FSAR 2.4.5, “Probable Maximum Surge and Seiche Flooding”

NRC Audit
South Texas Project
August 31, 2010

James R. (Bob) Bailey, Ph.D., P.E.

NRC Audit Plan: Item 1

- Provide a detailed description of the ADCIRC model including details of the Holland B model (or SWAN model) to generate hurricane wind distributions at the offshore.
- Provide a comparison of the wind models used in ADCIRC and SLOSH models.
- Provide a comparison of wind stresses produced by ADCIRC and SLOSH.

ADCIRC Model - Description

A 2D/3D hydrodynamic model (configured for this project in 2D) that simulates water level and current over an unstructured gridded domain. It is used to model:

- Tidal, wind, and wave driven circulation in coastal waters,
- Forecasts of hurricane storm surge and flooding,
- Transport and morphology of inlet sediments, and
- Disposal of dredging materials.

ADCIRC Wind Model

An asymmetric model based on Holland (1980):

$$p(r) = p_o + \Delta p \times \exp-\left(\frac{RMW}{r}\right)^B$$

Where: $p(r)$ = surface pressure a distance r from the storm center

p_o = central pressure

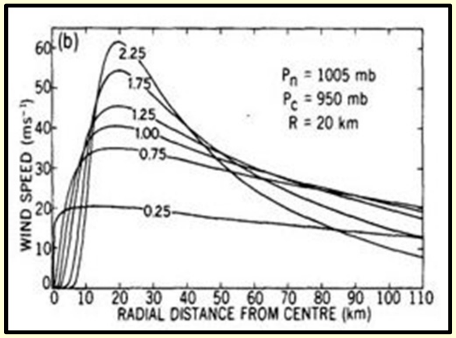
p_b = peripheral or background pressure

Δp = difference between central and background pressures

RMW = radius to maximum winds

r = distance from the storm center

B = pressure profile parameter (calculated)



ADCIRC Wind Model

The gradient wind V_G is a function of [$p(r)$, ρ, f] and V_G is a maximum value at *RMW*, hence:

$$V_{G\max} = \sqrt{\frac{B \times \Delta p}{e \times \rho}}$$

Where: V_G = gradient wind
B = pressure profile parameter
Δp = difference between central and background pressures
e = base of natural logarithms
ρ = density of air
f = Coriolis parameter

ADCIRC Wind Model

The maximum gradient wind V_{Gmax} is calculated using the maximum hurricane wind speed, $V_{max@10m}$:

$$V_{Gmax} = c \times V_{max@10m}$$

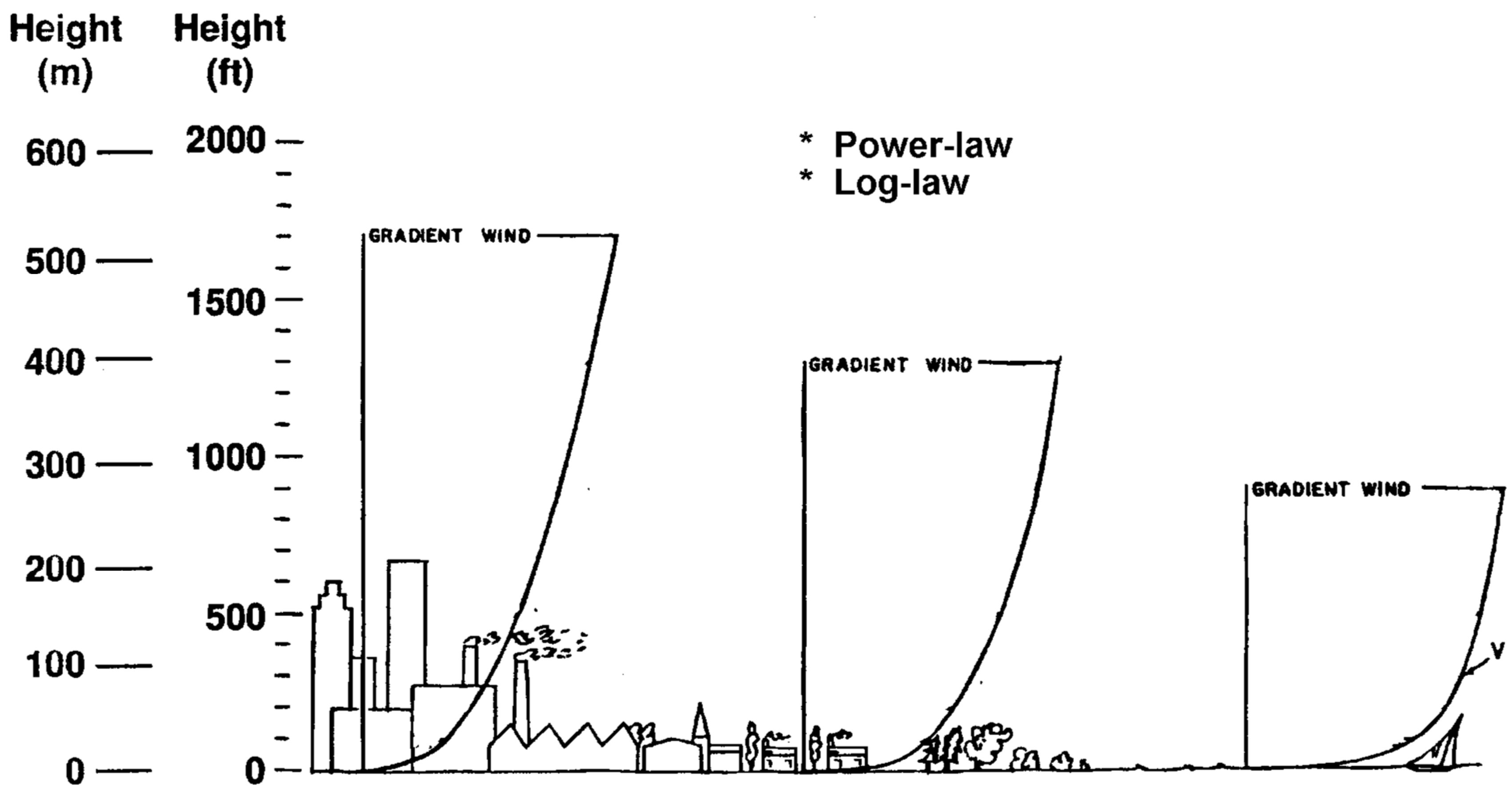
Where: V_{Gmax} = maximum gradient wind

c = surface profile constant

…enabling calculation of the Pressure Profile Parameter B:

$$B = \left[(V_{Gmax})^2 \times e \times \rho\right] / \Delta p$$

ADCIRC Wind Model

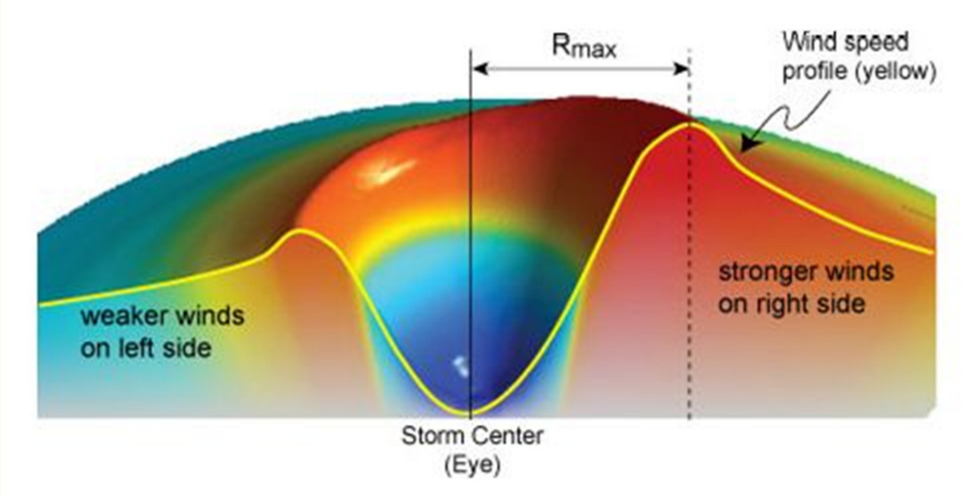


- * Power-law
- * Log-law

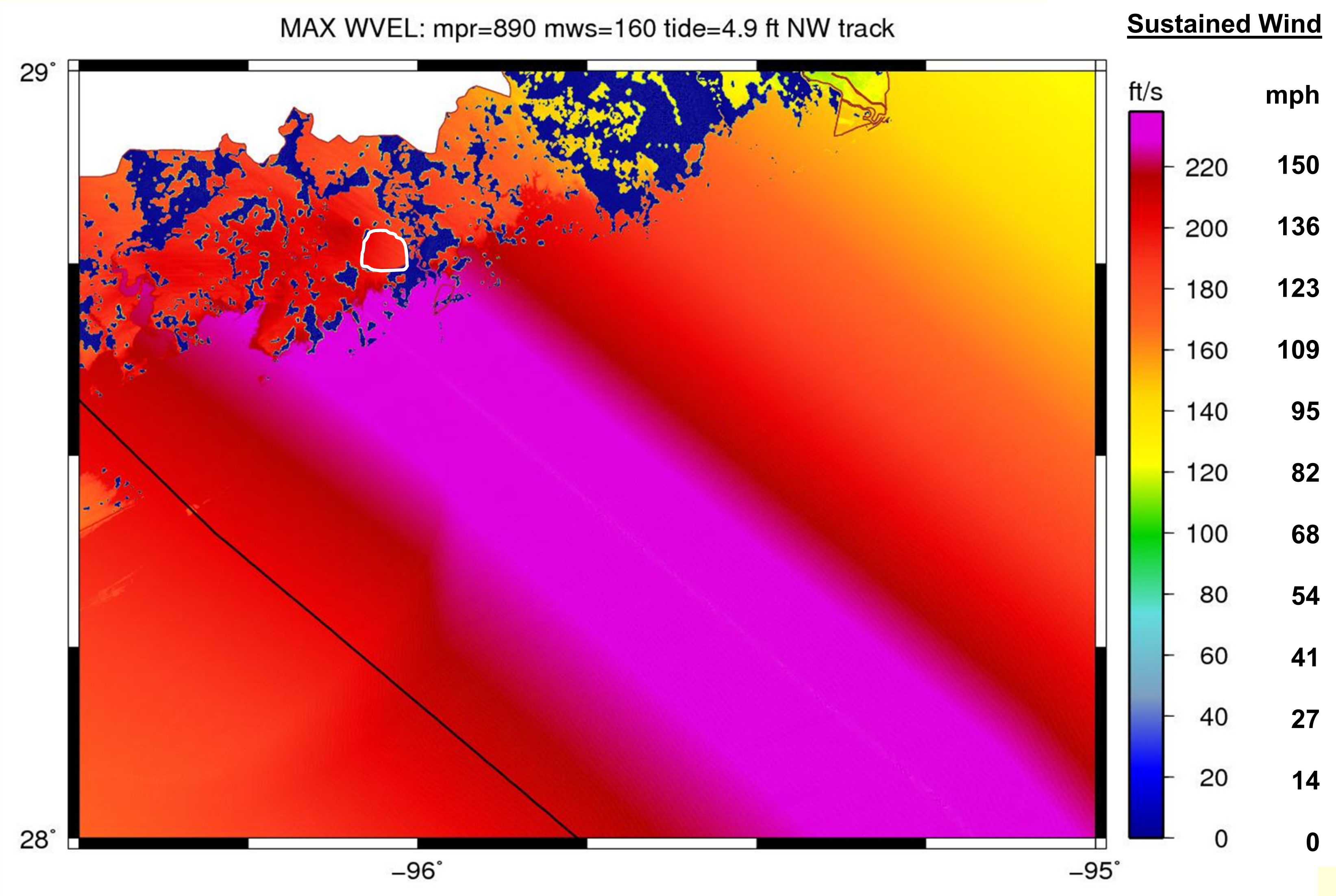
ADCIRC Wind Model

The wind field is adjusted to account for asymmetry associated with the forward movement, V_t, of the storm based on Mattocks et al (2006):

$$B = \frac{\left(c \times (V_{max@10m} - V_t)\right)^2 \times e \times \rho}{\Delta p}$$



ADCIRC Results - Wind



SLOSH Model - Description

- Designed as an operational tool for Emergency Managers.
- Computes storm surge heights from tropical cyclones using pressure, size, forward speed, and track data to create a model of the wind field.
- Consists of a set of equations derived from the Newtonian equations of motion (shallow water equations) and the continuity equation applied to a rotating fluid with a free surface.

SLOSH Wind Model

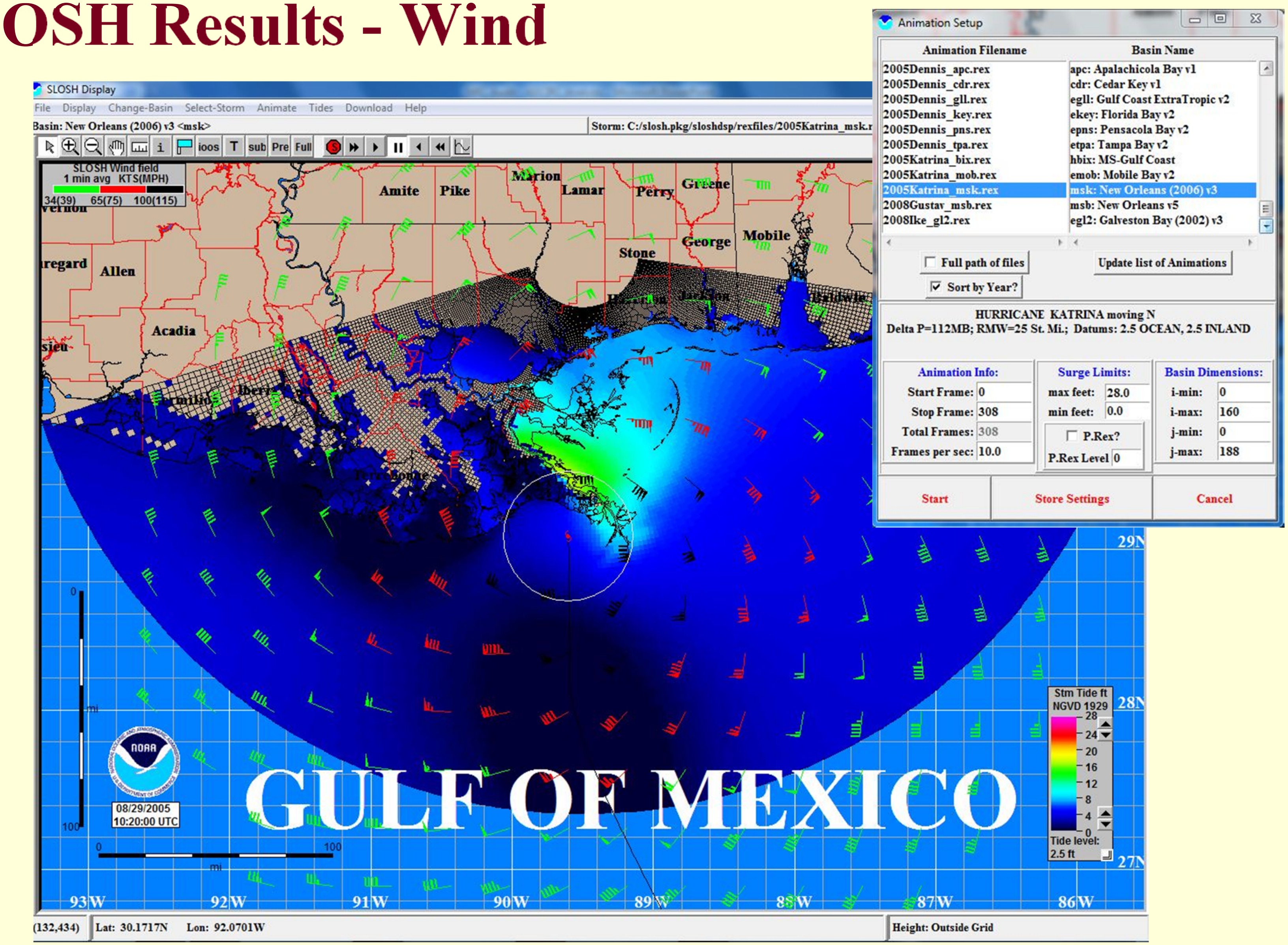
A circularly-symmetric profile based on Jelesnianski and Taylor (1973):

$$V(r) = V_R \times \left(\frac{2 \times R \times r}{R^2 \times r^2} \right)$$

Where: $V(r)$ = wind speed a distance *r* from the storm center
V_R = maximum hurricane wind speed
R = radius to maximum winds
r = distance from the storm center

However, V_R is not a direct input, but is approximated based on an iterative process using Δp.

SLOSH Results - Wind



Basin: New Orleans (2006) v3 <msk>

Storm: C:/slosh.pkg/sloshdsp/rexfiles/2005Katrina_msk.r

(132,434) Lat: 30.1717N Lon: 92.0701W

Height: Outside Grid

Animation Filename	Basin Name
2005Dennis_apc.rex	apc: Apalachicola Bay v1
2005Dennis_cdr.rex	cdr: Cedar Key v1
2005Dennis_gll.rex	egll: Gulf Coast ExtraTropic v2
2005Dennis_key.rex	ekey: Florida Bay v2
2005Dennis_pns.rex	epns: Pensacola Bay v2
2005Dennis_tpa.rex	etpa: Tampa Bay v2
2005Katrina_bix.rex	hbix: MS-Gulf Coast
2005Katrina_mob.rex	emob: Mobile Bay v2
2005Katrina_msk.rex	msk: New Orleans (2006) v3
2008Gustav_msb.rex	msb: New Orleans v5
2008Ike_gl2.rex	egl2: Galveston Bay (2002) v3

☐ Full path of files

Update list of Animations

☑ Sort by Year?

HURRICANE KATRINA moving N
Delta P=112MB; RMW=25 St. Mi.; Datums: 2.5 OCEAN, 2.5 INLAND

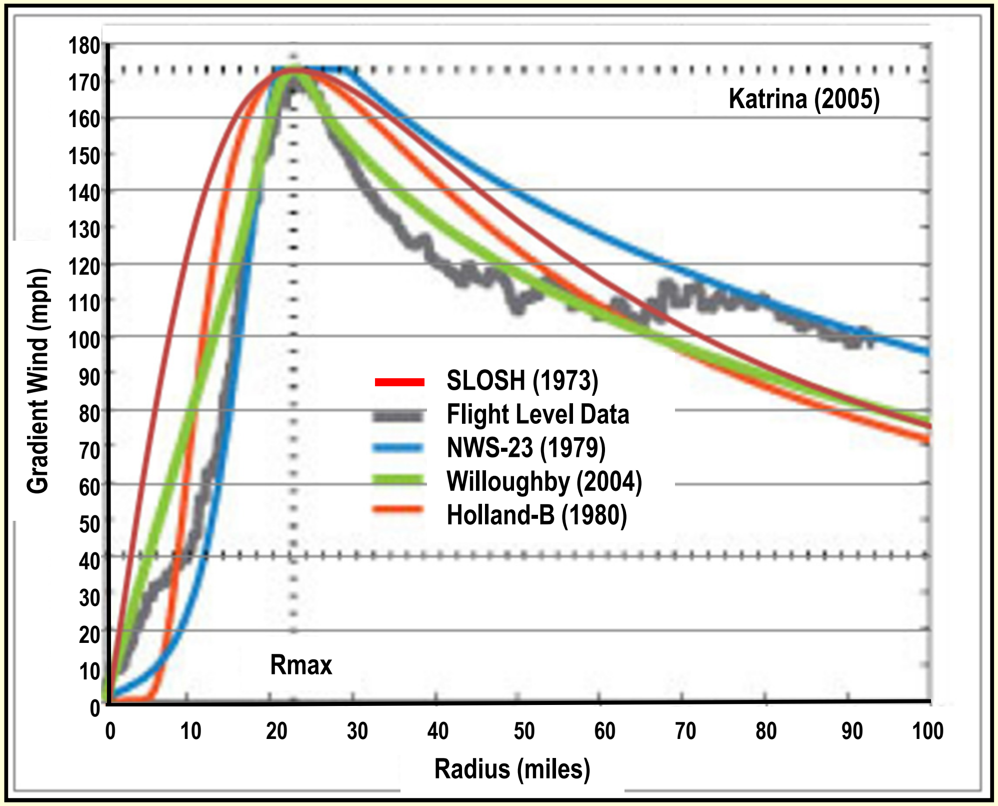
Animation Info:
Start Frame: 0
Stop Frame: 308
Total Frames: 308
Frames per sec: 10.0

Surge Limits:
max feet: 28.0
min feet: 0.0
☐ P.Rex?
P.Rex Level 0

Basin Dimensions:
i-min: 0
i-max: 160
j-min: 0
j-max: 188

Start | Store Settings | Cancel

Wind Model Comparison



Source: *Wind Profiles in Parametric Hurricane Models*, Dr. Ioana Dima and Dr. Melicie Desflots, AIR Worldwide, July 2010.

