# Development and Application of High-Resolution Models for Ocean Waves and Circulation

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**Friday, 24 February 2012**

## Education and Background

**Post-Doctoral Researcher**

- Institute for Computational Engineering and Sciences
- University of Texas at Austin
- November 2010 to present

**Research Assistant**

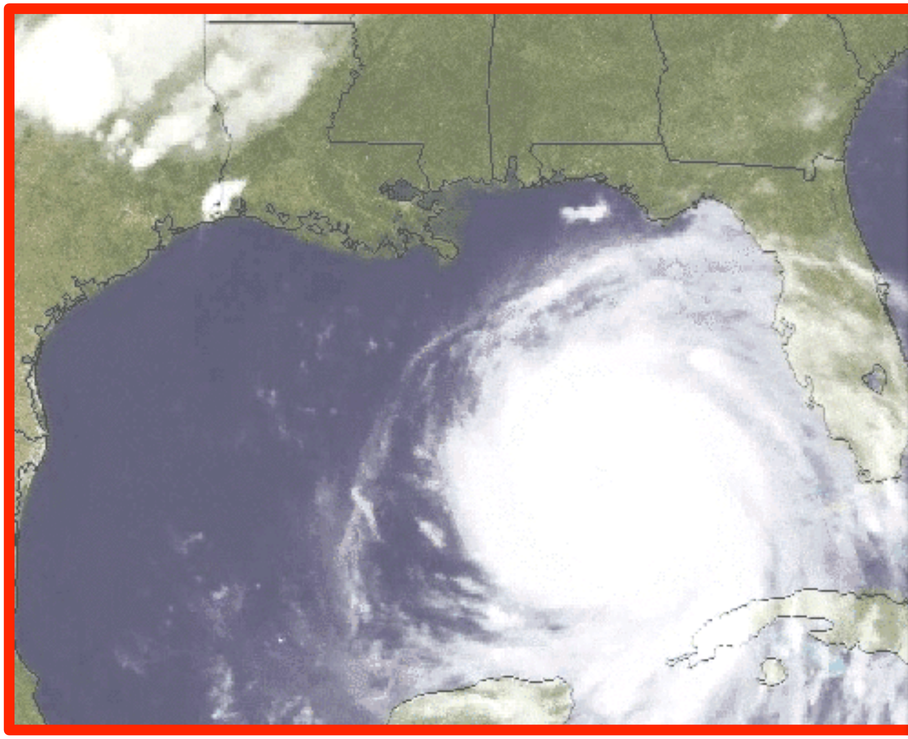
- Department of Civil Engineering and Geological Sciences
- University of Notre Dame
- August 2005 to October 2010
- PhD: 12 October 2010

**Research Assistant**

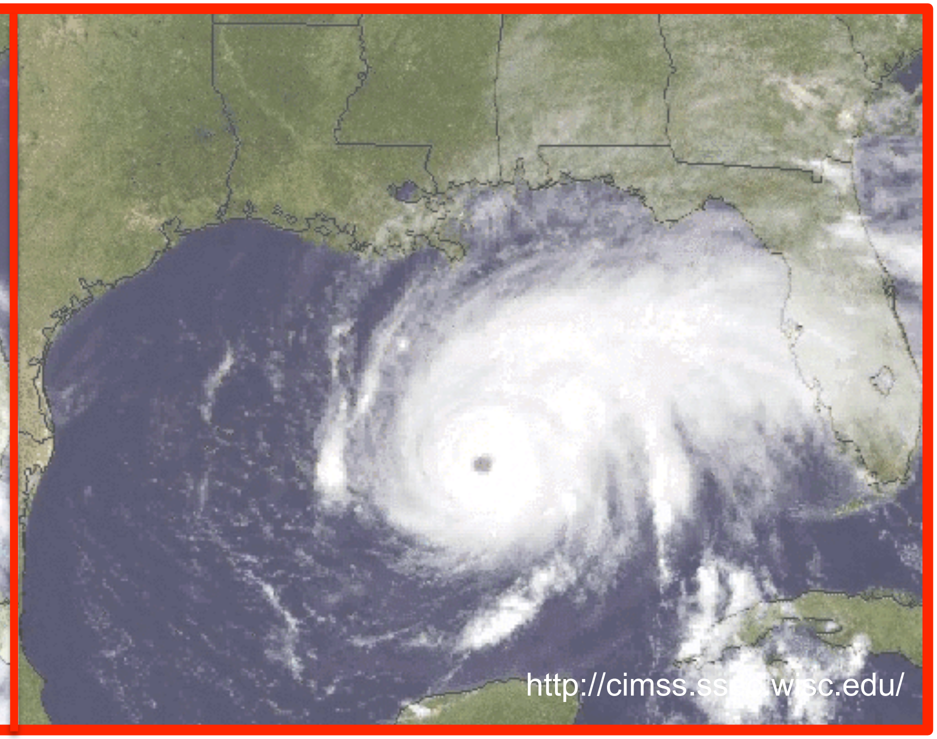
- School of Civil Engineering and Environmental Science
- University of Oklahoma
- June 1999 to July 2005
- MS: 23 June 2005

