High-Resolution Models for Ocean Waves and Circulation

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Southern Methodist University
Wednesday, 28 March 2012

Education and Background

Post-Doctoral Researcher

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

Research Assistant

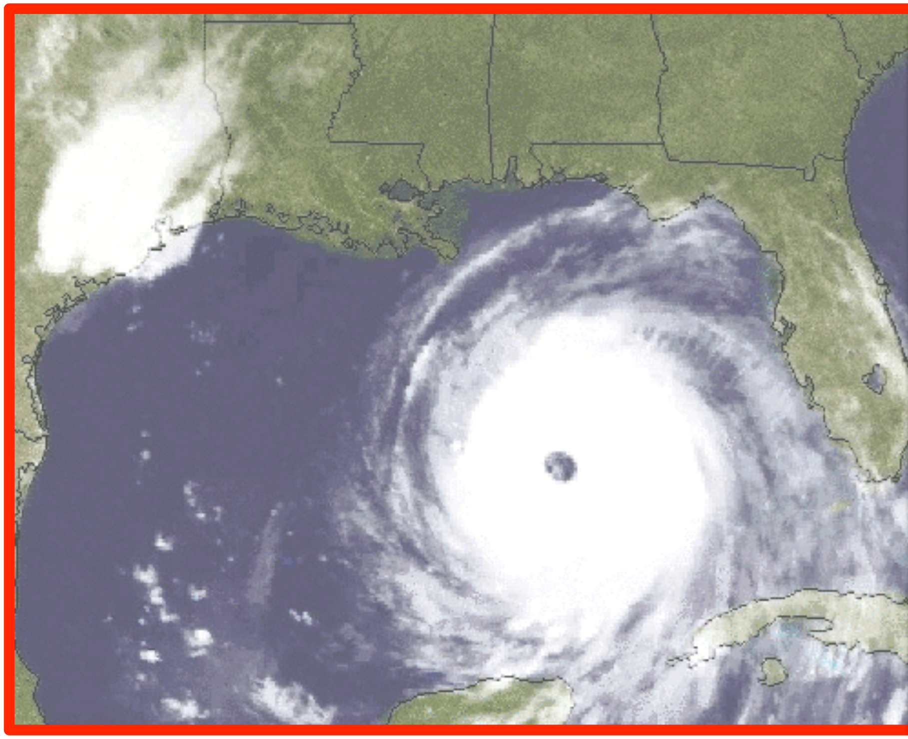
- Department of Civil Engineering and Geological Sciences
- University of Notre Dame
- August 2005 to October 2010
- PhD: 12 October 2010

Research Assistant

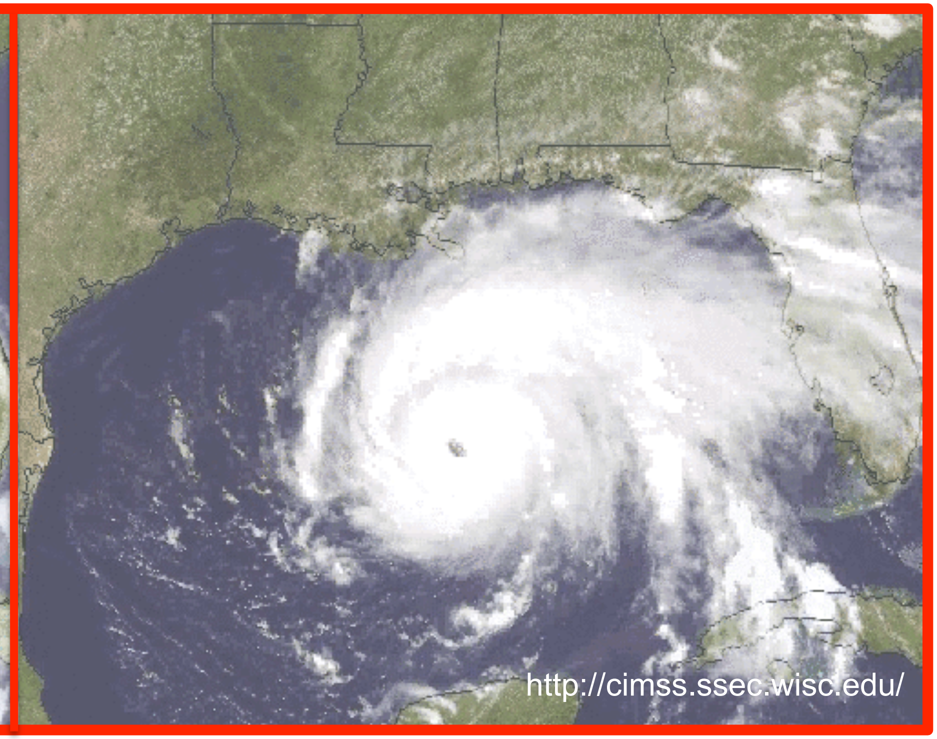
- School of Civil Engineering and Environmental Science
- University of Oklahoma
- June 1999 to July 2005
- MS: 23 June 2005

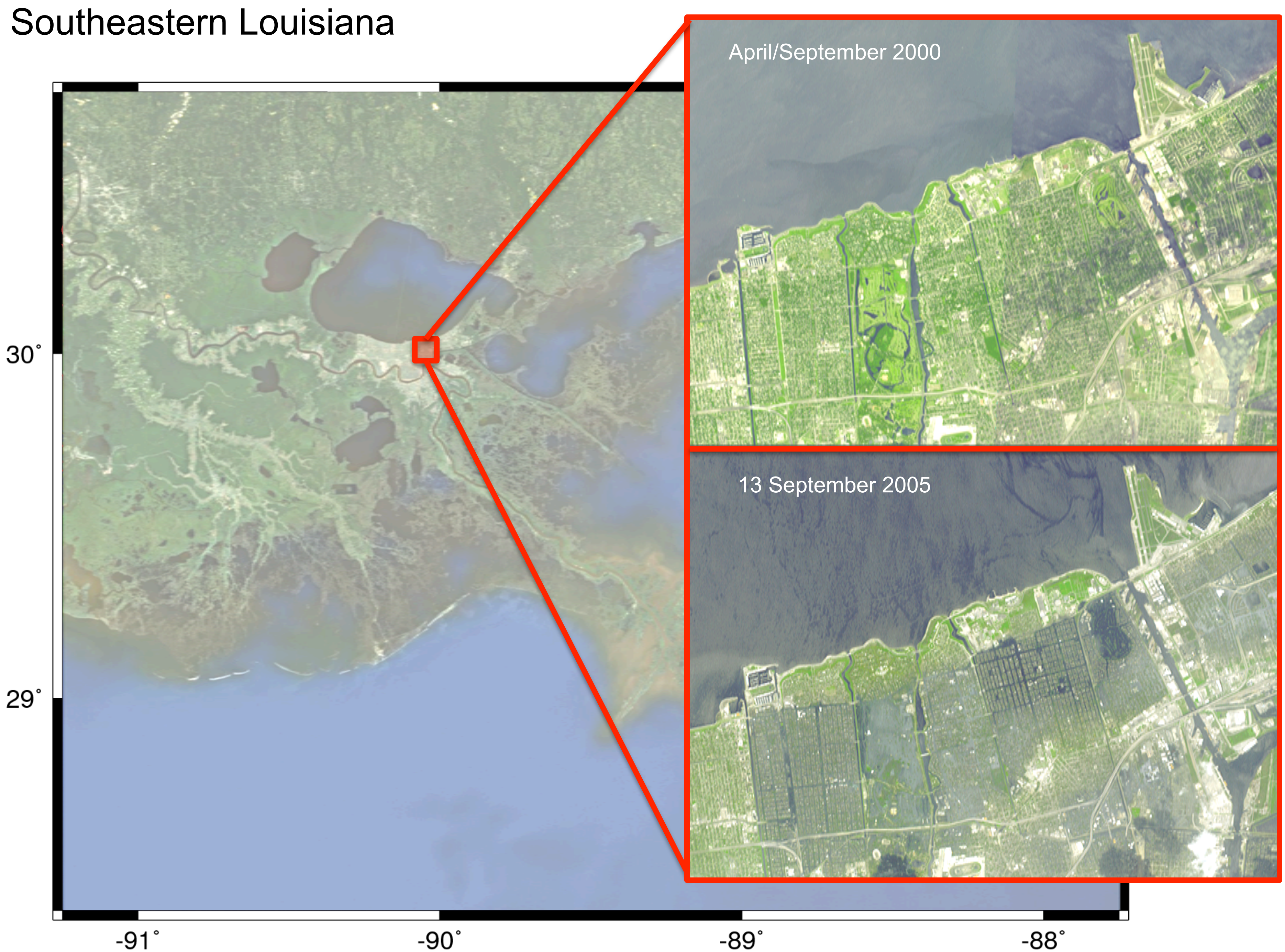
2005 Hurricane Season

Katrina : 08/28 – 08/29



Rita : 09/22 – 09/24




Southeastern Louisiana
April/September 2000
13 September 2005
30˚
29˚
-91˚
-90˚
-89˚
-88˚

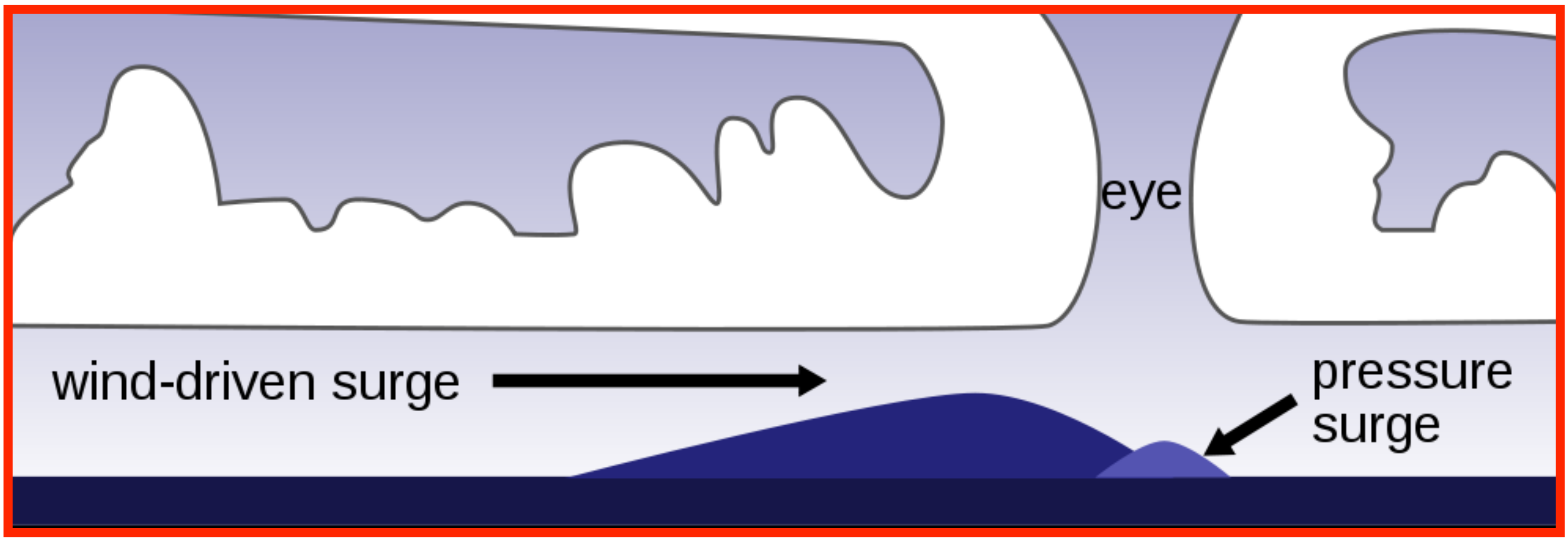
What We Did:
‘Tight’ Coupling of SWAN+ADCIRC

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.

