Potential Effects of Deepening of the Corpus Christi Ship Channel on Hurricane Storm Surge: A Case Study.

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Acknowledgment

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Abstract

We present an investigation of the potential impact of deepening the Corpus Christi Ship Channel through Aransas Pass on the magnitude of hurricane storm surge in the region of Corpus Christi and Port Aransas, Texas. Our investigation is based on mathematical models of the circulation of the seawater due to Hurricane Harvey and two synthetic hurricanes derived from Harvey. From the model, we ascertain the maximum storm surge as well as hydrograph time series at critical locations in the study region. Subsequent comparison of the surge for the model results of the current and proposed future channels are used to assess the effects on storm surge magnitude. Our model results indicate that the changes to maximum storm surge magnitude are small. However, there are some local areas where the models indicate an increase of up to 15 centimeter.

1 Introduction

The Corpus Christi ship channel extends from the Gulf of Mexico to the port of Corpus Christi (POCC) through Corpus Christi Bay and Aransas Pass [5] (see Figure 1). The current channel depth was established in 1989 and has an average depth of $14.33m$ $(47ft)$, which is maintained through a continuous dredging operation [5]. The channel allows cargo ships to enter and exit the system of bays to reach the port of Corpus Christi through the Aransas Pass which is the only remaining natural tidal inlet nearby. Due to

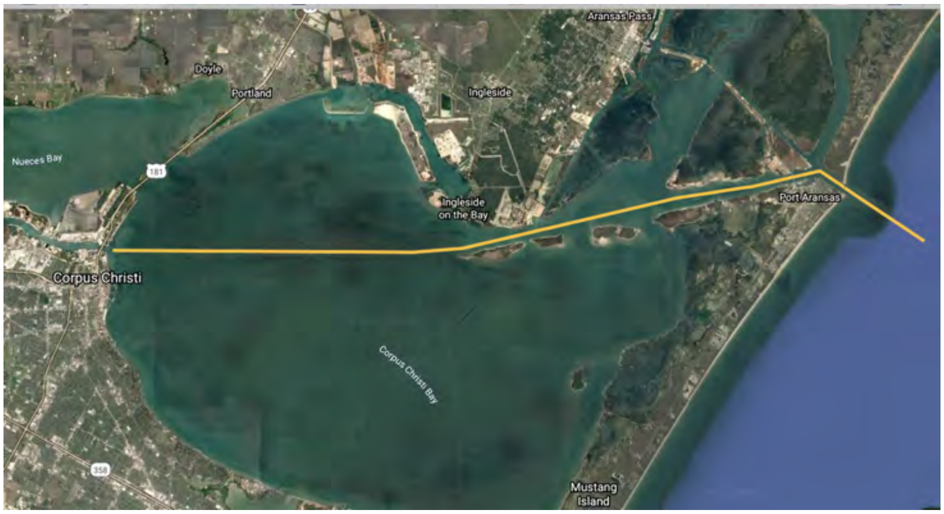


Figure 1: Location of the Corpus Christi ship channel.

the growth and expansion of the Port of Corpus Christi, it has been proposed to deepen the ship channel through the pass to $21.33m$ $(70ft)$ to accommodate larger ships at the port. Hence, the characteristics of the seawater circulation through the pass and Corpus Christi bay is likely to be altered. In a previous study [10], we considered the effects of a deepened channel on the transport of Red Drum fish larvae modeled as passive particles. While the flow velocity through the Aransas Pass changed noticeably, the overall change to particle transport through the pass to shallow seagrass beds where the larvae settle was very small.

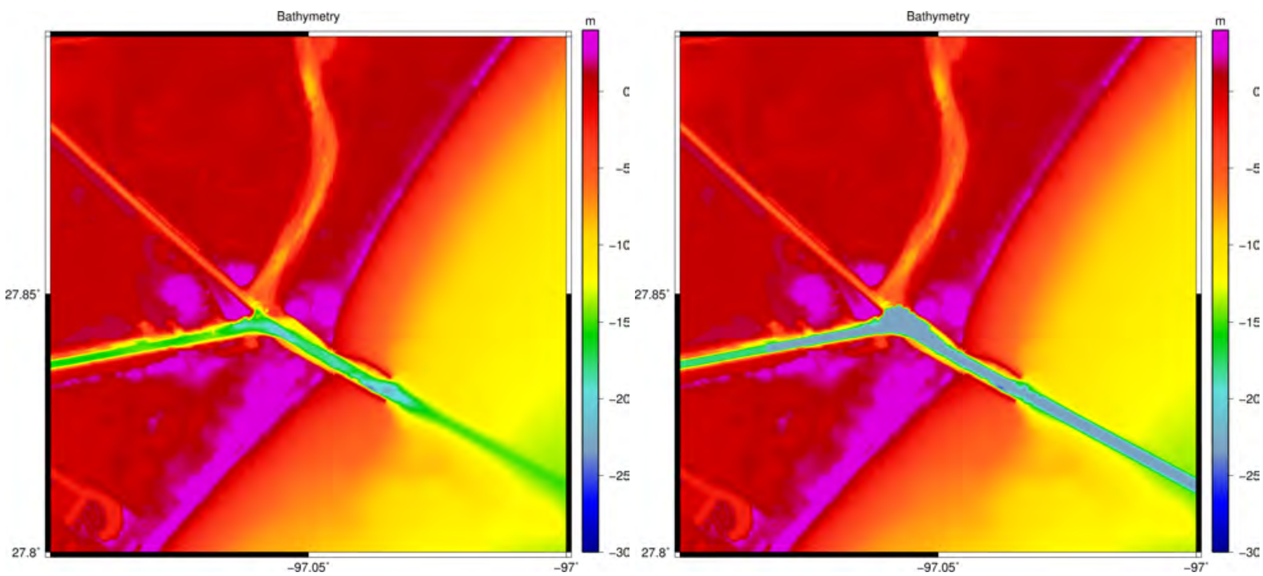
The Texas coastline near Corpus Christi is frequently impacted by hurricanes and smaller storms leading to potentially damaging storm surges. Corpus Christi and Port Aransas have been affected by numerous storms, e.g., in 2017, the area was impacted by Hurricane Harvey. Hurricane Harvey was a special event as it lead to storm surge originating both from the Gulf of Mexico and from within Corpus Christi bay as noted in [4]. In this work, we assess the effects of the deeper channel on the resulting storm surge. To this end, we develop two models for the circulation of seawater for the current channel and the proposed deeper channel. In particular, we consider Hurricane Harvey and its original track as well as synthetic versions in which the track of Hurricane Harvey is shifted towards the Aransas Pass. From these models, we ascertain both sea surface elevation and the flow velocity field for the entire model domain and time span of consideration.

In the following report, we describe in detail the modeling methodology used in Section 2. In Section 3, we present the results from our model and compare findings based on current and proposed channel depths for hurricane Harvey and its derived versions. Finally, in Section 4 we conclude this report with remarks on the findings. The term "bathymetry" is used throughout this document and it refers to the depth of water relative to the North American Vertical Datum of 1988 (NAVD88). Here, we use the convention that the bathymetry is positive, i.e., dry land, above NAVD88.

2 Modeling Methodology

To model the storm surge near the Aransas Pass due to Hurricane Harvey, we use a numerical (computer) model, the advanced circulation (ADCIRC) model [8]. ADCIRC solves the governing mathematical model for coastal circulation (referred to as hydrodynamics), the Shallow Water equations using a numerical method, the finite element method [7]. Furthermore, before a hurricane makes landfall, it often generates large waves in the deep ocean far away from the coastline. In such cases, ADCIRC alone may not capture the full spectrum of wave energy transfer. Hence, we employ an approach in which ADCIRC is coupled to a wave model in the deep ocean, simulating waves nearshore (SWAN). SWAN is a phase-averaged wave model based on the action balance equation [1]; it was coupled with ADCIRC in 2011 [2]. ADCIRC+SWAN solves for wave-current interaction during hurricanes and is a fundamental code used in hurricane forecasting and hindcasting, and is the basis of a real-time storm surge forecast system.

To assess the effects of the change in the bathymetry of the ship channel, we develop two distinctive ADCIRC+SWAN models which use different finite element meshes (i.e., domain discretizations). The meshes are identical in span and resolution, however, one contains the current bathymetry and the second has the proposed deeper channel bathymetry. In Figure 2 we show the current and proposed bathymetries in the Aransas Pass. To ensure accurate results, these meshes cover the entire Gulf of Mexico and the



(a) Existing.

(b) Proposed.

Figure 2: Bathymetry (in meters) near the Aransas Pass.

western Atlantic Ocean and are of very high resolution along the Texas coast. The mesh with the current bathymetry is routinely used in operational storm surge forecasting with ADCIRC+SWAN and has been extensively validated, see, e.g., [6]. The meshes contain 3,352,598 nodes distributed among 6,675,517 finite elements with refinement along the Texas coast ranging from $100m$ down to $30m$ resolution whereas in the deep ocean the resolution is of order kilometers, see this mesh and its extent in Figure 3. For the current channel, this mesh was further validated in our previous study [10] and we do not perform further validations in the current study.

The ADCIRC+SWAN models developed here employs two types of forcing: tides and meteorological. The tidal forcing is obtained using OceanMesh2D [9], which utilizes the TPXO9 tidal model [3].Hurricane Harvey made landfall August 25^{th} 2017 and produced surges that exceeded $3m$ in locations on the Texas coast [4]. To ensure the model accuracy, we follow the modeling approach laid out in [4] in which ADCIRC+SWAN is run for 21 days forced only with tides. This tidal "spin-up" is subsequently used as an initial condition for a full ADCIRC+SWAN run forced with tides and meteorological data. In particular, we use Generalized Asymmetric Holland Model for the hurricane winds and pressure fields based on the best track information determined by the National Hurricane Center. This second run starts August 23^{rd} and ends August 31^{st}, several days after the storm surge has receded back into the ocean.

To assess the impact of the channel depth on the magnitude of storm surge, we compare the surge of hurricane Harvey as well as its shifted versions in the study area. Hurricane Harvey originally made landfall

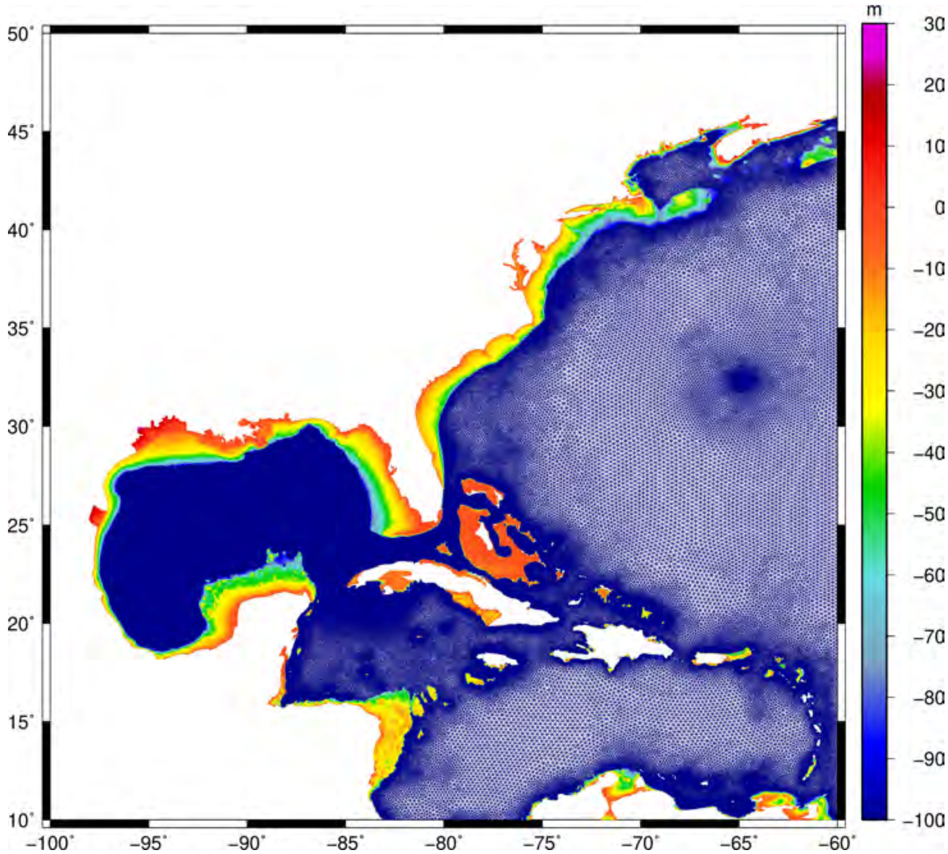
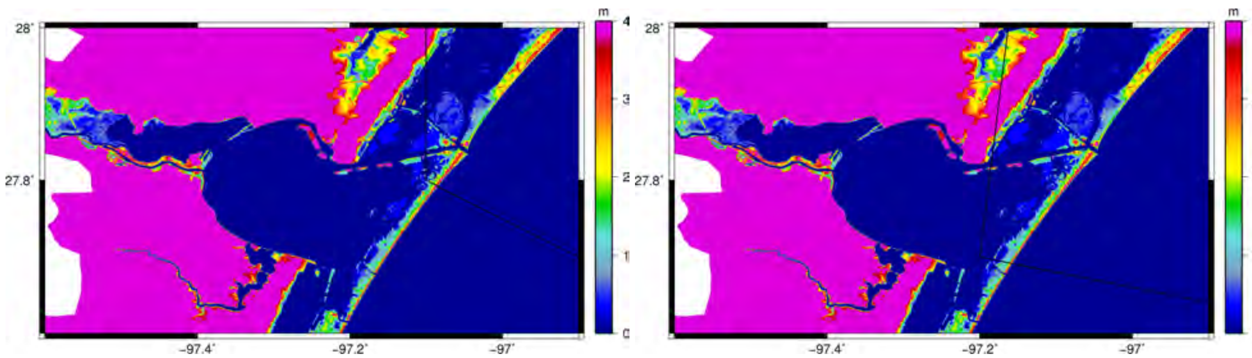


Figure 3: Model domain covered by the ADCRIC finite element mesh. Note that the colorbar denotes the bathymetry measured in meters cut off at $100m$ for the sake of presentation.

on San José island approximately $25km$ northeast of the Aransas Pass. The two synthesized versions we consider are based on the same Generalized Asymmetric Holland Model as Harvey, however, the track of the storm is shifted. As noted in [4], the storm surge from Harvey was a result of both onshore winds from the coast, as well as significant winds parallel to the coastline near Corpus Christi where a surge was generated behind the barrier islands. Hence, we are led to consider two different synthesized hurricane tracks: first, a case in which the eye of the storm passes over the city of Port Aransas, and second, a case where the eye is shifted in a southwestern direction such that the maximum onshore winds pass through the Aransas Pass. In Figure 4, the two shifted hurricane tracks are shown in the study area as the black solid lines.

