Hurricane Wave and Storm Surge Forecasting for the Carolina Coast

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Lecture Series: *Science on the Sound*
Coastal Studies Institute, Manteo, NC
21 November 2013

About Me

North Carolina State University

- Civil, Construction, and Environmental Engineering
  - Assistant Professor: 08/2013 to present

CCEE Department, Mann Hall, NCSU

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University of Texas at Austin

- Institute for Computational Engineering and Sciences
  - Research Associate: 09/2012 to 07/2013
  - Postdoctoral Researcher: 11/2010 to 08/2012

University of Notre Dame

- Civil Engineering and Geological Sciences
  - Graduate Researcher: 08/2005 to 10/2010

University of Oklahoma

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  - Graduate Researcher: 06/2004 to 07/2005
  - Undergraduate Researcher: 06/1999 to 05/2004

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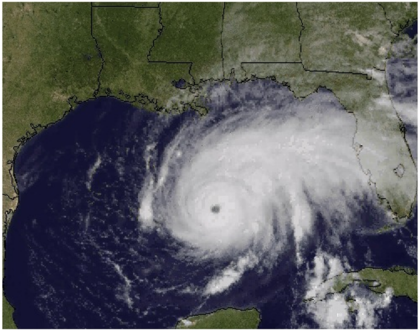
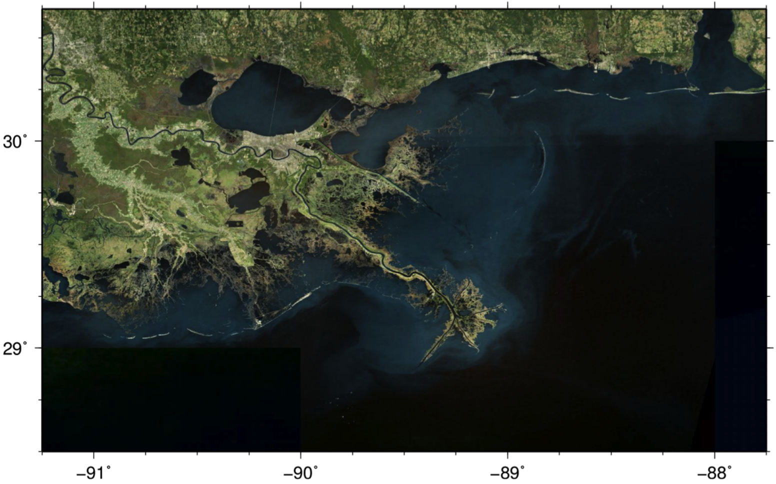
Hurricane Season 2005 – Impacts on Southern Louisiana

Katrina: 08/28 - 08/29

Rita: 09/22 - 09/24

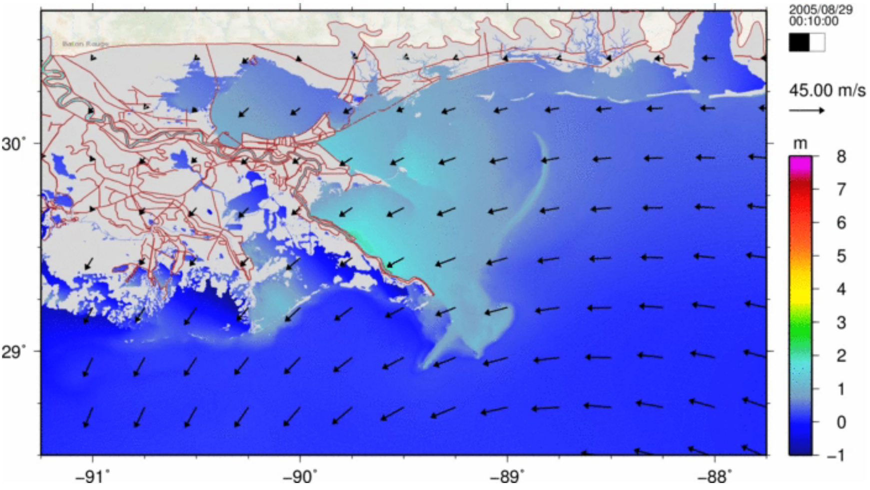


Hurricane Season 2005 – Flooding of New Orleans



Hurricane Season 2005 – Flooding of New Orleans

Hurricane Season 2005 – Katrina on 29 August



S Bunya, JC Dietrich, *et al.* (2010). A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave and Storm Surge Model for Southern Louisiana and Mississippi: Part I Model Development and Validation. *Monthly Weather Review*, 138(2), 345-377.

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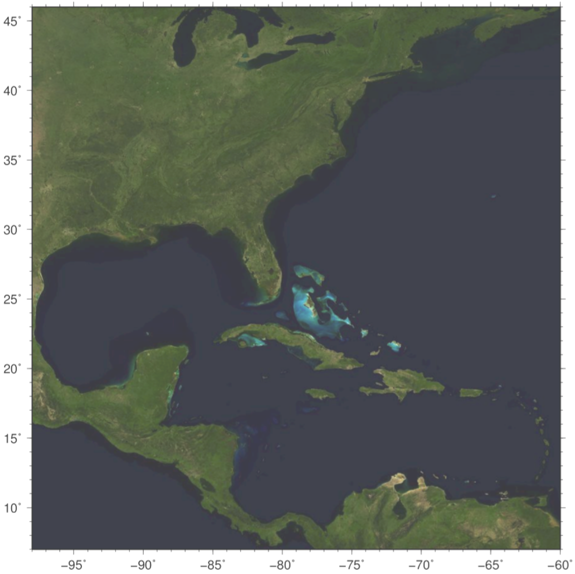
Spatial Scales – Gulf and Atlantic Coasts



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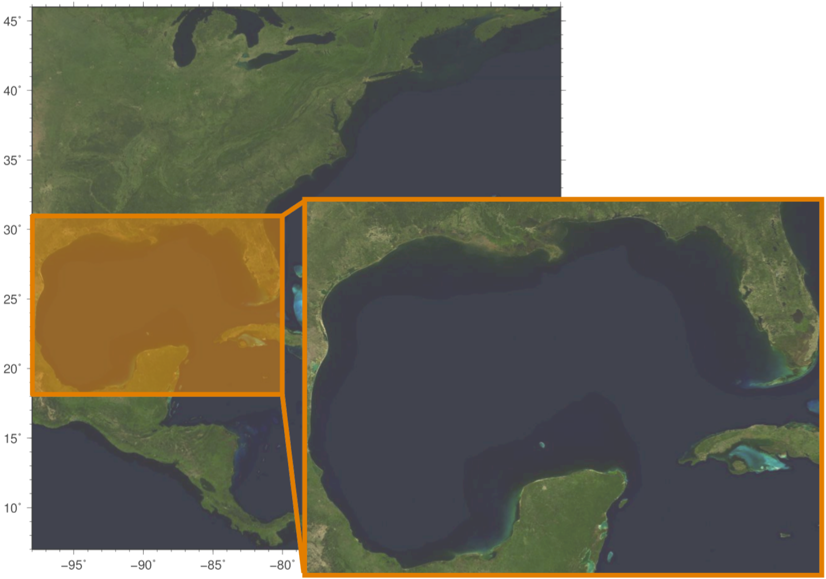