Wind Model Comparison

ADCIRC

- Dynamic atmospheric model.
- Requires five input parameters:
    - Central Pressure, p_o
    - Background Pressure, p_b
    - Radius of Maximum Winds, RMW
    - Maximum Wind Speed, $V_{max\ @10m}$
    - Forward Velocity, V_f
- Multiple number of dynamic surface friction coefficients.

SLOSH

- Simplified parametric model.
- Requires three input parameters:
    - Central Pressure, p_o
    - Background Pressure, p_b
    - Radius of Maximum Winds, RMW
- Limited number of static surface friction coefficients.

ADCIRC and SLOSH – Wind Stresses

Both models calculate surface stress at the air-water boundary layer in a similar manner:

$$\sigma(r) = k_1 \times C_d \times \left(V_{max@10m}\right)^2$$

Where: $\sigma(r)$ = surface stress at a distance r from storm center

k_1 = relative fluid density

C_d = surface drag coefficient

$V_{max@10m}$ = hurricane wind speed at a distance r from storm center

NRC Audit Plan: Item 2

- Discuss the Probable Maximum Hurricane (PMH) scenarios and parameters used in both ADCIRC and SLOSH models.
- Provide ADCIRC and SLOSH input and discuss the set up of the model (e.g., model grids, surface structures, etc.) for all simulated PMH scenarios.
- Provide graphical comparison of model inputs, computational grids, PMH storm tracks, topographic features, simulated water surface elevations, and other modeling components of ADCIRC and SLOSH to facilitate staff’s review (also covered in Item 3).

PMH Parameters – STP 3 & 4 FSAR

Table 2.4S.5-2 Probable Maximum Hurricane Characteristics

Peripheral Pressure (p_w)	30.12 in. Hg.	1020 Mb
Central Pressure (p_o)	26.19 in. Hg.	887 Mb
Radius of Maximum Winds (R)	5 to 21 nautical miles	6 to 24 miles
Forward Speed (T)	6 to 20 knots	7 to 23 mph

SLOSH PMH Model Input (Scenario 1)

- Central Pressure: 26.19 in. Hg (887 Mb)
- Peripheral (Background) Pressure: 30.12 in. Hg (1020 Mb)
- Radius-to-Maximum Wind: 21 NM (24 miles)
- Forward Speed: 20 knots (23 mph)
- Direction: Northwest
- 10% Exceedance High Tide and Initial Rise: 5.0 feet
- Wave estimated using USACE CEM: 3.3 feet
- No decay until landfall.
- Resulting Maximum Sustained Wind Speed Calculated by SLOSH: 162 knots (186 mph)

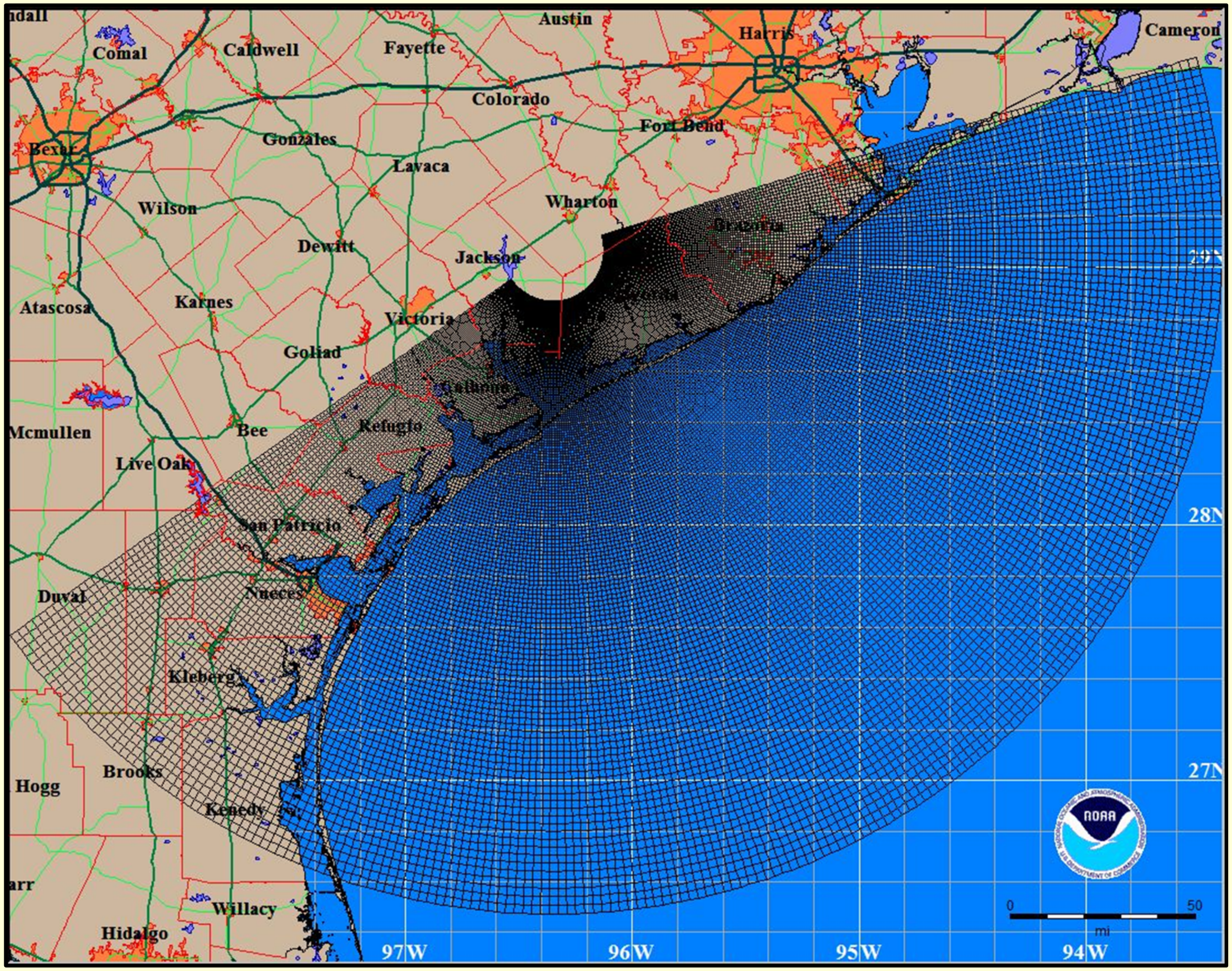
ADCIRC PMH Model Input – Initial Run

- Central Pressure: 26.19 in. Hg (887 Mb)
- Peripheral (Background) Pressure: 29.92 in. Hg (1013 Mb)
- Maximum Sustained Wind Speed: 140 knots (161 mph)
- Radius-to-Maximum Wind: 21 NM (24 miles)
- Forward Speed: 20 knots (23 mph)
- Direction: Northwest
- 10% Exceedance High Tide and Initial Rise: 3.5 feet
- Wave dynamically calculated during program execution using SWAN (Delft University of Technology): ≈ 2.0 feet
- No decay until landfall.

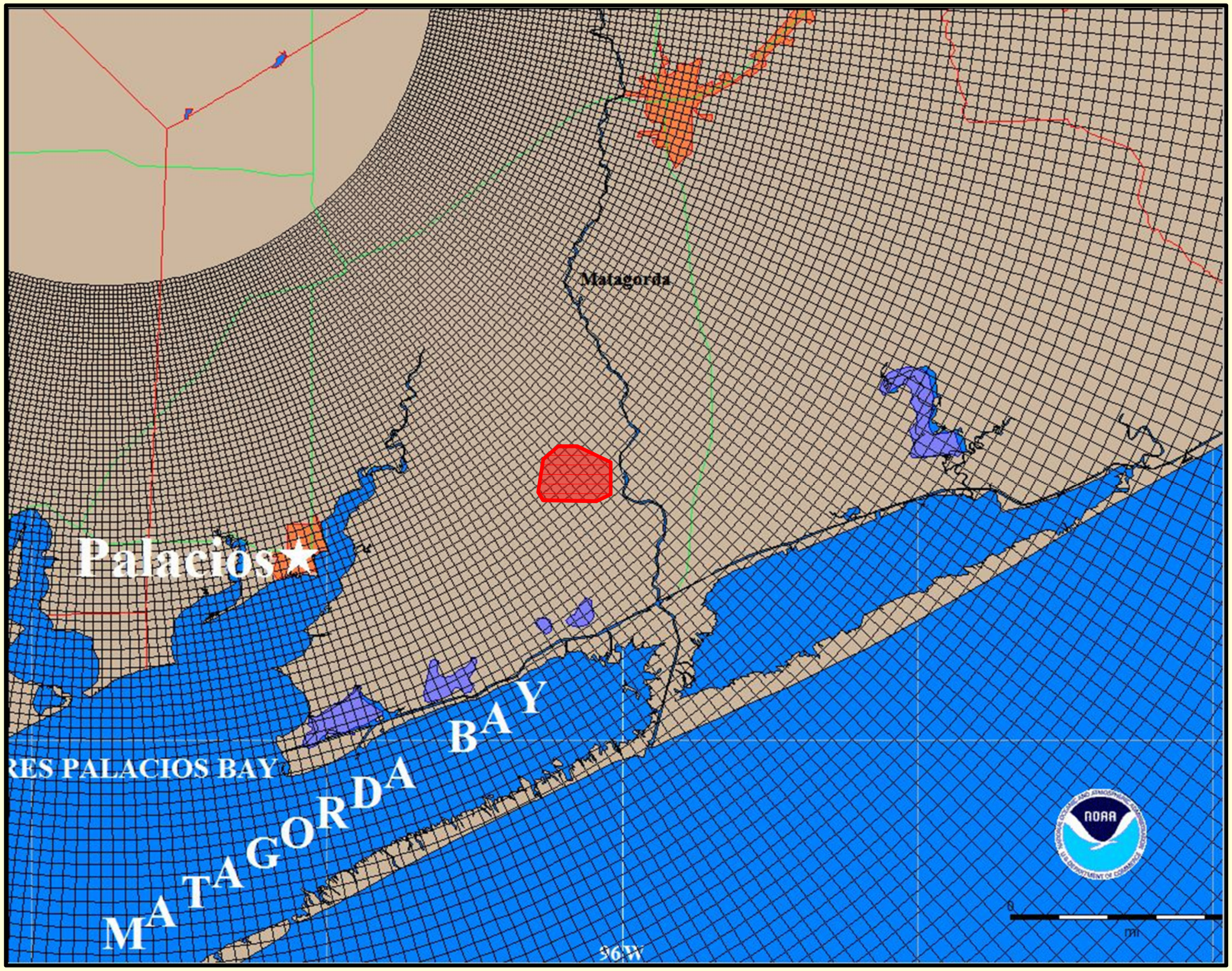
ADCIRC PMH Model Input – Final Runs

- Central Pressure: 26.28 in. Hg (890 Mb)
- Peripheral (Background) Pressure: 29.92 in. Hg (1013 Mb)
- Maximum Sustained Wind Speed: 160 knots (184 mph)
- Radius-to-Maximum Wind: 21 NM (24 miles)
- Forward Speed: 20 knots (23 mph)
- Direction: Northwest and North
- 10% Exceedance High Tide and Initial Rise: 4.9 feet
- Wave dynamically calculated during program execution using SWAN (Delft University of Technology): ≈ 2.0 feet
- No decay until landfall.

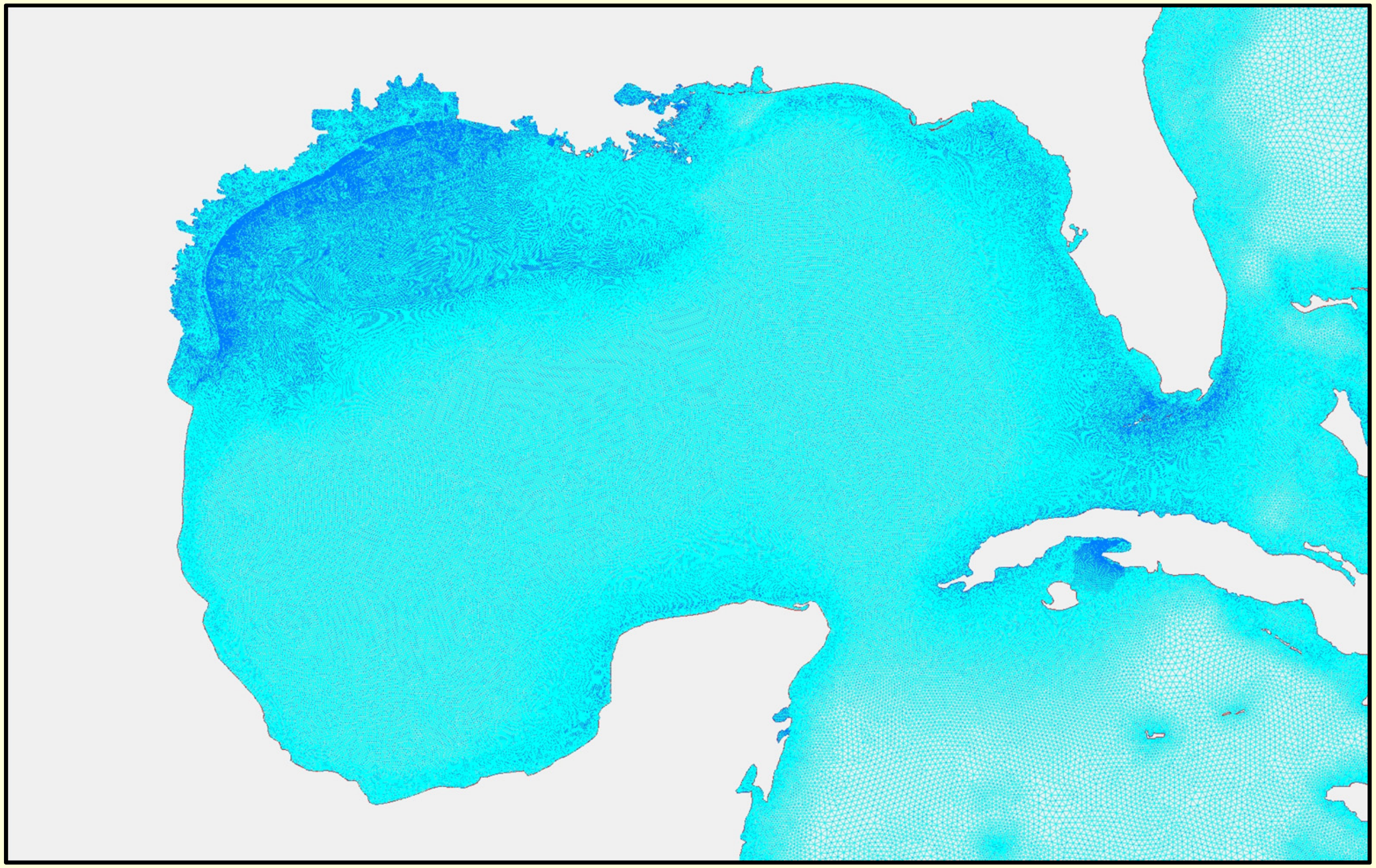
SLOSH Grid (Matagorda Bay Basin)



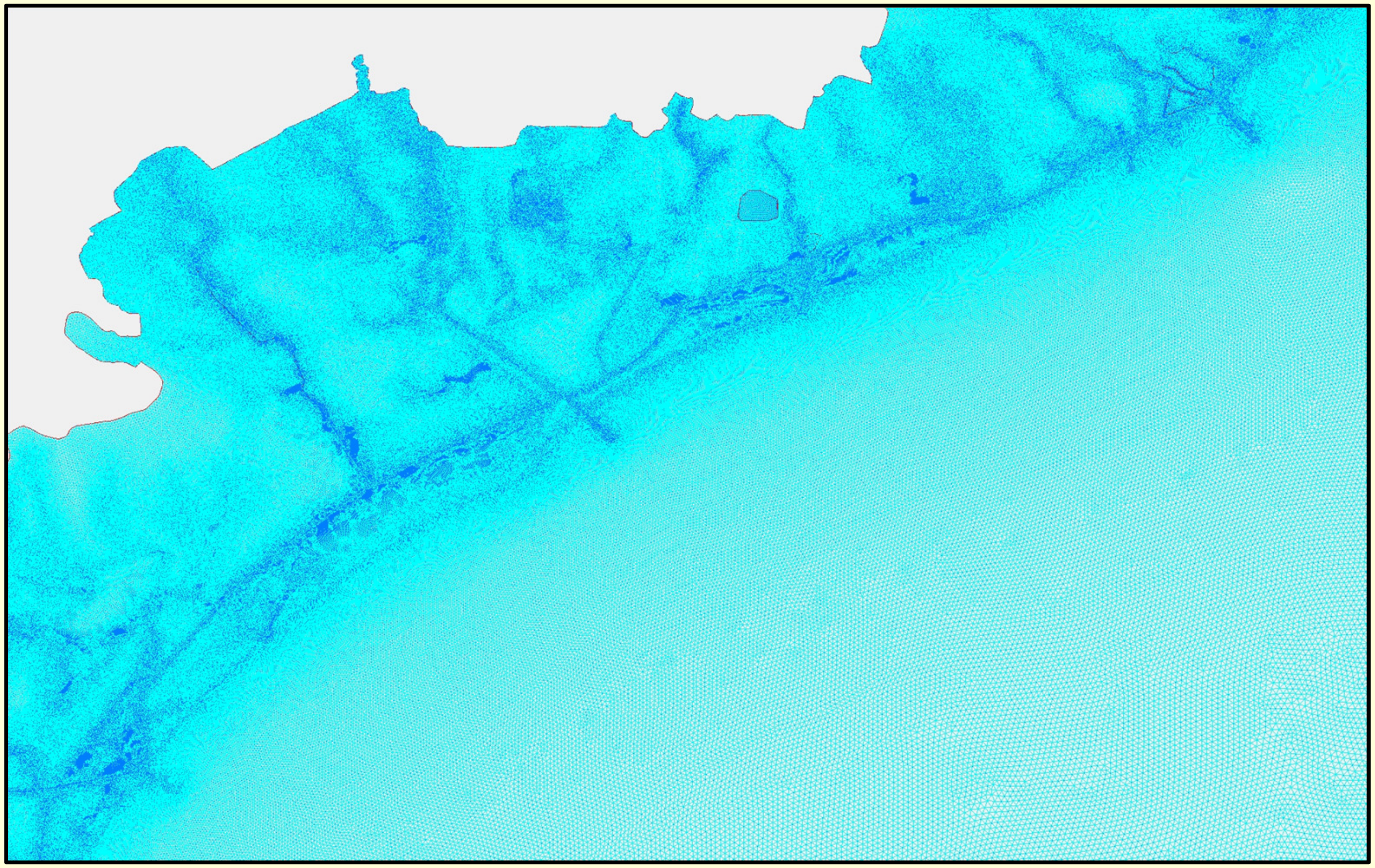
SLOSH Grid (Matagorda Bay Basin)