3 Results

Here, we present results for the maximum storm surge elevation near Corpus Christi Bay. Furthermore, we also present hydrographs in this area to compare the surge magnitude and timing at existing gauge locations. We first consider Hurricane Harvey's original track and subsequently the synthesized versions described in Section 2 and shown as the black lines in Figure 4. The gauges we consider are from the National Oceanic and Atmospheric Administration (NOAA) and their detailed information can be found online at *https://tidesandcurrents.noaa.gov*. In particular, we use the gauges "Aransas Wildlife Refuge" (ID 8774230), "Port Aransas" (ID 8775237), and "USS Lexington" (ID 8775296). In addition, we also compare hydrographs for synthetic gauges in Aransas Pass as shown in Figure 5.



(a) Shifted track 1

(b) Shifted track 2

Figure 4: Synthetic hurricane tracks over the bathymetry (in meter) in the study area.

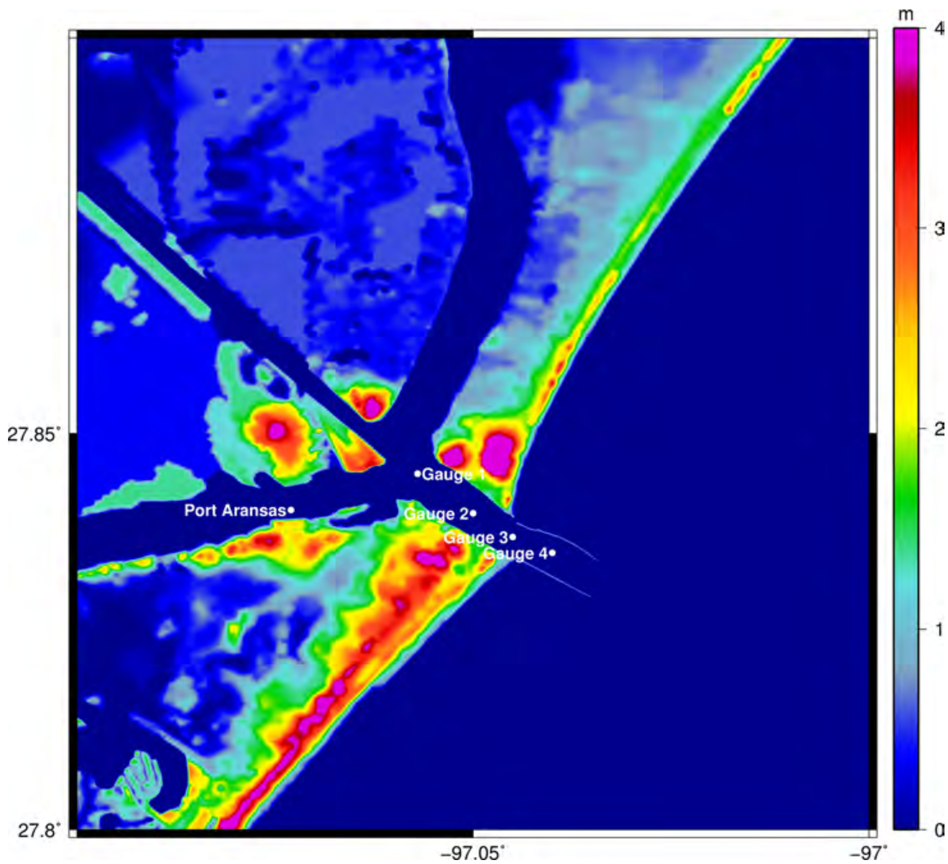


Figure 5: NOAA gauge Port Aransas and synthetic elevation gauges in Aransas Pass.

3.1 Hurricane Harvey

Hurricane Harvey's original track was such that it created a significant amount of surge near Port Aransas and in the bays behind the Aransas Pass. The alongshore winds lead to surges of more than two meters in Port Aransas whereas the onshore winds lead to approximately a two meter surge in the pass itself. This is shown in Figure 6, the maximum storm surge based on the best track Hurricane Harvey hindcast data and the current channel depth. In Figure 7, the maximum storm surge based on the best track Hurricane Harvey hindcast data and the proposed channel depth. Visual inspection and comparison of the surge in

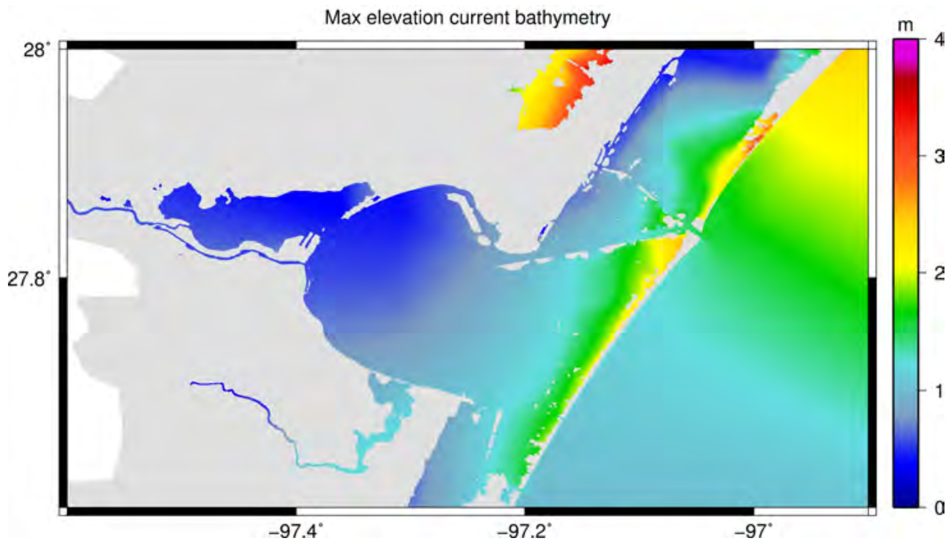


Figure 6: Maximum storm surge (in meters) in the region of interest.

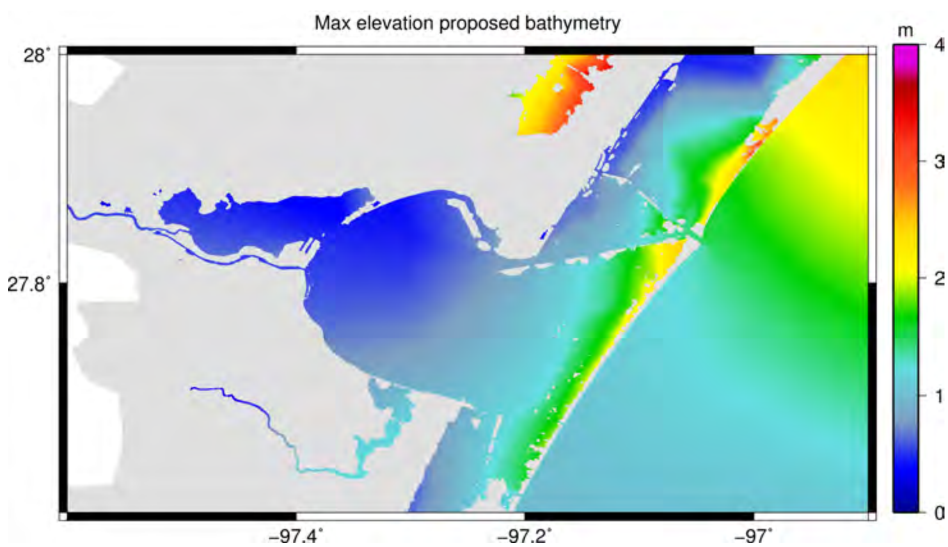


Figure 7: Maximum storm surge (in meters) in the region of interest.

Figures 6 and 7 is not straightforward due to the magnitude of the surge in both cases. Thus, we also present figures where the difference between the maximum surge of the current versus the proposed channel depths are shown, i.e., negative numbers indicate an increased surge with the proposed channel. In Figure 8 this difference is shown for the region and in Figure 9, the difference near Port Aransas. From these results, it is indicated that the deeper channel does not significantly change the storm surge magnitude. In fact the model results suggest that the maximum surge near Port Aransas and Corpus Christi will decrease slightly. The regions where the maximum surge is increased is located north of the Aransas Pass. The strong alongshore winds of Hurricane Harvey is the likely source of this effect as these winds generate a surge that propagates in the bays behind the barrier islands. The deeper channel may accommodate a large amount of water due to its increased cross section, some of which appear to propagate to the north fork in the Aransas Pass, the Lydia Ann Channel.

Next, we present the hydrographs at the locations introduced above. In the Aransas Pass, we present only gauges 1 and 4 as the two other are similar. In Figures 10 through 19, these hydrographs are presented. The common trend in all these is that the maximum surge is reduced in all locations with the

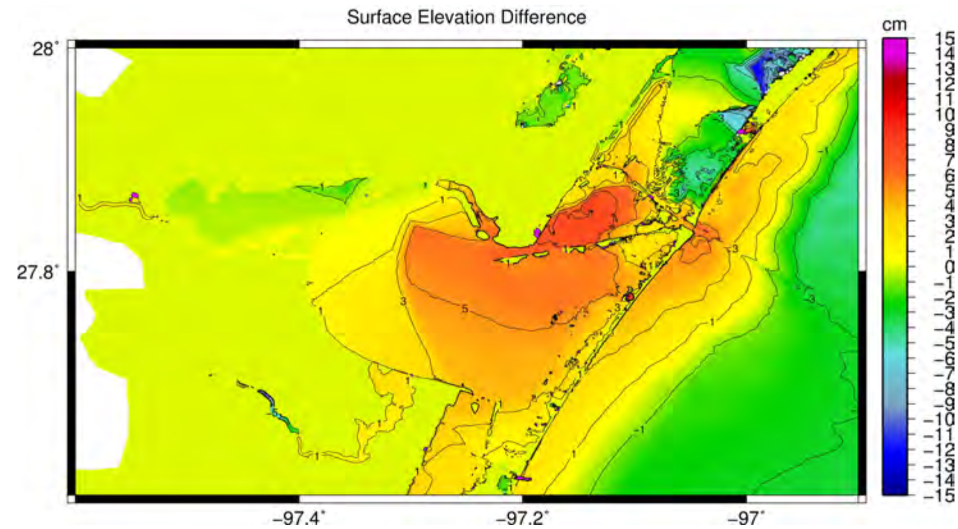


Figure 8: Maximum storm surge difference (in centimeters) in the region of interest.