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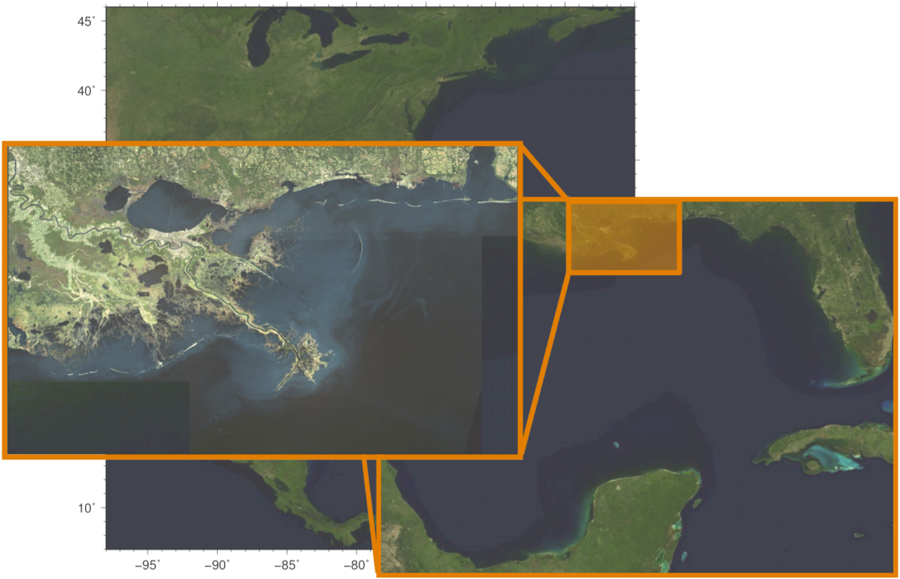

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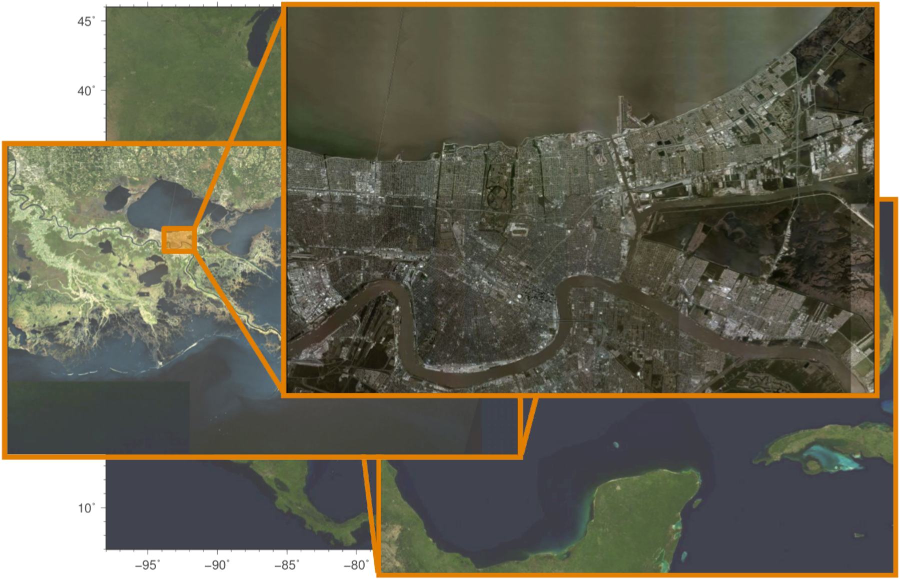
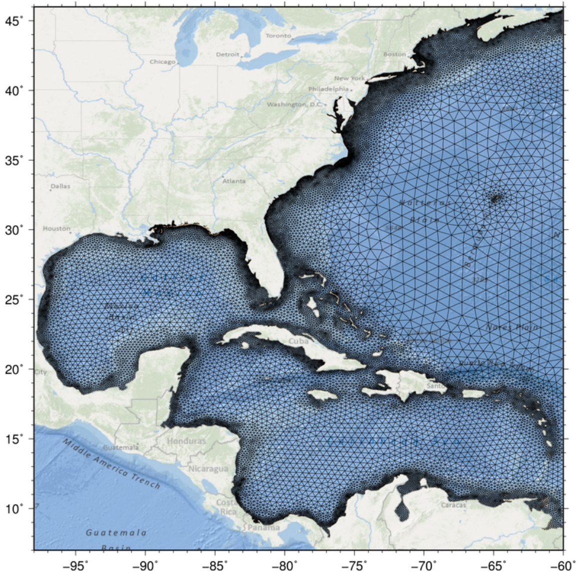
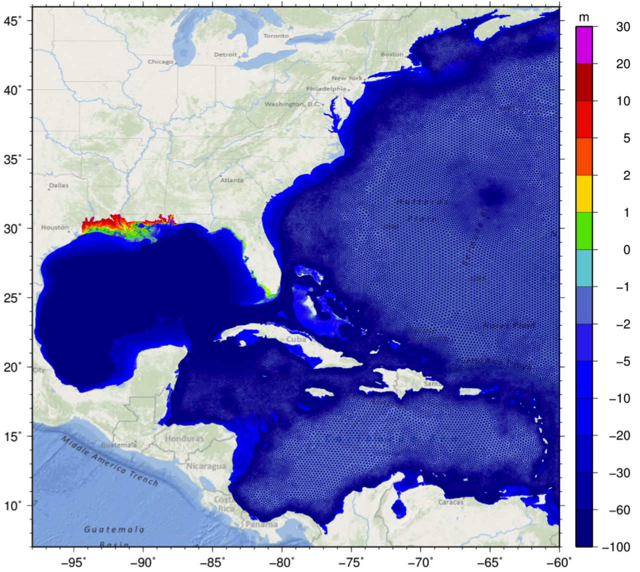


Spatial Scales – Unstructured, Finite-Element Meshes



Spatial Scales – SL16 Mesh for Southern Louisiana



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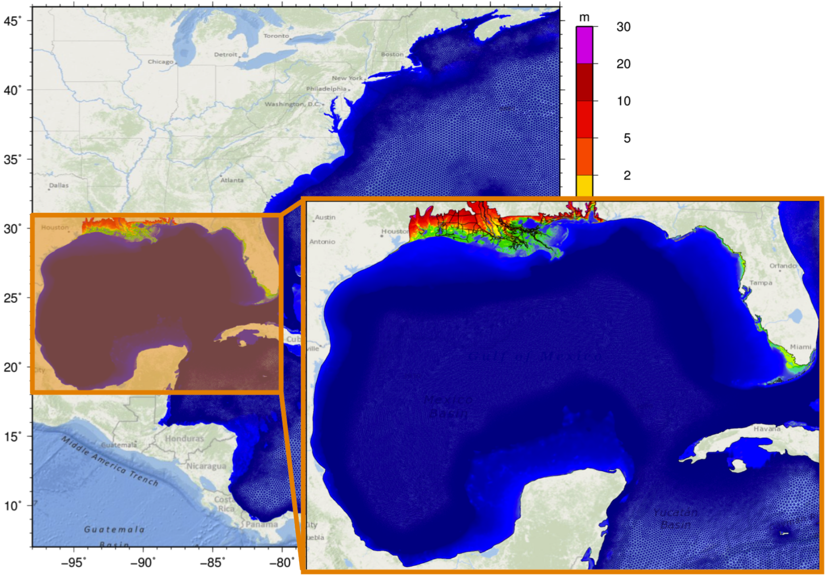