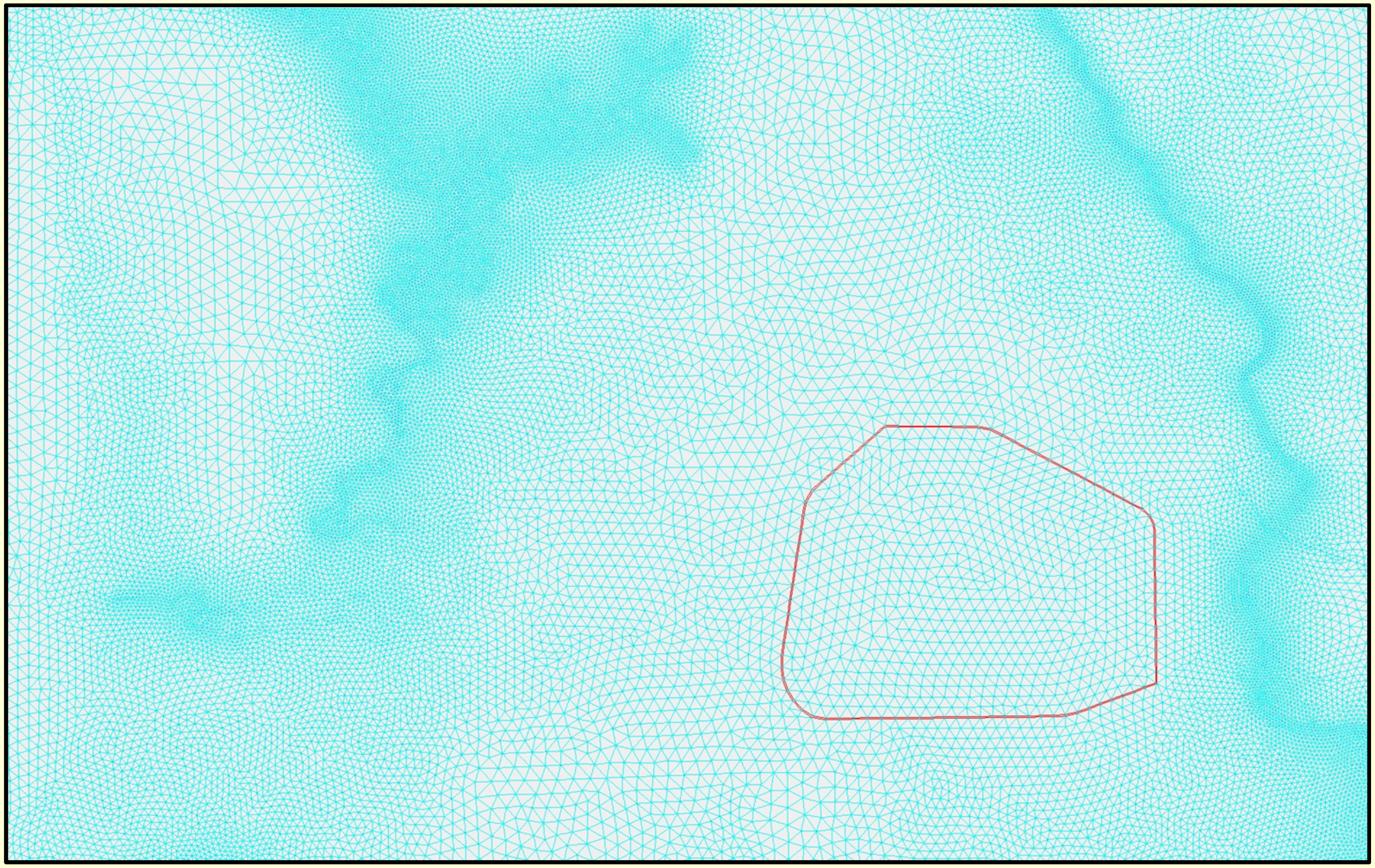
ADCIRC Texas Grid (Version 13)



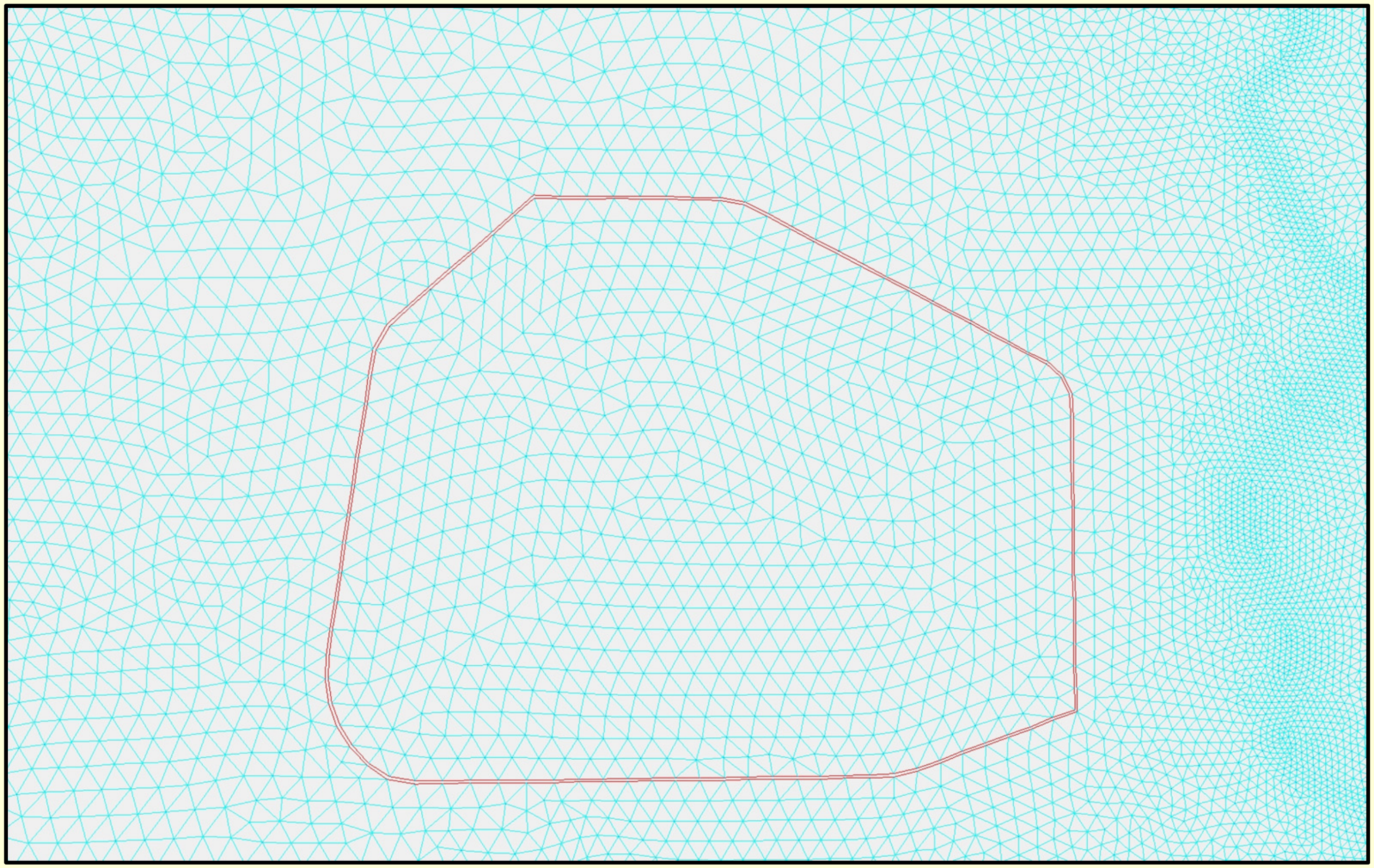
ADCIRC Texas Grid (Version 13)



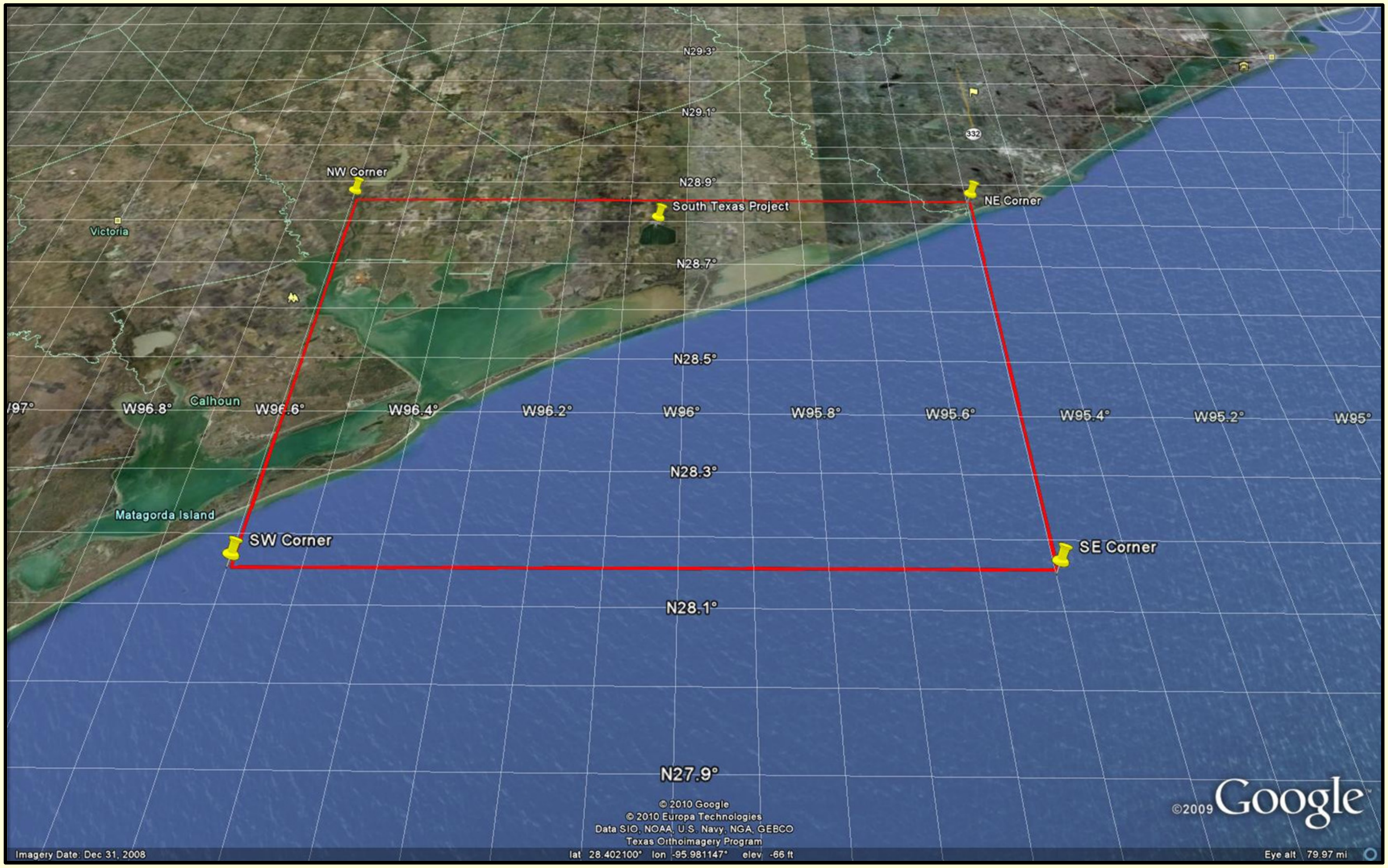
ADCIRC Texas Grid (Version 13)



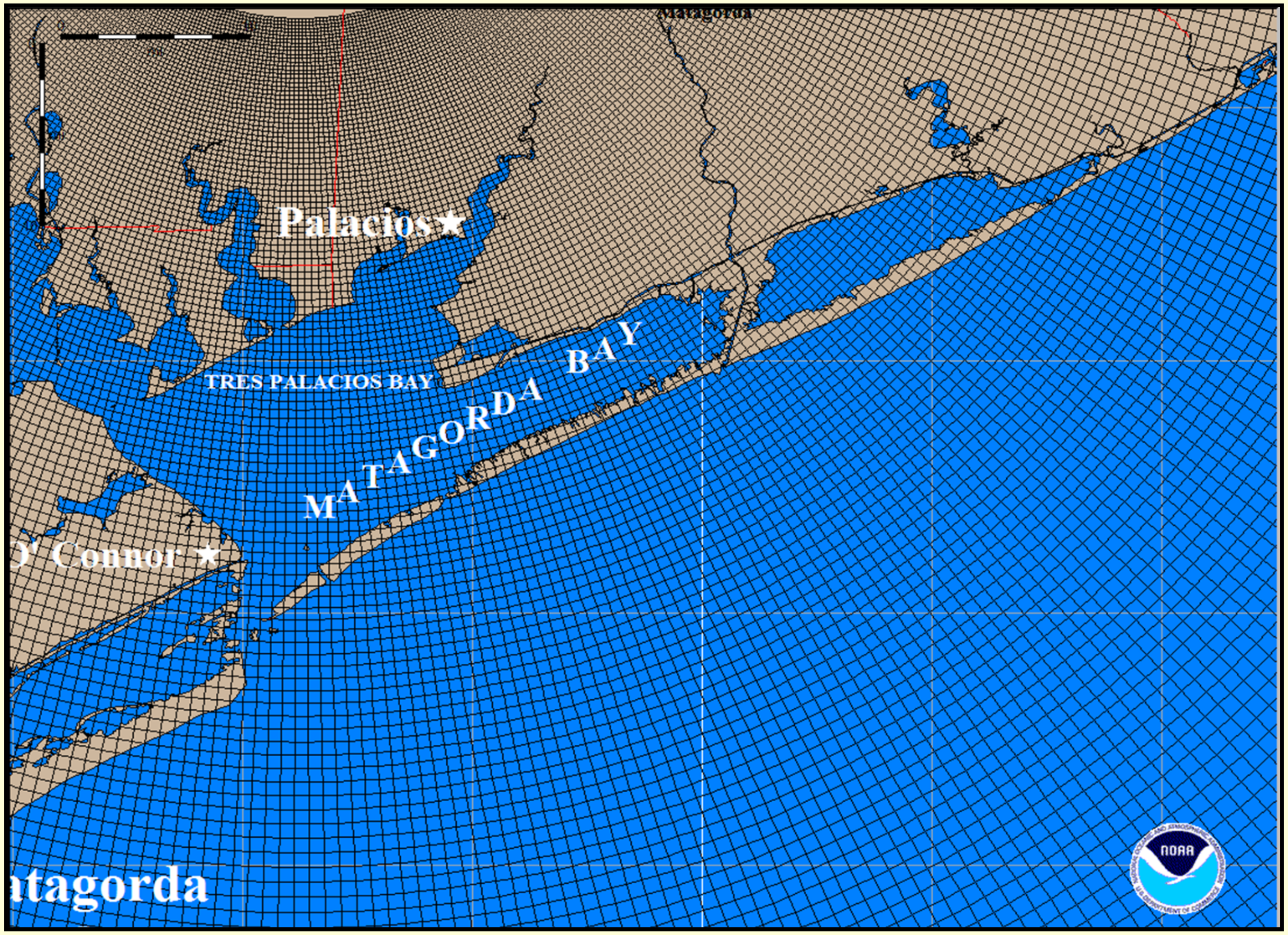
ADCIRC Texas Grid (Version 13)



