave process of interest near the Dow Thumb would be wind-wave generation so the existing STWAVE modeling in this area seems to be adequate for both the without-project and with-project evaluations. Proxy storms that directly impact the Freeport area included FEMA North Texas storm 27, storm 77 and Hurricane Ike and were previously run at a higher resolution using CMS-Wave for the I-wall reliability study.

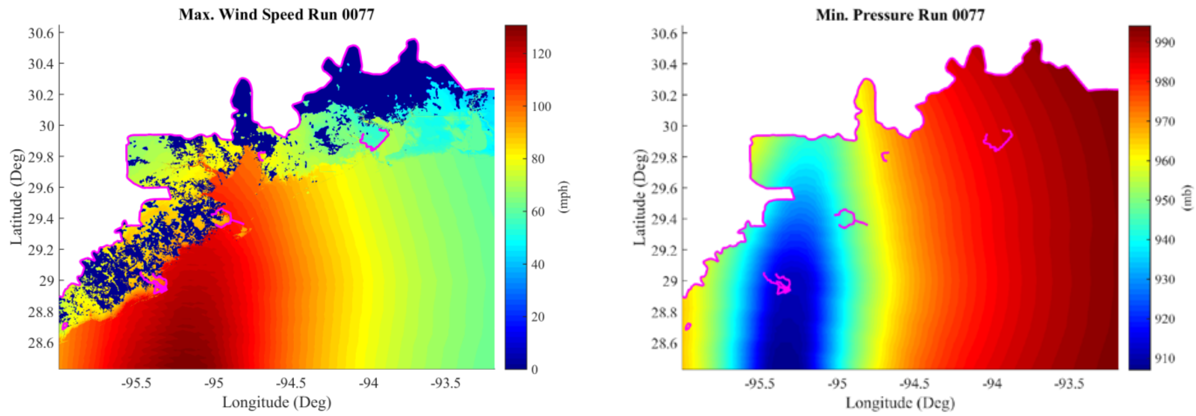
Storm 27 is a synthetic tropical storm that has a forward speed of approximately 11 mph, maximum wind speed of approximately 130 mph with a radius of maximum winds ranging between 22 and 32 nautical miles with a minimum central pressure of 900 mb. See Figure 7 for color contour plots of the maximum wind speeds and minimum surface pressures for storm 27 that occurred over the course of the simulation. Tidal effects were not included in the ADCIRC simulation.




(a) (b)

Figure 7: Color contours of the (a) maximum wind speeds and (b) minimum surface pressure over the entire domain for the length of the storm simulation for storm 27.

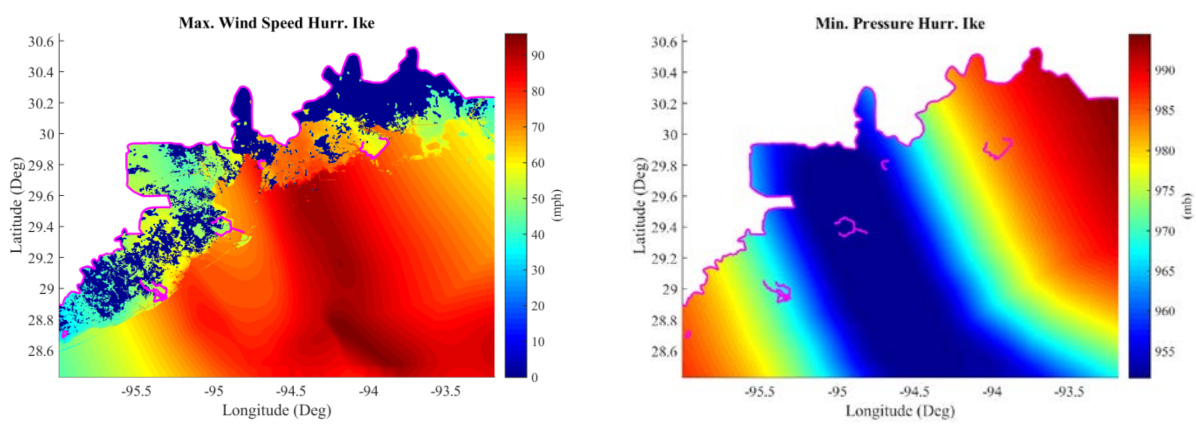
Storm 77 is also a synthetic tropical storm from the North Texas suite of FEMA storms. It has a forward speed of approximately 11 mph, maximum wind speed of approximately 130 mph with a radius of maximum winds ranging between 18 and 25 nautical miles with a minimum central pressure of 900 mb. See Figure 8 for color contour plots of the maximum wind speeds and minimum surface pressures for storm 77 that occurred over the course of the simulation. Tidal effects were not included in the ADCIRC simulation.




(a) (b)

Figure 8: Color contour contours of the (a) maximum wind speeds and (b) minimum surface pressure over the entire domain for the length of the storm simulation for storm 77.

Hurricane Ike made landfall in Galveston, TX on September 13, 2008. Ike had maximum winds of 145 mph and a lowest surface pressure of 935 mb during its existence. Ike had a wind speed of 110 mph (category 2 hurricane) when it made landfall in TX. A more thorough description of the reconstructed Hurricane Ike wind and pressure fields is supplied in the FEMA 2011 report and will not be included here. However, in Figure 9 color contour plots of the maximum wind speeds and minimum surface pressures for Hurricane Ike that occurred over the course of the simulation are shown. The ADCIRC simulations for Hurricane Ike include time dependent tidal forcing.




(a) (b)

Figure 9: Color contour contours of the (a) maximum wind speeds and (b) minimum surface pressure over the entire domain for the length of the storm simulation for Hurricane Ike, 2008.