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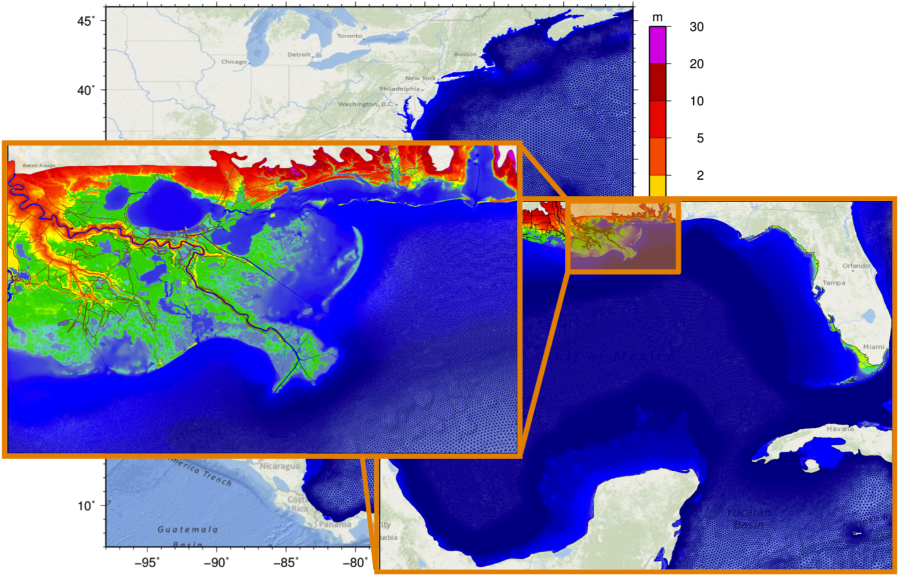

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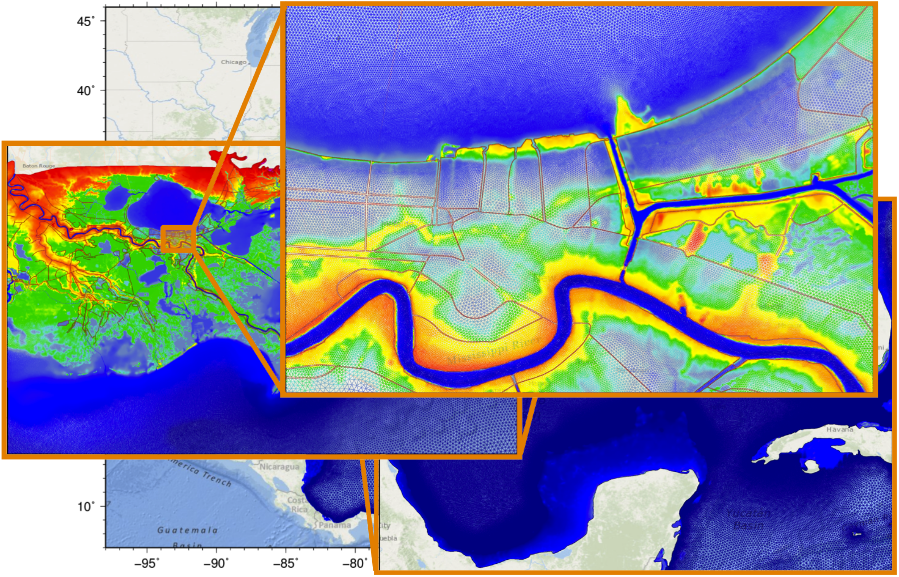
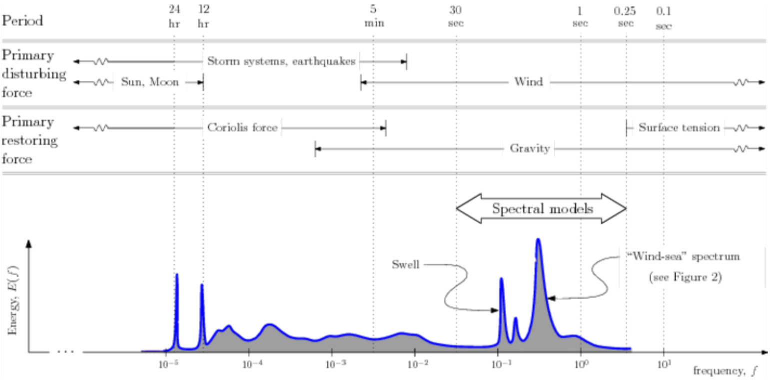


Waves and Storm Surge – Temporal Scales

Sea surface can be described with both *long* and *short* waves

- Long waves due to tides, storm surge
- Short waves due to wind (swell and wind-sea)



Waves and Storm Surge – SWAN

For short waves, we use a model called SWAN

- SWAN = Simulating WAves Nearshore
- Does not represent the phase of each individual wave
  - Conserved quantity is the action density $N(t, x, y, \sigma, \theta)$
  - Can be integrated to compute statistical wave properties

Solves the action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot \left[(\mathbf{c}_g + \mathbf{U}) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

Solution methods in geographic (x, y) and spectral (σ, θ) spaces:

- Gauss-Seidel in geographic space
- Iterative solution of matrix system in spectral space

Waves and Storm Surge – ADCIRC

For long waves, we use a model called ADCIRC

- ADCIRC = ADvanced CIRCulation
- Does represent the phases of tides and/or storm surge

Solves the generalized wave continuity equation for water levels ζ:

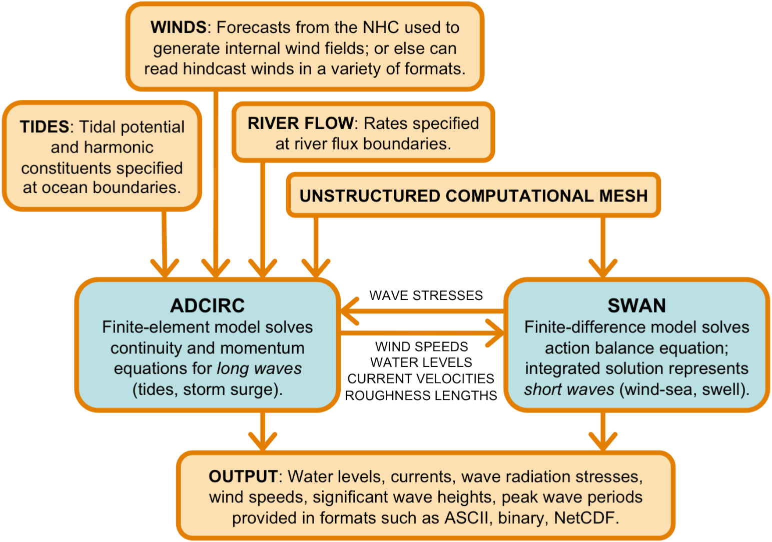
$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

Solves the depth-averaged momentum equations for currents (U, V):

$$\frac{DU}{Dt} - fV = -g \frac{\partial}{\partial x} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

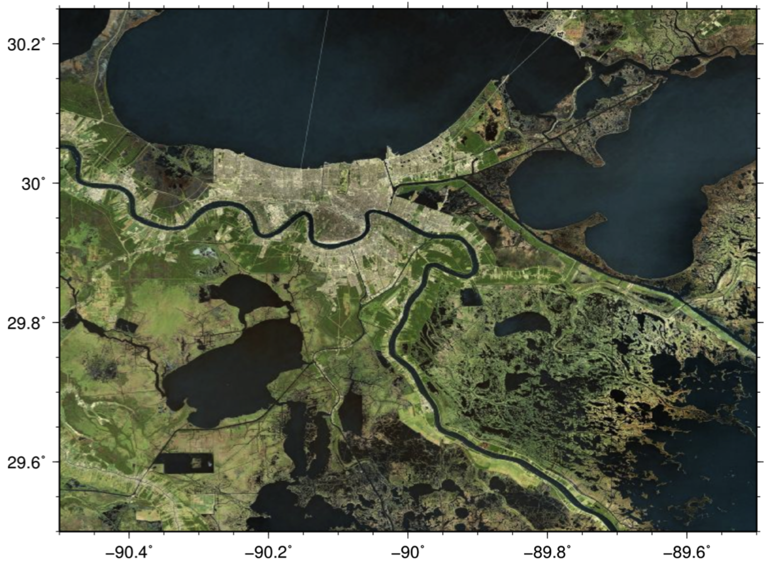
$$\frac{DV}{Dt} + fU = -g \frac{\partial}{\partial y} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

SWAN+ADCIRC – Flow Chart



JC Dietrich, et al. (2011). Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations. *Coastal Engineering*, 58, 45-65, DOI:10.1016/j.coastaleng.2010.08.001.