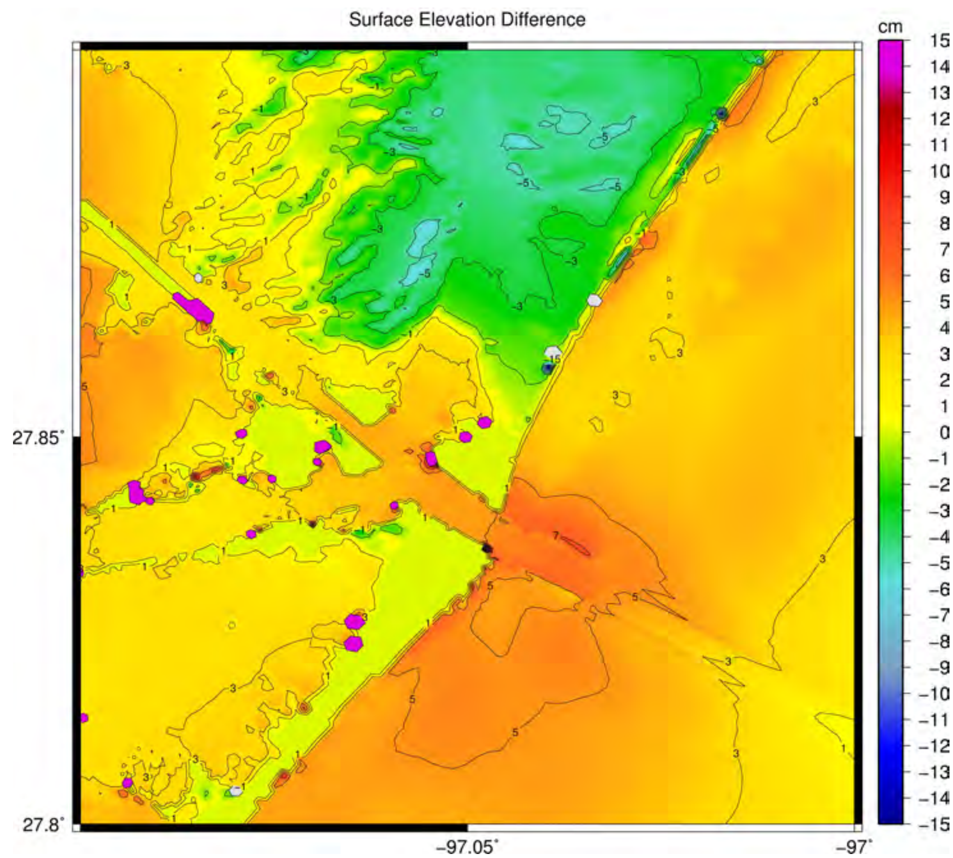


Figure 9: Maximum storm surge difference (in centimeters) in the Aransas Pass.

exception being Aransas Wildlife Refuge, which experiences a modest surge increase. As seen from the visual results, the surge is increased in the region north of Aransas Pass. This is likely due to the alongshore winds from Hurricane Harvey. The difference plots shown in these figures indicate that the deeper channel leads to increased water levels in some locations as the surge recedes back into the Gulf of Mexico, see, e.g.,

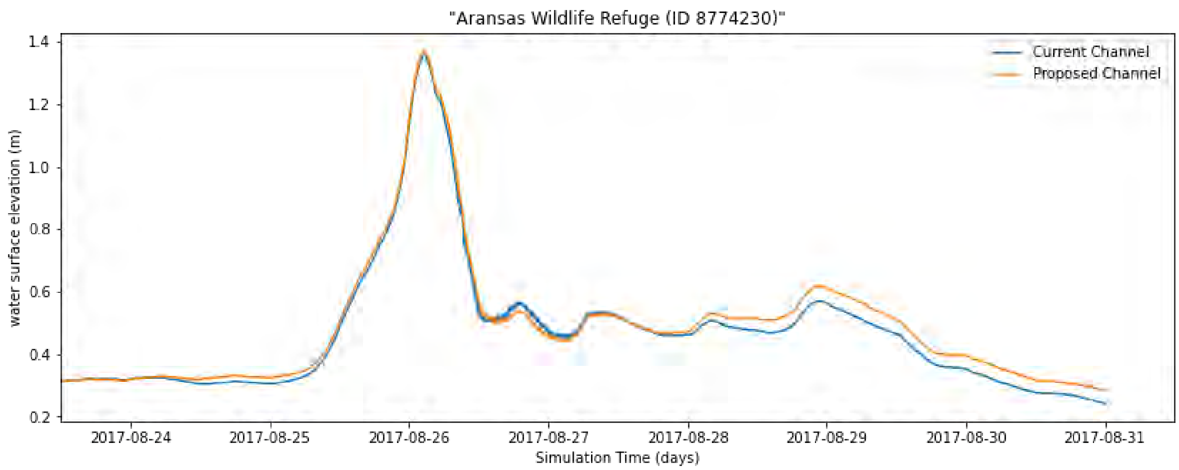


Figure 10: Hydrograph (in meters) at Aransas Wildlife Refuge.

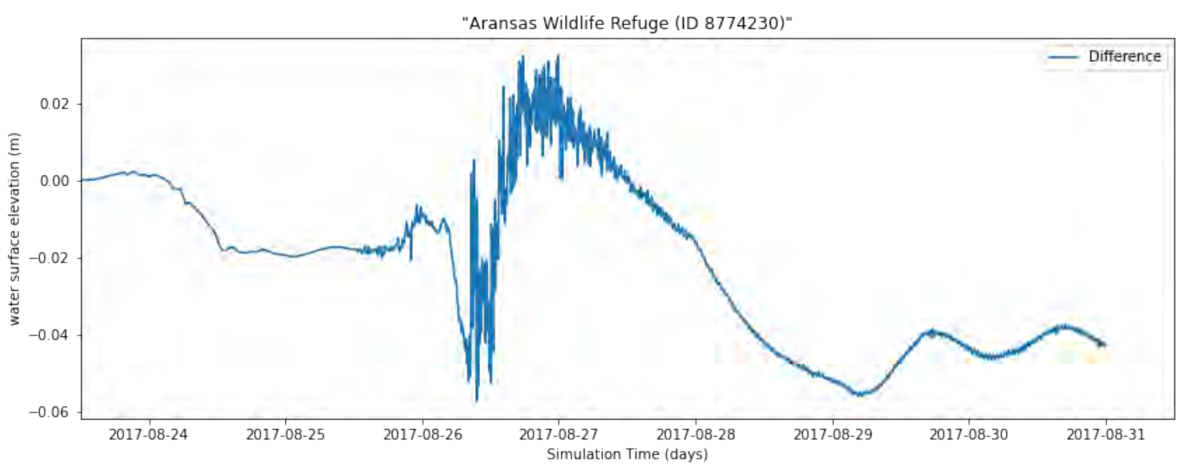


Figure 11: Hydrograph difference (in meters) at Aransas Wildlife Refuge.

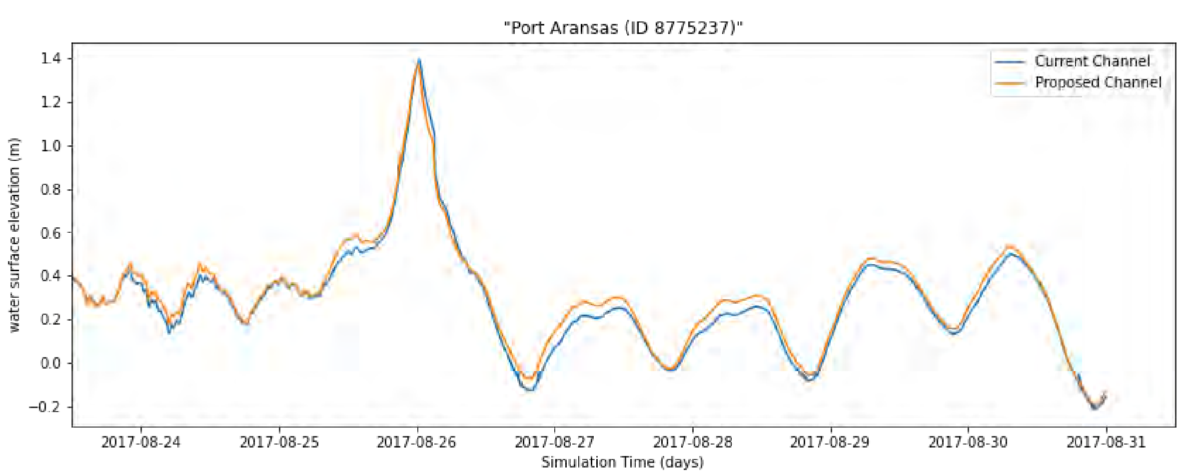


Figure 12: Hydrograph (in meters) at Port Aransas.

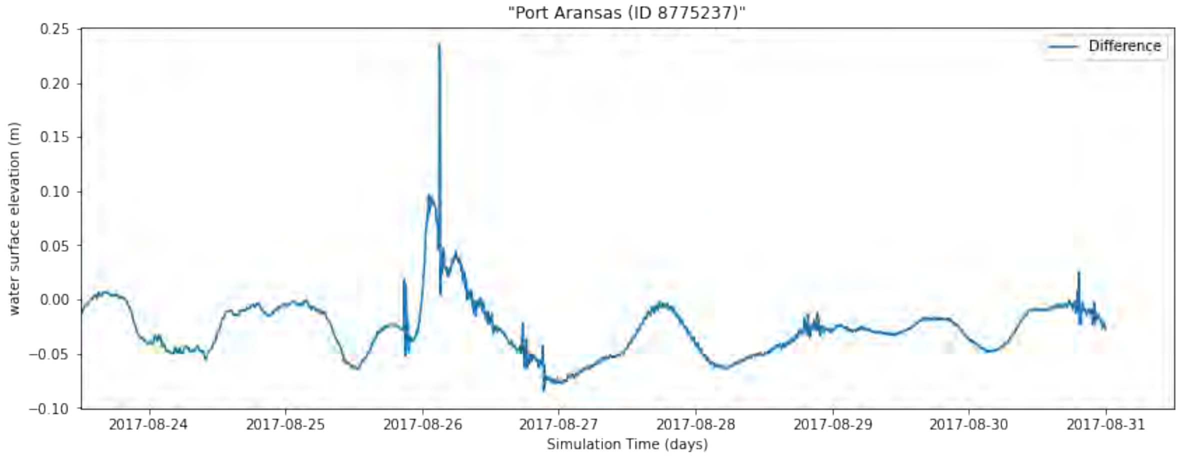


Figure 13: Hydrograph difference (in meters) at Port Aransas.

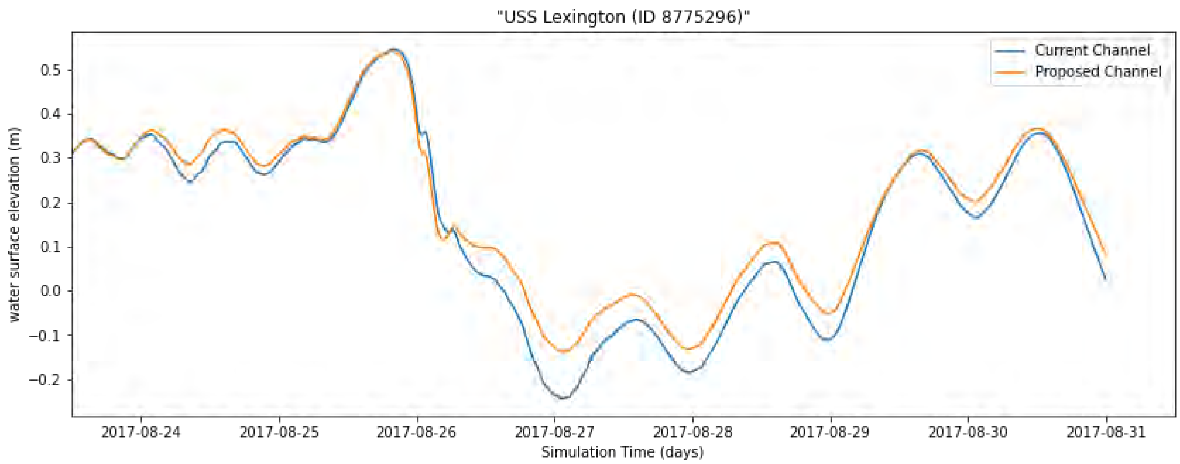


Figure 14: Hydrograph (in meters) at USS Lexington.

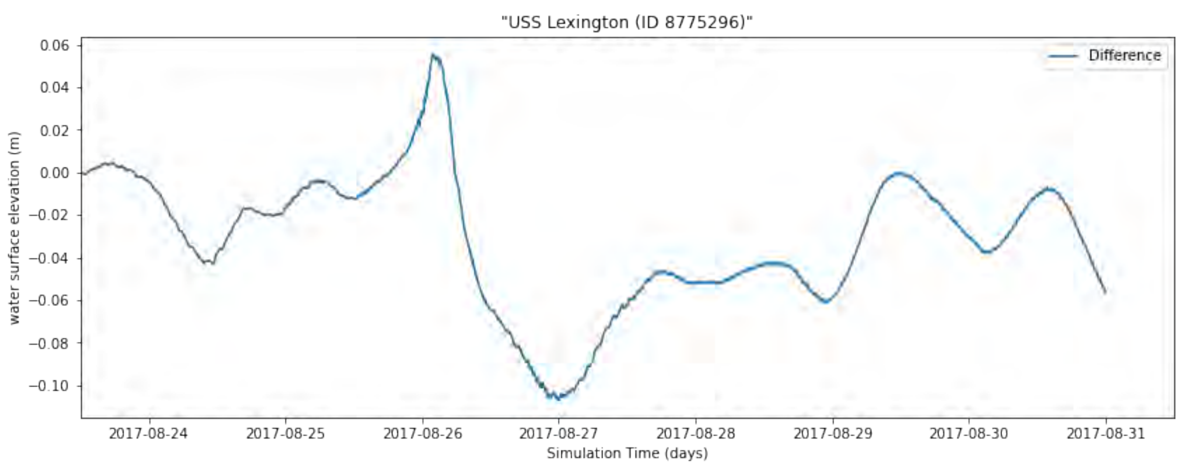


Figure 15: Hydrograph difference (in meters) at USS Lexington.