## RESULTS Part I: Without-Project Comparison between Present Day and Future Sea Level Rise

CSTORM-MS simulations were performed using the two sets of three storm (27, 77 and Ike) inputs described above. The first set of CSTORM simulations used a present day sea level configuration and the second set used a future sea level rise value of 2.4 feet. The maximum sea surface elevations computed by the ADCIRC model during the coupled ADCIRC and STWAVE simulations for all six model simulations are shown in the first two columns of Figures 8-10. For each of Figure 10-Figure 13, the contour plot areas displayed are increasingly focusing on the Freeport Harbor area from one row to the next. This allows for the large scale dynamics to be seen as well as the high resolution results in the harbor area itself.

Under present day water levels, the maximum surge level over the entire domain for storm 27 was approximately 33 feet, storm 77 was 25 feet and Hurricane Ike was 39 feet. Along the open coast in front of Freeport Harbor, the maximum surge for storm 27 was between 18 and 22 feet, for storm 77 it was 15 to 18 feet, and for Hurricane Ike it was approximately 8 feet. Inundation behind the flood protection areas occurred for all three simulations with the least amount of inundation happening with Hurricane Ike with only a few areas being wet with about 1 foot of water. Storm 77's inundation levels behind the flood protections ranged from barely wet areas to some areas with approximately 12 feet of water. Storm 27 showed the most inundation in the Freeport Harbor area with nearly the entire area behind the flood protection system flooded with water levels between 15 and 17 feet.

When considering the future SLR of 2.4 feet simulations, the maximum surge level over the entire domain for storm 27 was 33 feet, storm 77 was 33 feet and Hurricane Ike had a maximum surge of almost 42 feet. Along the open coast in front of Freeport Harbor, the maximum for storm 27 was between 20 and 24 feet, for storm 77 it was 17 to 21 feet, and for Hurricane Ike it was approximately 10 to 11 feet. Inundation behind the flood protection areas occurred for all three simulations with the least amount of inundation happening with Hurricane Ike with a few areas being wet, more so than the present day condition, with about 1 to 2 feet of water. Storm 77's inundation levels behind the flood protections showed more inundation area than the present day simulation and had levels ranging from 11 feet to 17 feet of water. Storm 27 again had the most inundation in the Freeport Harbor area with nearly the entire area behind the flood protection system flooded with water levels around 20 feet.

The last column of Figure 10-Figure 13 shows the difference in maximum sea surface elevations between the SLR simulations minus the present day simulations. The maximum surge levels resulting from the 2.4 feet of SLR clearly have non-linear responses, in that the resulting maximum sea surface elevations are often more 2.4 feet higher than the present day conditions. This is to be expected for this region. Figure 13 shows larger images of the difference plots, for each storm, between the maximum sea surface elevations for the SLR simulation minus the present day simulation in the Freeport Harbor area only. The differences in the surge levels behind the flood protection systems in the Freeport Harbor between the SLR and present day water level conditions varied significantly depending on the storm. Storm 27 had maximum sea surface elevation difference ranging from about 2 feet to 5 feet more water under the SLR simulation. Storm 77 had the most significant differences of the three storms with differences ranging from about 4 feet to more than 8 feet. Smaller differences were observed for Hurricane Ike except for one area that had differences on the order of 5 to 6 feet likely due to backwater flooding, rather than overtopping.

| Existing Conditions | Future Sea Level Rise (2.4ft) | Difference (SLR – Existing) |
|---|---|---|

