Development and Application of Coupled Hurricane Wave and Surge Models for Southern Louisiana

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Monday, 18 July 2011

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

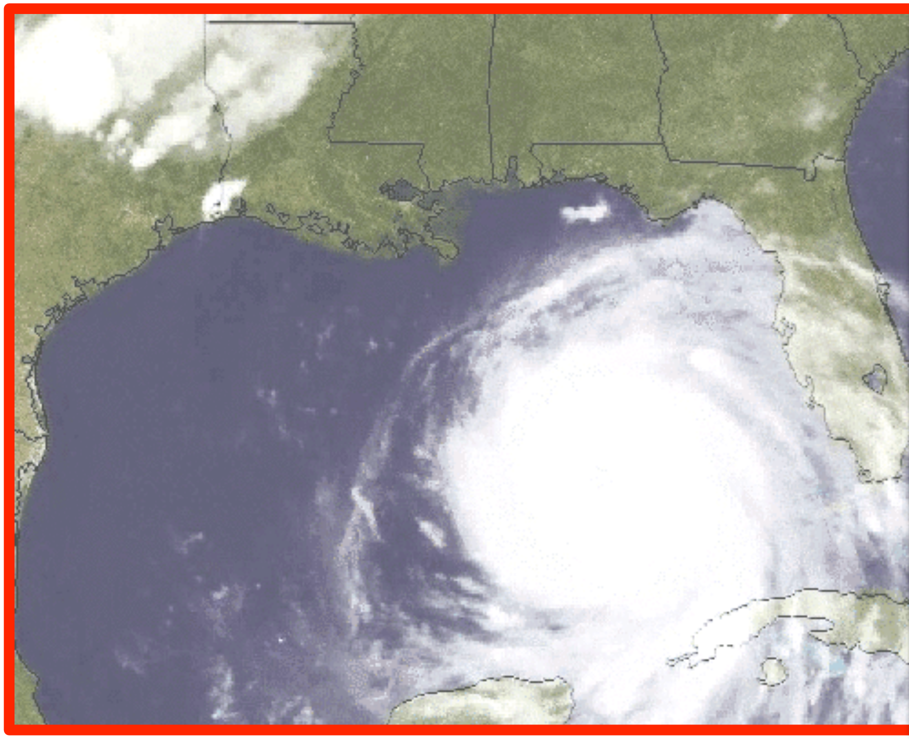
B.A. Ebersole, *et al.* (2010). "Development of Storm Surge Which Led to Flooding in St. Bernard Polder during Hurricane Katrina." *Ocean Engineering*, 37, 91-103.

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.

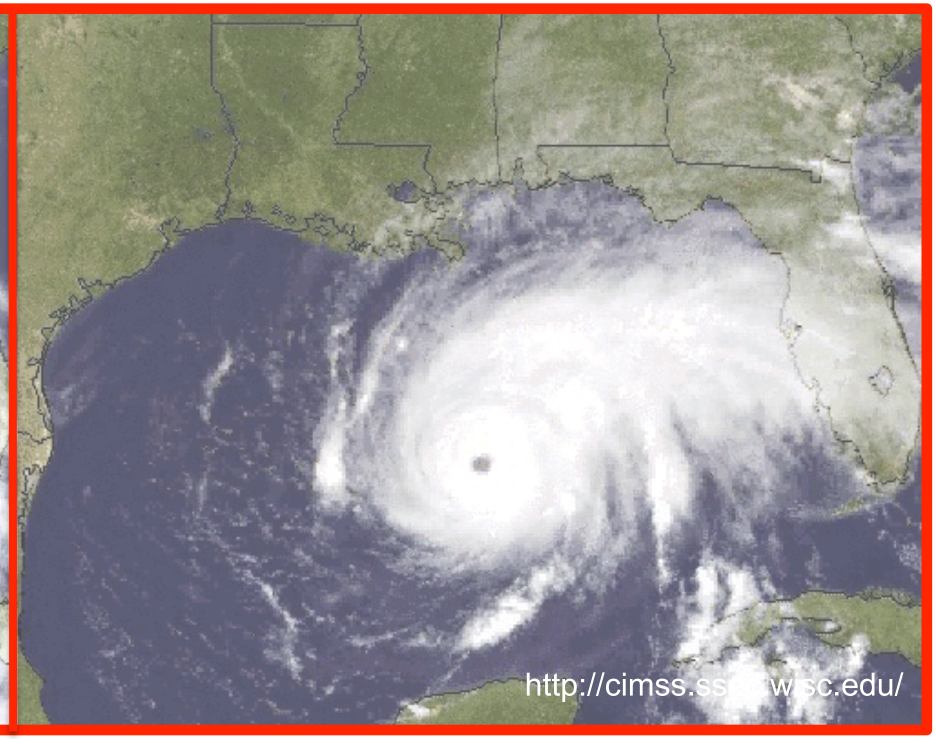
J.C. Dietrich, *et al*. (2010). "A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi, Part II: Synoptic Description and Analysis of Hurricanes Katrina and Rita." *Monthly Weather Review* 138, 378-404.