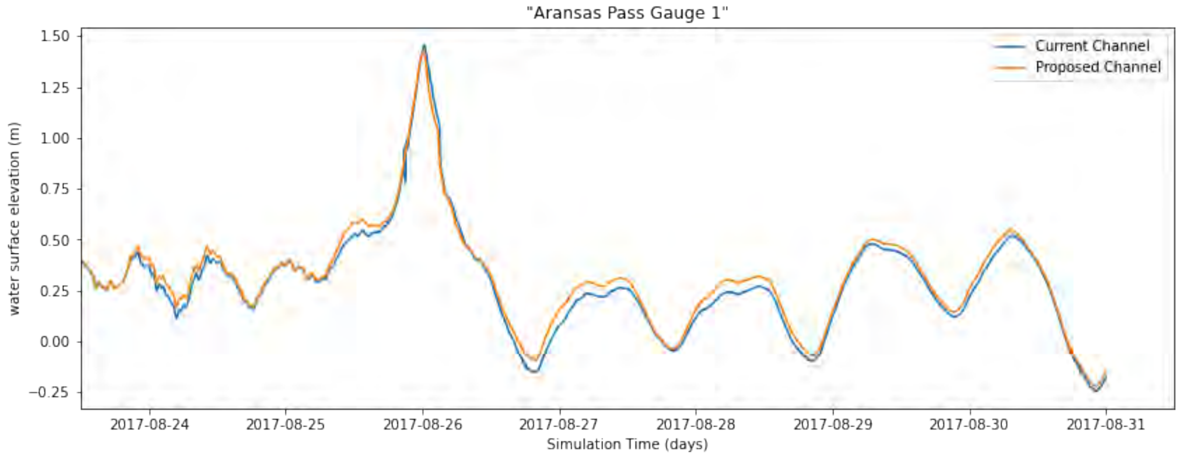


Figure 16: Hydrograph (in meters) at gauge 1.

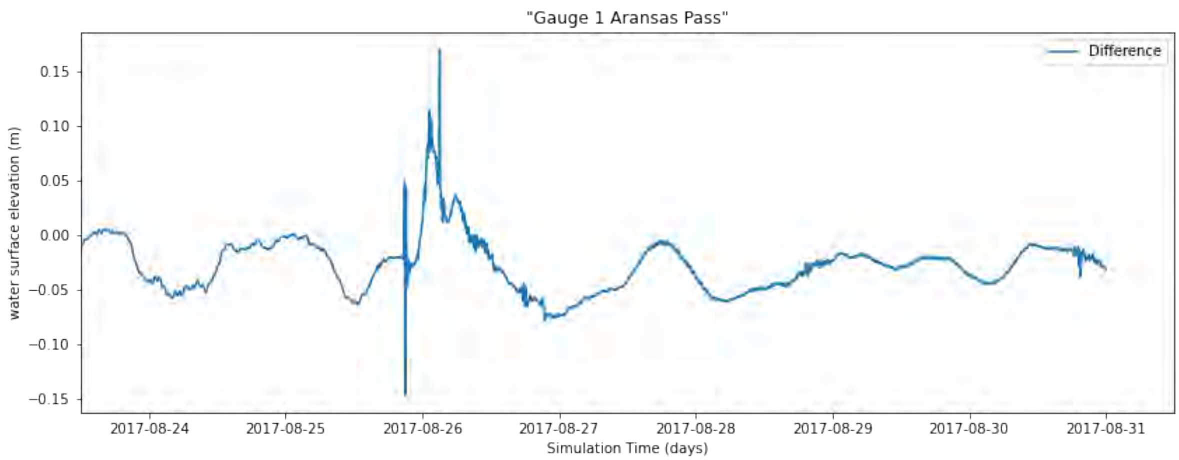


Figure 17: Hydrograph difference (in meters) at gauge 1.

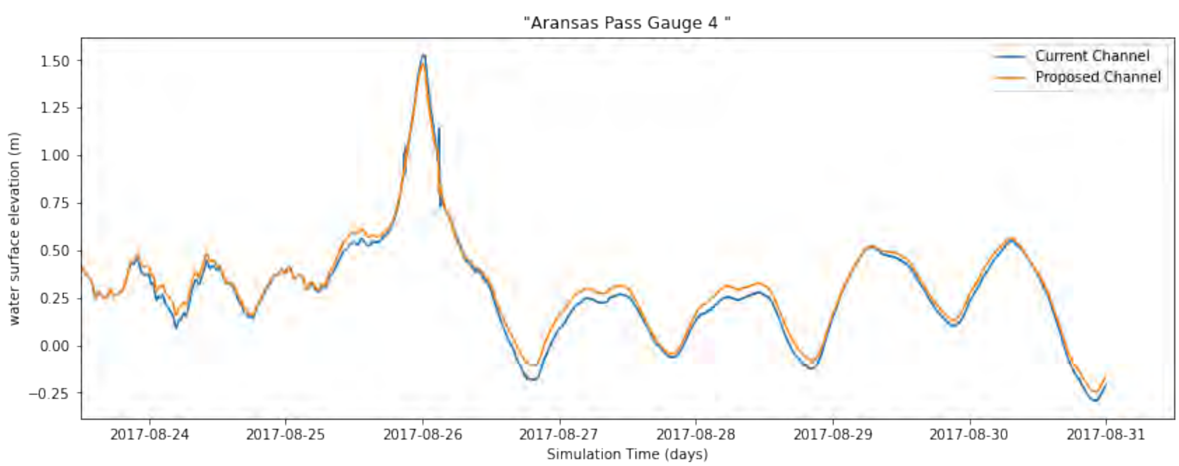


Figure 18: Hydrograph (in meters) at gauge 4.

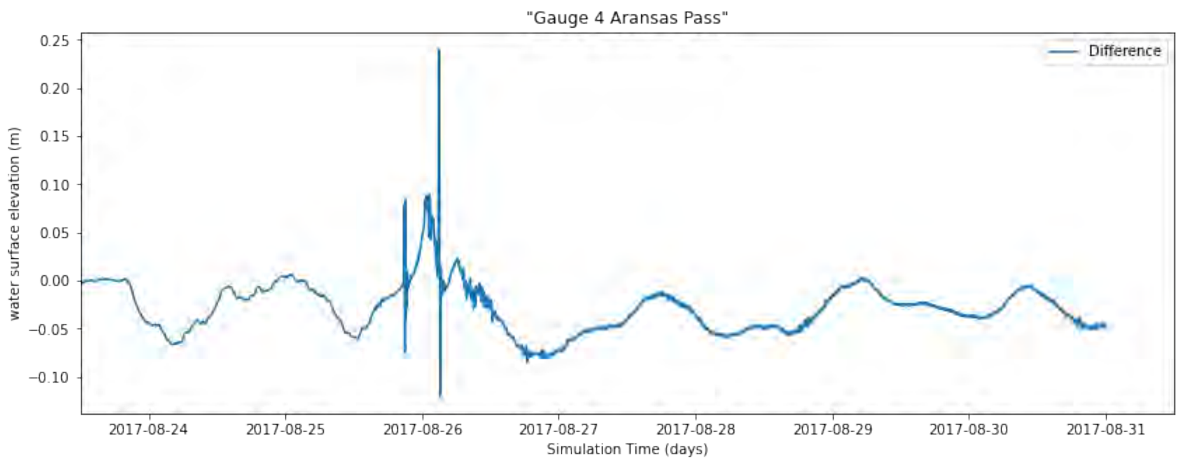


Figure 19: Hydrograph difference (in meters) at gauge 4.

Figures 19 and 15.

3.2 Synthetic Hurricane Harvey - Version One

To assess potential effects of different storm tracks, we now consider the case shown in Figure 4(a), a synthetic version of Hurricane Harvey. In particular, we consider a case where the eye of the hurricane passes over Port Aransas. In this case, both the alongshore and onshore winds lead to significant surges in the region, in some locations more than 3 meters. This is shown in Figures 20 and 21, where the track of this synthetic hurricane is also shown. As intuitively expected, this track leads to significantly larger surge in this region. Visual inspection and comparison of the surge in Figures 20 and 21 reveals more

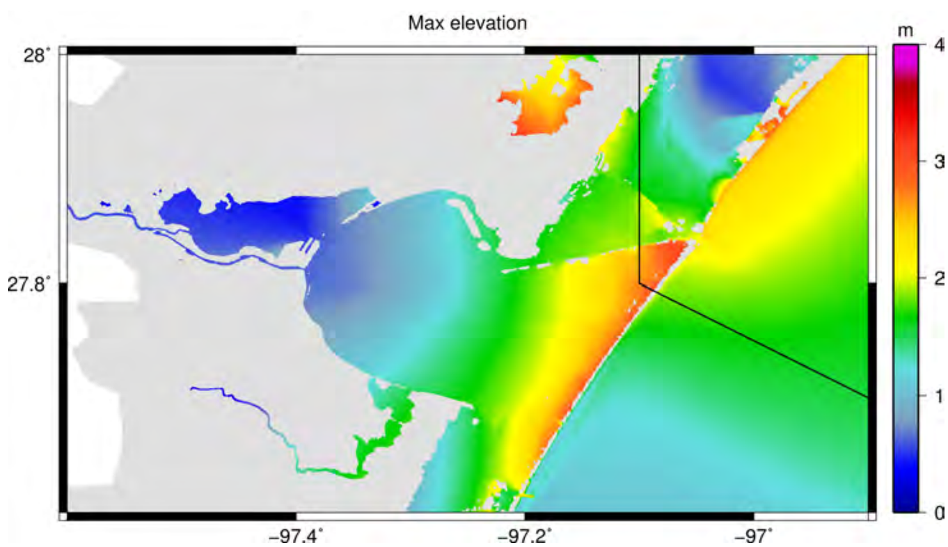


Figure 20: Maximum storm surge (in meters) in the region of interest for the current channel depth.

changes than the previously considered case. In particular, the maximum surge propagating through Corpus Christi Bay is noticeably reduced with the proposed channel depth. For clarity, we also present figures where the difference between the maximum surge of the current versus the proposed channel depths are shown. Figure 22 shows this difference for the region and Figure 23 shows the difference near Port Aransas. These results differ significantly from the original Harvey track as the surge in the region is much larges

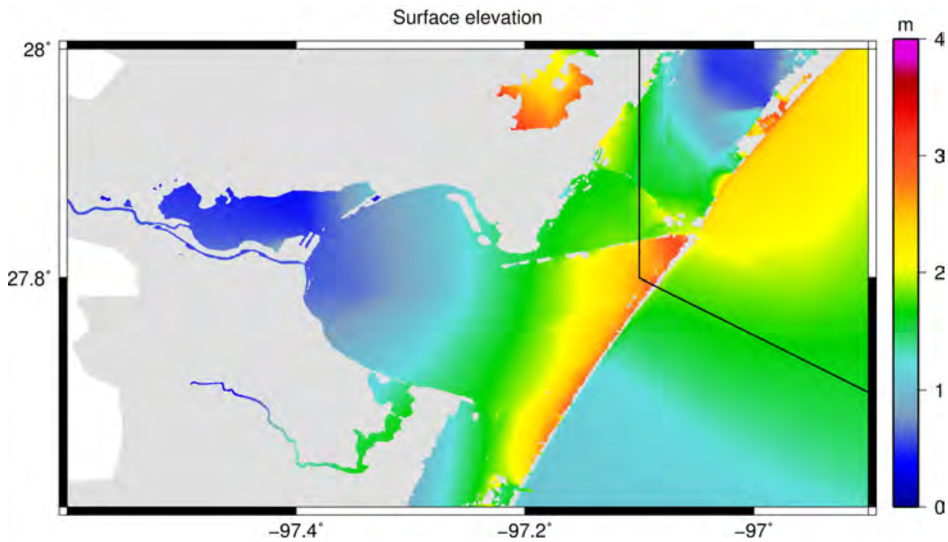


Figure 21: Maximum storm surge (in meters) in the region of interest for the proposed channel depth.

and therefore more impacted by bathymetry changes. However, the trend observed previously is the same, i.e., the model suggest that the maximum surge near Port Aransas and Corpus Christi will decrease and regions where the maximum surge is increased are located north of the Aransas Pass. This observed increase is slightly different than for the original Harvey track: the magnitude of the increase is smaller and the far northeastern area shown in Figure 22 now exhibit a decreased maximum surge.

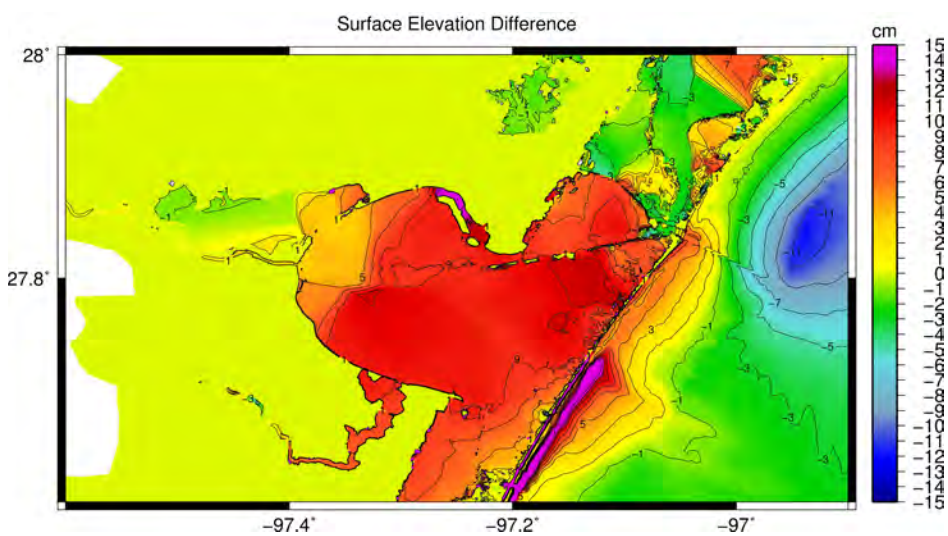


Figure 22: Maximum storm surge difference (in centimeters) in the region of interest.