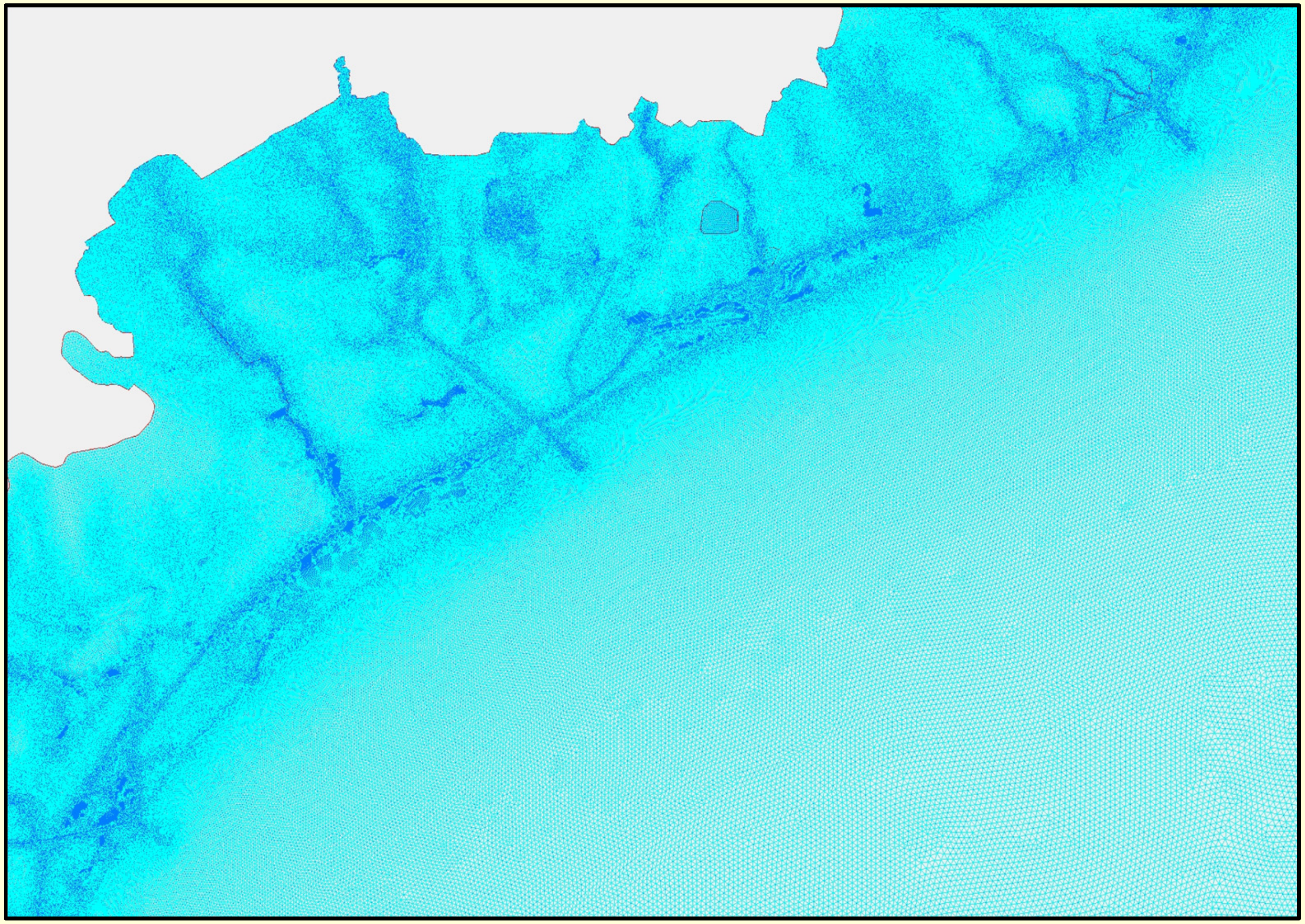
ADCIRC Grid vs. SLOSH Grid



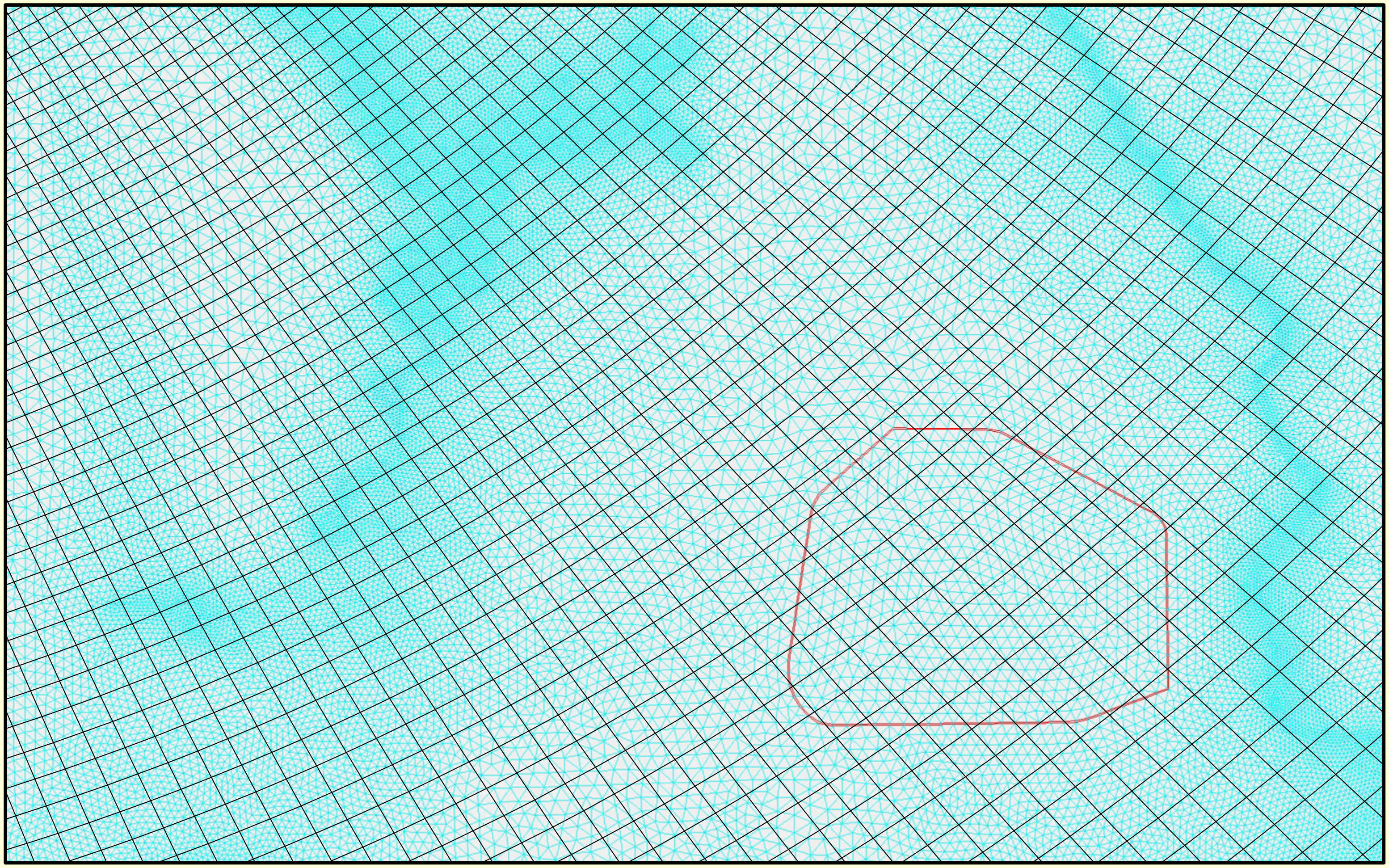
SLOSH Grid


Matagorda
Palacios★
TRES PALACIOS BAY
MATAGORDA BAY
'Connor ★
tagorda
NOAA

ADCIRC Grid



Grid Overlay



GRID FEATURES: SLOSH v. ADCIRC

Grid Sub-boundary:
Latitude 28.15 to 28.85 deg
Longitude -95.5 to -96.6 deg

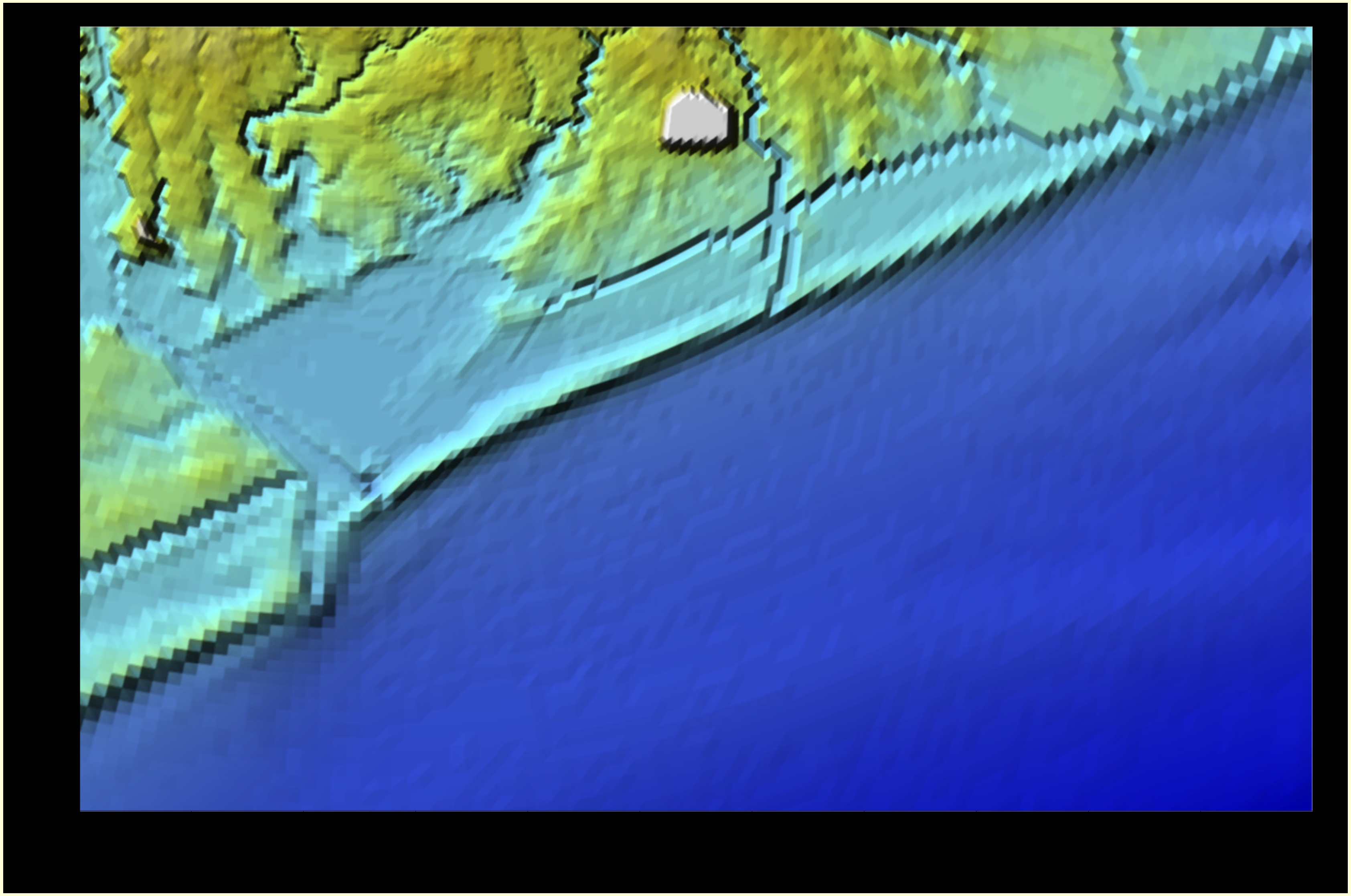
Grid Feature	SLOSH[1]	ADCIRC[1]
Number of Elements	11,800	713,000
Representative[2] Element Area (m^2)	396,000	21,900
Average Element Area (m^2)	707,000	11,600
Maximum Element Area (m^2)	3,009,000	357,000
Minimum Element Area (m^2)	109,000	700

[1] Values are approximate.
[2] Located within the reservoir.

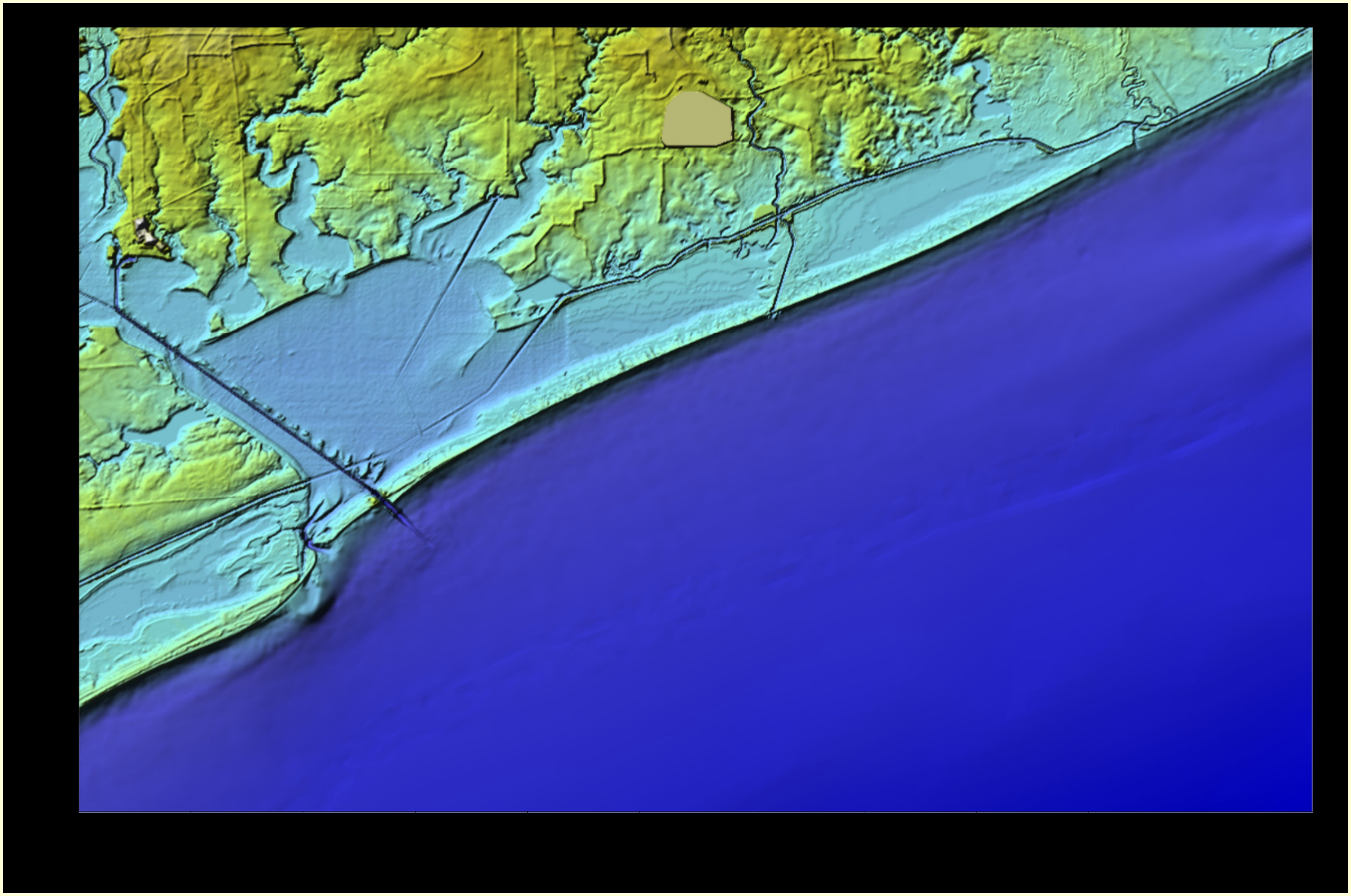
NRC Audit Plan: Item 3

- Discuss topographic data used to simulate ADCIRC model and how the data are different from those used in the SLOSH grids.
- Provide illustrations to indicate topographic features resolved by the ADCIRC and SLOSH grids.