# 2005 Hurricane Season

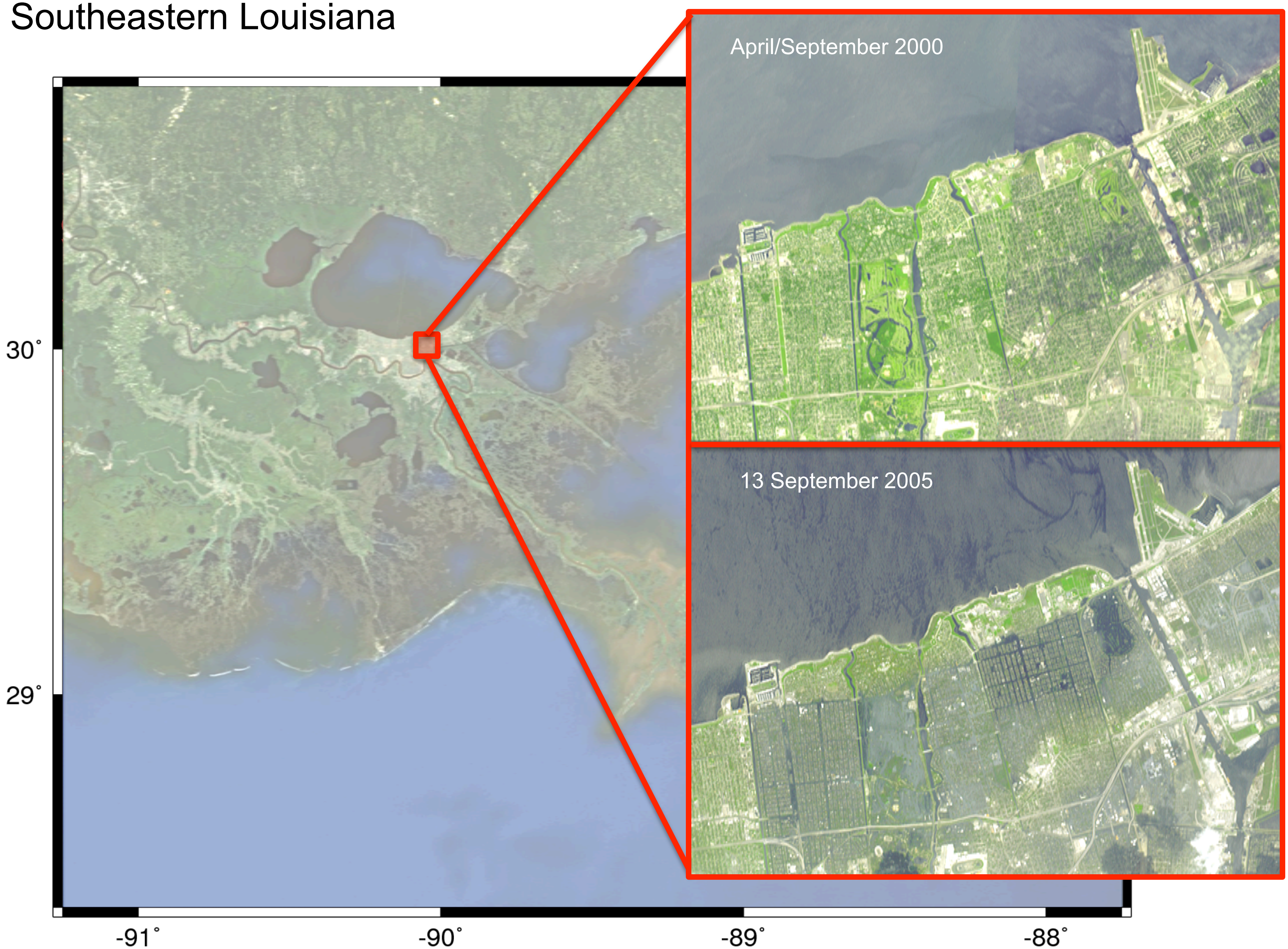
Katrina : 08/28 – 08/29



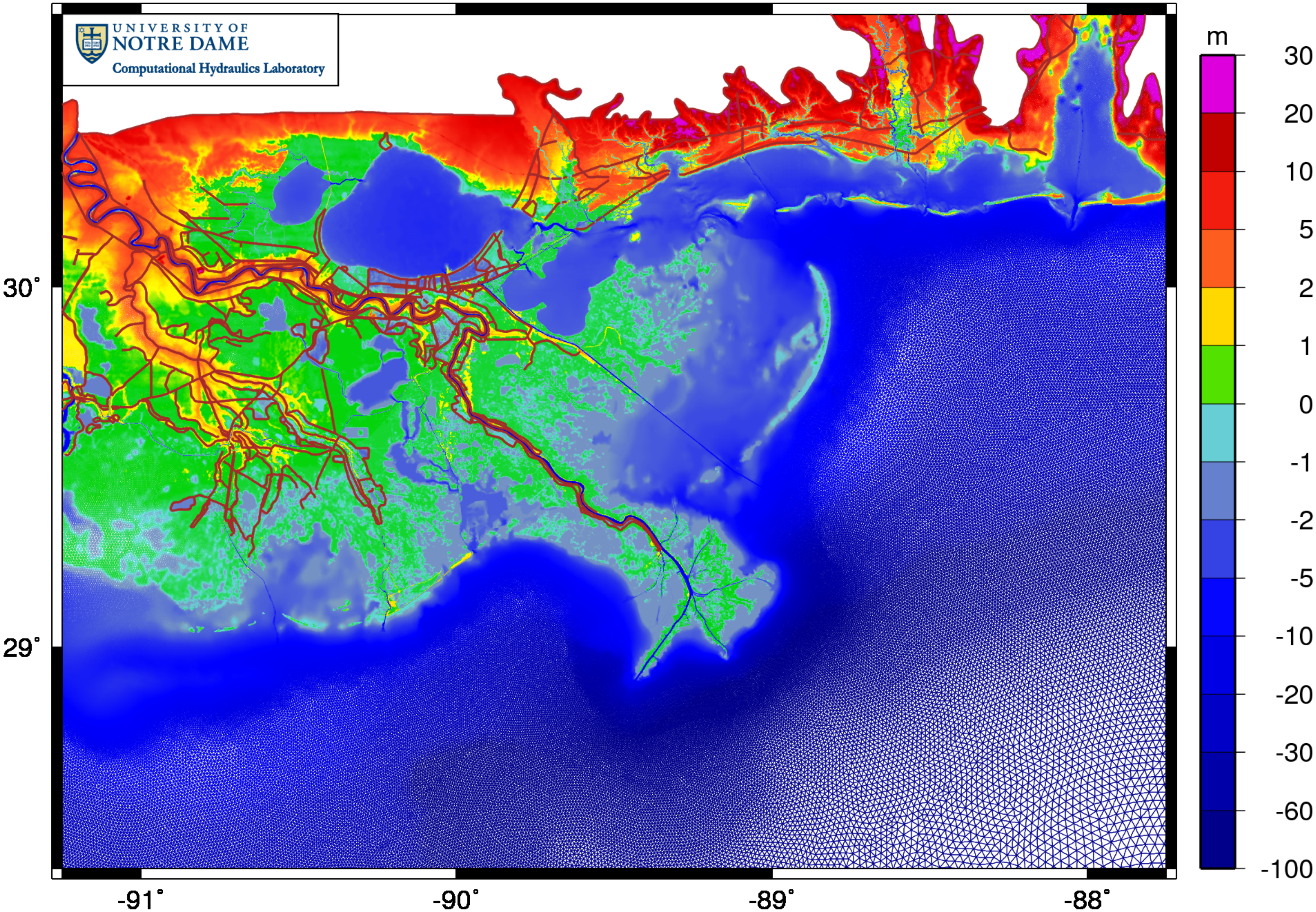
Rita : 09/22 – 09/24



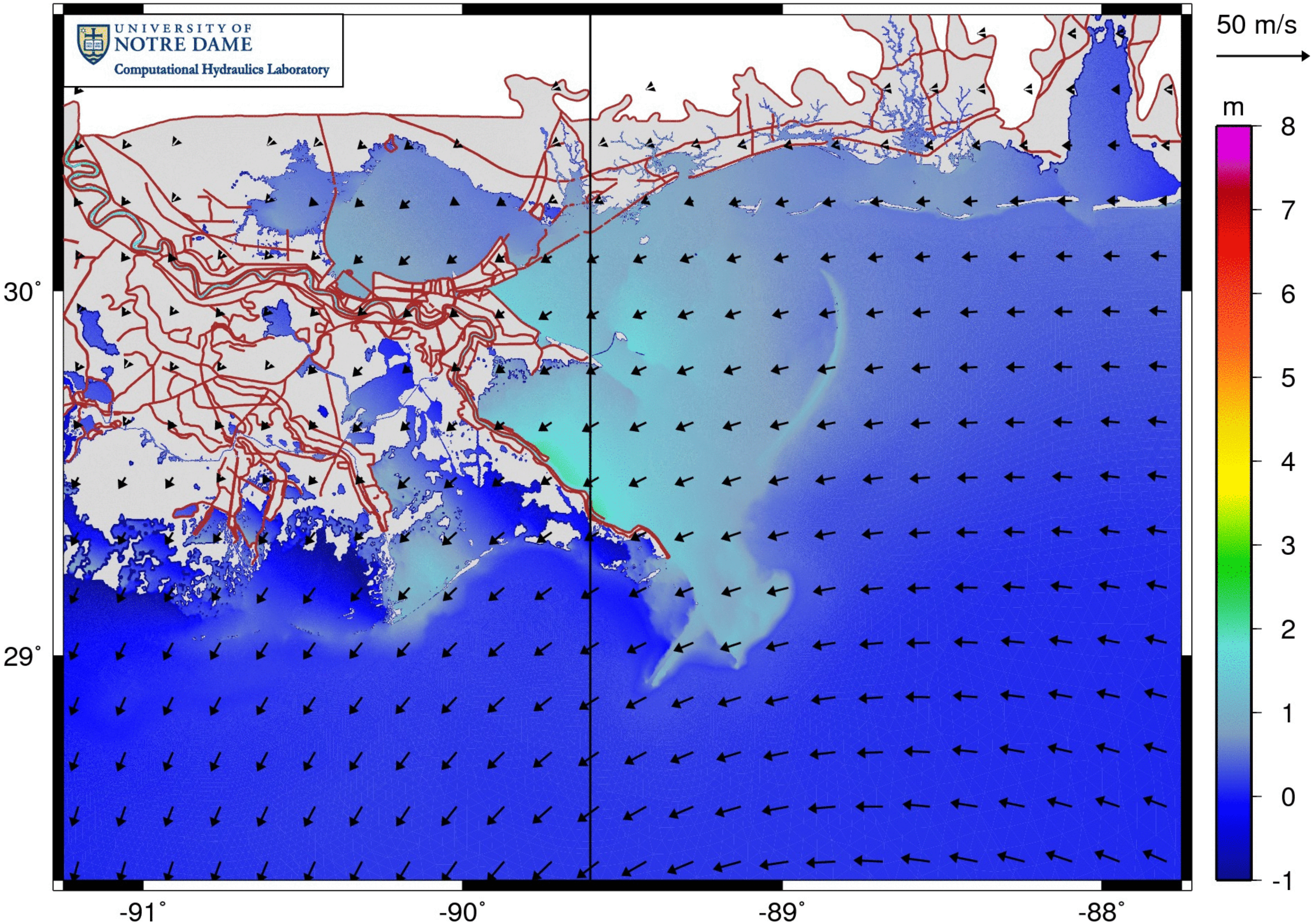
# Southeastern Louisiana



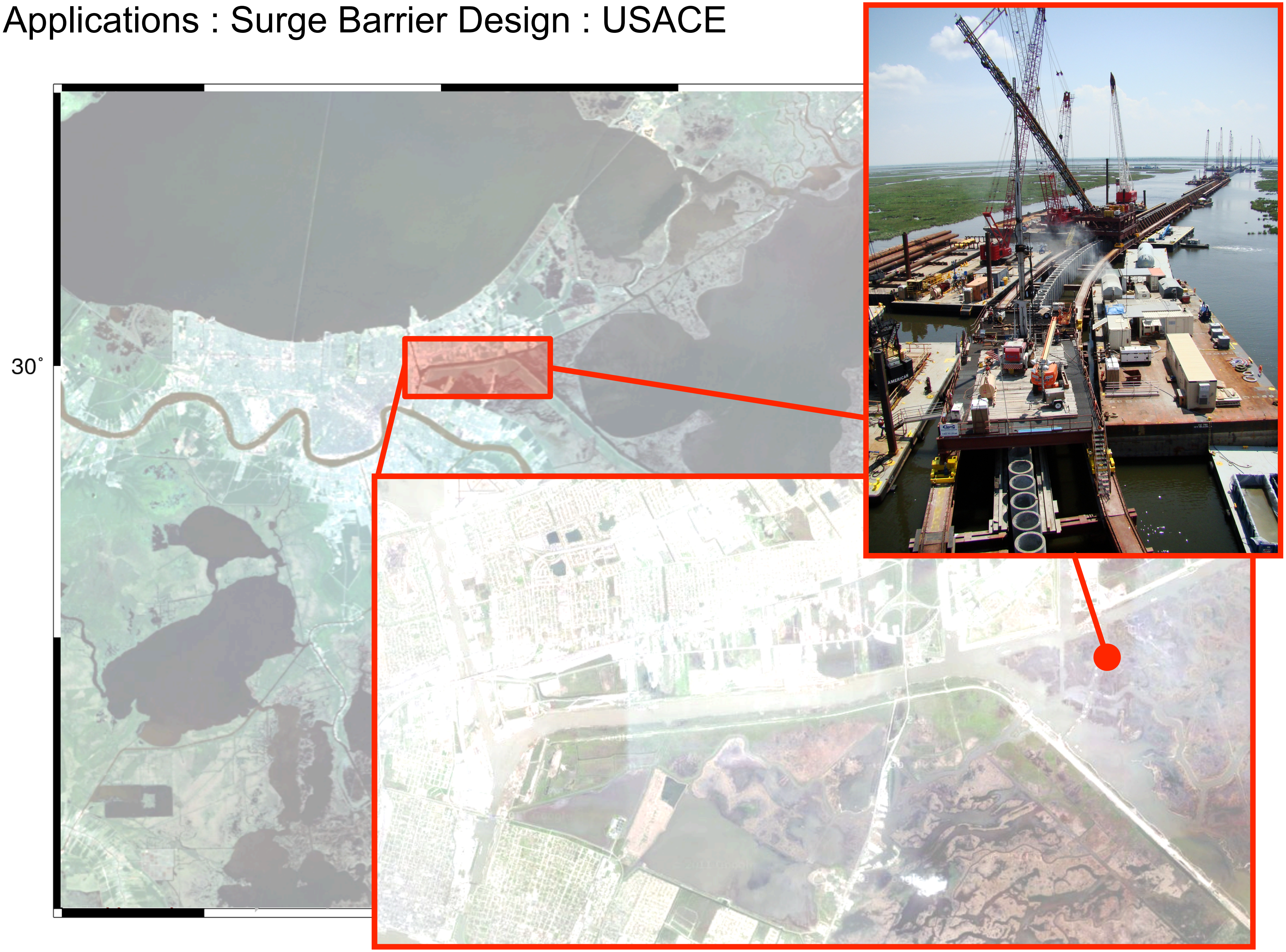
# SL16 : Bathymetry and Topography



# Application : Hurricane Hindcasting : Katrina (2005)



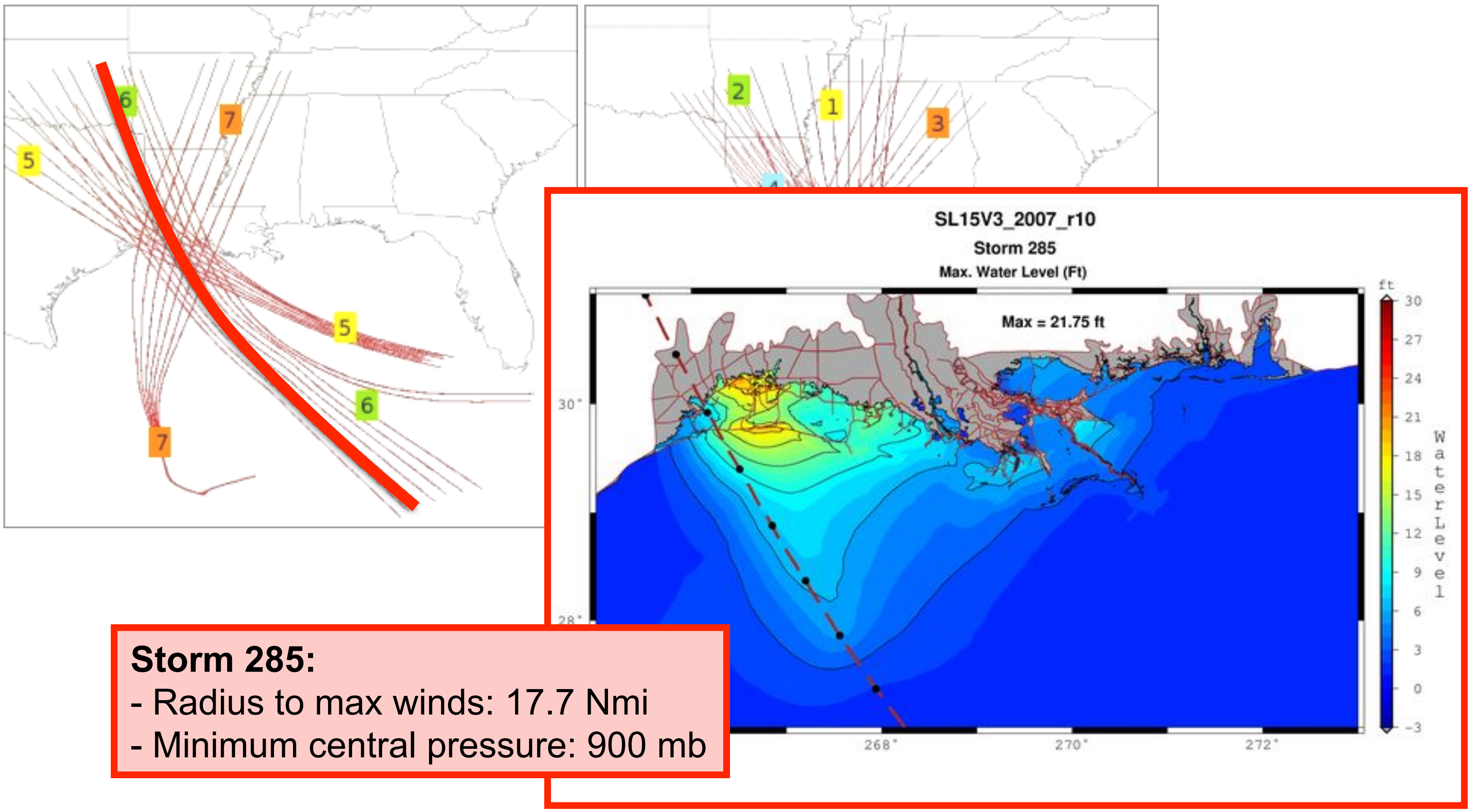
# Applications : Surge Barrier Design : USACE



Applications : Flood Insurance Rate Maps : FEMA

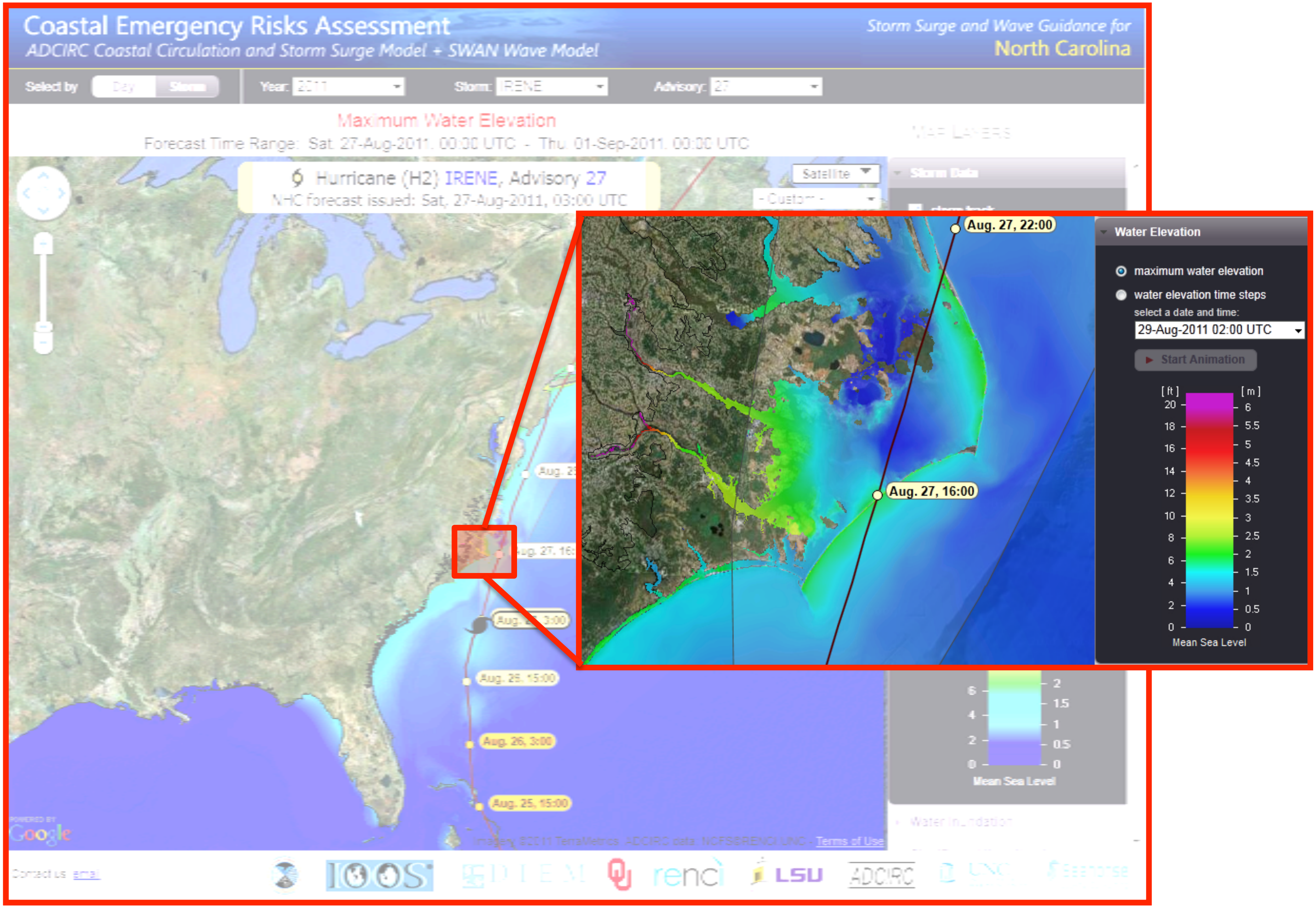
**Joint Probability Method with Optimal Sampling (JPM-OS):**

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

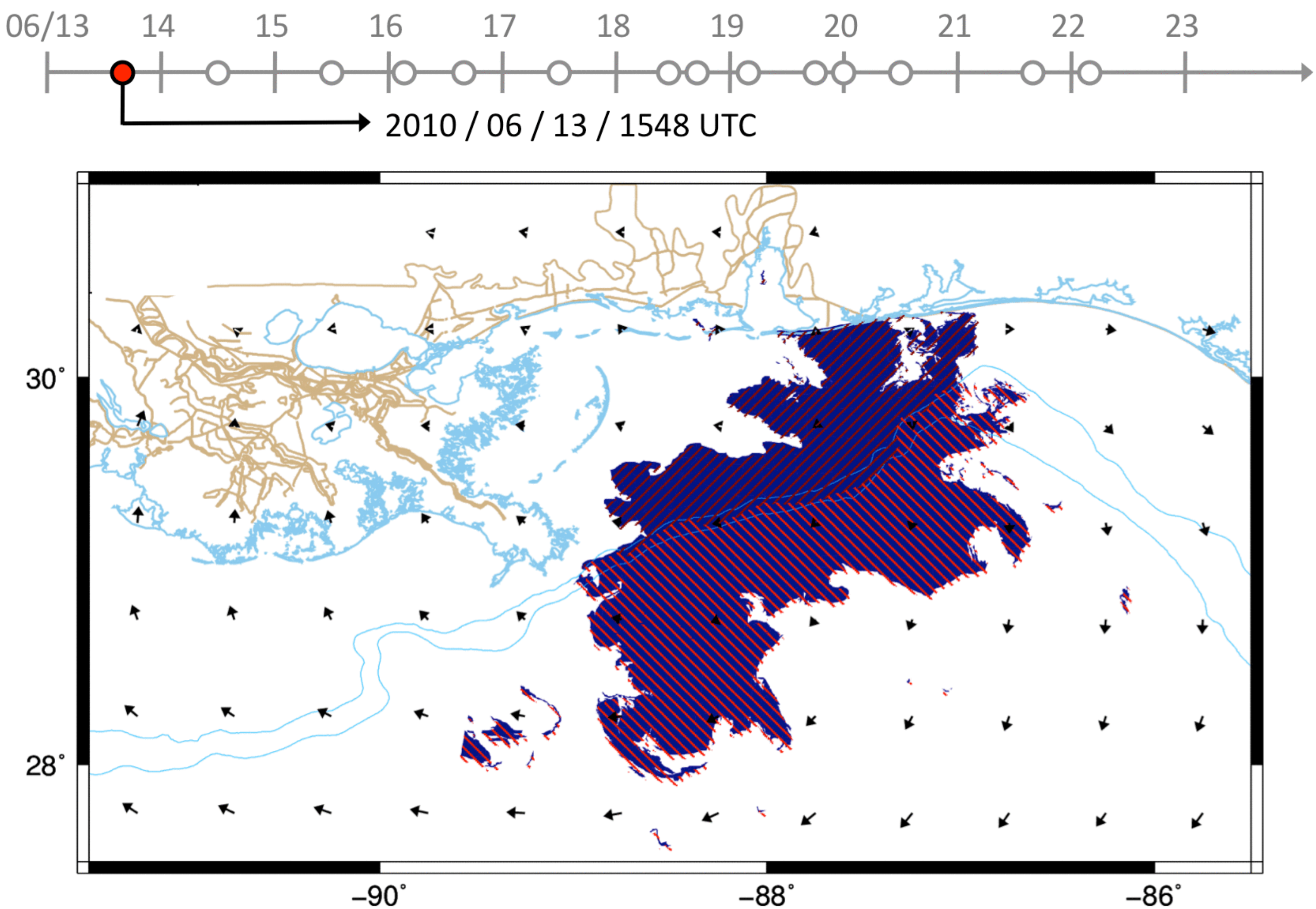



**Storm 285:**
- Radius to max winds: 17.7 Nmi
- Minimum central pressure: 900 mb

# Applications : Hurricane Forecasting : Irene (2011)



# Applications : Nearshore Oil Transport : NSF/DHS




**Satellite Imagery** **Predicted Particle Locations**

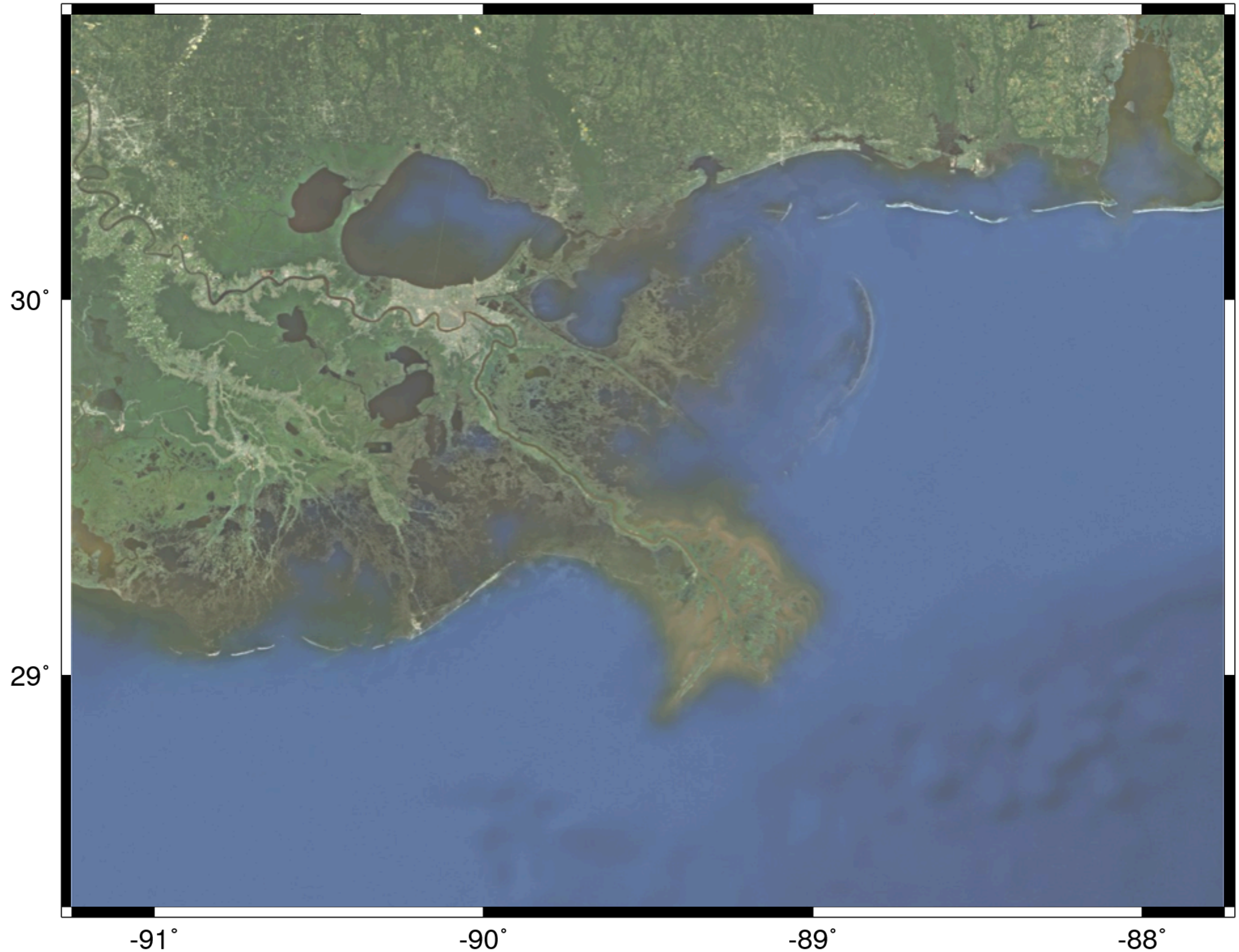
## **Where We Were**:
## ‘Loose’ Coupling of Hurricane Waves and Surge

B.A. Ebersole, *et al.* (2010). "Development of Storm Surge Which Led to Flooding in St. Bernard Polder during Hurricane Katrina.” *Ocean Engineering*, 37, 91-103.