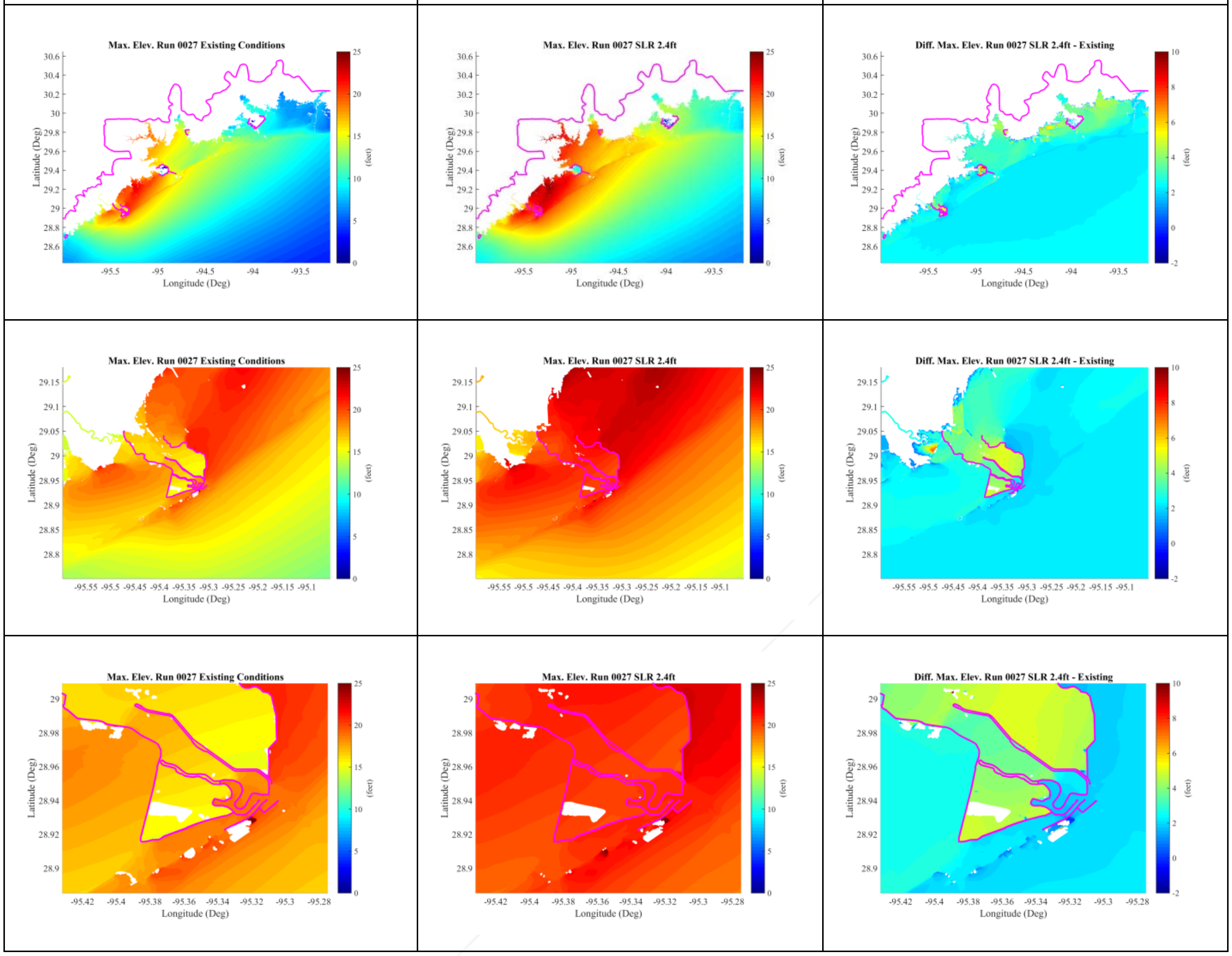



Figure 10: Comparison of maximum sea surface elevations from ADCIRC for synthetic tropical storm number 27 for existing conditions and for a future sea level rise of 2.4 feet.

| Existing Conditions | Future Sea Level Rise (2.4ft) | Difference (SLR – Existing) |
|---|---|---|

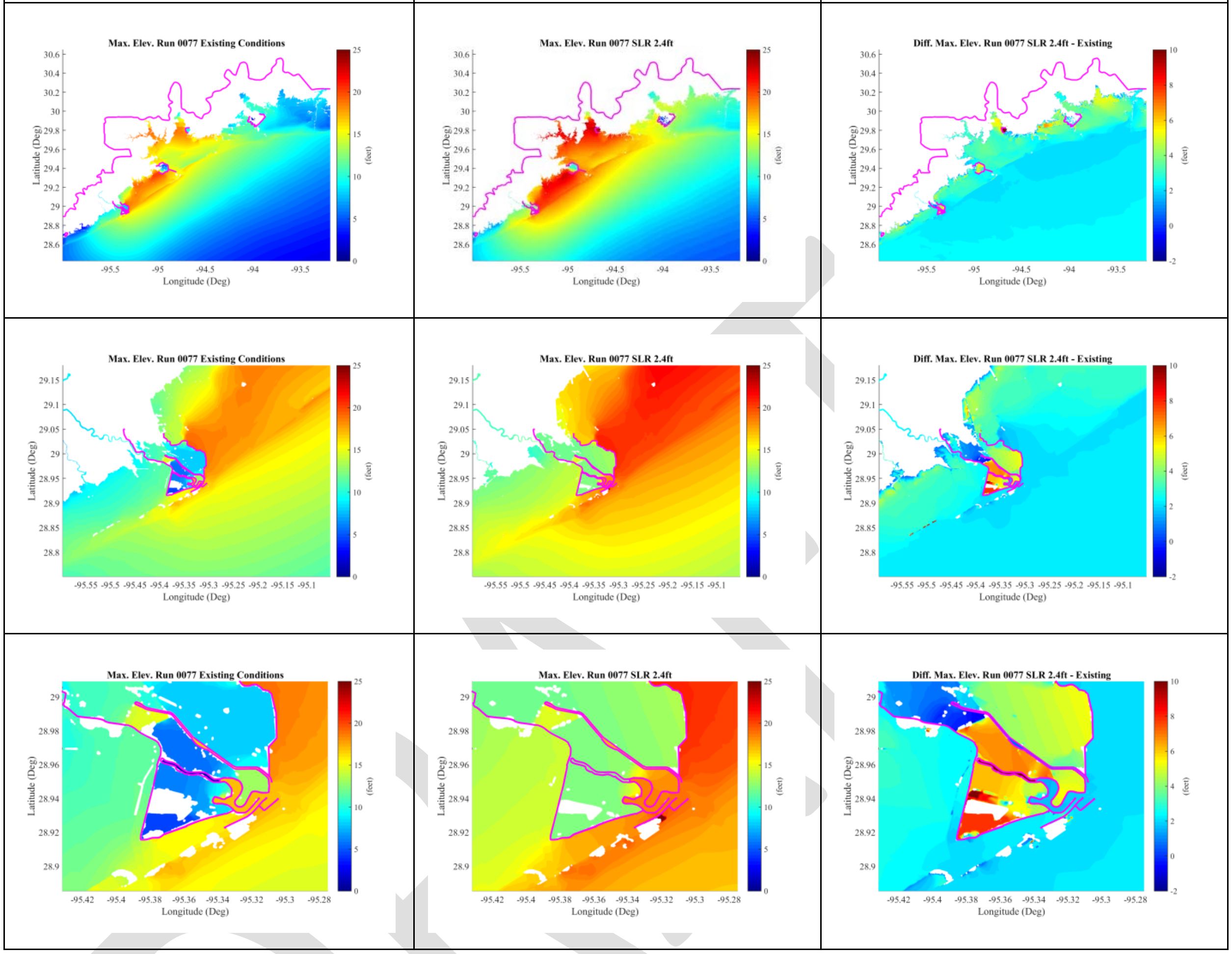



Figure 11: Comparison of maximum sea surface elevations from ADCIRC for synthetic tropical storm number 77 for existing conditions and for a future sea level rise of 2.4 feet.