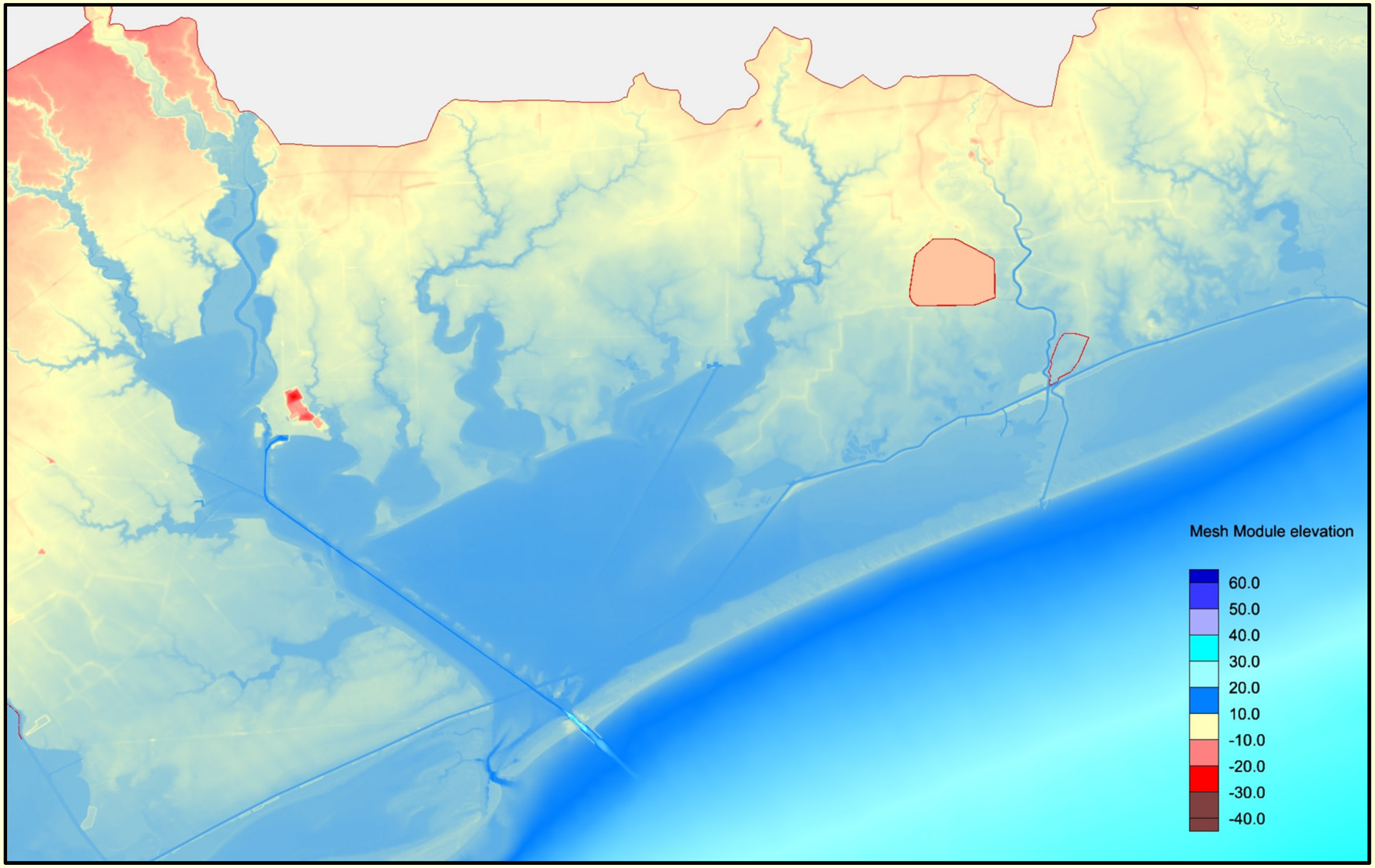
Topographic Data – SLOSH



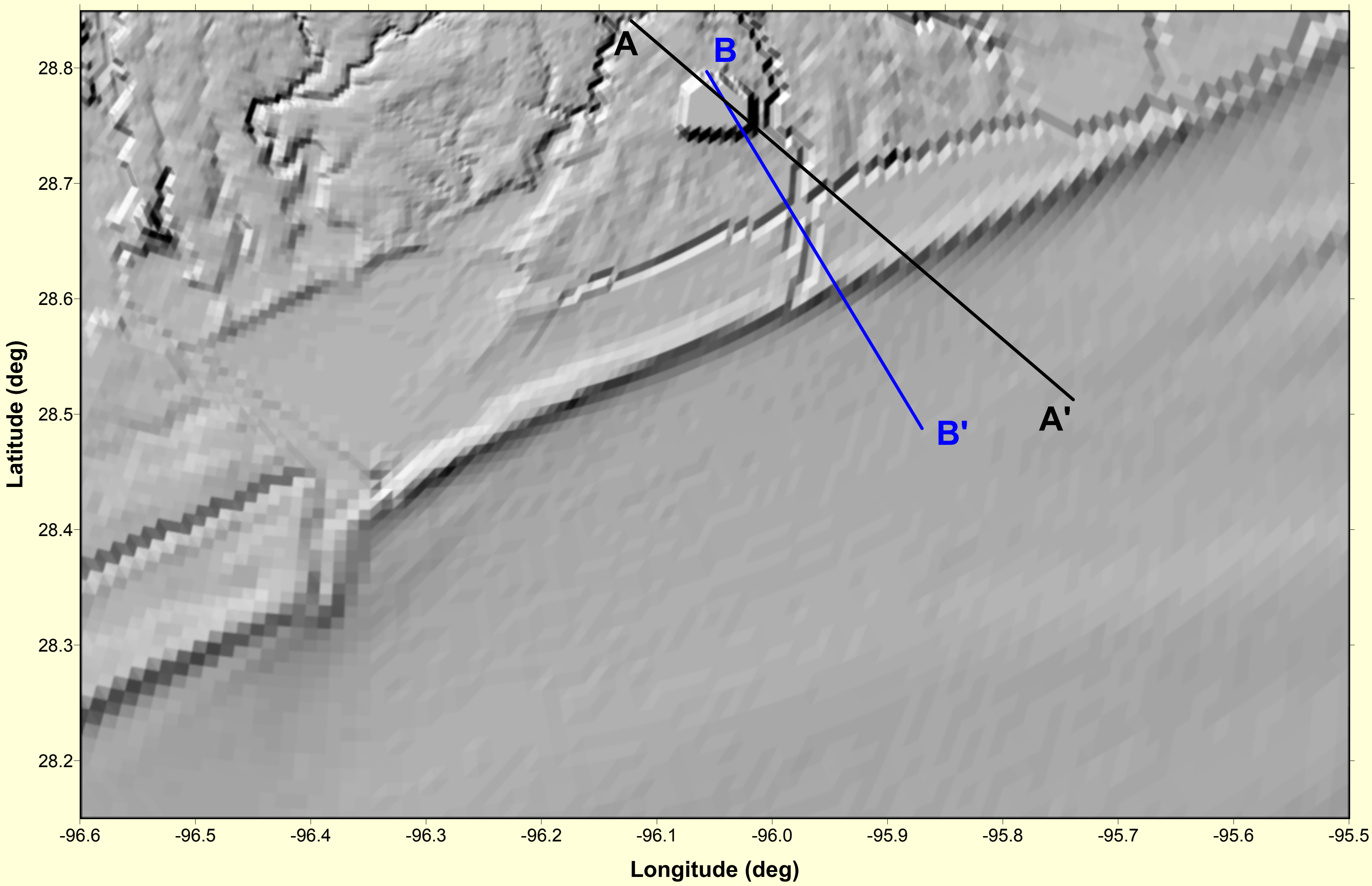
Topographic Data – ADCIRC



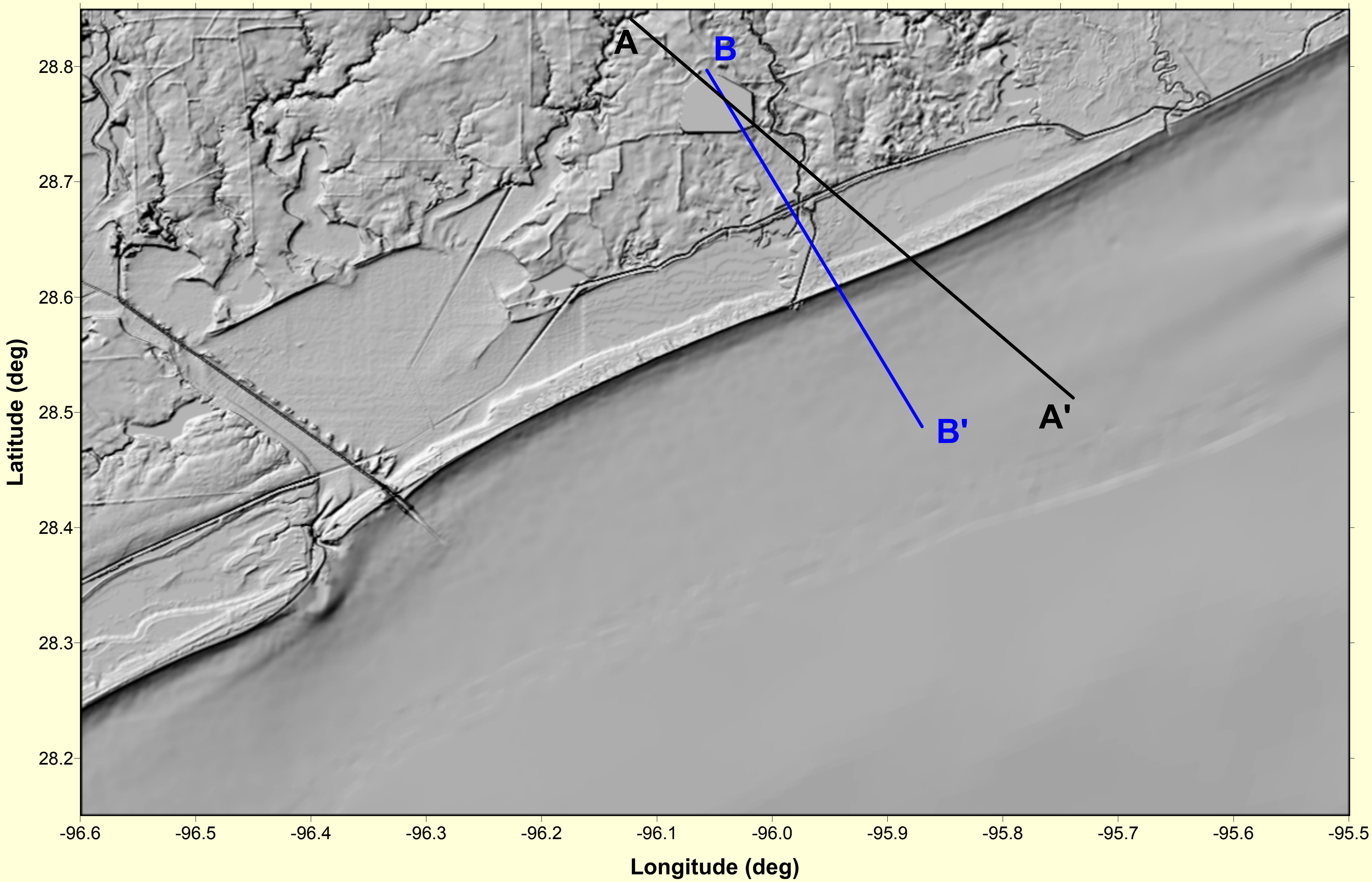
Topographic Features – ADCIRC



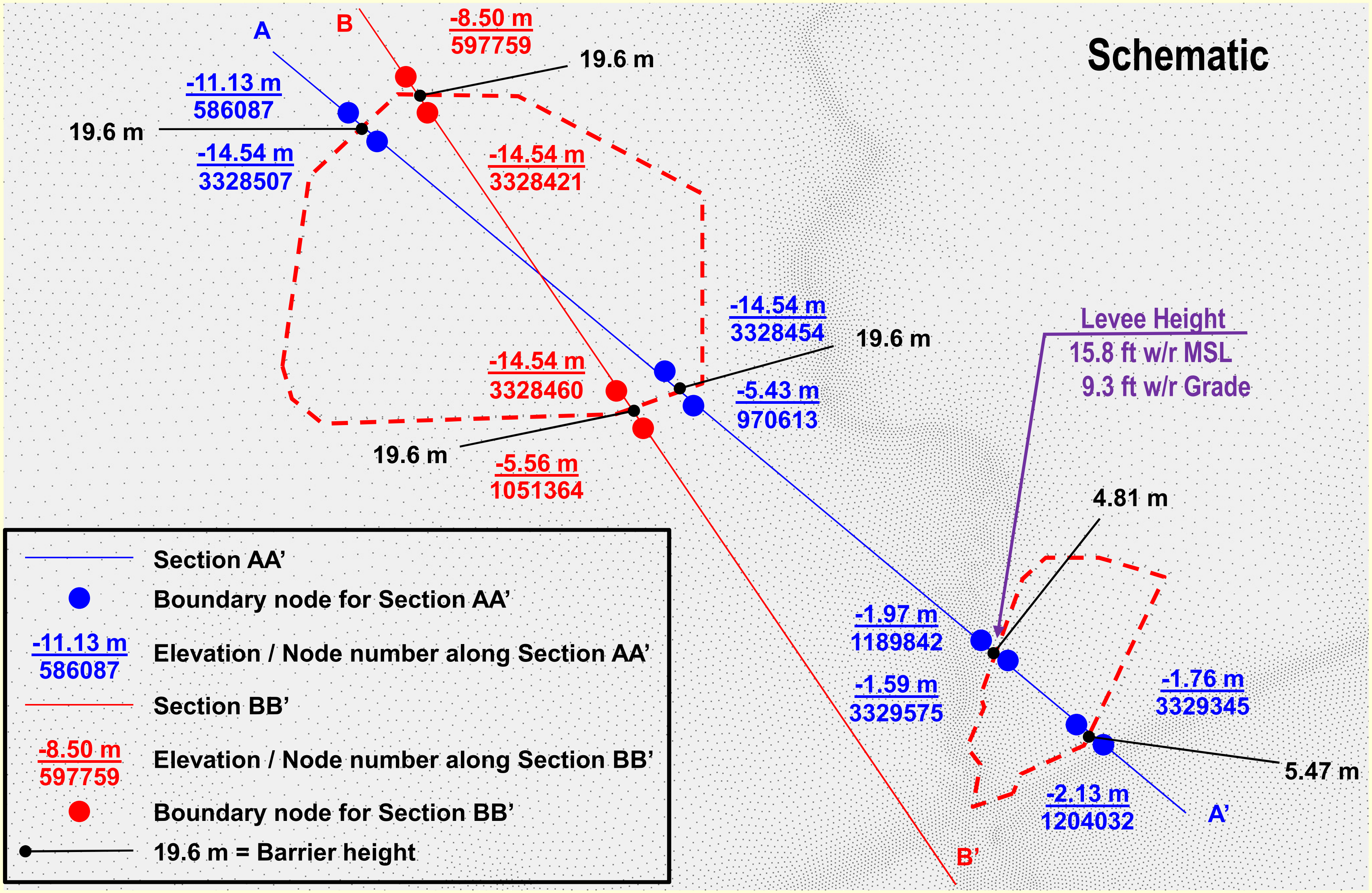
Cross Sections AA’ and BB’ for SLOSH



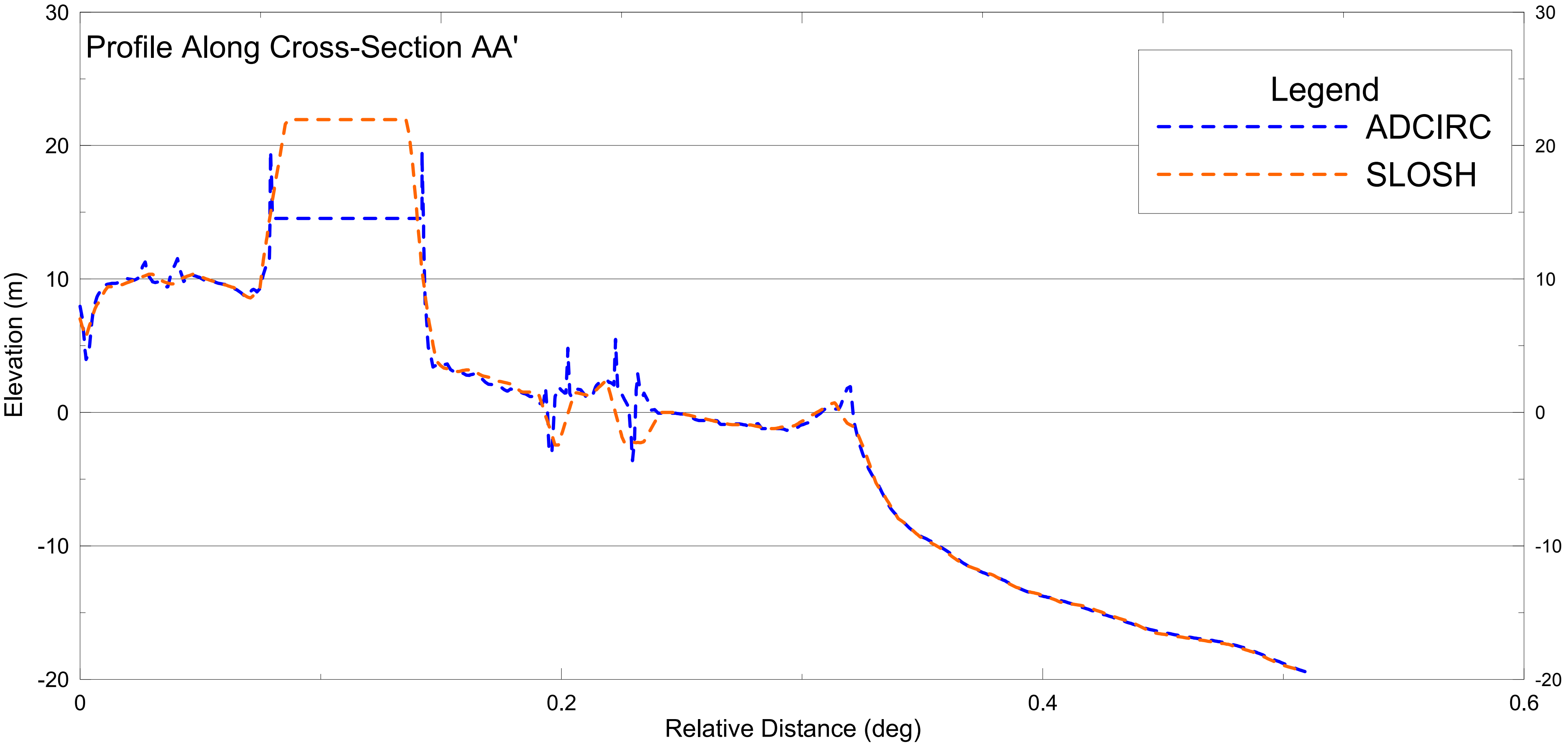
Cross Sections AA’ and BB’ for ADCIRC



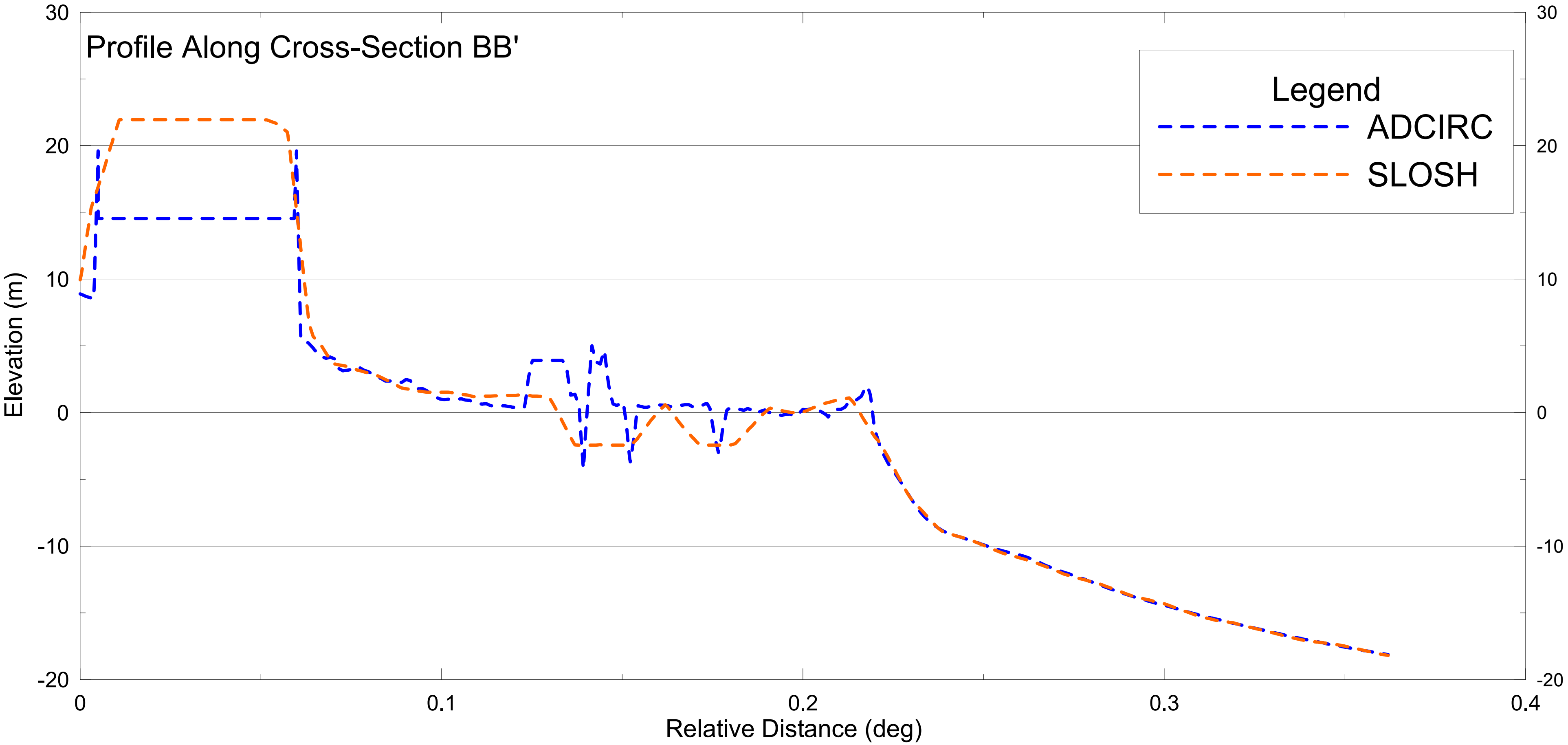
Boundary Node Features and Barrier Heights at Sections AA’ and BB’



Cross Section A-A’ for SLOSH and ADCIRC



Cross Section B-B' for SLOSH and ADCIRC



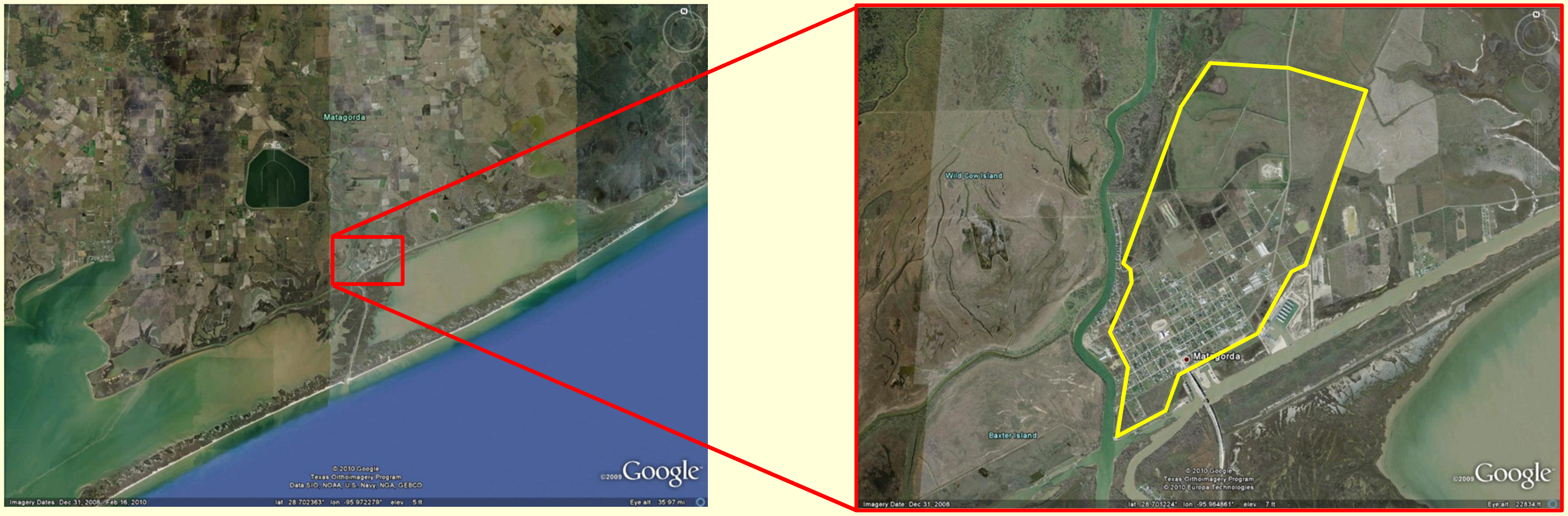
Effect of Matagorda Levee

"A hurricane in 1942 forced the county to build a levee. It was wise planning for it minimized damage in 1961 when Hurricane Carla hit the area. "

www.texasescapes.com/TexasGulfCoastTowns/MatagordaTexas.htm

"The Historical town of Matagorda was spared by the just recent completion of the levee which totally surrounded the town. But I remember so well all the debris on top of that levee! The storm surge of sea water had reached the very top of that levee. Matagorda would have been completely wiped off the map if that levee had not been there."

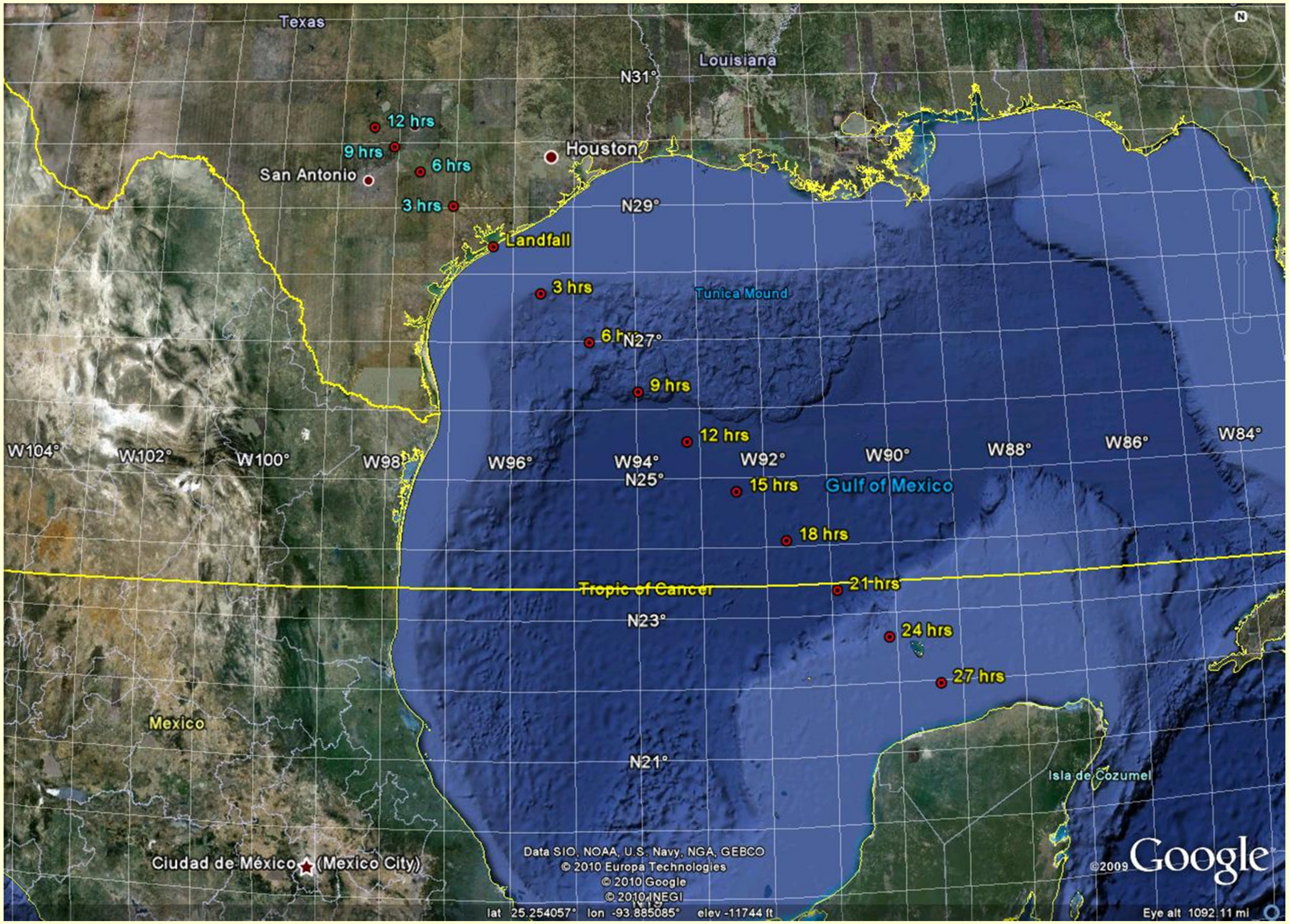
www.gendisasters.com/texas/2497/hurricane-carla-hits-texas-coast,-sept-1961



NRC Audit Plan: Item 4

- **Discuss the results and interpretation of the ADCIRC and SLOSH simulations. Provide graphical comparison of the output from the two models to facilitate staff's review.**