Next, we present the hydrographs at the locations introduced above. In the Aransas Pass, we present only gauges 1 and 4 as the other two are similar. In Figures 24 through 33, these hydrographs are presented. Here, we observe that the storm surge does not significantly change at its peak on August 26^{th}. At the Aransas Wildlife Refuge gauge in Figures 24 and 25, the maximum storm surge is increased and occurs at a slightly later time for the proposed channel. In Port Aransas, the results in Figures 26 and 27, indicate little difference in the maximum surge. However, we observe a large difference in the receding phase of the surge. At the USS Lexington in Corpus Christi, the deeper channel leads to a slightly reduced surge as shown in Figures 28 and 29. The synthetic gauges in Aransas Pass exhibit minor changes in the maximum

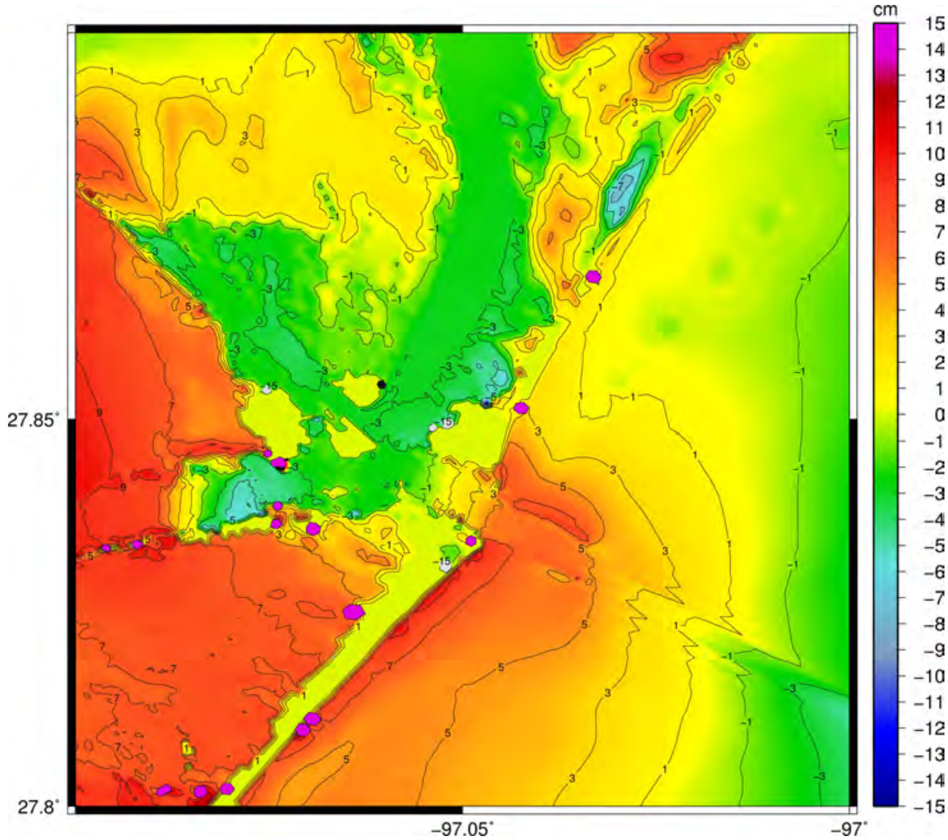


Figure 23: Maximum storm surge difference (in centimeters) in the Aransas Pass.

surge magnitude as seen in Figures 30 through 33

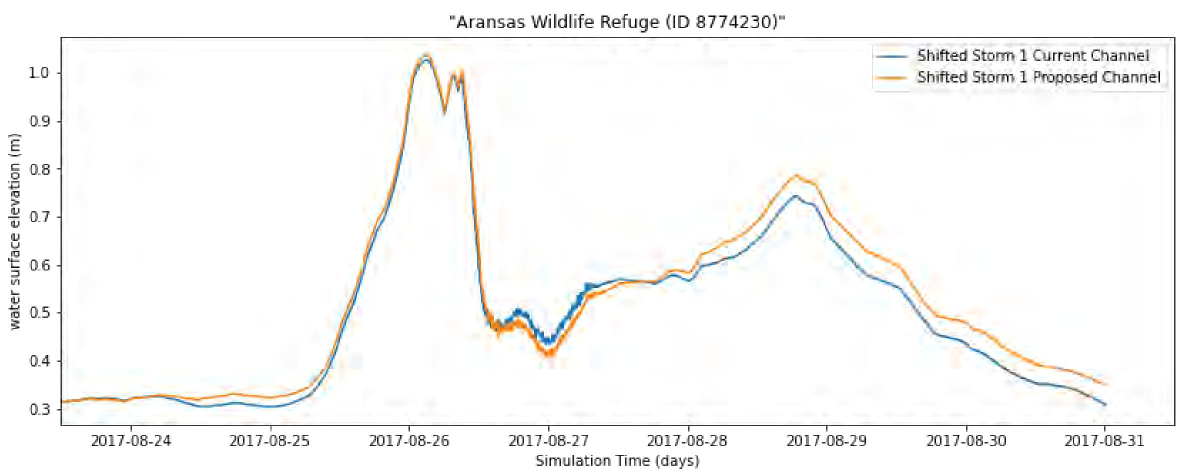


Figure 24: Hydrograph (in meters) at Aransas Wildlife Refuge.

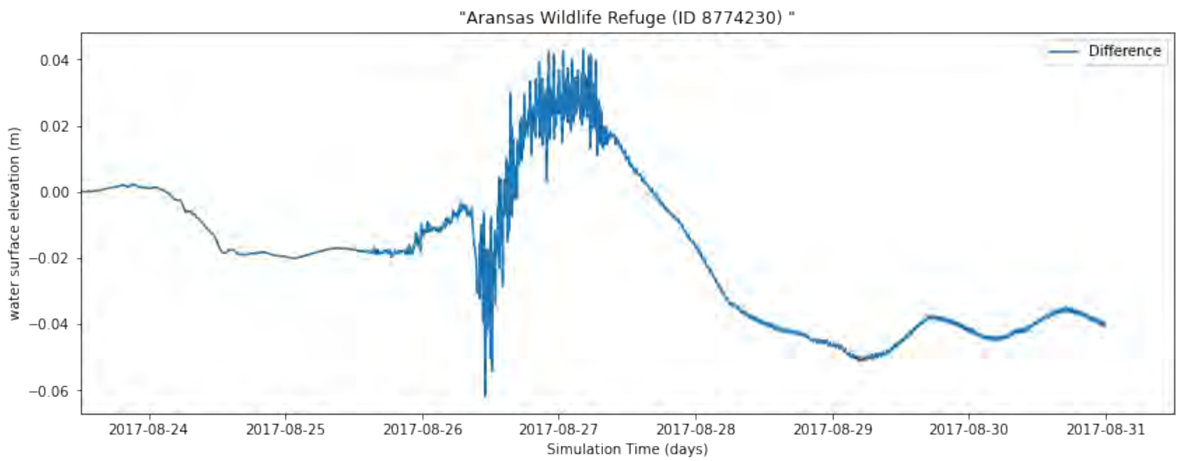


Figure 25: Hydrograph difference (in meters) at Aransas Wildlife Refuge.

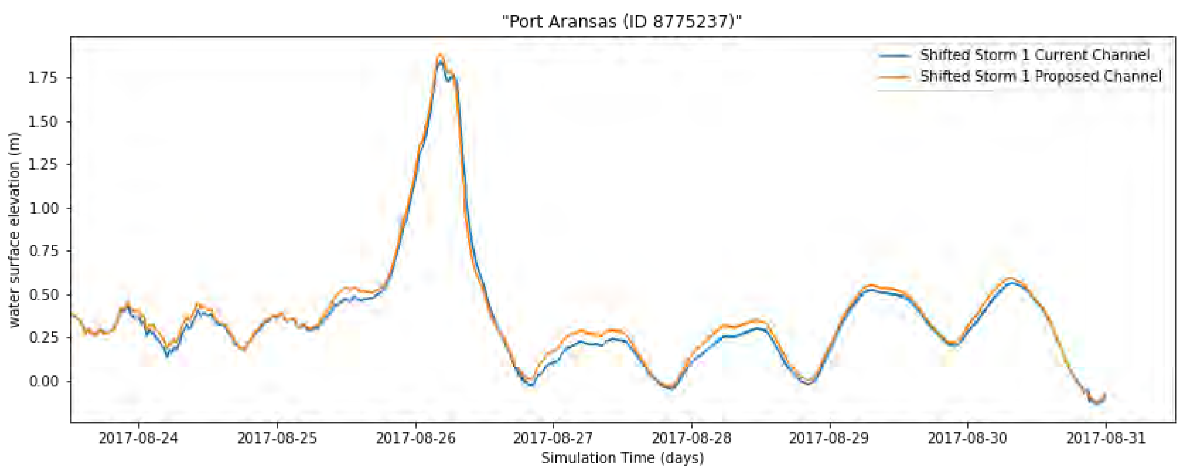


Figure 26: Hydrograph (in meters) at Port Aransas.

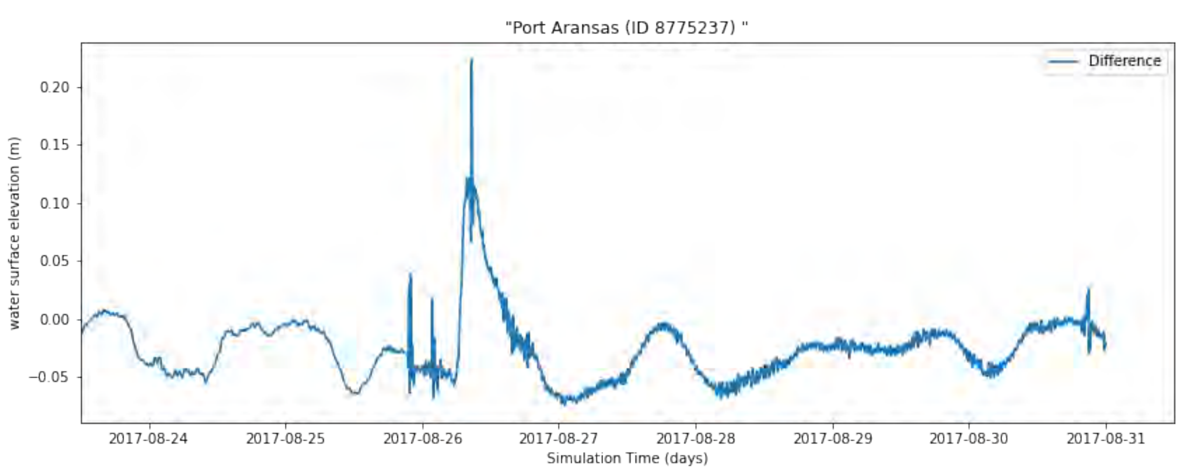


Figure 27: Hydrograph difference (in meters) at Port Aransas.

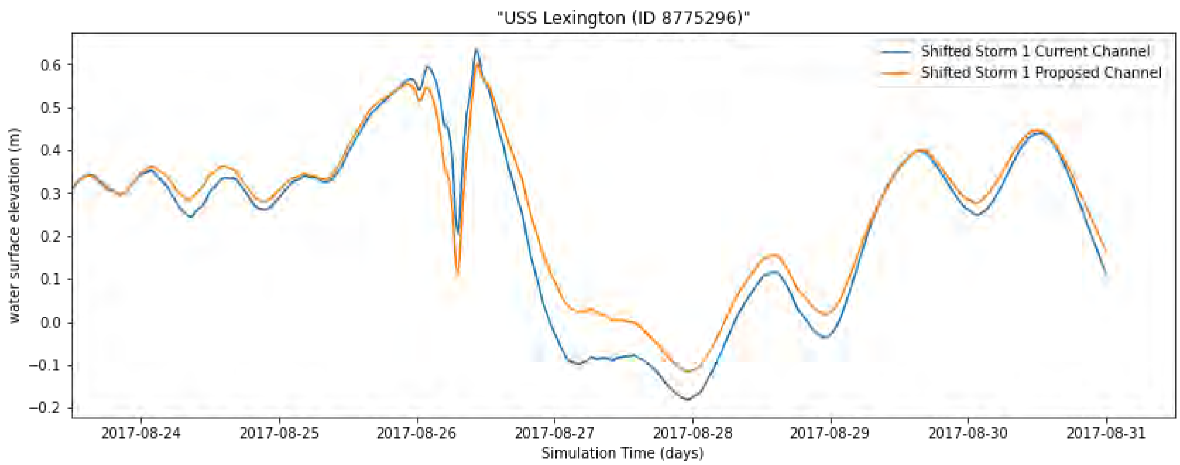


Figure 28: Hydrograph (in meters) at USS Lexington.

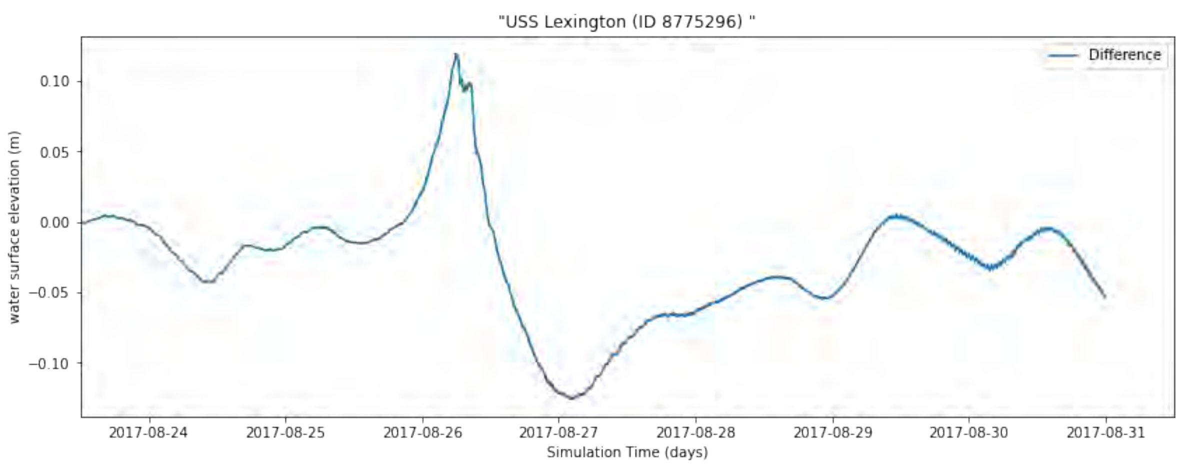


Figure 29: Hydrograph difference (in meters) at USS Lexington.

