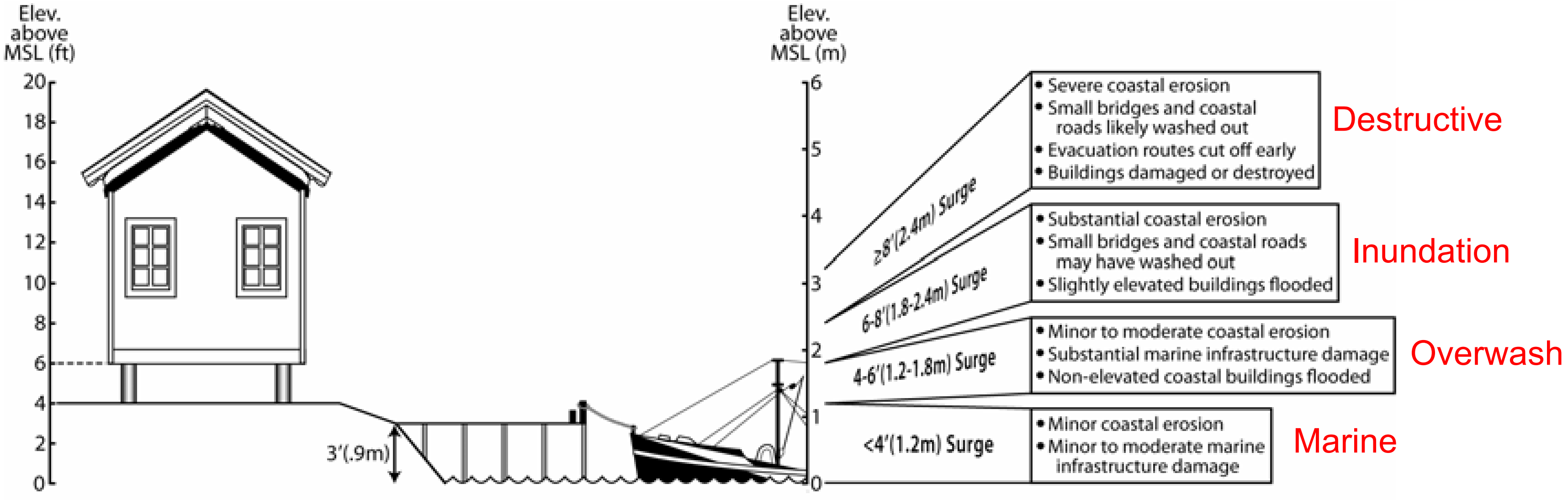
The Power of Storm Surge

A neighborhood in Long Beach, MS August 29, 2005

Why Model Storm Surge?

1) Storm surge impacts can be devastating to life and property
A cubic yard of water weighs about 1,700 pounds.

2) Resulting damage affects infrastructure, economy, and environmental conditions.



Storm surge impacts in communities along the U.S. Gulf coast

Hal Needham and Barry D. Keim (2011).

Models are an economically feasible virtual laboratory to assist in coastal planning

STORM SURGE MODELING

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Universidad Técnica Federico Santa María,
2–13 January, 2013 — Valparaíso, Chile

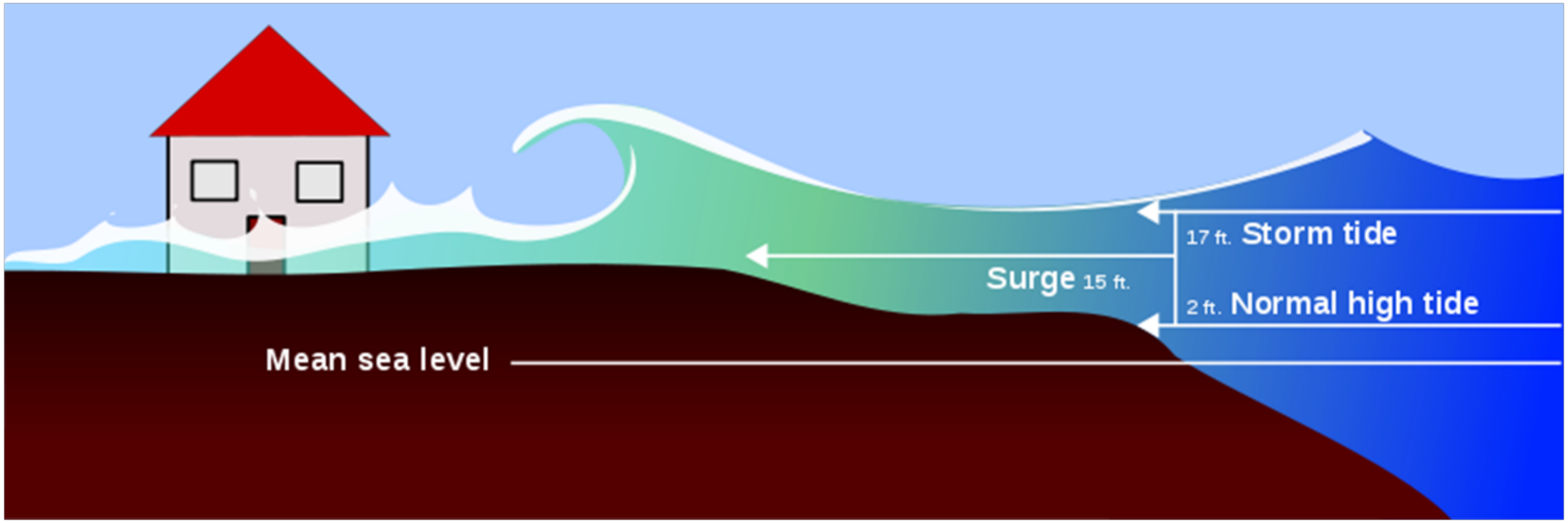
STORM SURGE MODELING

Outline

1) What is Storm surge?
2) Factors Contributing to Storm Surge
3) Simulation requirements
4) Operational Surge Models
5) ADCIRC – Katrina Example
6) Considerations
    a) domain size
    b) inundation algorithm
    c) bottom friction representation
    d) specification of GWCE weighting parameter
    e) surface roughness and wind drag
7) Drivers for accurate surge modeling

What is Storm Surge?

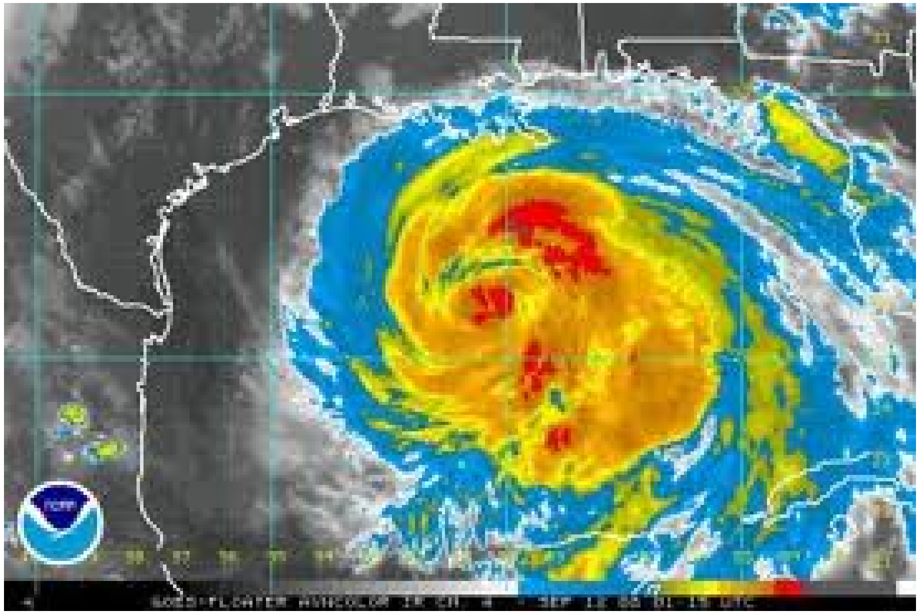
Abnormal sea level elevations (or depressions) caused by wind and atmospheric pressure



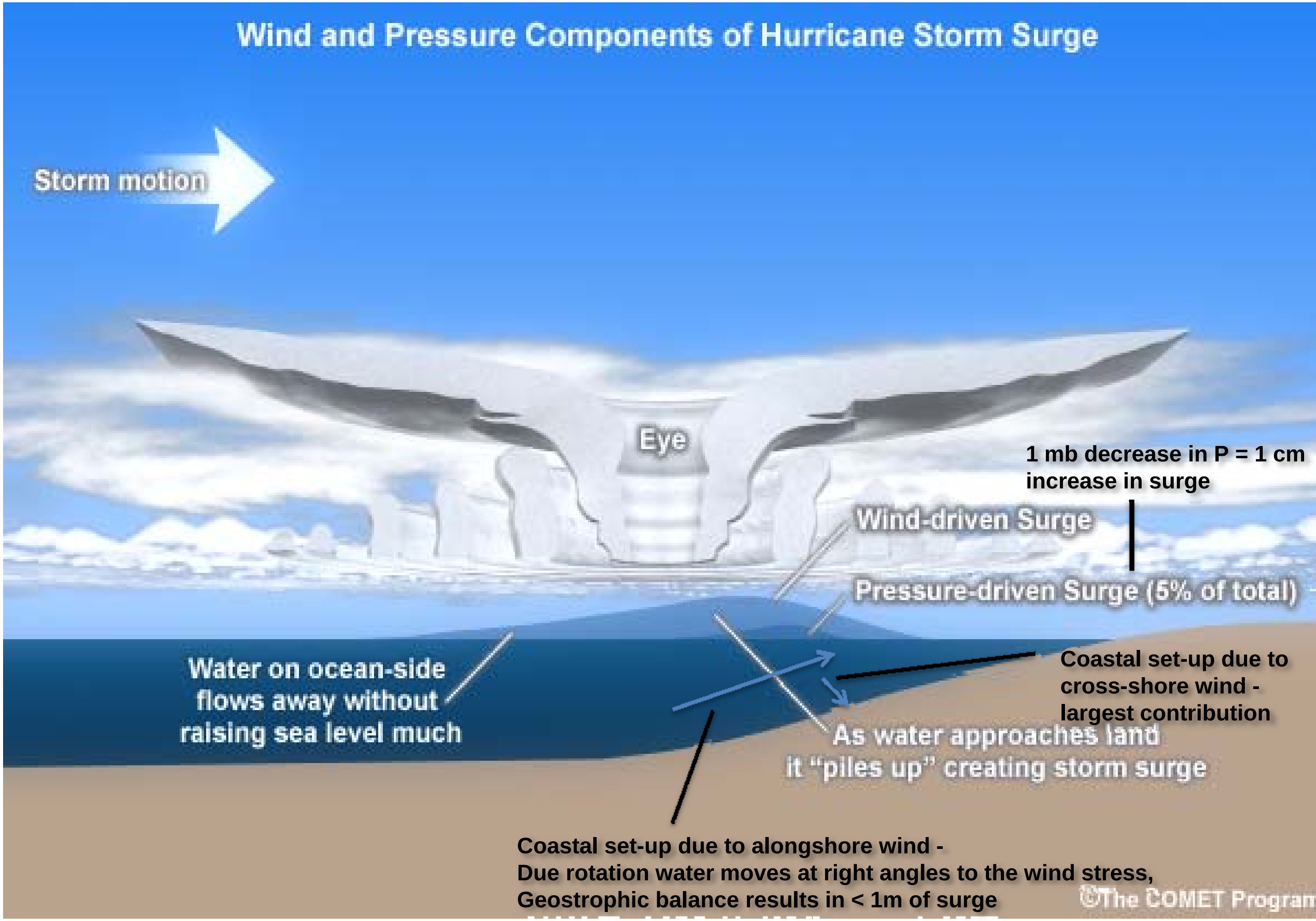
"Piling up of water at the coast"

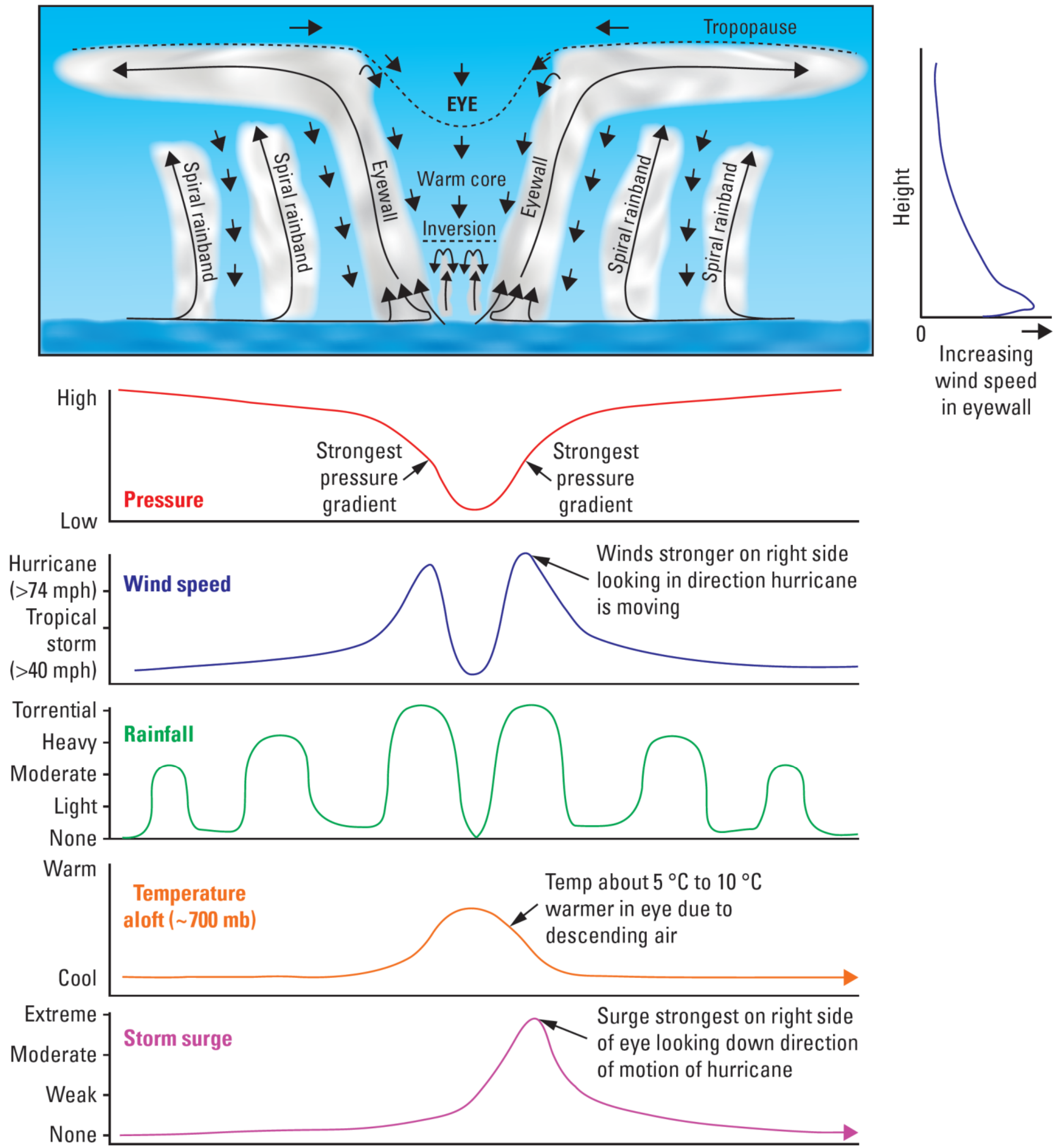
What is Storm Surge?

- How it all piles up:
  - *low pressure system* (storm) generates wind
  - *wind* blows across the sea surface
  - *friction* between the wind and water pushes the water in the direction of the wind
  - *tides* caused by the gravity of the sun and moon contribute to the rise in ocean surface
  - the ocean starts to pile up along the coastline
  - *waves* form on top of the newly arisen sea



Components of Storm Surge




Tropopause
EYE
Warm core
Inversion
Eyewall
Eyewall
Spiral rainband
Spiral rainband
Spiral rainband
Spiral rainband
Height
0
Increasing wind speed in eyewall
High
Low
Pressure
Strongest pressure gradient
Strongest pressure gradient
Hurricane (>74 mph)
Tropical storm (>40 mph)
Wind speed
Winds stronger on right side looking in direction hurricane is moving
Torrential
Heavy
Moderate
Light
None
Rainfall
Warm
Cool
Temperature aloft (~700 mb)
Temp about 5 °C to 10 °C warmer in eye due to descending air
Extreme
Moderate
Weak
None
Storm surge
Surge strongest on right side of eye looking down direction of motion of hurricane

Factors Contributing to Storm Surge

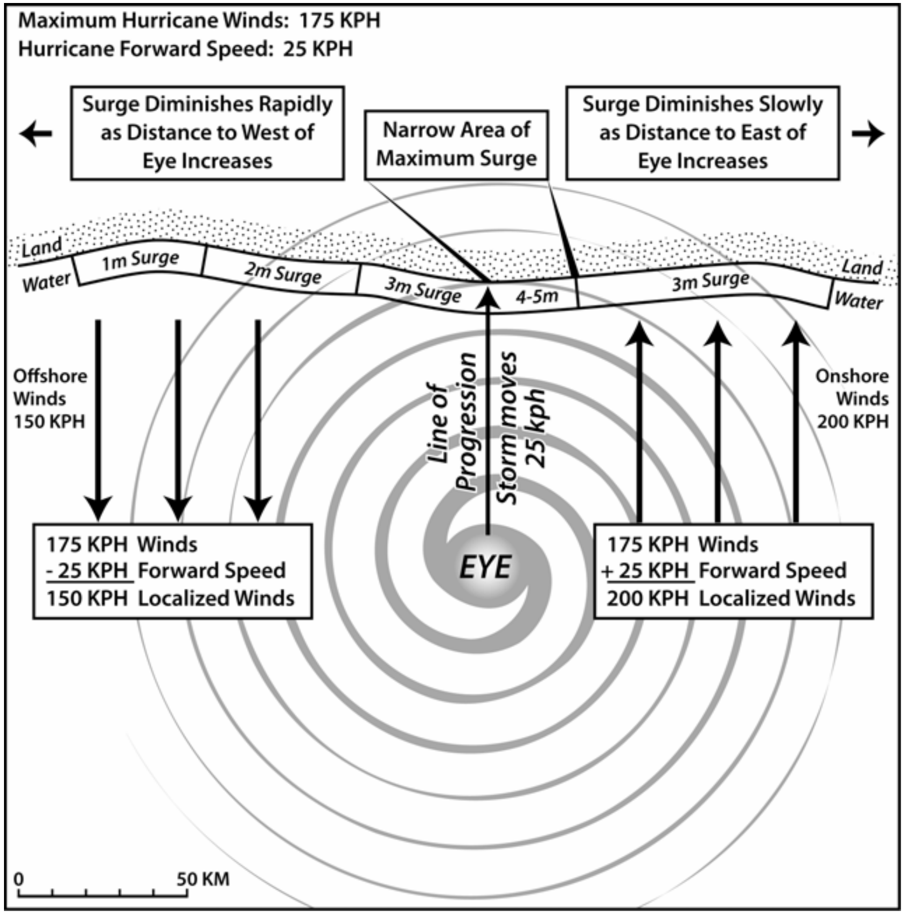
- Wind – usually associated with a tropical storm or hurricane

  speed, direction, angle of approach to the coast

- Storm forward speed and size affects:

  fetch – the distance over which the wind interacts with the surface of the ocean

  time – the length of time wind blows over an area of the ocean

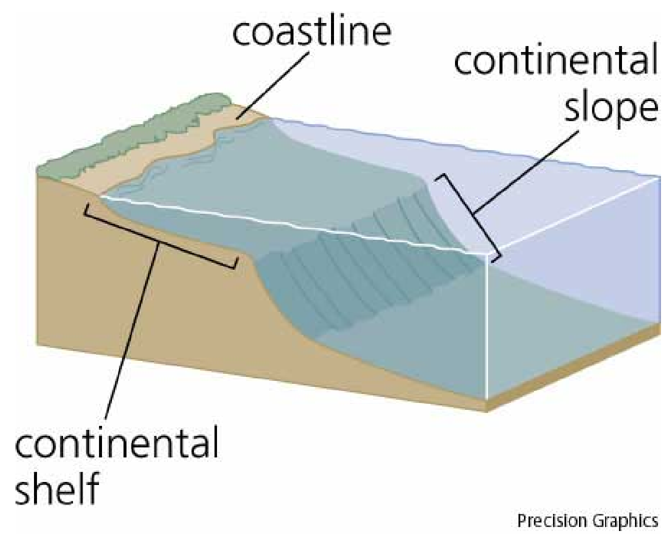


Strong wind + large fetch + long time + track perpendicular to the coast =

Highest Surge

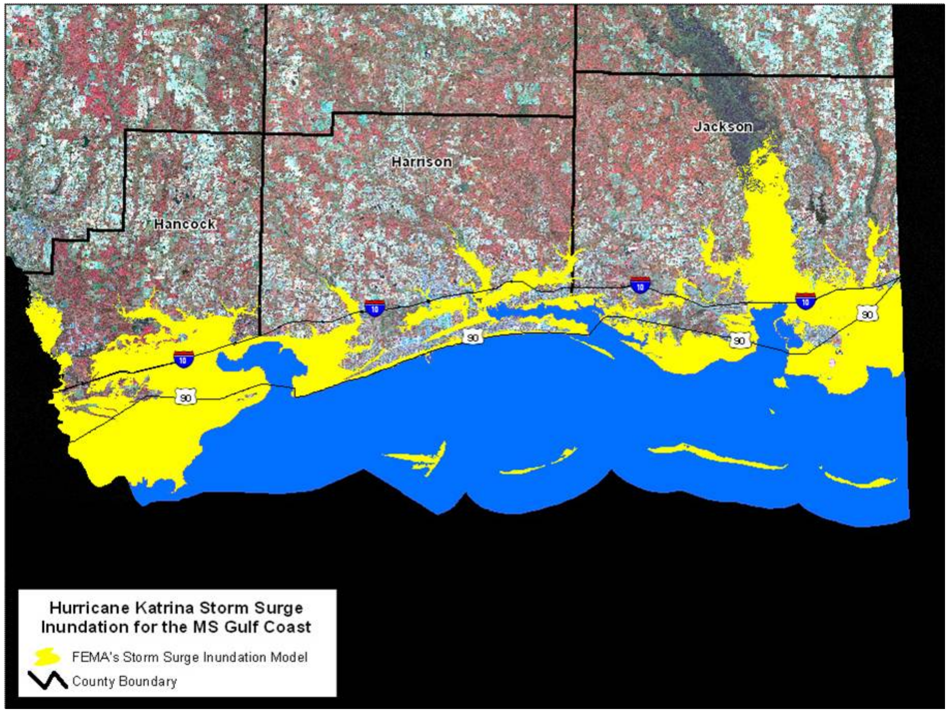
Factors Contributing to Storm Surge

- Low (air) storm pressure over the ocean
- Tides - phase of the tide dictates contribute to storm surge height
- Waves – additive to storm surge
- Slope and width of the continental shelf
  - in shallow water the sea surface slope required to balance the across shelf wind stress is inversely proportional to water depth. Hence wide, shallow shelves are prone to larger storm surges.
- Coastal geometry
  - by varying fetch and direction relative to a hurricane, embayment geometry is very important, as are the water depths and land elevations.
- Friction
  - presence of barrier islands, land cover with high surface roughness



What Storm Surge is Not

- Storm surge is not:
  - High tide
  - High waves
  - Swell - waves outside the fetch
  - Limited to the immediate coast – affects adjoining rivers and bays



Katrina Storm surge along the coast also forced adjoining waters in bays and bayous to rise. As a result residents as far as 10 miles inland were flooded. Some areas were flooded from the south (coastal ocean water) and from the north (overflowing bays and bayous).