ADCIRC – Modeled Storm Track

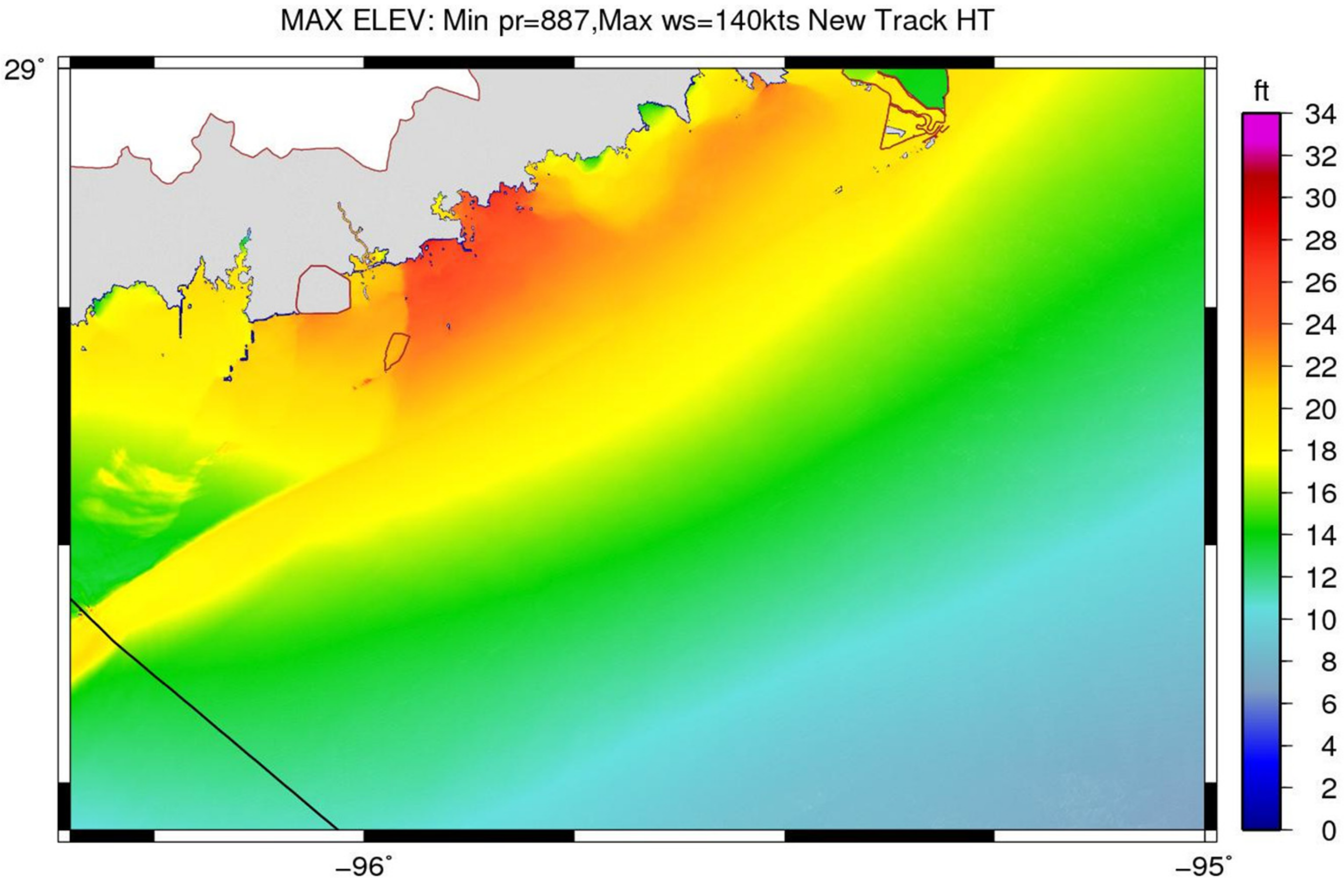


ADCIRC – Modeled Storm Features: Initial Run

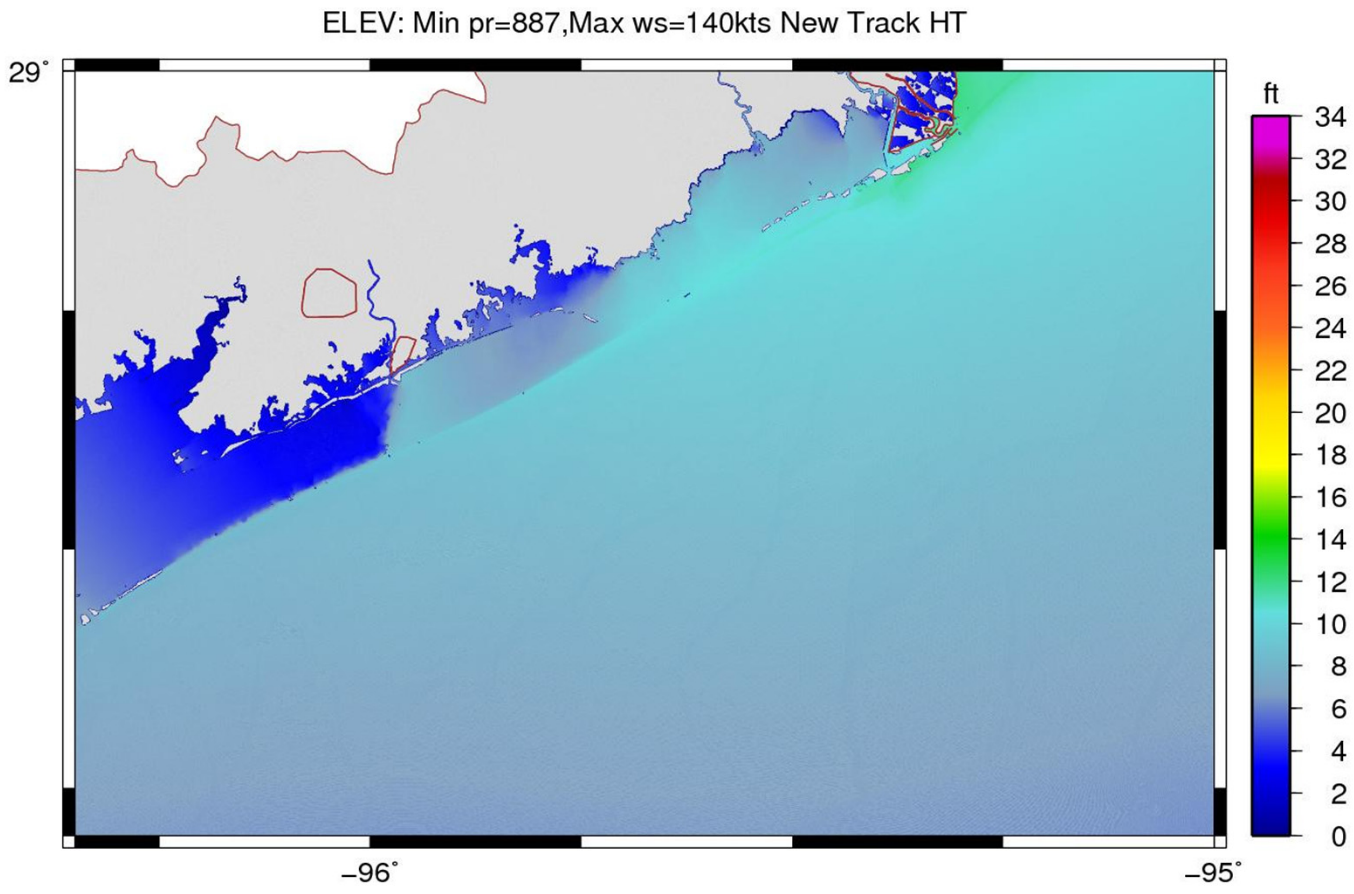
Center of Eye	Time to Landfall (hrs)	Coordinates		Storm Features			Distance Between Points		Forward Speed	
		Latitude (°N)	Longitude (°W)	Category (SSI)	Central Pressure (Mb)	Radius to Max. Winds (miles)	(nm)	(miles)	(mph)	(knots)
D	-12	30.2625	98.4274	1	994	10	26	30	10	8.7
C	-9	29.9549	98.0623	2	979	13	34	39	13	11.3
B	-6	29.5640	97.5969	3	964	16	44	51	17	14.7
A	-3	29.0355	97.0089	4	944	20	52	60	20	17.3
Landfall	0	28.4219	96.3197	5	887	24	60	69	23	20
1	3	27.7161	95.5254	5	887	24	60	69	23	20
2	6	26.9944	94.7330	5	887	24	60	69	23	20
3	9	26.2680	93.9553	5	887	24	60	69	23	20
4	12	25.5414	93.1924	5	887	24	60	69	23	20
5	15	24.8149	92.4344	5	887	24	60	69	23	20
6	18	24.0900	91.6700	5	887	24	60	69	23	20
7	21	23.3717	90.9060	4	944	20	60	69	23	20
8	24	22.6775	90.1187	3	964	16	60	69	23	20
9	27	21.9840	89.3373	2	979	13				

- **Maximum Sustained Wind Speed: 140 knots (161 mph)**
- **10% Exceedance High Tide and Initial Rise: 3.5 feet**