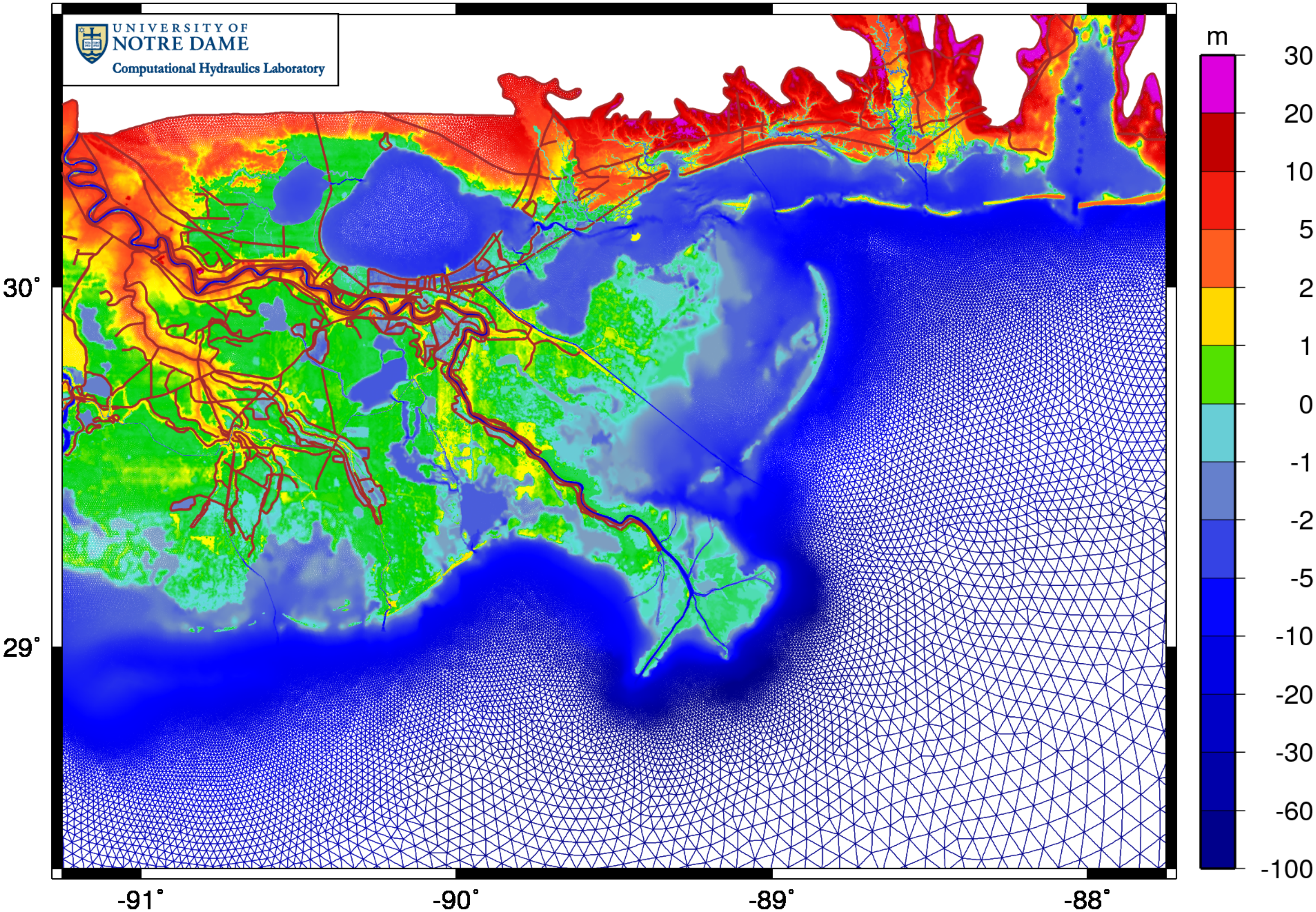
S. Bunya, *et al*. (2010). "A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi, Part I: Model Development and Validation." *Monthly Weather Review* 138, 345-377.

J.C. Dietrich, *et al*. (2010). "A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi, Part II: Synoptic Description and Analysis of Hurricanes Katrina and Rita." *Monthly Weather Review* 138, 378-404.

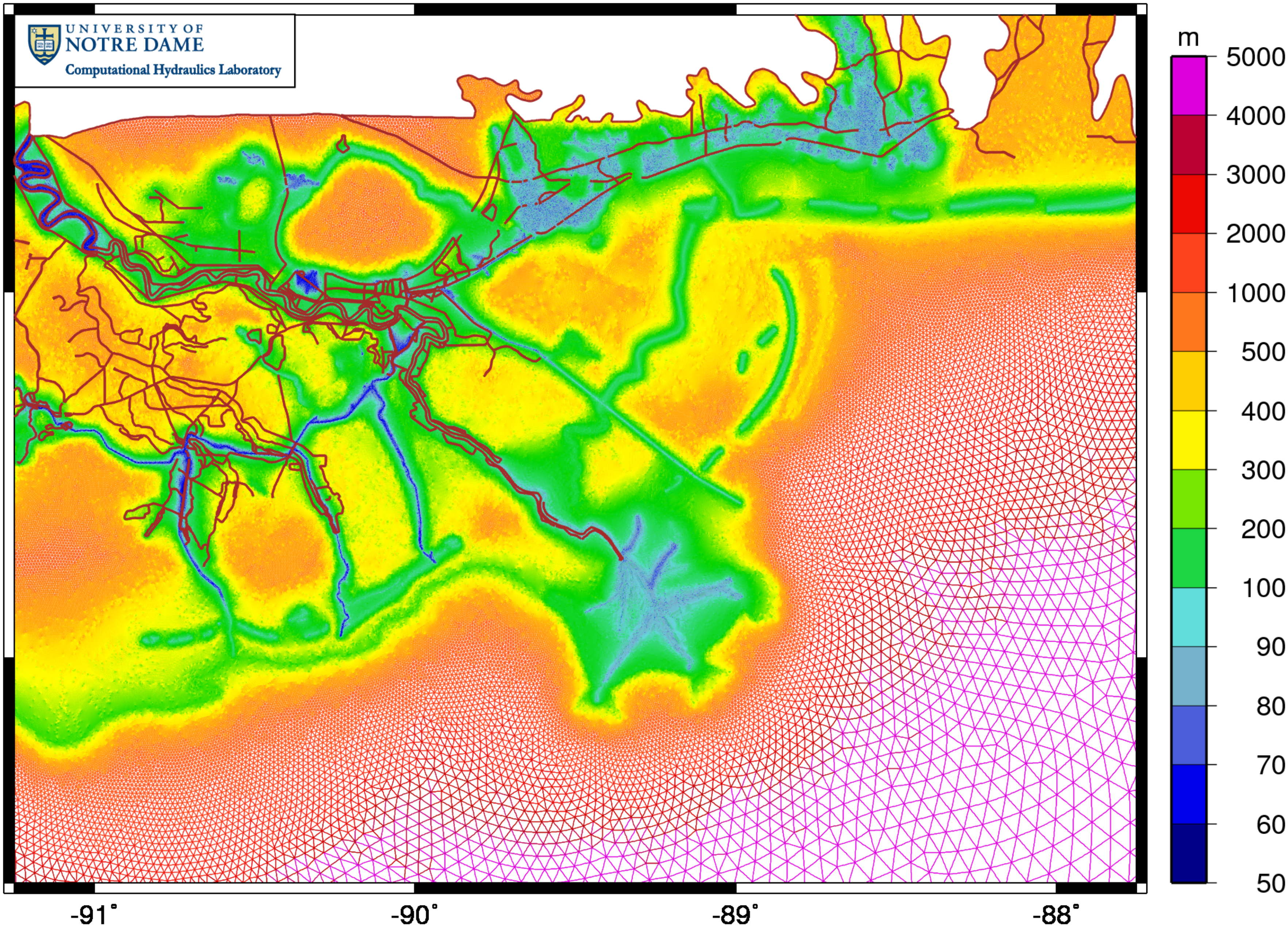
# Southeastern Louisiana



# SL15 : Bathymetry and Topography



## SL15 : Mesh Sizes



ADCIRC : Governing Equations

## ADvanced CIRCulation (ADCIRC):

- Solves the Generalized Wave Continuity Equation (GWCE):

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

where:

$$\tilde{J}_x = -Q_x \frac{\partial U}{\partial x} - Q_y \frac{\partial U}{\partial y} + fQ_y - \frac{g}{2}\frac{\partial \zeta^2}{\partial x} - gH \frac{\partial}{\partial x}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0} + \left(M_x - D_x\right) + U\frac{\partial \zeta}{\partial t} + \tau_0 Q_x - gH\frac{\partial \zeta}{\partial x}$$

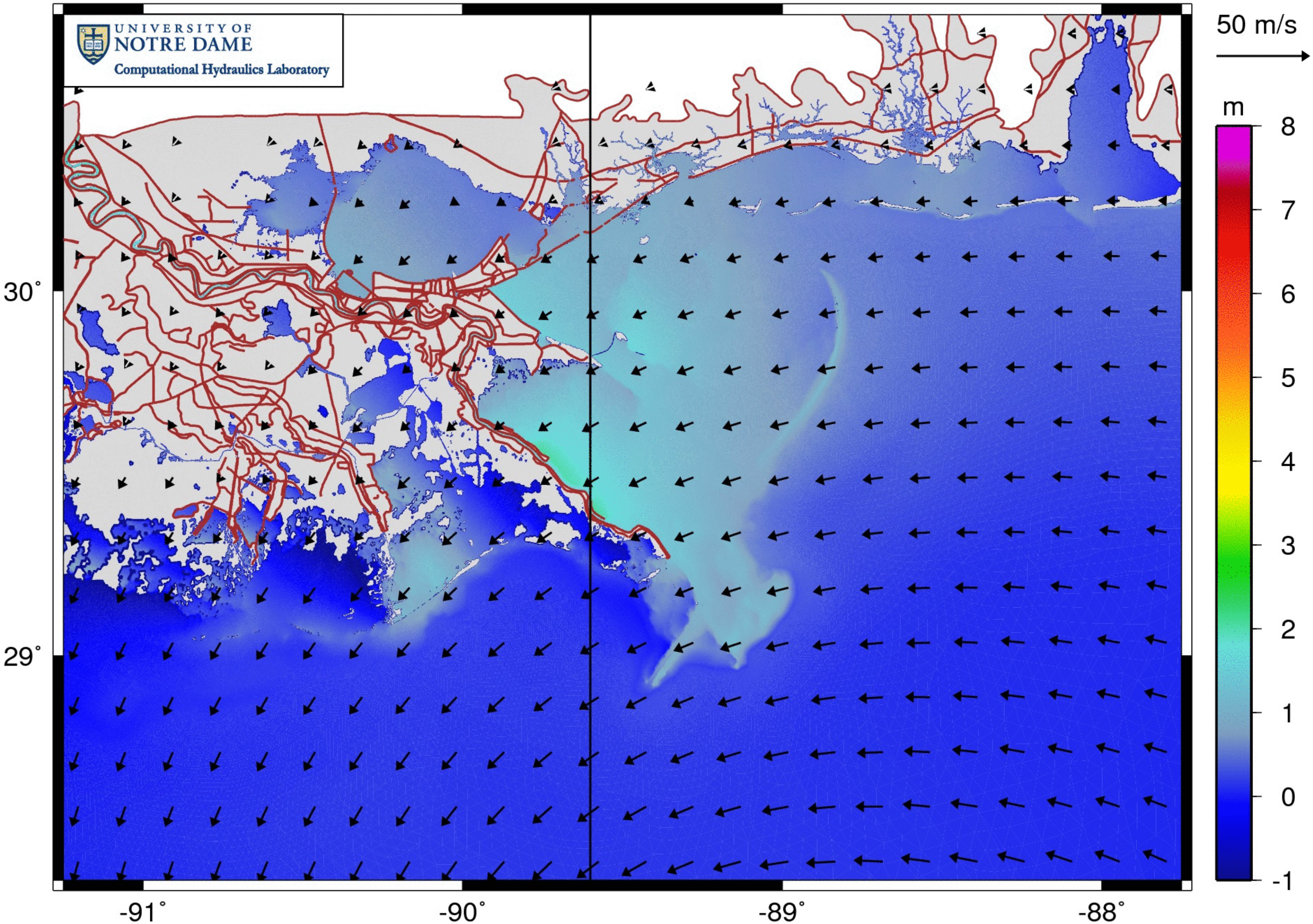
$$\tilde{J}_y = -Q_x \frac{\partial V}{\partial x} - Q_y \frac{\partial V}{\partial y} - fQ_x - \frac{g}{2}\frac{\partial \zeta^2}{\partial y} - gH \frac{\partial}{\partial y}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0} + \left(M_y - D_y\right) + V\frac{\partial \zeta}{\partial t} + \tau_0 Q_y - gH\frac{\partial \zeta}{\partial y}$$

- Solves the vertically-integrated momentum equations:

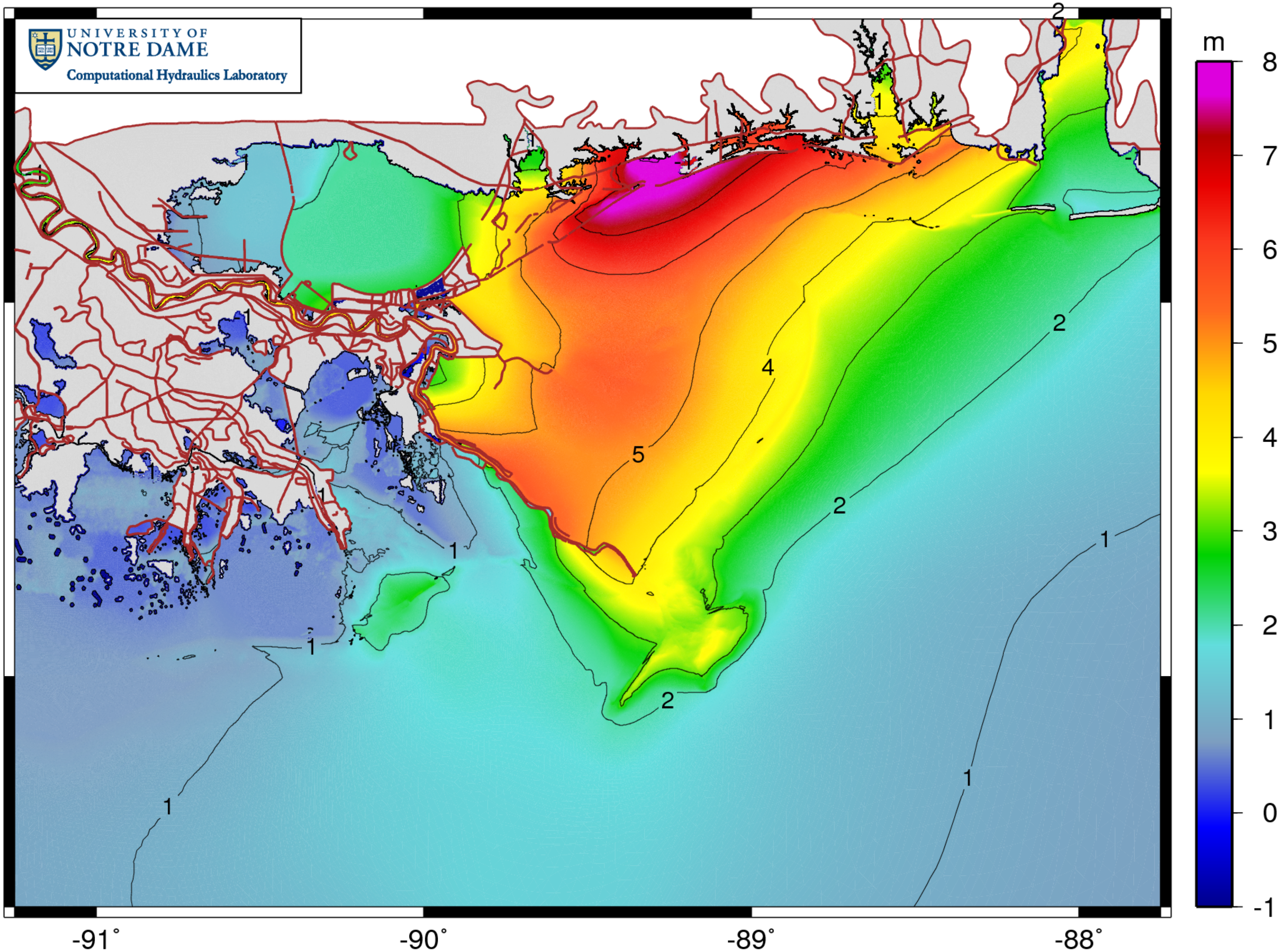
$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -g\frac{\partial}{\partial x}\left[\zeta + \frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