Hurricane Storm Surge Simulation Requirements

- A high resolution, physics-based circulation model with flooding and drying capabilities.

- A high resolution water depth (bathymetry) and land (topography) elevation data set on which to overlay the model.

- Accurate (time and space) wind and pressure fields to drive the model.

- Land cover/ land use data base for establishing bottom friction coefficients and wind drag modifications

Operational Storm Surge Prediction

- Operational surge forecast models used today, e.g.
  - Extended Area Continental Shelf Model: fine grid (CS3X) – National Oceanography Center, England
  - Shallow Water Hydrodynamic Finite Element Model (SHYFEM), Institute of Marine Sciences - National Research Council (ISMAR), Italy

  In the U.S.:
  - SLOSH (Sea, Lake, and Overland Surges from Hurricanes), National Weather Service/National Hurricane Center
  - ADCIRC – (Advanced CIRCulation), Army Corps of Engineers, US Navy

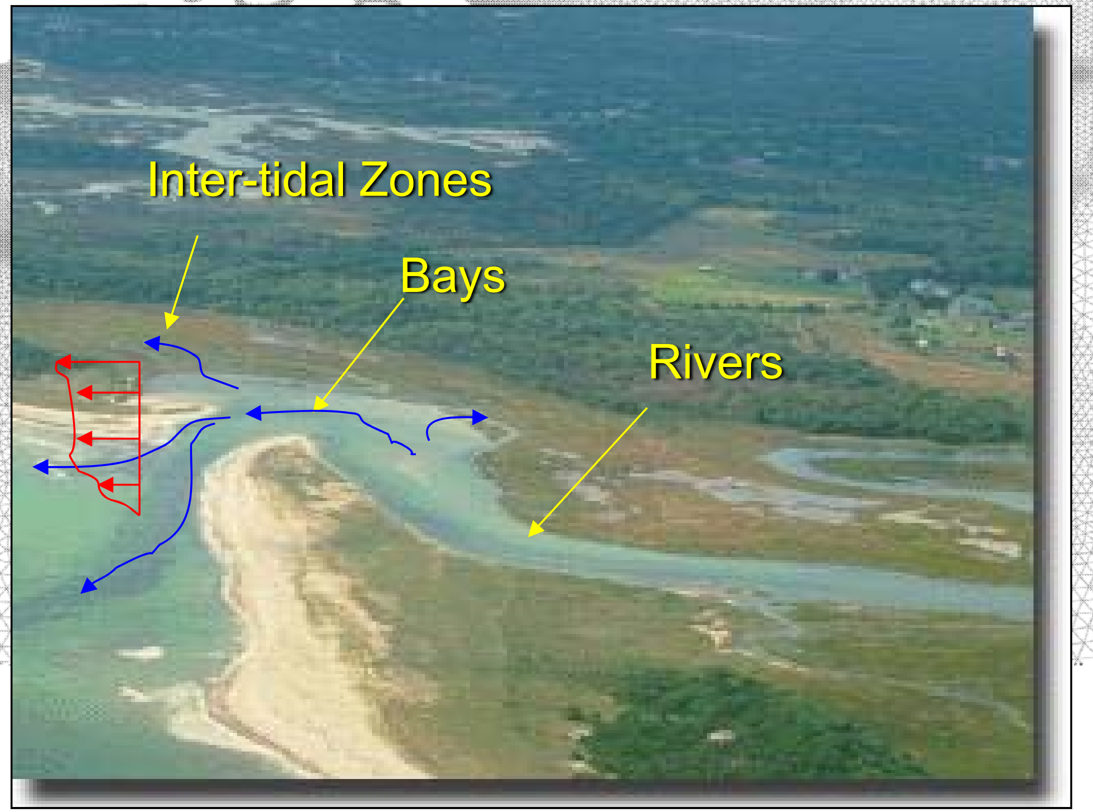
Criteria for Success

- Accurate and flexible dynamical model
- Ability to meet operational time constraints
- Automated, rapid relocation
- Generation of meaningful operational products
- Quantification of forecast skill

ADvanced CIRCulation Model

Predictive Capability for Coastal Circulation

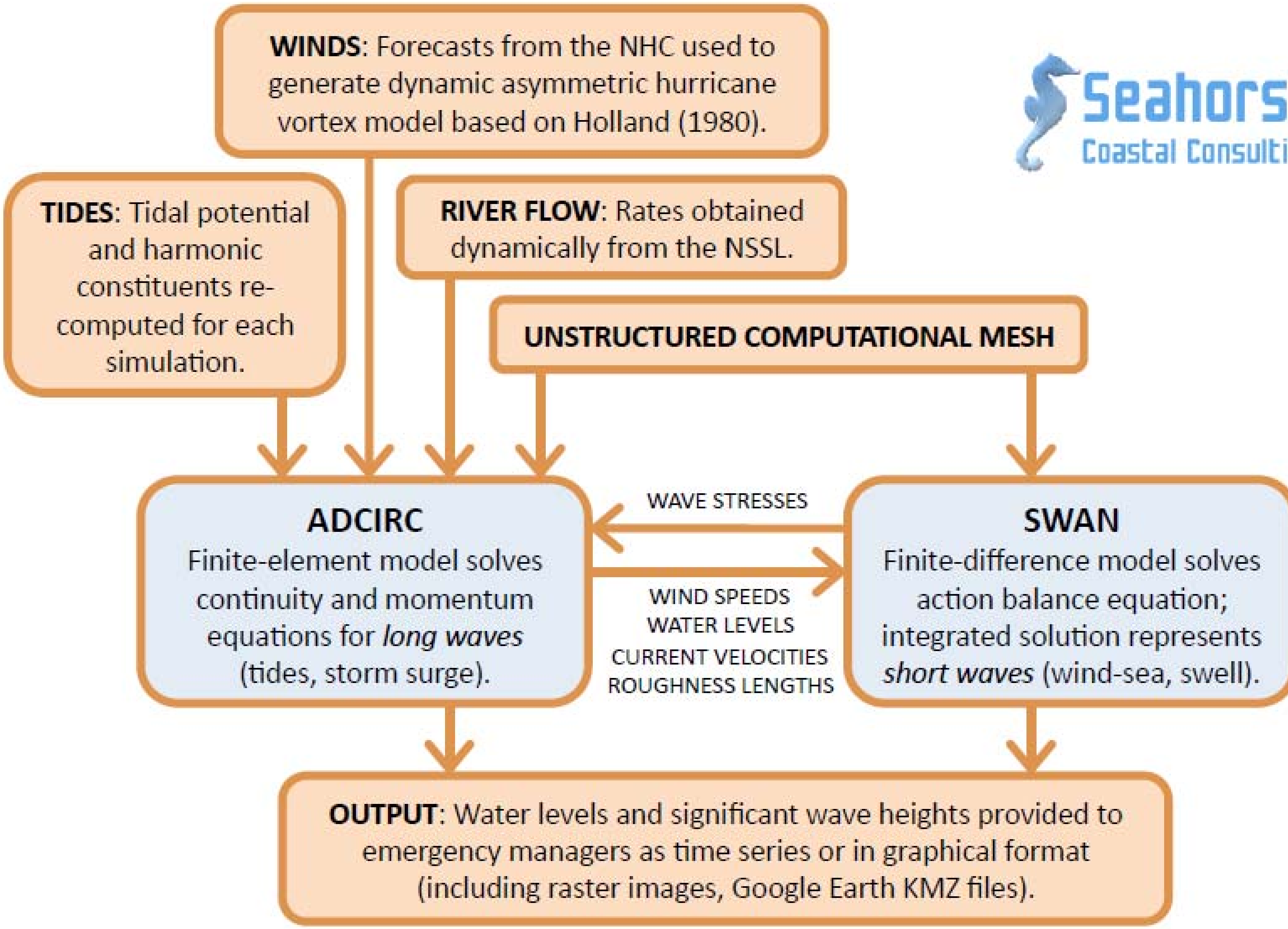
- High resolution (meters) currents, water levels, temperature, and salinity in littoral environments that include bays, estuaries, inter-tidal marshes and rivers



ADCIRC Model

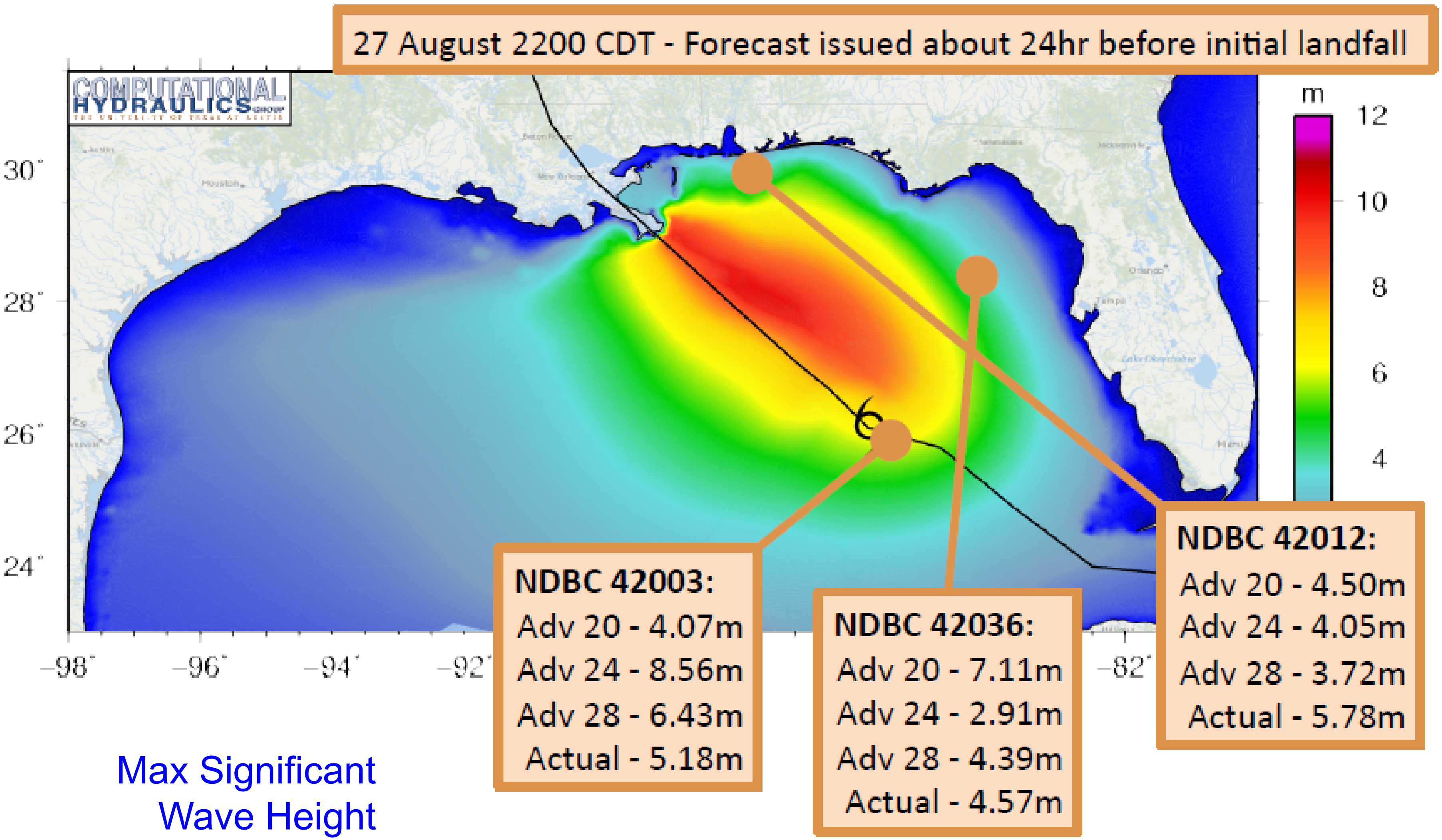
- 3D coastal ocean dynamics
- Forcing from tides, wind, waves, buoyancy, and rivers
- Shoreline inundation/recession
- Utilizes unstructured grids (based on finite elements)
- MPI parallelization