Some Images Stolen From *Wikipedia*



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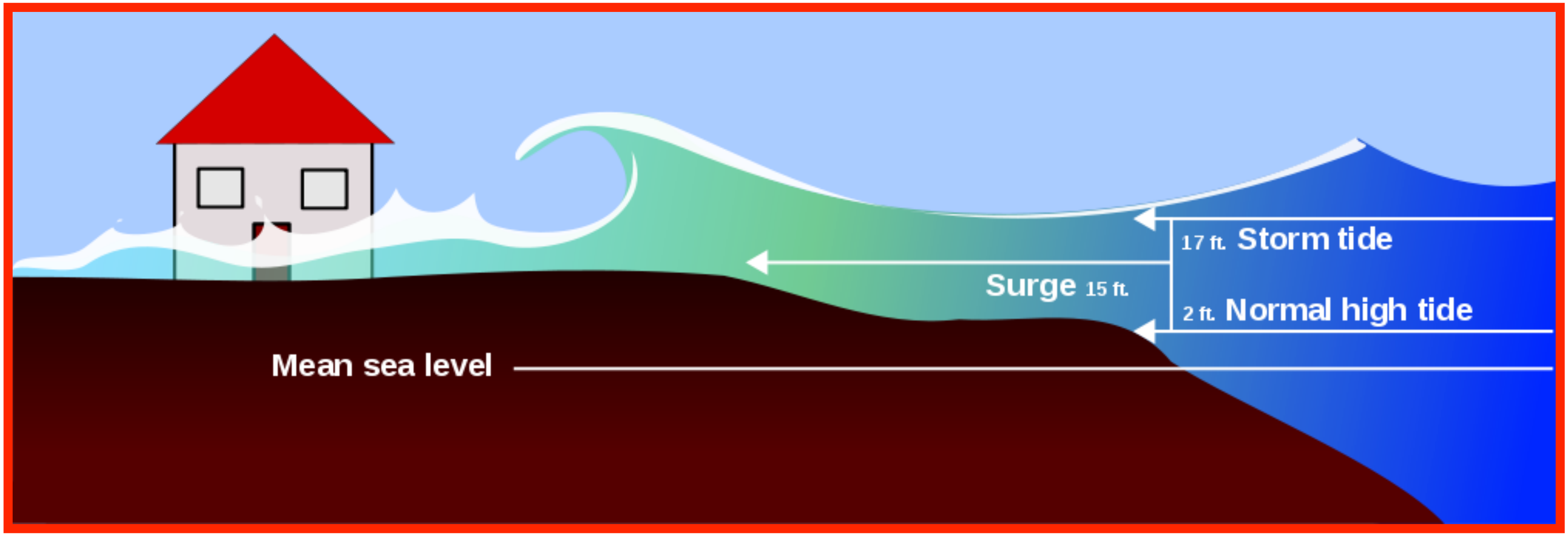
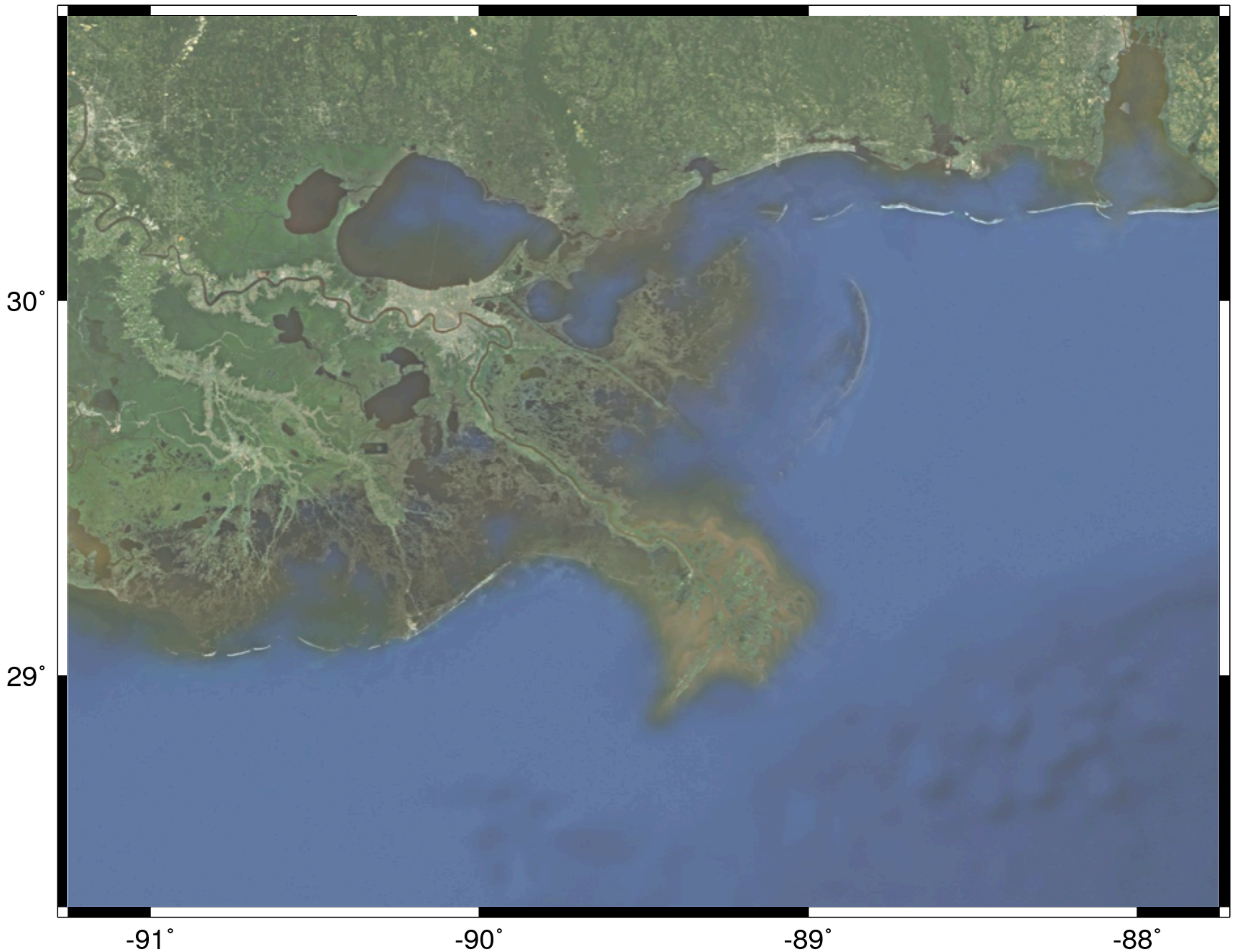
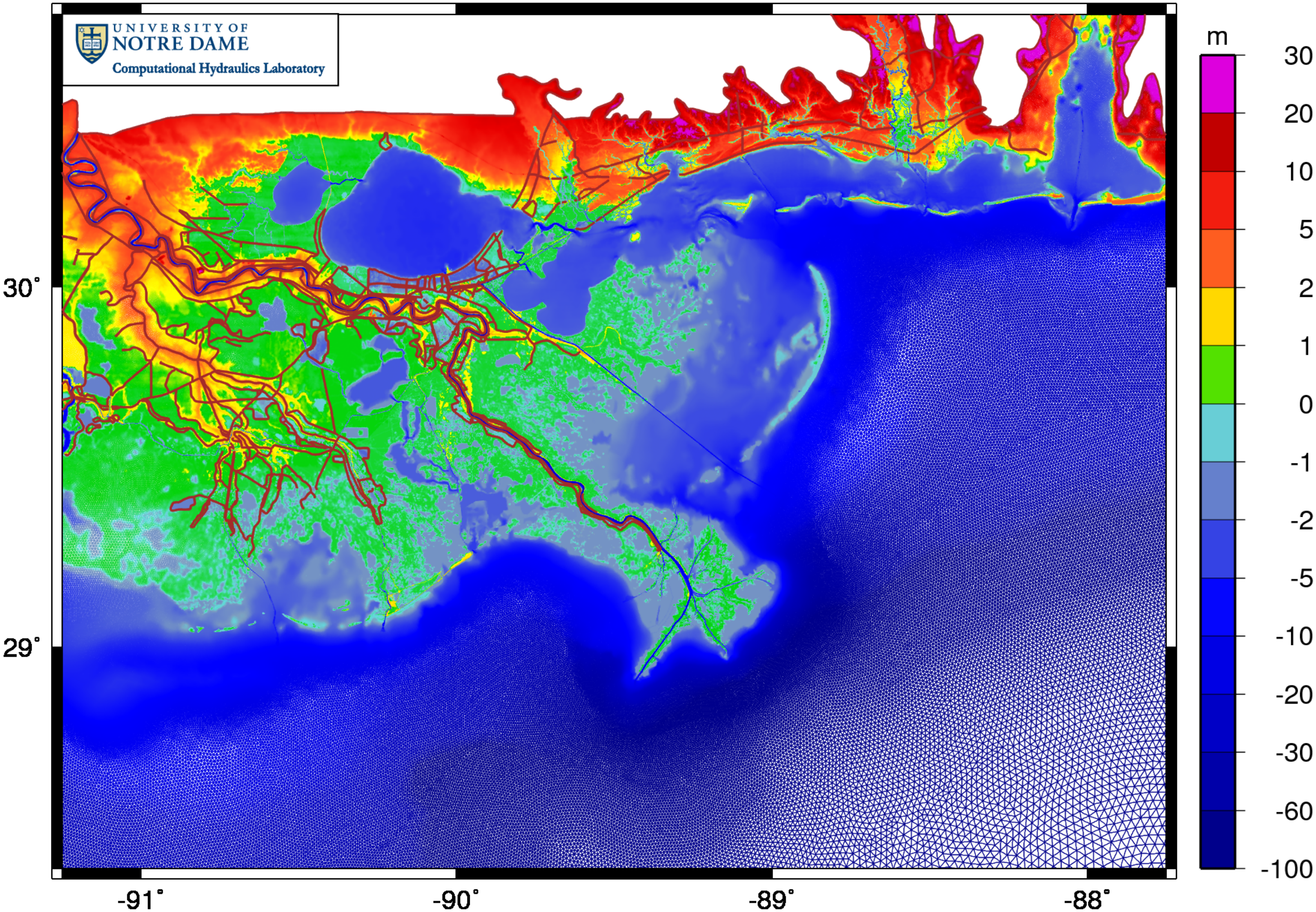


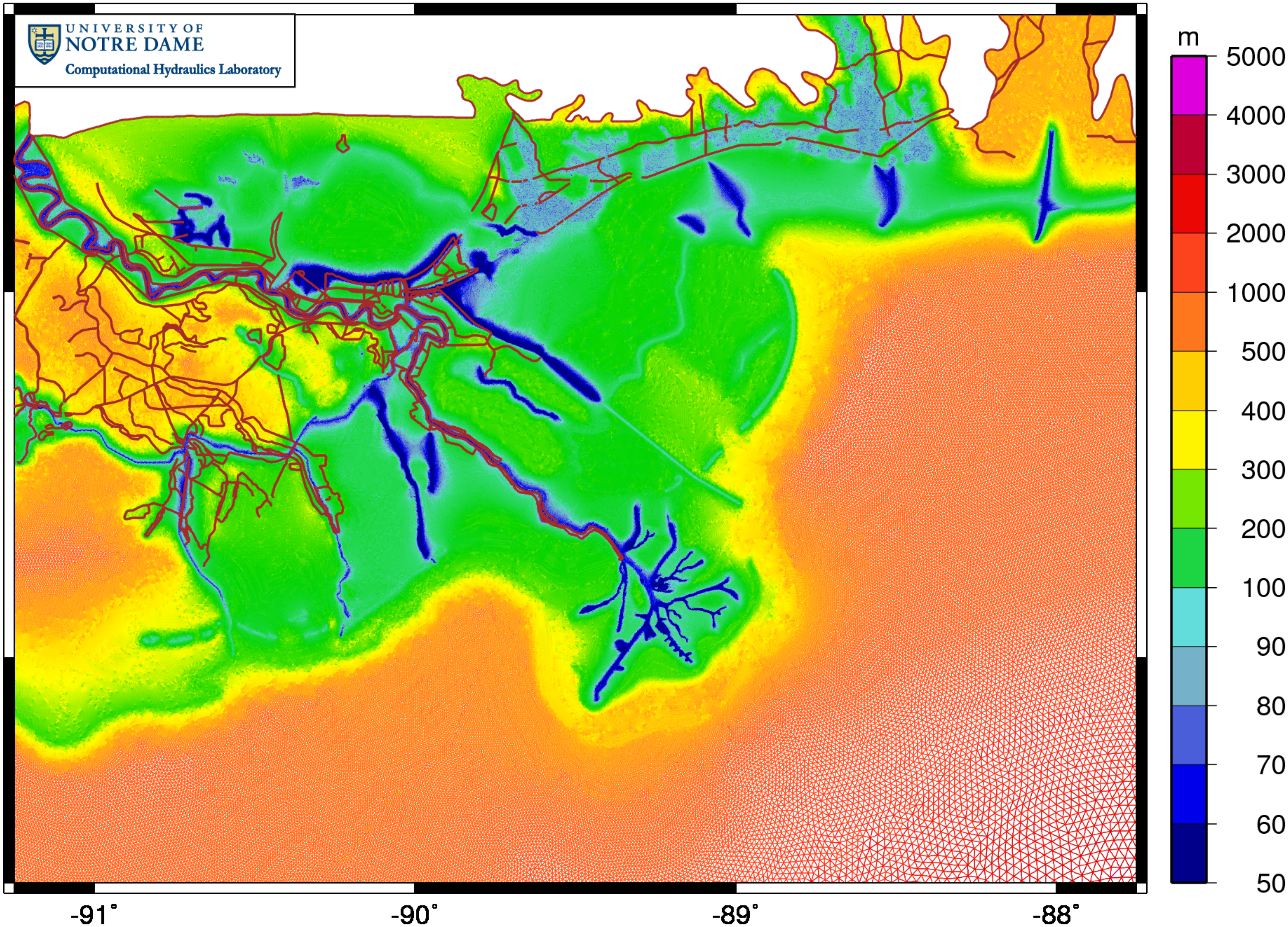
Southeastern Louisiana



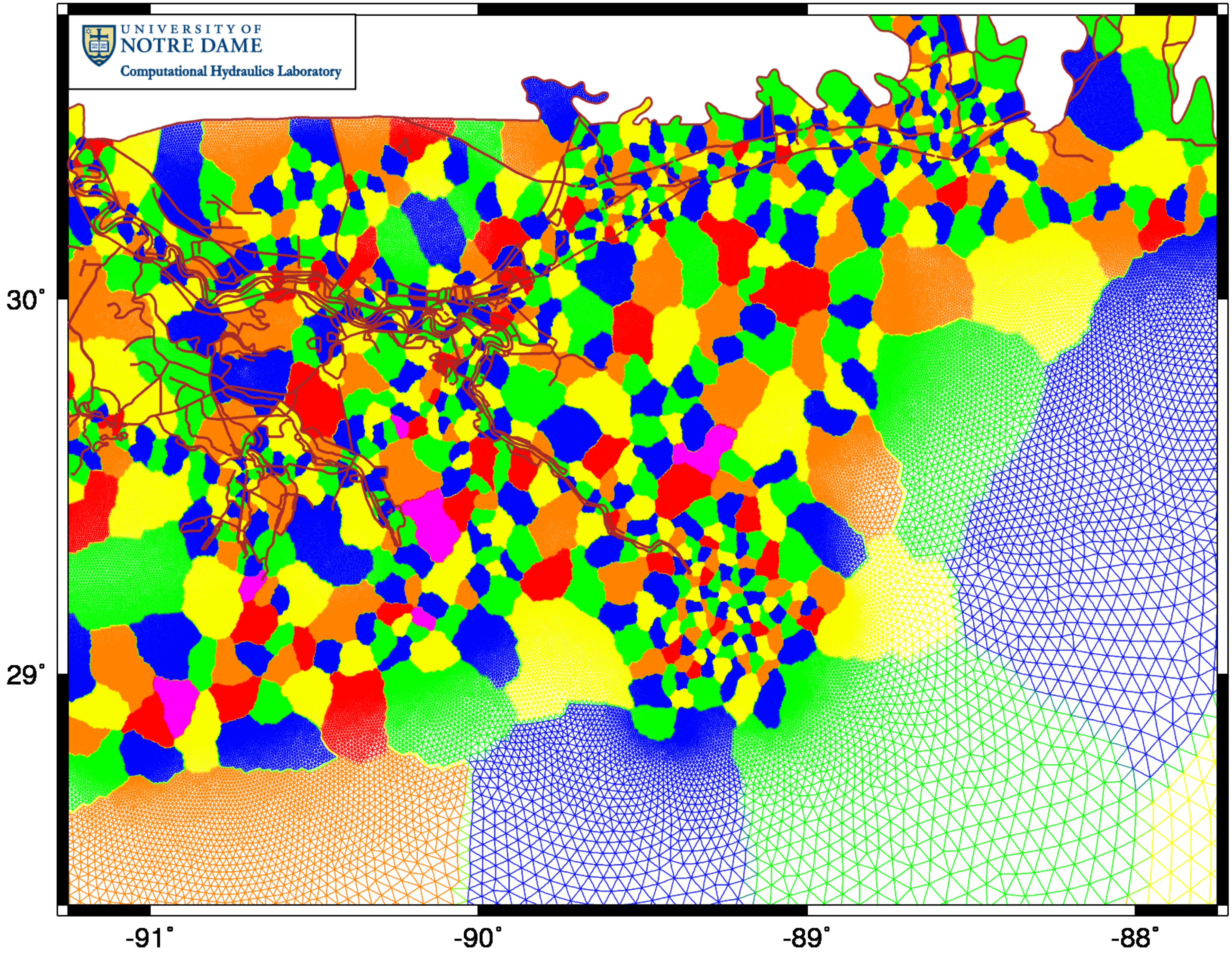
SL16 : Bathymetry and Topography



SL16 : Mesh Sizes



SL16 : Domain Decomposition



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:

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

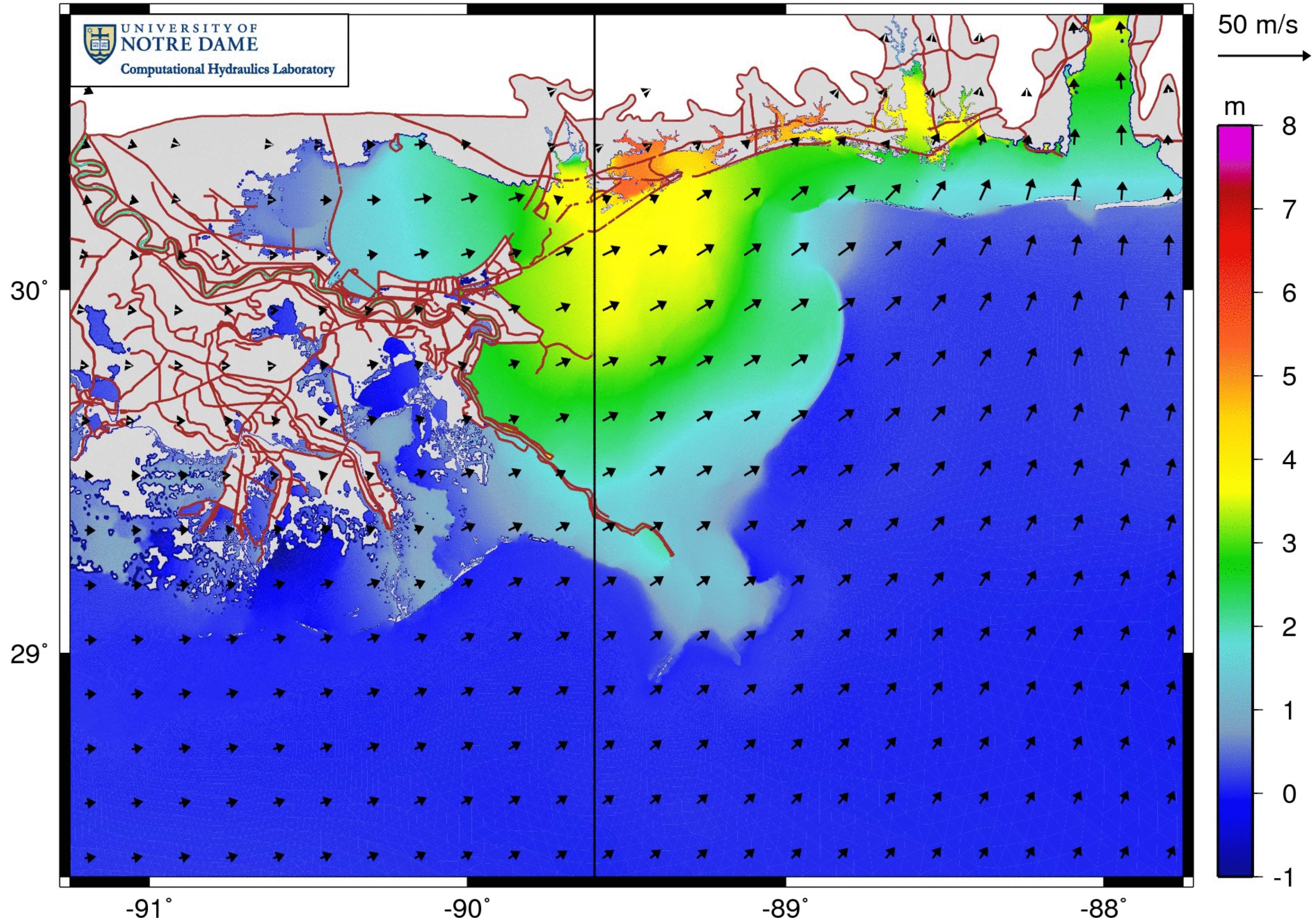
$$\tilde{J}_y = -Q_x \frac{\partial V}{\partial x} - Q_y \frac{\partial V}{\partial y} - fQ_x - \frac{g}{2} \frac{\partial \zeta^2}{\partial y} - gH \frac{\partial}{\partial y}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0} + \left(M_y - D_y\right) + V \frac{\partial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

- Solves the vertically-integrated momentum equations:

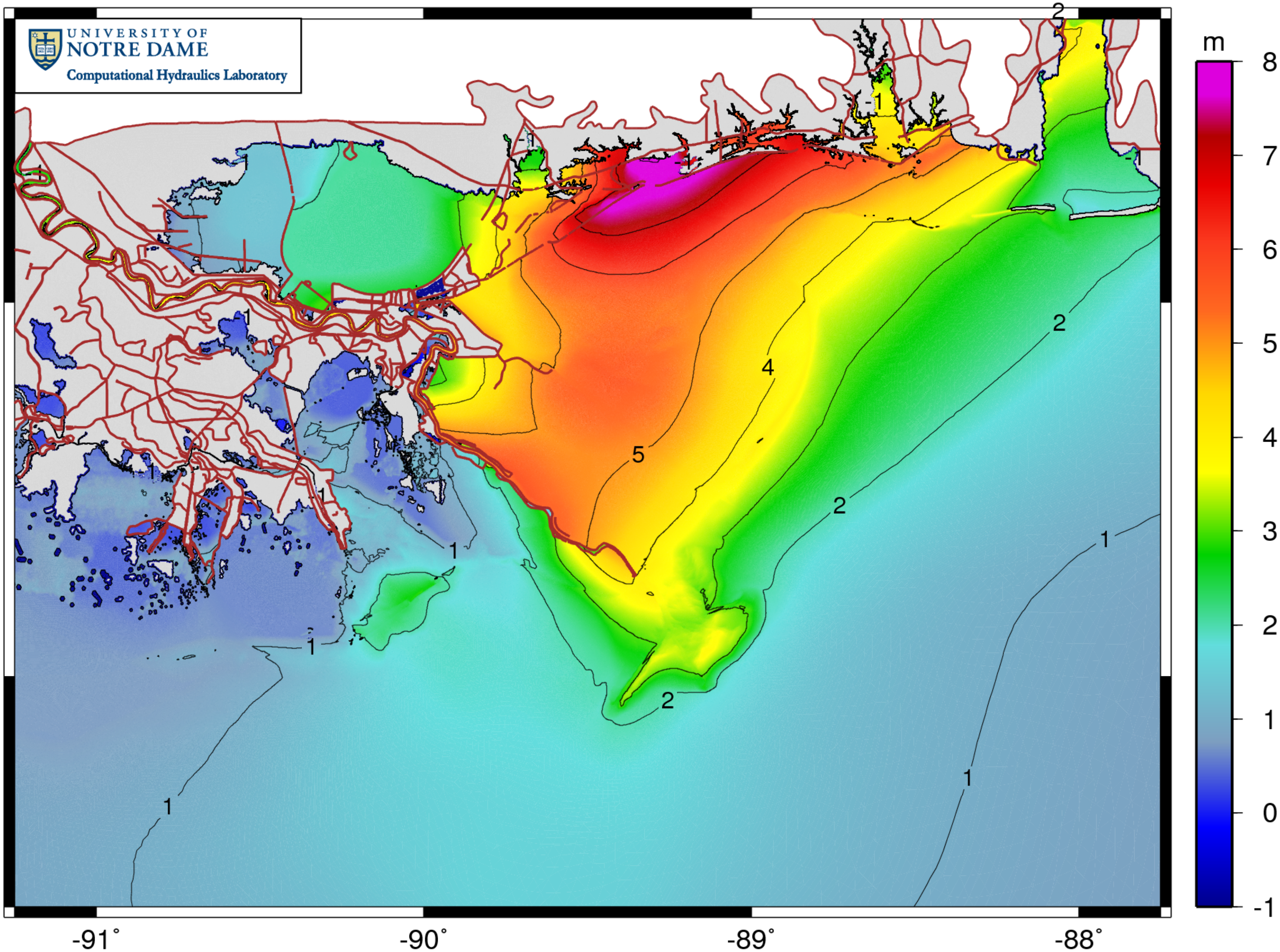
$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \frac{\partial}{\partial x}\left[\zeta + \frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

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

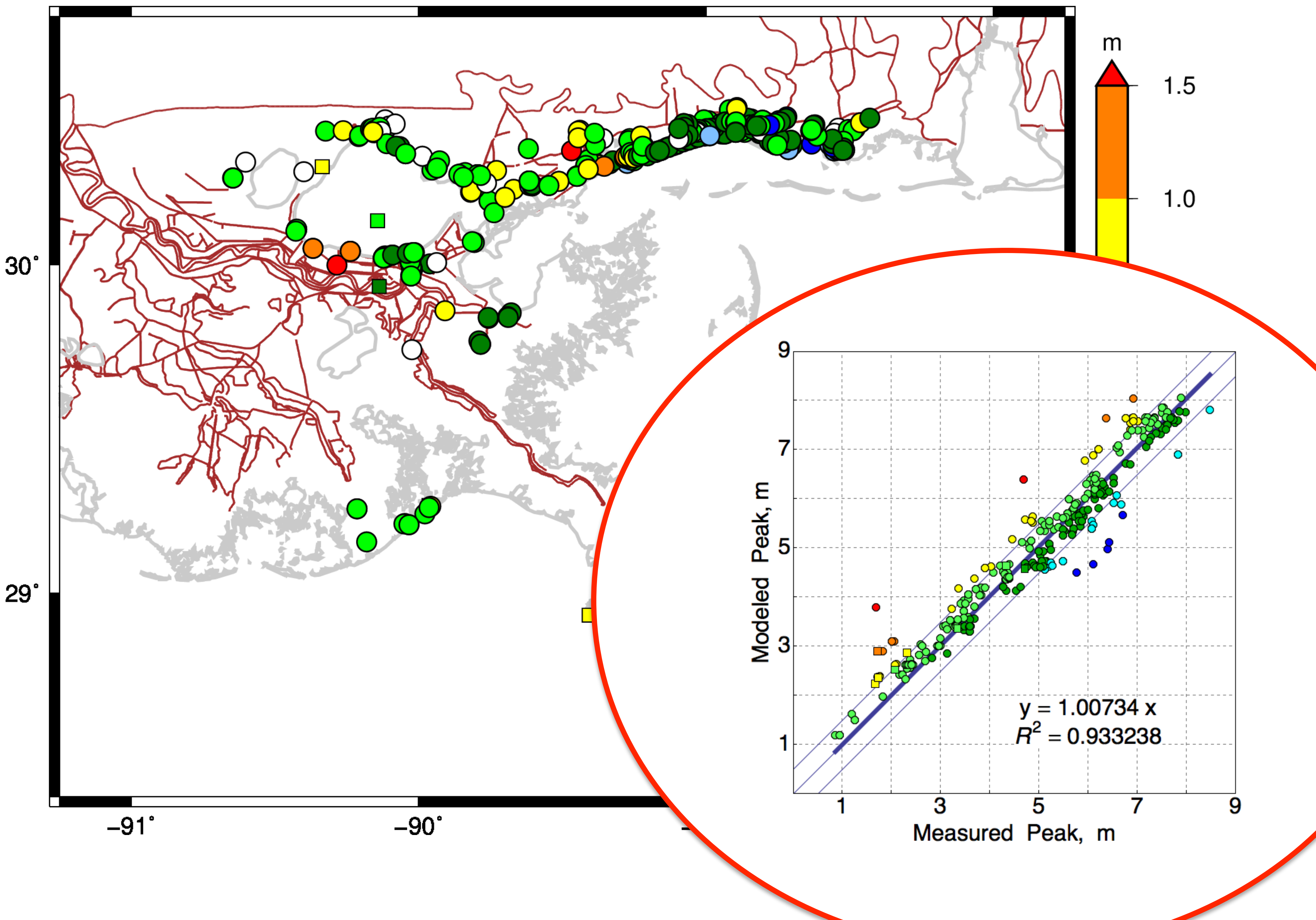
Katrina : Water Levels : Day of Landfall



Katrina : Water Levels : Maximum



Katrina : High-Water Marks



‘Tight’ Coupling of SWAN+ADCIRC

Simulating WAves Nearshore (SWAN):