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

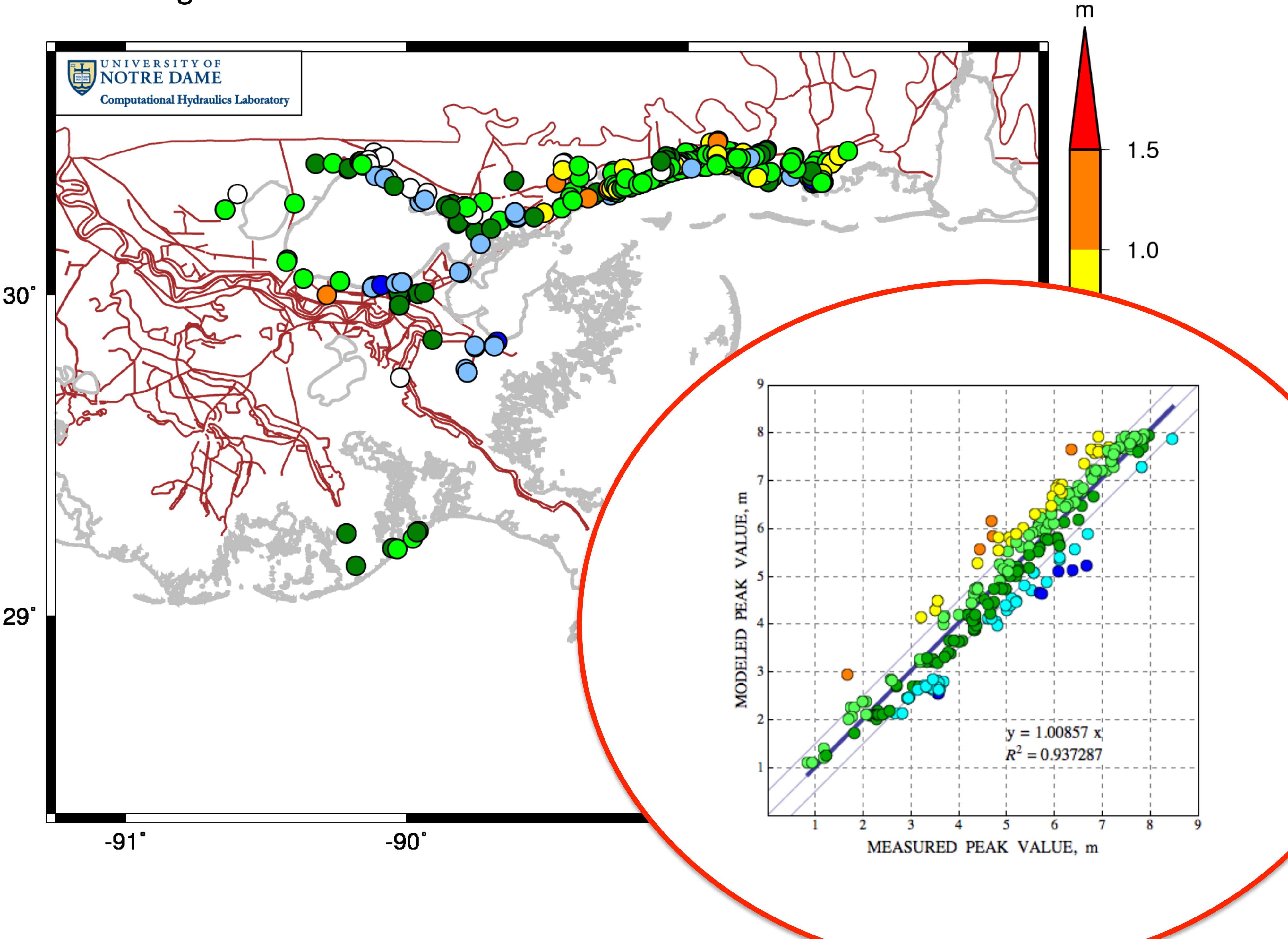
Katrina : Water Levels : 2005/08/29



# Katrina : Water Levels : Maximum



# Katrina : High-Water Marks



‘Loose’ Coupling to STWAVE

**STeady-state WAVE (STWAVE):**

- Propagates wave action density *N*( *t*, *x*, *y*, σ, θ )
- Developed by USACE

**Passing of Radiation Stress Gradients:**

- Integrate action density to get radiation stresses:

$$S_{xx} = \rho_0 g \iint \left( n\cos^2\theta + n - \frac{1}{2} \right) \sigma N d\sigma d\theta$$

$$S_{xy} = \rho_0 g \iint \left( n\sin\theta\cos\theta \right) \sigma N d\sigma d\theta$$

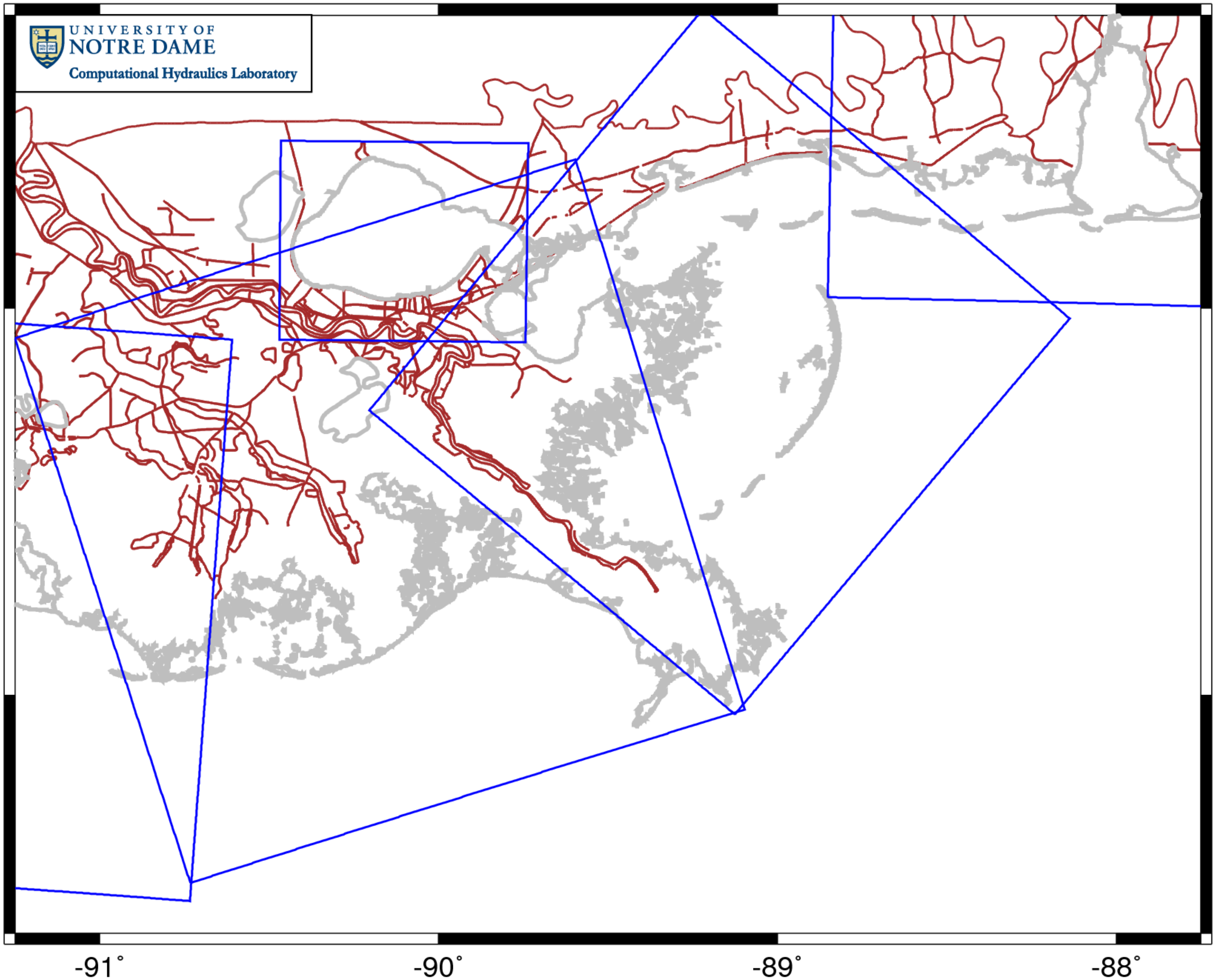
$$S_{yy} = \rho_0 g \iint \left( n\sin^2\theta + n - \frac{1}{2} \right) \sigma N d\sigma d\theta$$

- Pass the gradients as surface stresses to ADCIRC:

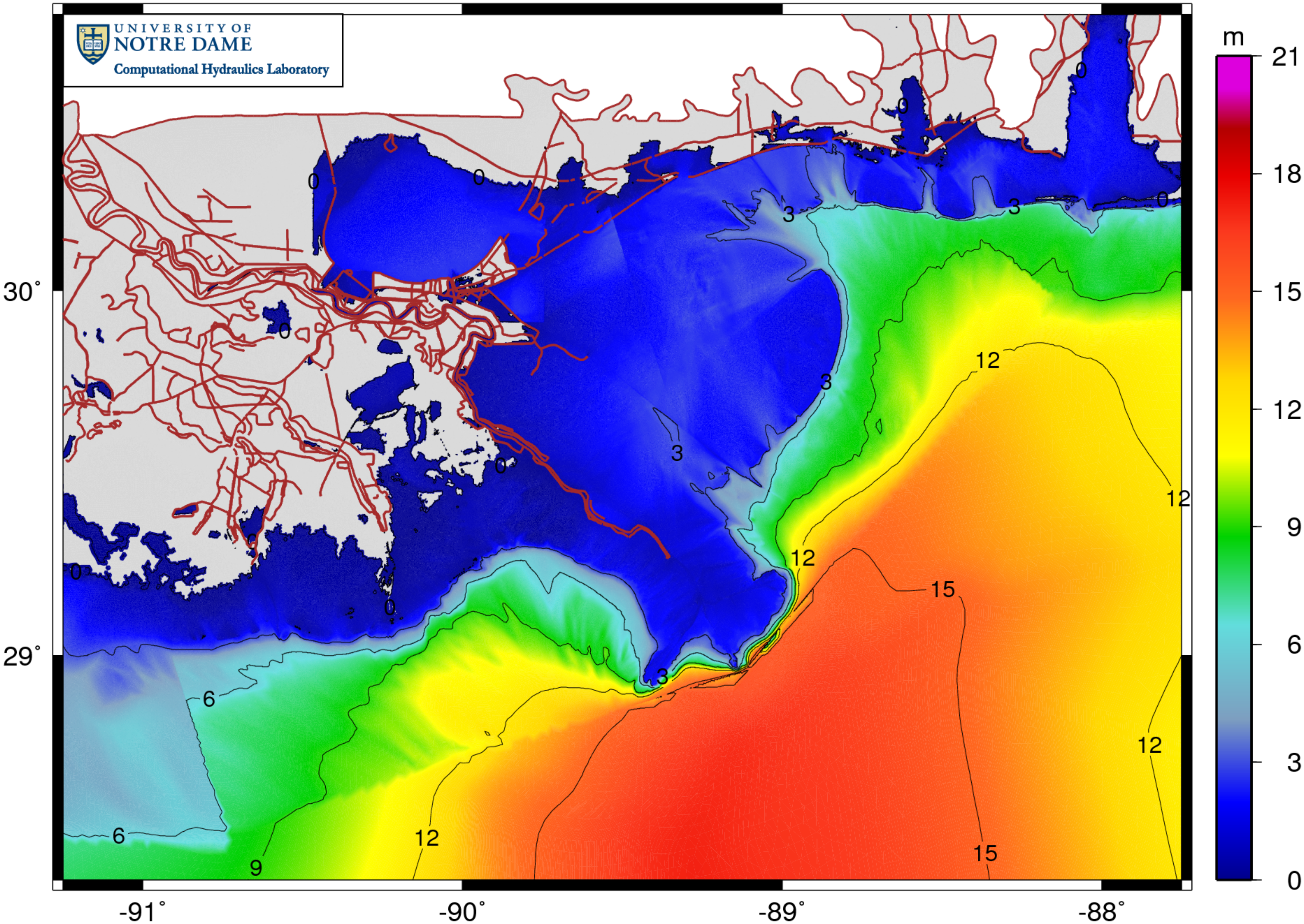
$$\tau_{sx,waves} = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}$$

$$\tau_{sy,waves} = -\frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y}$$

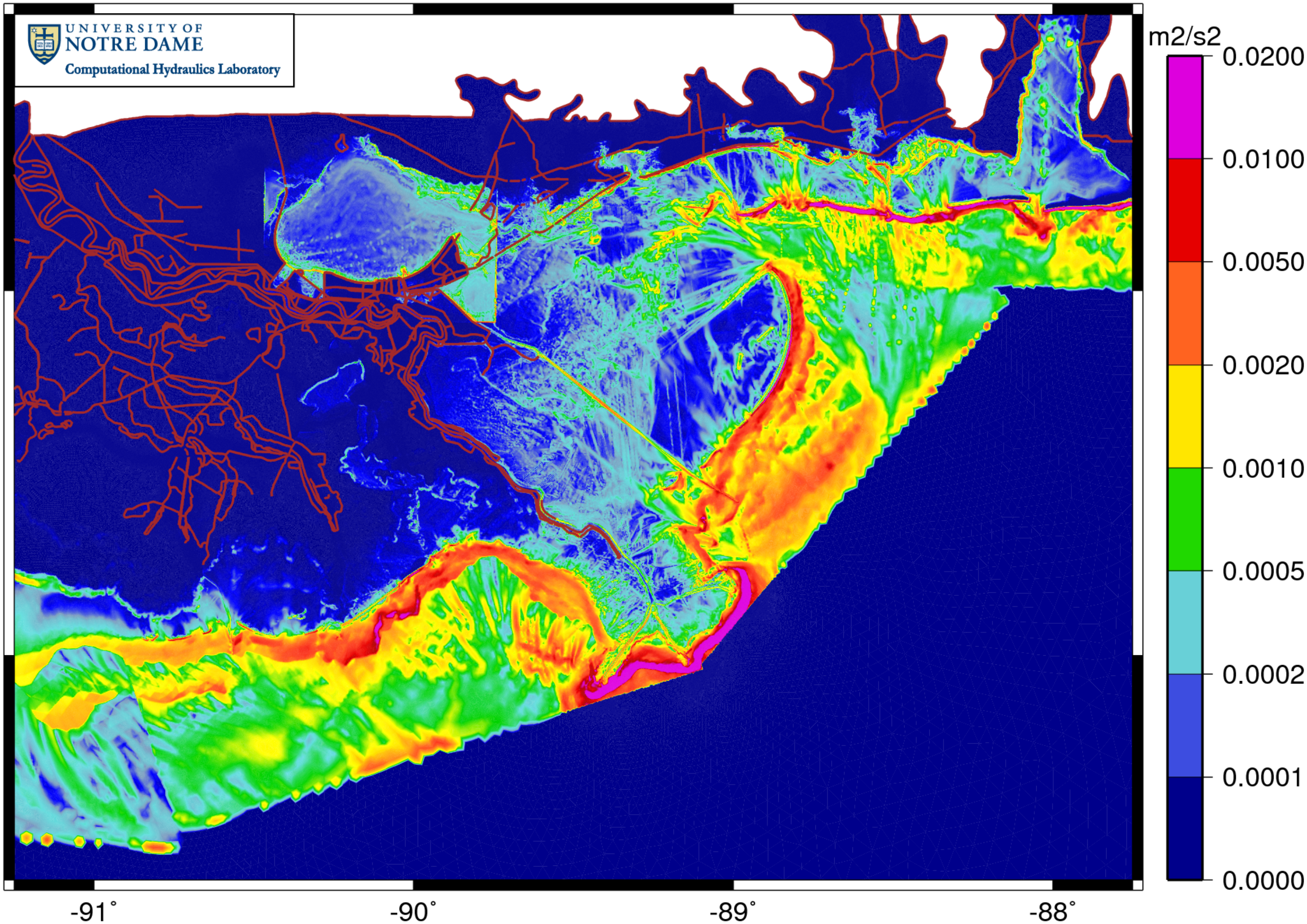
‘Loose’ Coupling to STWAVE



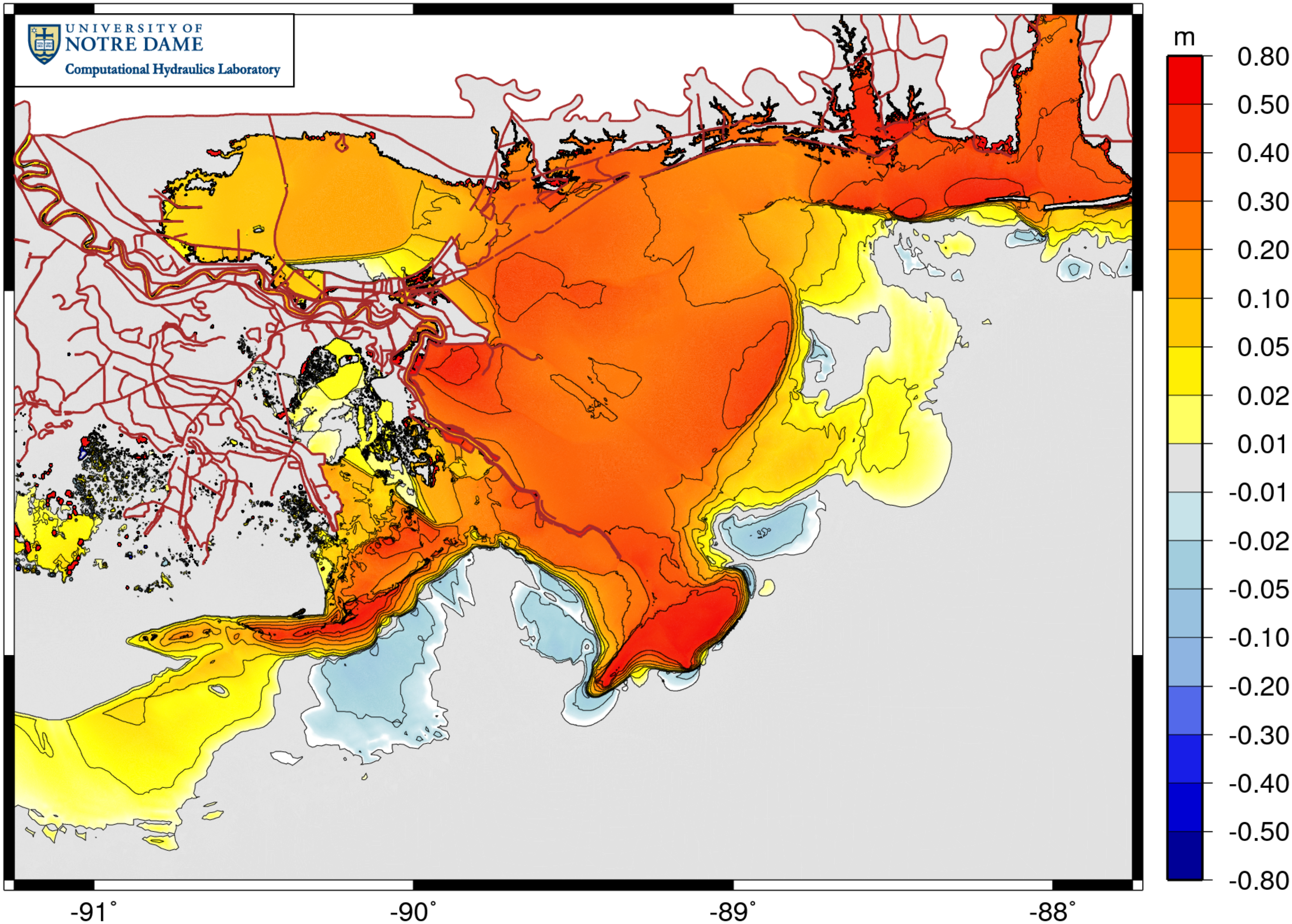
# Katrina : Significant Wave Heights : Maximum



Katrina : Radiation Stress Gradients : Maximum



# Katrina : Wave-Driven Setup : Maximum



## **What We Did**:
## ‘Tight’ Coupling of SWAN+ADCIRC

M. Zijlema (2010). “Computation of Wind-Wave Spectra in Coastal Waters with SWAN on Unstructured Grids.” *Coastal Engineering*, 57, 267-277.