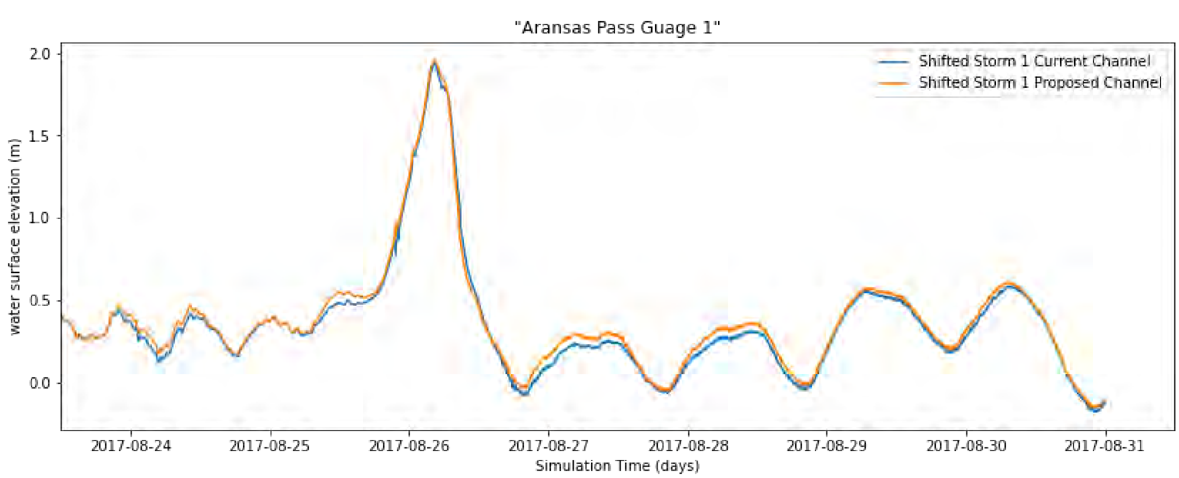


Figure 30: Hydrograph (in meters) at gauge 1.

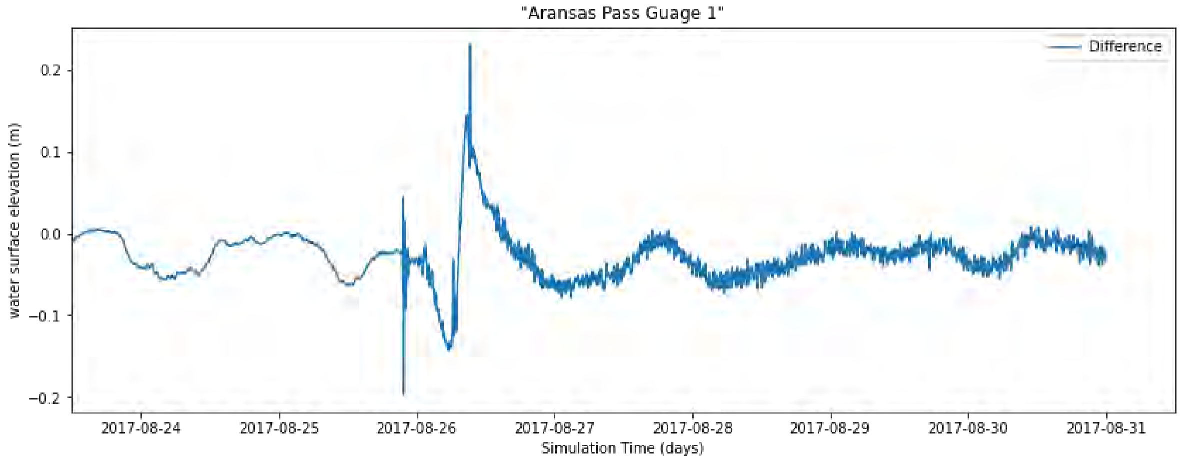


Figure 31: Hydrograph difference (in meters) at gauge 1.

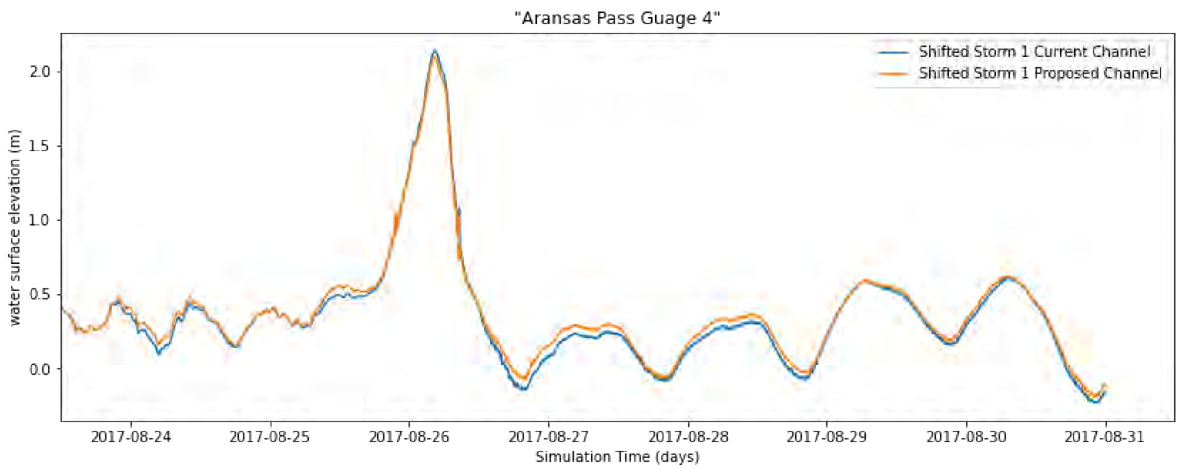


Figure 32: Hydrograph (in meters) at gauge 4.

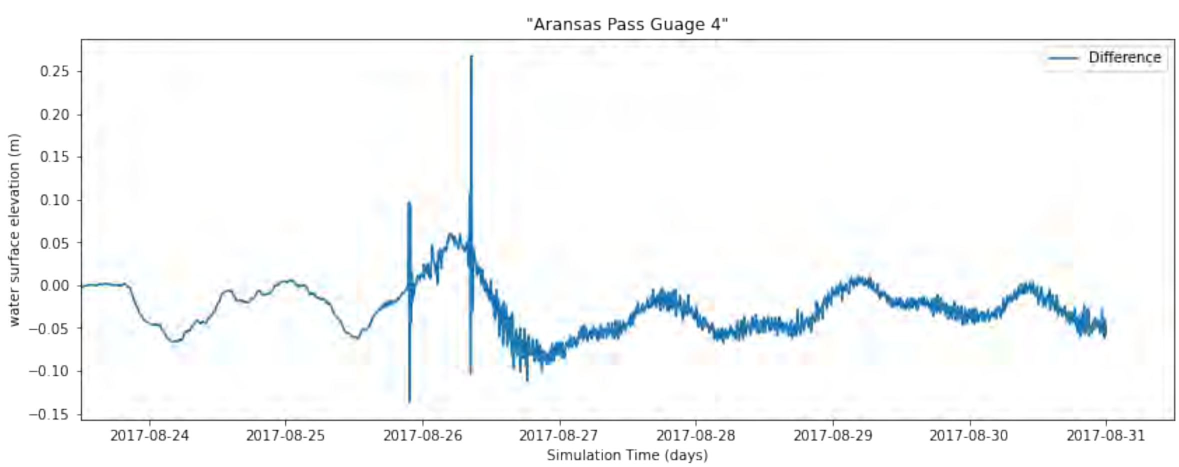


Figure 33: Hydrograph difference (in meters) at gauge 4.

3.3 Synthetic Hurricane Harvey - Version Two

Finally, we consider a synthetic Hurricane Harvey in which maximum onshore winds pass directly through Aransas pass, see Figure 34 for the wind vectors and water surface elevation at landfall. As the storm now

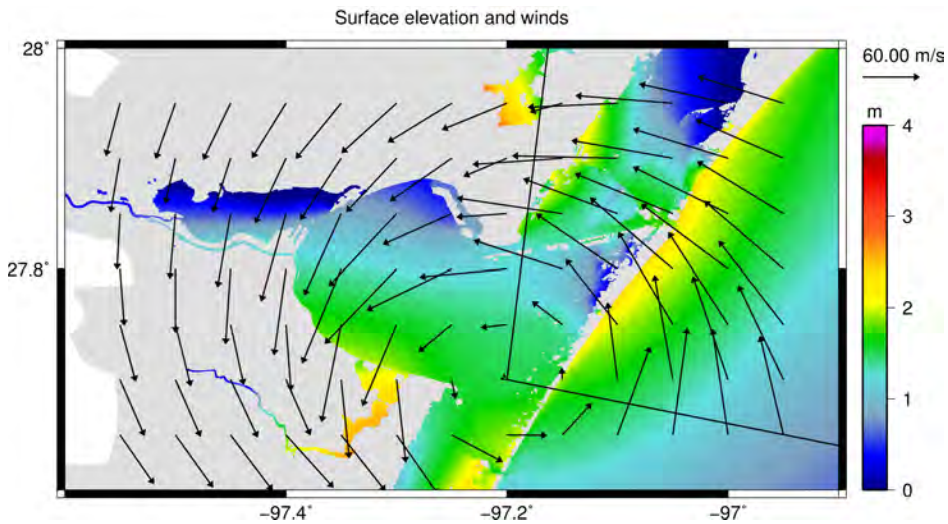


Figure 34: Water surface elevations (in meters) and wind vectors in the region of interest.

makes landfall further south before following a northbound trajectory, the surge in Corpus Christi bay is now significantly greater than the previous two cases. Hence, in this case, the winds lead to significant surges in both Port Aransas and large portions of Corpus Christi bay. This can be seen in Figures 35 and 36, where the track of this synthetic hurricane is also included. Again, this track leads to significantly larger surge in this region than the original Hurricane Harvey considered in Section 3.1. Visual inspection and

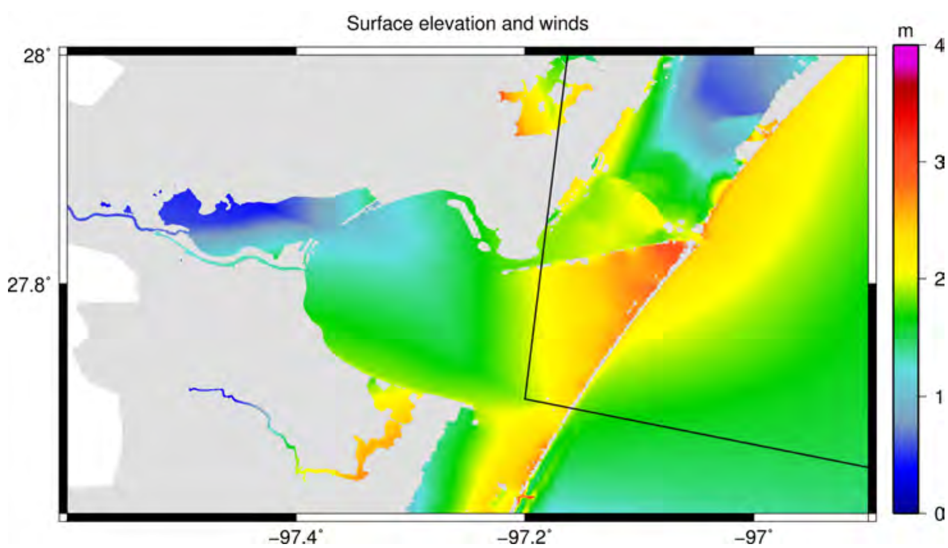


Figure 35: Maximum storm surge (in meters) in the region of interest for the current channel depth.

comparison of the surge in Figures 35 and 36 reveal more changes than the previously considered synthetic case. In particular, the maximum surge propagating through Corpus Christi bay is noticeably reduced with the proposed channel depth. For clarity, we also present figures where the difference between the maximum surge of the current versus the proposed channel depths are shown. Figure 37 shows this difference for the region and Figure 38 shows the difference near Port Aransas. These results differ significantly from the

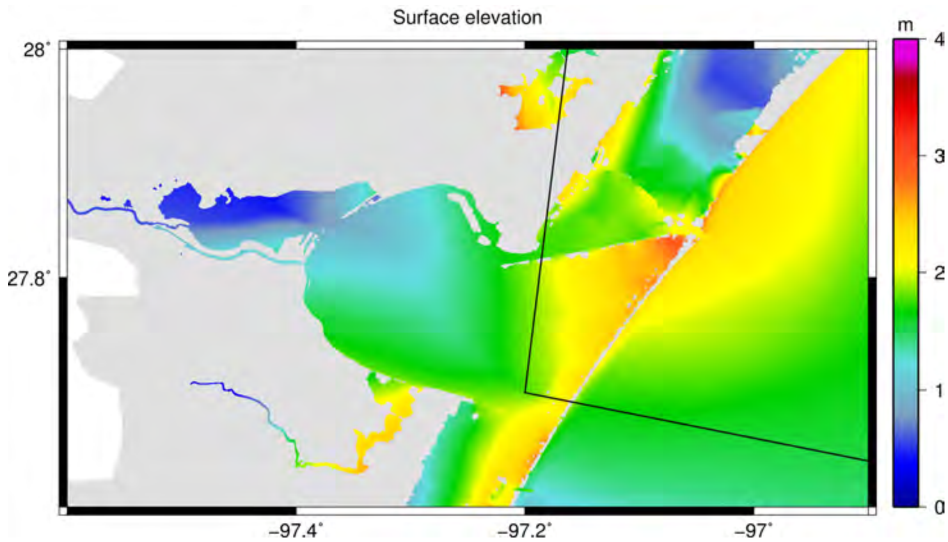


Figure 36: Maximum storm surge (in meters) in the region of interest for the proposed channel depth.