2005 Hurricane Season

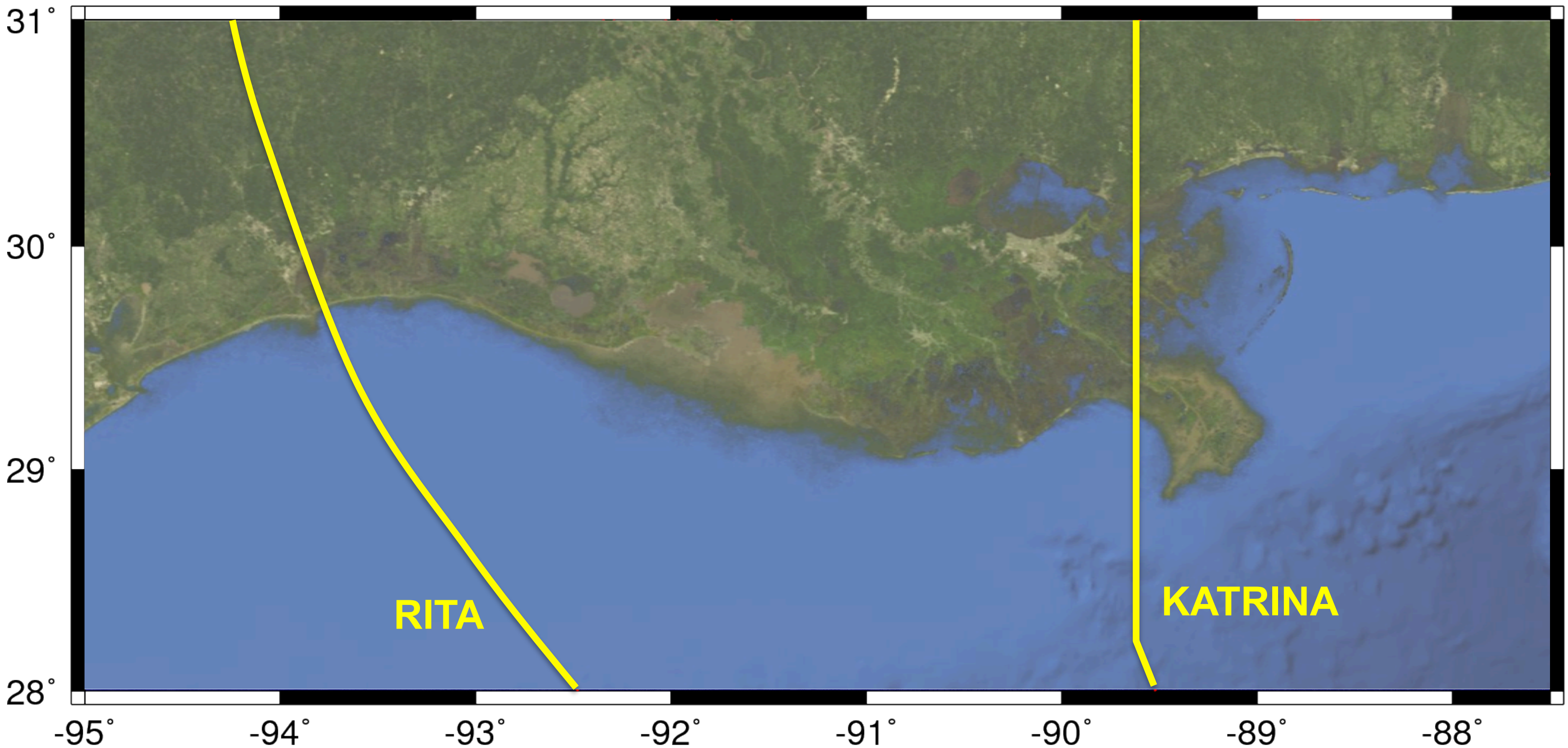
Katrina : 08/28 – 08/29



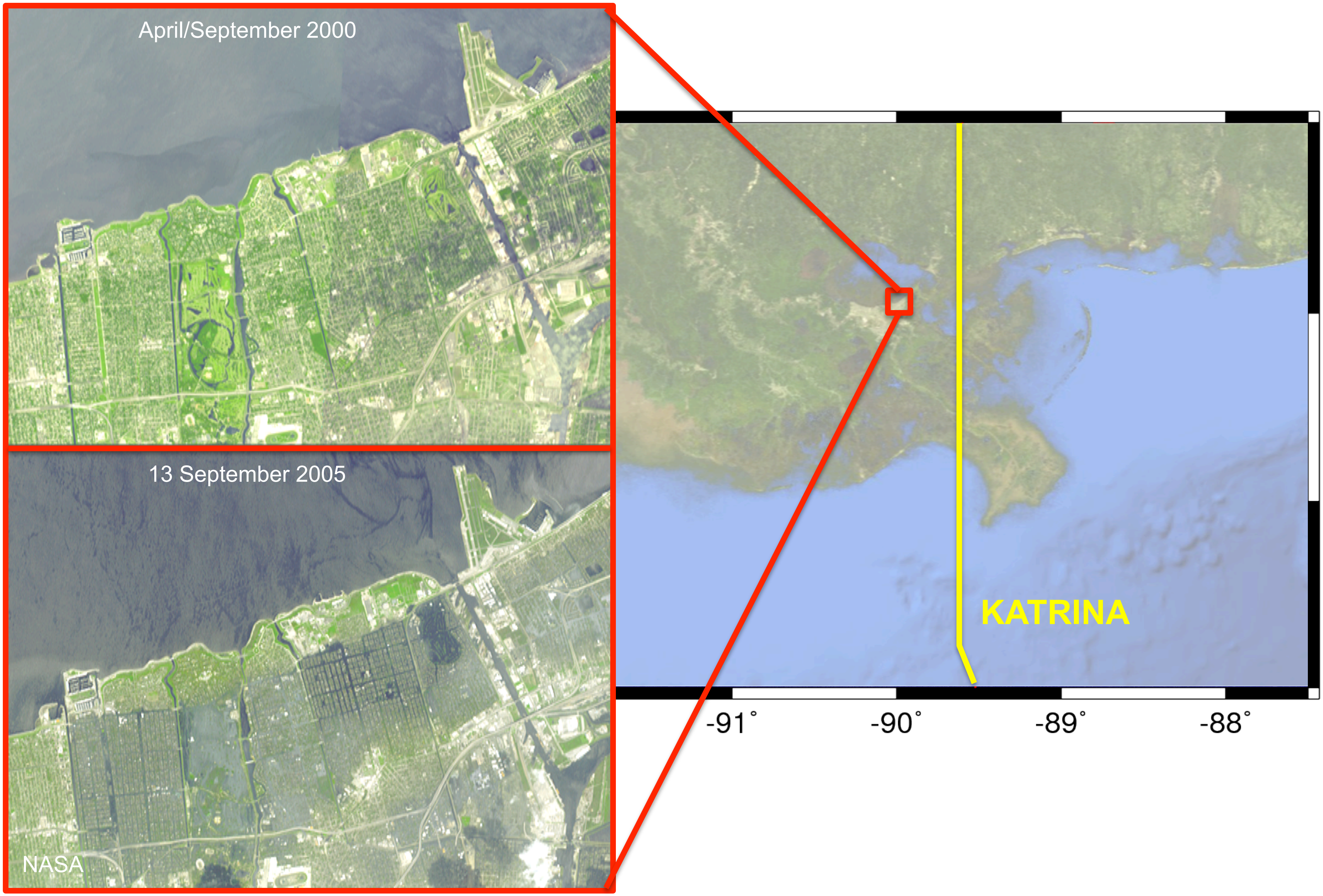
Rita : 09/22 – 09/24



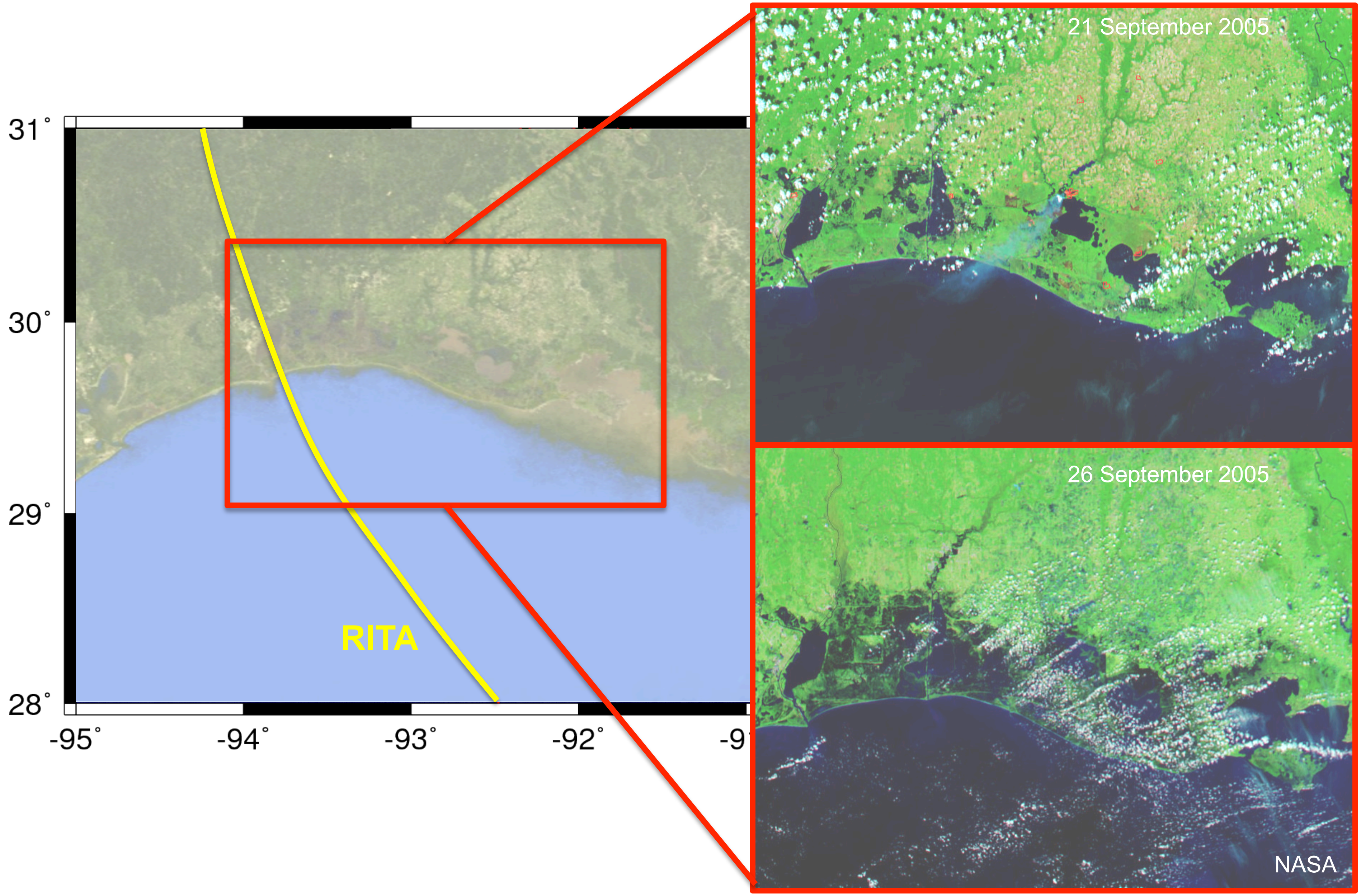
2005 Hurricane Season



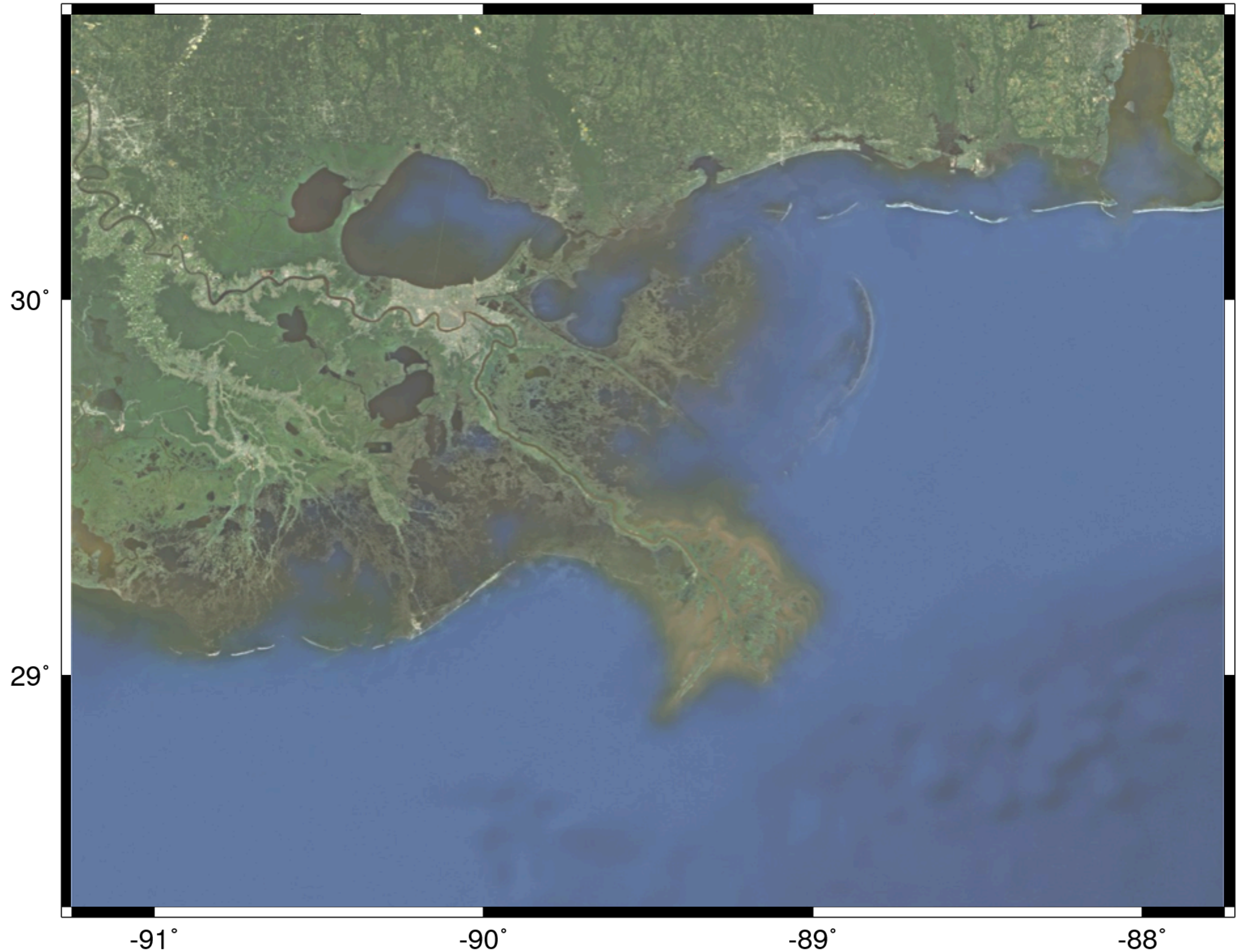
2005 Hurricane Season : Katrina : Inundation of New Orleans



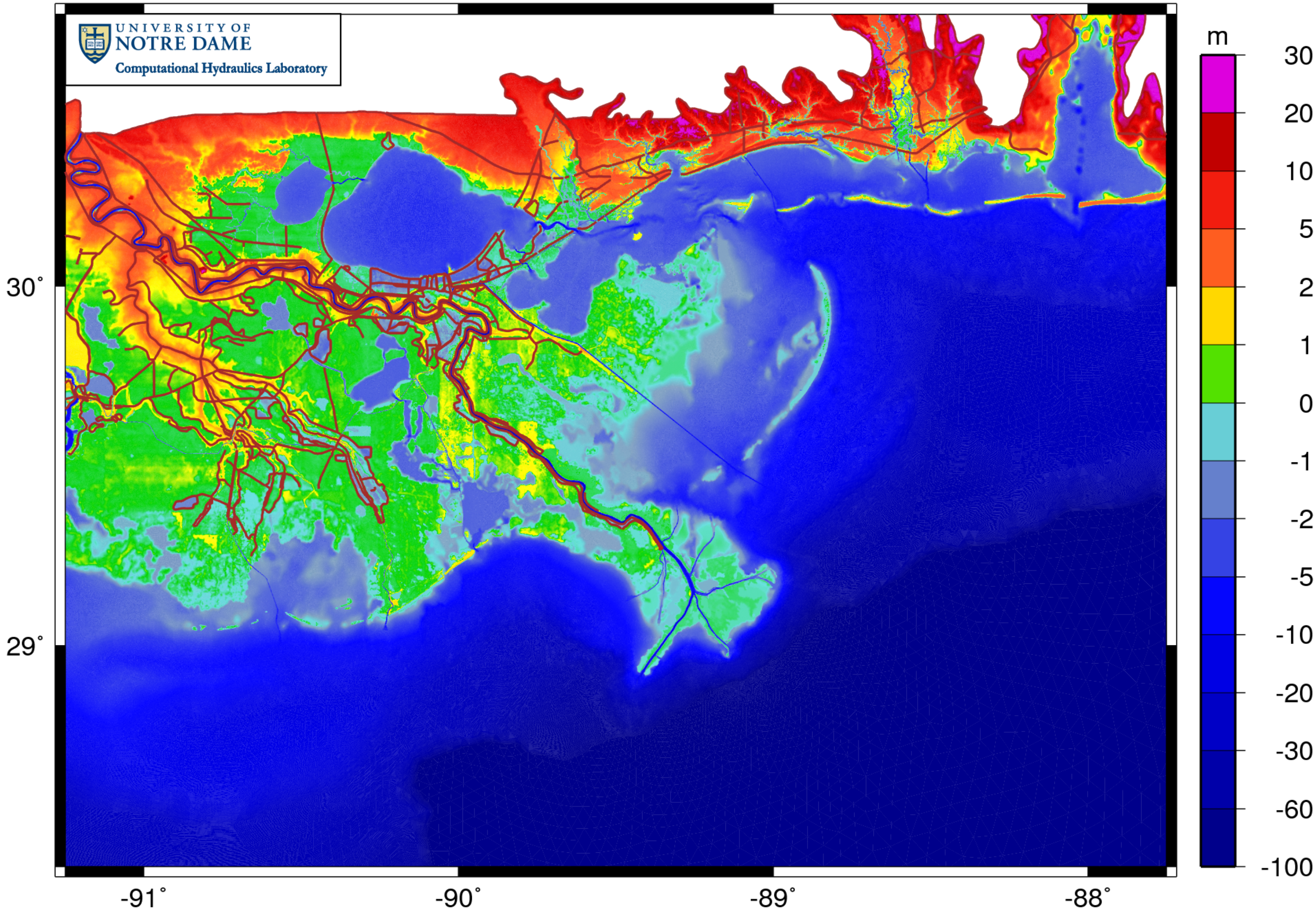
2005 Hurricane Season : Rita : Inundation of Cameron Parish



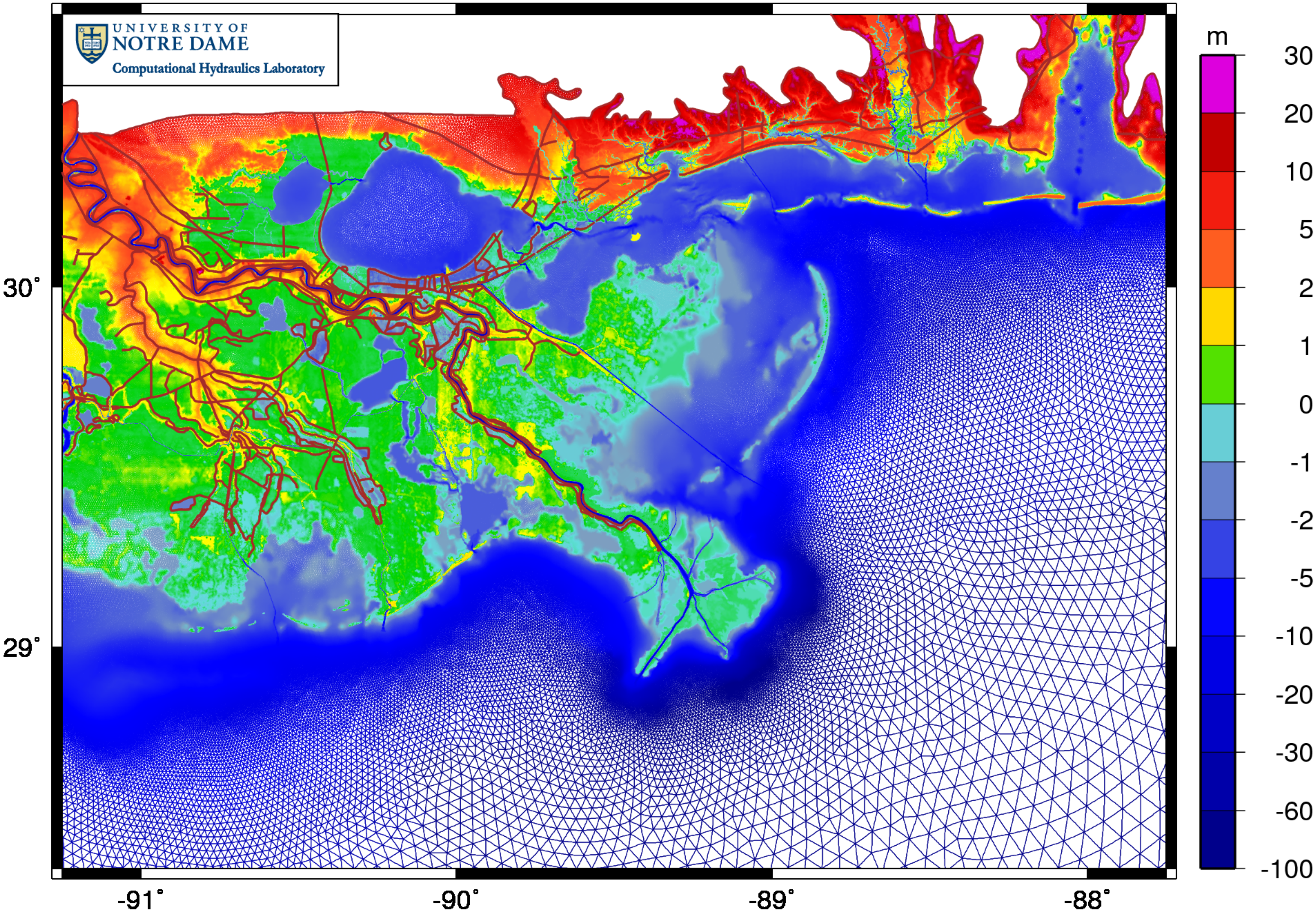
Southeastern Louisiana



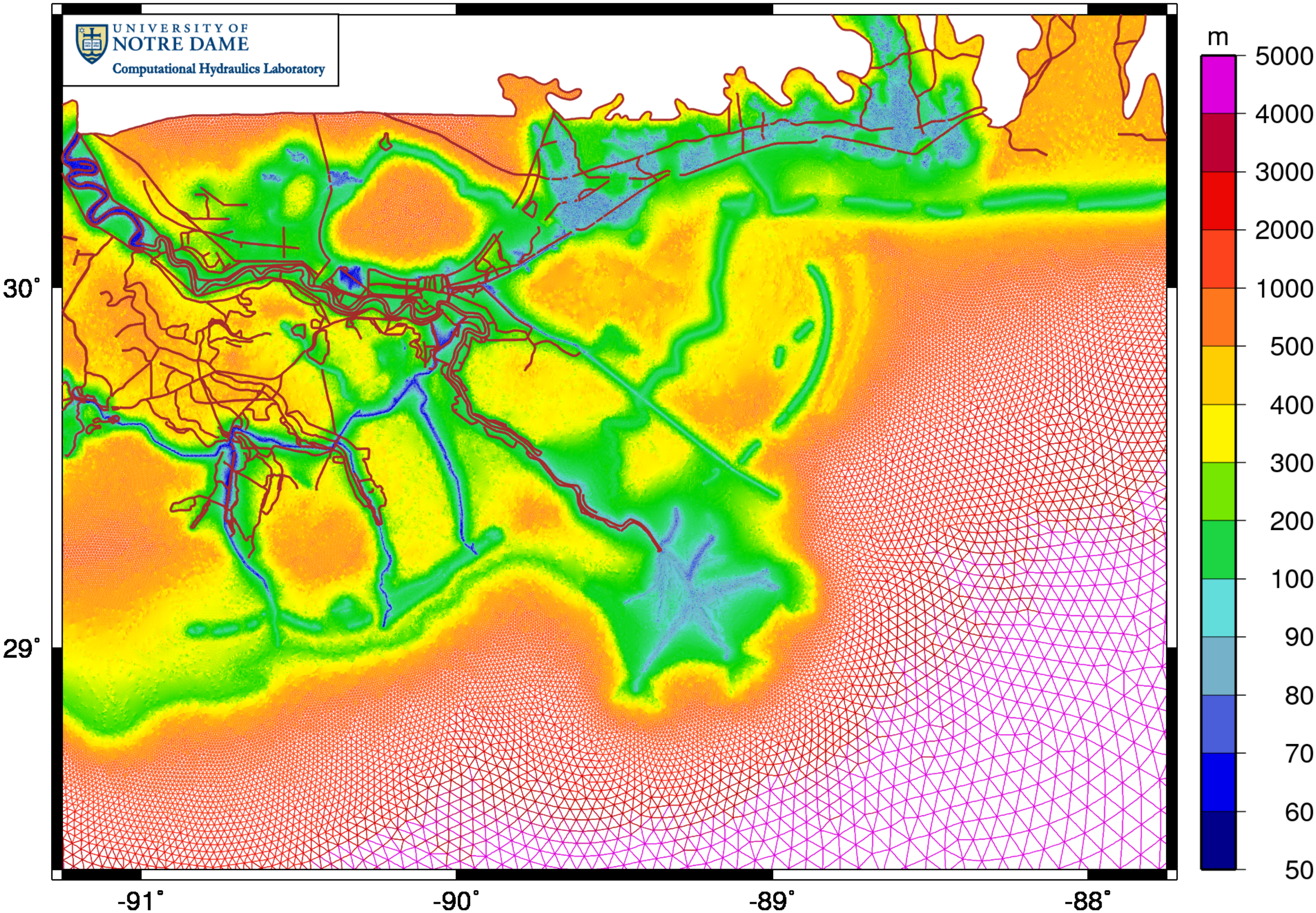
SL15 : Bathymetry and Topography



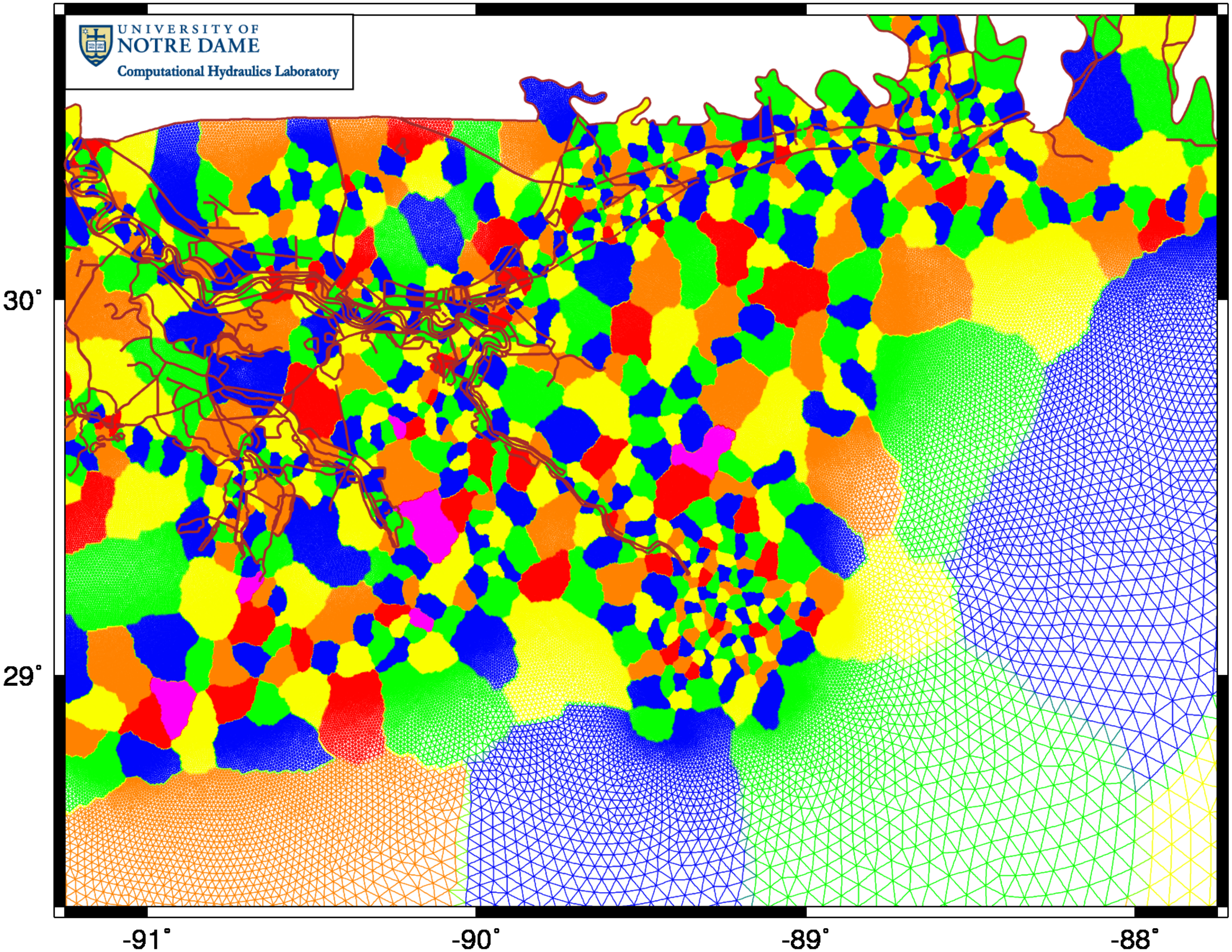
SL15 : Bathymetry and Topography



SL15 : Mesh Sizes



SL15 : 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:

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

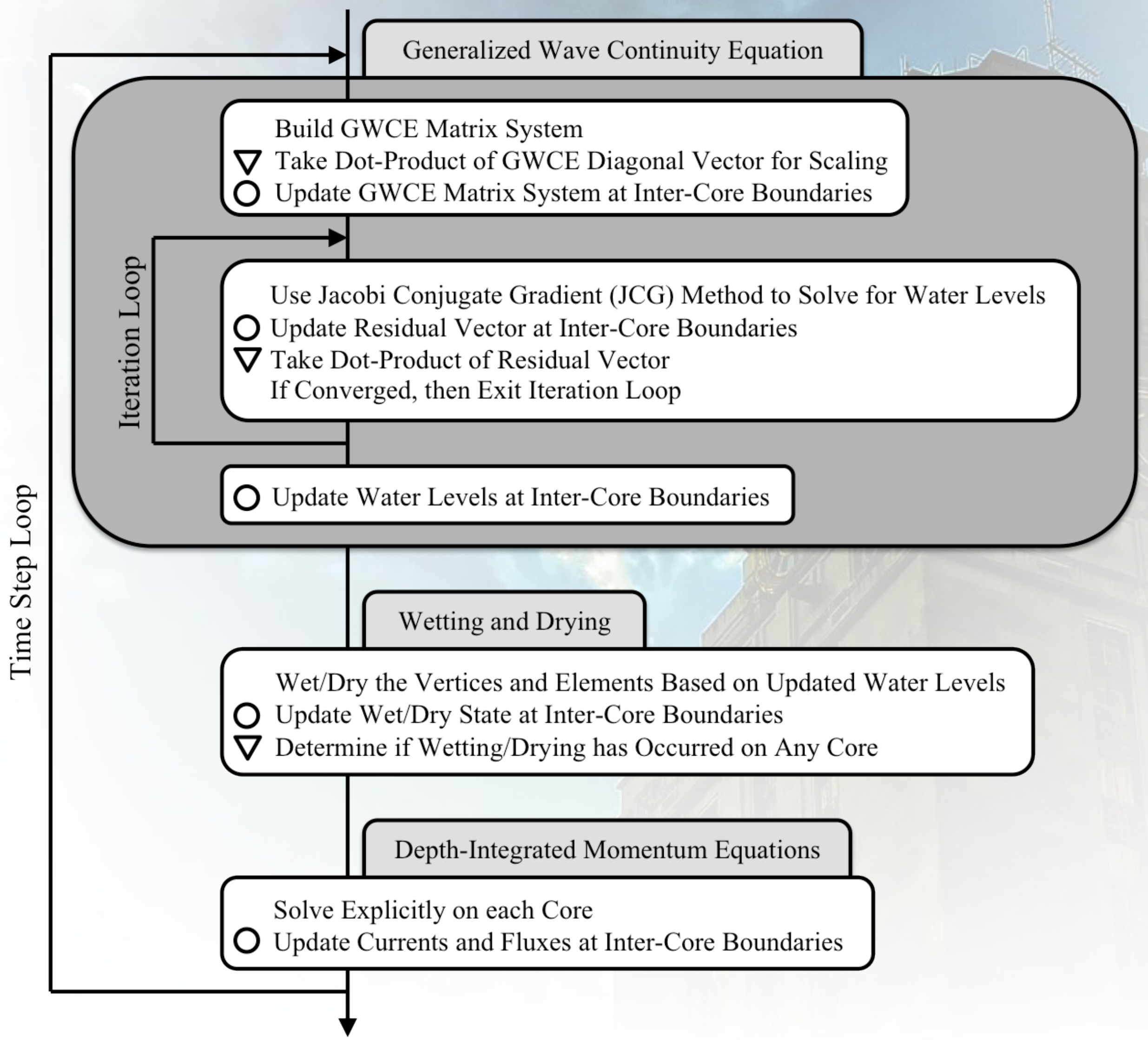
$$\tilde{J}_y = -Q_x \frac{\partial V}{\partial x} - Q_y \frac{\partial V}{\partial y} - fQ_x - \frac{g}{2} \frac{\partial \zeta^2}{\partial y} - gH \frac{\partial}{\partial y}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0} + \left(M_y - D_y\right) + V \frac{\partial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

- Solves the vertically-integrated momentum equations:

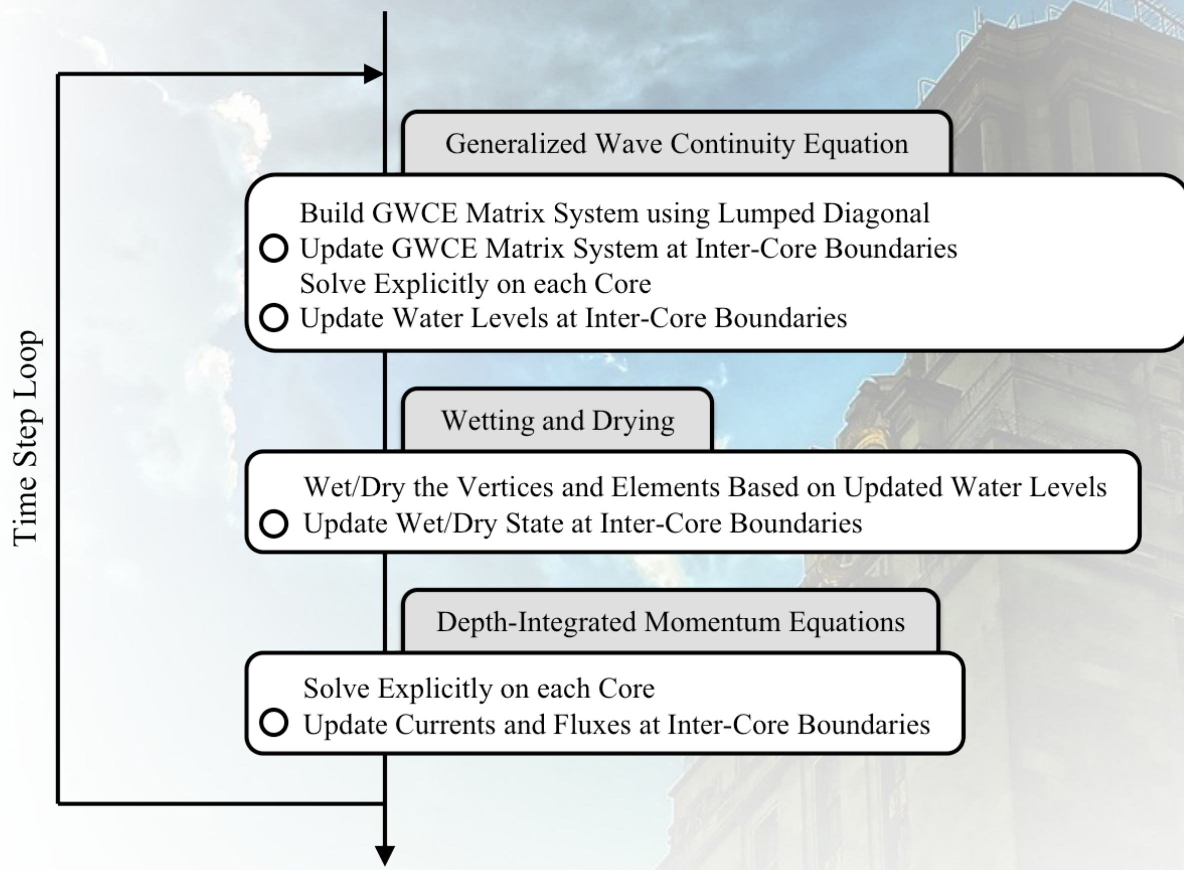
$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \frac{\partial}{\partial x}\left[\zeta + \frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

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

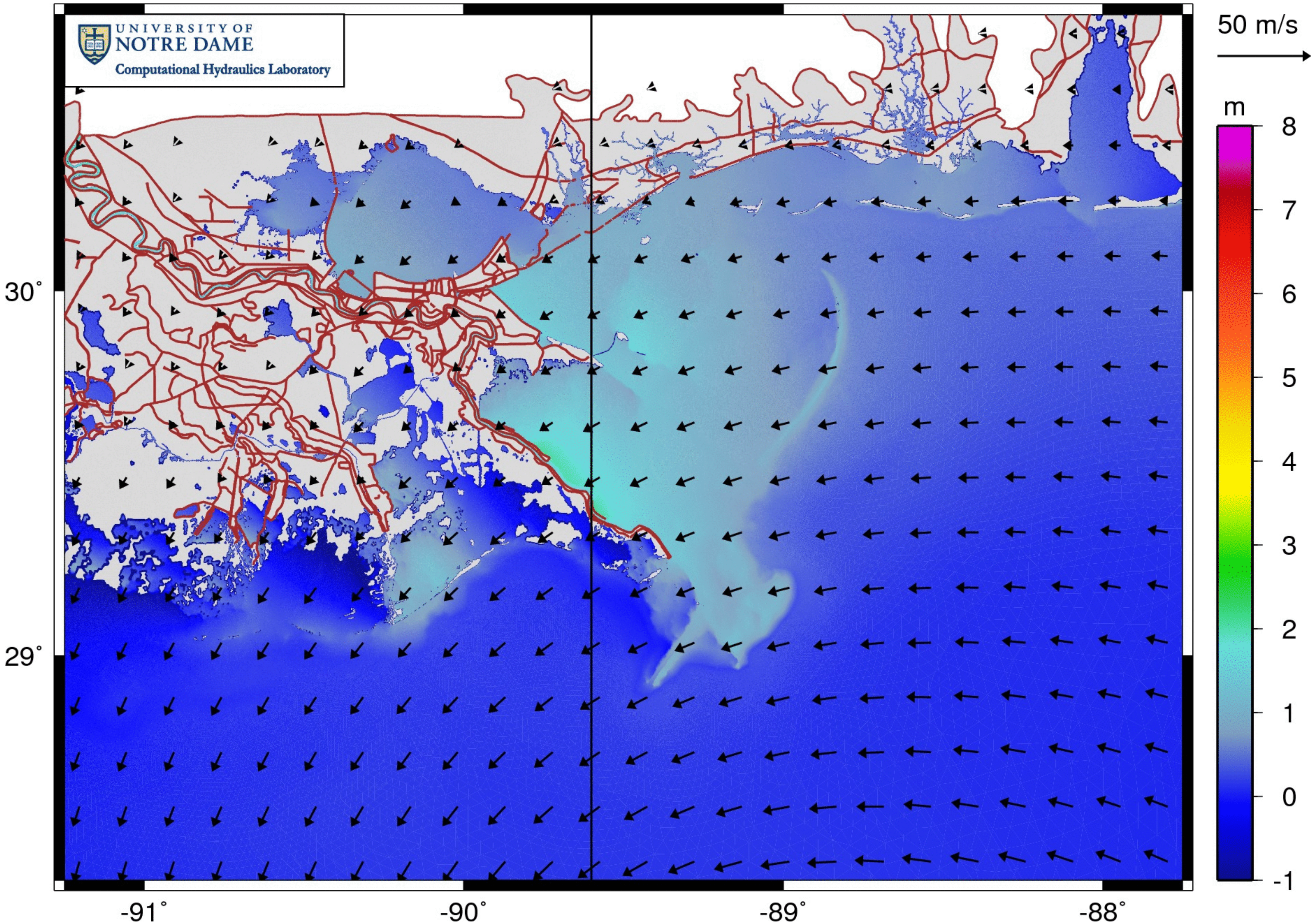
ADCIRC : Flowchart : Implicit Solution of GWCE



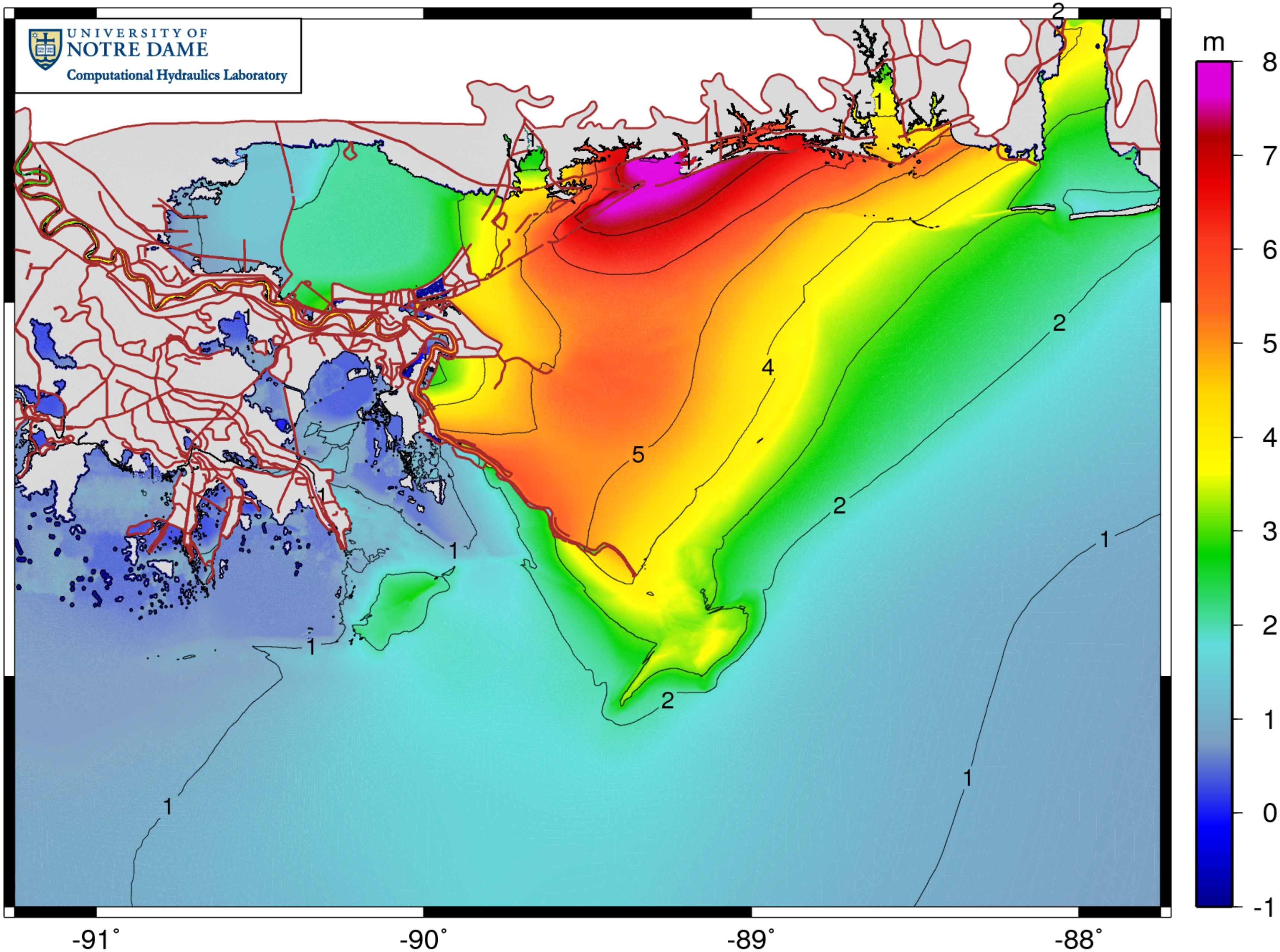
ADCIRC : Flowchart : Explicit Solution of GWCE