J.C. Dietrich, *et al*. (2011). "Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations." *Coastal Engineering*, 58, 45-65.

J.C. Dietrich, *et al.* (2012). “Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge.” *Journal of Scientific Computing*, in press.

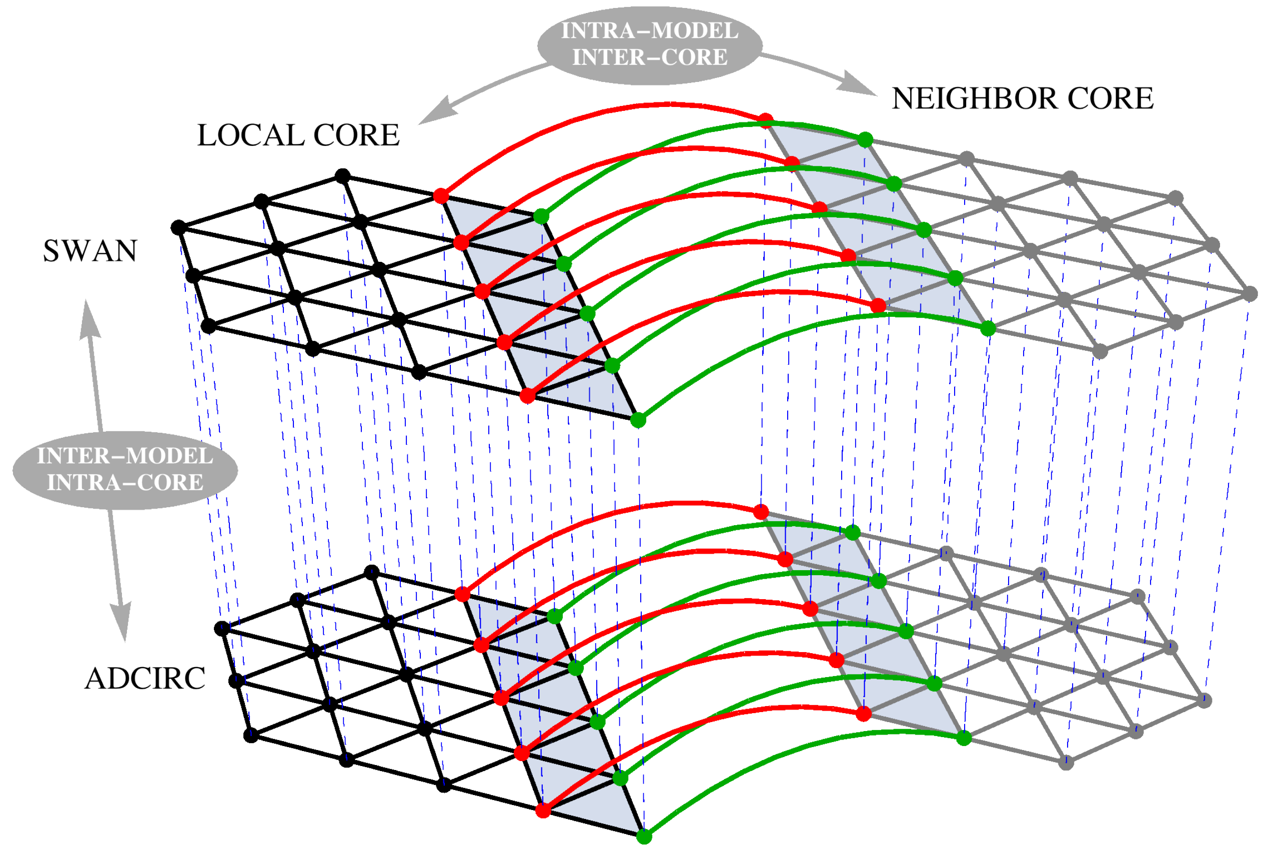
‘Tight’ Coupling of SWAN+ADCIRC

**Simulating WAves Nearshore (SWAN):**

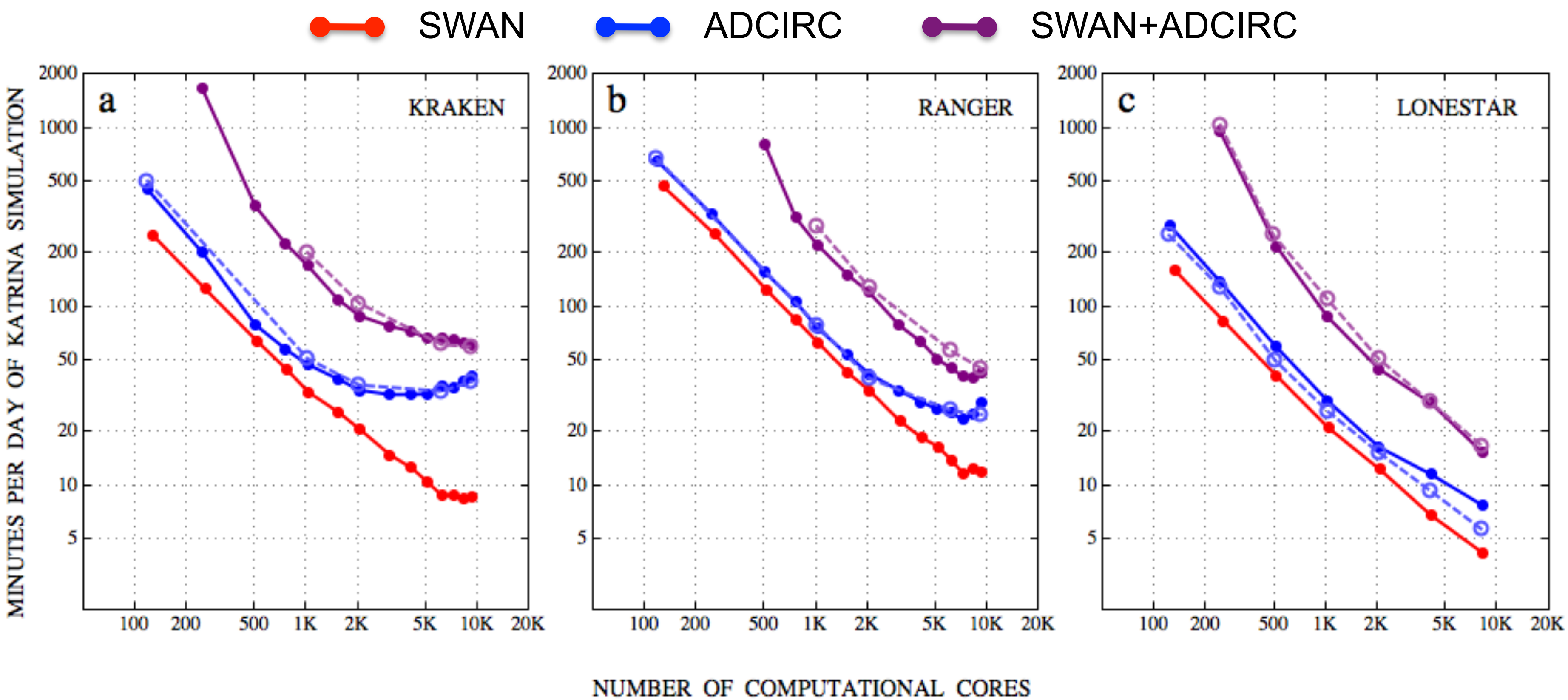
- Solves the action balance equation:

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

- Communication is optimized for high-performance computing:

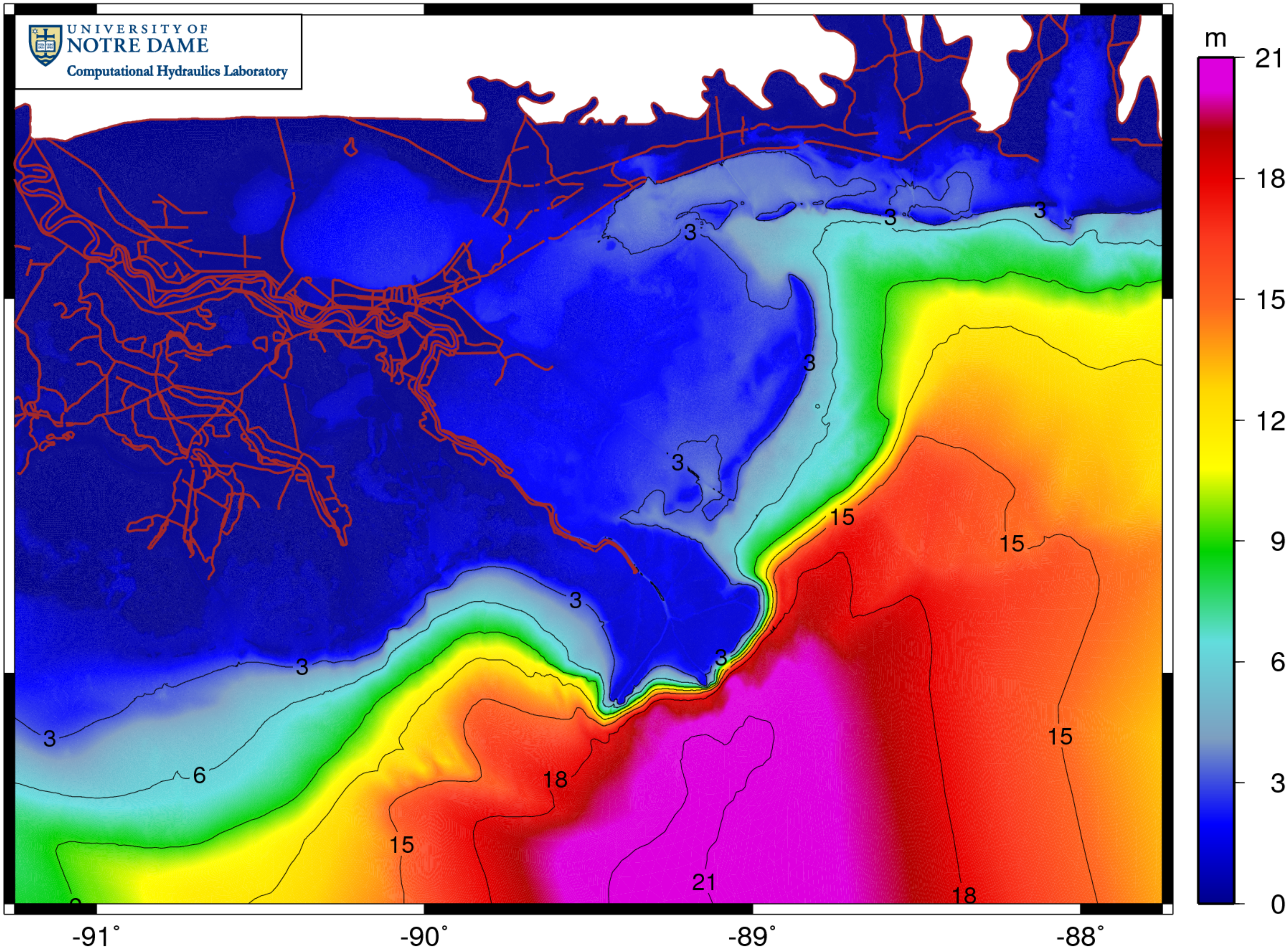


# ‘Tight’ Coupling of SWAN+ADCIRC

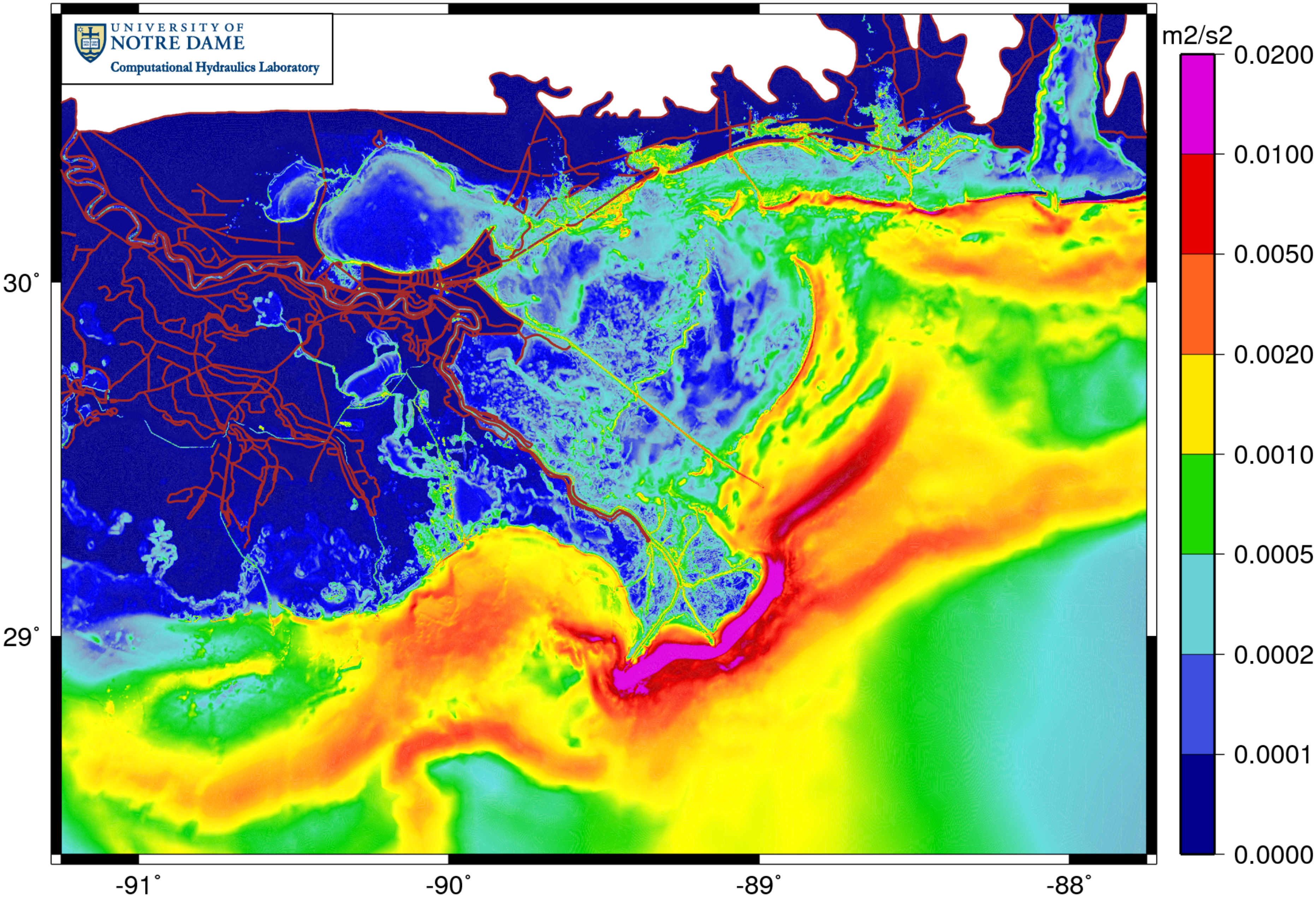



| | Kraken | Ranger | Lonestar |
|---|---|---|---|
| Node | Cray XT5 | Sun Blade x6420 | Dell PowerEdge M610 |
| CPU | 2 Six-core AMD Opteron 8435 | 4 Quad-core AMD Opteron 8356 | 2 Six-core Xeon 5680 |
| Frequency | 2.6 GHz | 2.3 GHz | 3.33 GHz |
| Architecture | AMD K10 (Istanbul) | AMD K10 (Barcelona) | Intel Nehalem (Westmere-EP) |