Gustav (2008) – Near Flooding of New Orleans



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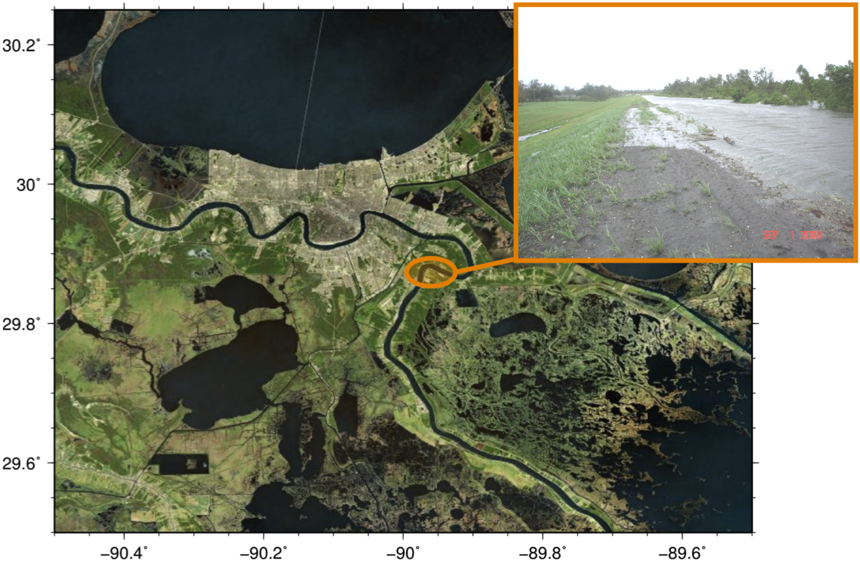

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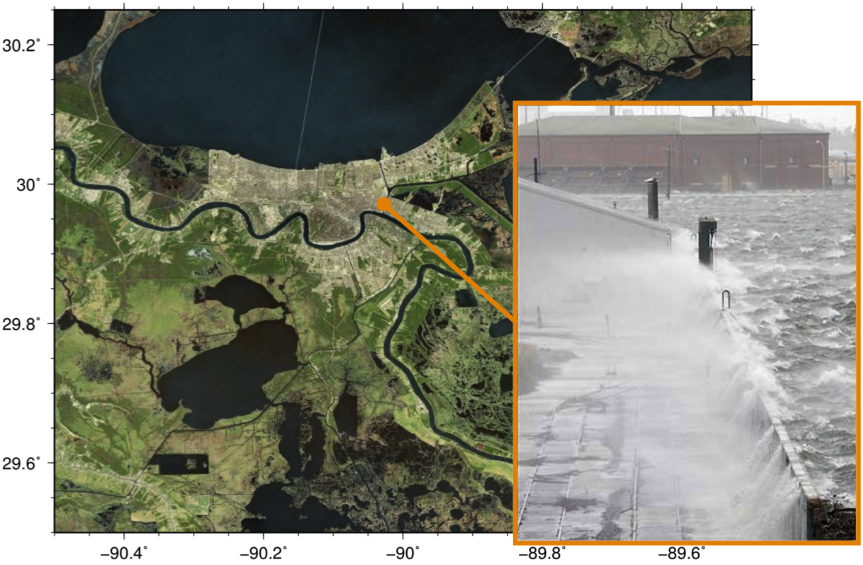
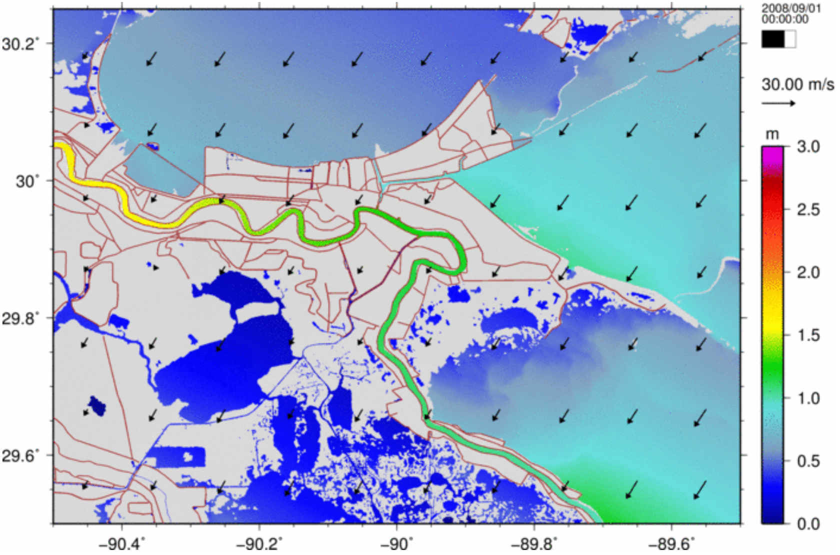
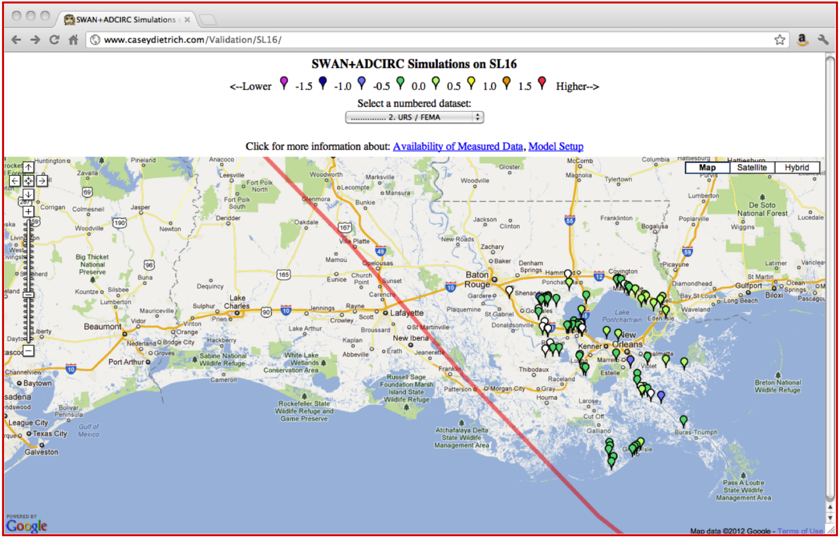


Gustav (2008) – Day of Landfall



JC Dietrich, et al. (2011). Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Validation and Synoptic Analysis in Southern Louisiana. *Monthly Weather Review*, 139(8), 2488-2522.