- Solves the action balance equation:

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

Passing of Radiation Stress Gradients:

- Integrate action density to get radiation stresses:

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

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

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

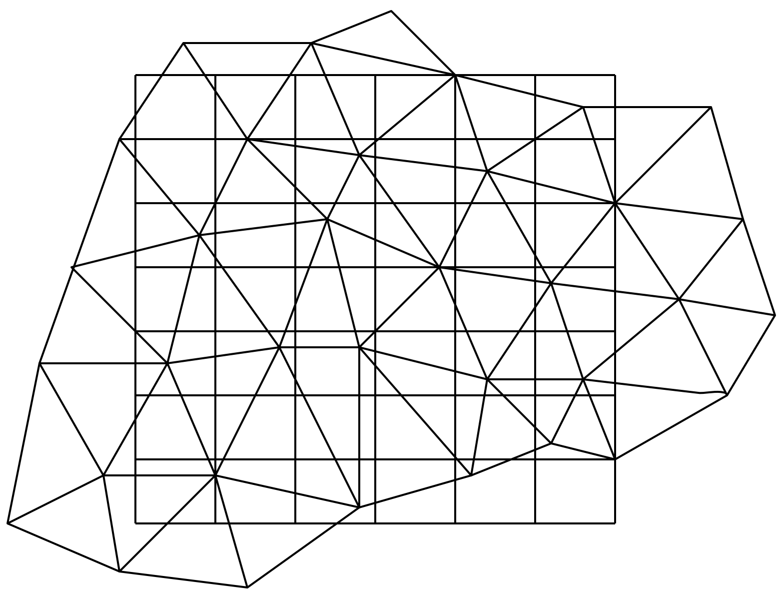
- Pass the gradients as surface stresses to ADCIRC:

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

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

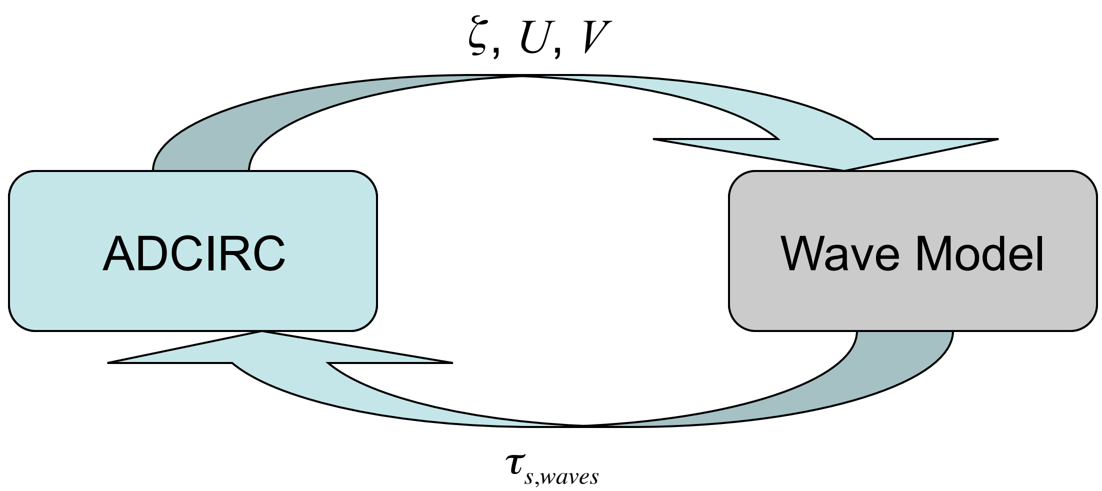
Disadvantages of 'Loose' Coupling

1. **Interpolation:**
   - Wave and circulation models run on different meshes
     - Wave models on structured meshes
     - ADCIRC on unstructured, finite element mesh
   - Results must be interpolated onto each mesh



Disadvantages of 'Loose' Coupling

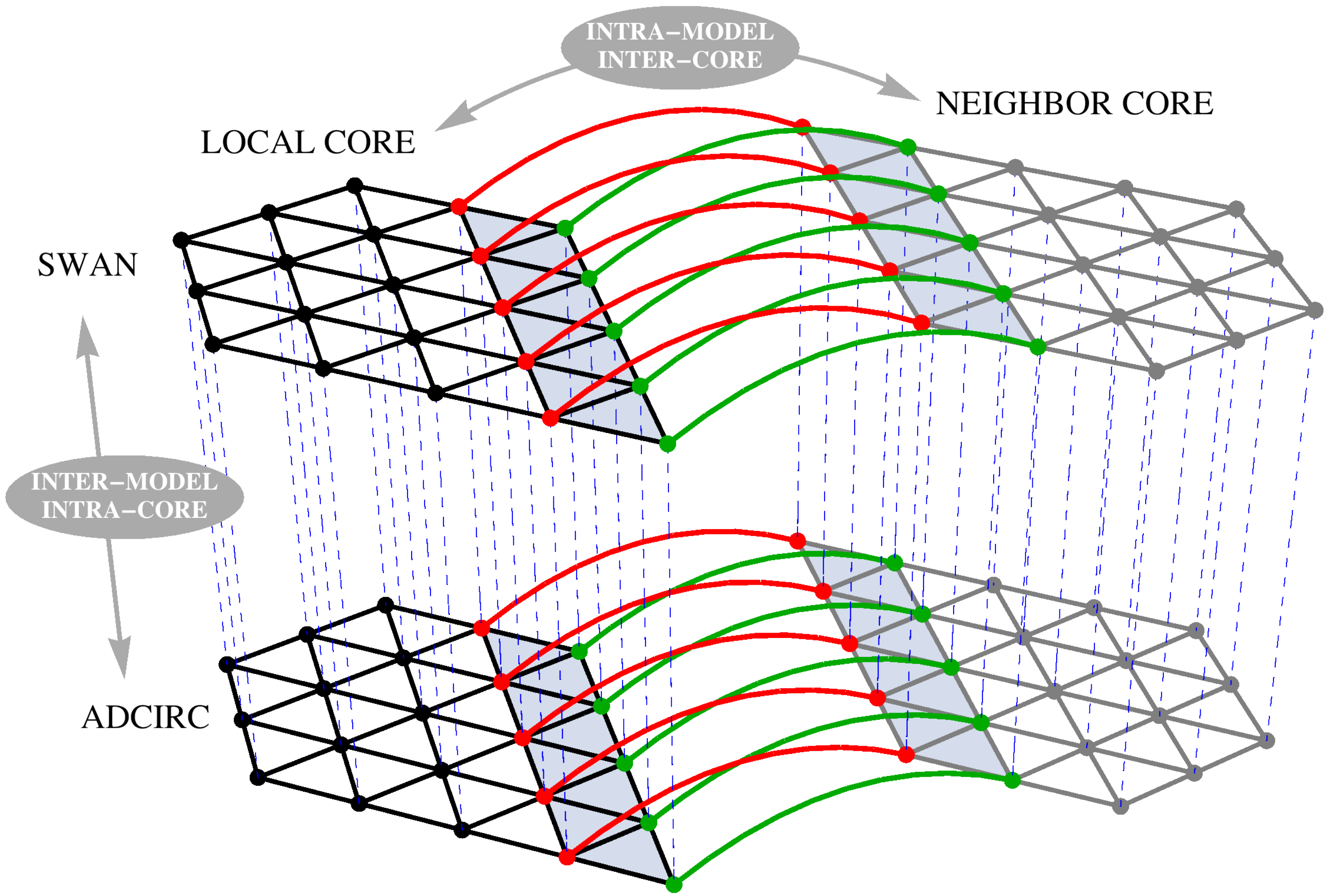
2. **Interpolation at Wave Model Boundaries**
3. **Coverage in Deep Water**
4. **Iteration**
   - Models coupled through input files
     - Winds, water levels and currents passed to wave model
     - Radiation stress gradients passed to ADCIRC
   - Process can be automated, but is still inefficient



‘Tight’ Coupling of SWAN+ADCIRC

Simulating WAves Nearshore (SWAN):

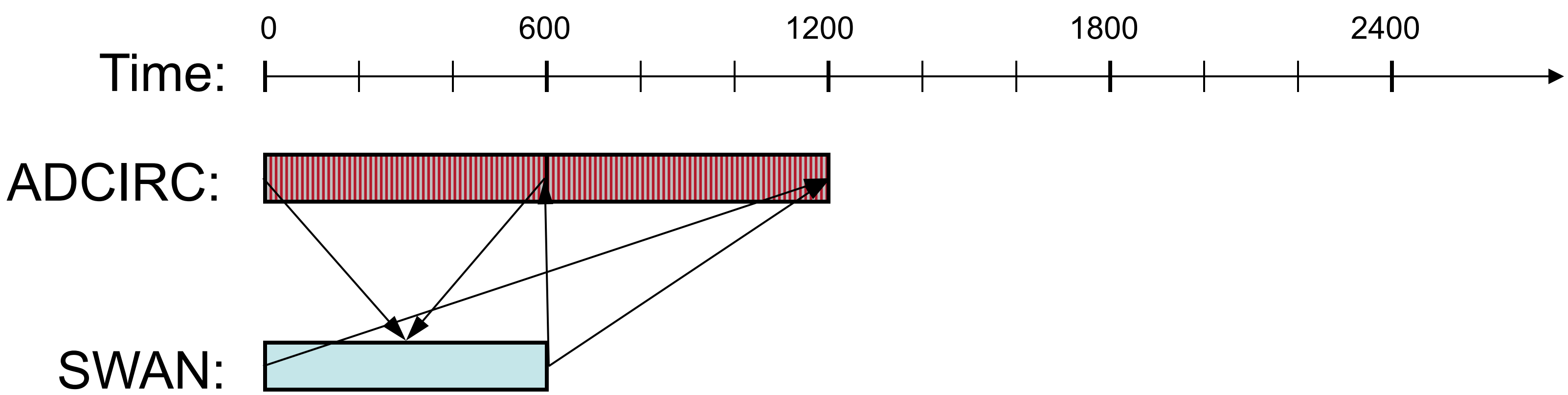
- Communication is optimized for high-performance computing:



‘Tight’ Coupling of SWAN+ADCIRC

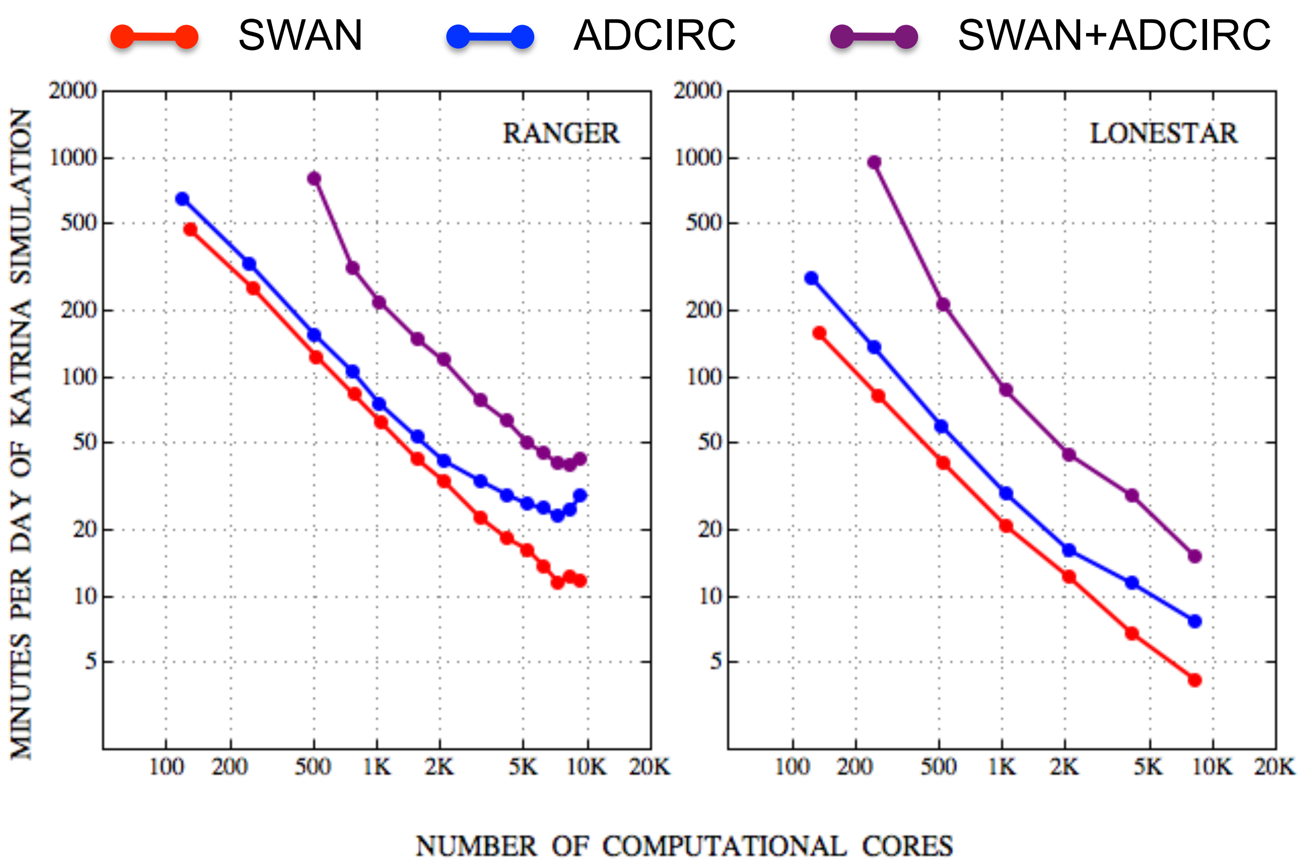
Schematic of Coupling:

- ADCIRC is run for 600 seconds (Δt = 1 sec)
- Water levels (ζ) and currents (U,V) are passed to SWAN
- SWAN is run for 600 seconds (Δt = 600 sec)
- Radiation stresses (S) and their gradients ($\tau_{s,waves}$) are computed; gradients are passed to ADCIRC
- Repeat