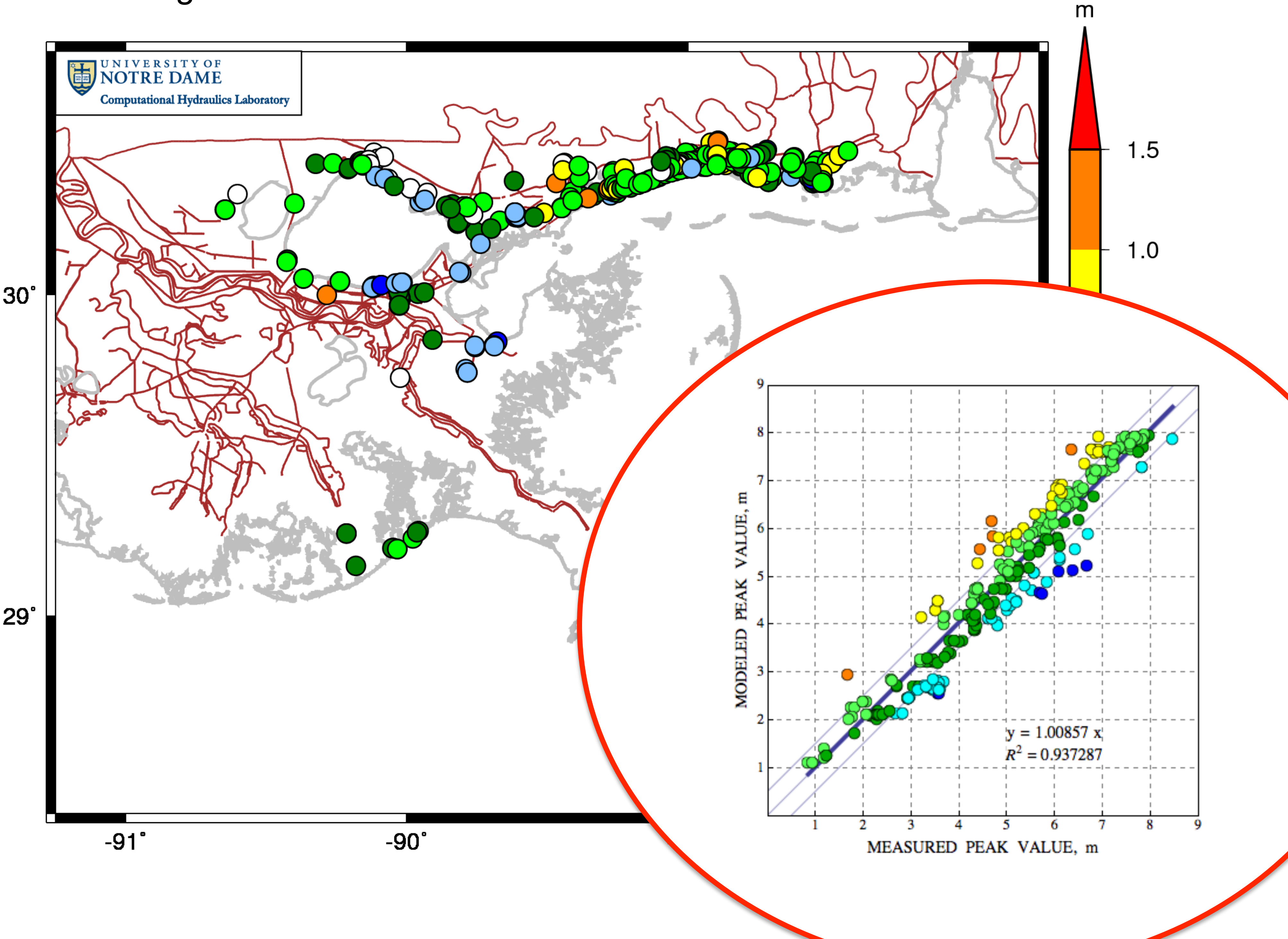
Katrina : Water Levels : 2005/08/29



Katrina : Water Levels : Maximum



Katrina : High-Water Marks



‘Loose’ Coupling to STWAVE

STeady-state WAVE (STWAVE):

- Propagates wave action density $N(t, x, y, \sigma, \theta)$
- Developed by USACE

Passing of Radiation Stress Gradients:

- Integrate action density to get radiation stresses:

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

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

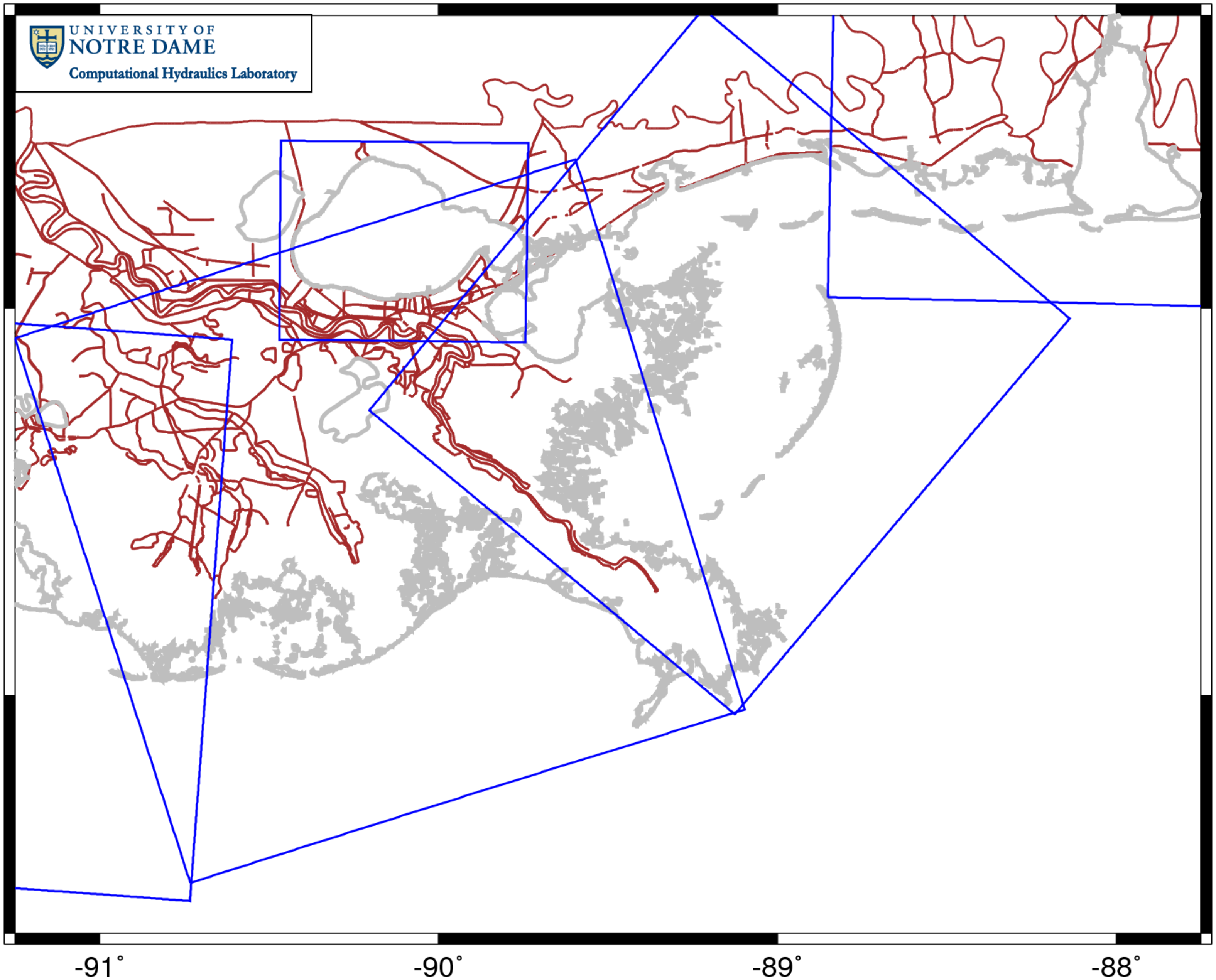
$$S_{yy} = \rho_0 g \iint \left(n\sin^2\theta + n - \frac{1}{2} \right) \sigma N d\sigma d\theta$$

- Pass the gradients as surface stresses to ADCIRC:

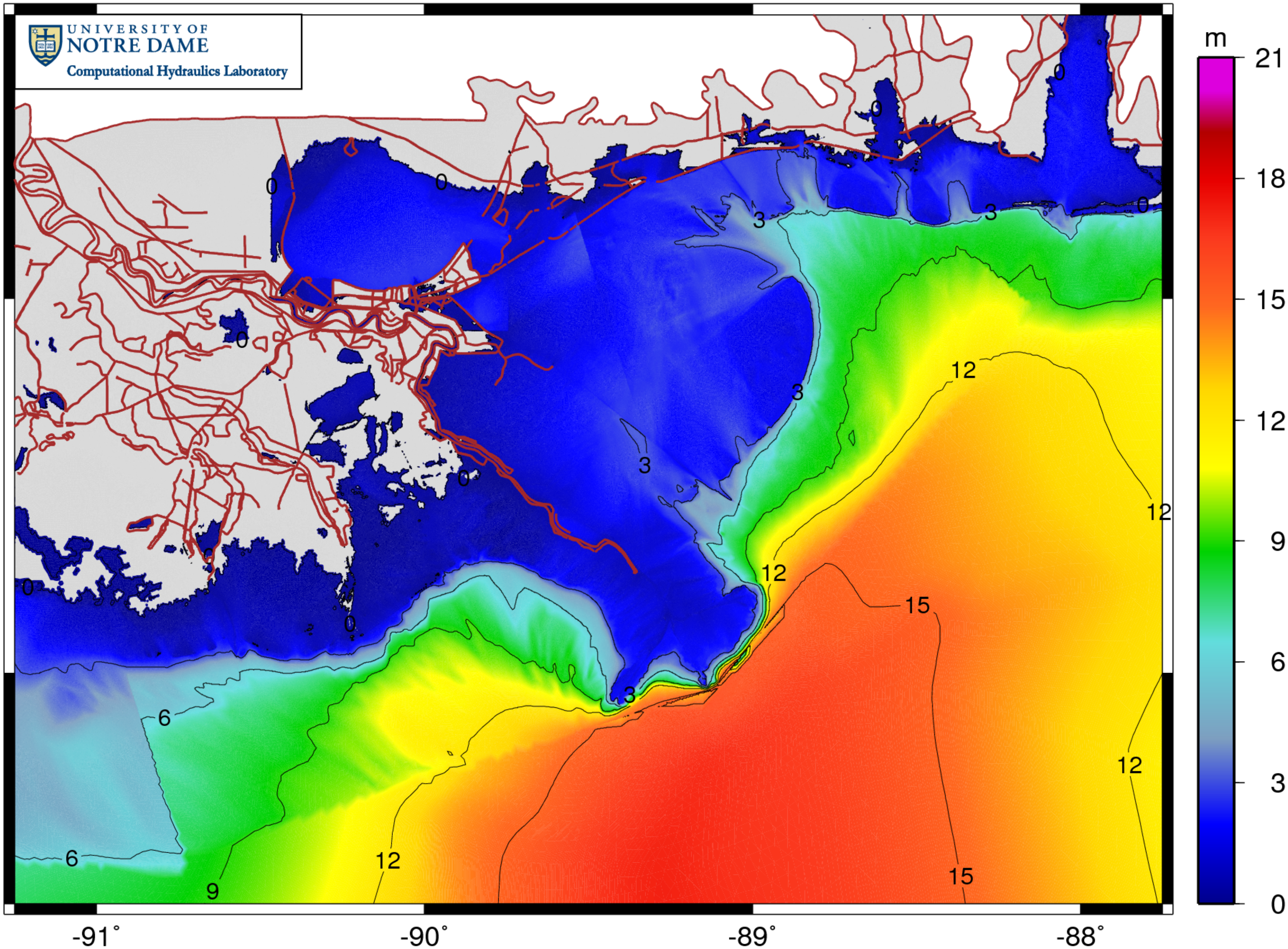
$$\tau_{sx,waves} = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}$$