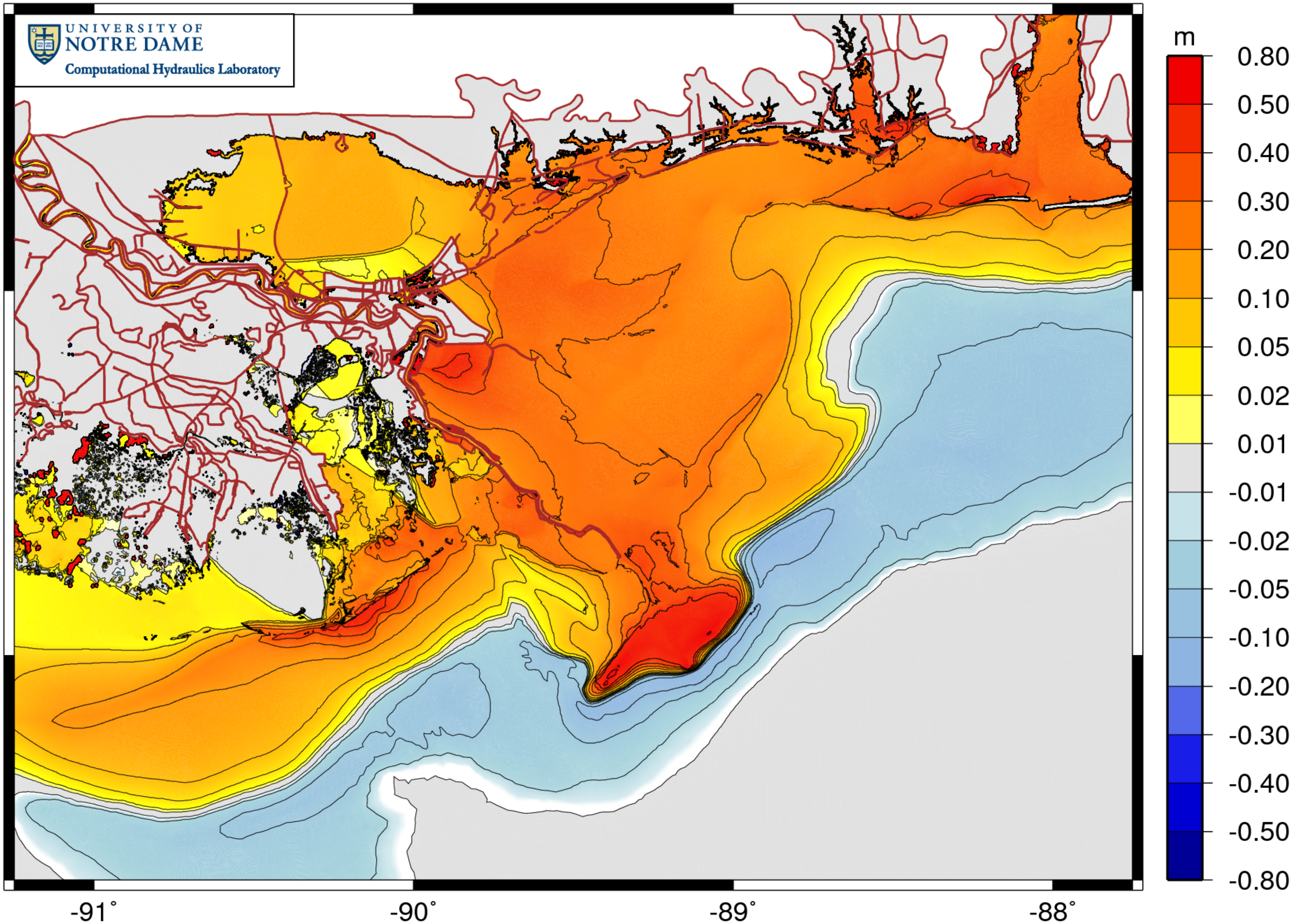
# Katrina : Significant Wave Heights : Maximum



# Katrina : Radiation Stress Gradients : Maximum



Katrina : Wave-Driven Setup : Maximum



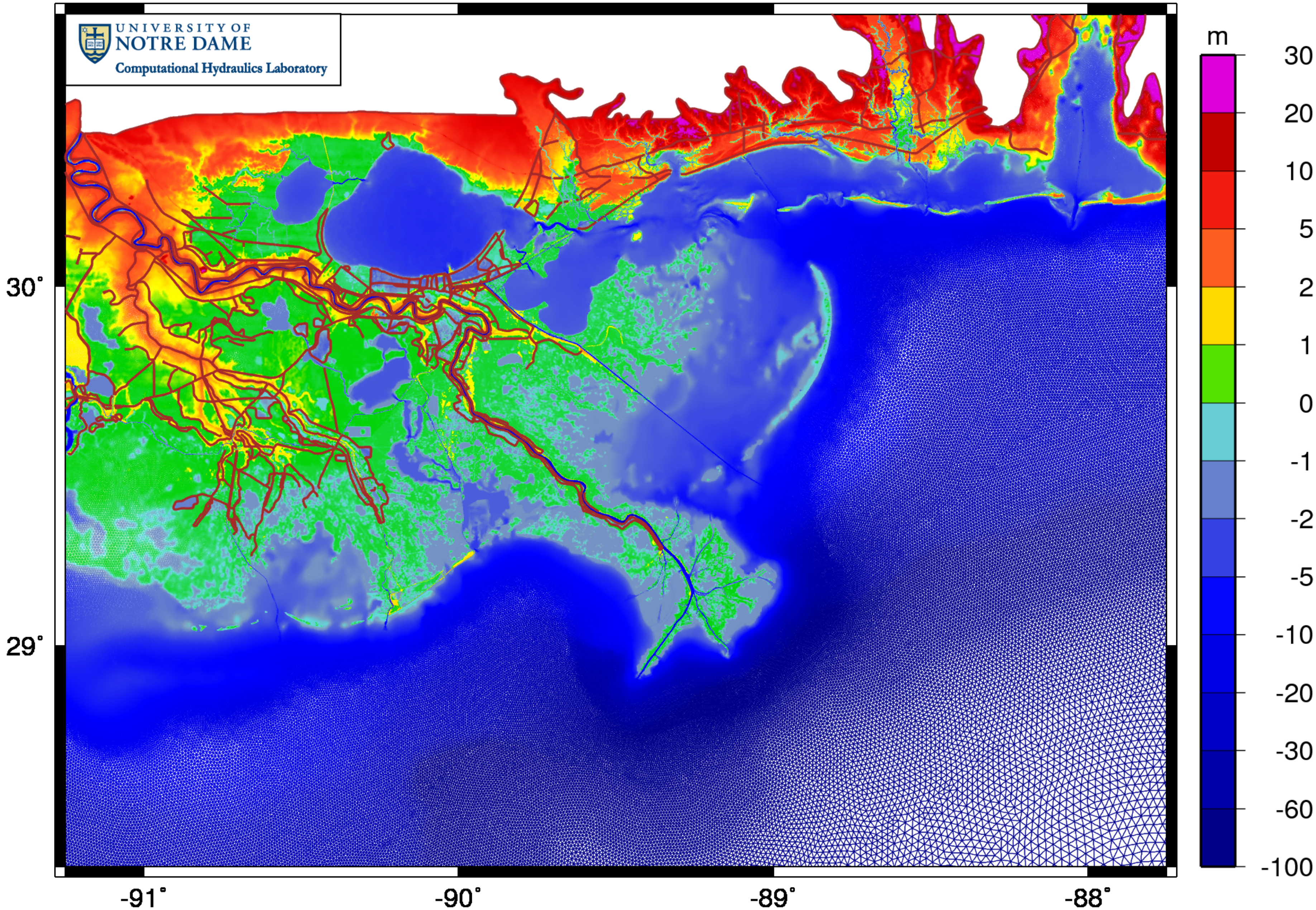
## **Where We Are Now**:
## Better Integration of Hurricane Physics


A.B. Kennedy, et al. (2011). "Origin of the Hurricane Ike Forerunner Surge." *Geophysical Research Letters*, 38, L08608.

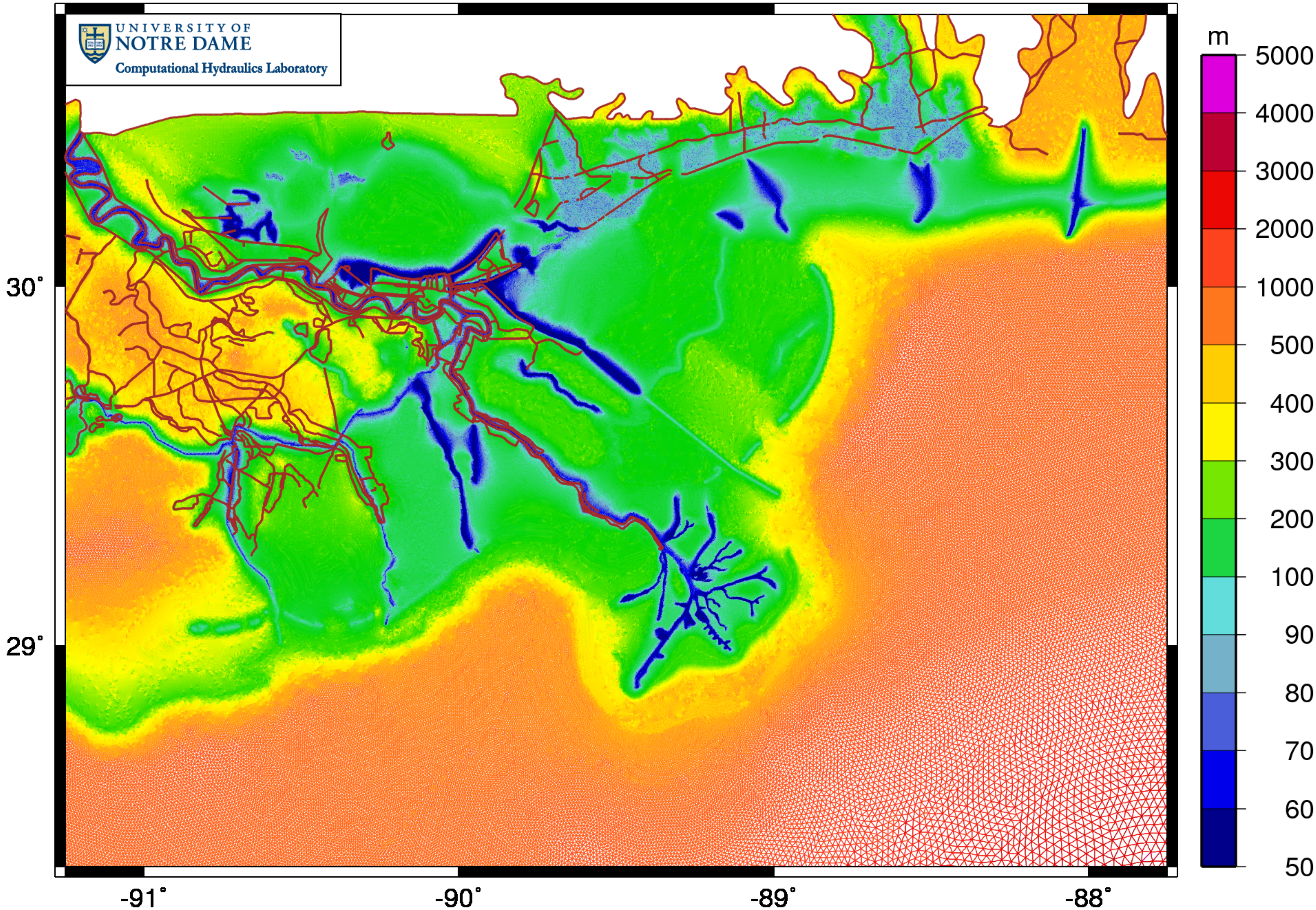
J.C. Dietrich, *et al*. (2011). "Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Synoptic Analysis and Validation in Southern Louisiana." *Monthly Weather Review*, 139(8), 2488-2522.

M.E. Hope, et al. (2012). "Hindcast and Validation of Hurricane Ike (2008) Waves, Forerunner, and Storm Surge." *Monthly Weather Review*, in preparation.