ASGS : ADCIRC Surge Guidance System



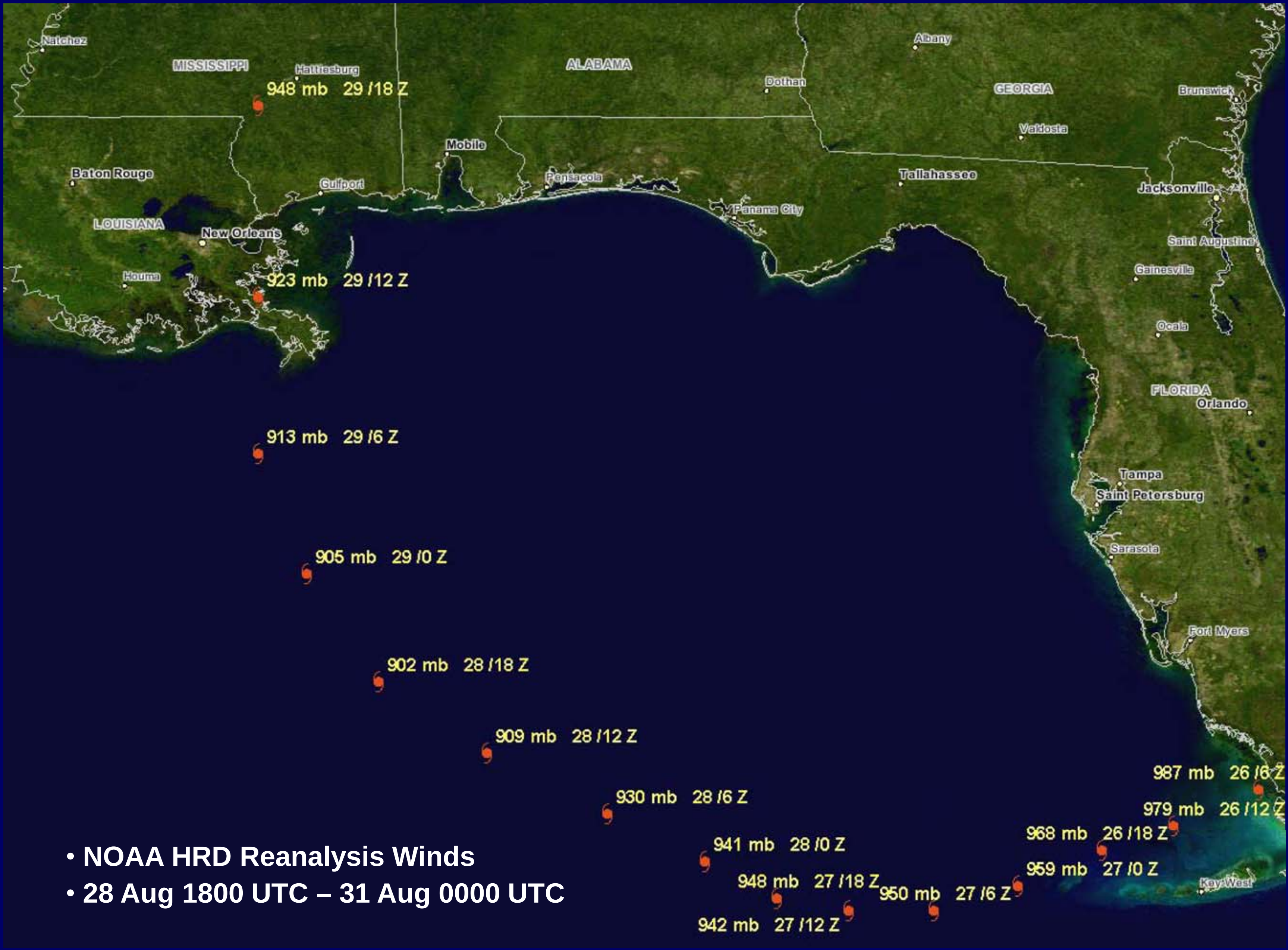
Seahorse Coastal Consulting

Forecast Modeling for Hurricane Issac, Aug. 2012



Max Significant Wave Height

Hurricane Katrina Storm Surge and Inundation



- **NOAA HRD Reanalysis Winds**
- **28 Aug 1800 UTC – 31 Aug 0000 UTC**

Hurricane Winds

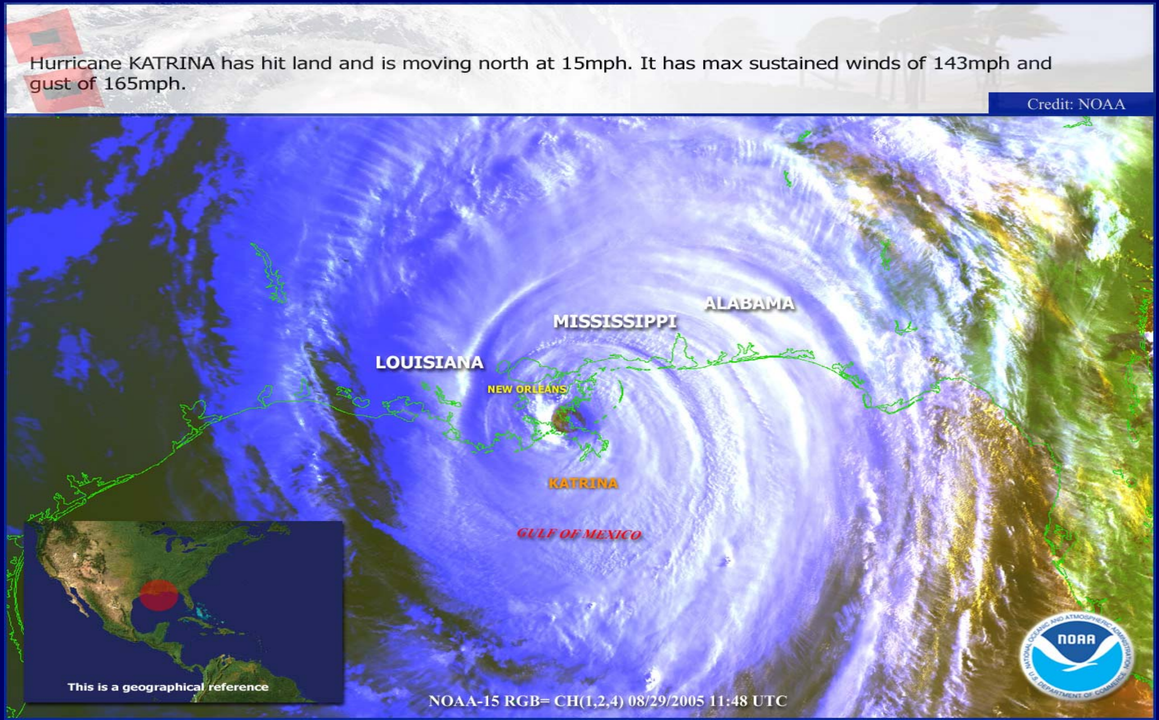
NOAA HRD H*Wind Reanalysis

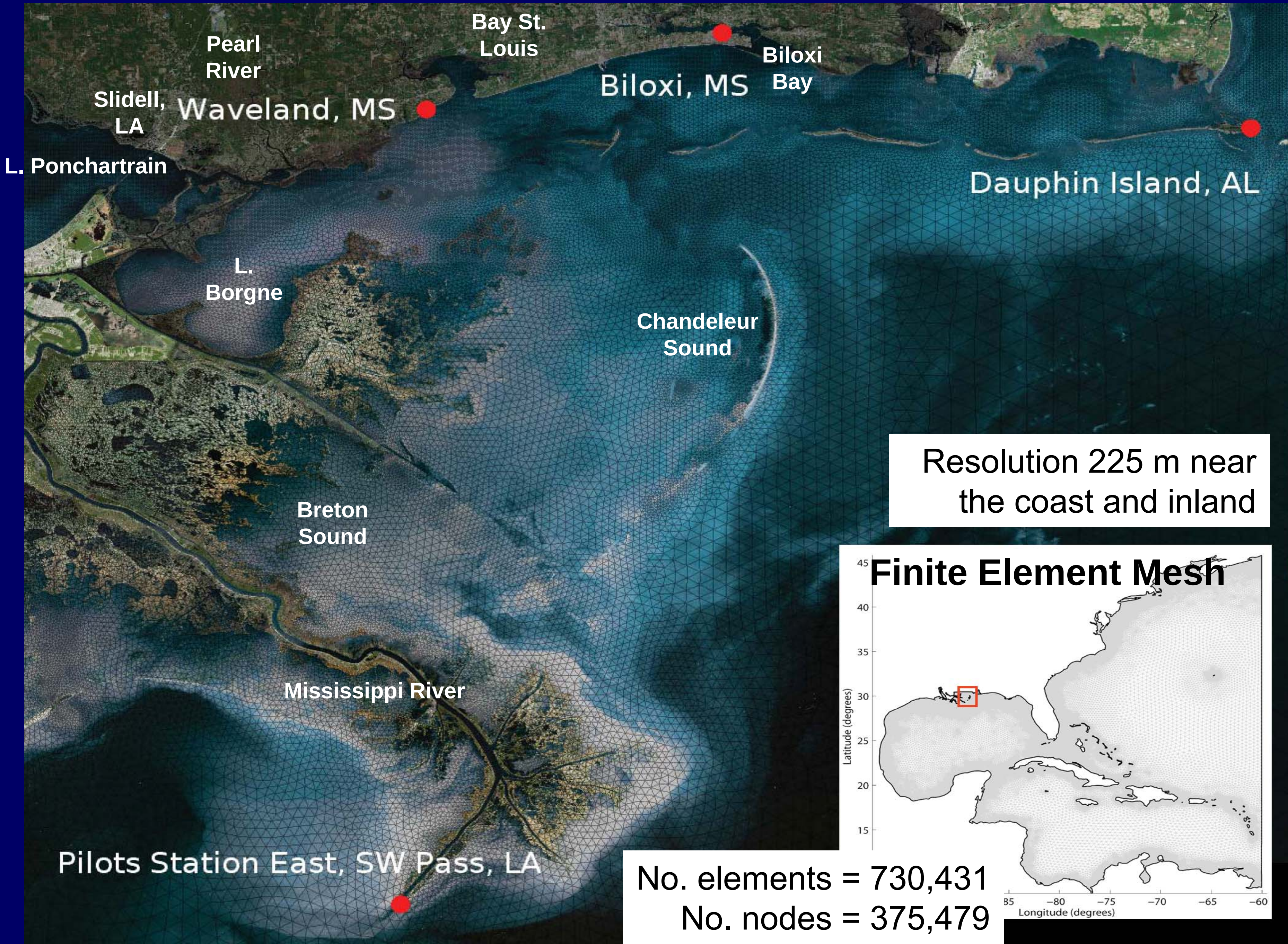
www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/wind.html

28 Aug 1800 UTC – 30 Aug 1000 UTC

Lagrangian interpolation to 15-minute intervals

Garratt surface wind drag parameterization

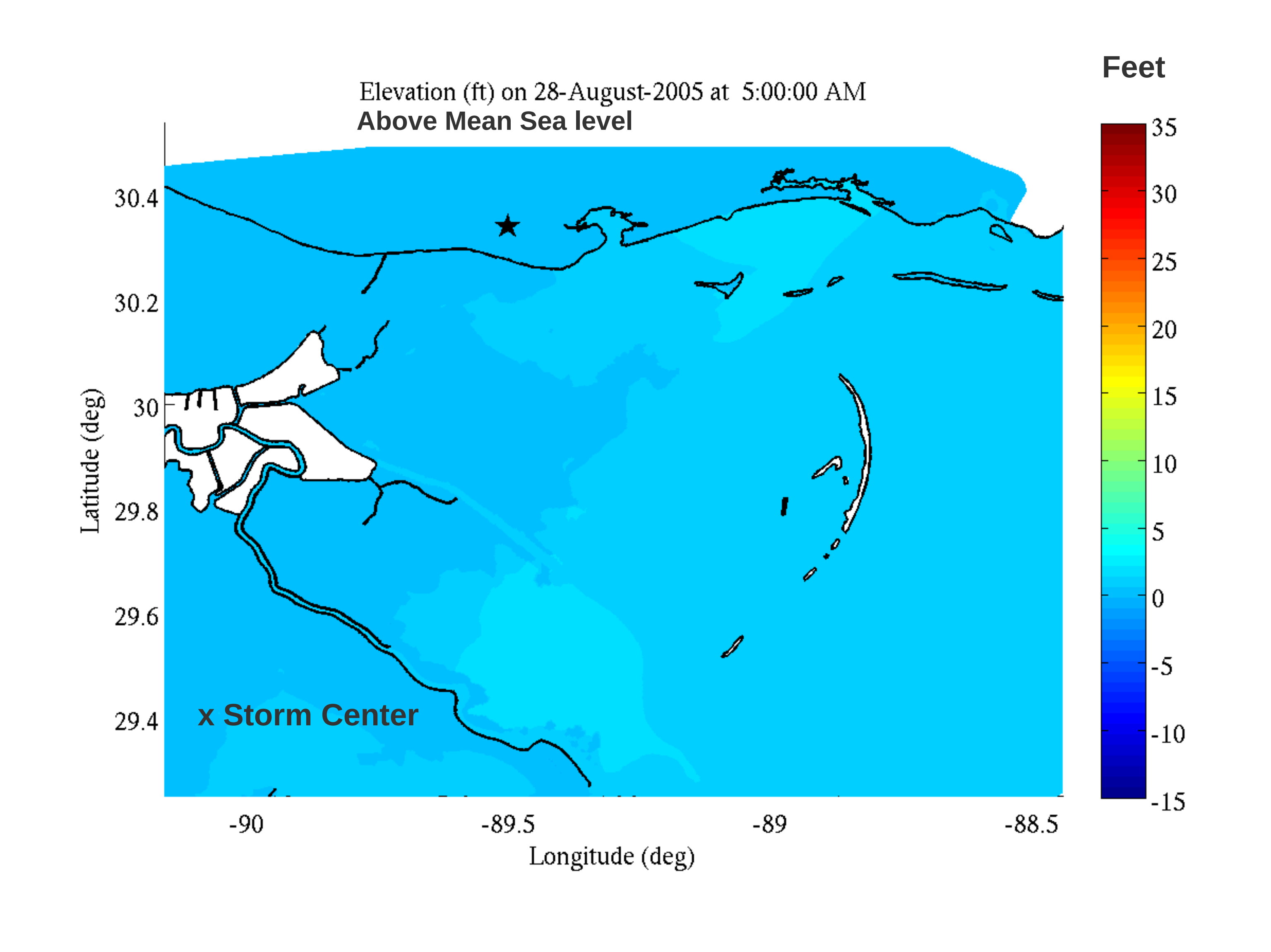



Bay St. Louis
Pearl River
Biloxi Bay
Biloxi, MS
Slidell, LA
Waveland, MS
L. Ponchartrain
Dauphin Island, AL
L. Borgne
Chandeleur Sound
Resolution 225 m near the coast and inland
Breton Sound
Finite Element Mesh
Latitude (degrees)
Longitude (degrees)
45
40
35
30
25
20
15
85
−80
−75
−70
−65
−60
Mississippi River
Pilots Station East, SW Pass, LA
No. elements = 730,431
No. nodes = 375,479

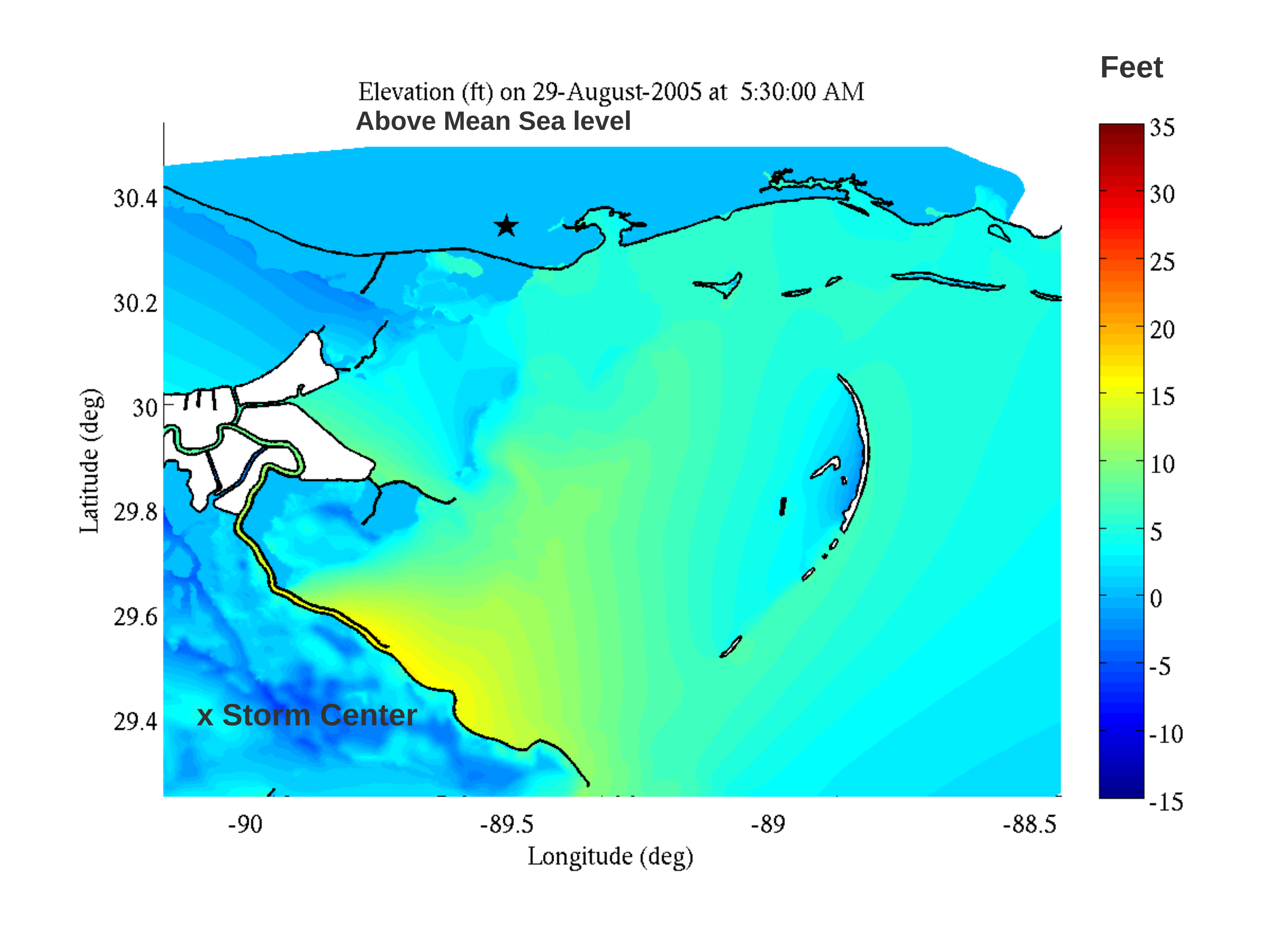
Hindcast Description

- Tides forced at boundary from Grenoble FES99
- Tidal potential forced within the domain
- Wetting and drying
- Nonlinear hybrid bottom friction relation
- Constant frictional coefficient
- Time step of 1 sec
- 15 day ramp-up of forcing
- 3 days and 10 hrs simulated
  8/27 0000 UTC - 8/30 1000 UTC
- 128 processors NAVOCEANO IBM-P4
- ~1 CPU hour/ simulation day