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

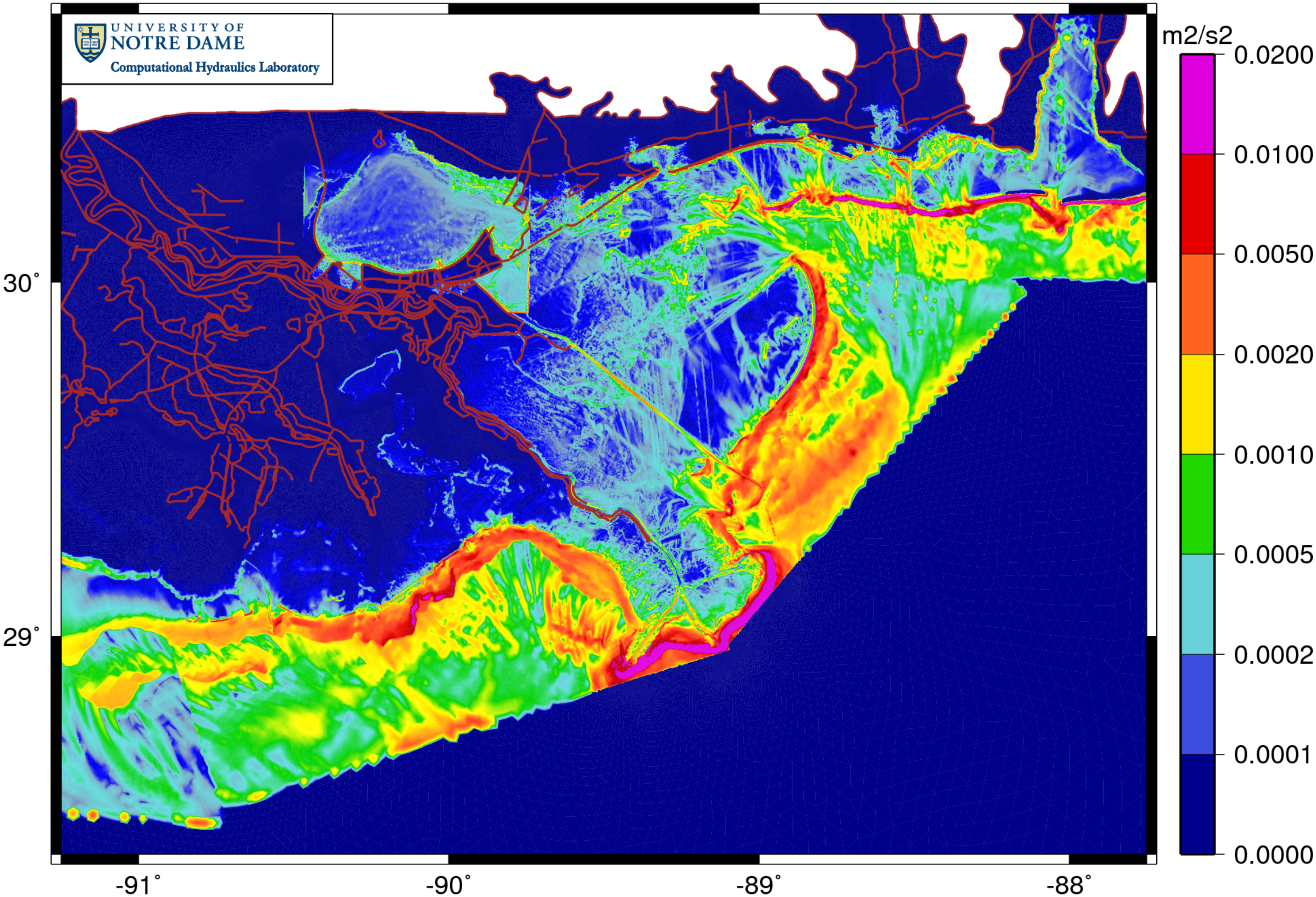
‘Loose’ Coupling to STWAVE



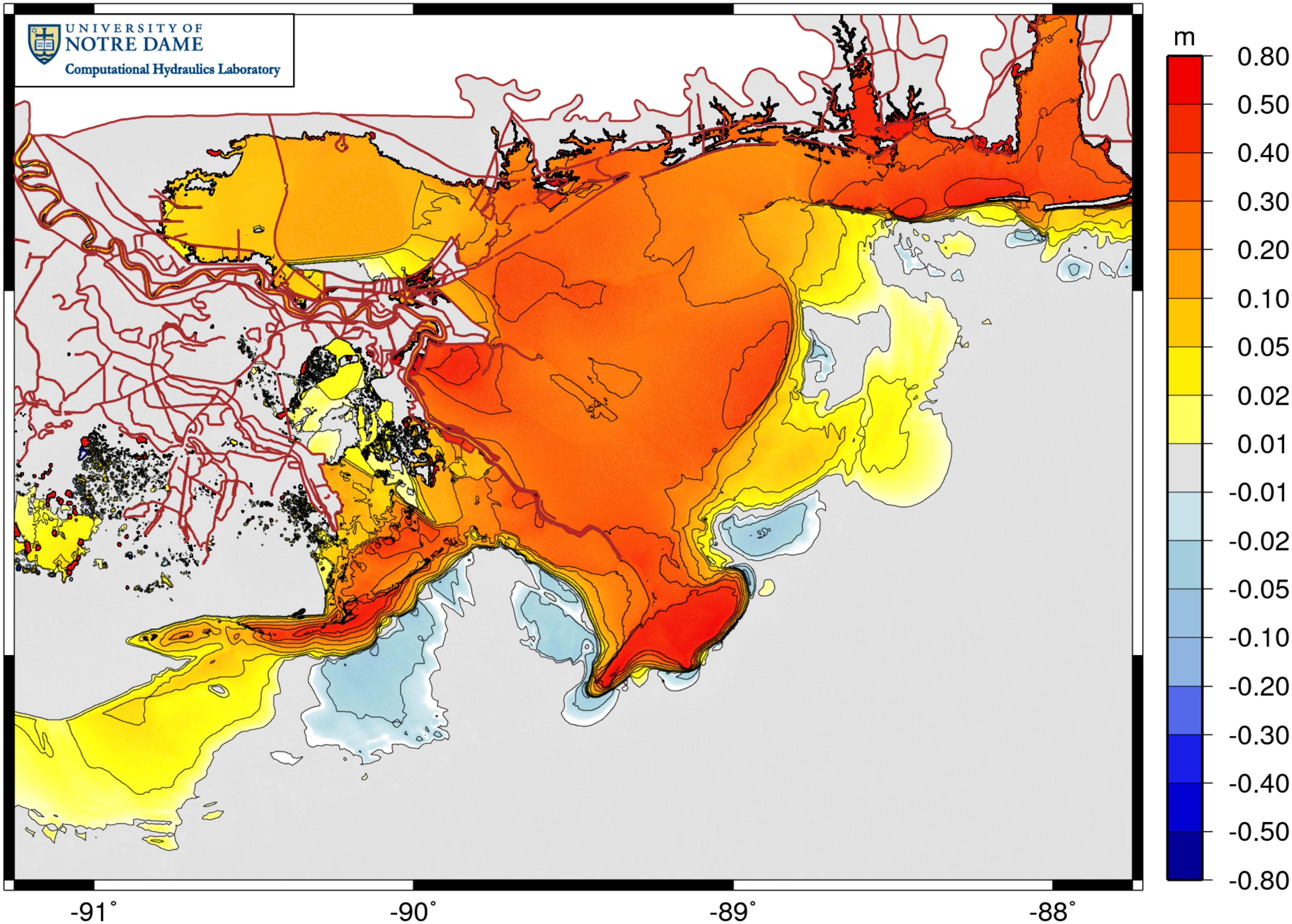
Katrina : Significant Wave Heights : Maximum

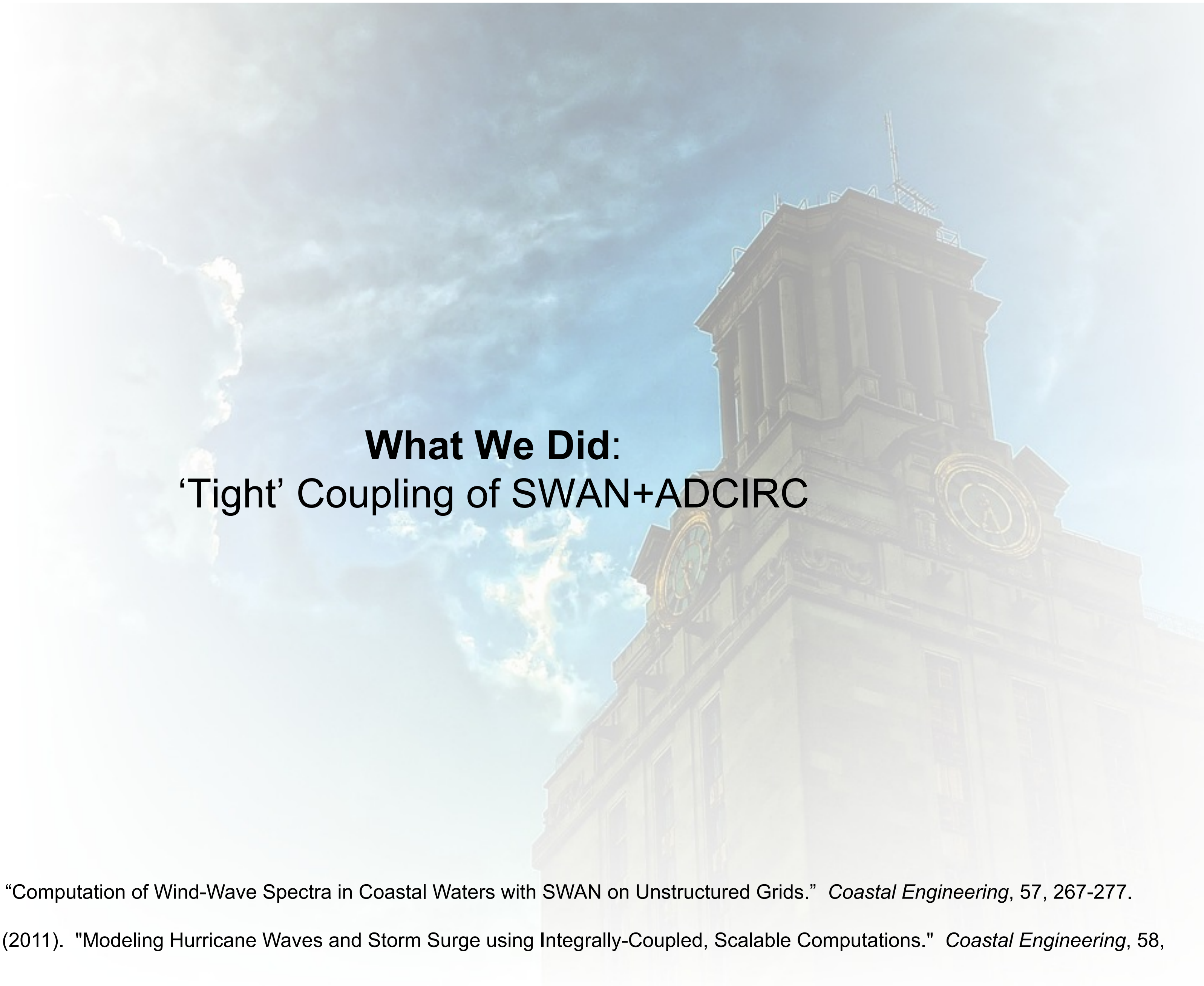


Katrina : Radiation Stress Gradients : Maximum



Katrina : Wave-Driven Setup : Maximum





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

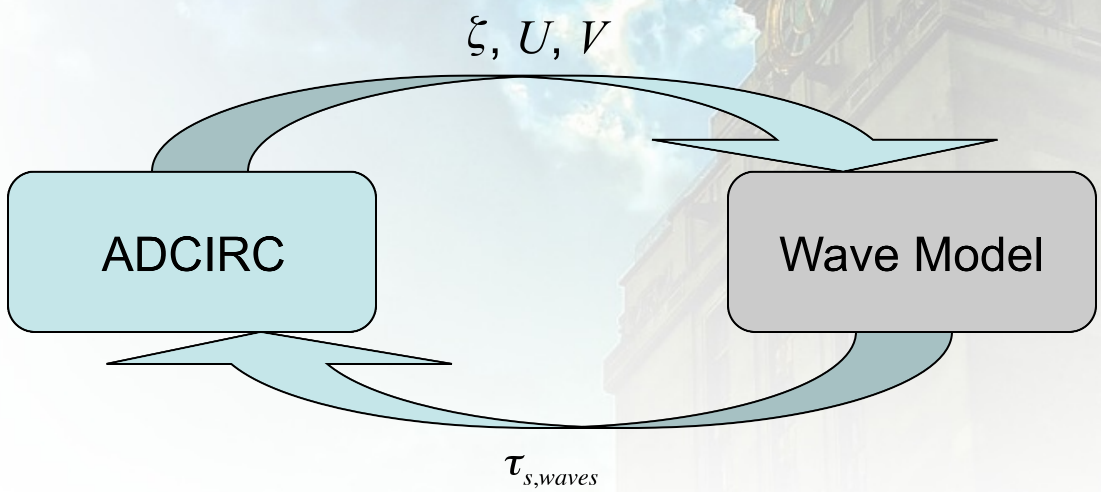
M. Zijlema (2010). “Computation of Wind-Wave Spectra in Coastal Waters with SWAN on Unstructured Grids.” *Coastal Engineering*, 57, 267-277.

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.* (2011). “Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge.” *Journal of Scientific Computing*, in review.

Disadvantages of ‘Loose’ Coupling

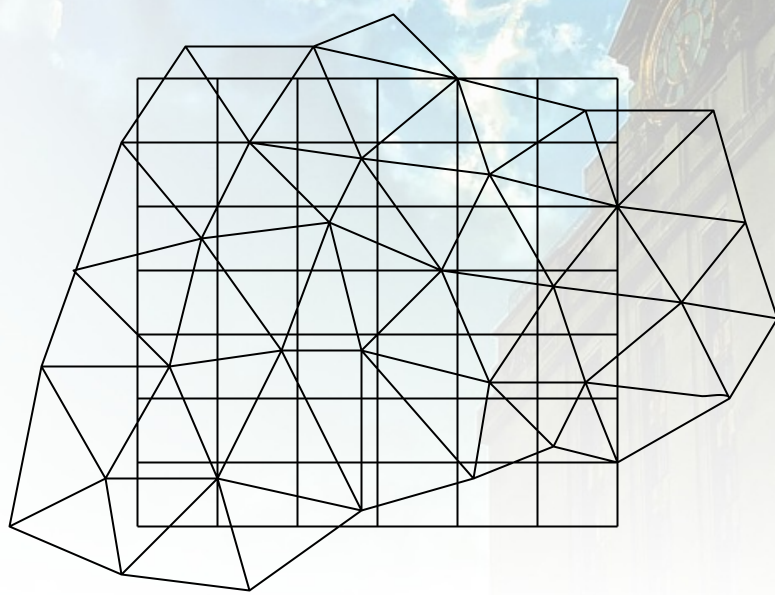
1. **Interpolation at Wave Model Boundaries**
2. **Coverage in Deep Water**
3. **Iteration**
    - Models coupled through input files
        - Winds, water levels and currents passed to wave model
        - Radiation stress gradients passed to ADCIRC
    - Process can be automated, but is still inefficient



Disadvantages of ‘Loose’ Coupling

4. Interpolation:

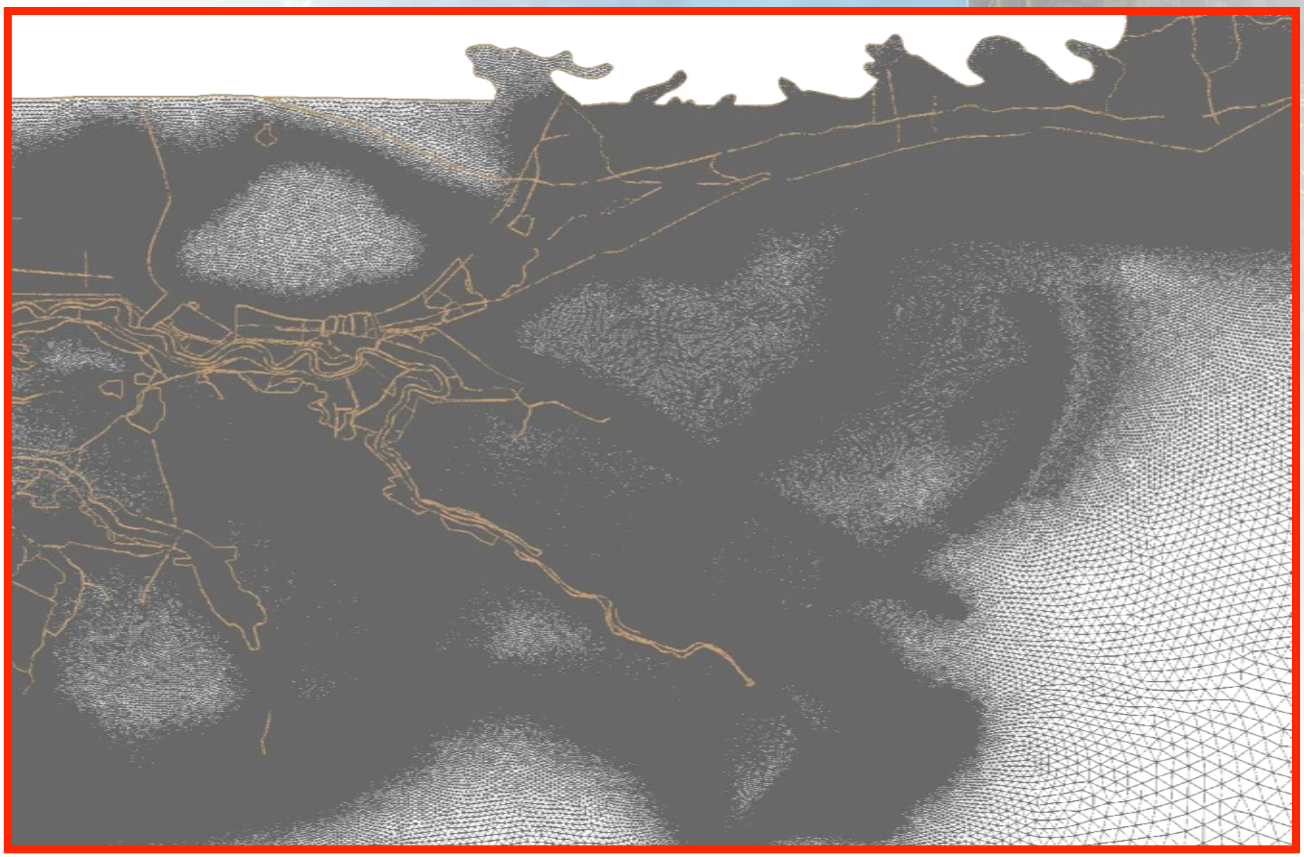
- Wave and circulation models run on different grids
  - Wave models on structured meshes
  - ADCIRC on unstructured, finite element mesh
- Results must be interpolated onto each mesh



Disadvantages of ‘Loose’ Coupling

5. Resolution in wave breaking zones:

- Circulation model has no knowledge of wave breaking
- Must over-resolve these zones



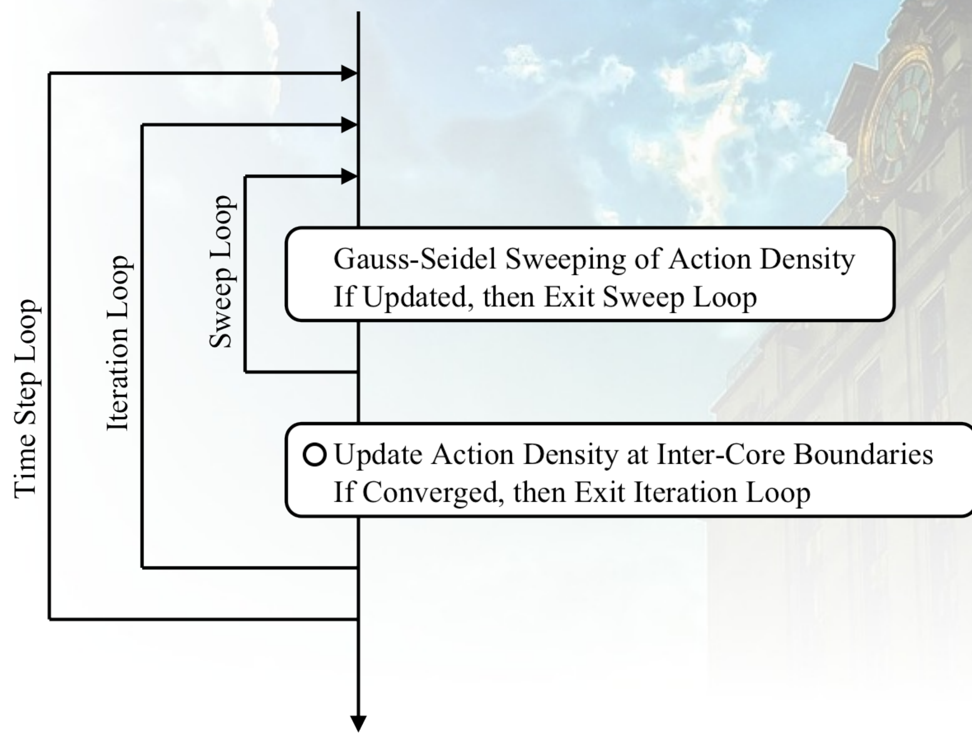
‘Tight’ Coupling of SWAN+ADCIRC

Simulating WAves Nearshore (SWAN):