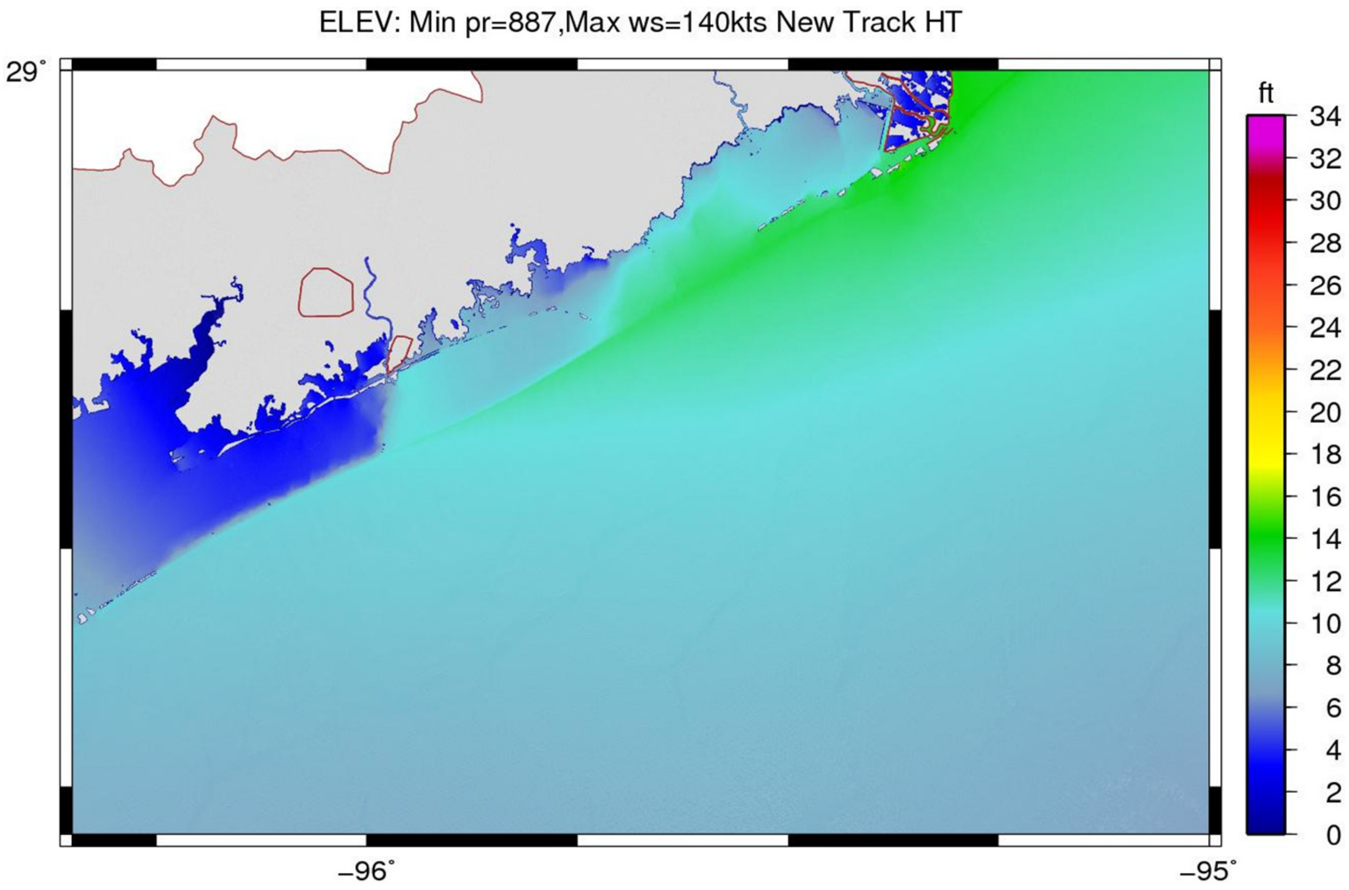
ADCIRC Results – Initial Run



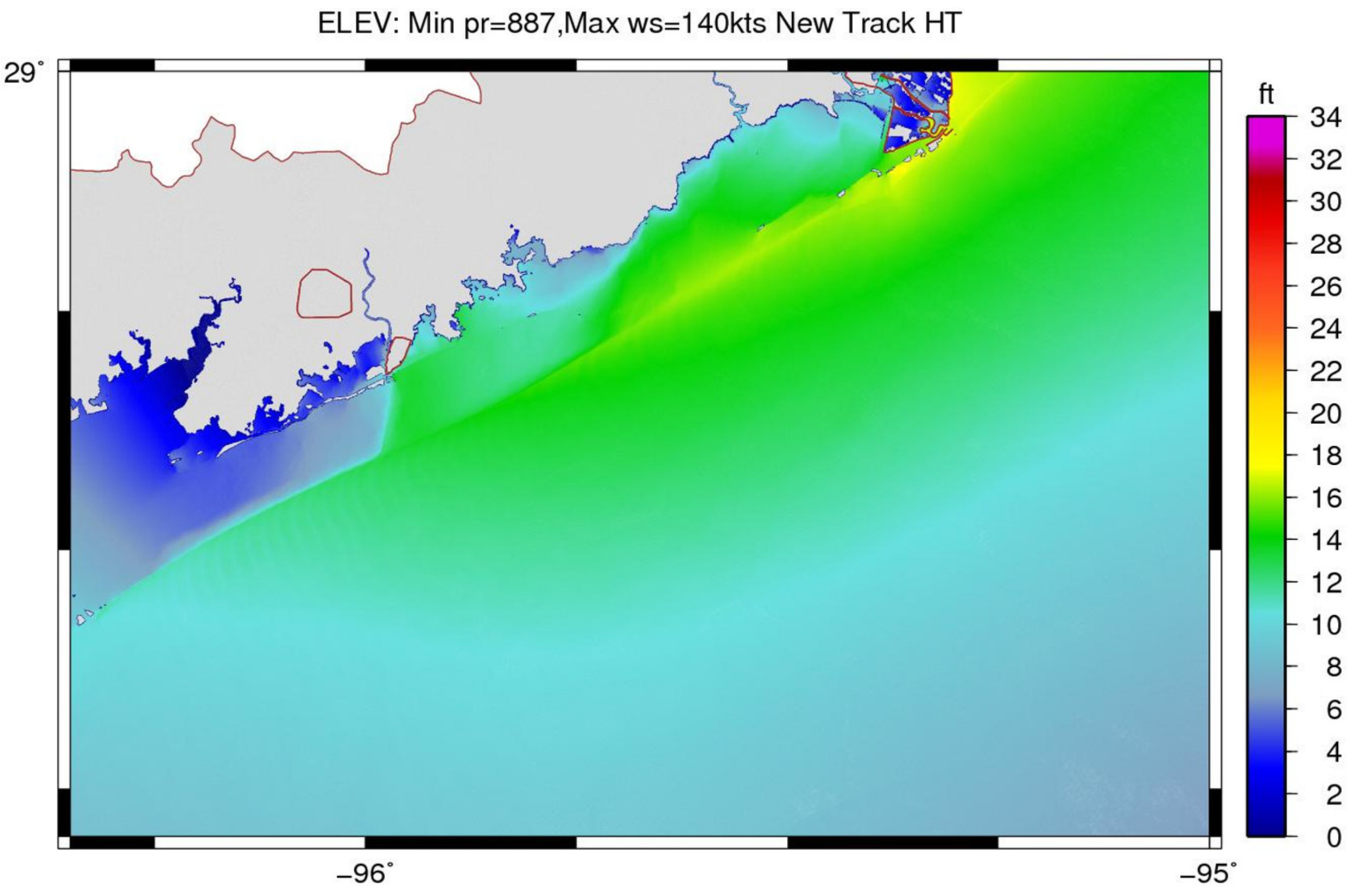
ADCIRC Initial Run – Step 1



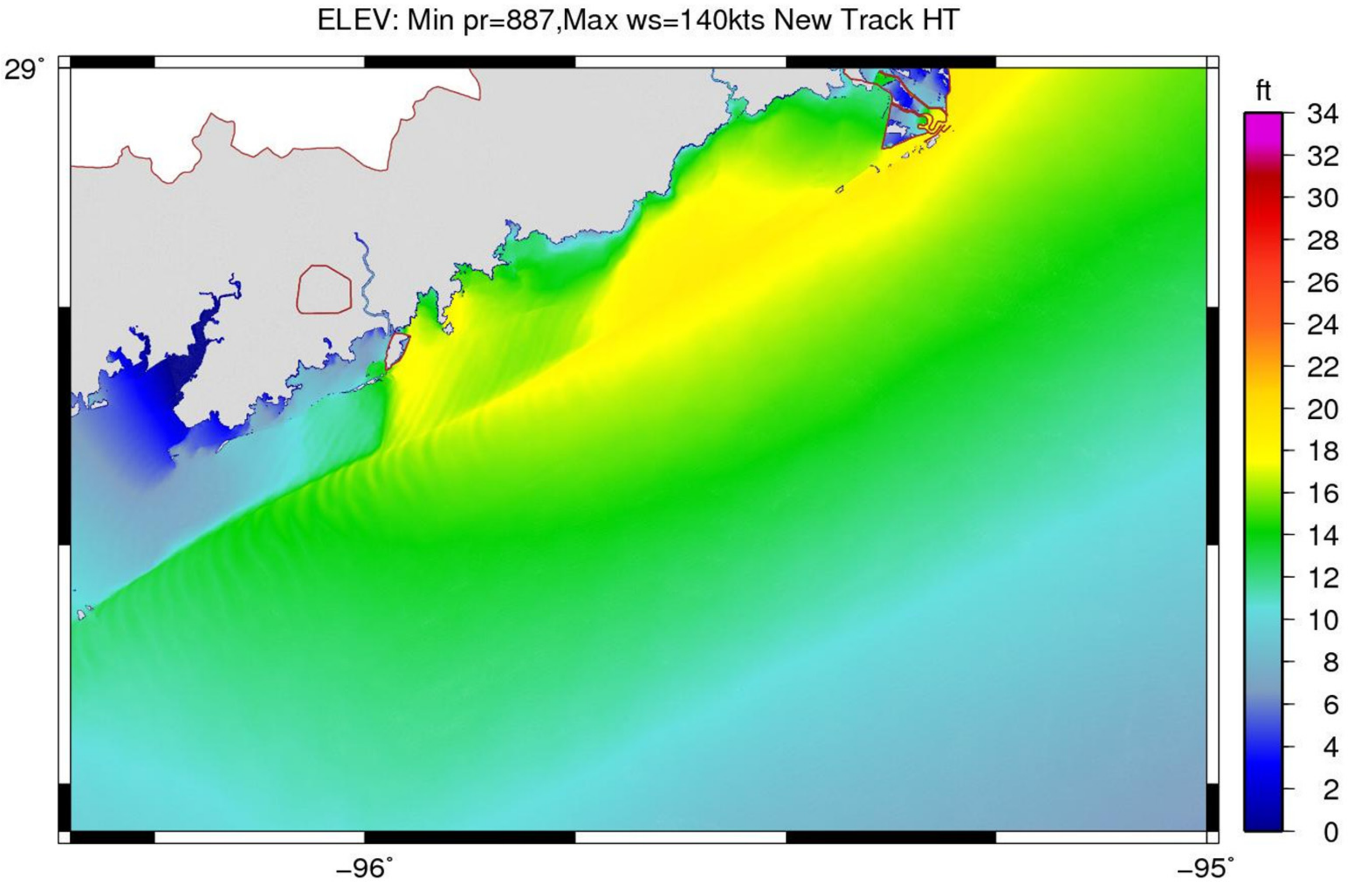
ADCIRC Initial Run – Step 2



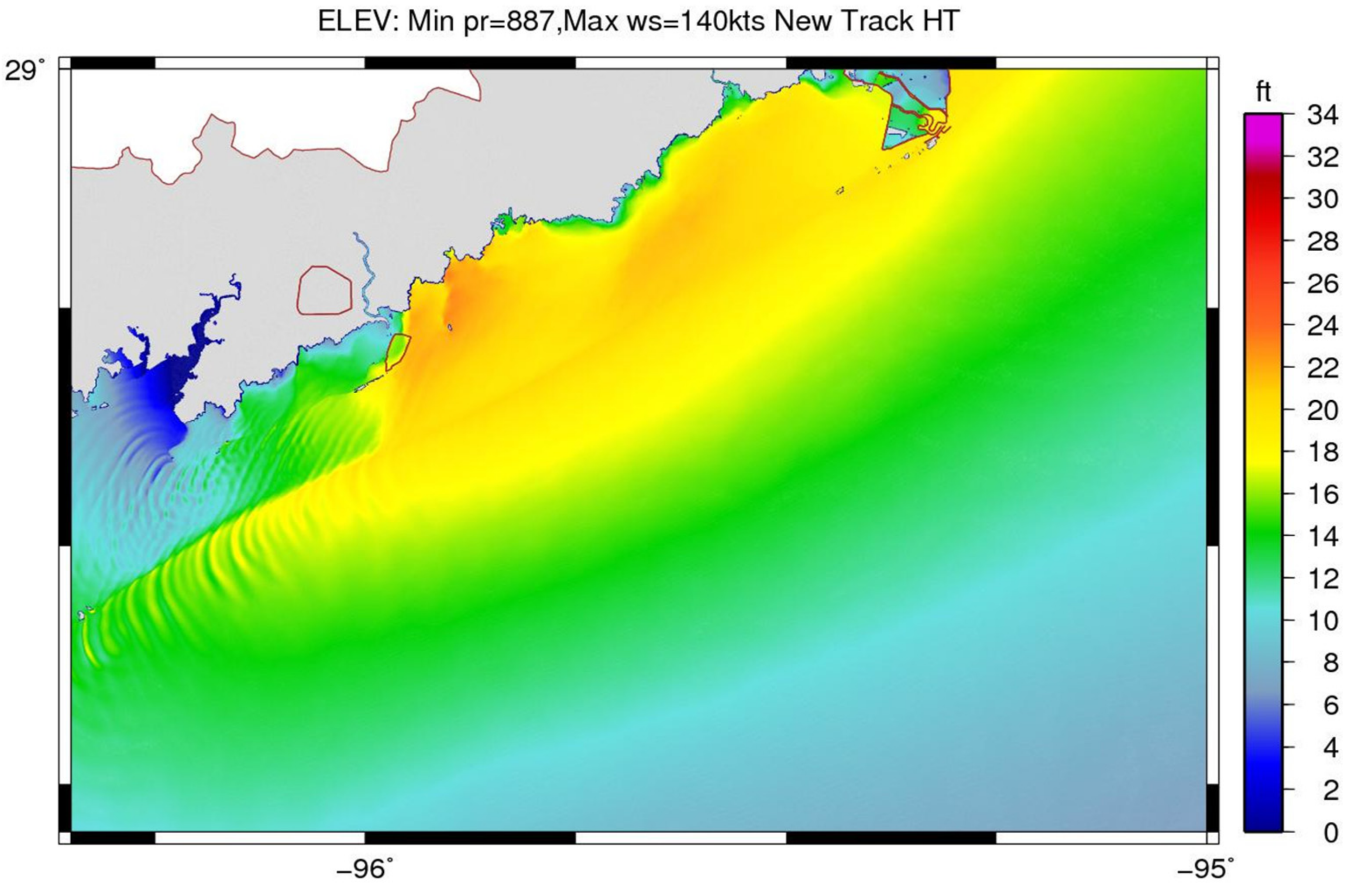
ADCIRC Initial Run – Step 3



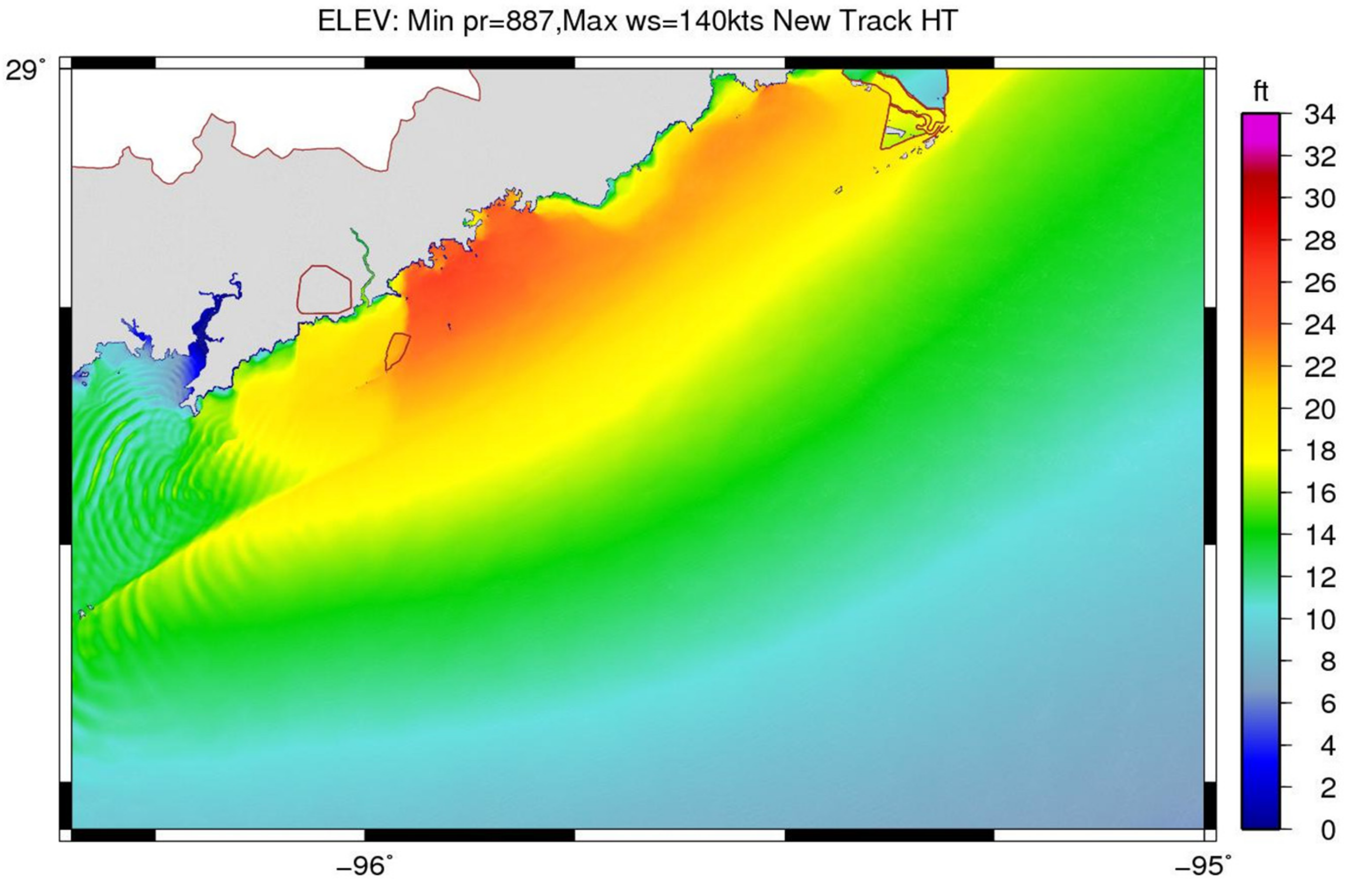
ADCIRC Initial Run – Step 4



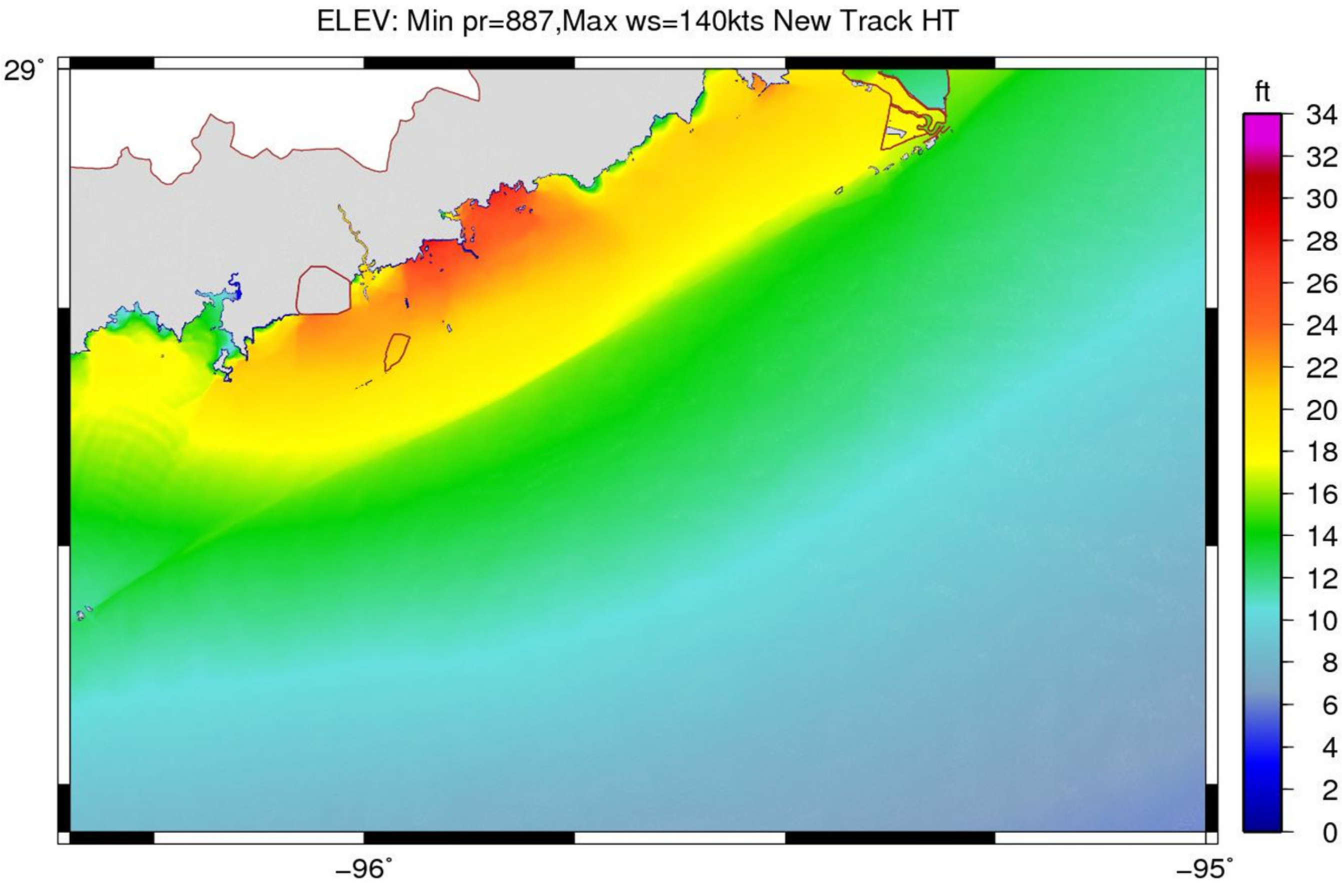
ADCIRC Initial Run – Step 5



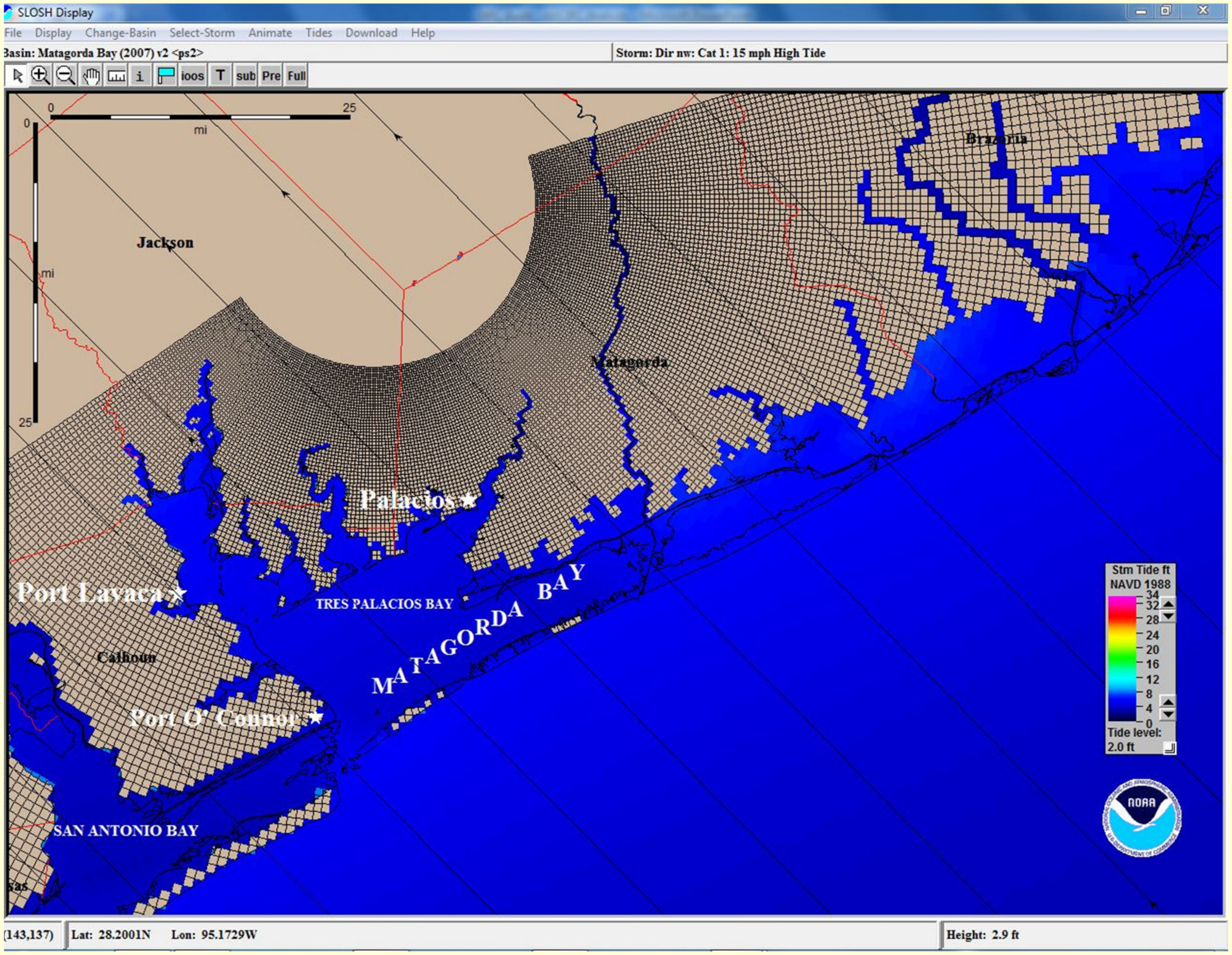
ADCIRC Initial Run – Step 6



ADCIRC Initial Run – Step 7



SLOSH: Cat 1 NW 15 MPH High Tide



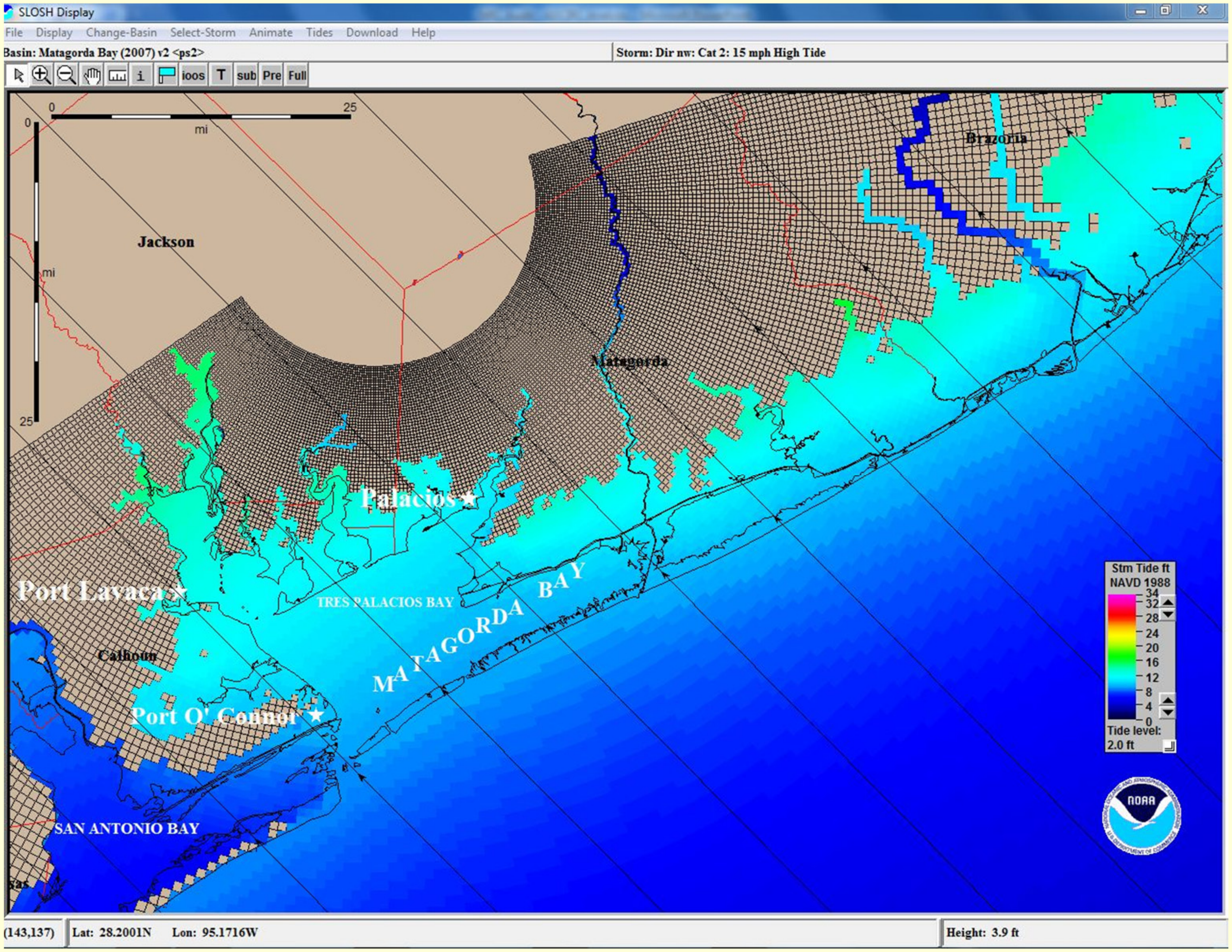
Basin: Matagorda Bay (2007) v2 <ps2>

Storm: Dir nw: Cat 1: 15 mph High Tide

(143,137) Lat: 28.2001N Lon: 95.1729W

Height: 2.9 ft

SLOSH: Cat 2 NW 15 MPH High Tide



Basin: Matagorda Bay (2007) v2 <ps2>

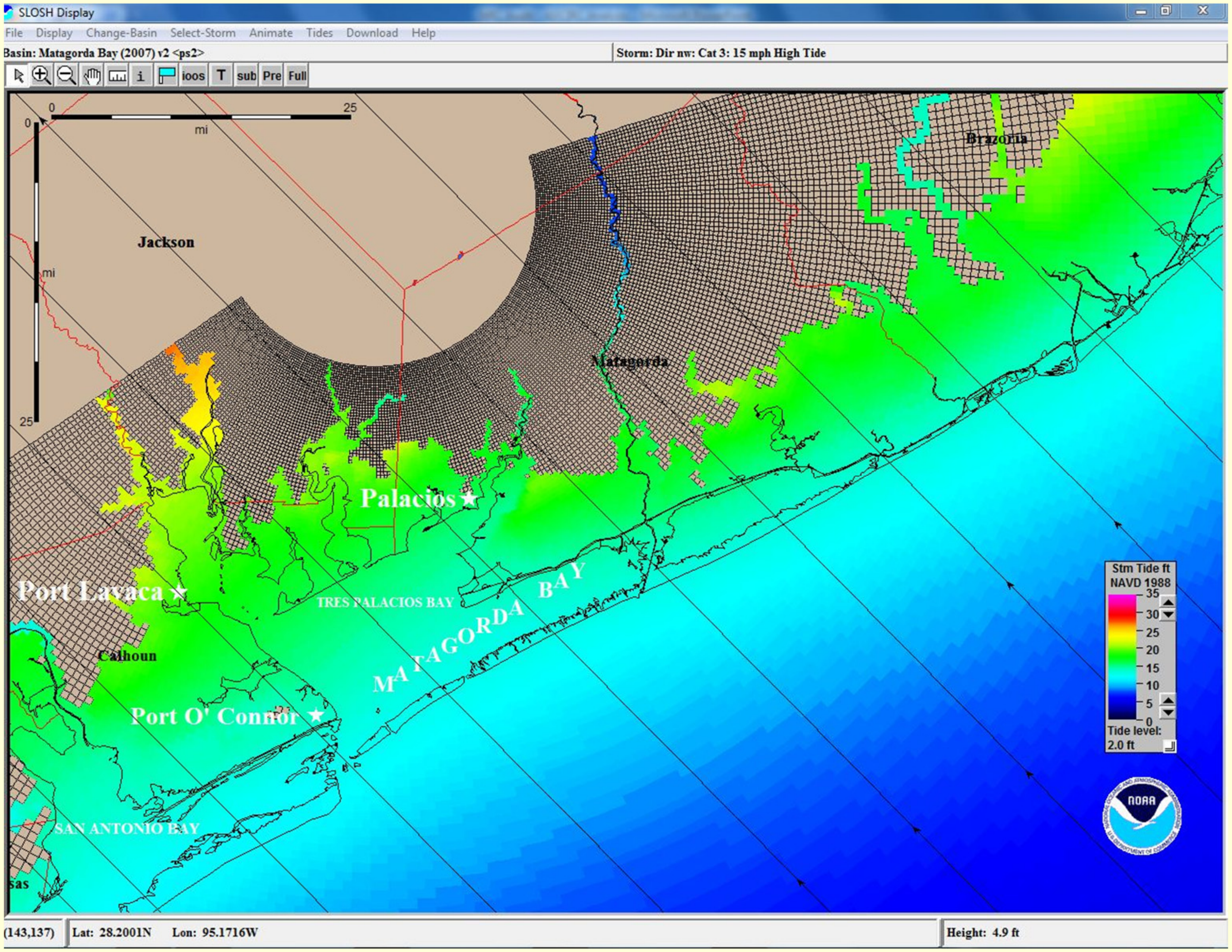
Storm: Dir nw: Cat 2: 15 mph High Tide

Tide level: 2.0 ft

(143,137) Lat: 28.2001N Lon: 95.1716W

Height: 3.9 ft

SLOSH: Cat 3 NW 15 MPH High Tide



Basin: Matagorda Bay (2007) v2 <ps2>

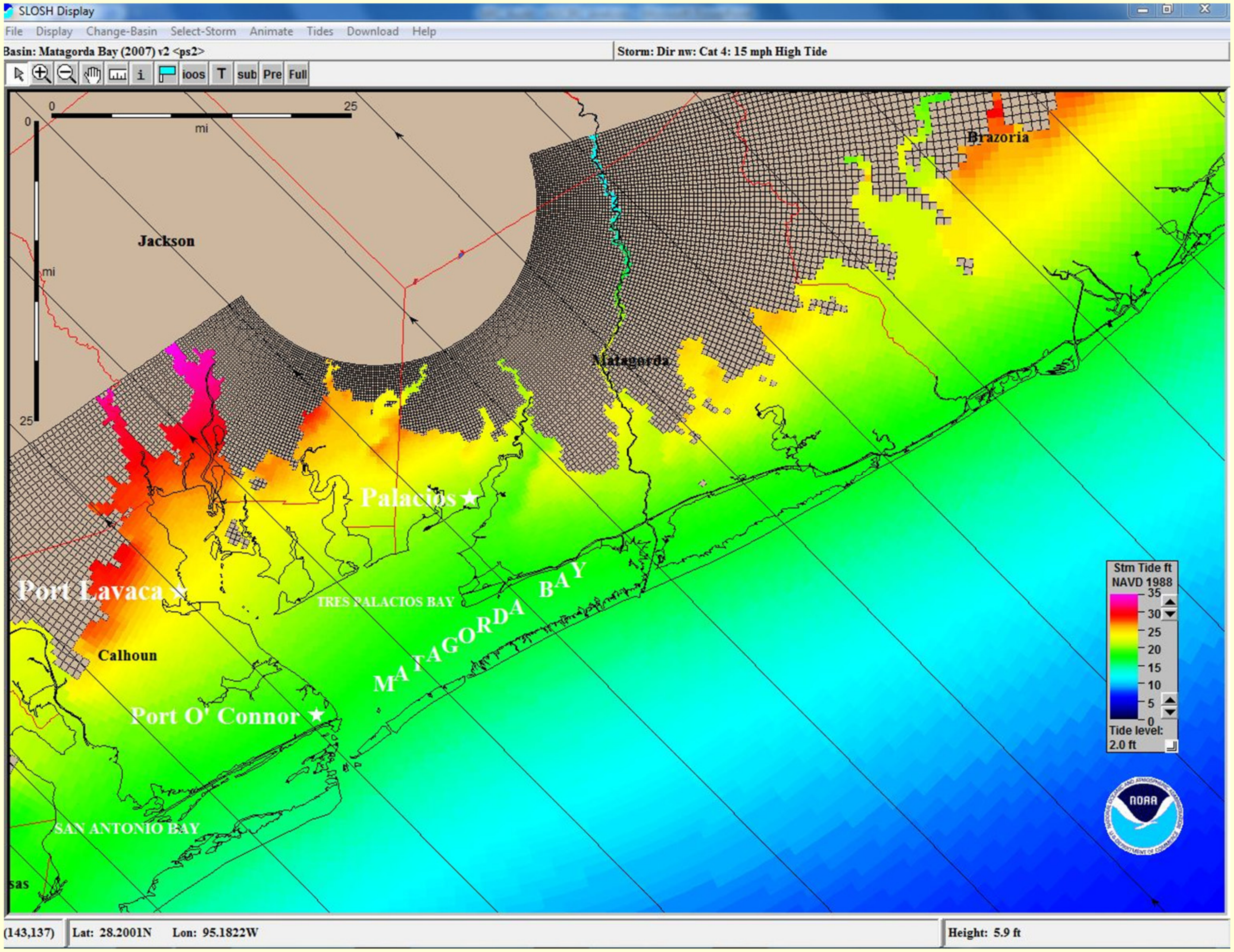
Storm: Dir nw: Cat 3: 15 mph High Tide

Tide level: 2.0 ft

(143,137) Lat: 28.2001N Lon: 95.1716W

Height: 4.9 ft

SLOSH: Cat 4 NW 15 MPH High Tide



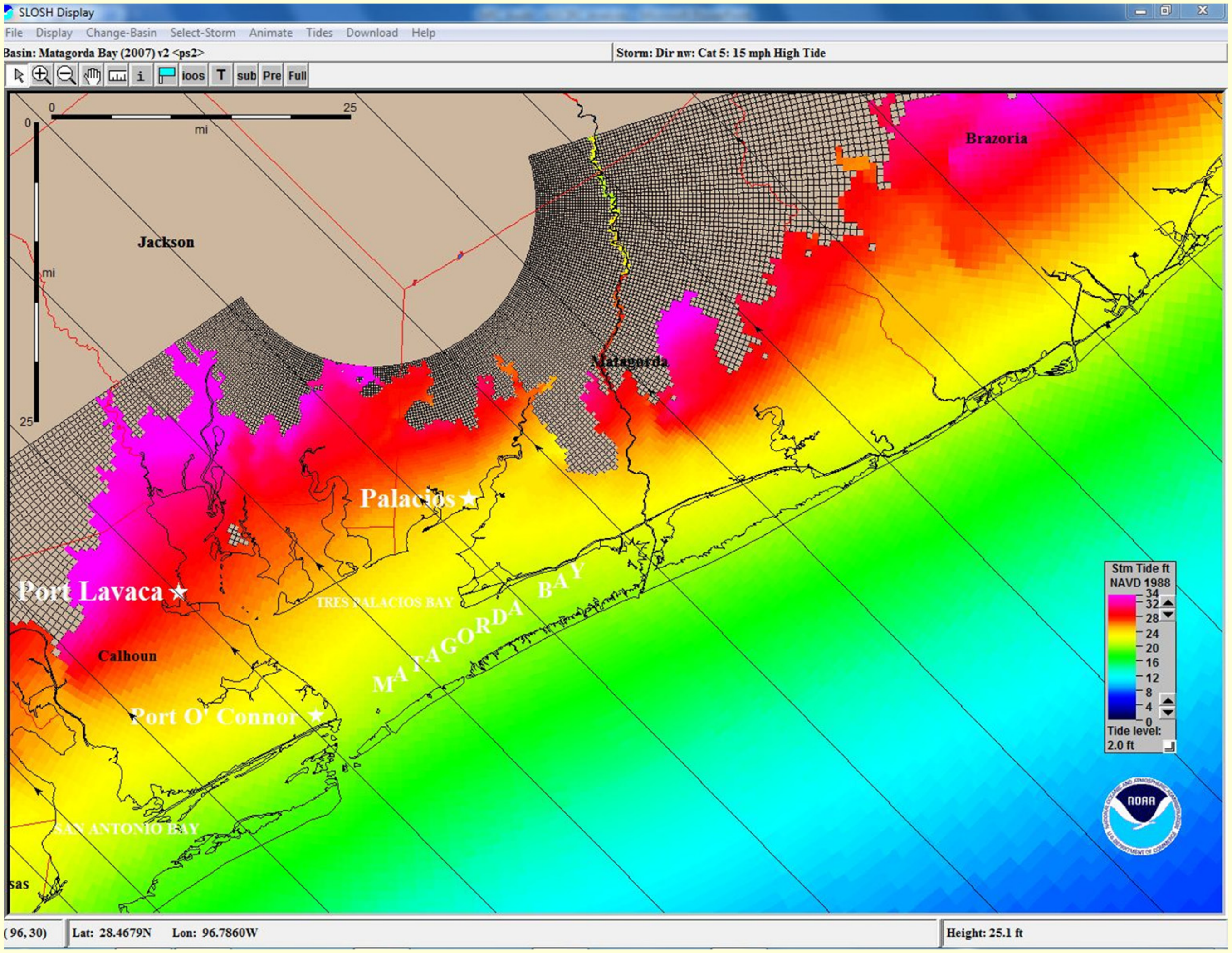
Basin: Matagorda Bay (2007) v2 <ps2>

Storm: Dir nw: Cat 4: 15 mph High Tide

(143,137) Lat: 28.2001N Lon: 95.1822W

Height: 5.9 ft

SLOSH: Cat 5 NW 15 MPH High Tide



Basin: Matagorda Bay (2007) v2 <ps2>

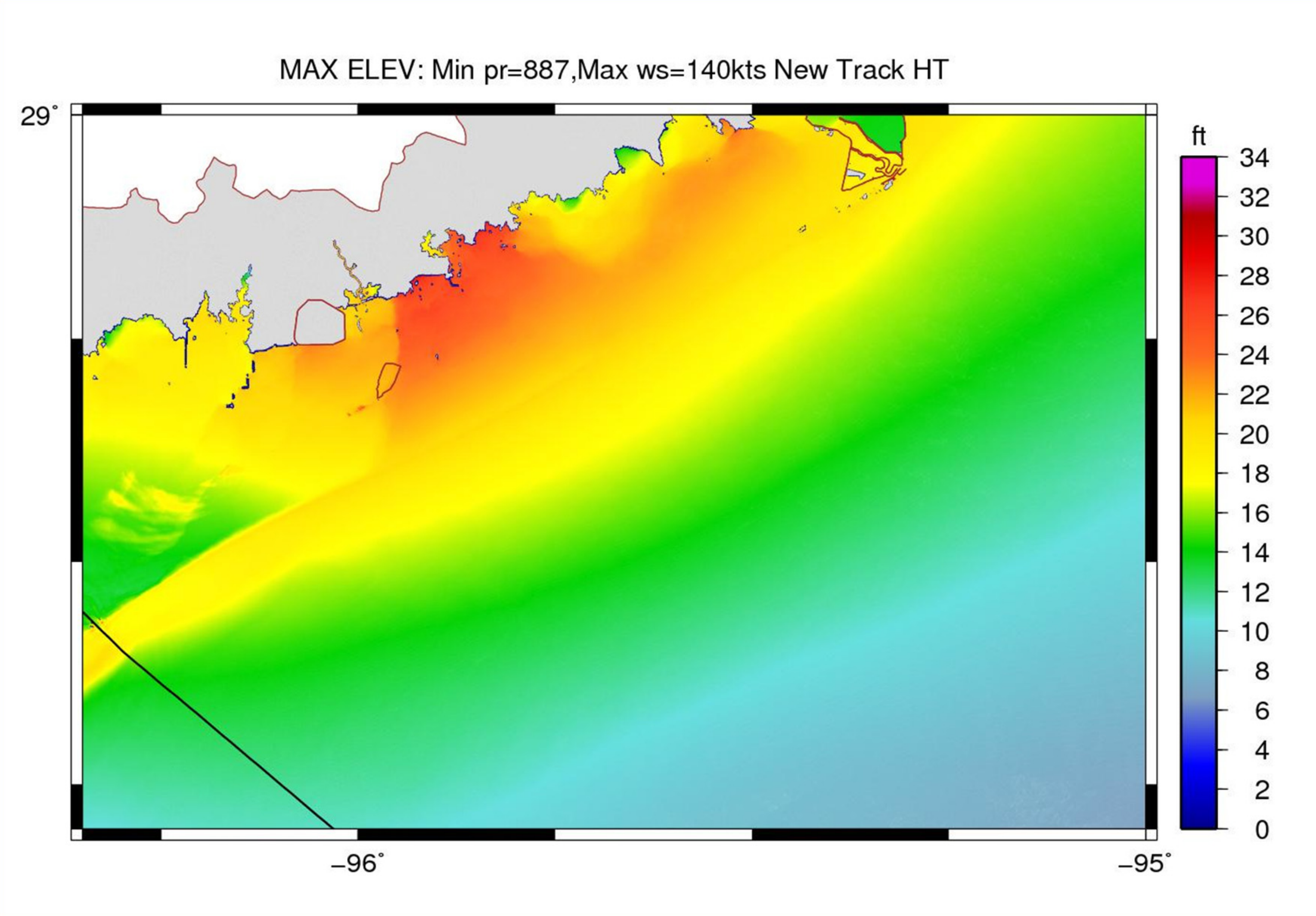
Storm: Dir nw: Cat 5: 15 mph High Tide

(96, 30)

Lat: 28.4679N Lon: 96.7860W

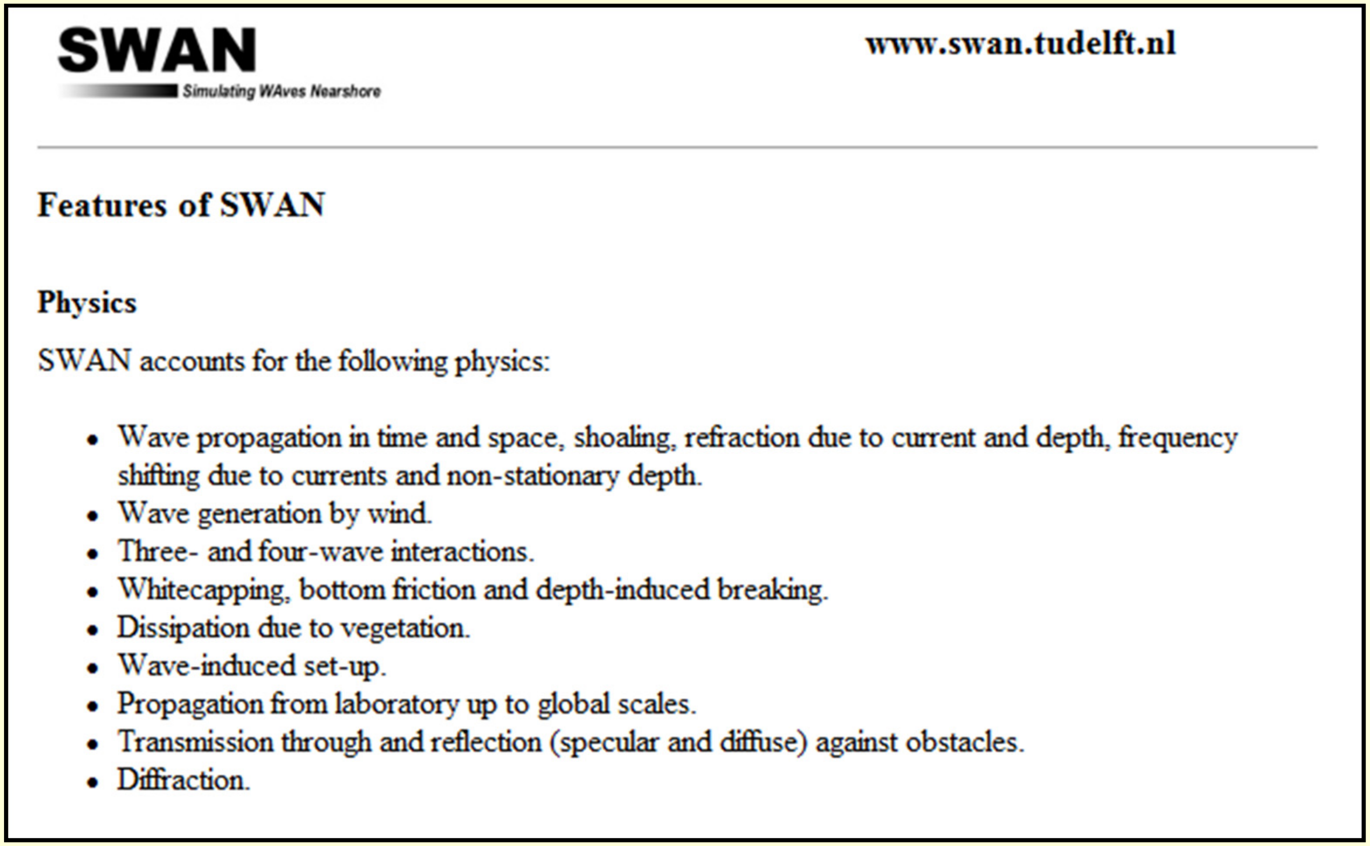
Height: 25.1 ft

ADCIRC: Cat 5 NW 23 MPH 10% High Tide



SWAN

- **Coupled to ADCIRC and uses the same grid.**



SWAN

Simulating WAves Nearshore

www.swan.tudelft.nl

Features of SWAN

Physics

SWAN accounts for the following physics:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.
- Wave generation by wind.
- Three- and four-wave interactions.
- Whitecapping, bottom friction and depth-induced breaking.
- Dissipation due to vegetation.
- Wave-induced set-up.
- Propagation from laboratory up to global scales.
- Transmission through and reflection (specular and diffuse) against obstacles.
- Diffraction.

Model Comparison – NOAA Comments