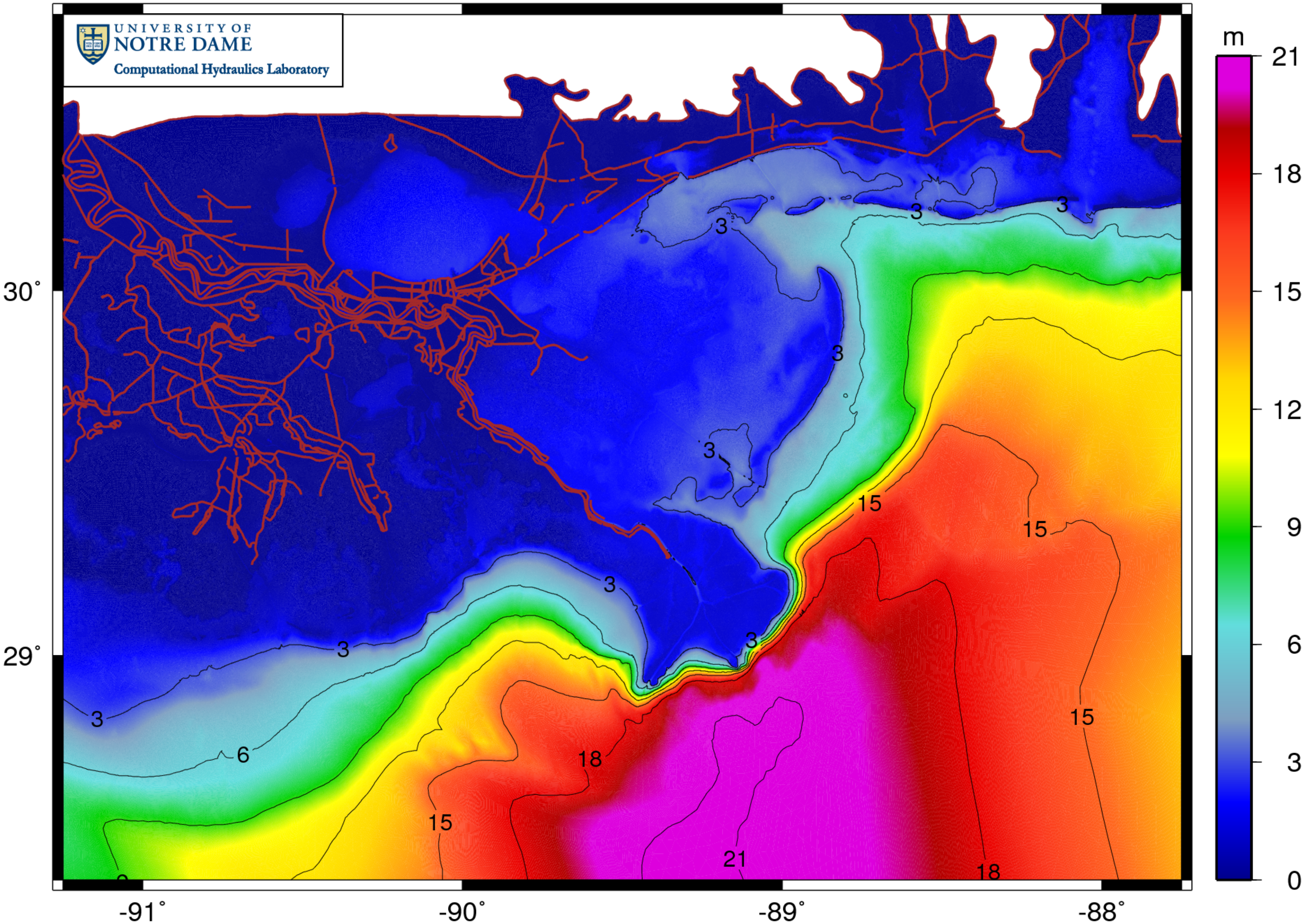
- SWAN and ADCIRC are always extrapolating in time

‘Tight’ Coupling of SWAN+ADCIRC

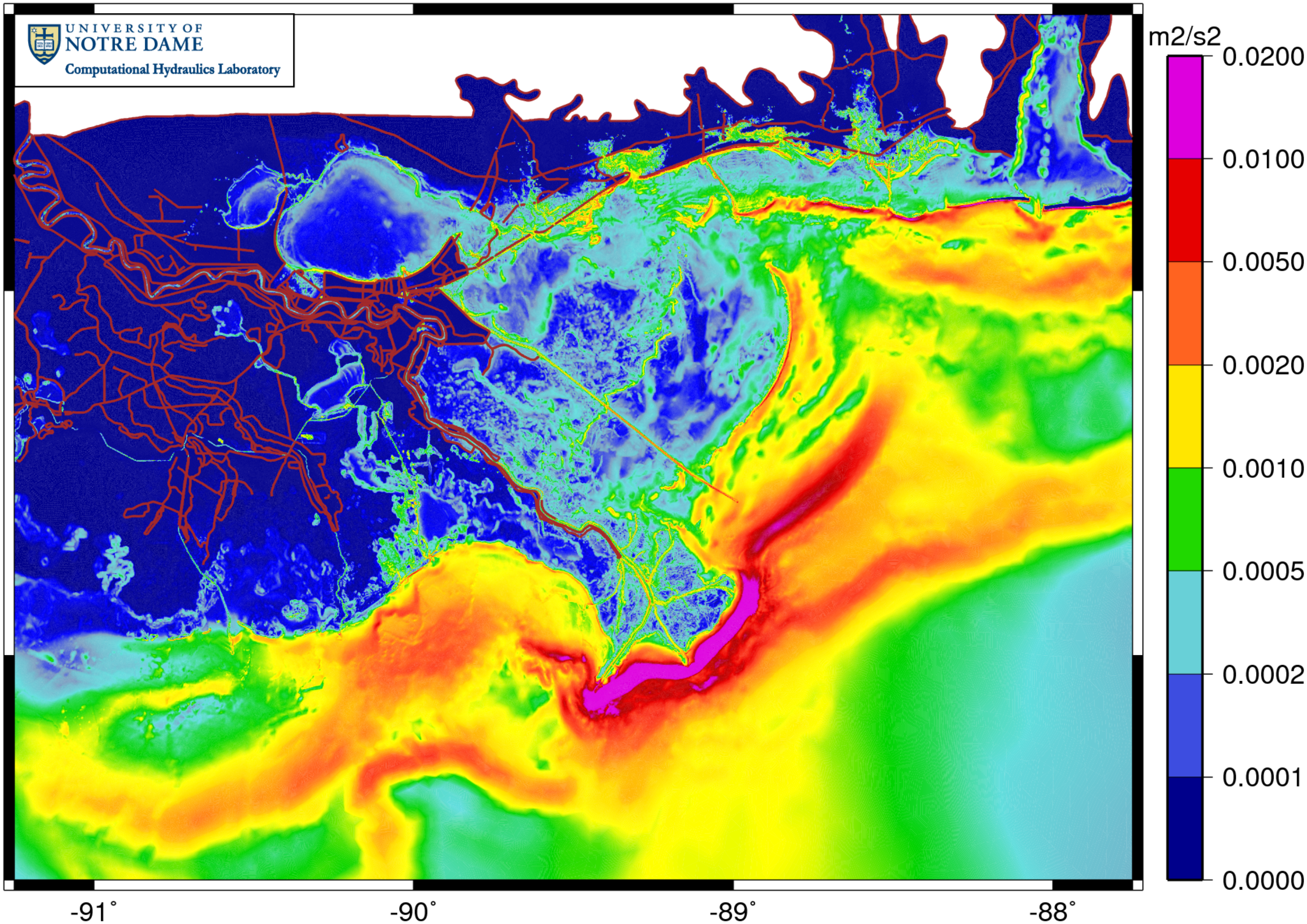


	Ranger	Lonestar
Node	Sun Blade x6420	Dell PowerEdge M610
CPU	4 Quad-core AMD Opteron 8356	2 Six-core Xeon 5680
Frequency	2.3 GHz	3.33 GHz
Architecture	AMD K10 (Barcelona)	Intel Nehalem (Westmere-EP)

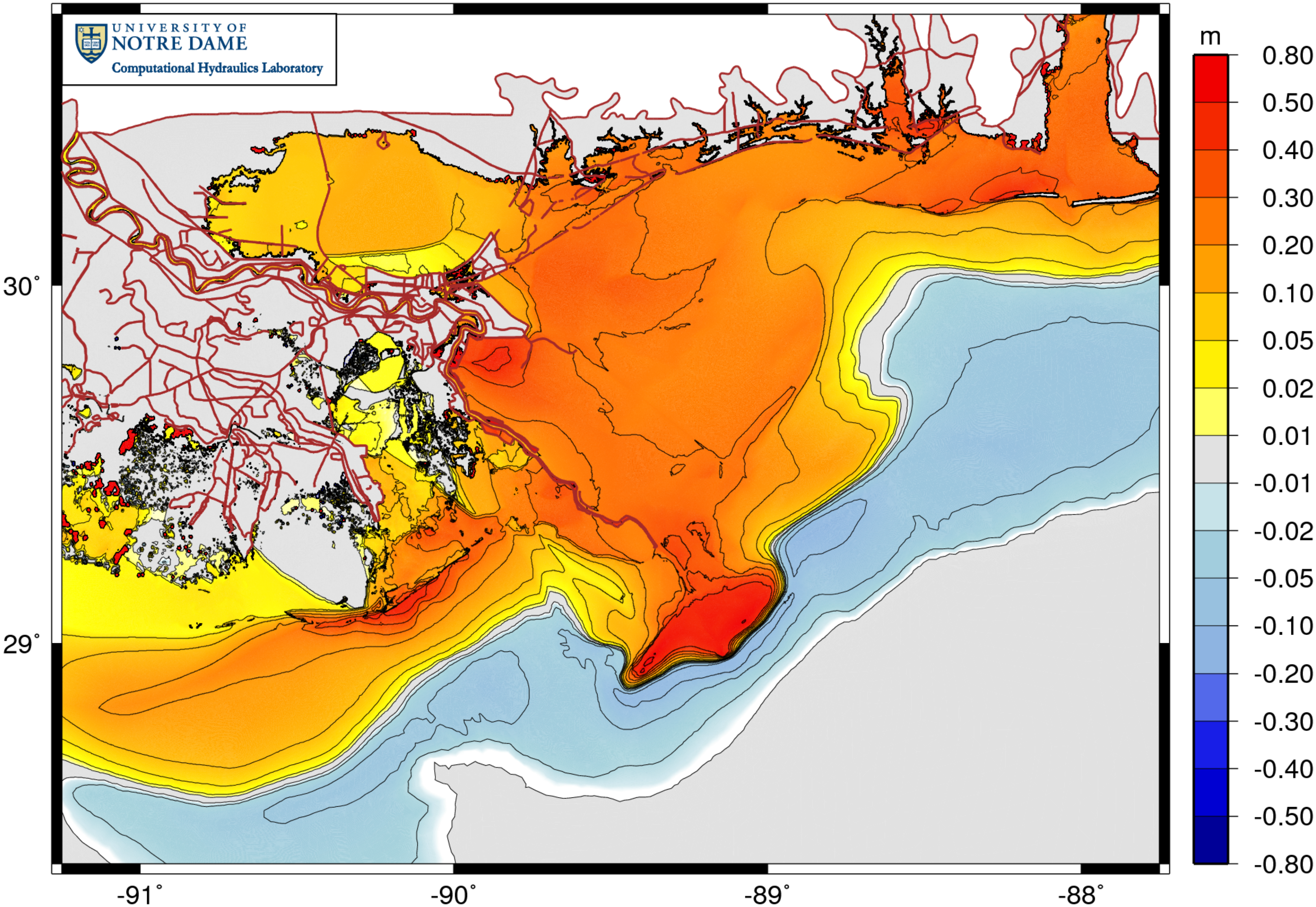
Katrina : Significant Wave Heights : Maximum



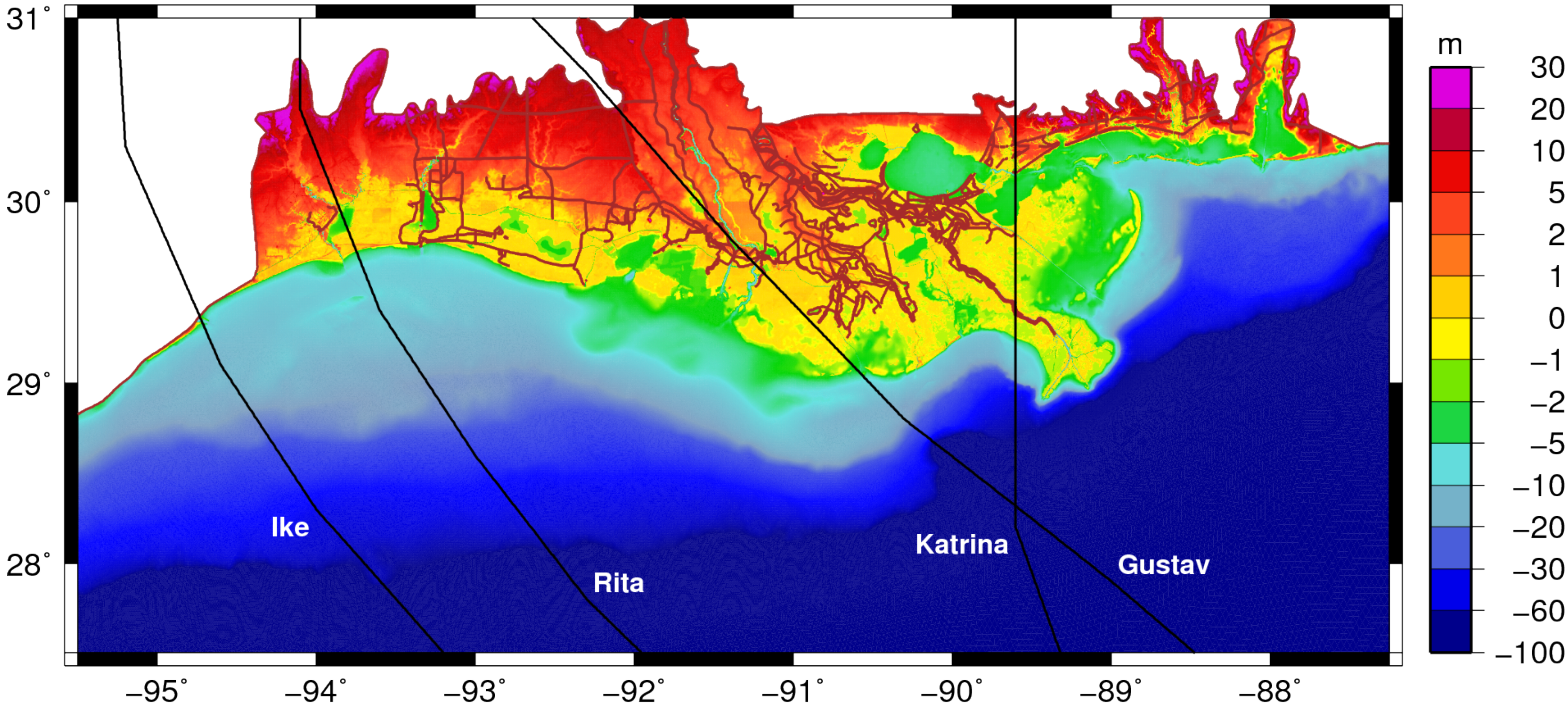
Katrina : Radiation Stress Gradients : Maximum