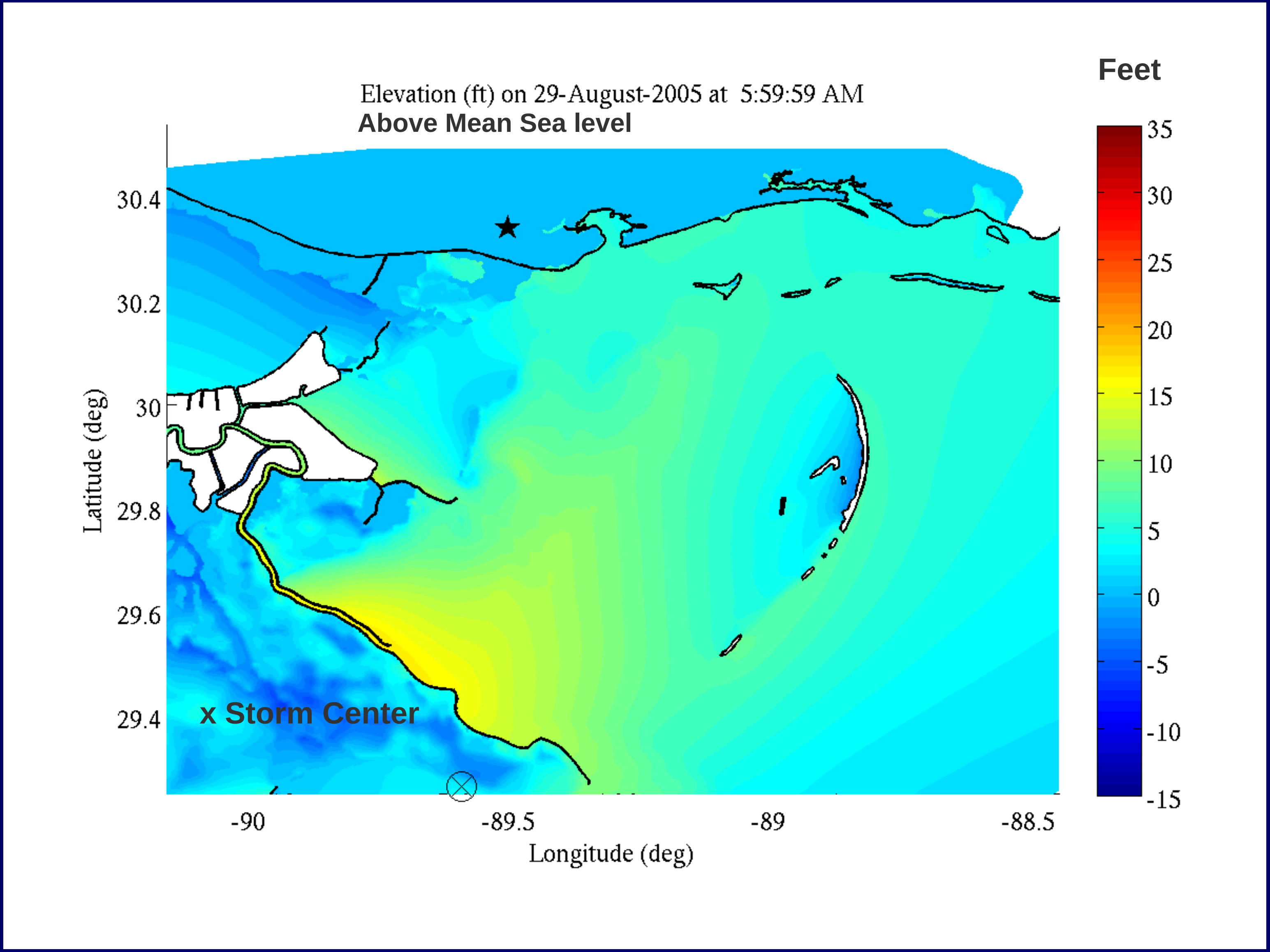
ADCIRC Computed Tides + Surge



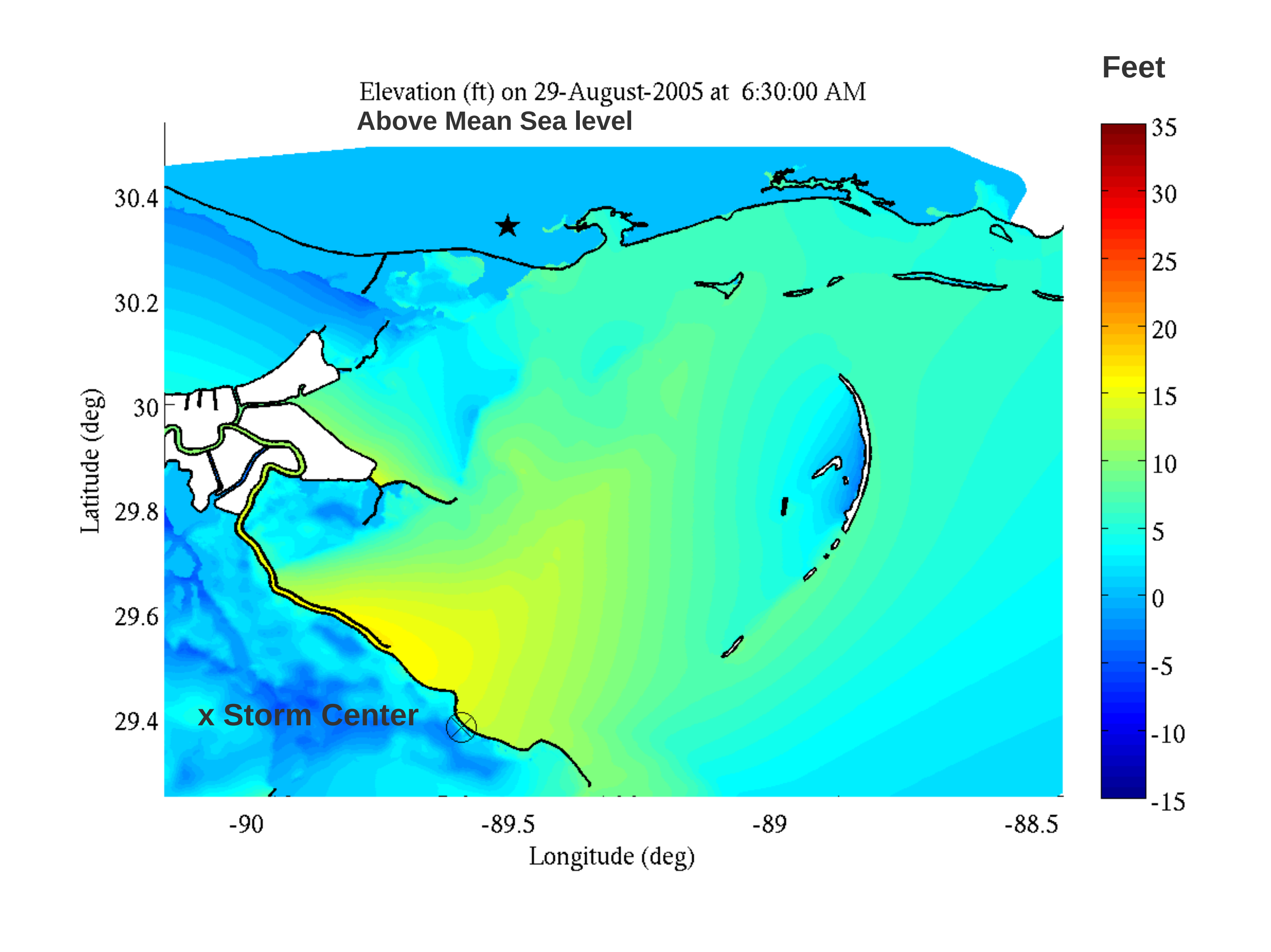
ADCIRC Computed Tides + Surge



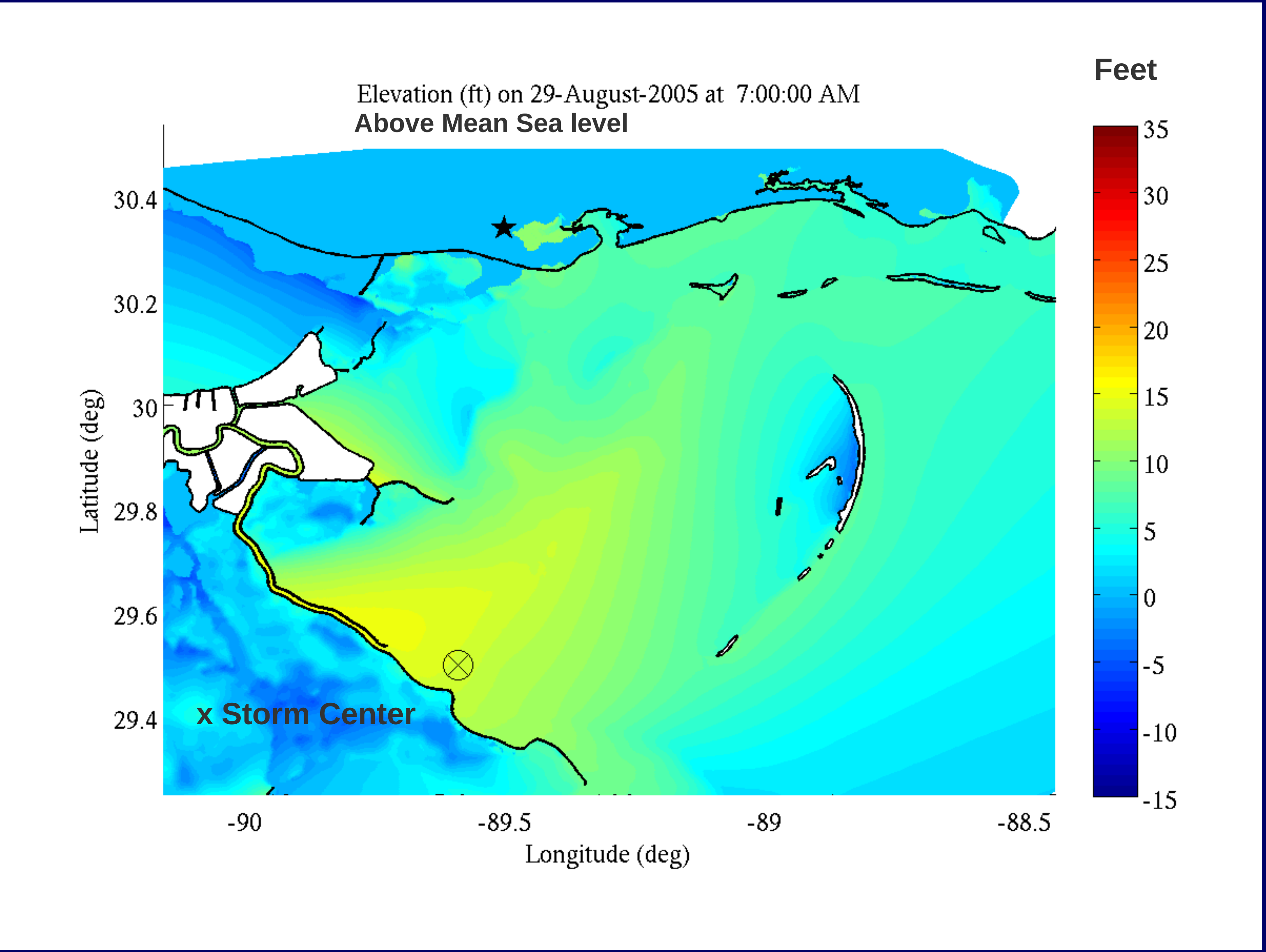
ADCIRC Computed Tides + Surge



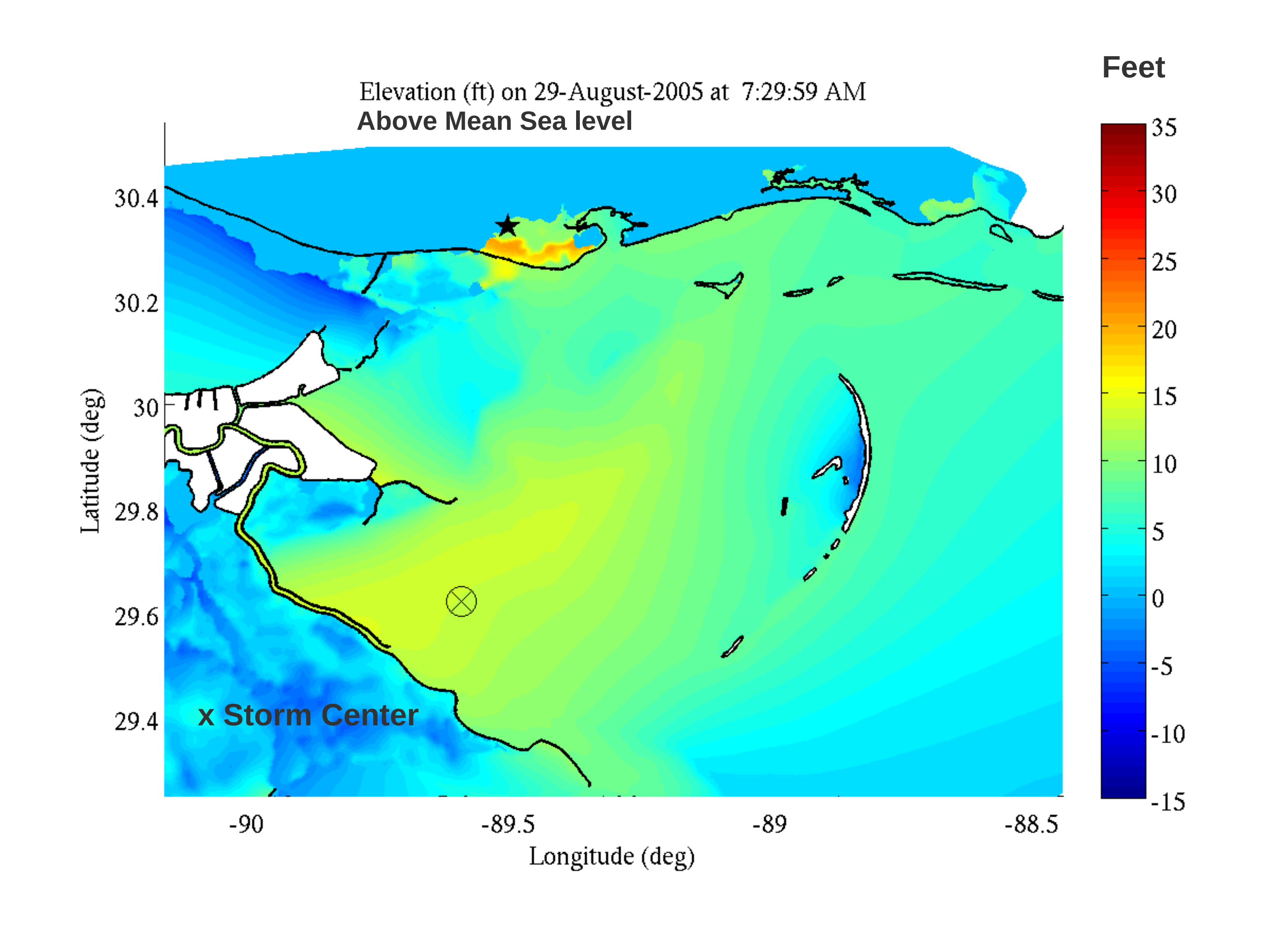
ADCIRC Computed Tides + Surge



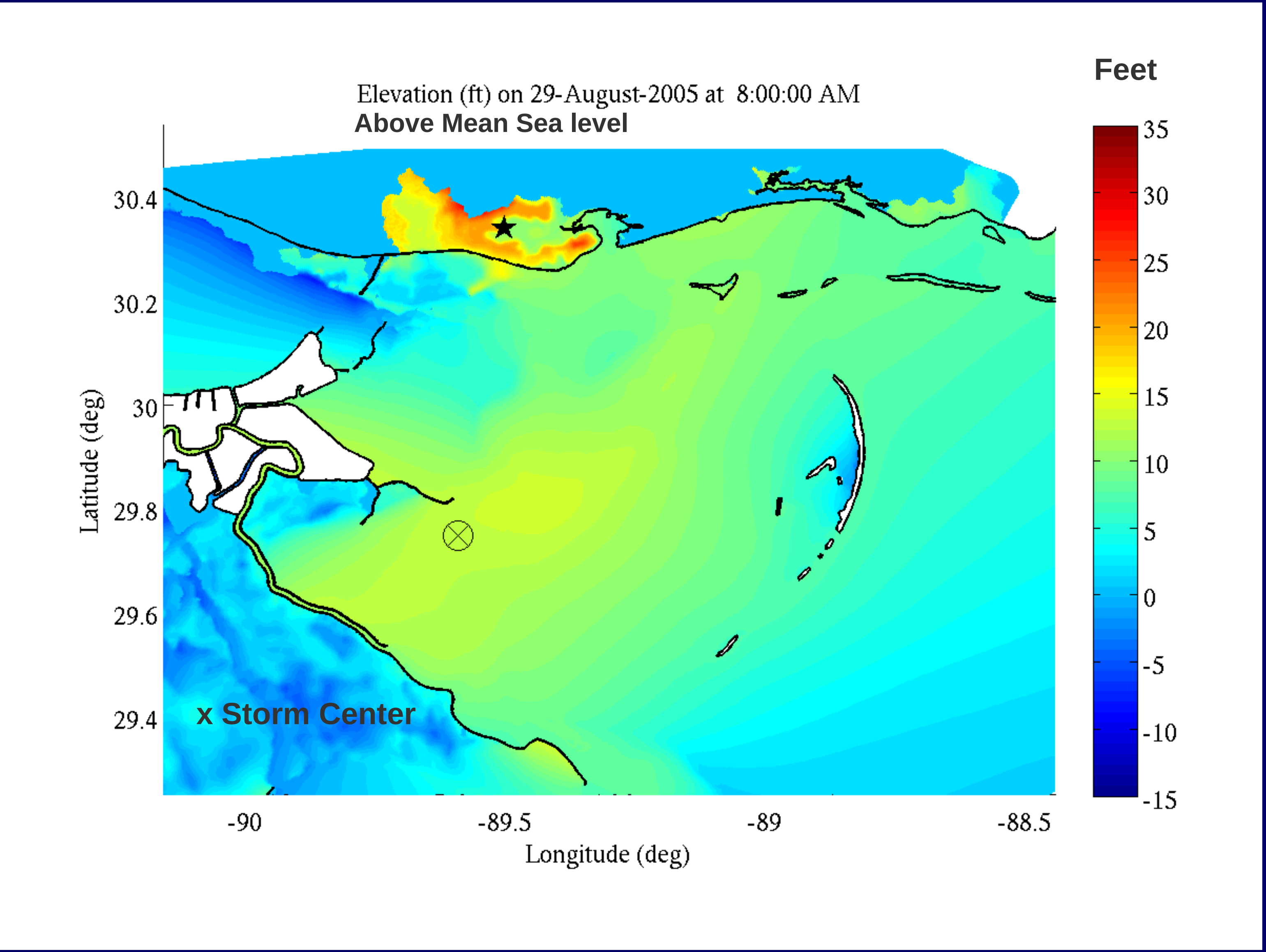
ADCIRC Computed Tides + Surge



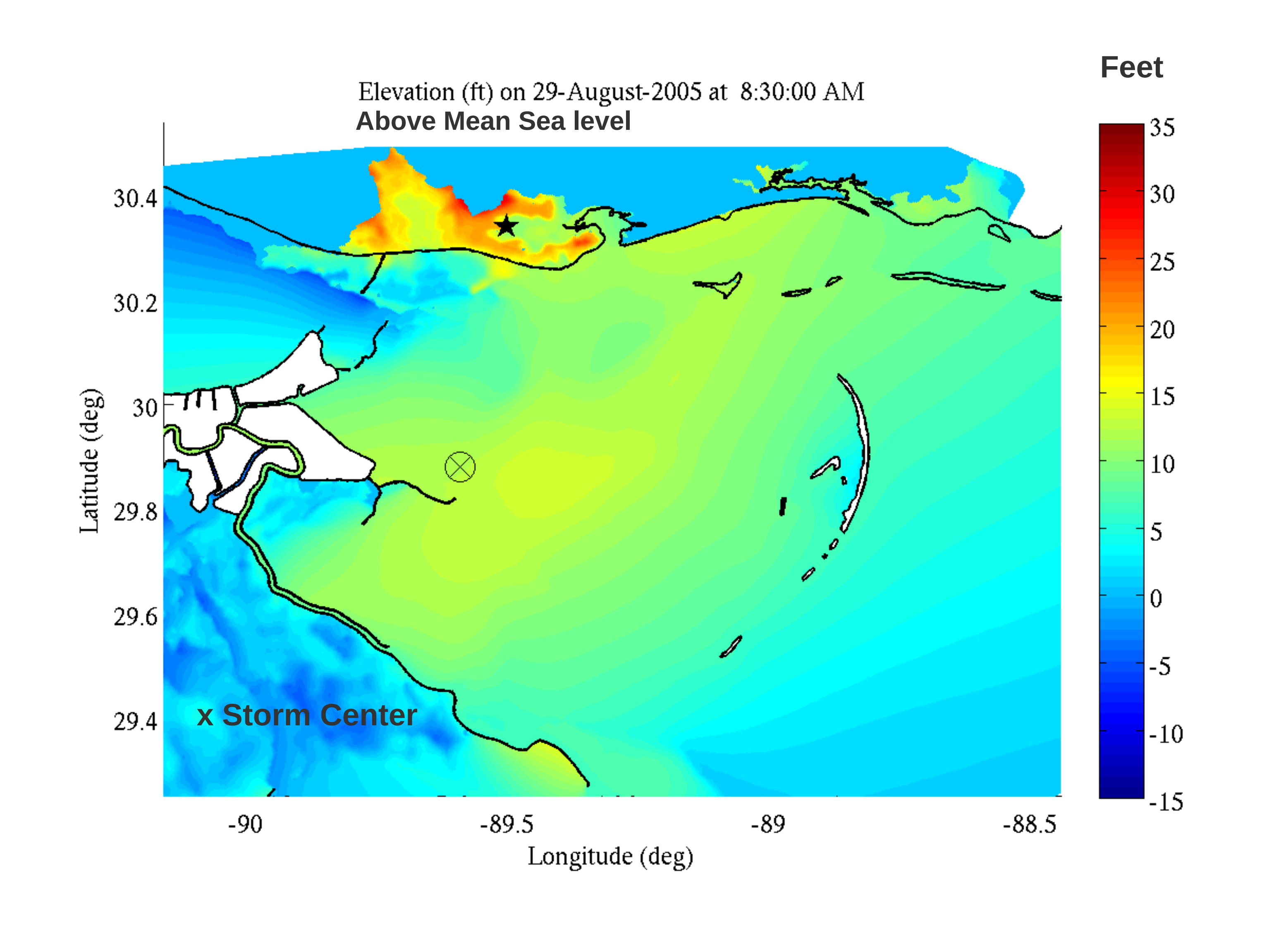
ADCIRC Computed Tides + Surge



ADCIRC Computed Tides + Surge



ADCIRC Computed Tides + Surge



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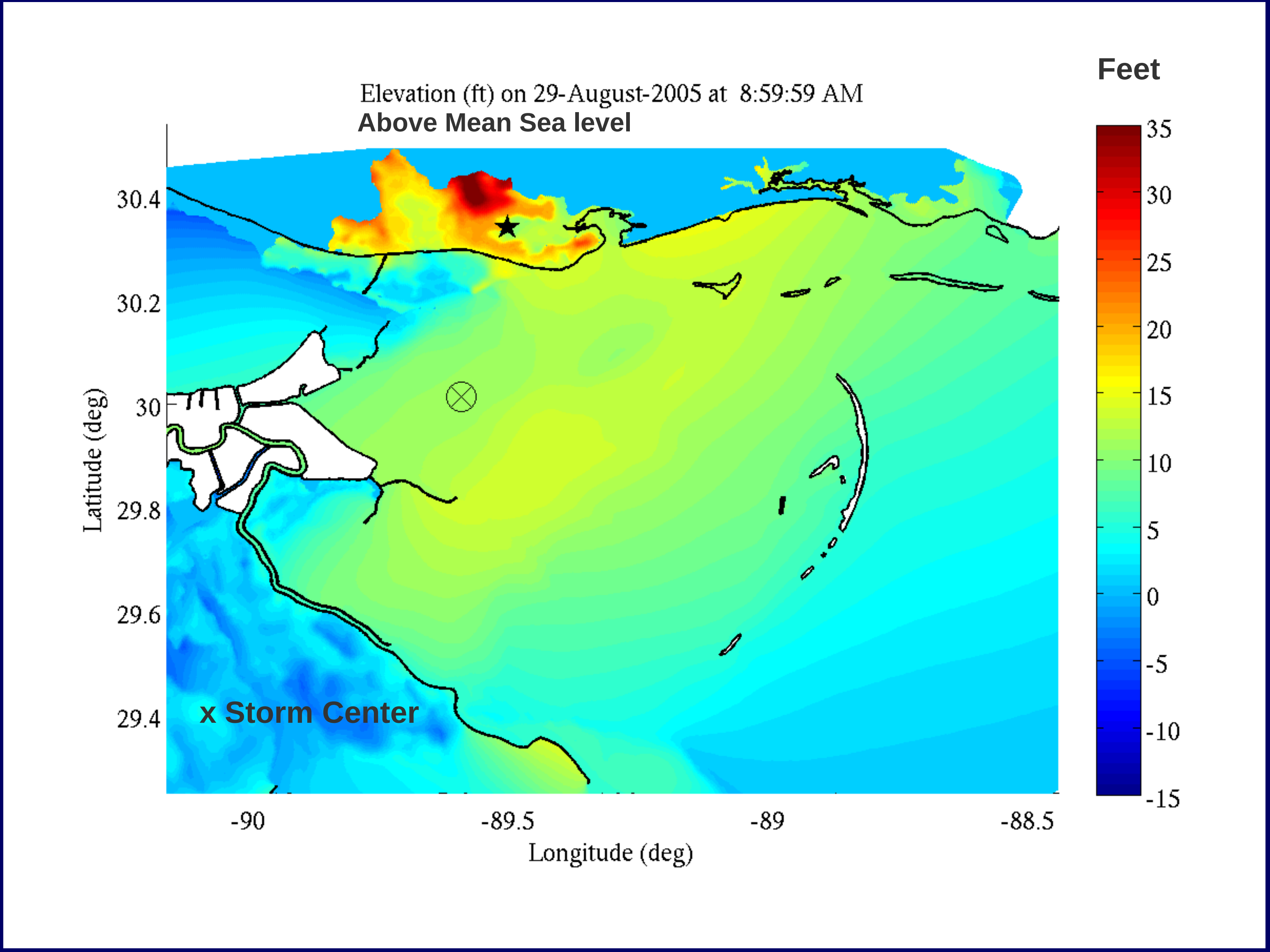

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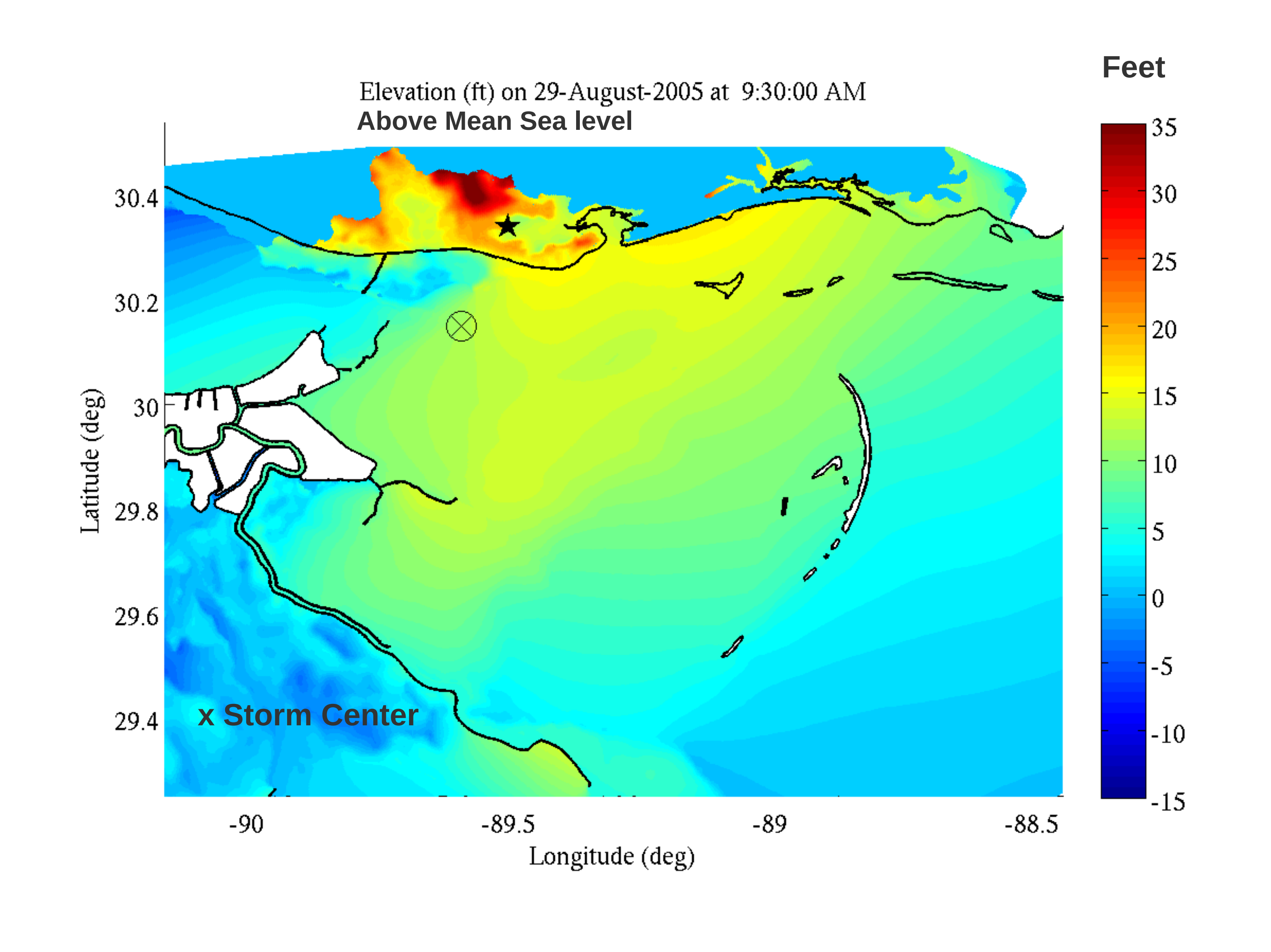