Inland, the numerical solution is coarse, but dynamic feedback effects from the bay onto the shelf are approximated. A coarse mesh does not give a detailed description of inland surges across terrain complicated by obstructions and small inland water bodies. However, it can give adequate detail along open coastlines. Only in a gross sense can the inland surge distribution be useful as a guide for forecasting or planning purposes.

Jelesnianski et al, NWS-48, NOAA, April 1992

Model Comparison – NOAA Comments

For operational convenience, wind over inundated terrain is modeled as flowing over an inland body of water (i.e., a lake).

In reality, the friction terms should be higher over inundated terrain and vary according to type of terrain.

Accordingly, computed surge values may be suspect over densely foliated terrain.

Jelesnianski et al, NWS-48, NOAA, April 1992

Model Comparison – NOAA Comments

The main reason for the SLOSH grid coarseness is the fact that it is used primarily in a forecast mode or in a simulation study mode which means computational speed is key.

Surge heights don’t vary dramatically over short distances, except where the flow is blocked by a levee or barrier.

Arthur Taylor, NOAA, 2010

Model Comparison – NOAA Comments

Experiments are being conducted through NOAA's IOOS* program to compare output results between the two models. One of the first issues to address is to make sure they use the same wind fields.

While ADCIRC might produce more accurate surge estimates, it will be difficult to discern that difference due to the errors in the wind estimate.

Arthur Taylor, NOAA, August 2010

* Integrated Ocean Observing System: http://ioos.gov

Model Comparison – Summary

ADCIRC	SLOSH
More advanced wind model.	Simplified Wind Model.
Multiple Friction Coefficients.	Limited Friction Coefficients.
Finer resolution with more frictional variations.	Coarser resolution with limited frictional variations.
Very good delineation of irregular shorelines.	Fair delineation of irregular shorelines.
Model includes wave setup (SWAN*).	Wave setup excluded.
Often includes features that block or accelerate storm surge flooding.	Sometimes omits features that block or accelerate storm surge flooding.
Robust validation for Texas.	Limited validation for Texas.

* Simulating WAves Near shore: www.swan.tudelft.nl

Model Comparison – Differences

- **Grid Resolution**
- **Terrain Features (City of Matagorda Levee)**
- **Wind Model**
- **Friction Coefficients**
  - Bottom
  - Surface
- **Pressure Differential**
  - SLOSH: 133 Mb
  - ADCIRC: 123 Mb to 126 Mb

FSAR 2.4.5, “Probable Maximum Surge and Seiche Flooding”

Questions/Comments