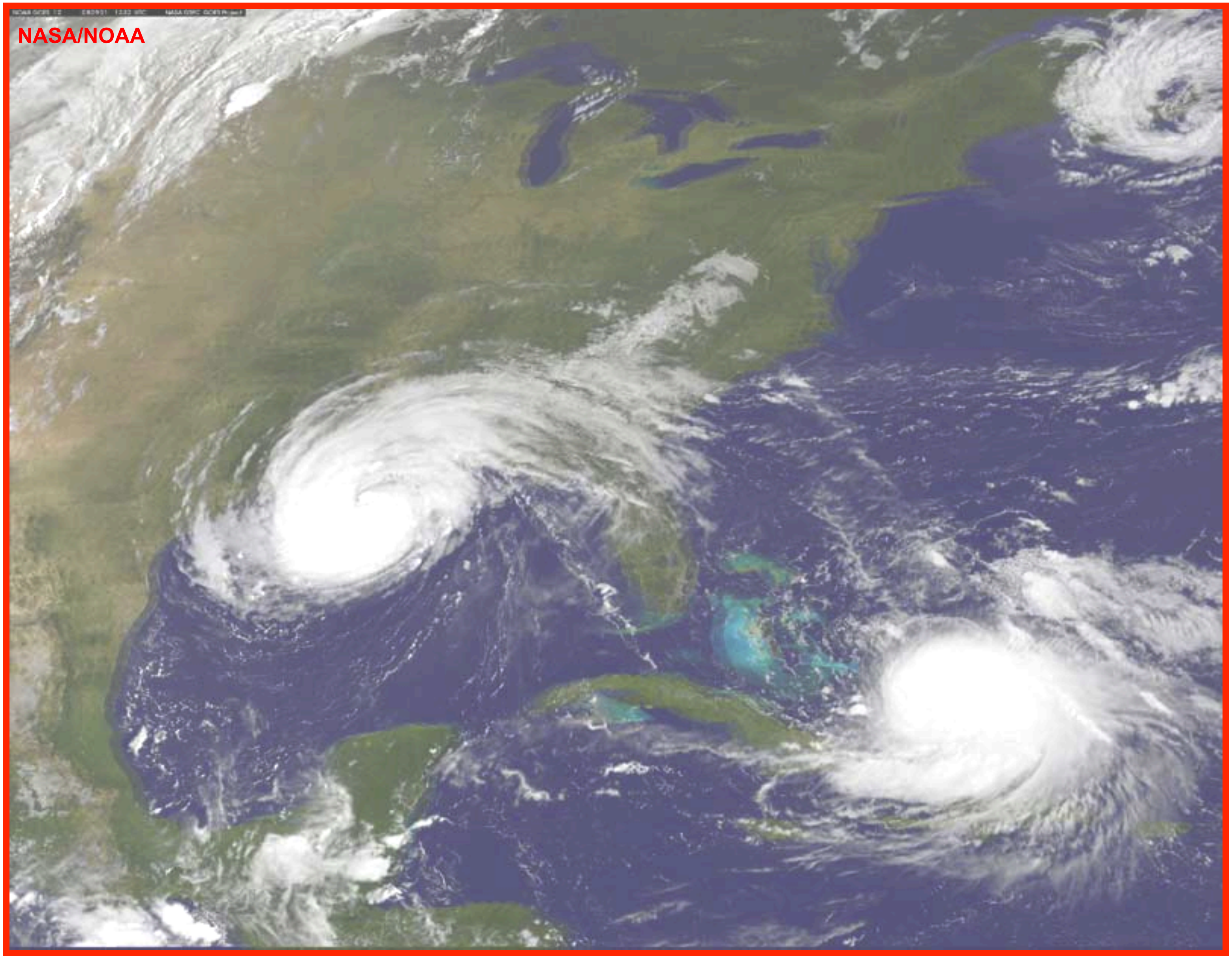
Katrina : Wave-Driven Setup : Maximum



Validation : Recent Storms



Gustav : Hurricane Season 2008

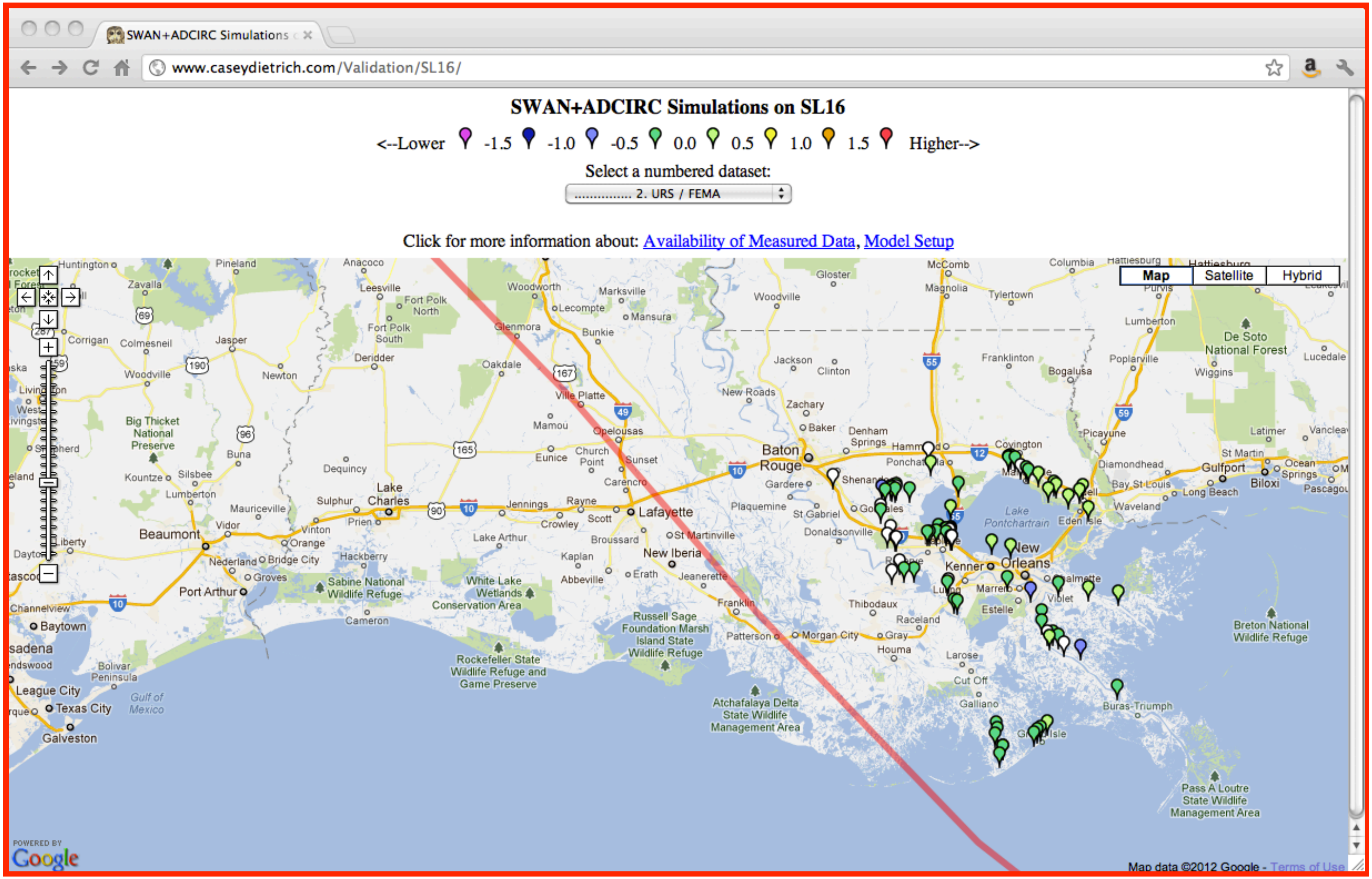


Gustav : Storm Surge near New Orleans

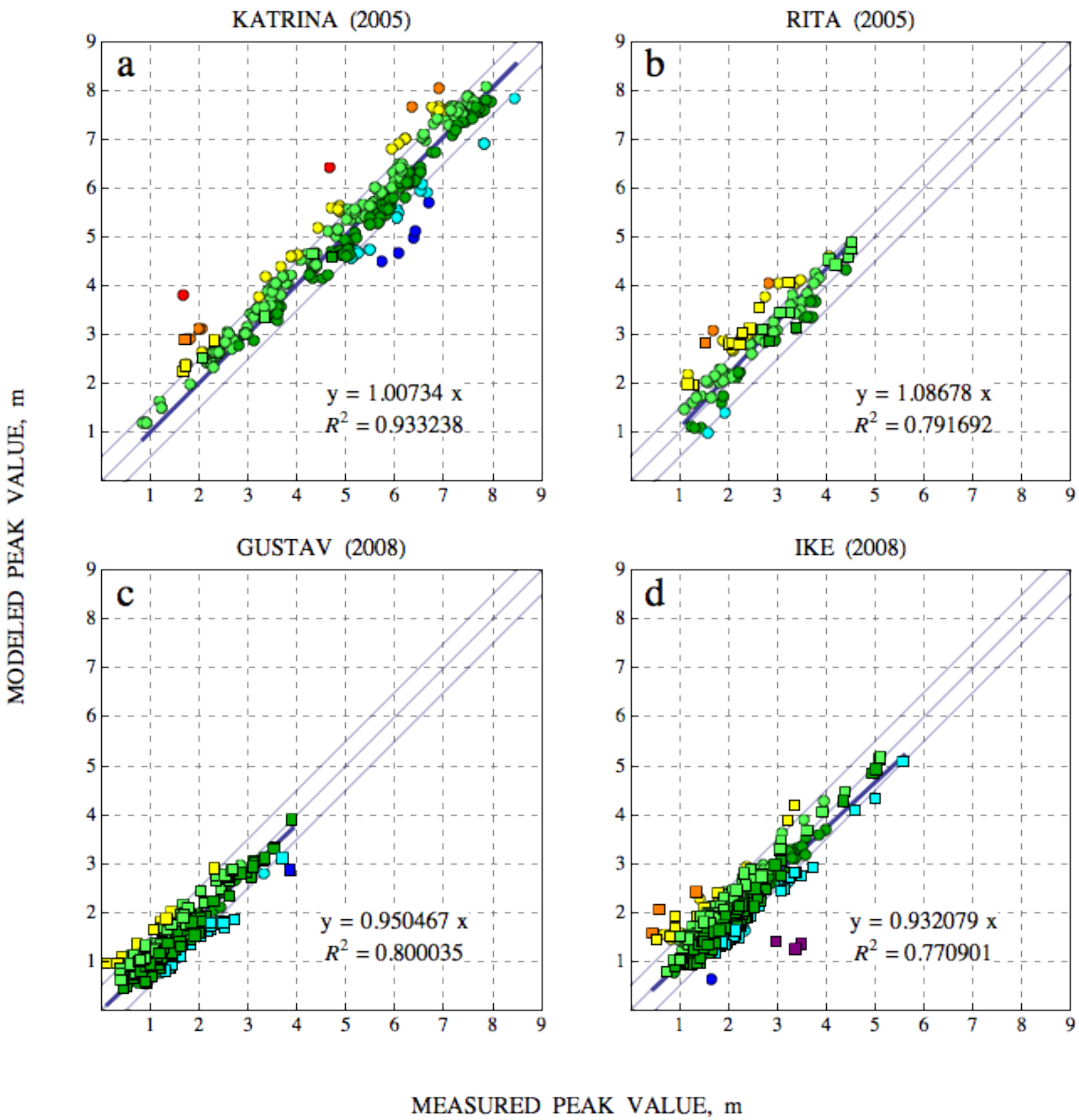
Validation : Increased Availability of Measurement Data