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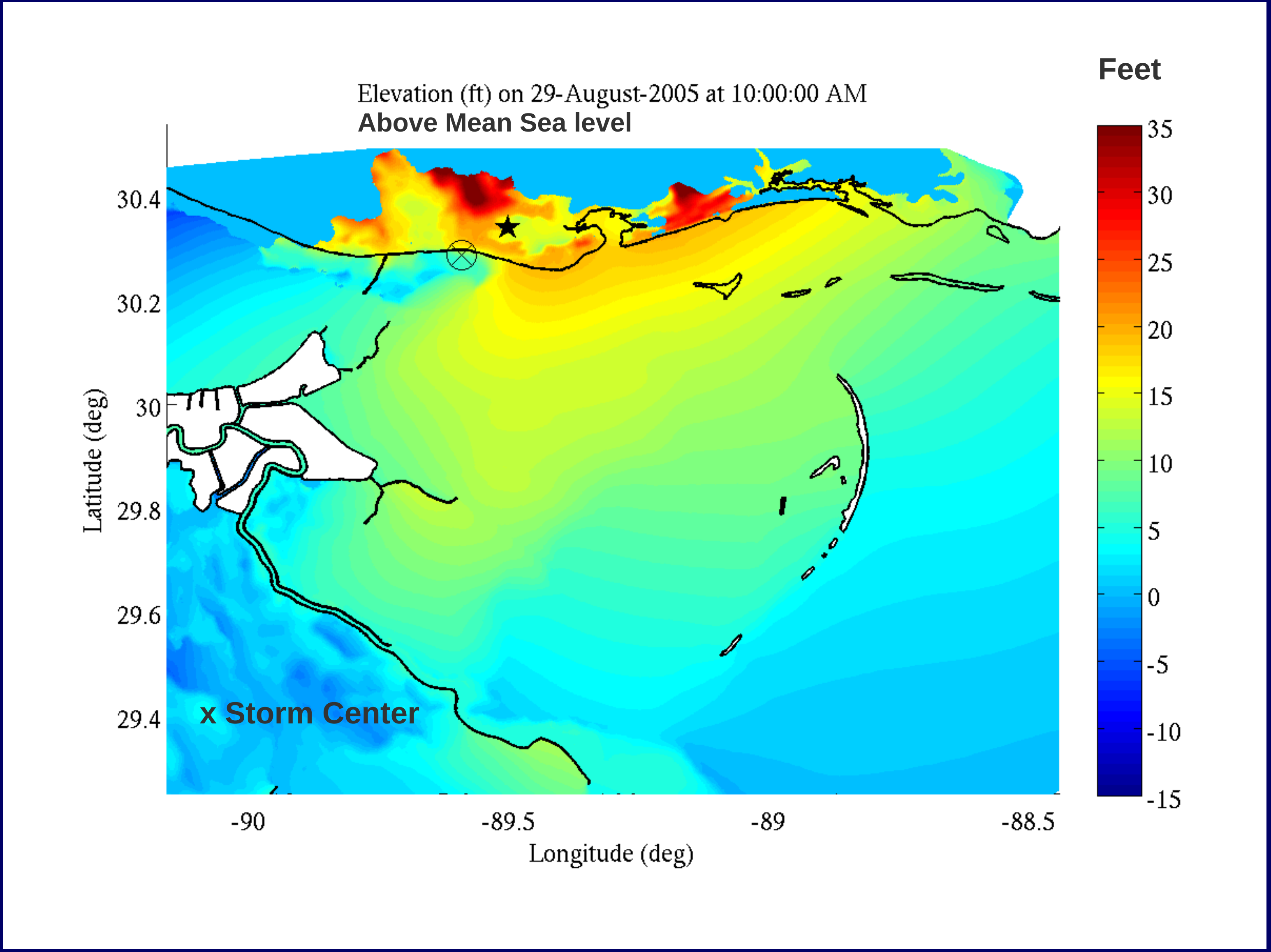

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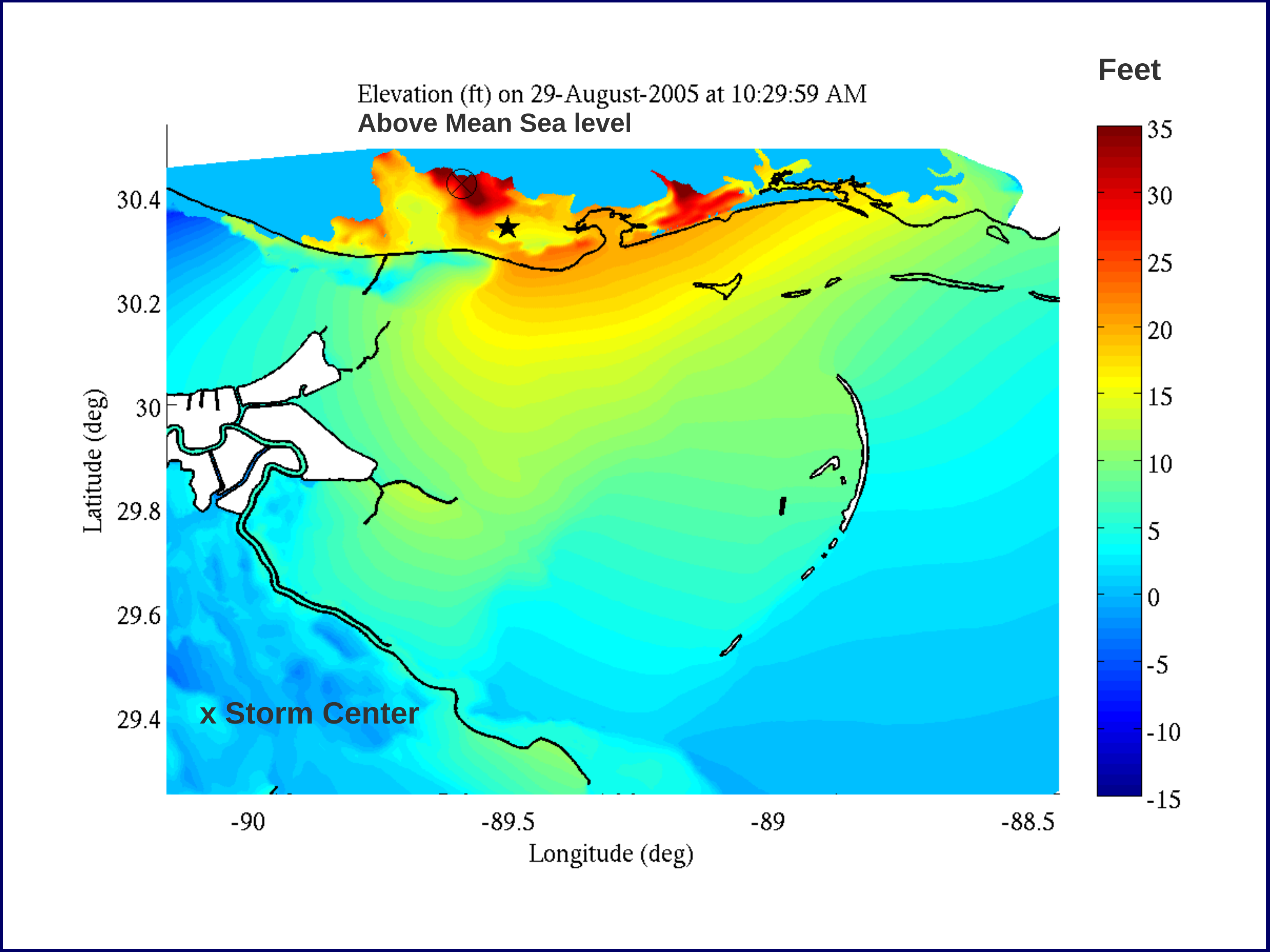
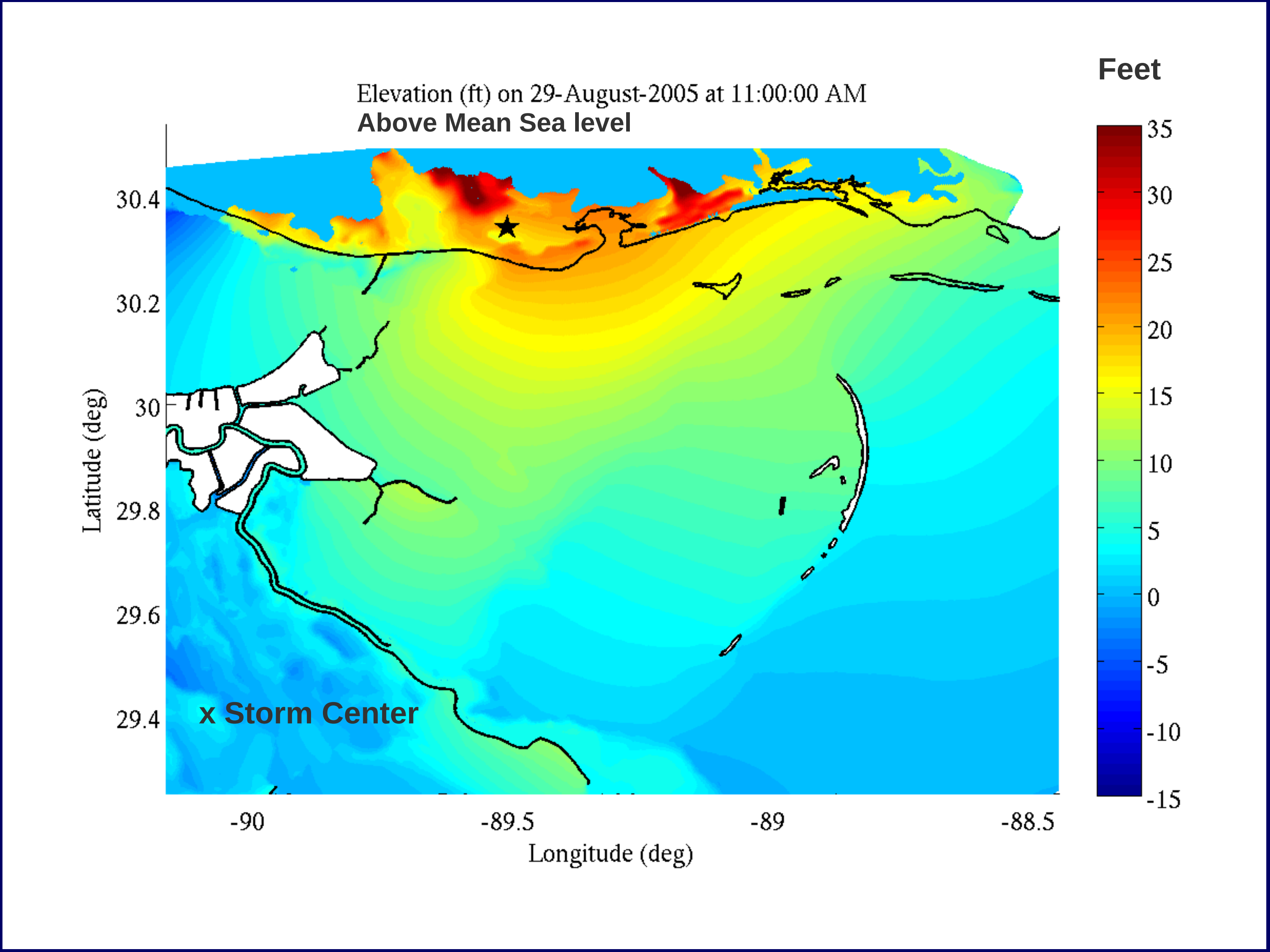
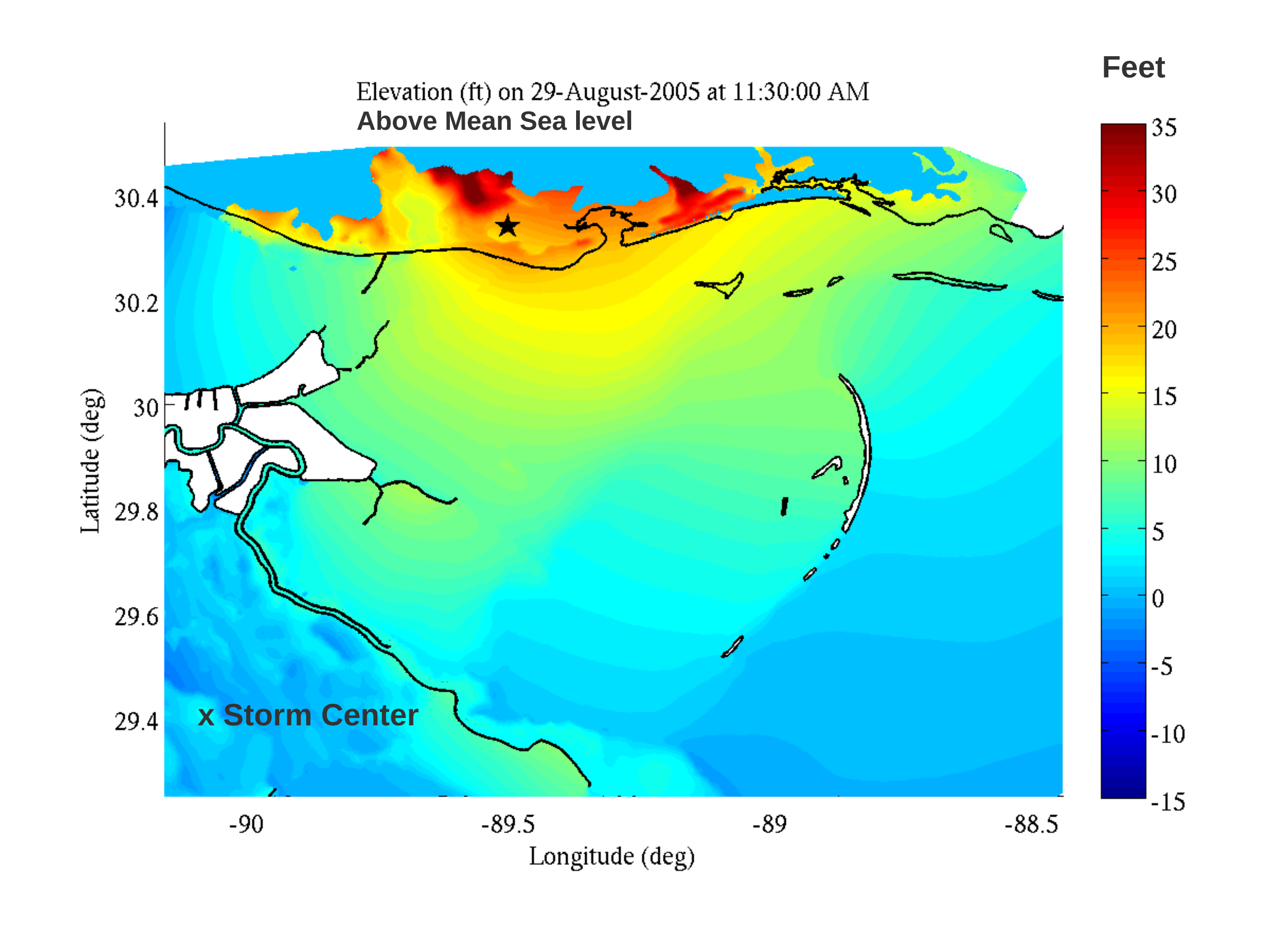