| Existing Conditions | Future Sea Level Rise (2.4ft) | Difference (SLR – Existing) |
|---|---|---|

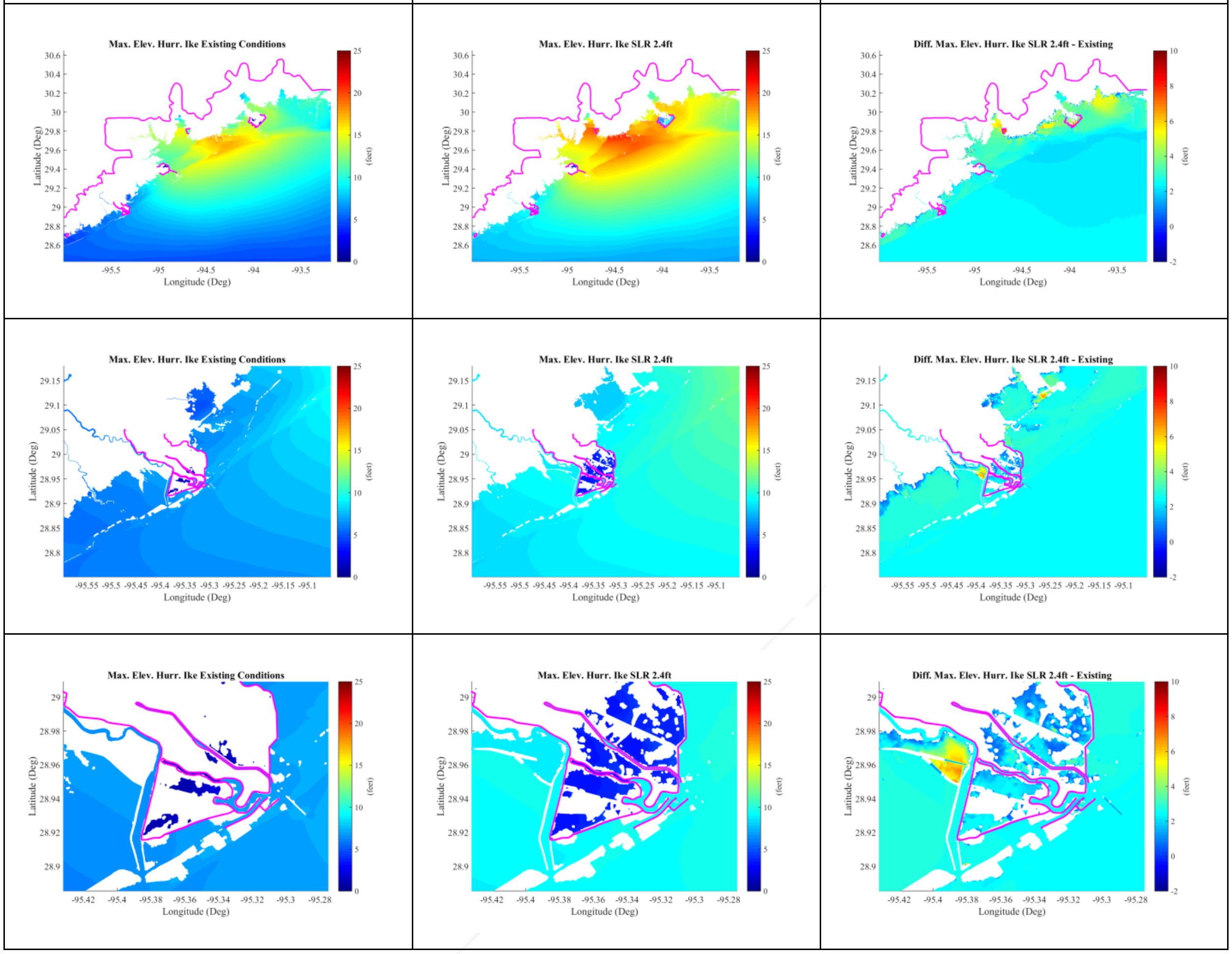
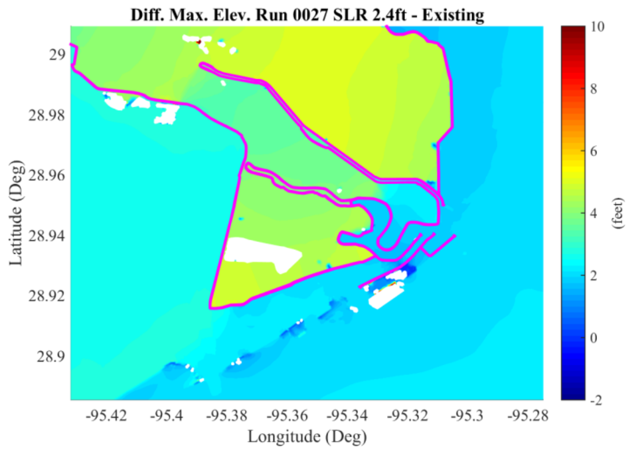
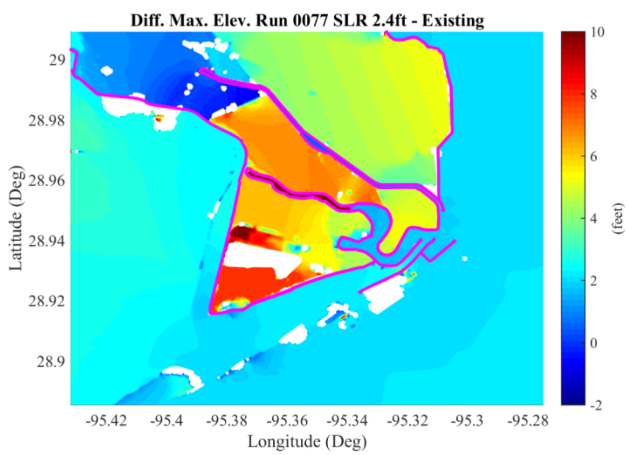