	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



What We Are Now:
Better Understanding of Nearshore Waves and Surge

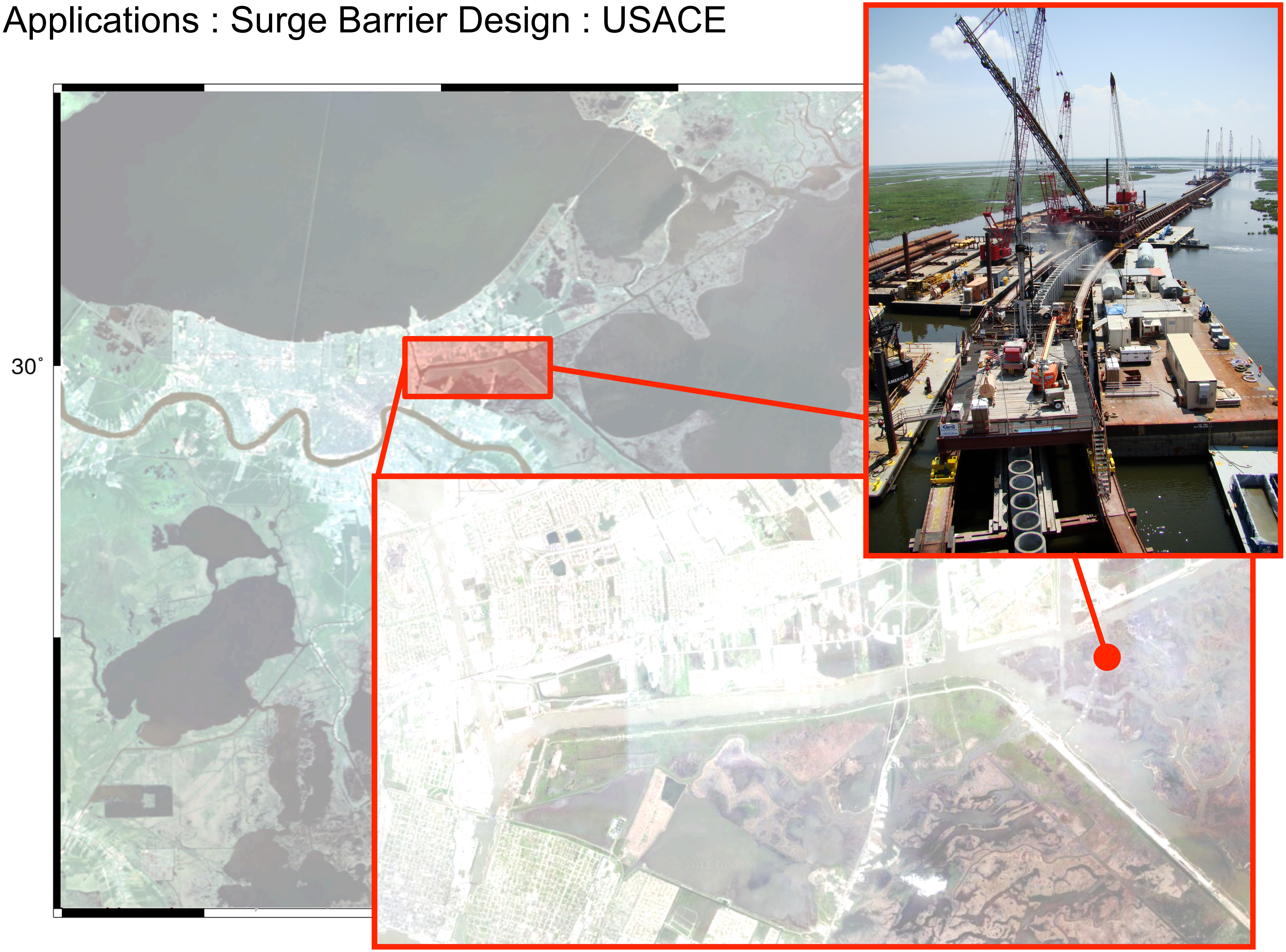
A.B. Kennedy, et al. (2011). "Origin of the Hurricane Ike Forerunner Surge." *Geophysical Research Letters*, 38, L08608.

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.

JC Dietrich, et al. (2011). "Surface Trajectories of Oil Transport along the Northern Coastline of the Gulf of Mexico." *Continental Shelf Research*, in review.

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

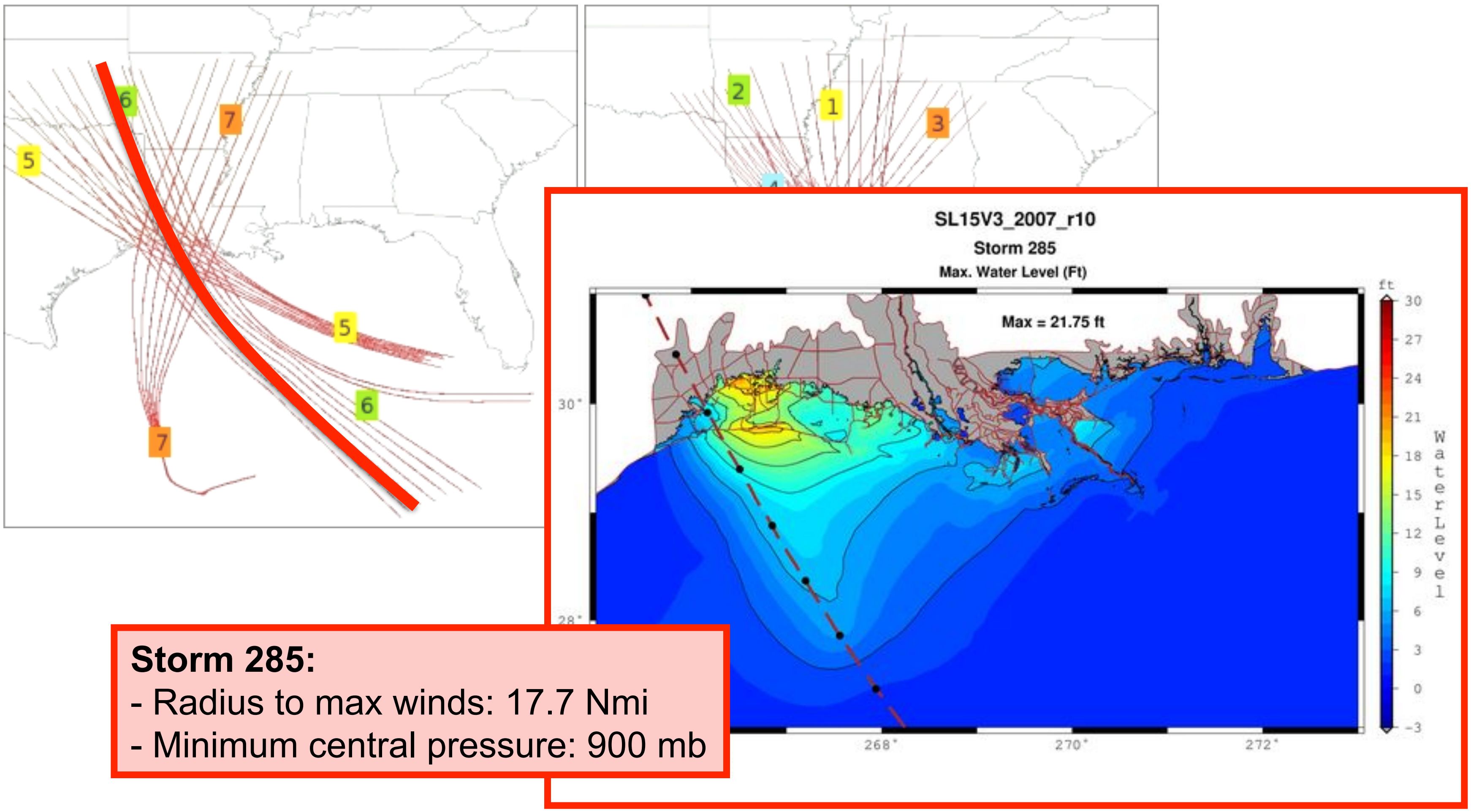
Applications : Surge Barrier Design : USACE



Applications : Flood Insurance Rate Maps : FEMA

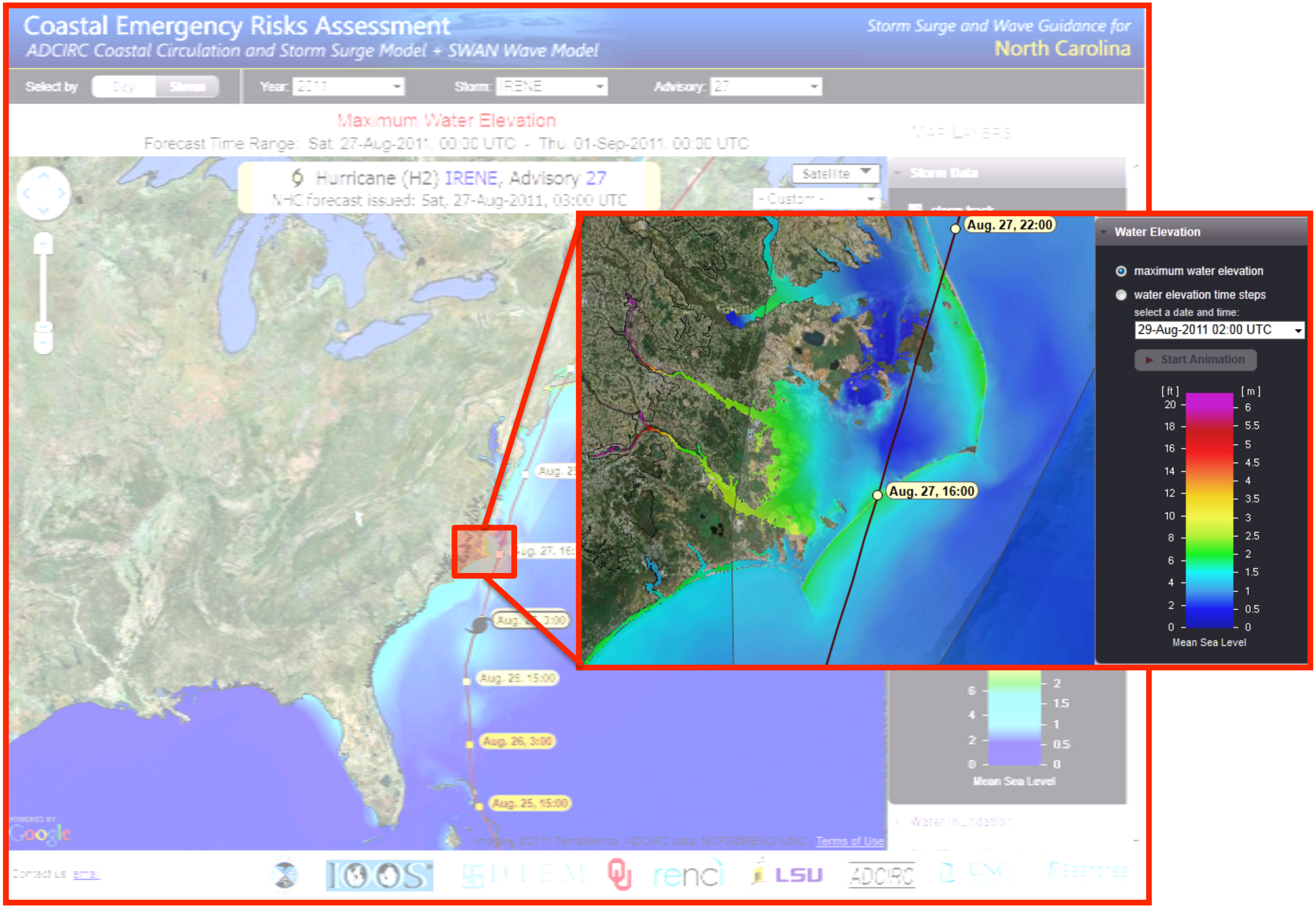
Joint Probability Method with Optimal Sampling (JPM-OS):