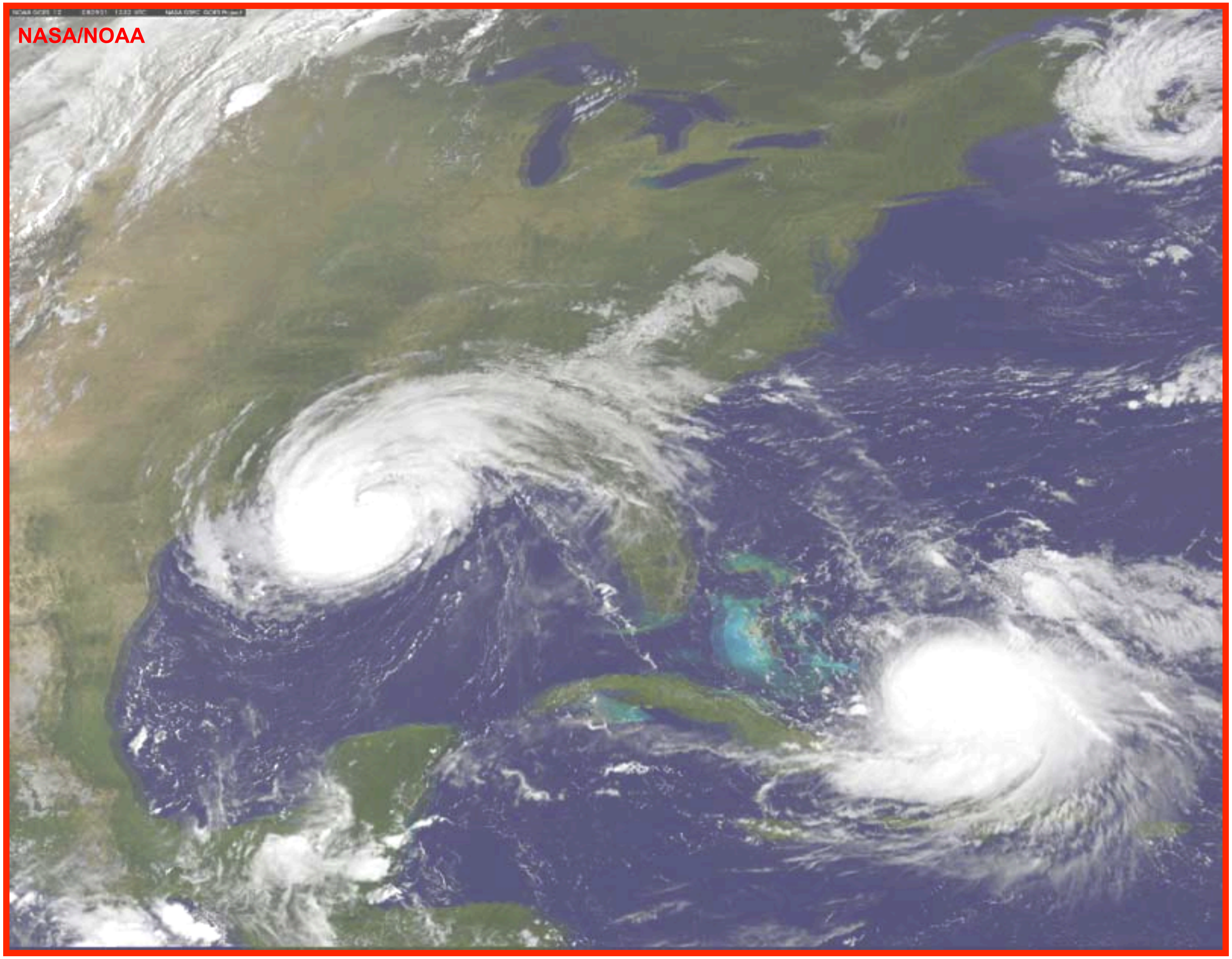
# SL16 : Bathymetry and Topography



SL16 : Mesh Sizes

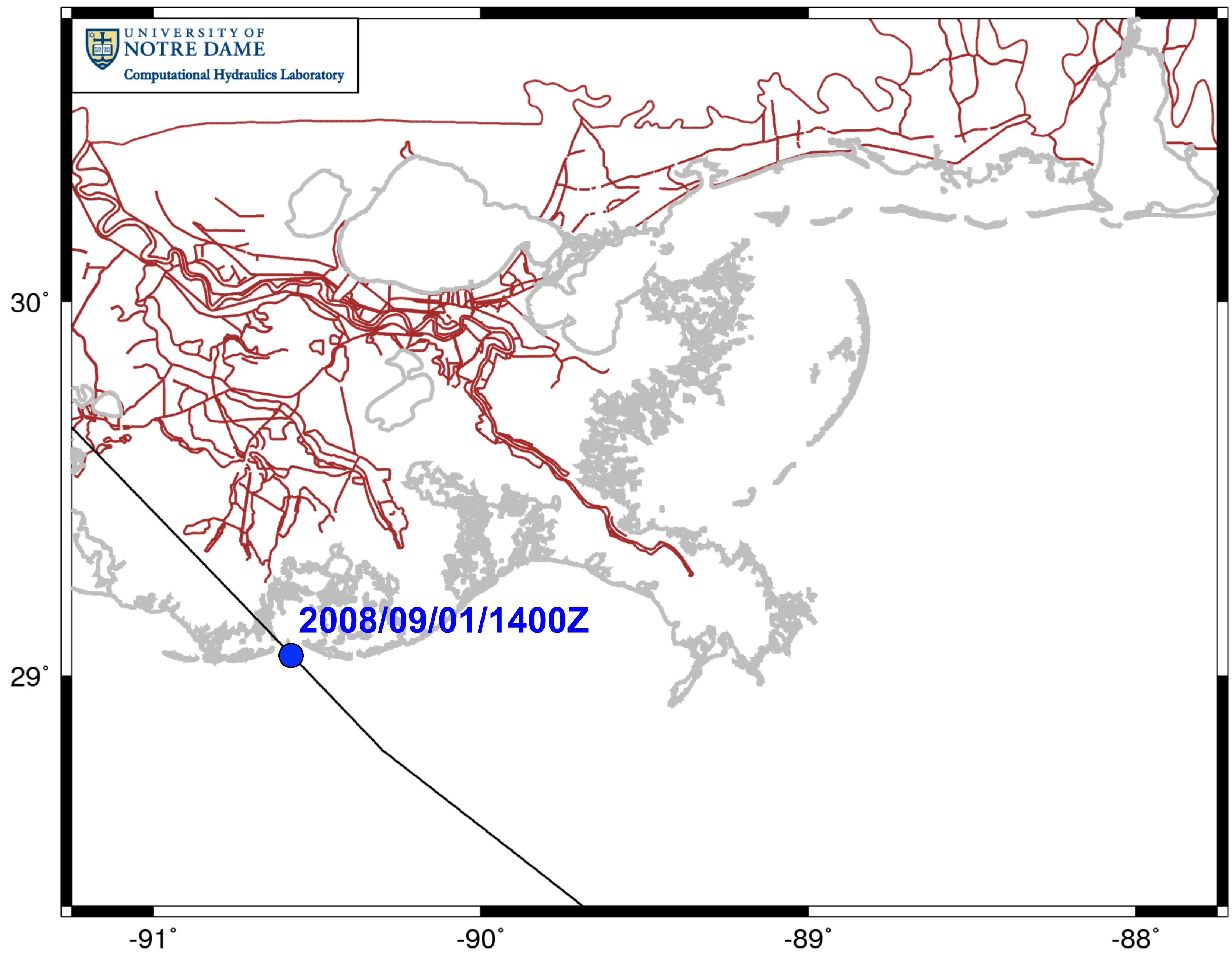


# Hurricane Season 2008

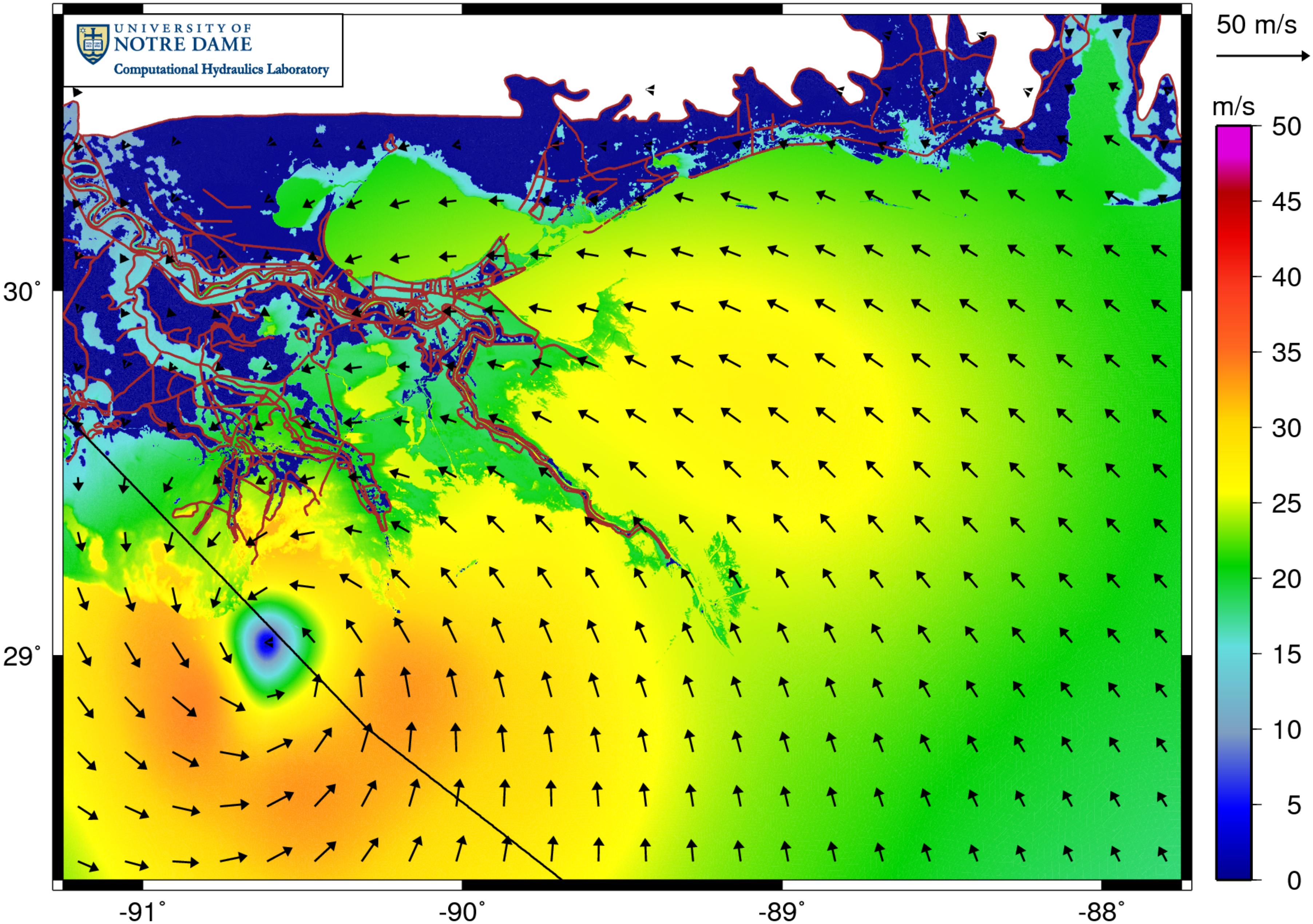


# Gustav : Storm Surge near New Orleans

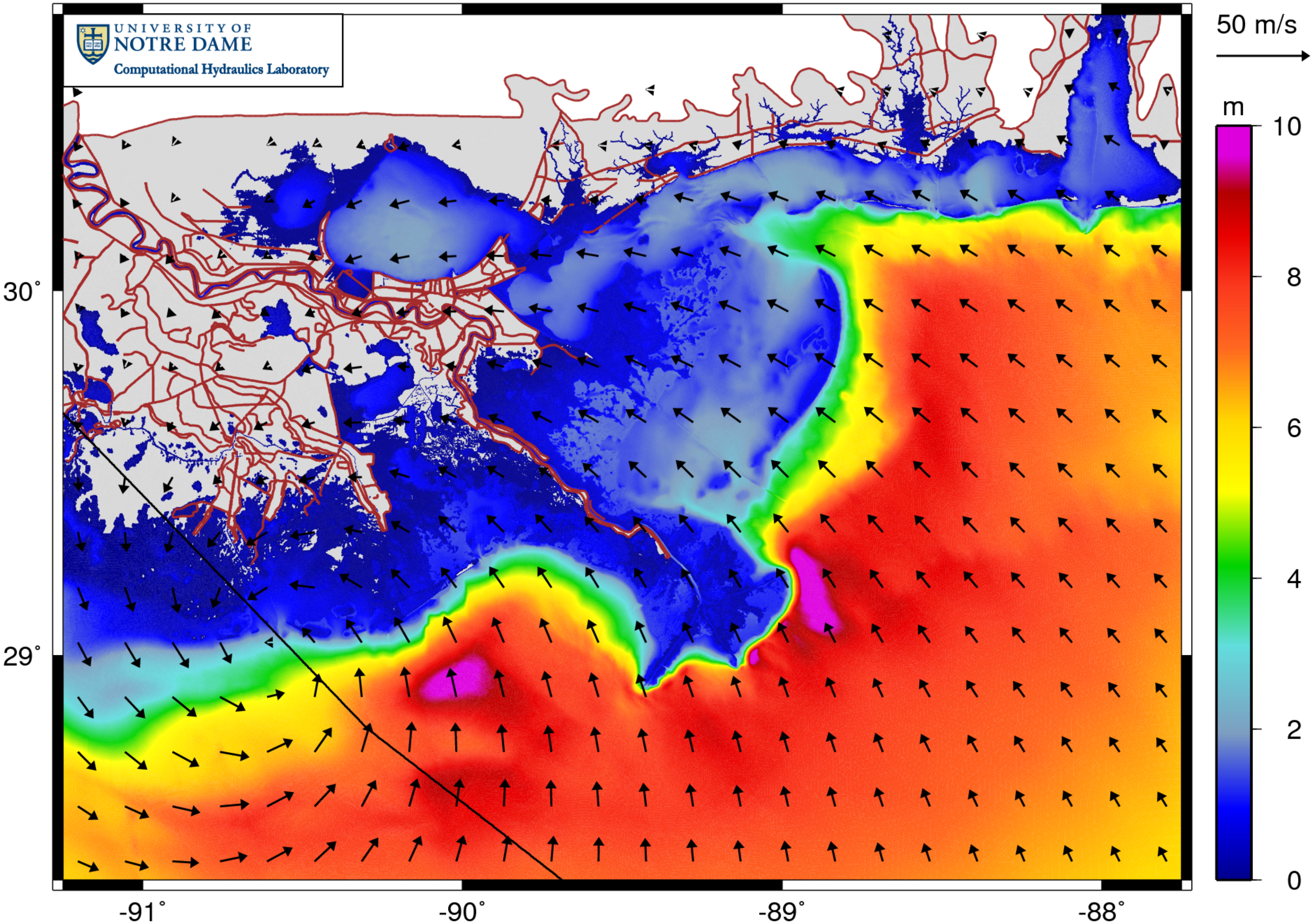
Gustav : Track



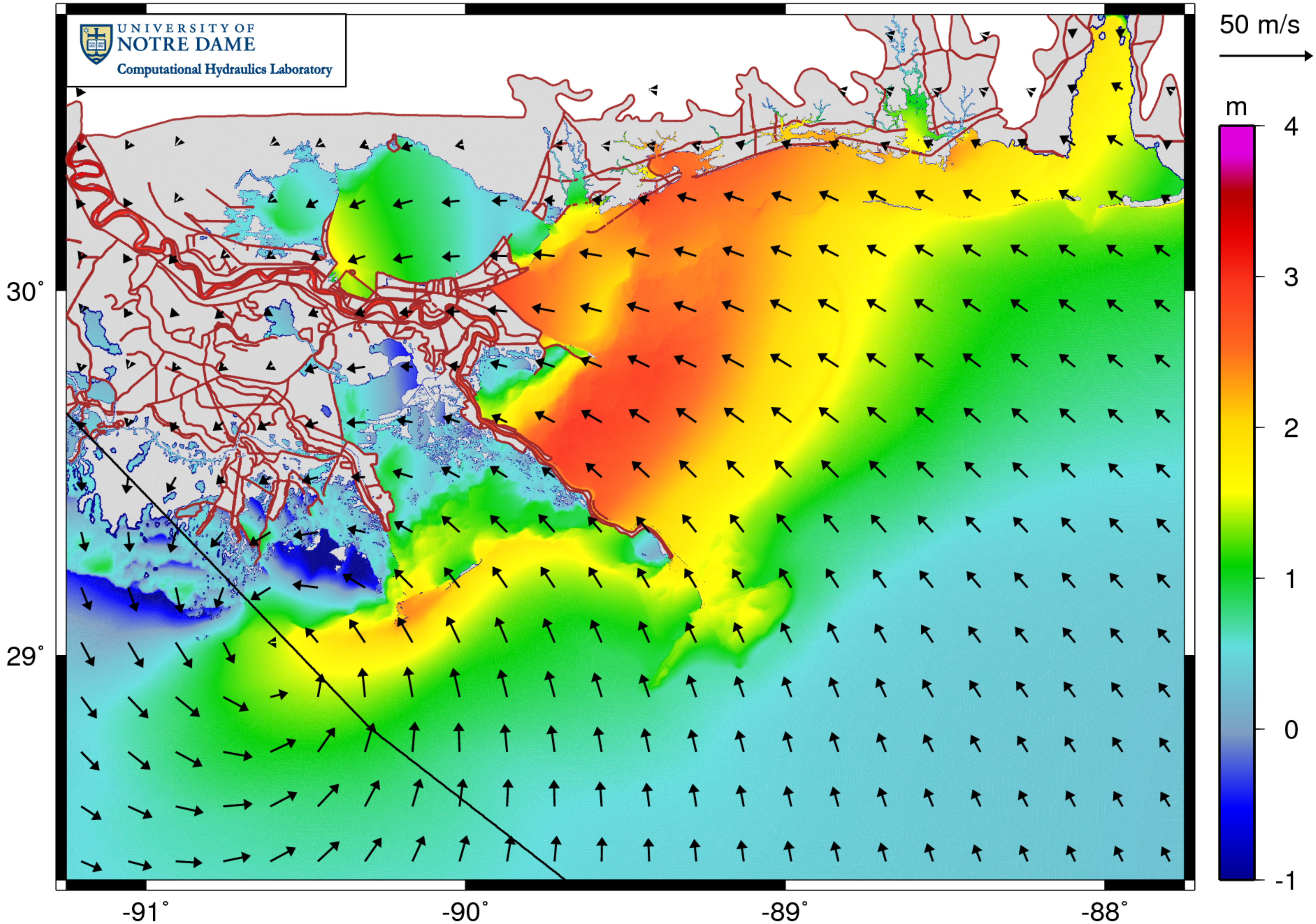
# Gustav : 2008/09/01/1400Z : Winds



Gustav : 2008/09/01/1400Z : Significant Wave Heights



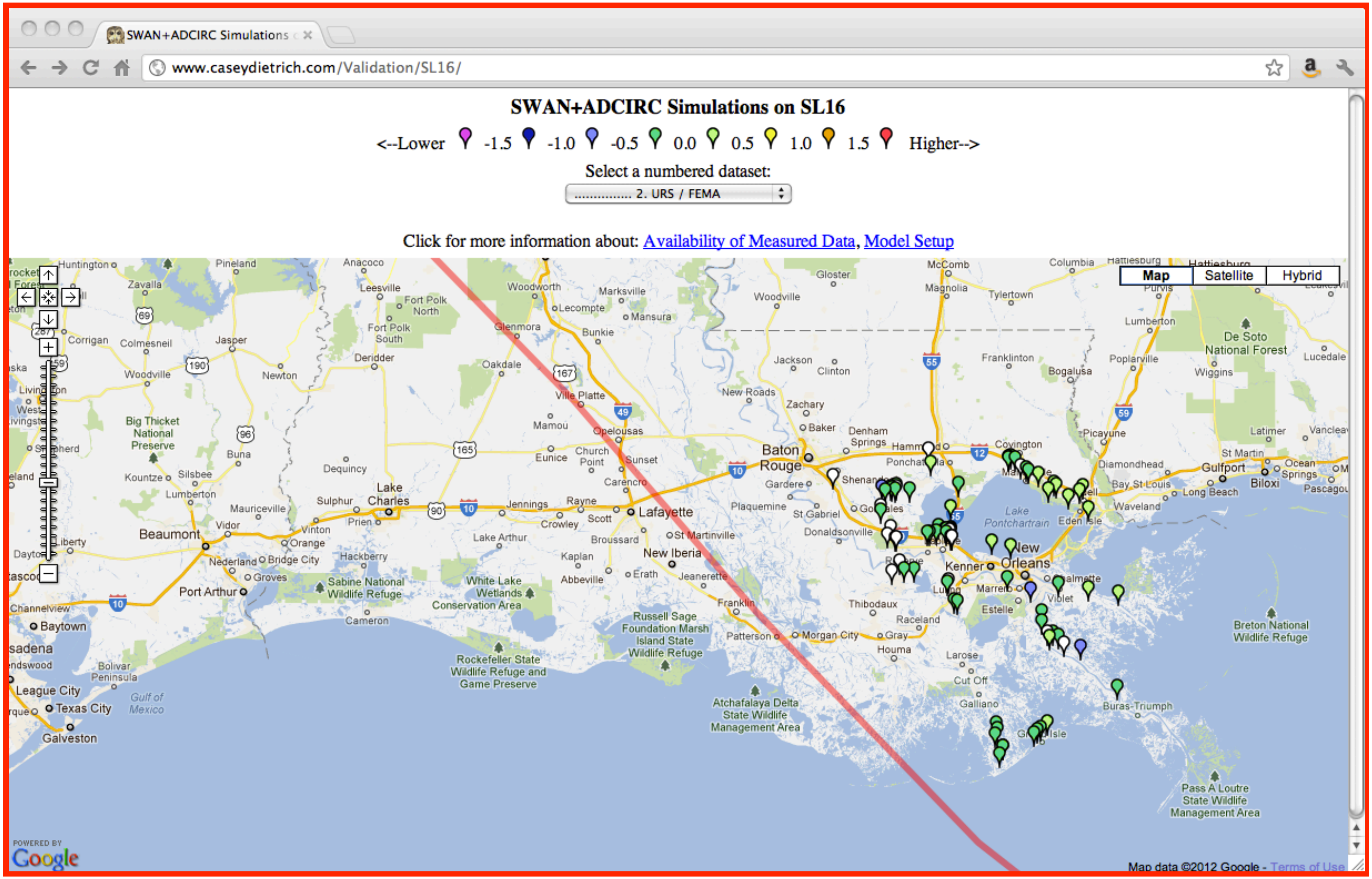
# Gustav : 2008/09/01/1400Z : Water Levels