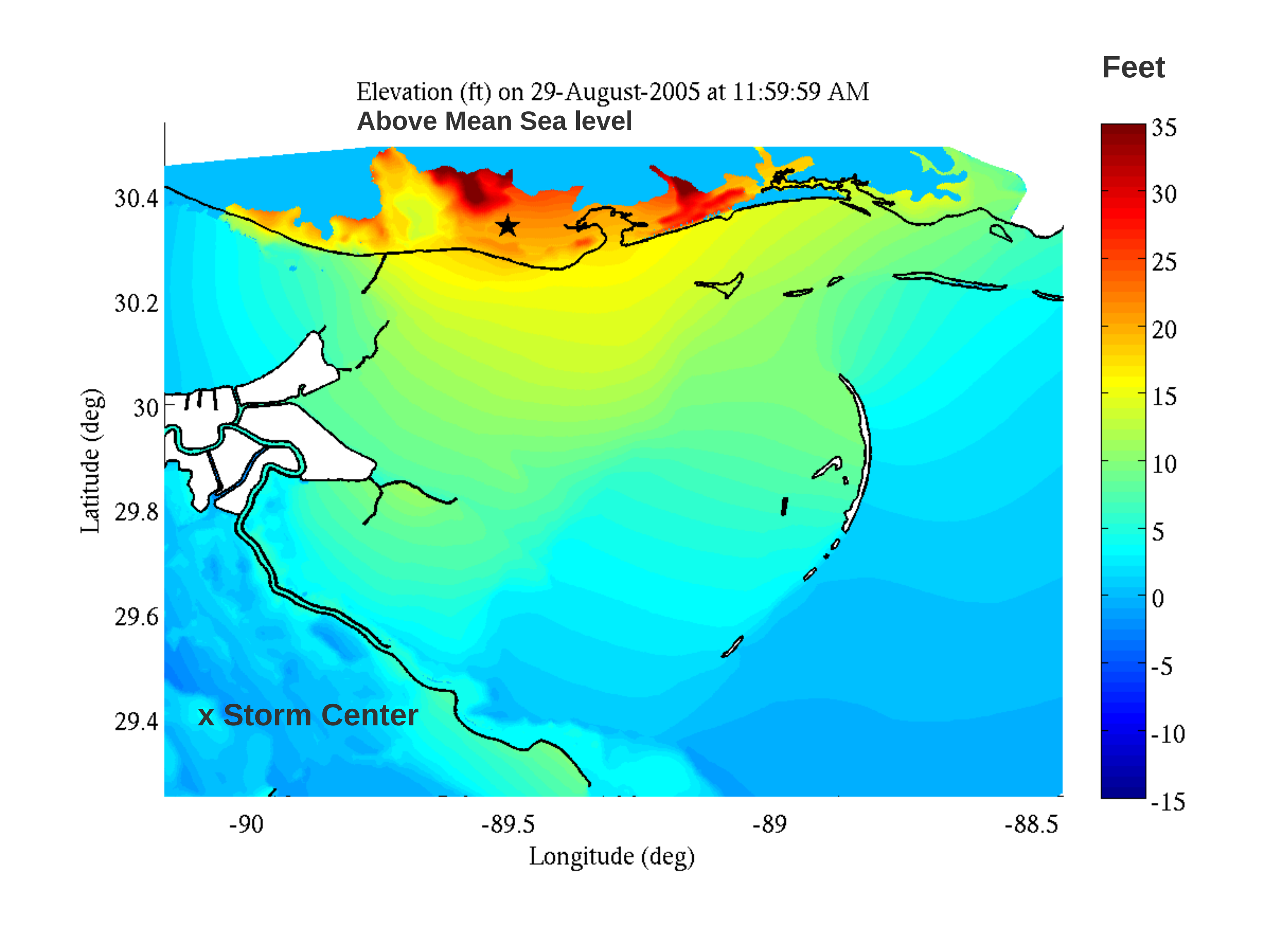
ADCIRC Computed Tides + Surge



ADCIRC Computed Tides + Surge

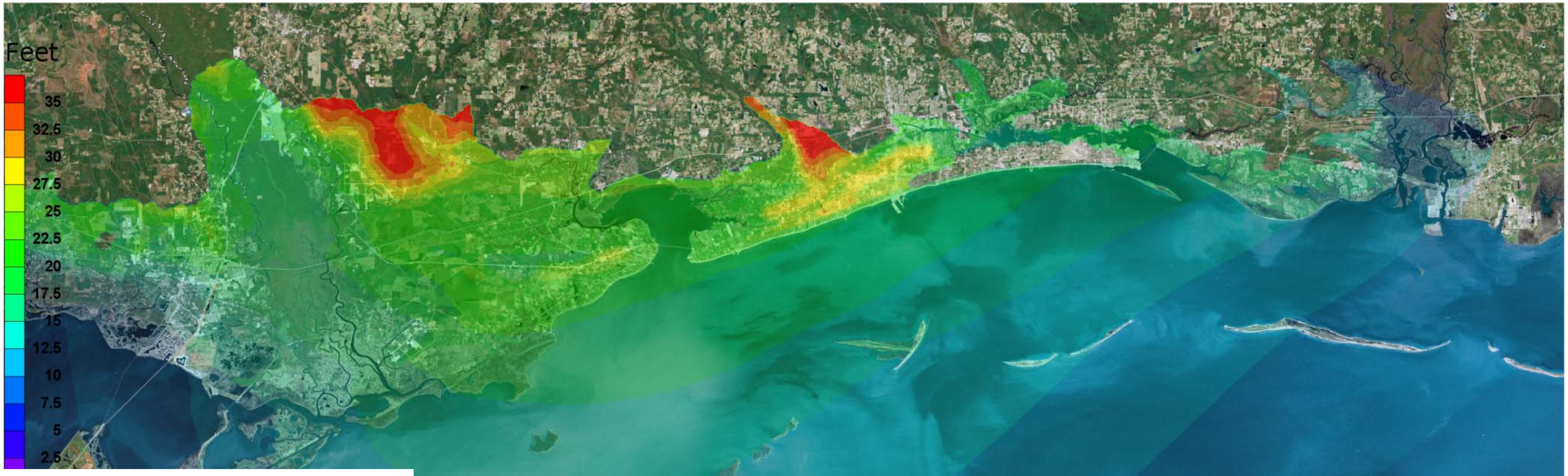


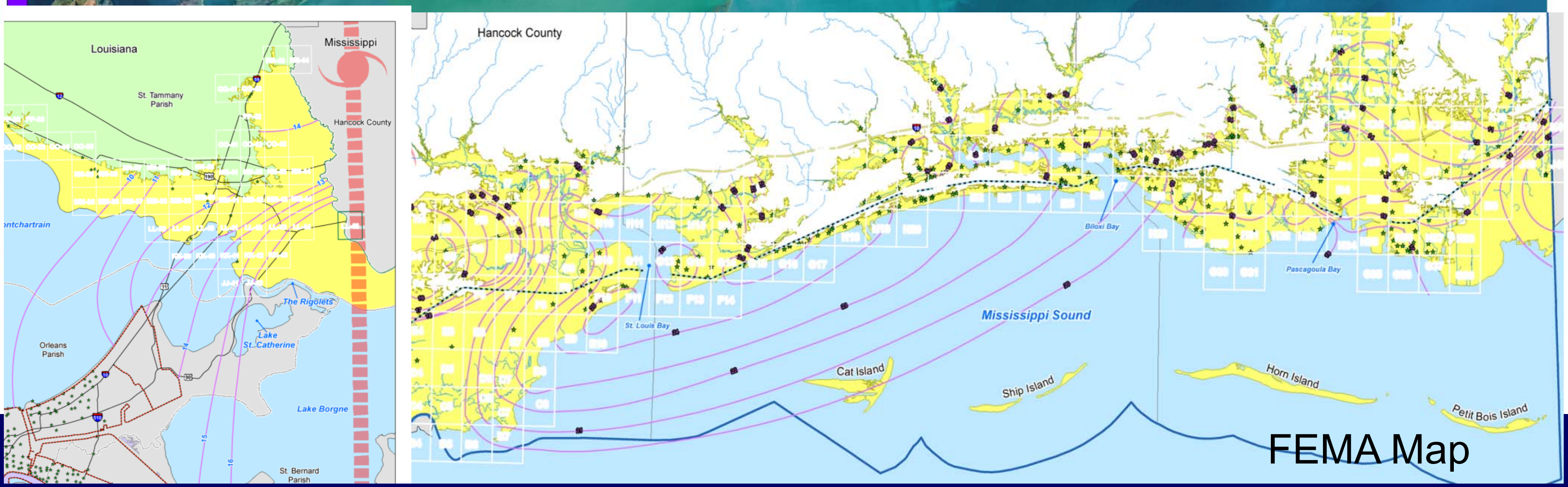
ADCIRC Computed Tides + Surge



Surge Inundation Map

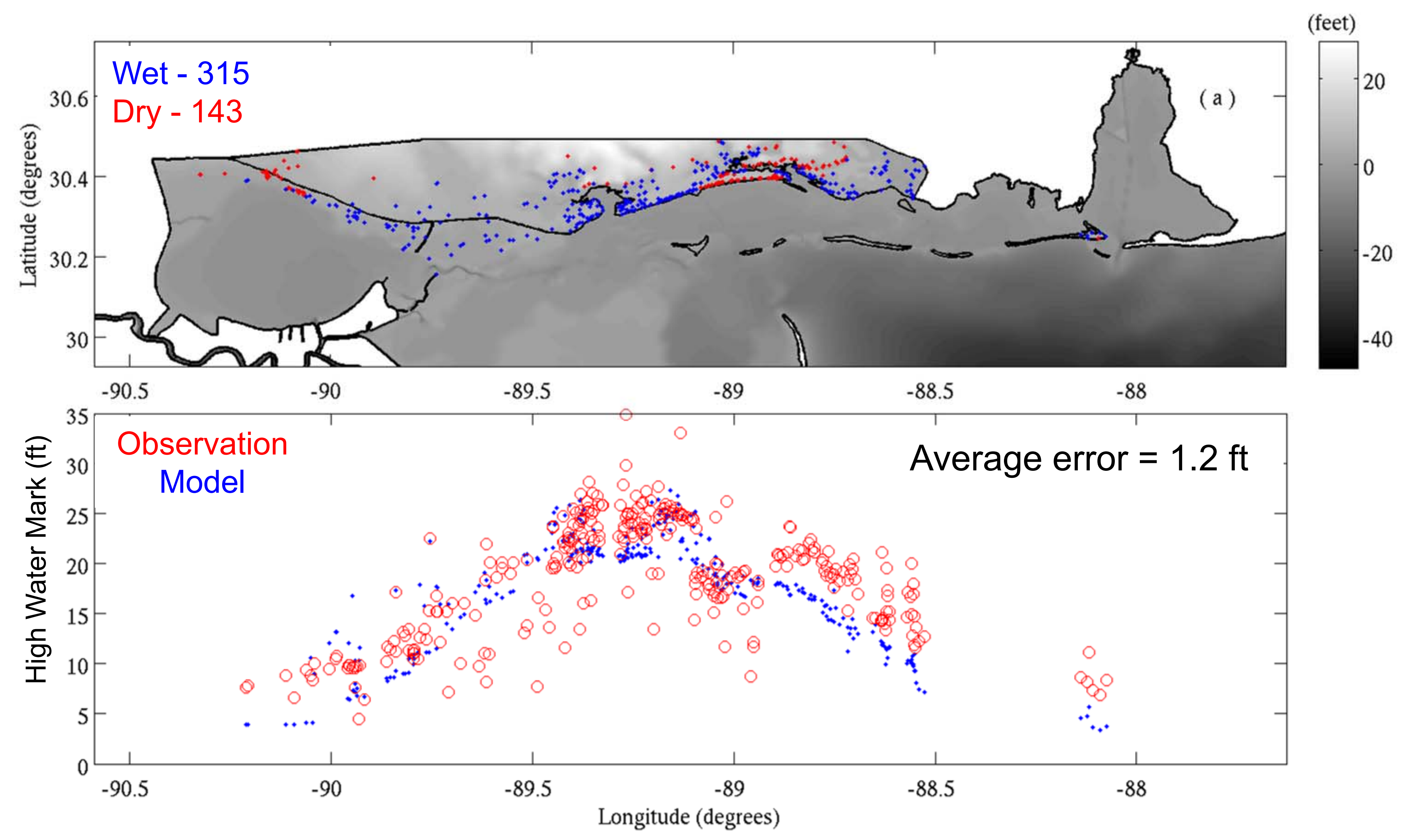
ADCIRC Model



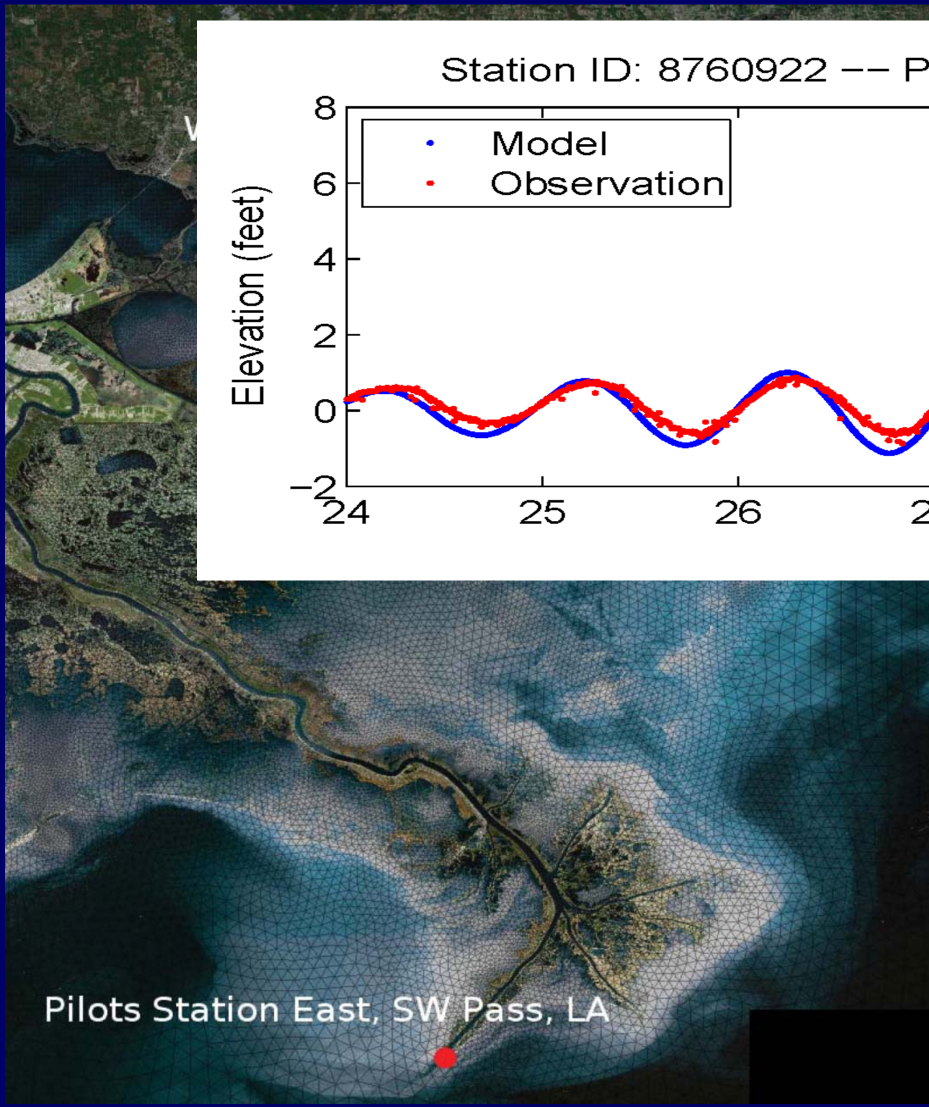


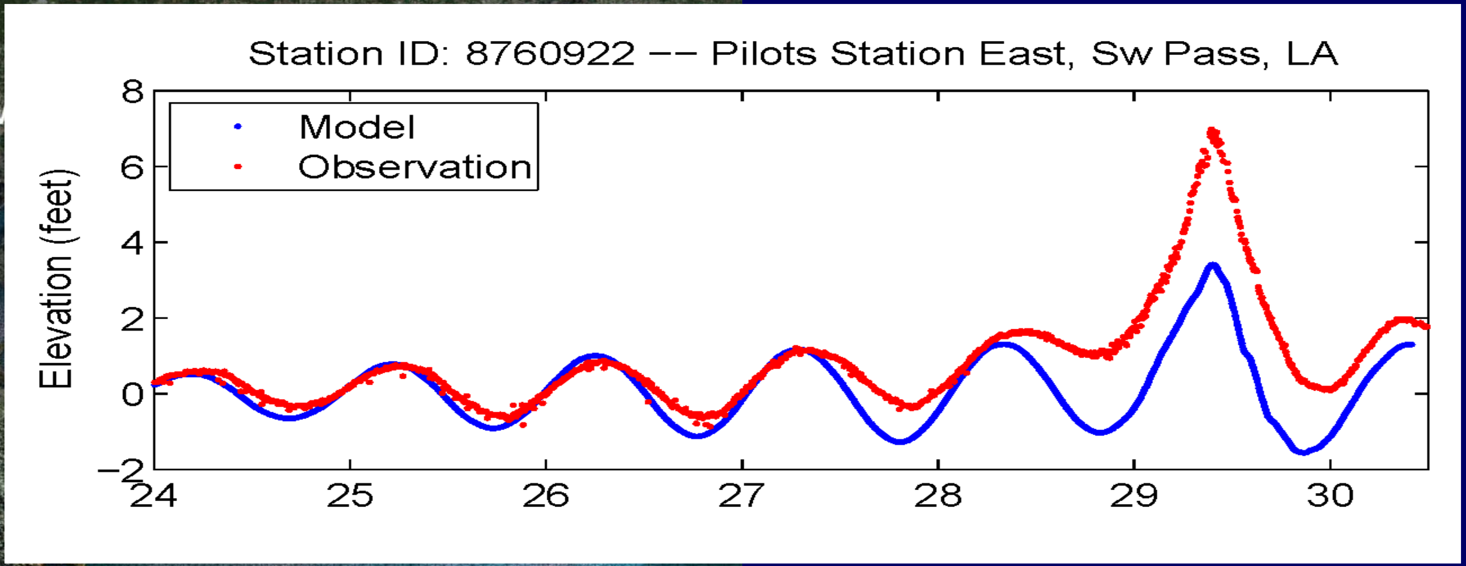
FEMA Map

Comparison to USGS High Water Marks



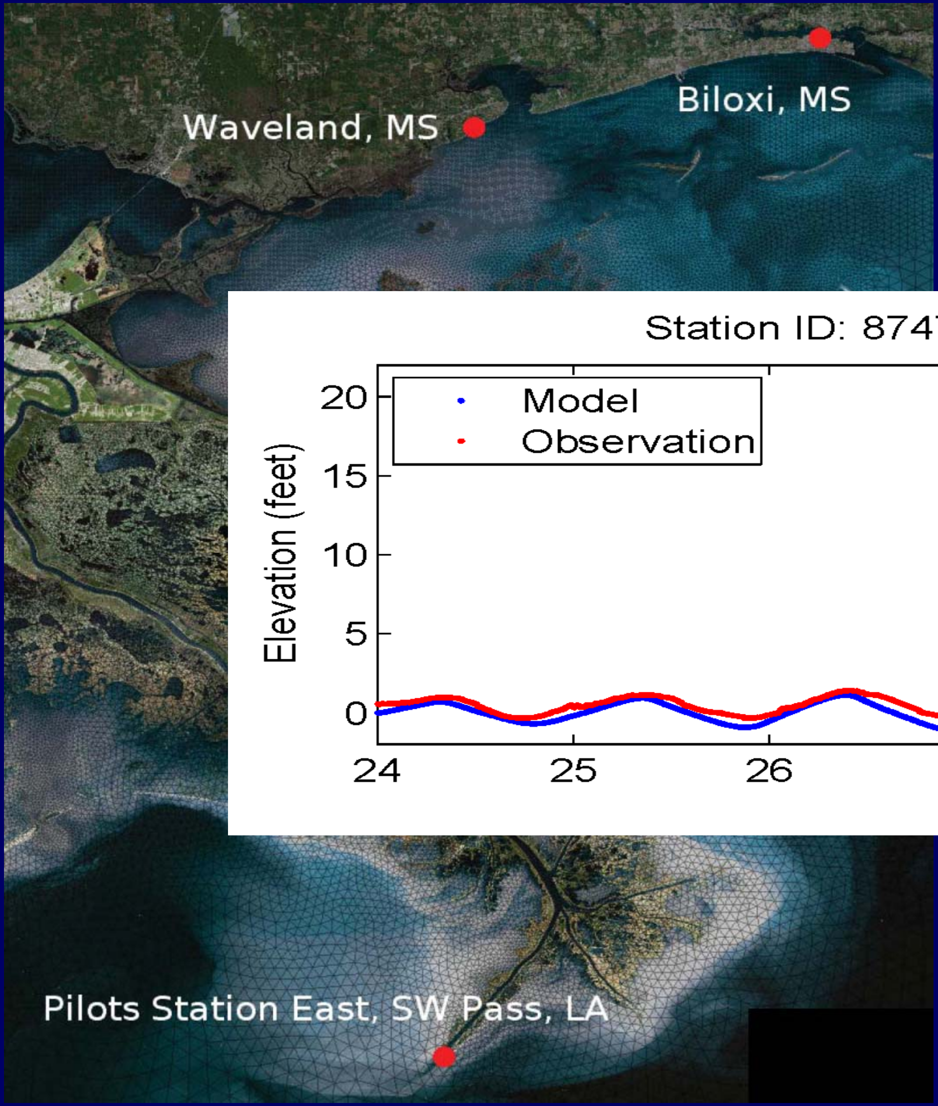
Water Level Comparisons

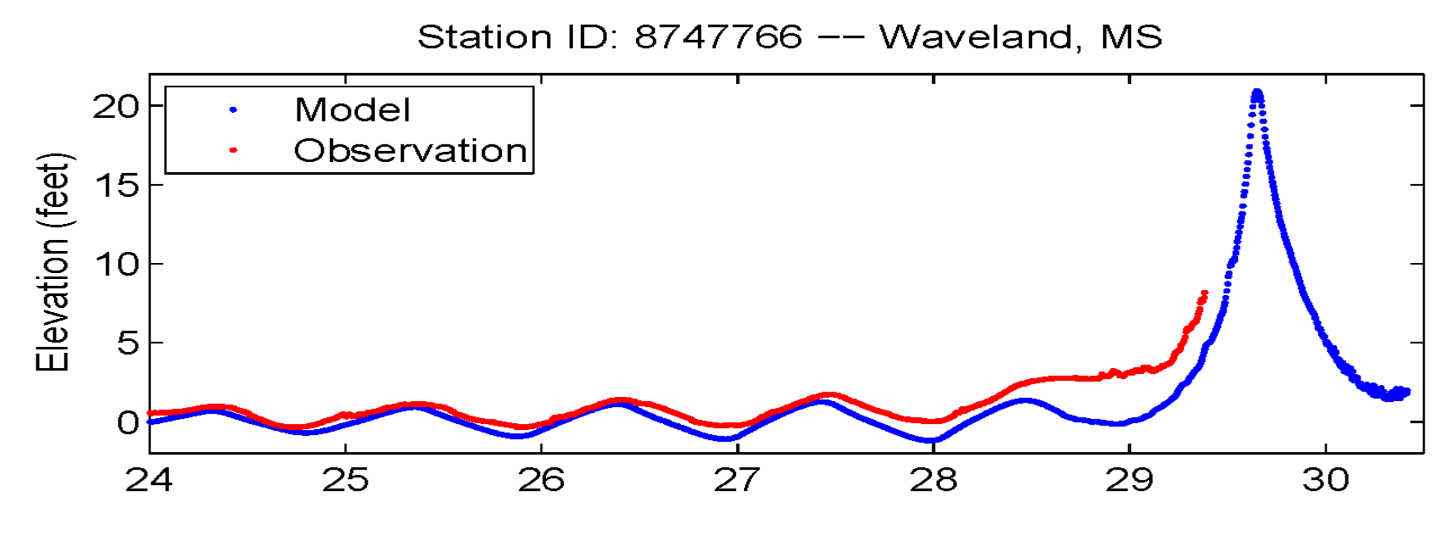




Correlation: 0.7515
RMS: 0.6745

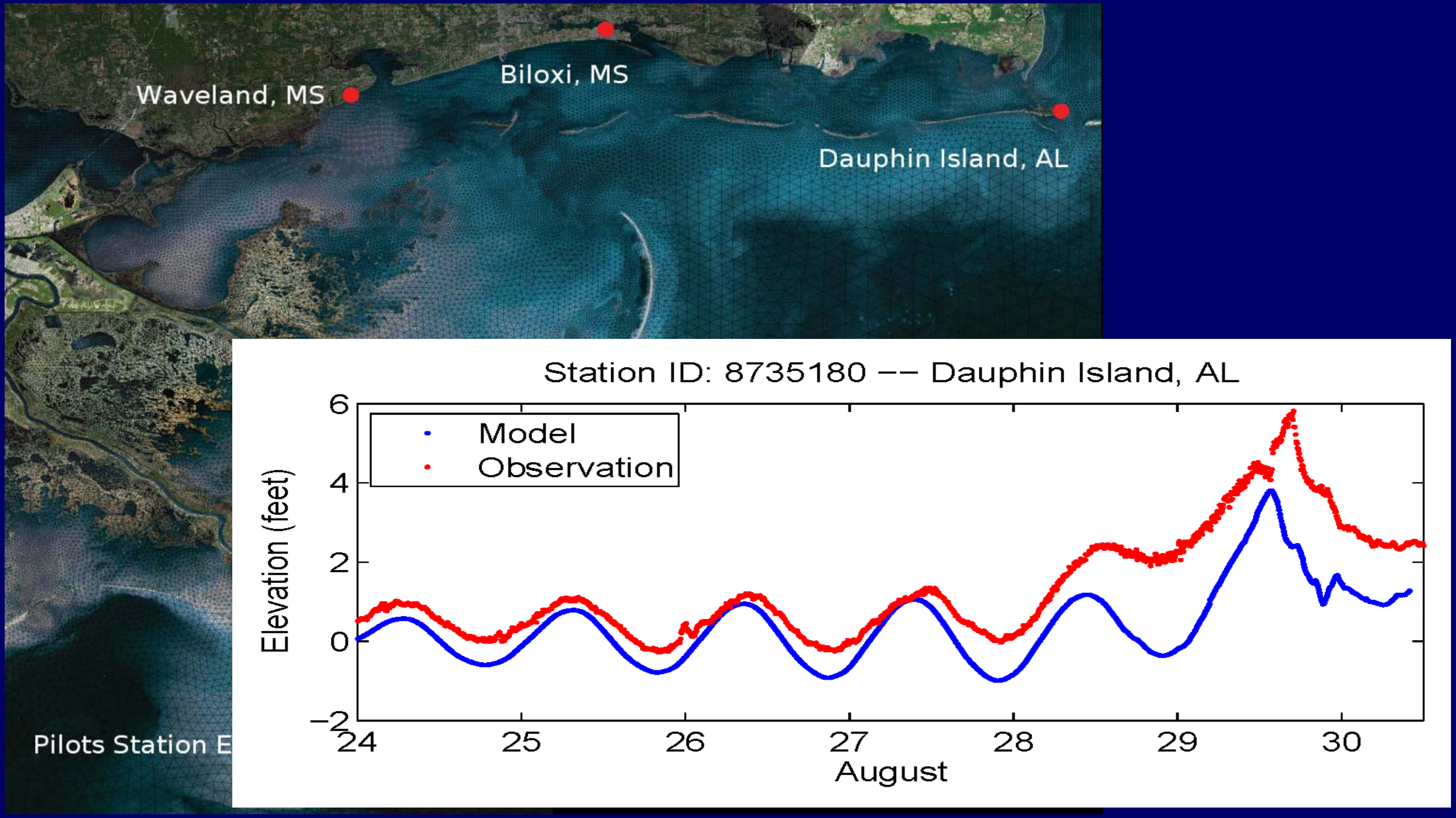
Water Level Comparisons





Correlation: 0.7606
RMS: 0.6969

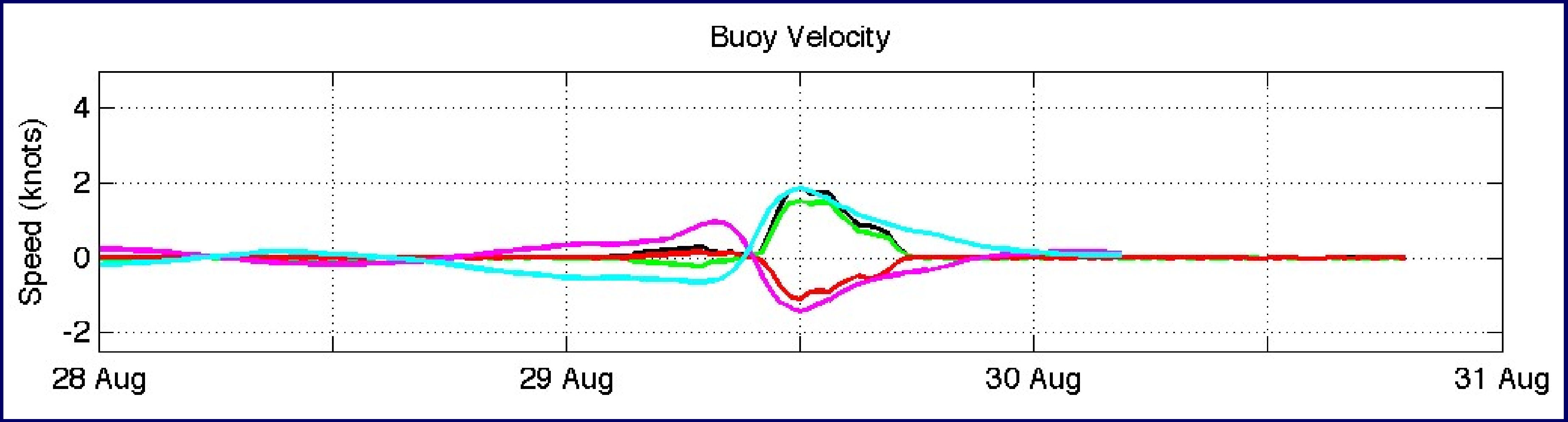
Water Level Comparisons



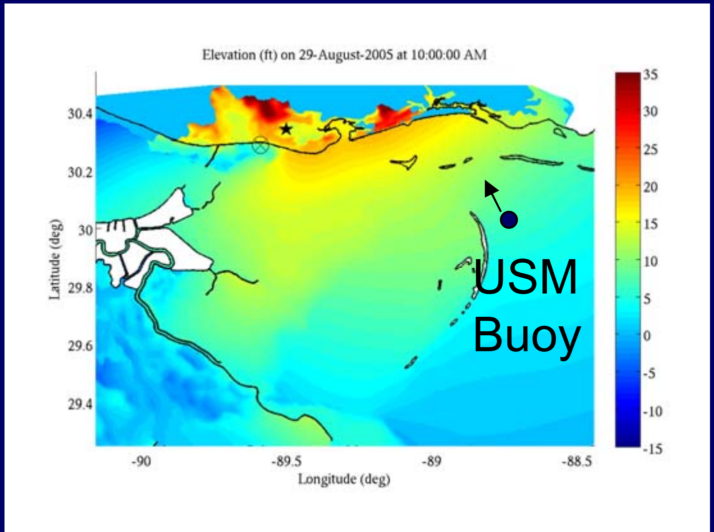
Correlation: 0.8428
RMS: 0.7072

Current Comparisons

USM Buoy (Courtesy of Dr. Stephan Howden)



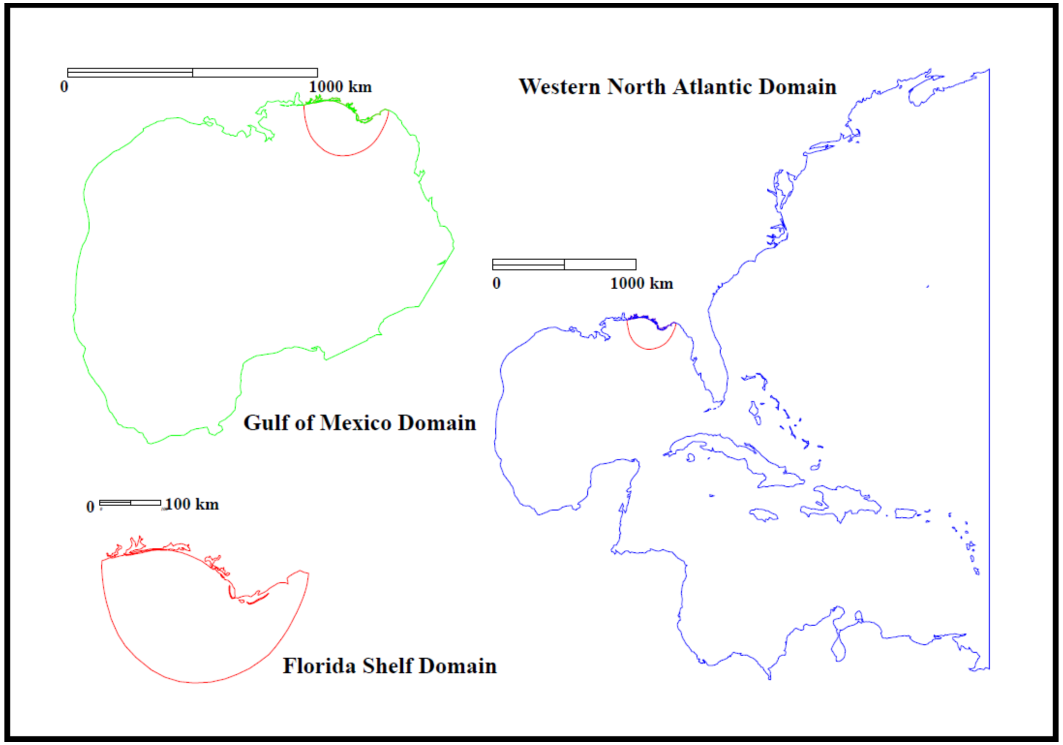
Observed	Modeled
Northward	Northward
Eastward	Eastward

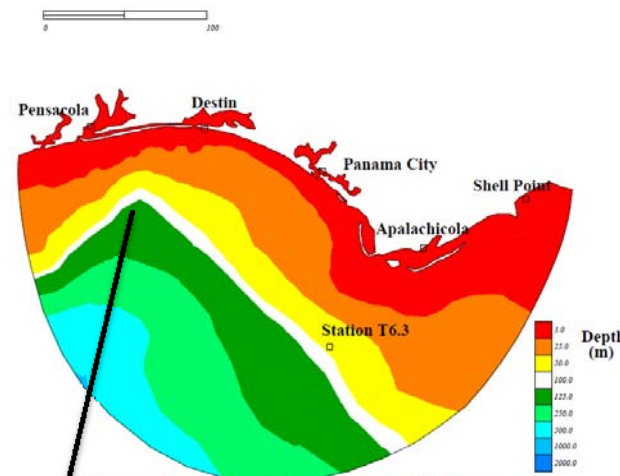


Hurricane Storm Surge Modeling

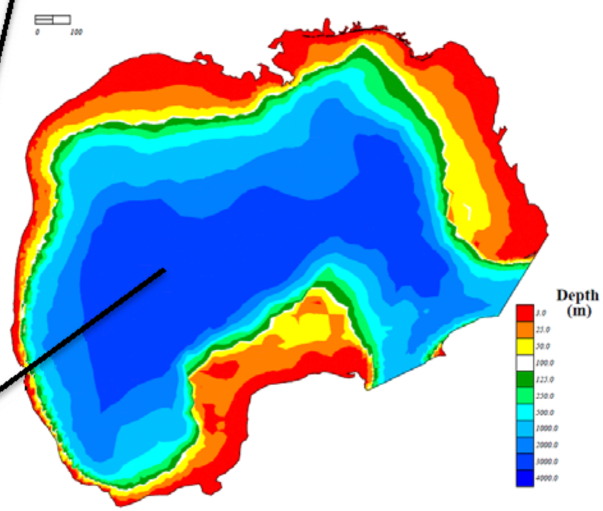
- The large domain strategy correctly captures
  - Basin to basin interactions
  - Basin to shelf dynamics
  - Shelf to adjacent coast/floodplain dynamics
  - Control structure and channel influence on flood propagation
- The large domain strategy significantly simplifies the specification of boundary conditions by selecting hydrodynamically simple boundaries