Figure 12: Comparison of maximum sea surface elevations from ADCIRC for Hurricane Ike for existing conditions and for a future sea level rise of 2.4 feet

Storm 27




Storm 77




Hurr. Ike

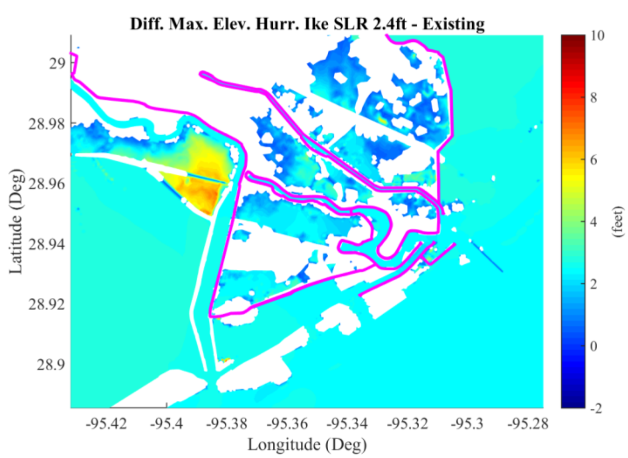



Figure 13: Comparing the difference in maximum sea surface elevation changes between future sea level rise conditions and present day conditions from ADCIRC.

## RESULTS Part 2: Comparison of With and Without-Project Conditions

The next sets of comparisons were performed to determine the impacts, if any, to maximum storm surge due to with project conditions in the Freeport Harbor. The same three storms were run using an updated ADCIRC mesh and STWAVE grid to capture with project conditions. Figure 14 shows a set of 9 color contour plots for the results for storm 27, showing in the first row without project conditions maximum surges for present and future SLR, the second row shows maximum surges for with project conditions under present and future SLR water levels and the third row shows plots of the difference in those maximum surges between the without and with project conditions for both water levels. The maximum surges for both with and without project conditions are very similar and range from approximately 13 feet to 23 feet over the project area with a small location of higher elevation south of the project area. This pocket of higher elevation is located at a levee (weir) structure in the ADCIRC mesh which was not very well resolved and its impact to the overall area is minimal. From the last row of images the main differences in maximum surge levels in the project area are on the order of a couple of inches and fall well within the range of model uncertainty. The pocket of higher differences is again in the aforementioned area where mesh resolution could have been improved to lessen the wetting and drying differences.

In Figure 15 the same set of conditions as just examined for storm 27 are shown for storm 77. For storm 77, the maximum surge results for without and with project conditions are shown in rows 1 and 2 and have very similar results with peak surges on the order of 19 to 20 feet. Notice in the present day water level plots that the hot spot of elevation that formed in storm 27 south of the project area did not occur for storm 77 under these conditions, because the water level was never high enough to flow over the internal weir structure (levee) in the ADCIRC mesh. Water levels for the with SLR scenarios were high enough to cause water to flow over the weirs and then the wetting and drying differences between the two sets of simulations can be seen, but are not negatively impacting the results. A larger view of the maximum difference color contour plots for without versus with project conditions for present day water levels is shown in Figure 16. This larger view allows one to see the extent of the inundation north of the Freeport levee systems where the peak surges are being observed. From the difference image, it is clear that the maximum difference between without and with project conditions are again on the order of a few inches which are well within the model uncertainty range. The slightly higher surge elevations within the levees in the north of the Dow thumb are due to increased flow through the weir on the northern most extents of the weir (levee) system.

The maximum surge level color contour plots for the Hurricane Ike simulations are shown in Figure 17. As mentioned earlier, this simulation had small storm surges compared to storms 27 and 77 for the Freeport Harbor area. The differences in without and with project conditions are again on the order of a couple of inches and fall well within the range of model uncertainty.