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

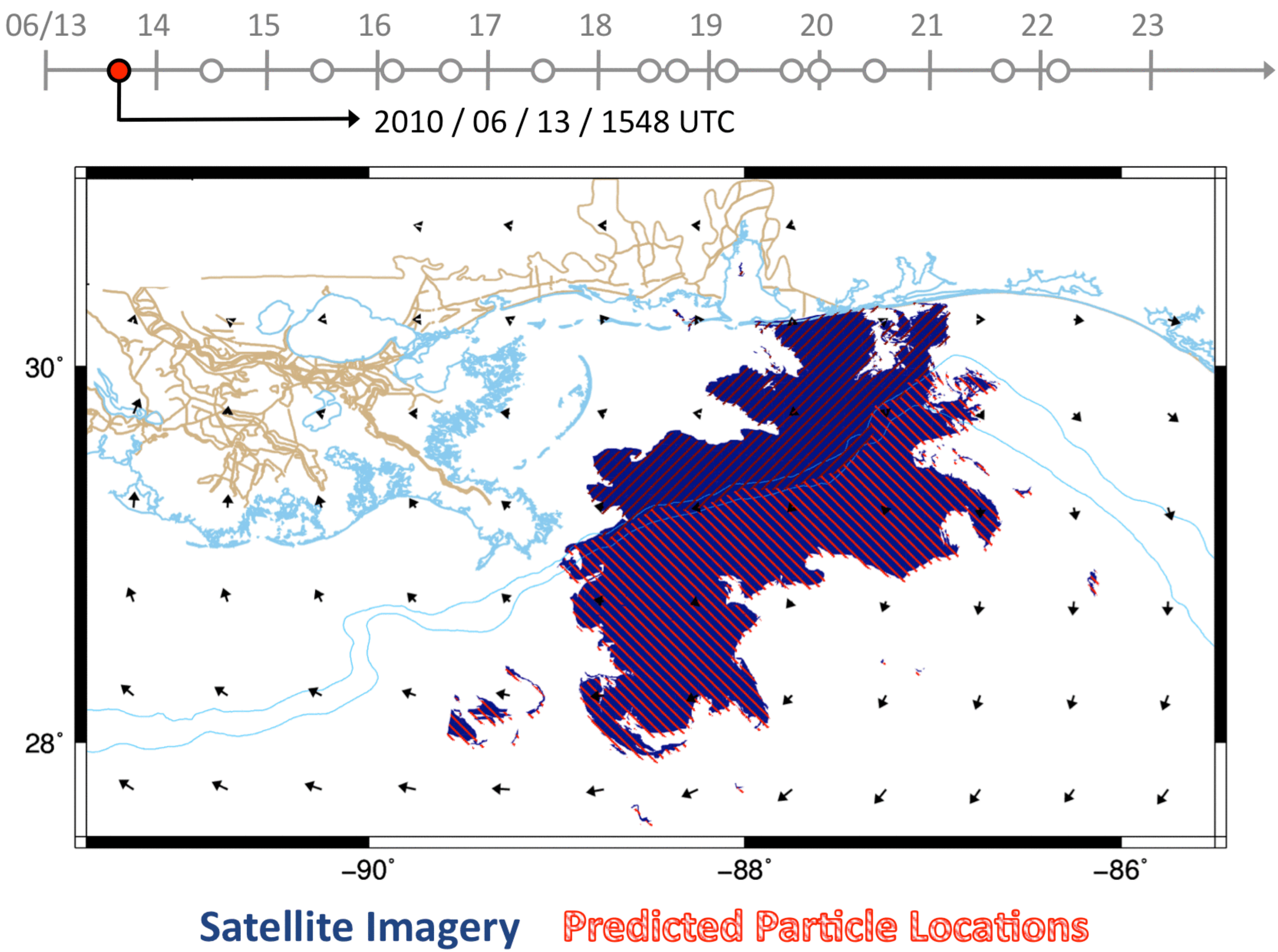


Storm 285:
- Radius to max winds: 17.7 Nmi
- Minimum central pressure: 900 mb

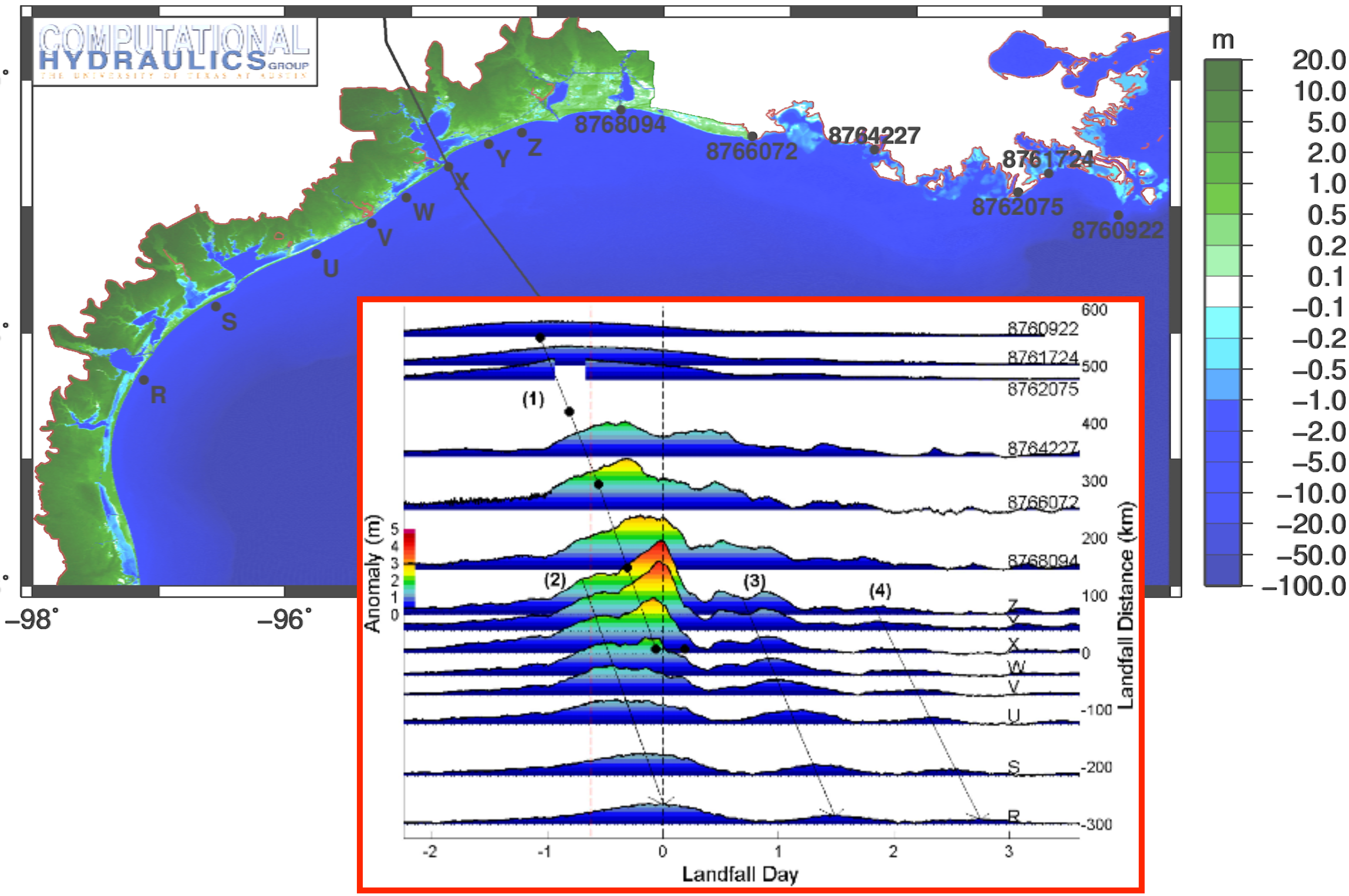
Applications : Hurricane Forecasting : Irene (2011)



Applications : Nearshore Oil Transport : NSF/DHS



Applications : Surge Forerunner : Ike (2008)



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.

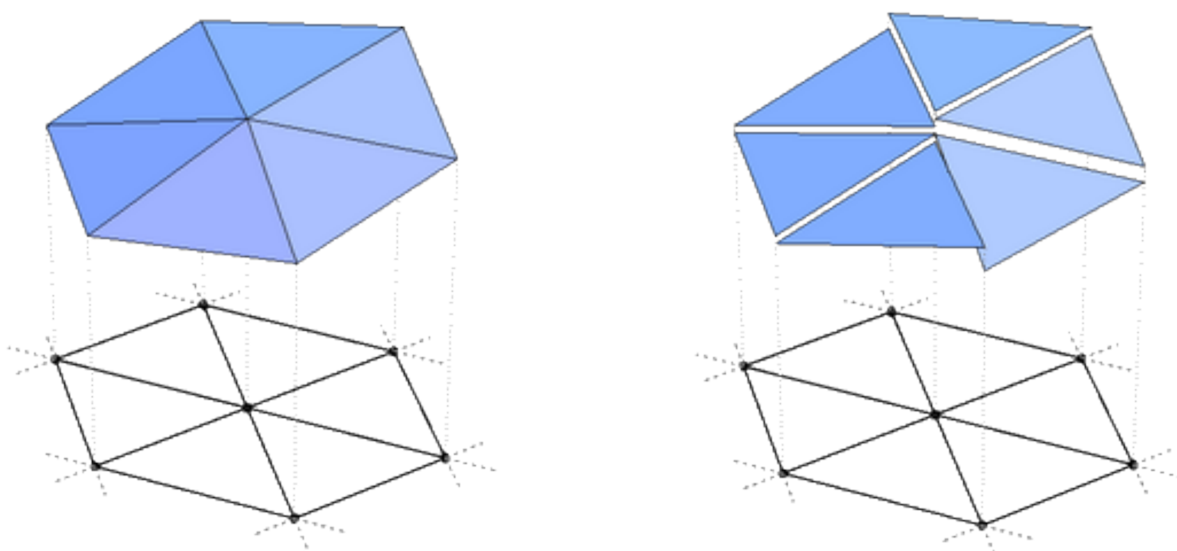
J.C. Dietrich, et al. (2012). "Effect of Coupled Circulation on a Nearshore Wave Model." *Coastal Engineering*, in preparation.

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

DG : Moving toward Adaptive Meshes

Discontinuous Galerkin (DG):

- Integrate over each <u>local element</u> instead of the <u>global domain</u>.
- 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]

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[b] Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, C
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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,
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 accurately 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)

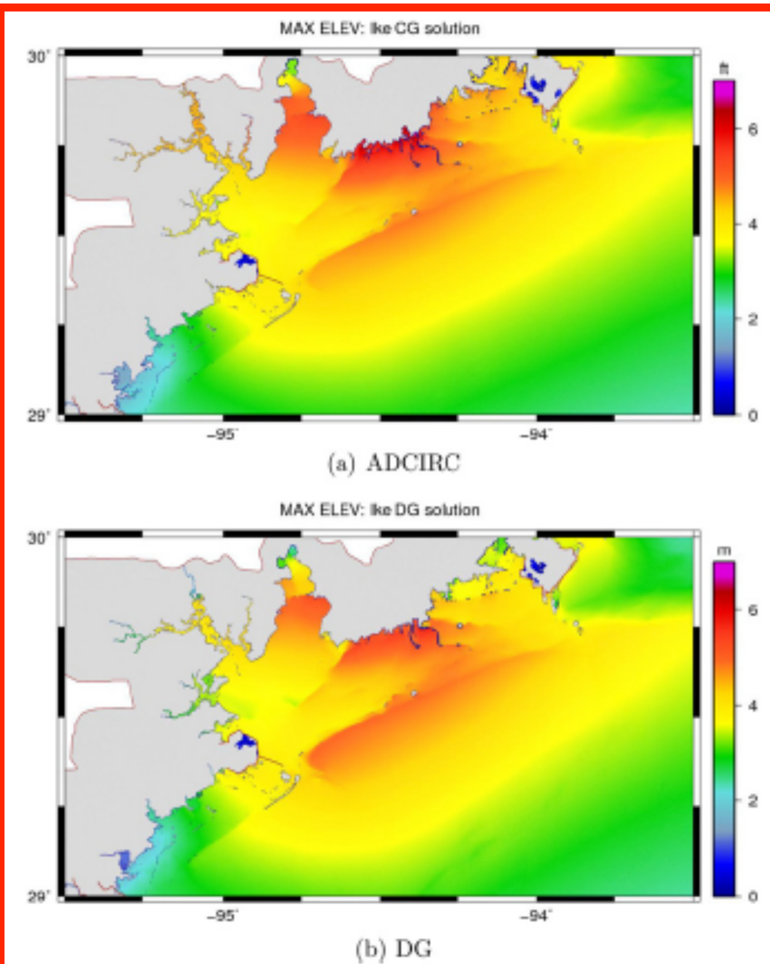


Fig. 8. Maximum water levels for ADCIRC (a) and DG (b) solutions during Hurricane Ike. Water elevation is in meters relative to the North American Vertical Datum of 1988 (NAVD88). The solution is plotted in the region between −93.5 and −95.5° longitude and 29 and 30° latitude.

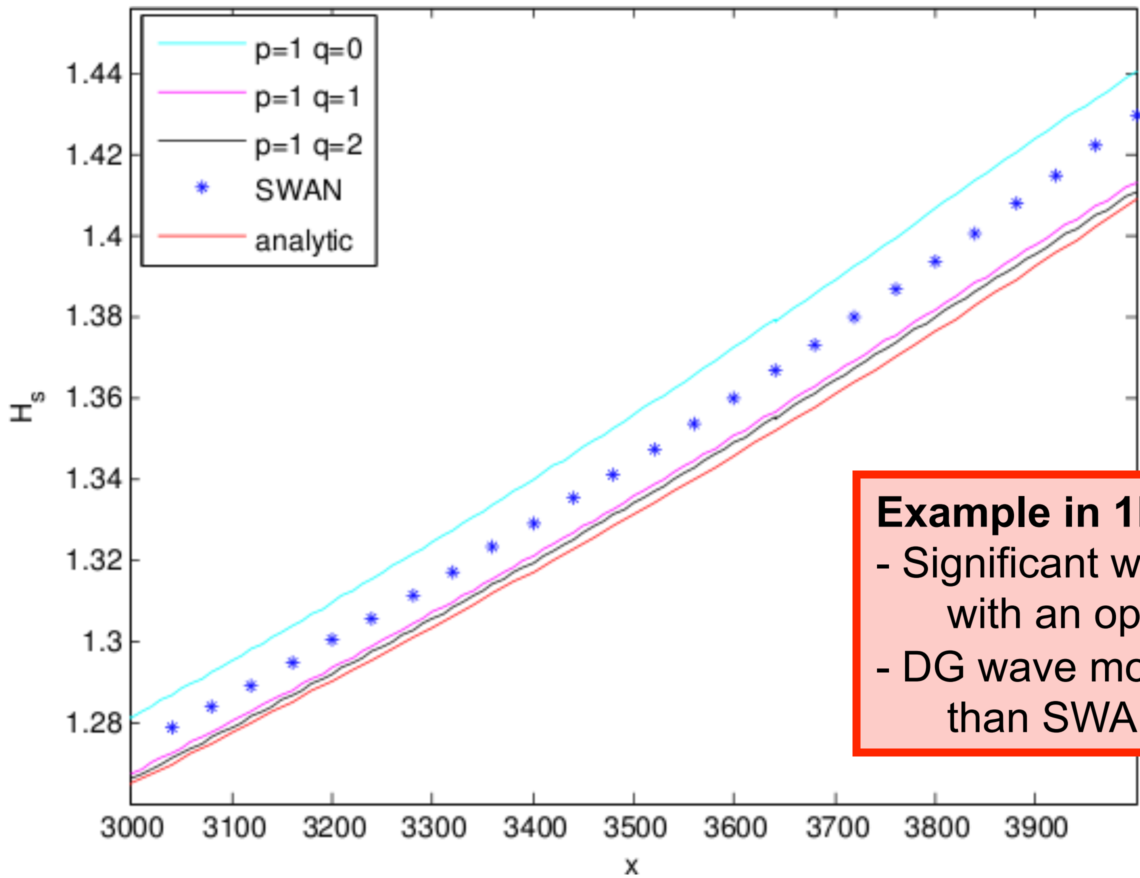
DG : Developing a Spectral Wave Model

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

'Tight' Coupling of SWAN+ADCIRC:

- Models use same unstructured mesh
- Information passed dynamically through local cache
- Coupled model is efficient to 1000s of computational cores
- SWAN is as accurate as other, structured-mesh wave models
- Wealth of measurement data

Better Understanding of Nearshore Waves and Circulation:

- Design of surge barrier to protect New Orleans
- Development of floodplain risk maps
- Forecasting of hurricanes, oil spill

Continue the Development of DG Models:

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

Thank You!

2011 Hurricane Season