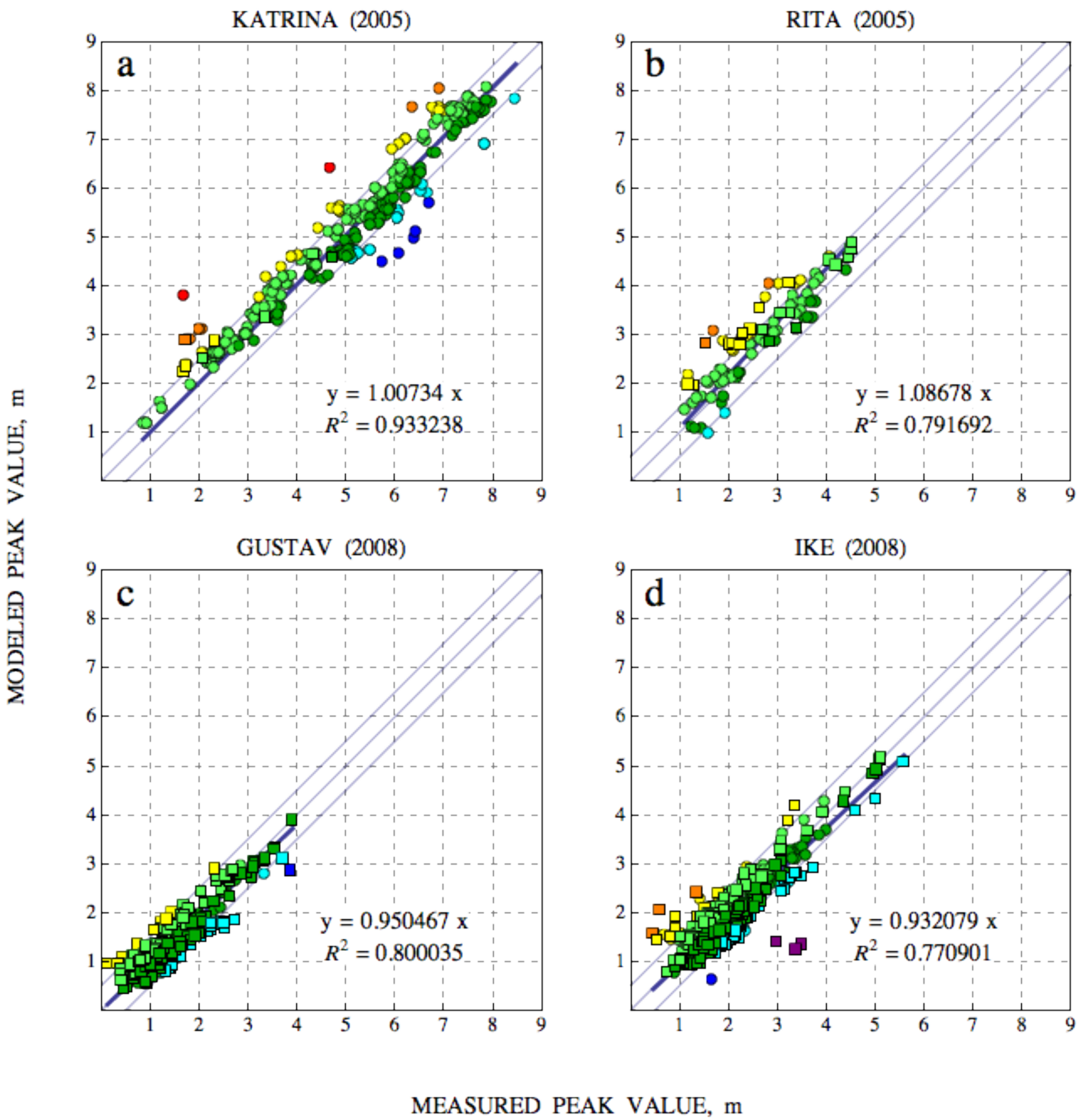
# Validation : Increased Availability of Measurement Data

| | Katrina (2005) | | Gustav (2008) | |
|---|---|---|---|---|
| High-Water Marks | **Total:** | **399** | **Total:** | **82** |
| | URS/FEMA | 193 | URS/FEMA | 82 |
| | USACE | 206 | | |
| Time Series | **Water Levels:** | **9** | **Water Levels:** | **443** |
| | | | CSI | 5 |
| | | | Andrew Kennedy | 16 |
| | NOAA | 3 | NOAA | 26 |
| | | | USACE-CHL | 6 |
| | | | USACE | 54 |
| | | | USGS (Deployable) | 61 |
| | USGS (Permanent) | 6 | USGS (Permanent) | 48 |
| | | | CRMS | 243 |
| | **Wave Parameters:** | **17** | **Wave Parameters:** | **39** |
| | NDBC | 14 | NDBC | 12 |
| | CSI | 3 | CSI | 5 |
| | | | Andrew Kennedy | 16 |
| | | | USACE-CHL | 6 |

# Validation : Web-Based Mapping of Results



# Validation : High-Water Marks



**Where We're Going**:

Increasing Efficiency and Accuracy with DG


E.J. Kubatko, et al. (2006). "hp Discontinuous Galerkin Methods for Advection Dominated Problems in Shallow Water Flow." *Computer Methods in Applied Mechanics and Engineering*, 196, 437-451.

C.N. Dawson, et al. (2011). "Discontinuous Galerkin Methods for Modeling Hurricane Storm Surge." *Advances in Water Resources*, 34, 1165-1176.

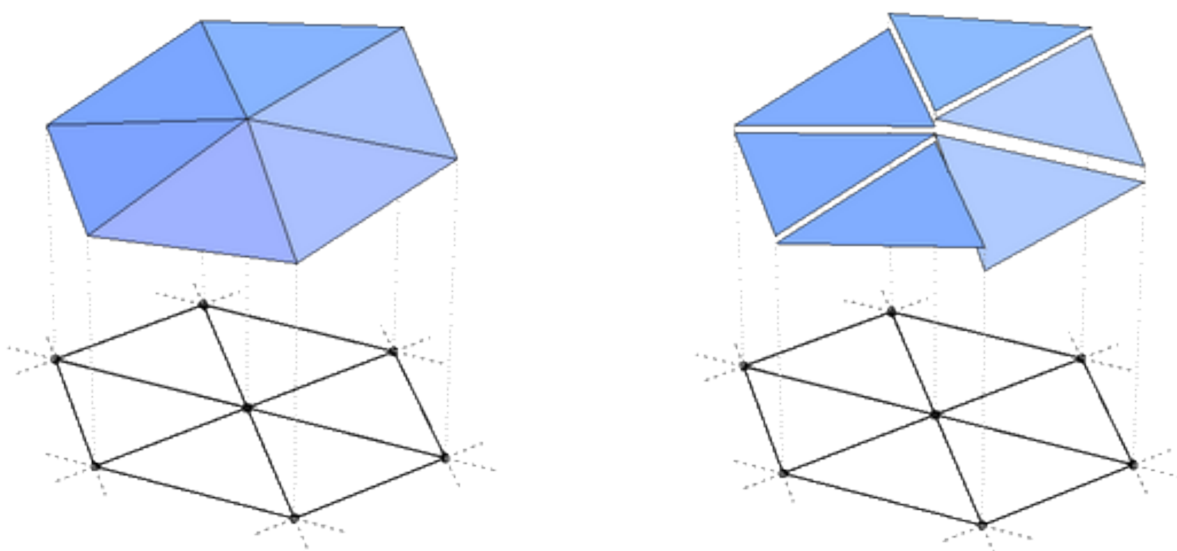
J.C. Dietrich, et al. (2012). "Effect of Coupled Circulation on a Nearshore Wave Model." *Coastal Engineering*, in preparation.

J.D. Meixner, et al. (2012), in preparation.

DG : Moving toward Adaptive Meshes

**Discontinuous Galerkin (DG):**

- Integrate over each local element instead of the global domain.
- Elements communicate through fluxes.
- Solution can be discontinuous along element edges.
- Much easier to refine adaptively the mesh in sizes (*h*) and/or interpolation order (*p*).



# DG : Storm Surge during Ike

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## Discontinuous Galerkin methods for modeling H

Clint Dawson [a,*], Ethan J. Kubatko [b], Joannes J. Westerink [c], Co
Craig Michoski [a], Nishant Panda [a]

[a] Institute for Computational Engineering and Sciences, 1 University Station, C0200, Austin, TX 78712, U
[b] Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, C
[c] Computational Hydraulics Laboratory, Department of Civil Engineering and Geological Sciences, 156 Fi

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Hurricane storm surge
Shallow water equations

ABSTRACT

Storm surge due to hurricanes and tropi
and long-term damage to coastal ecosys
used for two primary purposes: forecasti
evacuation of coastal populations, and h
gation strategies, coastal restoration and
Storm surge is modeled using the sha
events, models of wave energy. In this pa
in spherical coordinates. Tides, riverine f
and wind stress are all important for ch
ently multi-scale, both in space and time
ments in acquiring high-fidelity input (b
flow rates, levees, raised roads and railw
using unstructured finite element meshes, and numerical methods capable of capturing highly advective
flows, wetting and drying, and multi-scale features of the solution.
The discontinuous Galerkin (DG) method appears to allow for many of the features necessary to accu-
rately capture storm surge physics. The DG method was developed for modeling shocks and advection-
dominated flows on unstructured finite element meshes. It easily allows for adaptivity in both mesh ($h$)

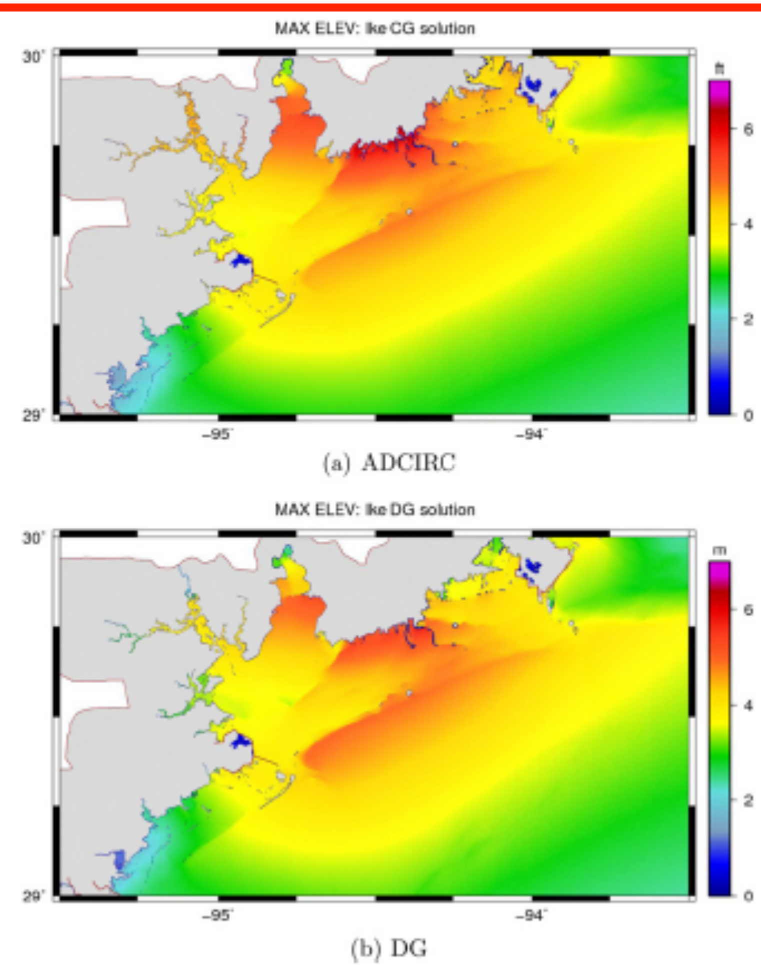
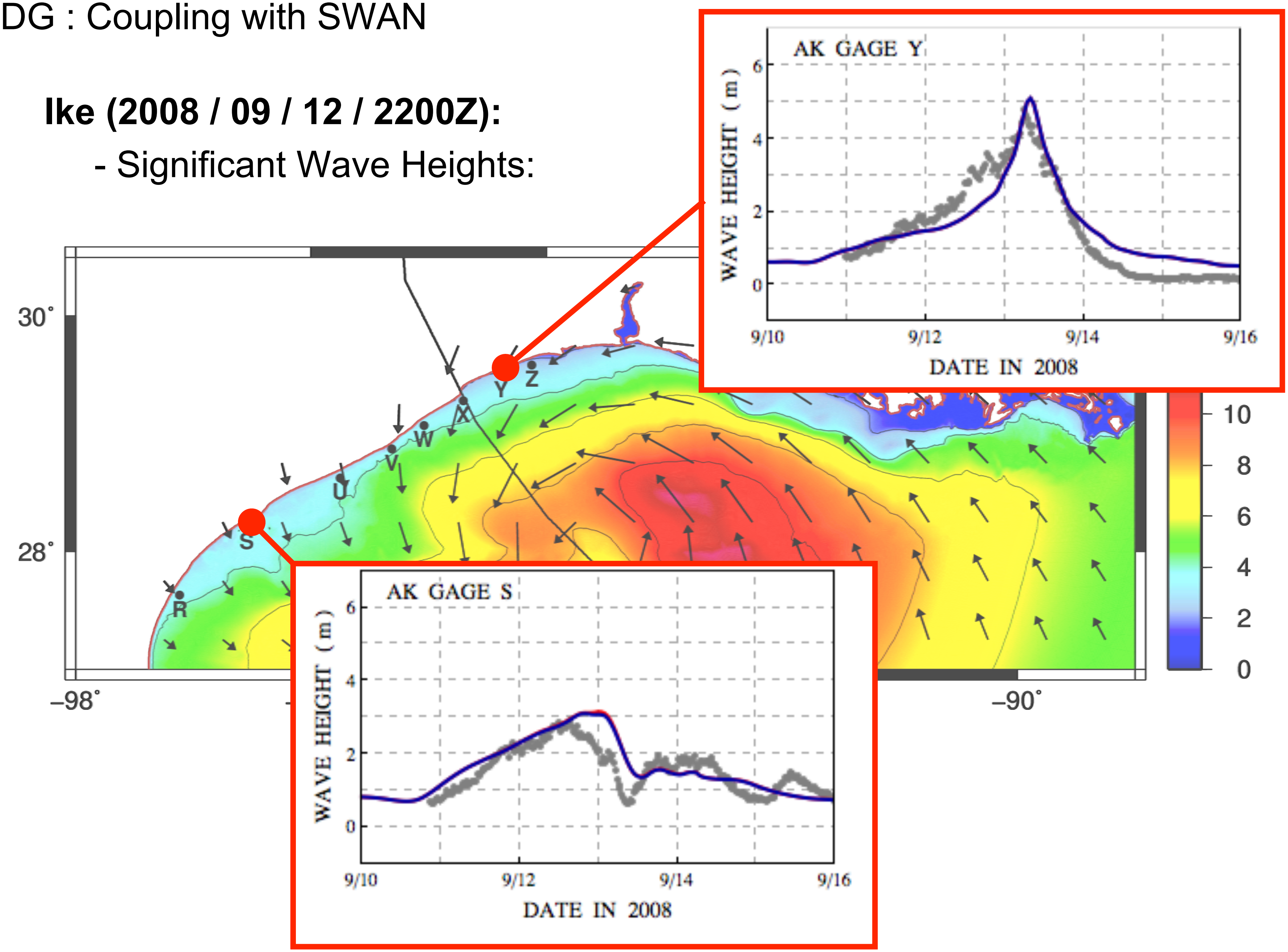



**Fig. 8.** Maximum water levels for ADCIRC (a) and DG (b) solutions during Hurricane Ike. Water elevation is in meters relative to the North American Vertical Datum of 1988 (NAVD88). The solution is plotted in the region between −93.5 and −95.5° longitude and 29 and 30° latitude.

DG : Coupling with SWAN

**Ike (2008 / 09 / 12 / 2200Z):**

- Significant Wave Heights:



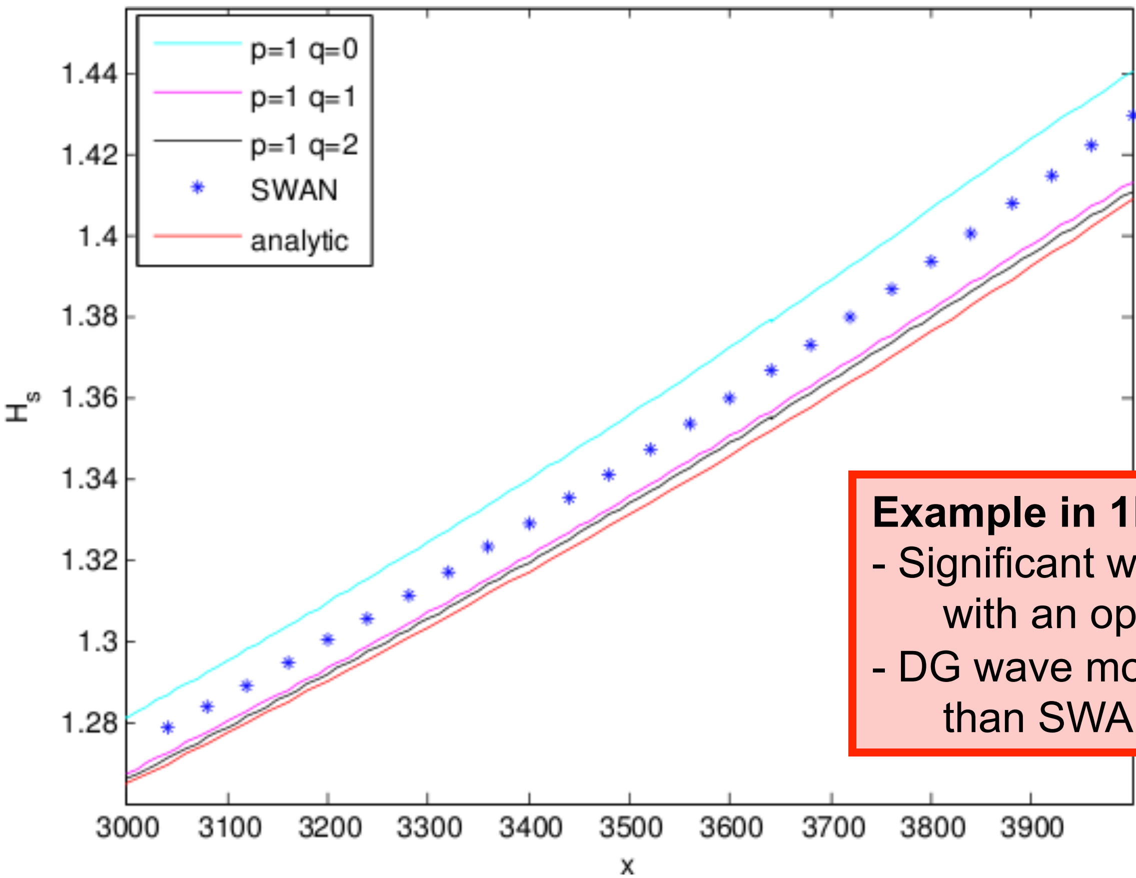
# DG : Developing a Spectral Wave Model

**Spectral Action Balance Equation:**

- DG is ideal for advection-dominated problems:

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

- Early success in one geographic dimension:




**Example in 1D:**
- Significant wave heights for a test case with an opposing current.
- DG wave model can be more accurate than SWAN.

## Conclusions and Future Work

**‘Loose’ Coupling of Waves and Surge:**

- Successful hindcasts of Katrina and Rita
- WAM and STWAVE were clunky but effective

**‘Tight’ Coupling of SWAN+ADCIRC:**

- Models use same unstructured mesh; Information passed dynamically
- SWAN is as accurate as WAM and STWAVE
- Coupled model is efficient to 1000s of computational cores

**SWAN+ADCIRC Hindcast of Gustav:**

- Next generation of meshes in Louisiana and Texas
- Wealth of measurement data, including nearshore waves

**Continue the Development of DG Models:**

- Coupling of SWAN with ADCIRC(DG)
- Developing a DG spectral wave model

# Thank You!

**2011 Hurricane Season**