<table>
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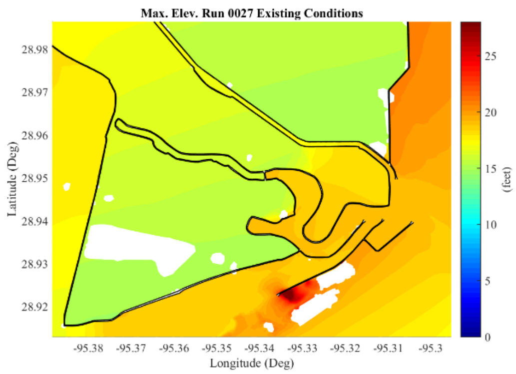
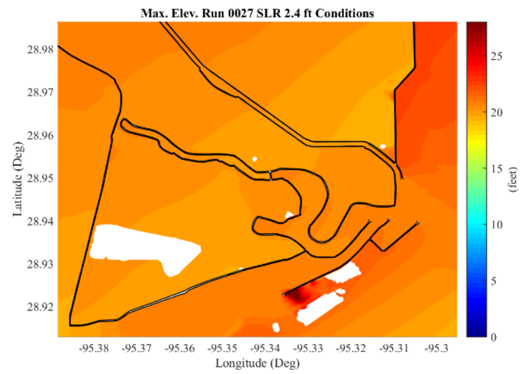
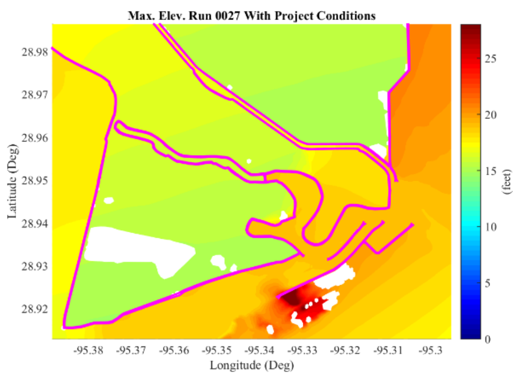
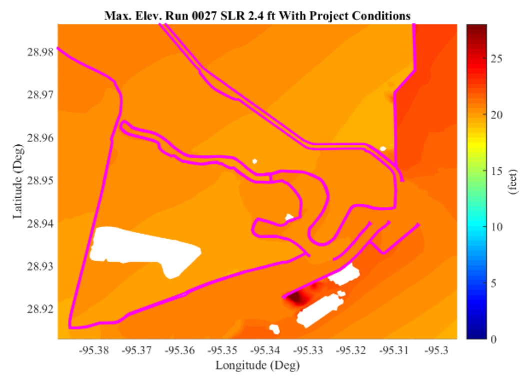
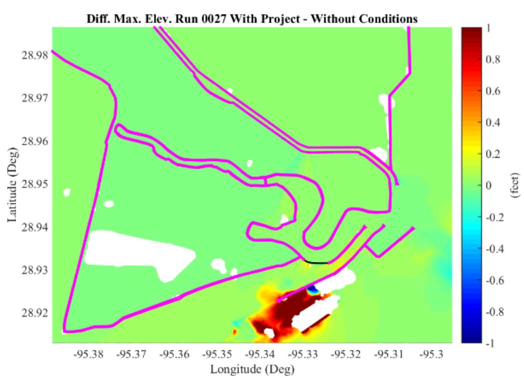
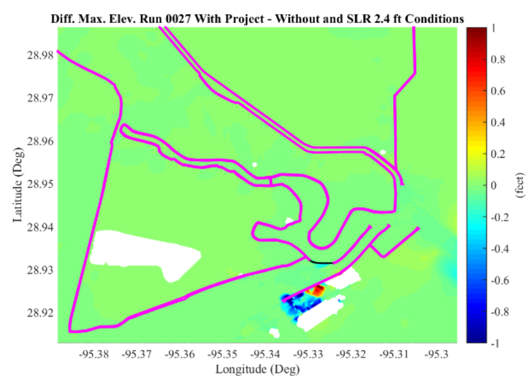
<tr><td>Without Project</td><td><br>(a)</td><td><br>(b)</td></tr>
<tr><td>With Project</td><td><br>(c)</td><td><br>(d)</td></tr>
<tr><td>Difference<br>(With Project – Without Project)</td><td><br>(e)</td><td><br>(f)</td></tr>
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Figure 14: Maximum storm surge levels for synthetic tropical storm 27 under (a) present day water levels and without-project, (b) future sea level rise and without-project, (c) present day water levels and with-project conditions, (d) future SLR and with-project conditions, difference in maximum surge levels between with project and without project for (e) present day water levels and (f) future SLR.