- Localize resolution in the unstructured grid to accurately resolve the physics

Use Large Domain Size





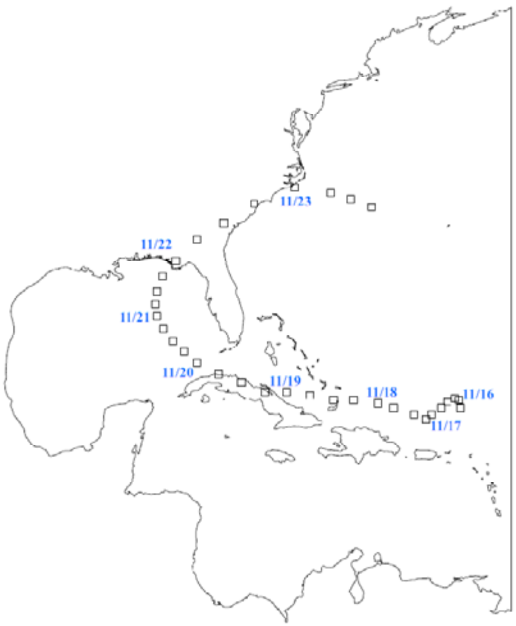
Florida Coast Domain Bathymetry Contours



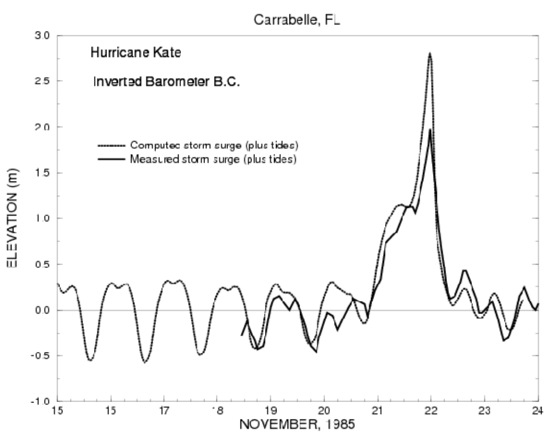
Gulf of Mexico Domain Bathymetry Contours

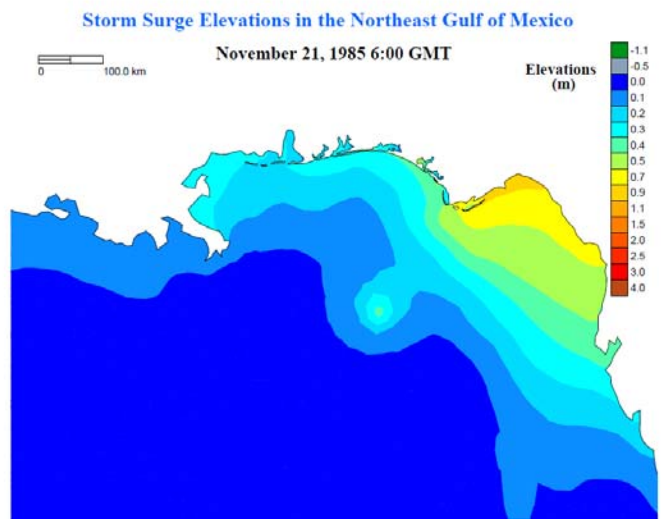
Domain	Area (km^2)	Max Depth (m)	Discretization		Grid Size (km)	
			Nodes	Elements	Max	Min
1	5.07×10^4	1094	1451	2326	32.5	0.5
2	1.41×10^6	3781	6325	11441	50.0	0.5
3	8.35×10^6	7765	22711	41407	105.0	0.5

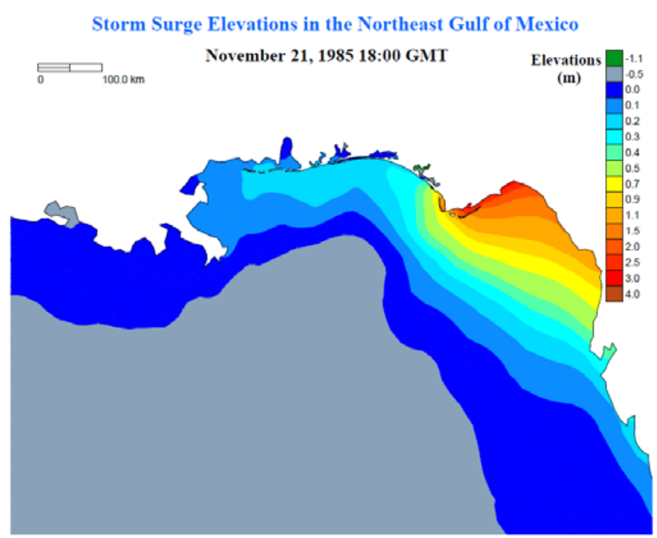
Use Large Domain Size



Path of Hurricane Kate
November, 1985

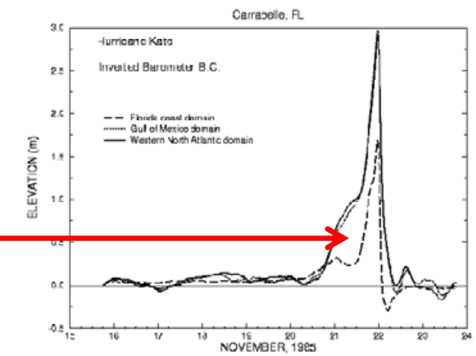






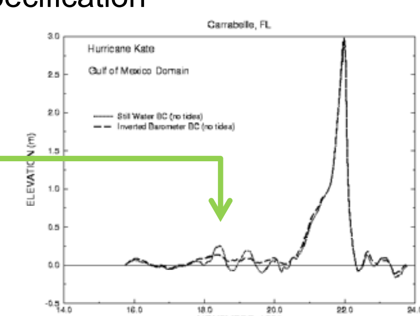
Florida Coast domain:

- Situated on shelf
- Small wrt storm size
- Large portions of cross-shelf boundaries



Gulf of Mexico domain:

- Captures peak surge
- Oscillatory behavior due to resonance of basin
- Sensitivity to boundary condition specification

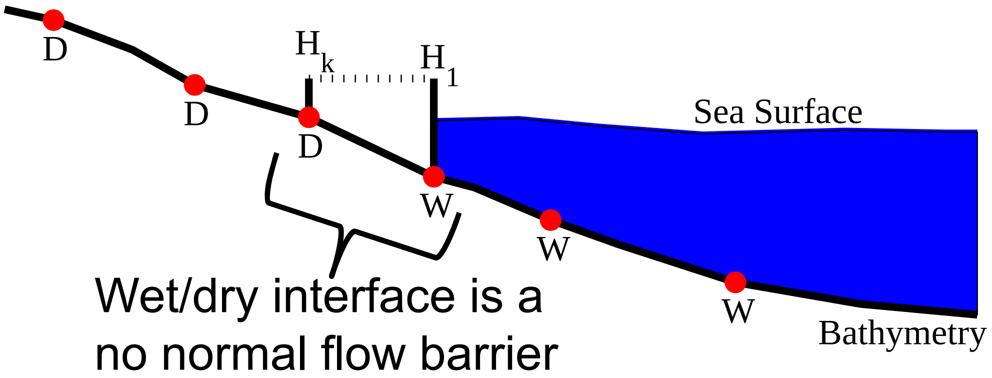


ADCIRC Inundation Algorithm

Based on1-D momentum balance between a pressure gradient and friction

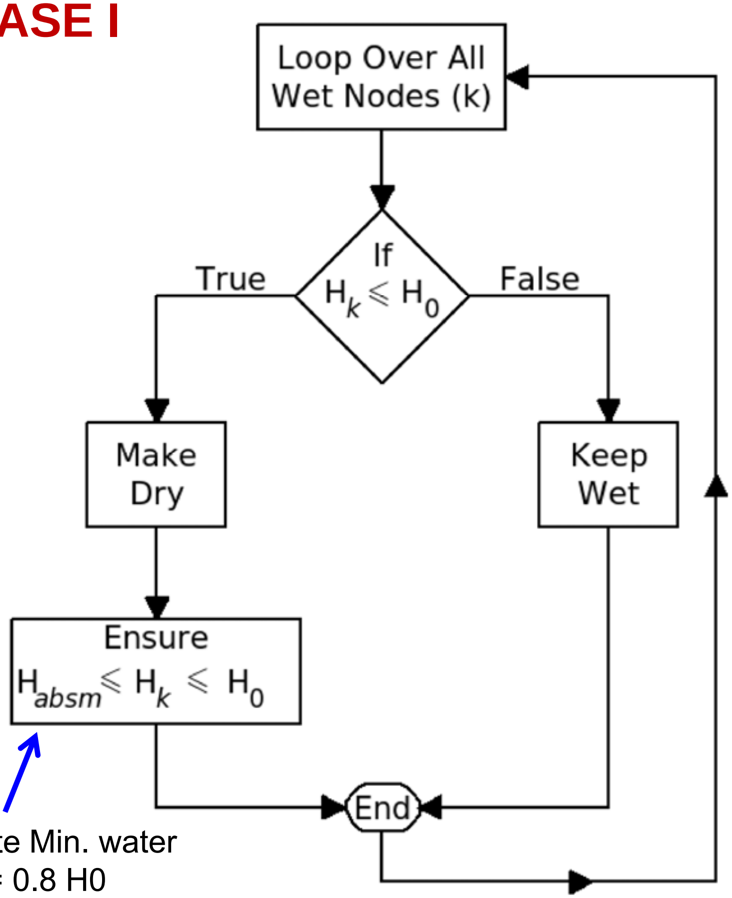
$$gH\frac{\partial \eta}{\partial x} = \tau_b = C_D v$$

Classify elements as either wet (sufficient water elevation) or dry (removed from computation) – effectively turn in and off elements for wetting/drying