Gustav (2008) – High-Water Marks



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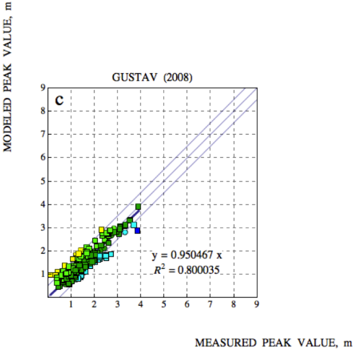

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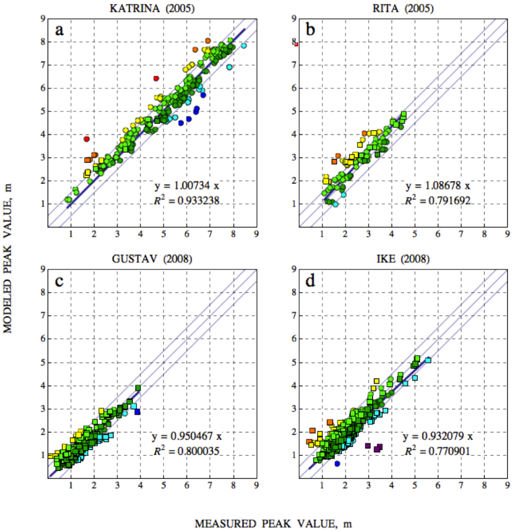

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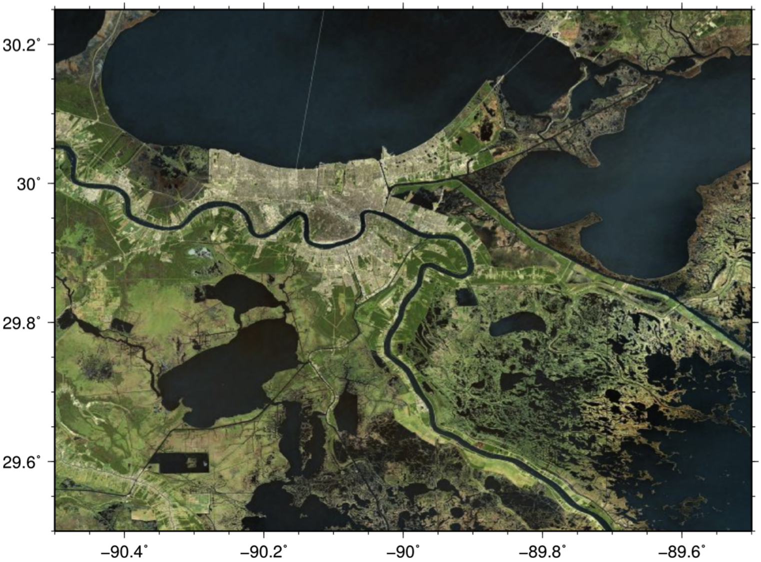
Applications – Surge Barrier Design – USACE



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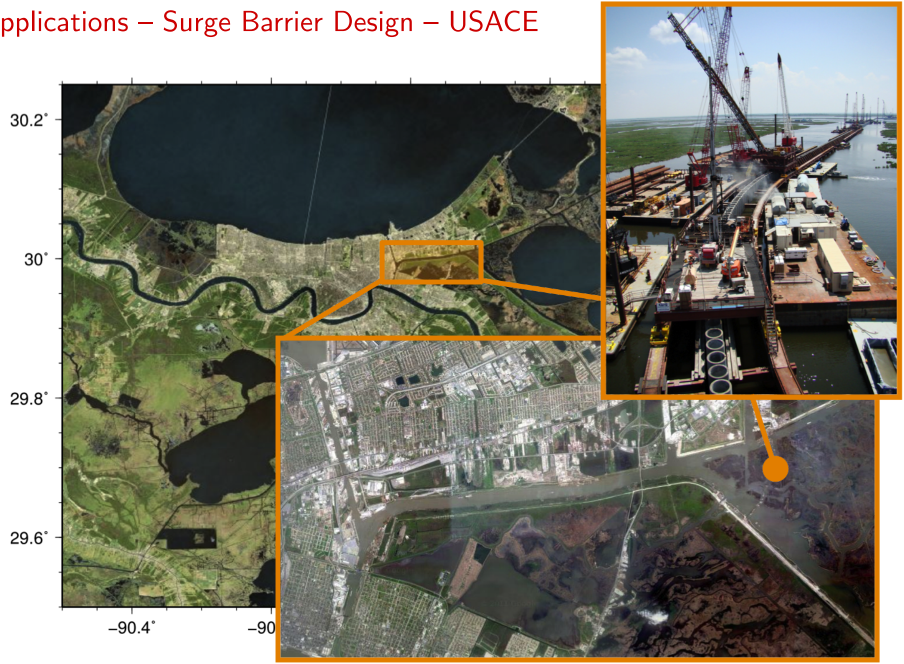
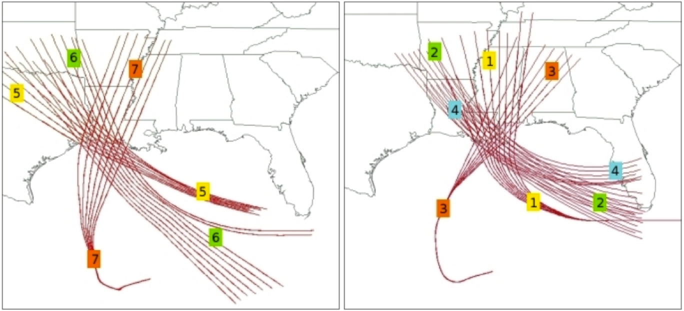


Applications – Floodplain Risk Maps – FEMA

Joint Probability Method with Optimal Sampling (JPM-OS):

- Hypothetical storms with varying characteristics
- Combine results to develop 100-yr flood maps



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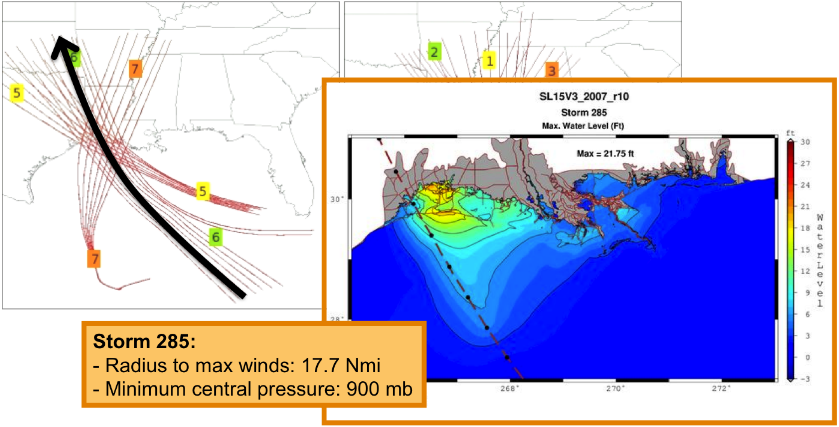


ASGS – Introduction

SWAN+ADCIRC can be employed in real-time via the ASGS

- ASGS = ADCIRC Surge Guidance System
- **Everything happens automatically**
  - Models are initialized, run and processed by Perl scripts

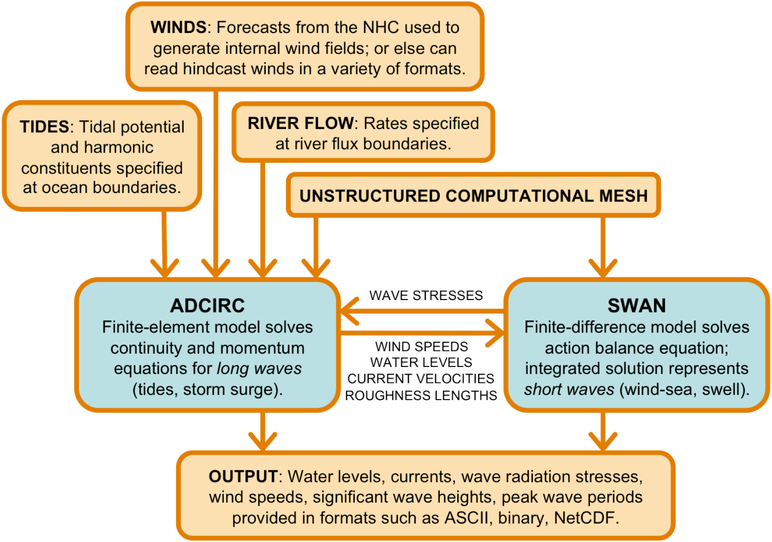
Wind fields from two sources:

1. Under normal conditions:
   - Downloaded from NAM model output by NOAA/NCEP
   - Converted into format compatible with SWAN+ADCIRC
2. Under hurricane conditions:
   - Download advisories from NOAA/NHC
   - Generate wind field using parametric model (Holland, 1980)

Guidance can be shared in multiple formats:

- Raster images (JPG, PNG, etc.)
- Geo-referenced raster images (Google Earth, GIS)
- Web service (`coastalemergency.org`)

ASGS – Flow Chart



ASGS – Development Teams

University of North Carolina at Chapel Hill

- Provide forecasts for Carolina and surrounding states via Google Maps application (`nc-cera.renci.org`)
- Guidance during Irene (2011) prompted Coast Guard to shift operations to avoid flooding of operations center

Louisiana State University

- Provide forecasts for Louisiana and northern Gulf states via Google Maps application (`cera.cct.lsu.edu`)

University of Texas at Austin

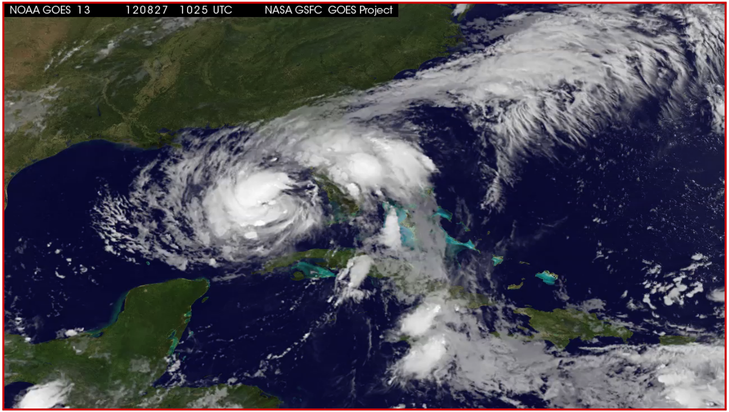
- Provide forecasts for storms impacting Texas coastline
- Partnerships with Texas State Operations Center
- During Isaac (2012), guidance shared with NWS offices in Fort Worth, Tallahassee and Miami

Isaac (2012) – Disorganized Movement across the Gulf

Passed over Hispaniola and Cuba as a tropical storm

- Low central pressure
- Late development of core

Finally developed into Category 1 storm as it approached Louisiana



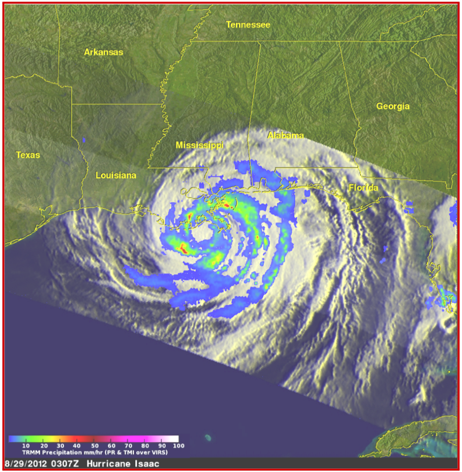
Isaac (2012) – Slow Crawl across Southern Louisiana

Two landfalls over 28-29 August:

- Mississippi River delta:
  - 1845 CDT / 2345 UTC
- Port Fourchon:
  - 0200 CDT / 0700 UTC

Extremely slow moving storm:

- Heavy rainfall:
  - 20in in New Orleans
  - 10in in Mississippi
- Surge pushed into marshes:
  - 3.4m near Shell Beach
  - 2.5m in Mississippi

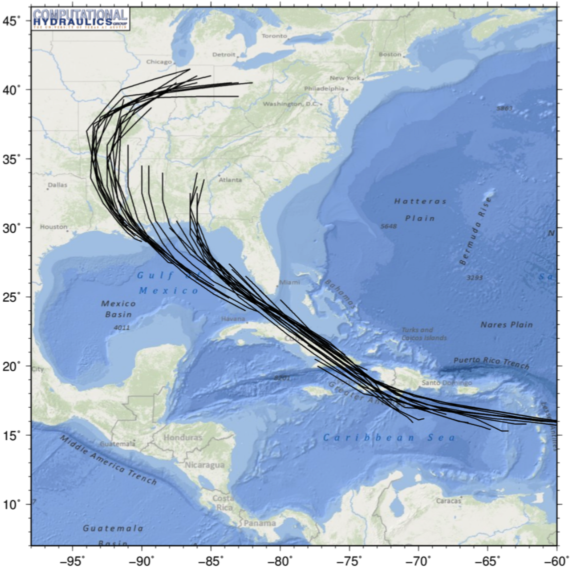


Isaac (2012) – Flooding outside New Orleans

Tested protection system around metropolitan New Orleans

- No flooding in city proper
- Overtopped levees around surrounding communities

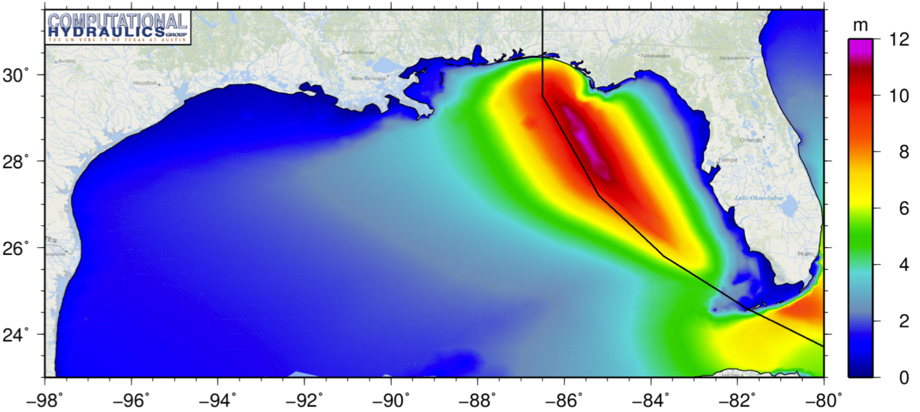
Isaac (2012) – Track Uncertainty



Isaac (2012) – Maximum Significant Wave Heights

Advisory 20:

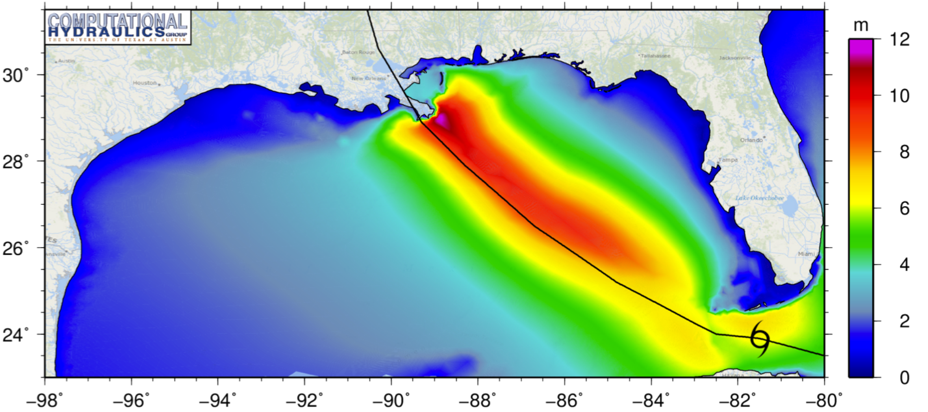
- Issued 25 August 2200 CDT
- Last forecast with projected landfall in Florida