- Solves the action balance equation:

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

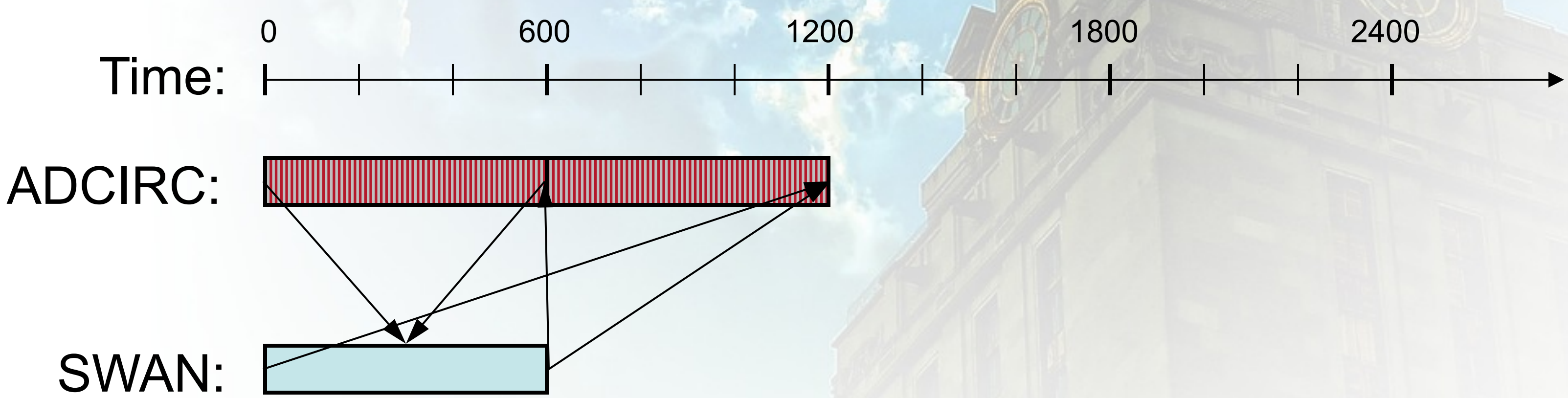
- Sweep the action densities throughout the domain:



‘Tight’ Coupling of SWAN+ADCIRC

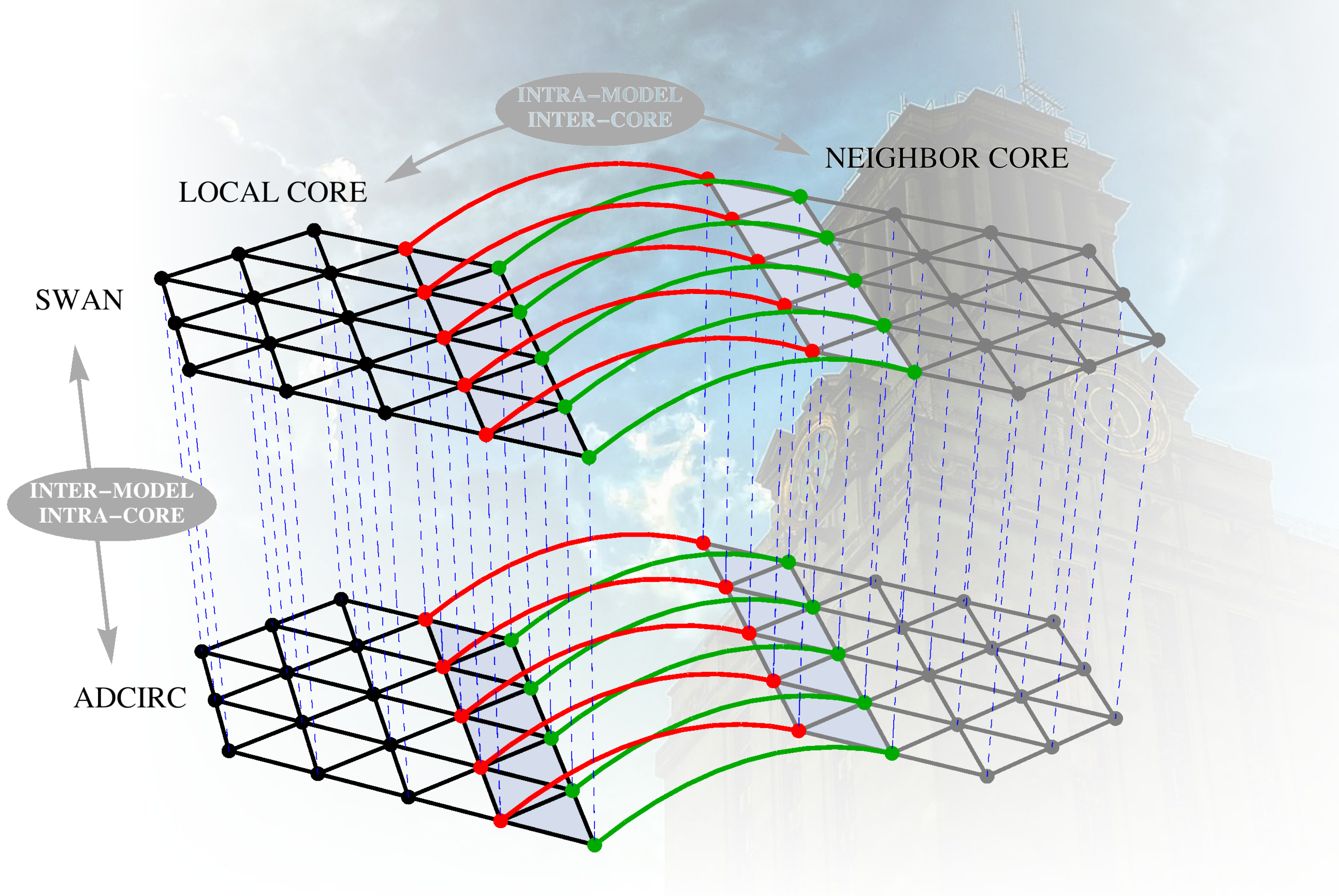
Schematic of Coupling:

- 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

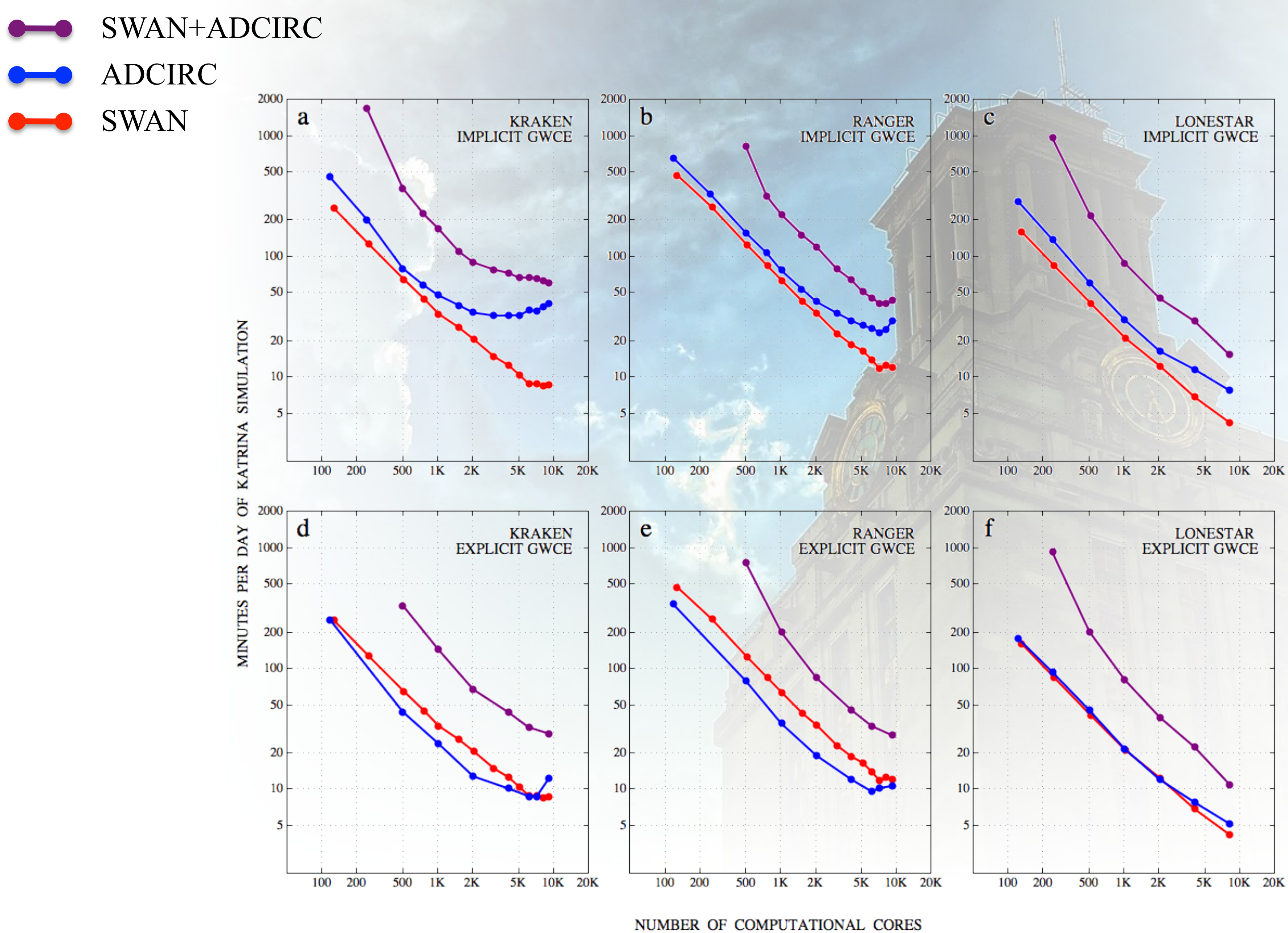


- SWAN and ADCIRC are always extrapolating in time

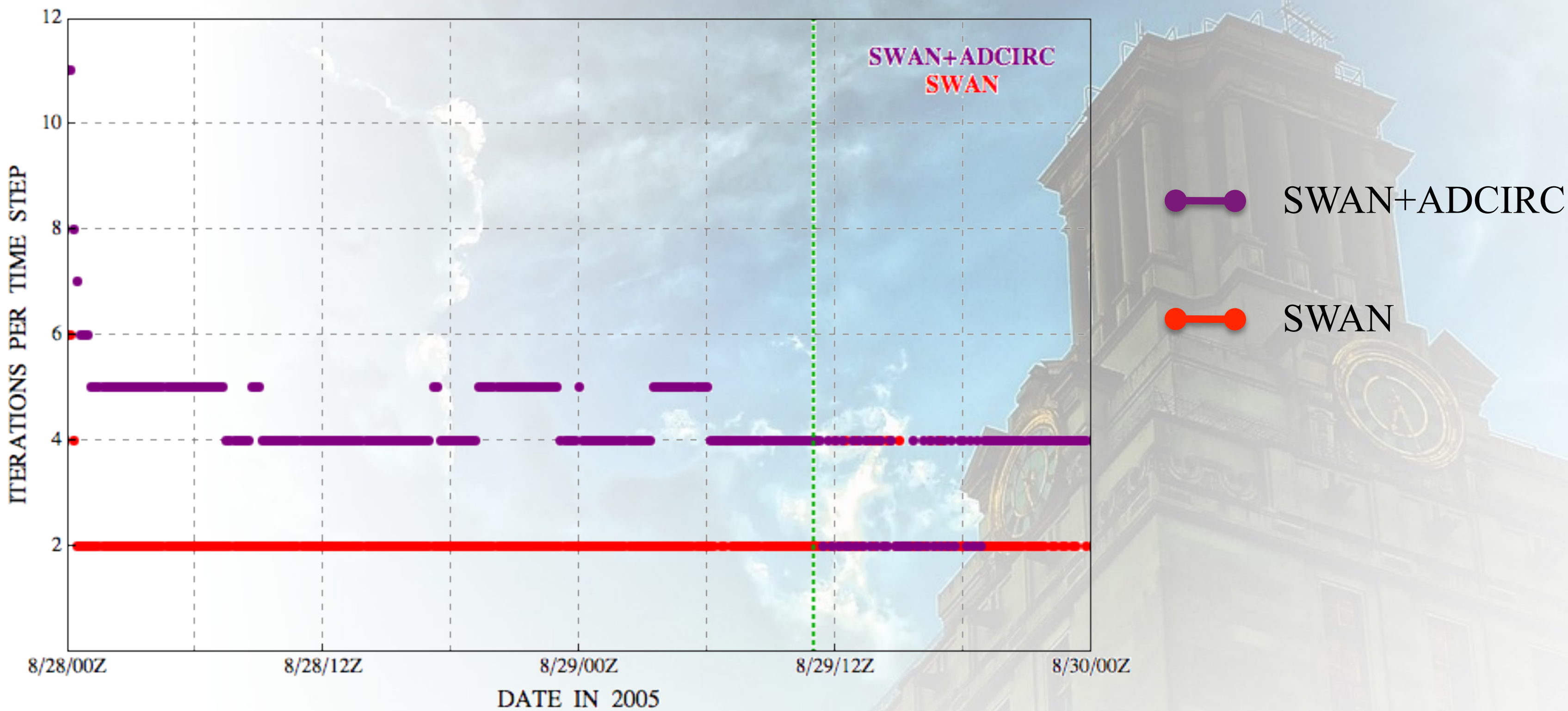
'Tight' Coupling of SWAN+ADCIRC



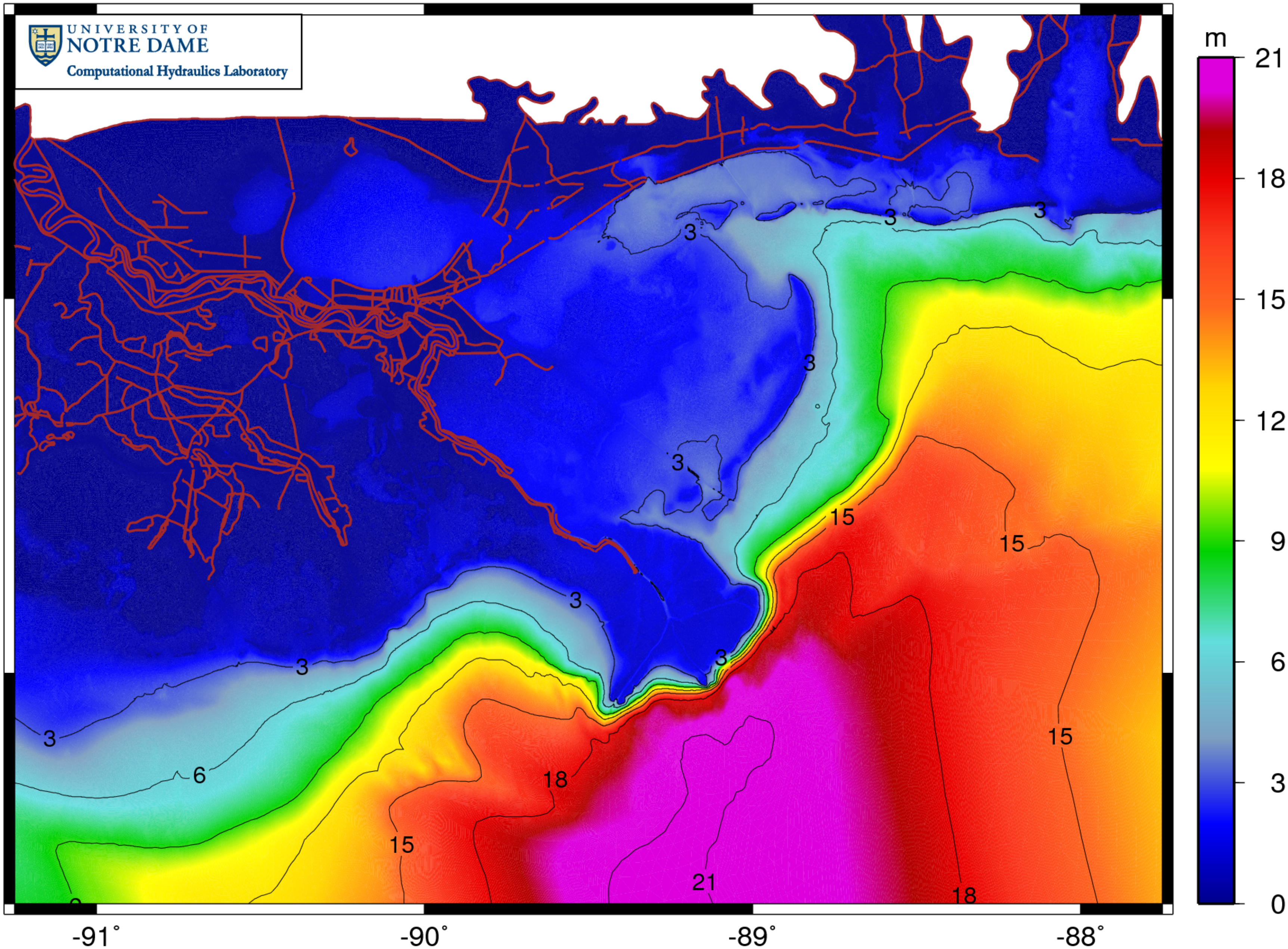
‘Tight’ Coupling of SWAN+ADCIRC



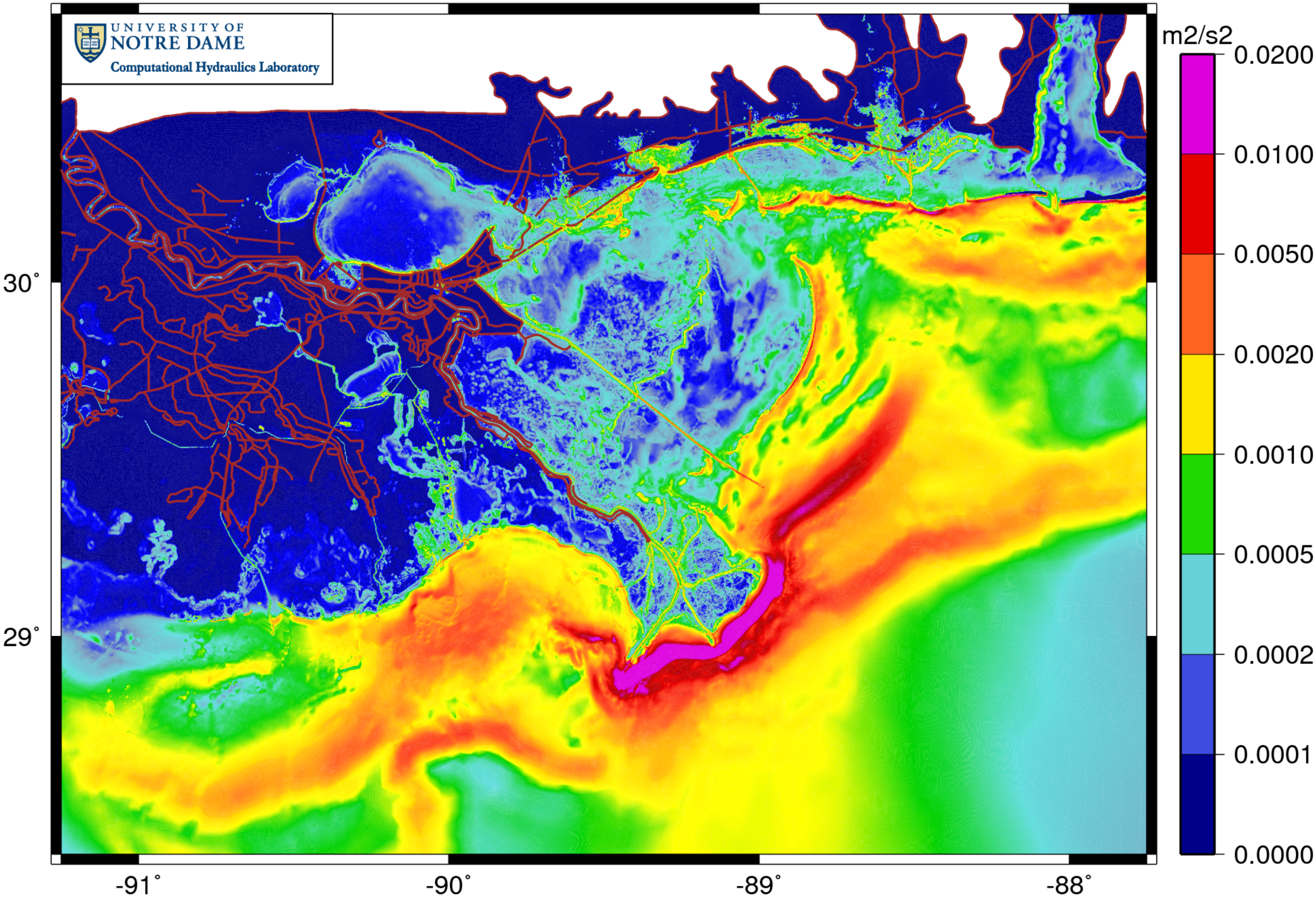
‘Tight’ Coupling of SWAN+ADCIRC



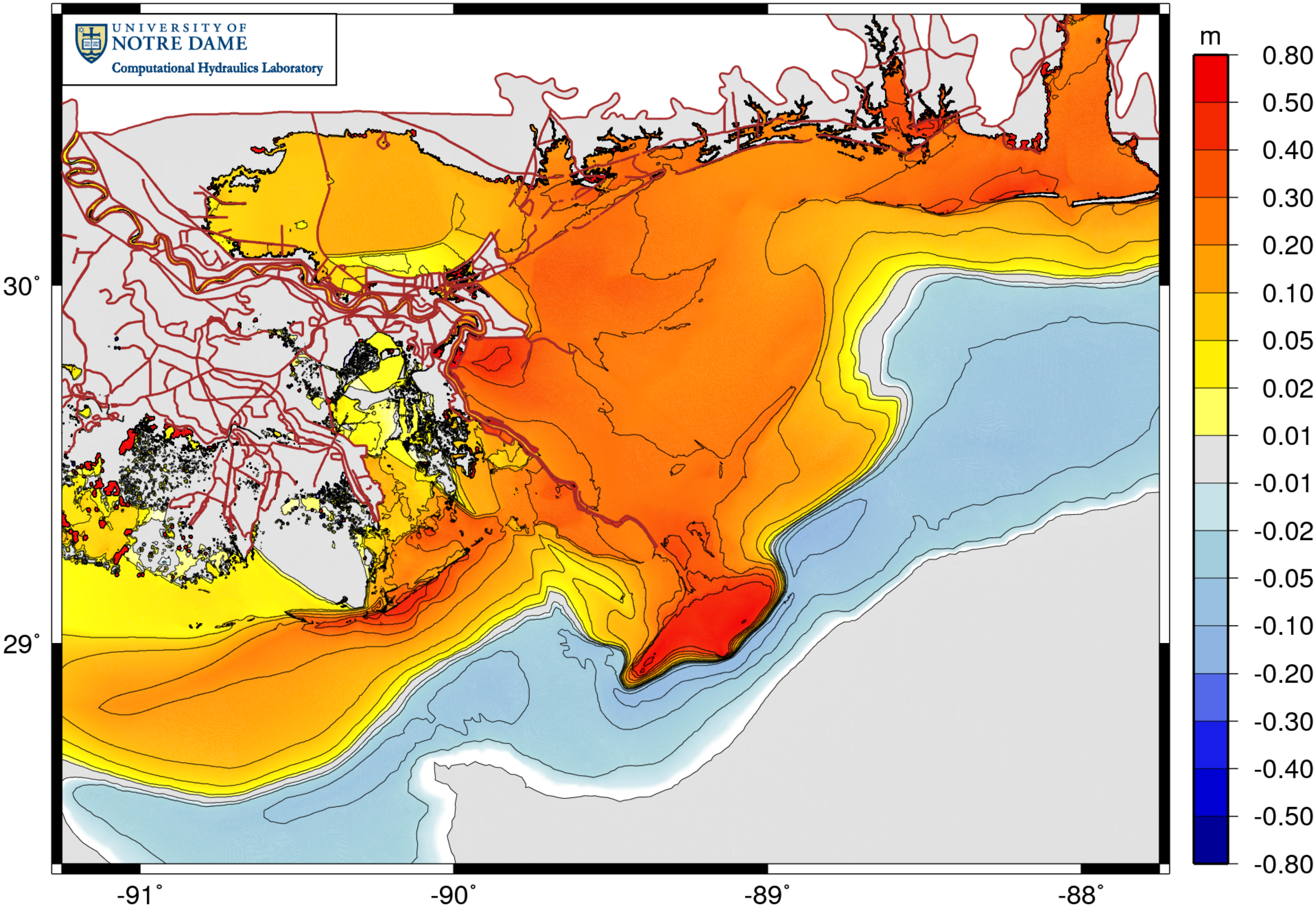
Katrina : Significant Wave Heights : Maximum



Katrina : Radiation Stress Gradients : Maximum



Katrina : Wave-Driven Setup : Maximum

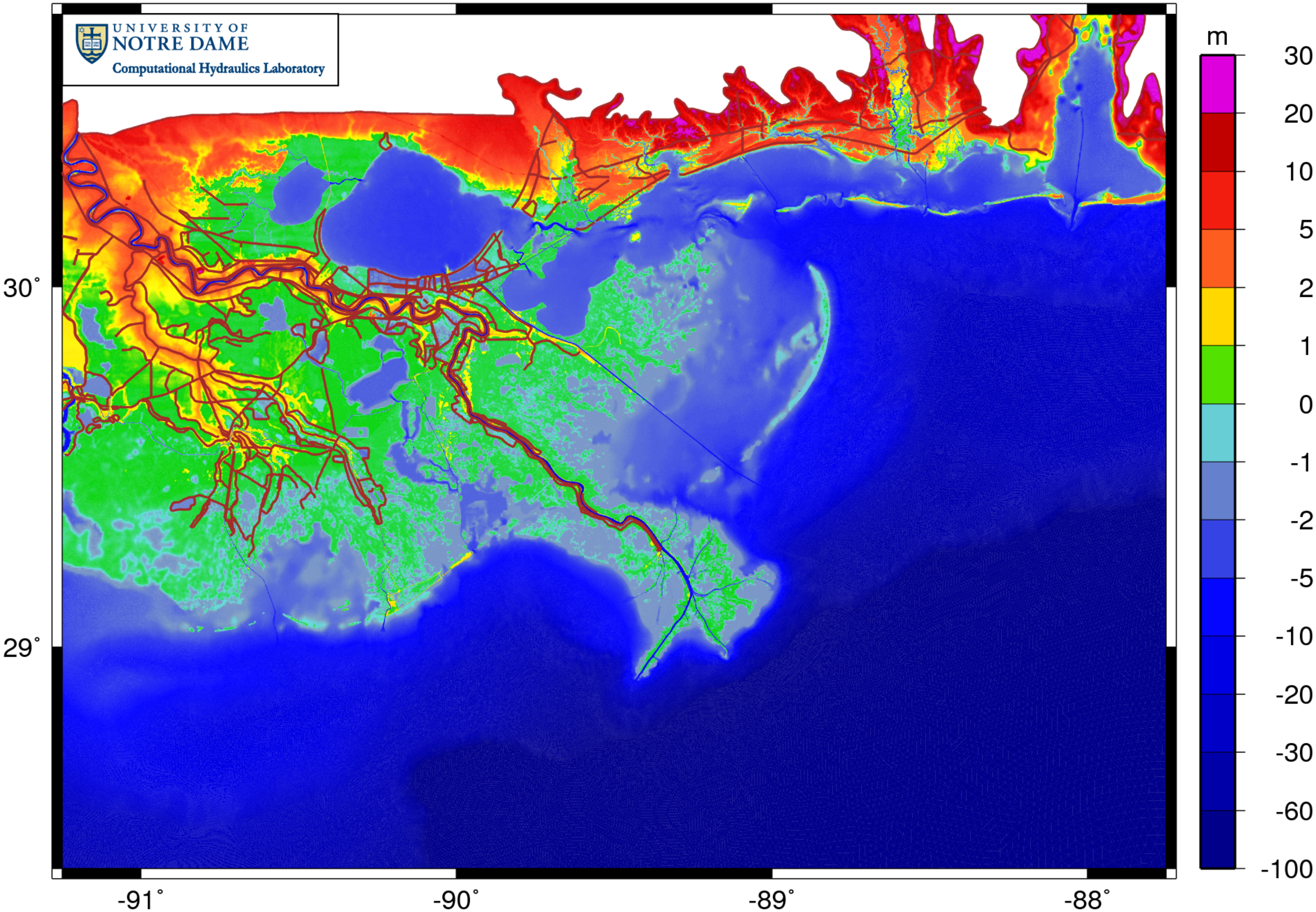


Where We're Going:
Better Integration of Hurricane Physics

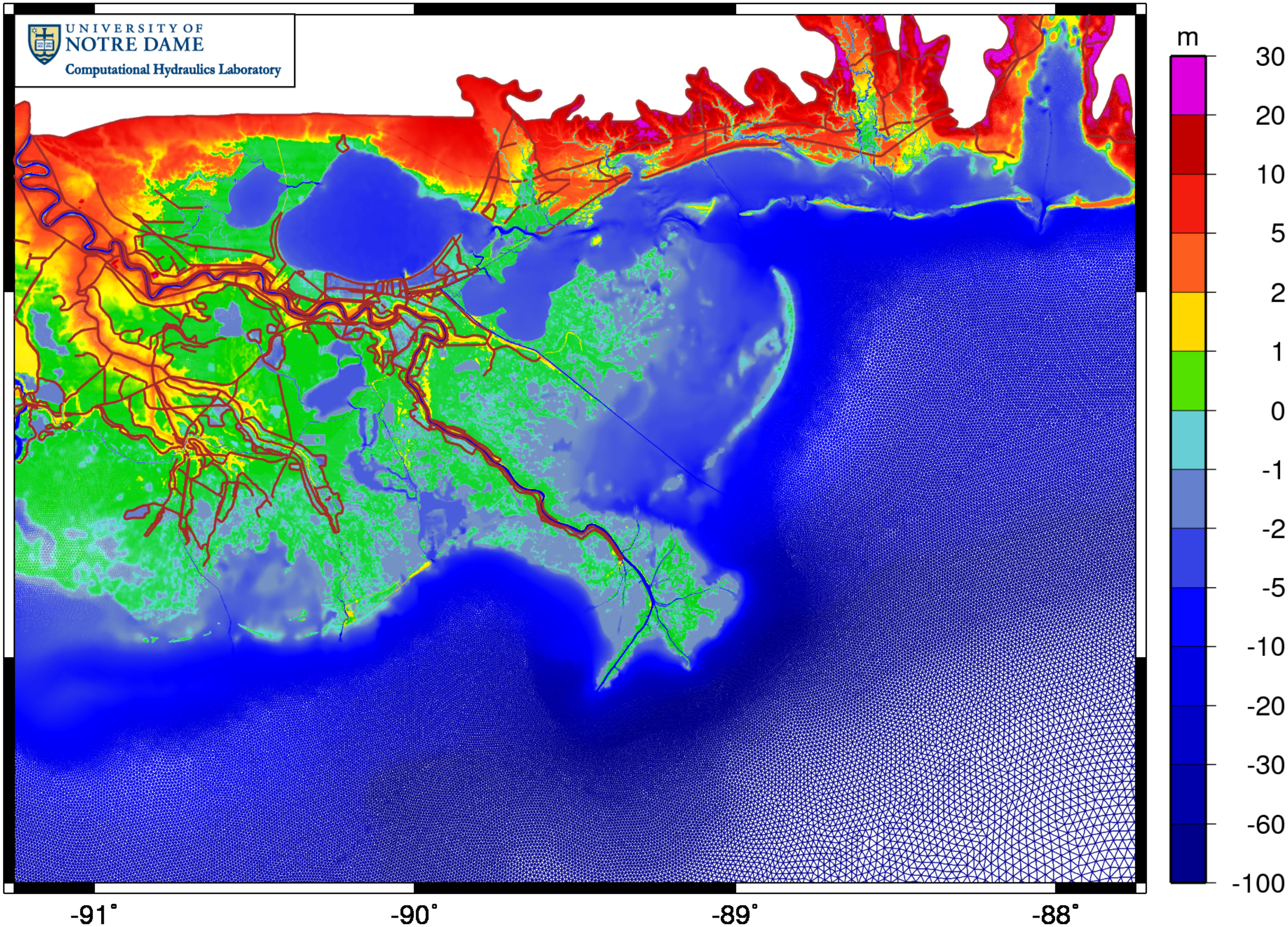
A.B. Kennedy, et al. (2011). "Origin of the Hurricane Ike Forerunner Surge." *Geophysical Research Letters*, 38, L08608.