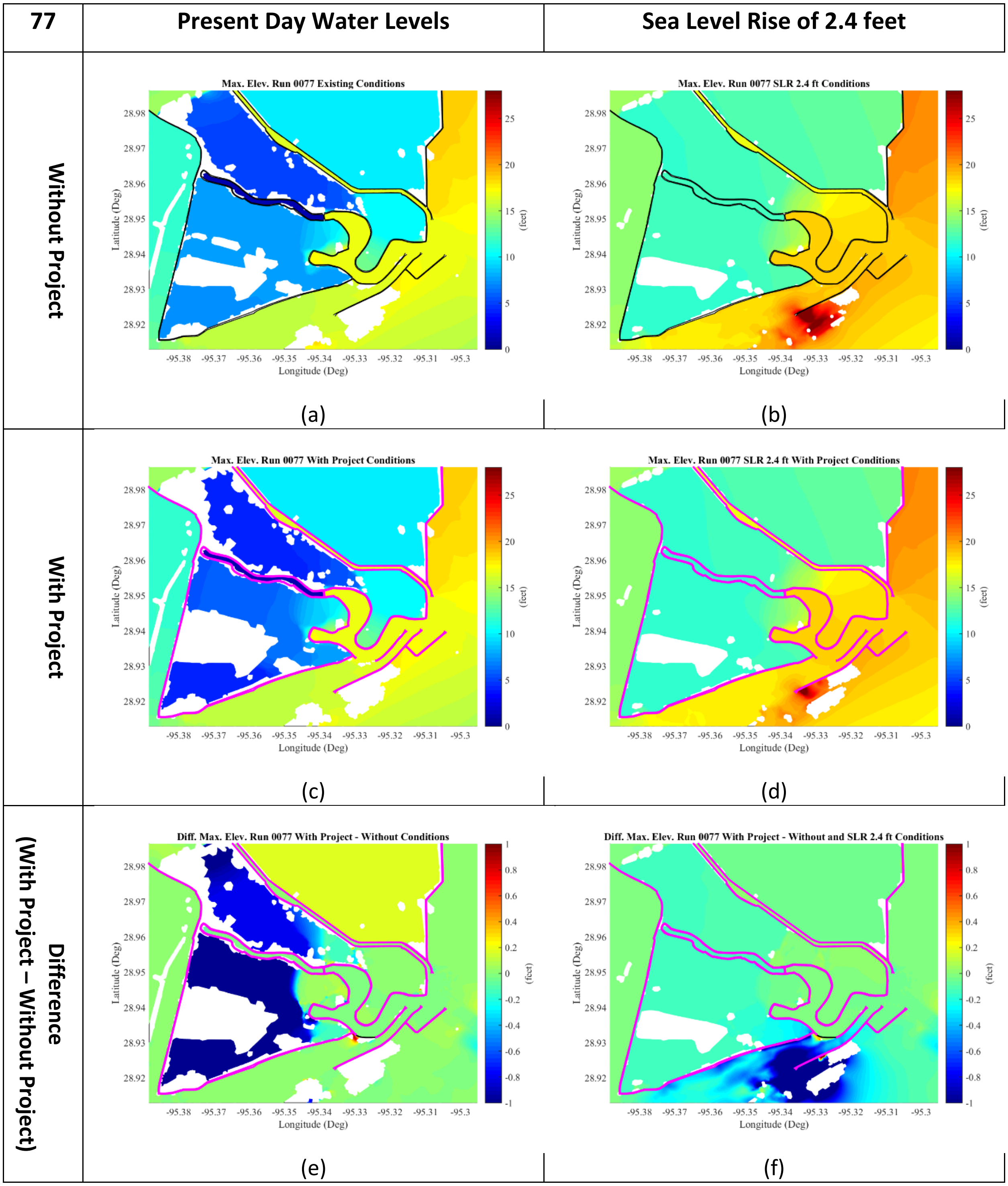
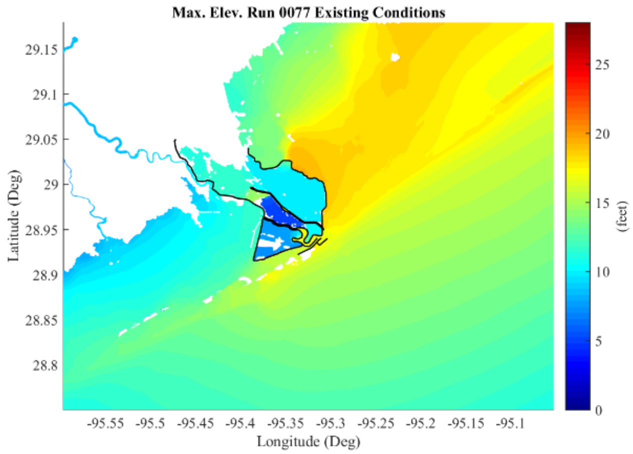



Figure 15: Maximum storm surge levels for synthetic tropical storm 77 under (a) present day water levels and without-project, (b) future sea level rise and without-project, (c) present day water levels and with-project conditions, (d) future SLR and with-project conditions, difference in maximum surge levels between with project and without project for (e) present day water levels and (f) future SLR.

<table>
<tr><th></th><th>Larger view of Storm 77 Under Present Day Water Levels</th></tr>
<tr><td>Without Project</td><td>
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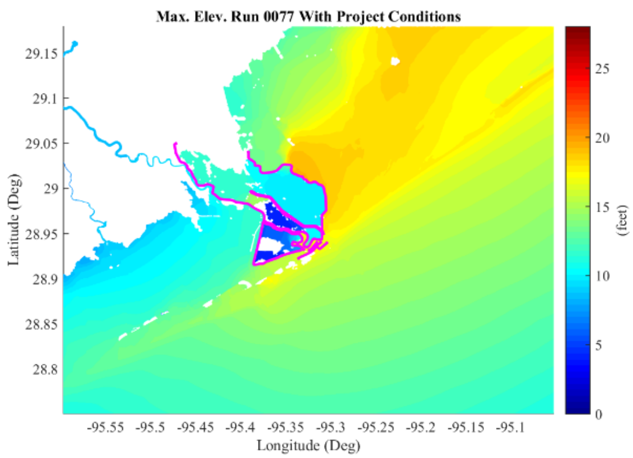
<tr><td>With Project</td><td>
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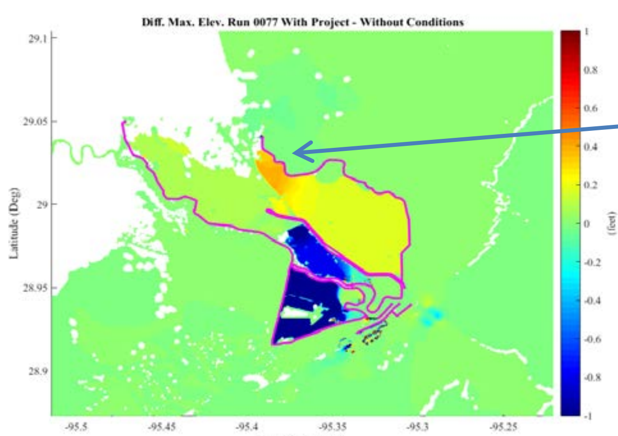
<tr><td>Difference<br>(With Project – Without Project)</td><td>

Higher flow through the weir on the order of 5 inches in this northern extent results in higher surges, on the order of 2 inches, in the southern extents.</td></tr>
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Figure 16: Larger view of the contour plots of maximum storm surge for storm 77 for without project and with project conditions and the differences under present day sea level values only.