ADCIRC Wetting/Drying Criteria

PHASE I



Absolute Min. water depth = 0.8 H0

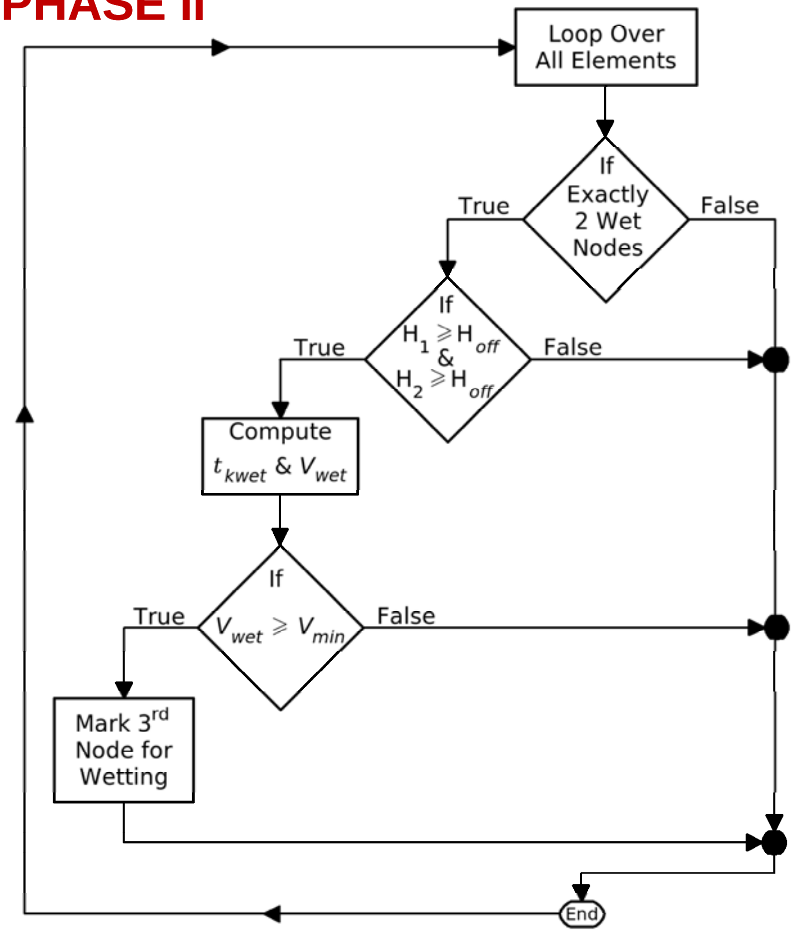
Drying
Nodal-based

Leaves residual water between H_{absm} and H_0

Results in asymmetric drying

ADCIRC Wetting/Drying Criteria

PHASE II



Wetting Phase
Elemental

Dry elements with 2 wet nodes are considered for wetting

For wetting from one node to the next,

$$H \geq 1.2 H_0$$

and

$$v_{wet} \geq v_{\min}$$

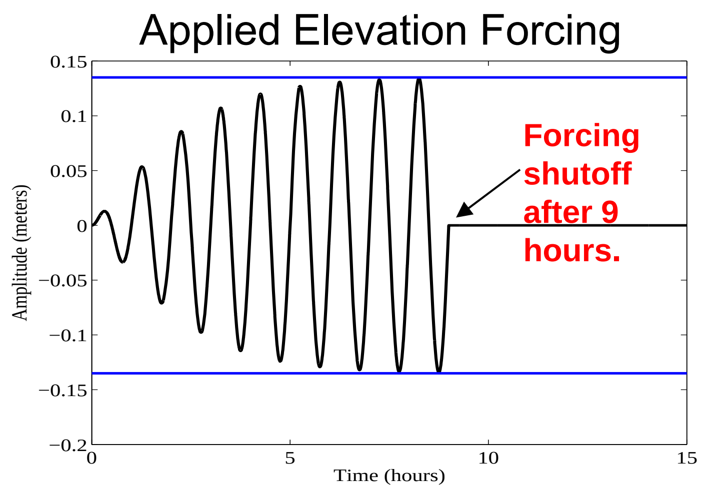
where

$$v_{wet} = g\left(\frac{\Delta\eta}{\Delta x}\right)\frac{1}{\tau_{wet}}$$

A larger H for wetting than drying eliminates numerical oscillations in the wetting/drying

No directionality of flow is considered

1D Wetting/Drying on Gentle Slope

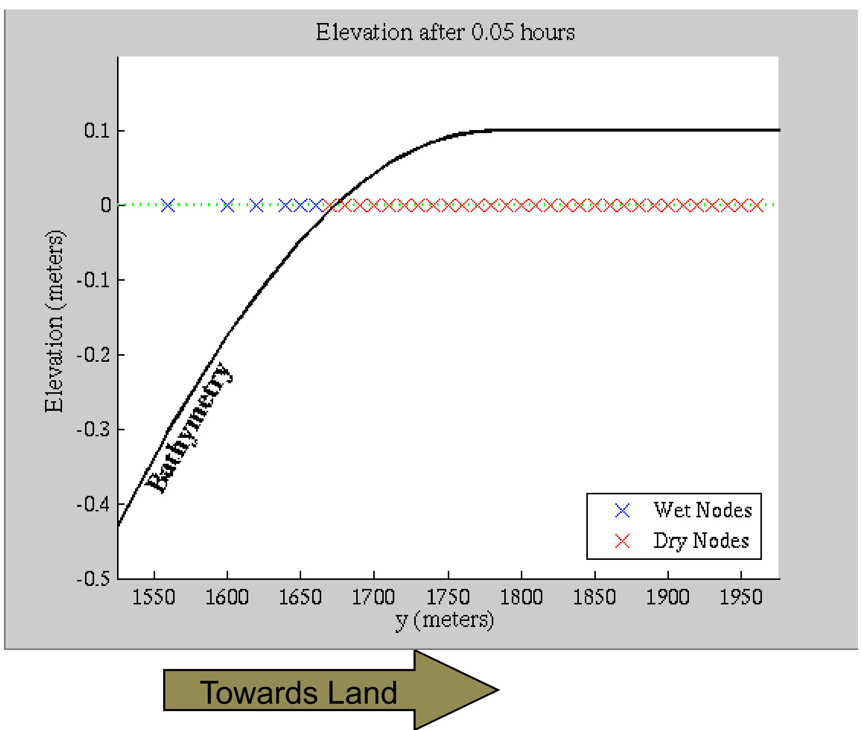


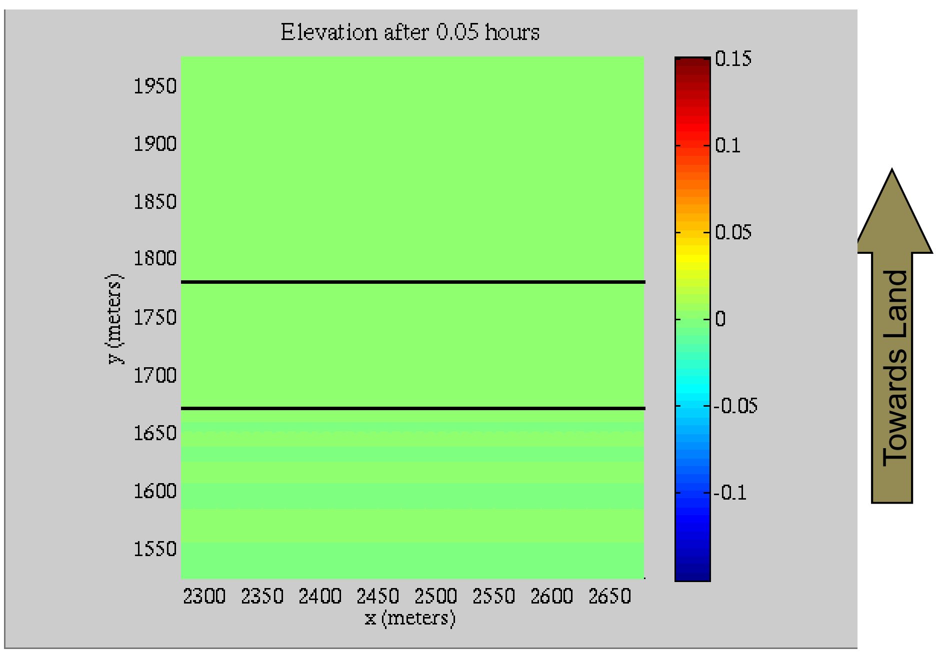
Issues:

- spatial asymmetry
- temporal asymmetry btw wetting and drying
- ponding

Solutions:

- appropriate grid spacing and parameter specifications
- gradient checking and smoothing
- elemental averaging
- moving towards DG flux-based approach





Hybrid Non-linear Bottom Friction

Bottom stress

$$\tau_b = C_D v$$

Drag coefficient

Hybrid formulation

Results in > friction coefficient in shallow water

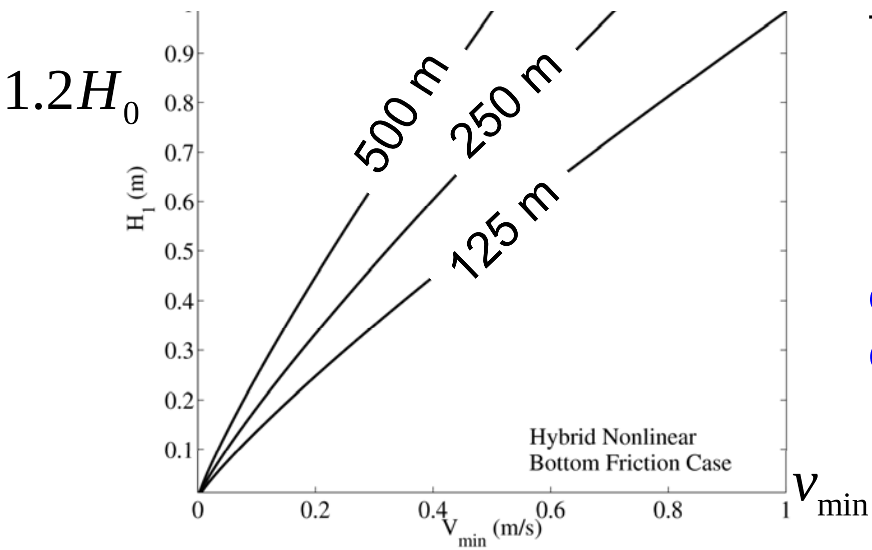
$$C_D = \max\left\{ C_{D\min}\left(1+\left(\frac{H_{break}}{H}\right)^{\theta}\right)^{\frac{\gamma}{\theta}}, 10^{-4} \right\}$$

Depth-dependent drag

Linear or quadratic drag coefficient

Depth for deep to shallow water switchover

Effect of mesh size for required $\Delta\eta = 0.1$ considering the two criteria for wetting



Typically Cdmin = 0.003; H_{break} = 2m; θ = 10; γ = 1.33333

For a given $v_{\min}$, a higher change is elevation is required for wetting at coarser resolution.

Specification of GWCE parameter, τ_0

Weighting parameter for the Generalized Wave Continuity Equation (GWCE)

$\tau_0 = 0$ ⟷ $\tau_0 = 1$

pure wave equation

(greatest mass imbalance)

primitive continuity formulation

(unstable solution)

Best results for a spatially and temporally variable, τ_0

$$\tau_0 = \tau_{0\min} + 1.5 \frac{C_d \left| v \right|}{H}$$

Within min and max limits τ_0, typically 0.005 to 0.2

Surface Roughness and Wind Drag

To improve wind accuracy, apply wind reduction due to enhanced friction (roughness) over land

Standard drag coefficient

Surface stress term $$\frac{\tau_{sx}}{\rho H} = \frac{C_d}{H}\frac{\rho_{air}}{\rho}\|W_{10}\|W_{10}$$

Full marine Wind speed at 10m

Reduce winds over land by applying a weighted roughness

$$W_{land} = f_d \cdot W_{10} \quad \text{where} \quad f_d = \left(\frac{z_{marine}}{z_0}\right)^{0.0706}$$

Ratio of marine roughness to land roughness

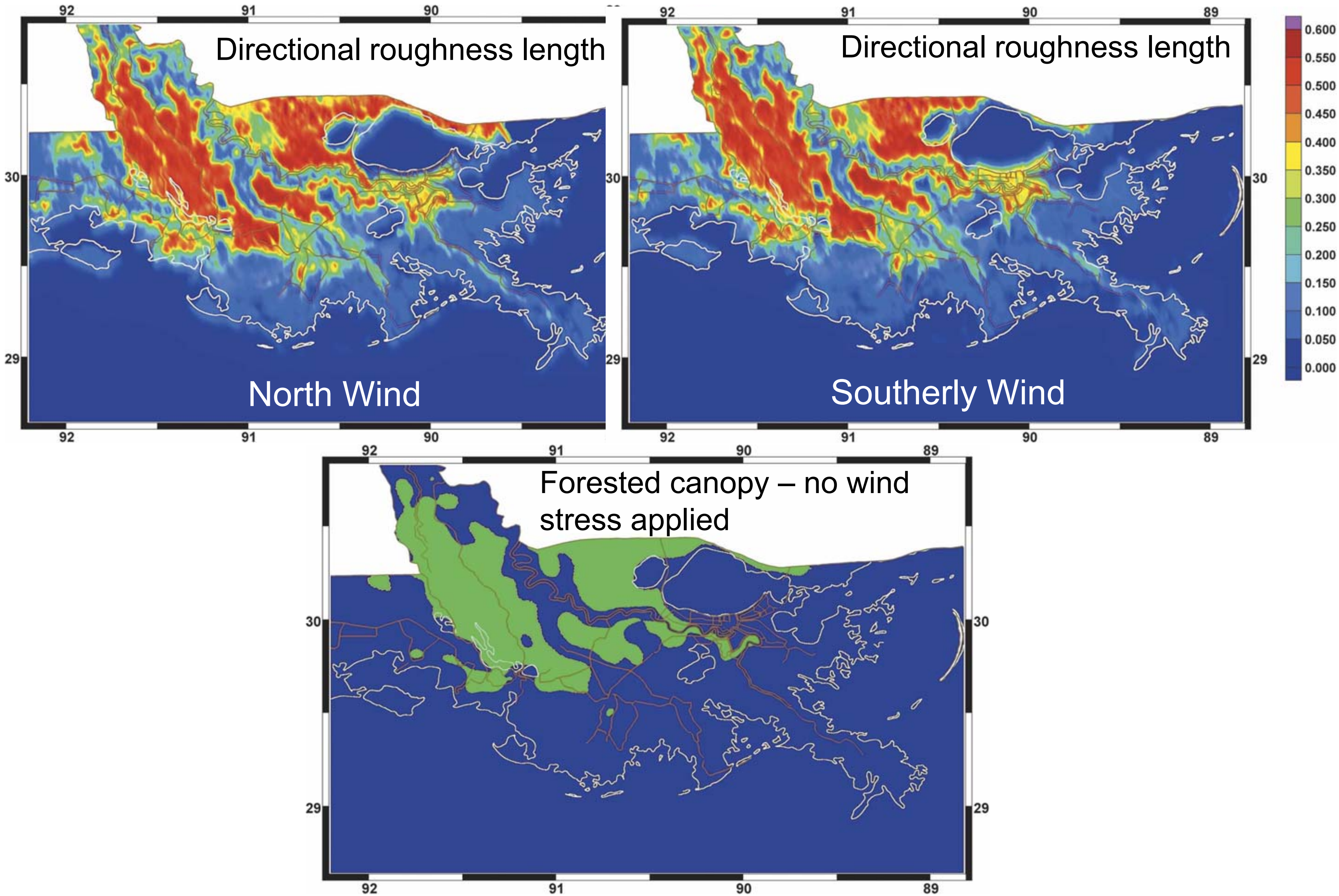
In areas where local vegetative canopy includes forested trees and thick shrubs, $W_{land} = 0$

Account for wind direction through a directionally dependent roughness value

- Use land use information from land cover databases to assign land roughness values for each land cover type

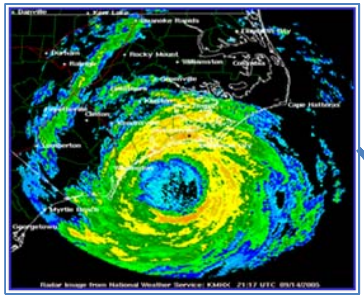
Westerink et al. 2008

Surface Roughness and Wind Drag



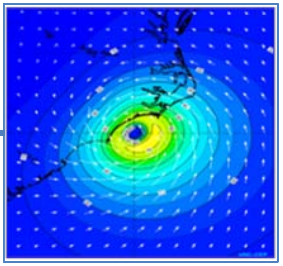
What's Next – Hydrodynamic-Hydrologic Model Coupling

Precipitation

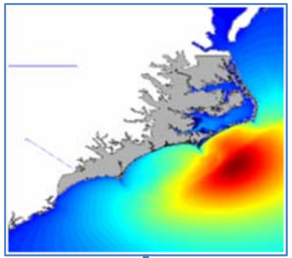


Hydrology Model

Wind Model

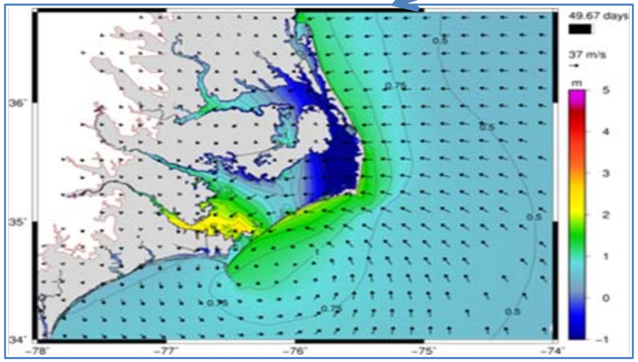


Wave Model

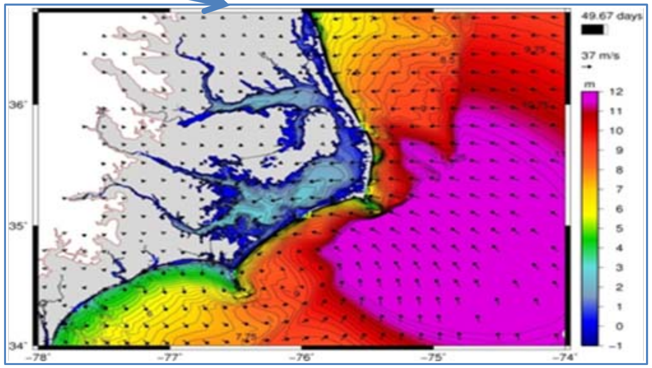


Better river discharge estimates

Hydrodynamic Model



Total Water Levels



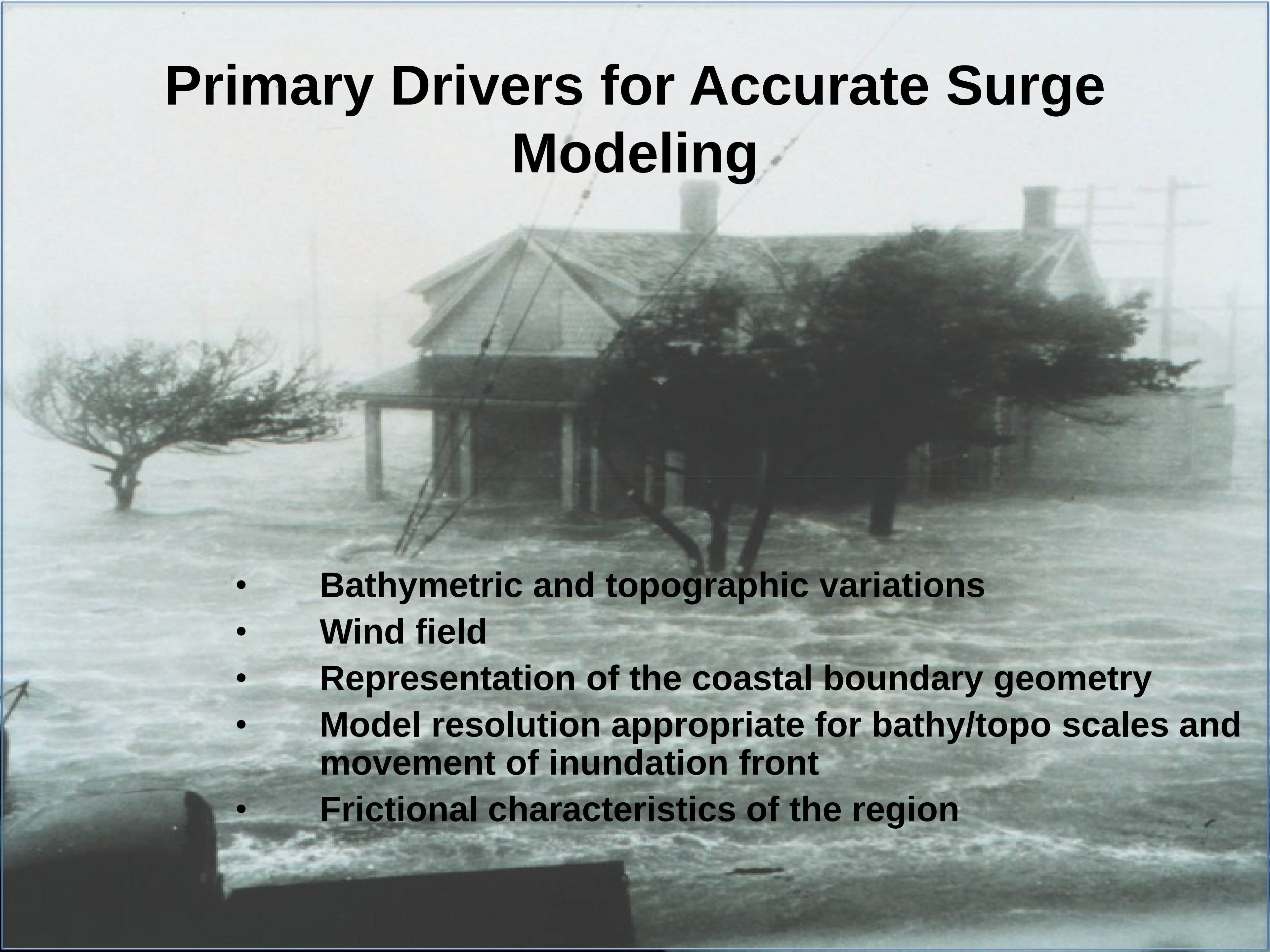
Significant Wave Heights

CI-FLOW
VanCooten et. al 2011, Bul Am. Met. Soc

Summary of Modeling Strategy

- Localized high resolution is critical to capture the physics of surge generation and propagation
- Large domains to capture the entire storm and its surge generation throughout the basin
- A physics based approach including tides, riverine flows, air-sea interaction and wave-current interaction

Primary Drivers for Accurate Surge Modeling



- Bathymetric and topographic variations
- Wind field
- Representation of the coastal boundary geometry
- Model resolution appropriate for bathy/topo scales and movement of inundation front
- Frictional characteristics of the region