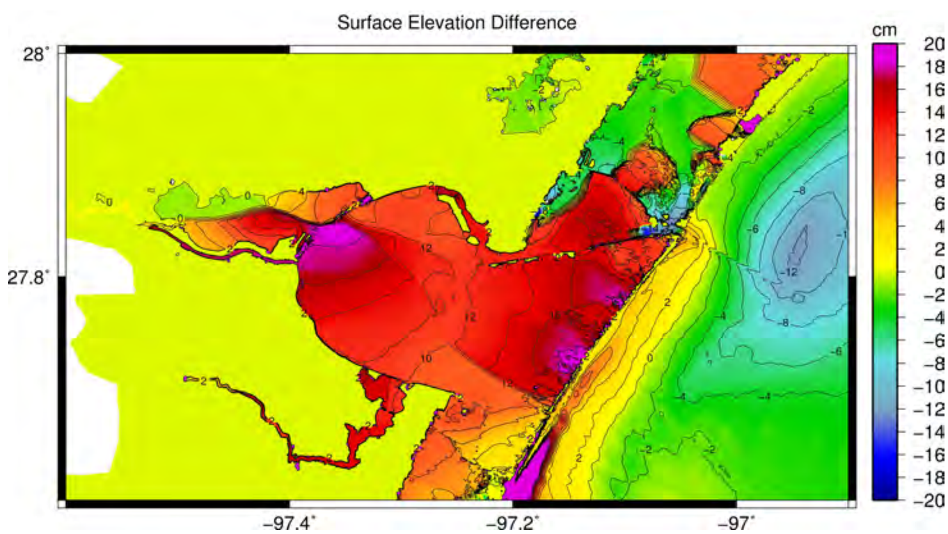


Figure 37: Maximum storm surge difference (in centimeters) in the region of interest.

original Harvey track as the surge in the region is much larger and therefore more impacted by bathymetry changes. However, the trend observed previously is the same, i.e., the model suggests that the maximum surge near Port Aransas and Corpus Christi will decrease and areas where the maximum surge is increased are located near Aransas Pass. This observed increase is however, different than for the original Harvey track: the magnitude of the increase is smaller and the far northeastern area shown in Figure 37 now exhibit a decreased maximum surge in a similar fashion to the first synthetic hurricane.

Next, we present the hydrographs at the locations introduced above. In the Aransas Pass, we present only gauges 1 and 4 as the two other are similar. In Figures 39 through 48, these hydrographs are presented. Here, the observation mirrors the previous case and we observe that there is no clear trend across these hydrographs other than that the storm surge does not significantly change at its peak on August 26^{th}. At the Aransas Wildlife Refuge gauge in Figures 39 and 40, the maximum storm surge is increased for the proposed channel. In Port Aransas, the results in Figures 41 and 42, indicate some difference in the maximum surge, an increase of approximately 15 centimeters. We also observe a large difference in the receding phase of the surge. At the USS Lexington in Corpus Christi, the deeper channel leads to a reduced surge as shown

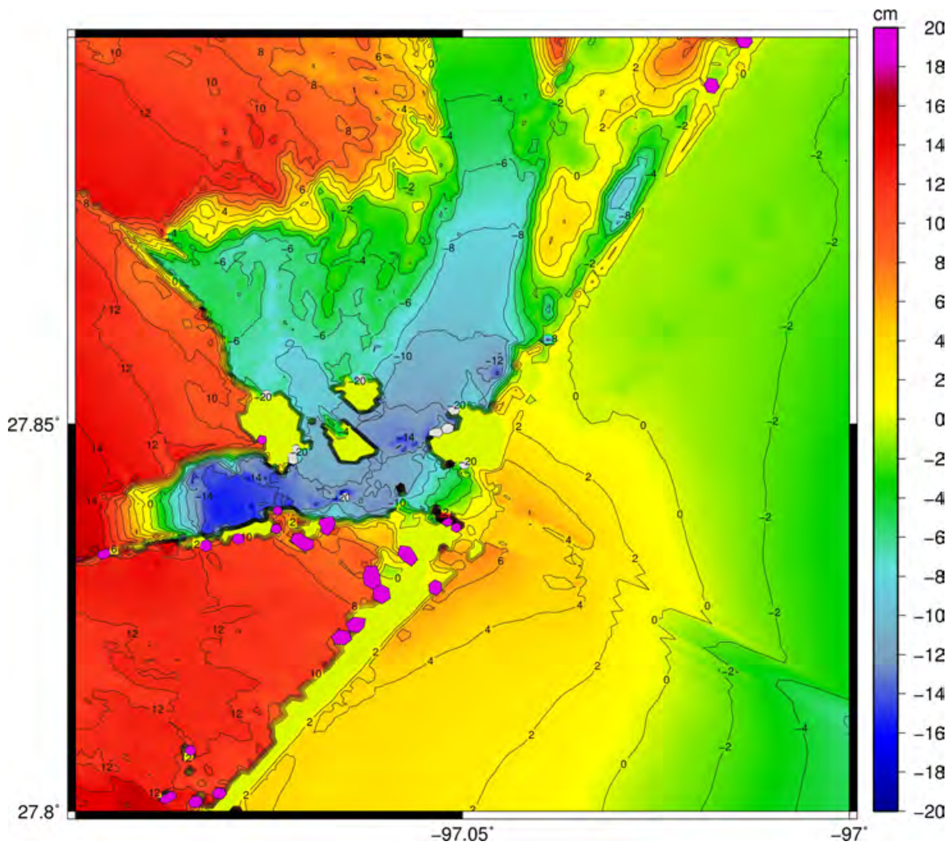


Figure 38: Maximum storm surge difference (in centimeters) in the Aransas Pass.

in Figures 43 and 44. The synthetic gauge 1 in Aransas Pass sees an increase in surge, whereas gauge 4 exhibits the converse as seen in Figures 45 through 48. This effect is also observed in Figure 38, where the portions of the pass near the ocean exhibits a reduction in maximum surge and the inland portions of the pass sees the converse.

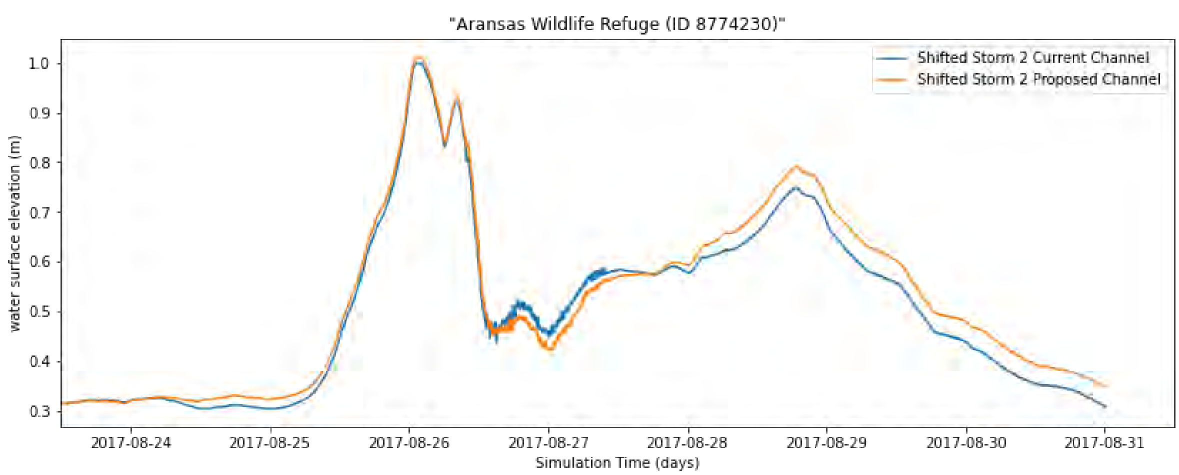


Figure 39: Hydrograph (in meters) at Aransas Wildlife Refuge.

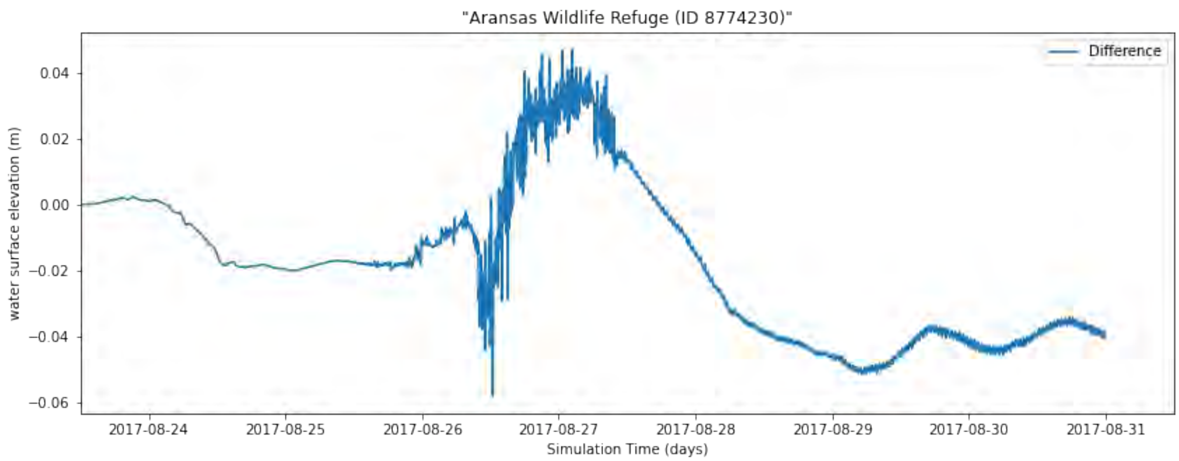


Figure 40: Hydrograph difference (in meters) at Aransas Wildlife Refuge.

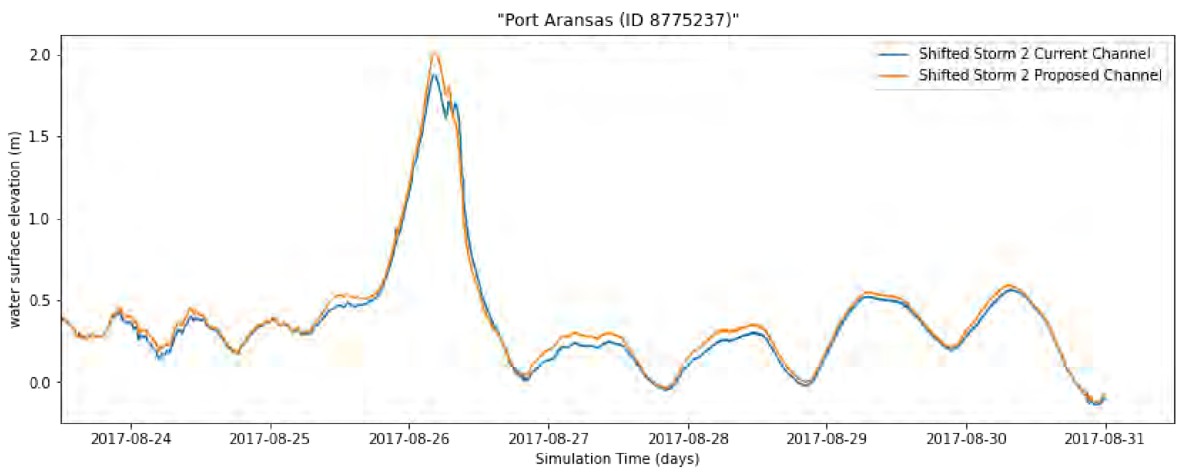


Figure 41: Hydrograph (in meters) at Port Aransas.