Isaac (2012) – Maximum Significant Wave Heights

Advisory 24:

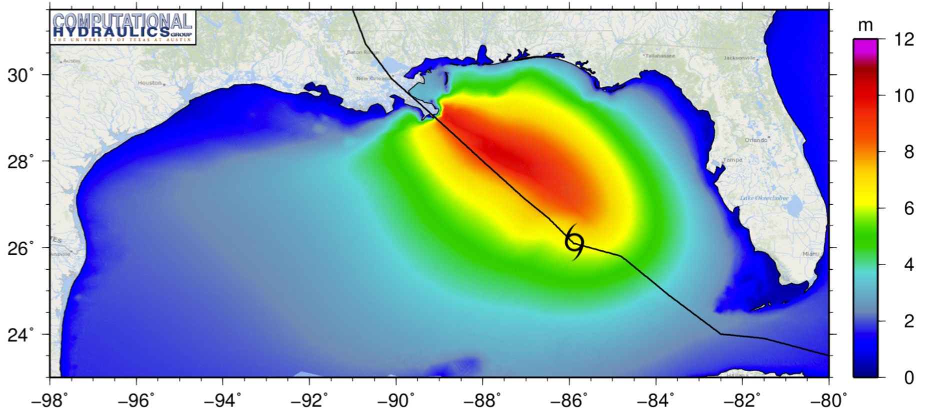
- Issued 26 August 2200 CDT
- First forecast with projected landfall in Louisiana



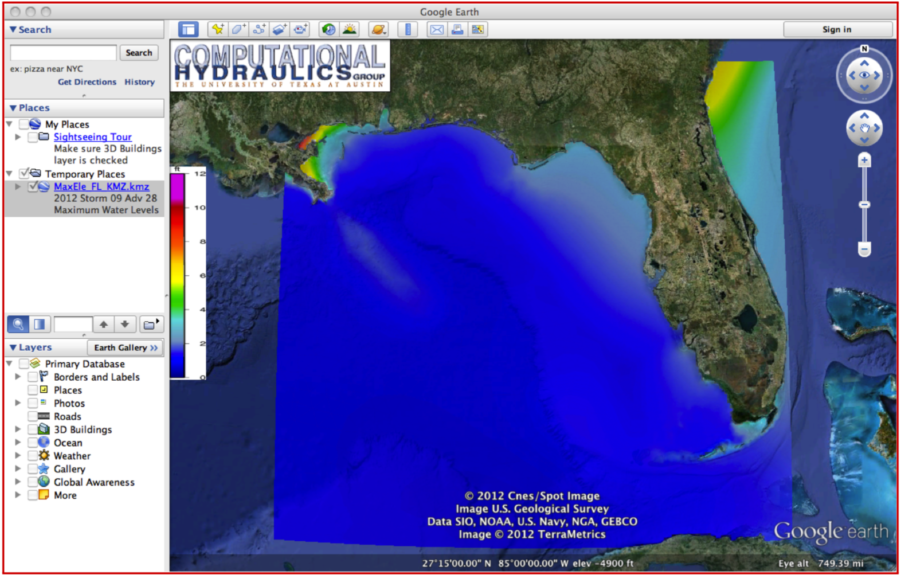
Isaac (2012) – Maximum Significant Wave Heights

Advisory 28:

- Issued 27 August 2200 CDT
- Forecast issued less than 24hr before initial landfall



Isaac (2012) – Maximum Water Levels



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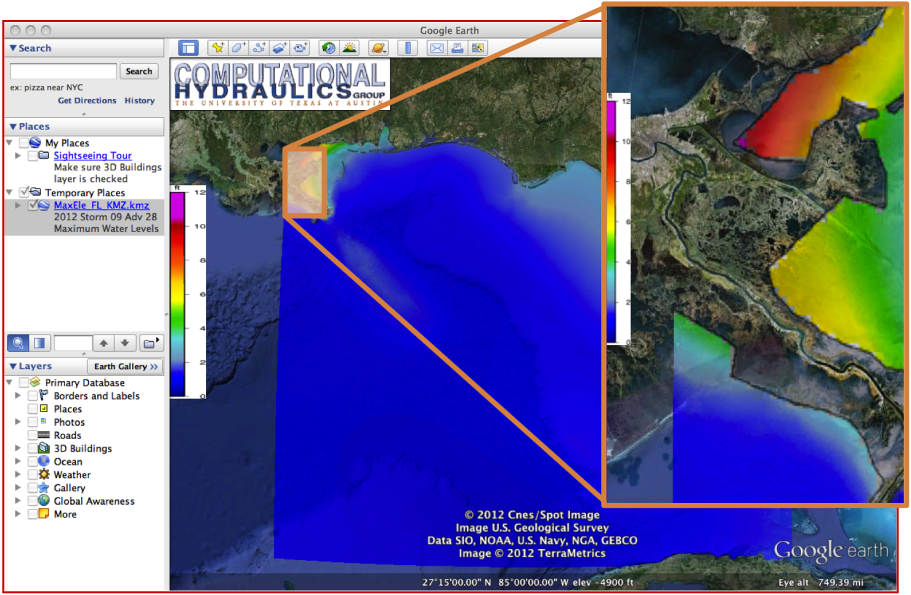

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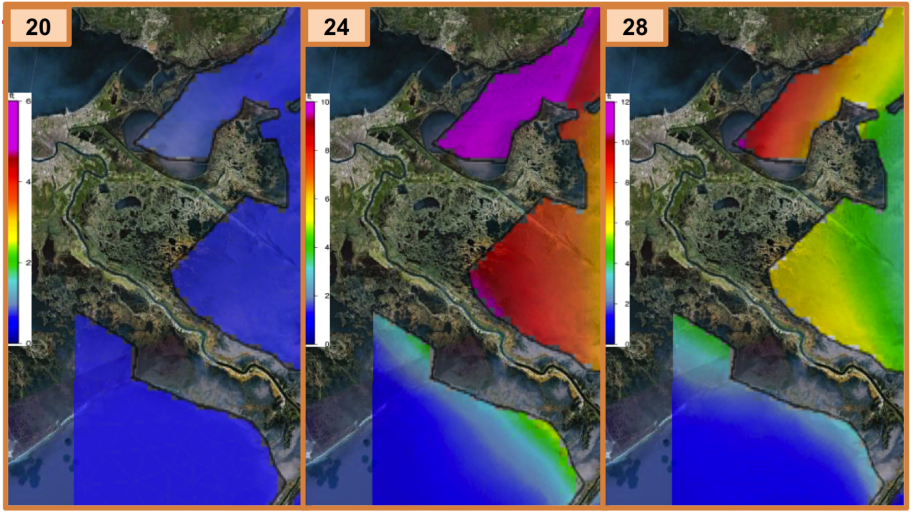