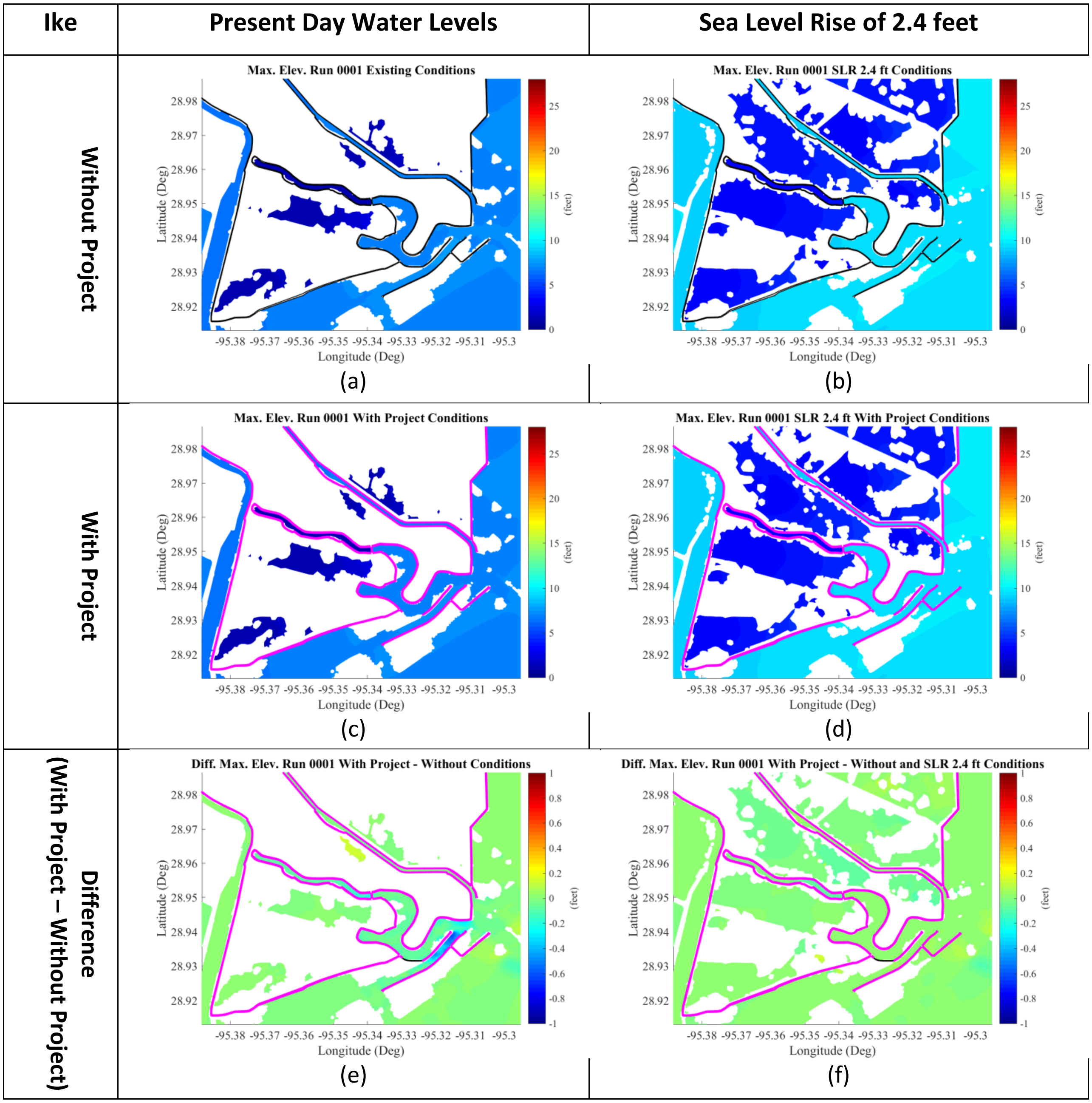


Figure 17: Maximum storm surge levels for Hurricane Ike (storm 1) under (a) present day water levels and without-project, (b) future sea level rise and without-project, (c) present day water levels and with-project conditions, (d) future SLR and with-project

## CONCLUSION AND RECOMMENDATION:

The first set of results within this report were intended to quantify the impact to surge levels in the Freeport Harbor area due to a 2.4 feet SLR for three proxy storms. The increased water levels due to the SLR added to flood inundation levels in the Freeport Harbor area. The added inundation amounts were often more than 2.4 feet due to non-linear effects included in the hydrodynamic model. The next set of results presented, were intended to quantify the impacts if any to the maximum surge levels in the area under with project conditions. For these three storms which represent different levels of storm intensity and return periods for the area, the with project conditions were not found to negatively impact the overall storm surge levels, under present day water levels or future SLR water levels.

## REFERENCES:

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**TABLE OF CONVERSIONS:**

Most measurements and calculations for this study were done in SI units and were converted to English for this report. The following Table can be used to convert SI units to English Customary units. Additionally, a value of 9.80665 $m/s^2$ was used to represent the acceleration due to gravity.

| **Multiply** | **By** | **To Obtain** |
|---|---|---|
| meters | 3.28084 | feet |
| meters per second (m/s) | 2.23694 | miles per hour (mph) |
| Pascals | 0.01 | millibars (mb) |

**ADDITIONAL INFORMATION:** This letter report was prepared by Thomas Chris Massey and Jeff A. Melby at the US Army Corps of Engineers, Engineer Research and Development Center, Coastal & Hydraulics Laboratory. Questions about this letter report can be addressed to Chris Massey (or Jeff Melby) at 601-634-2406 or *chris.massey@usace.army.mil*.