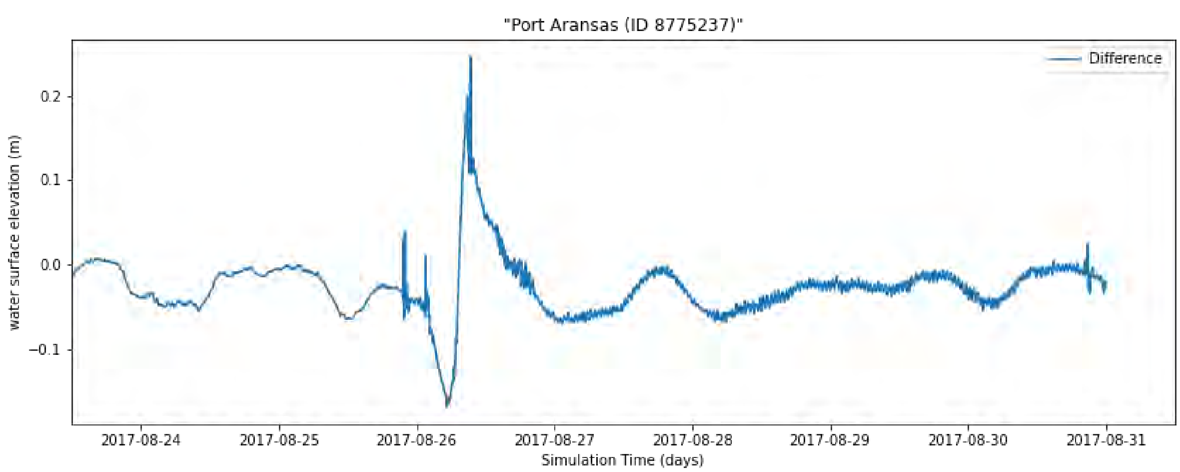


Figure 42: Hydrograph difference (in meters) at Port Aransas.

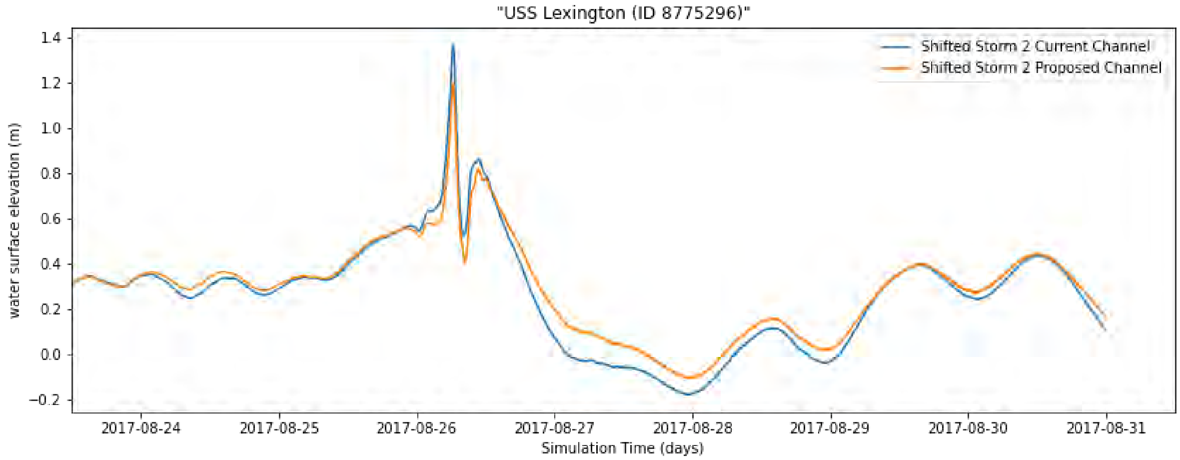


Figure 43: Hydrograph (in meters) at USS Lexington.

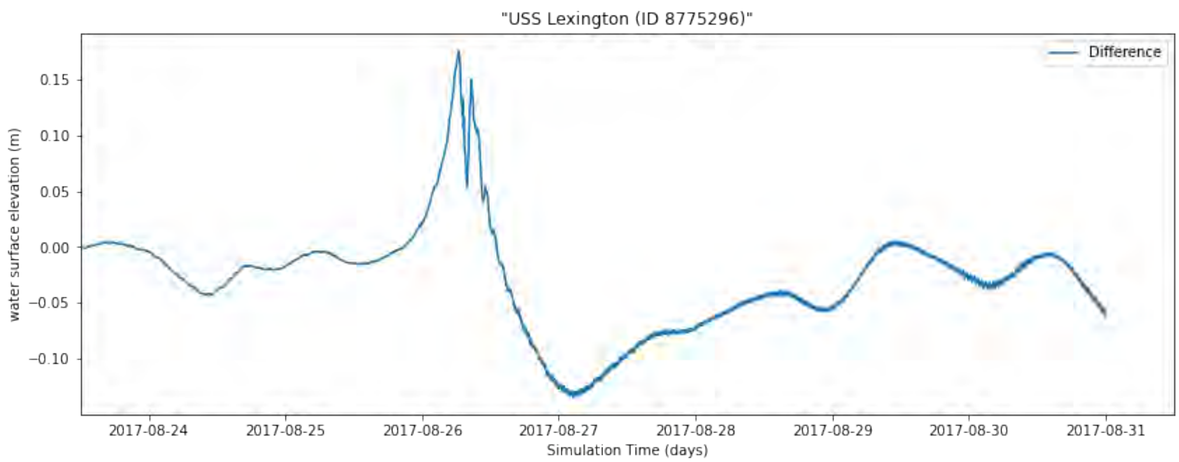


Figure 44: Hydrograph difference (in meters) at USS Lexington.

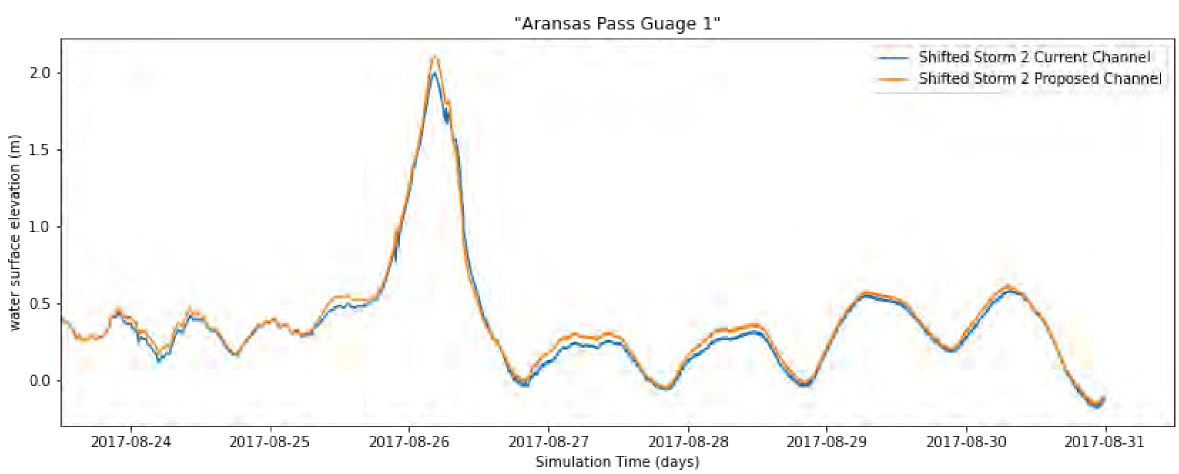


Figure 45: Hydrograph (in meters) at gauge 1.

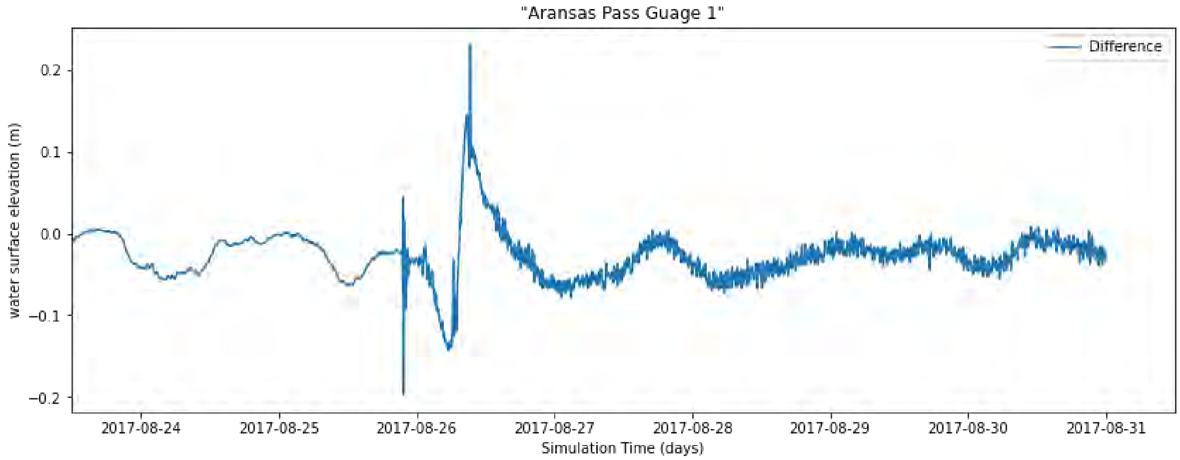


Figure 46: Hydrograph difference (in meters) at gauge 1.

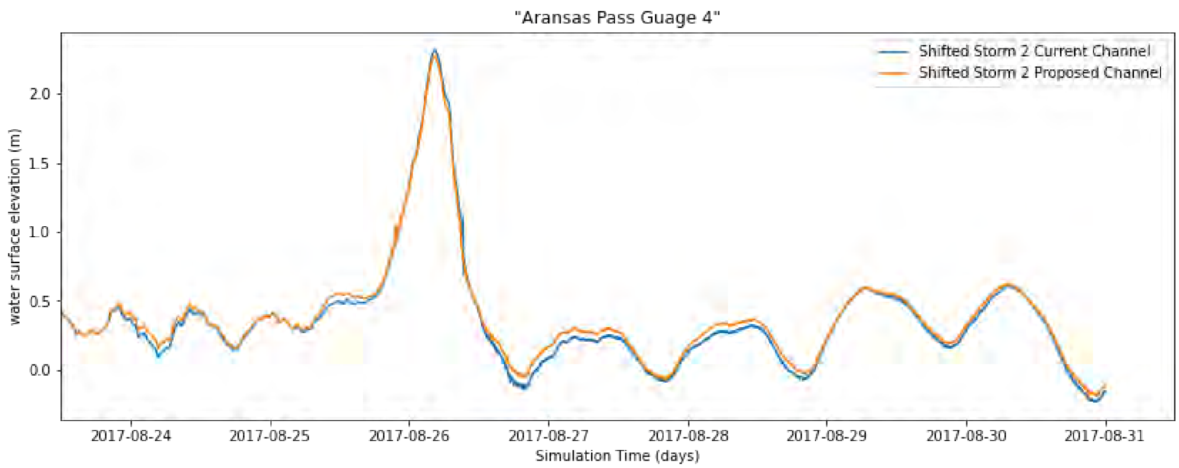


Figure 47: Hydrograph (in meters) at gauge 4.

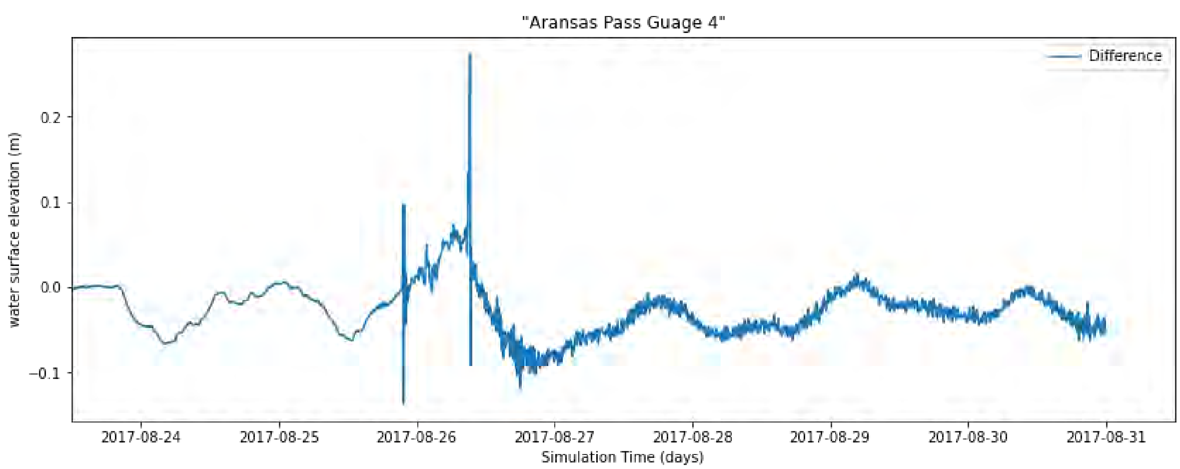


Figure 48: Hydrograph difference (in meters) at gauge 4.

4 Concluding Remarks

In this project, we have developed mathematical models governing coastal circulation and storm surge in the region of the Corpus Christi ship Channel. The models consider storm surge in this region due to Hurricane Harvey as well as synthesised hurricanes based on the wind an pressure fields of Hurricane Harvey. To this end, the study focuses on a time period of eight days in 2017 when Hurricane Harvey originally made landfall. To assess the magnitude and extent of the resulting storm surge, we consider the maximum surge magnitude ascertained from the ADCIRC model as well as surge time series in locations near Aransas Pass. The models consider the current bathymetry of the Corpus Christi Ship Channel an the proposed bathymetry of a dredged ship channel.

The results from the models (see, in particular Figures 8, 9, 22, 23, 37, 38) suggest that large portions of the region near the ship channel will experience smaller maximum surges from the considered hurricanes. However, as seen in these figures, some locations will see an increased maximum surge. In particular, a 15 centimeter increase in maximum surge can be seen in the darkest blue area in Figure 38. Finally, we note that while these models are of high resolution and has been validated extensively in previous studies, the dredging process may also impact storm surge in other ways, e.g., due to morphodynamic effects which are not part of the present study.

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