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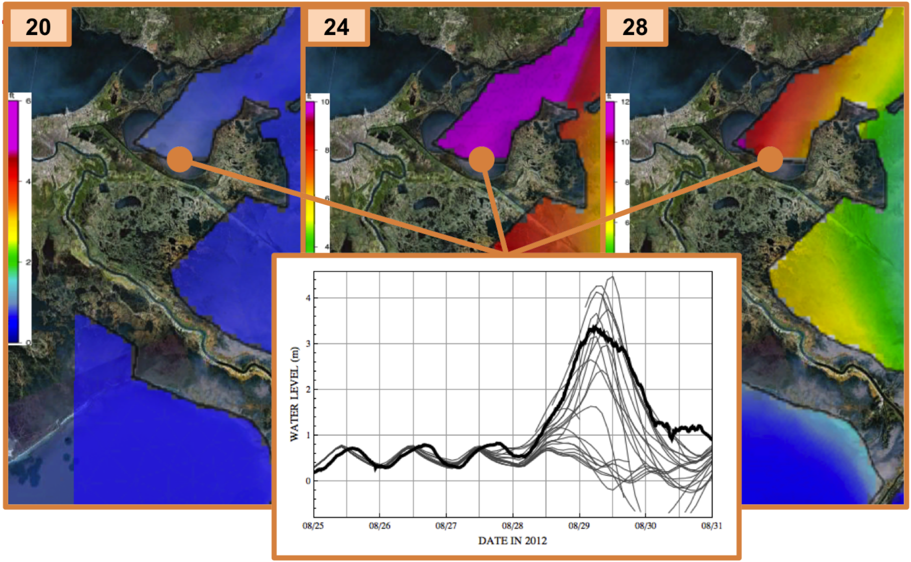

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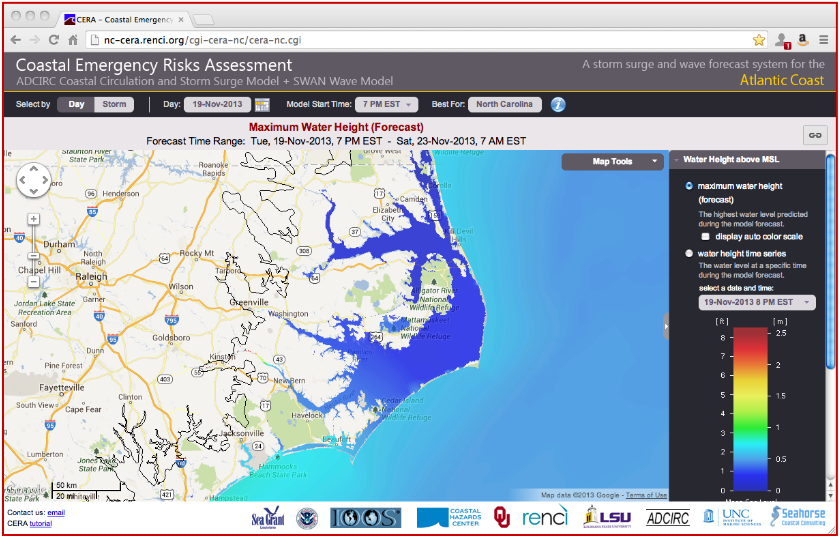
CERA for NC – Web-Based Guidance



CERA for NC – Waves and Coastal Flooding

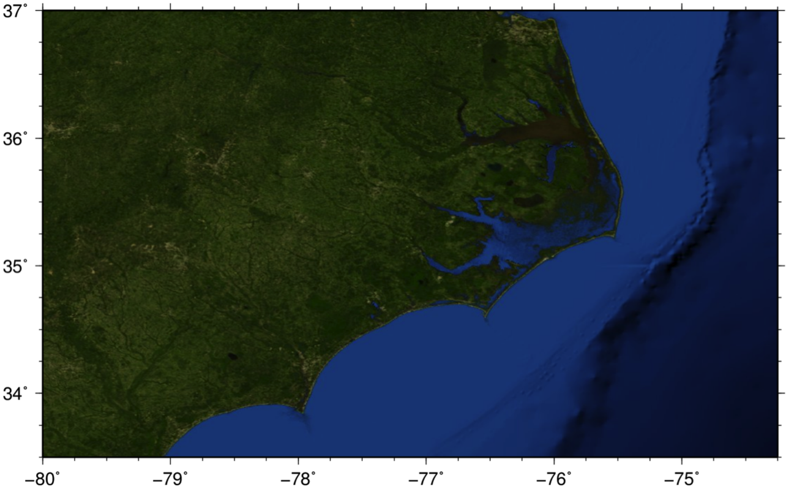
Updated everyday with new guidance:

- Normal conditions with base meteorology from NOAA/NCEP
- Extreme conditions with storm advisories from NOAA/NHC

Guidance is interactive within Google Maps:

- View results as a time series or as maxima
- Select layers for:
  - Water levels (above MSL or above ground)
  - Waves (significant heights, peak periods)
  - Wind speeds
  - Hydrographs at NOAA/NOS gage stations

CERA for NC – Unstructured Mesh



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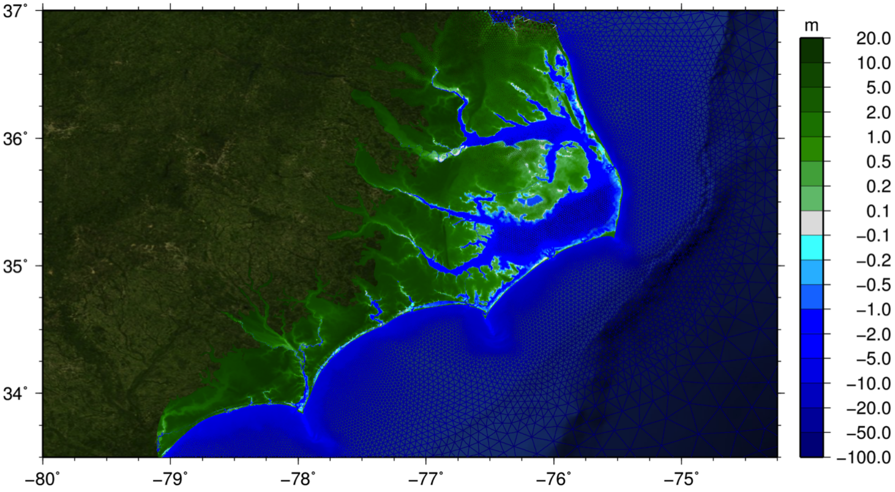

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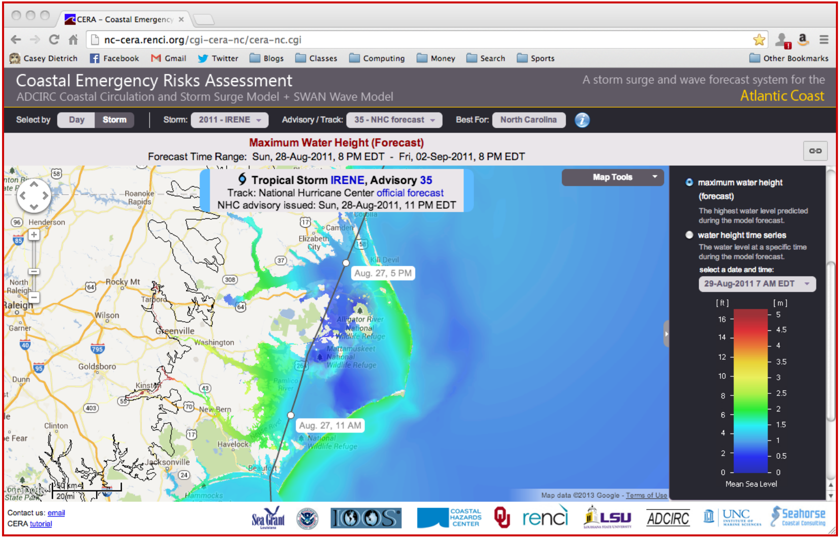

Conclusions

High-resolution models for southern Louisiana:

- Resolution varies from kilometers to meters in unstructured mesh
- Validation to wealth of measurement data

Real-time forecasting for Texas and North Carolina:

- ASGS can provide guidance in variety of formats
- Useful information despite track uncertainty during Isaac (2012)
- CERA Web-based guidance for NC coast