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

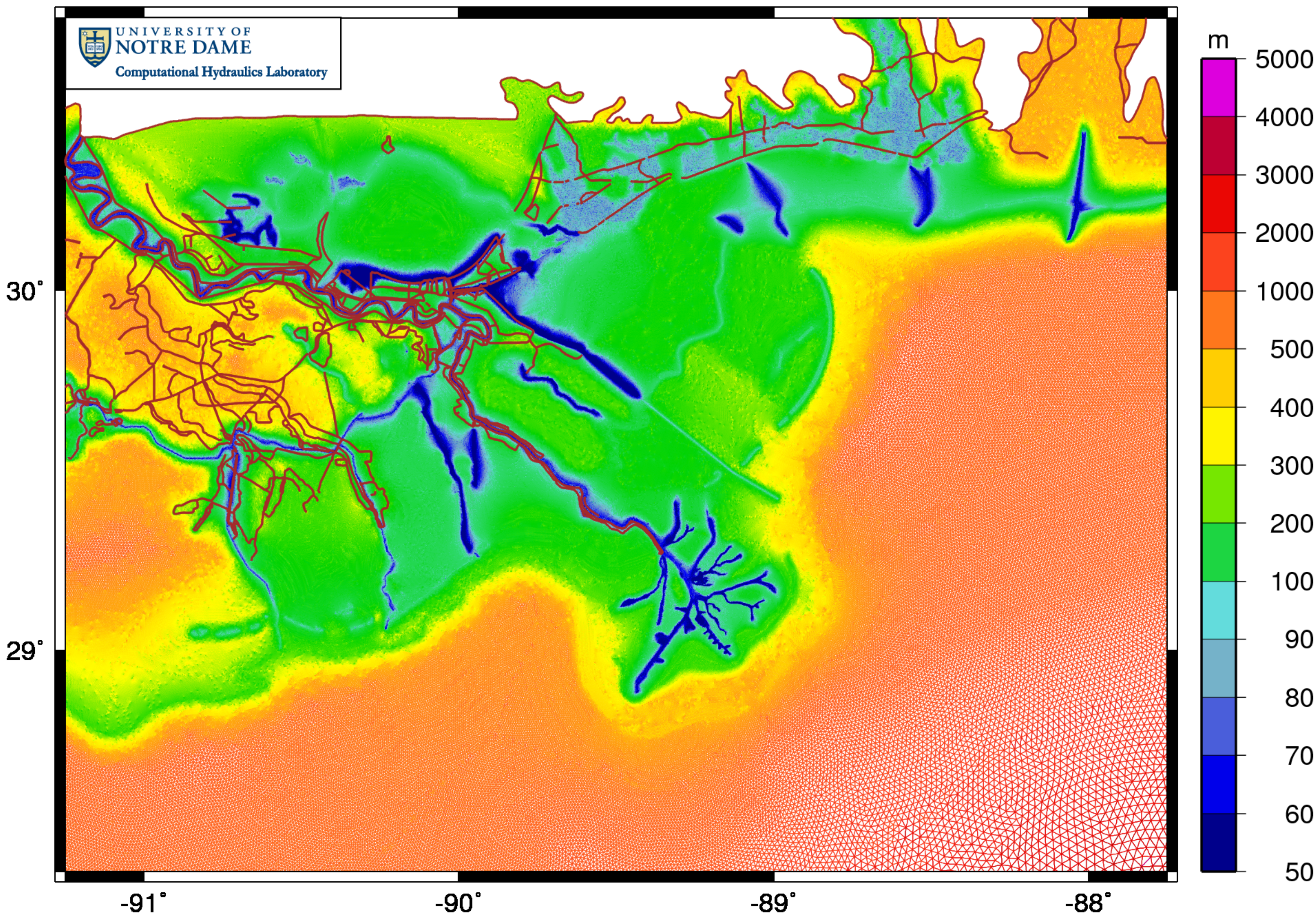
SL16 : Bathymetry and Topography



SL16 : Bathymetry and Topography



SL16 : Mesh Sizes



Integrated Coupling of Bottom Friction:

- ADCIRC converts its Manning's n values to bottom stresses:

$$\tau_b = \rho_0 \frac{gn^2}{H^{1/3}} \frac{Q}{H}$$

- In SWAN, bottom friction is a dissipation term:

$$S_{ds,b}(\sigma,\theta) = -C_b \frac{\sigma^2}{g^2 \sinh^2 kH} N(\sigma,\theta)$$

where C_b is a bottom friction coefficient that can be formulated as:

$$C_b = f_w \frac{g}{\sqrt{2}} U_{rms}$$

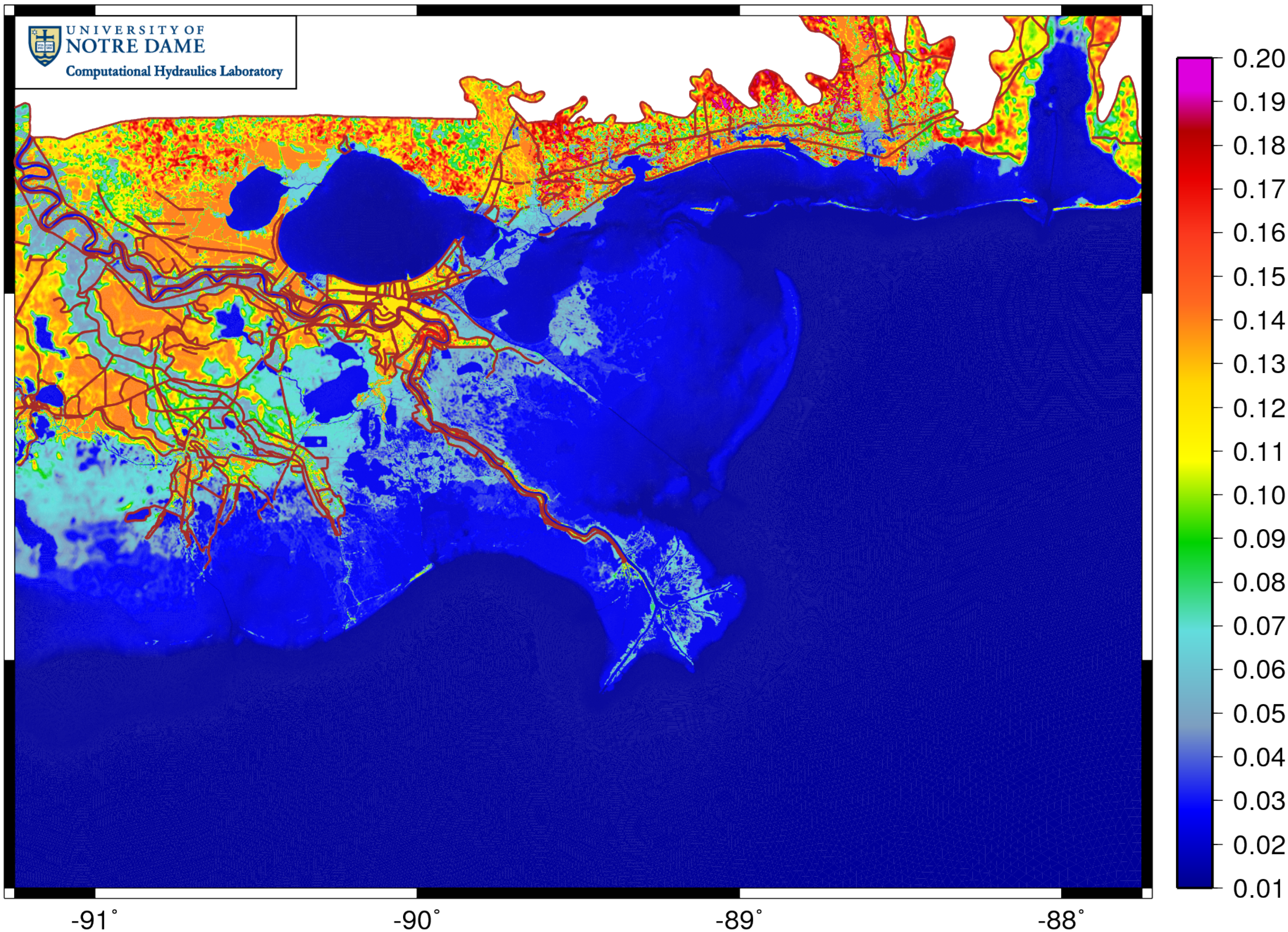
where f_w depends on the bottom roughness length scale, K_N.

- We can relate the friction lengths to our Manning's n values:

$$K_N = H \exp\left[-\left(1 + \frac{\kappa H^{1/6}}{n\sqrt{g}}\right)\right]$$

- Now we can pass spatially-variable friction lengths to SWAN!

Coupled Physics



Wind Drag based on Storm Sectors:

- SWAN+ADCIRC applies a sea-surface momentum stress:

$$\tau_{s,winds} = \rho_0 C_d U_{10}^2$$

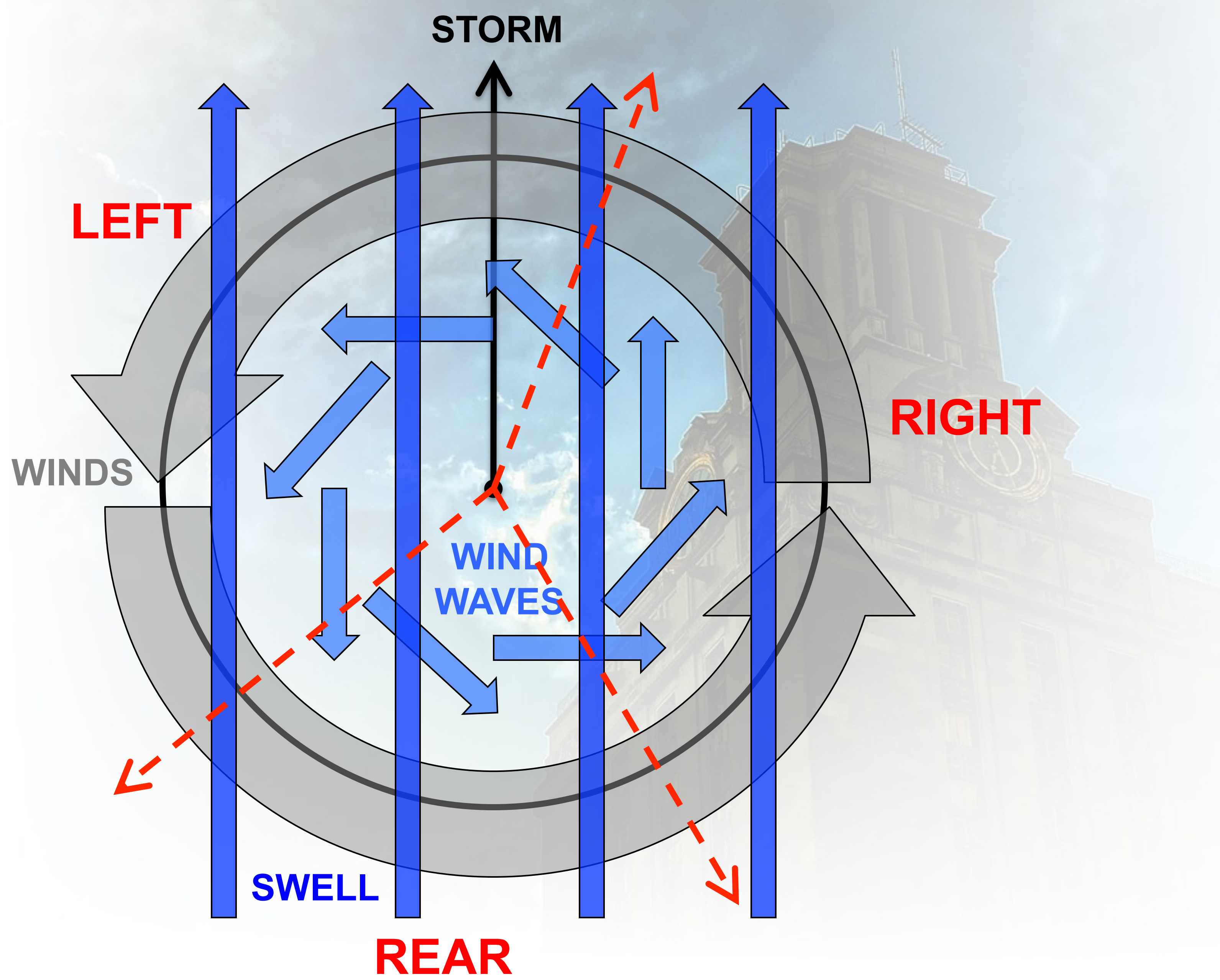
with similar expressions for the wind drag coefficient:

$$C_d = \frac{1}{1000}\left(\frac{15}{20} + \frac{40}{600} U_{10}\right)$$ ADCIRC (Garratt, 1977)

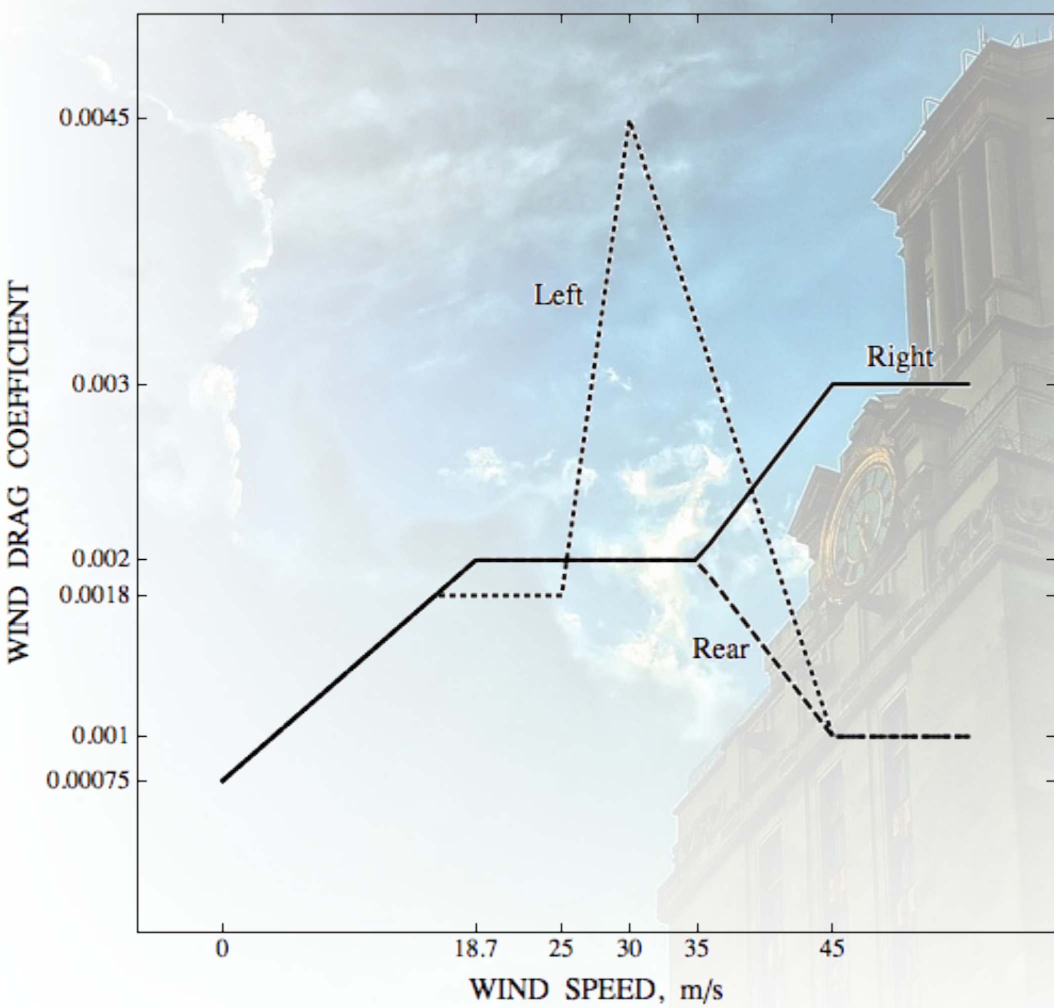
$$C_d = \frac{1}{1000}\left(\frac{16}{20} + \frac{39}{600} U_{10}\right)$$ SWAN (Wu, 1982)

with an upper limit of $C_d \leq 0.002$.

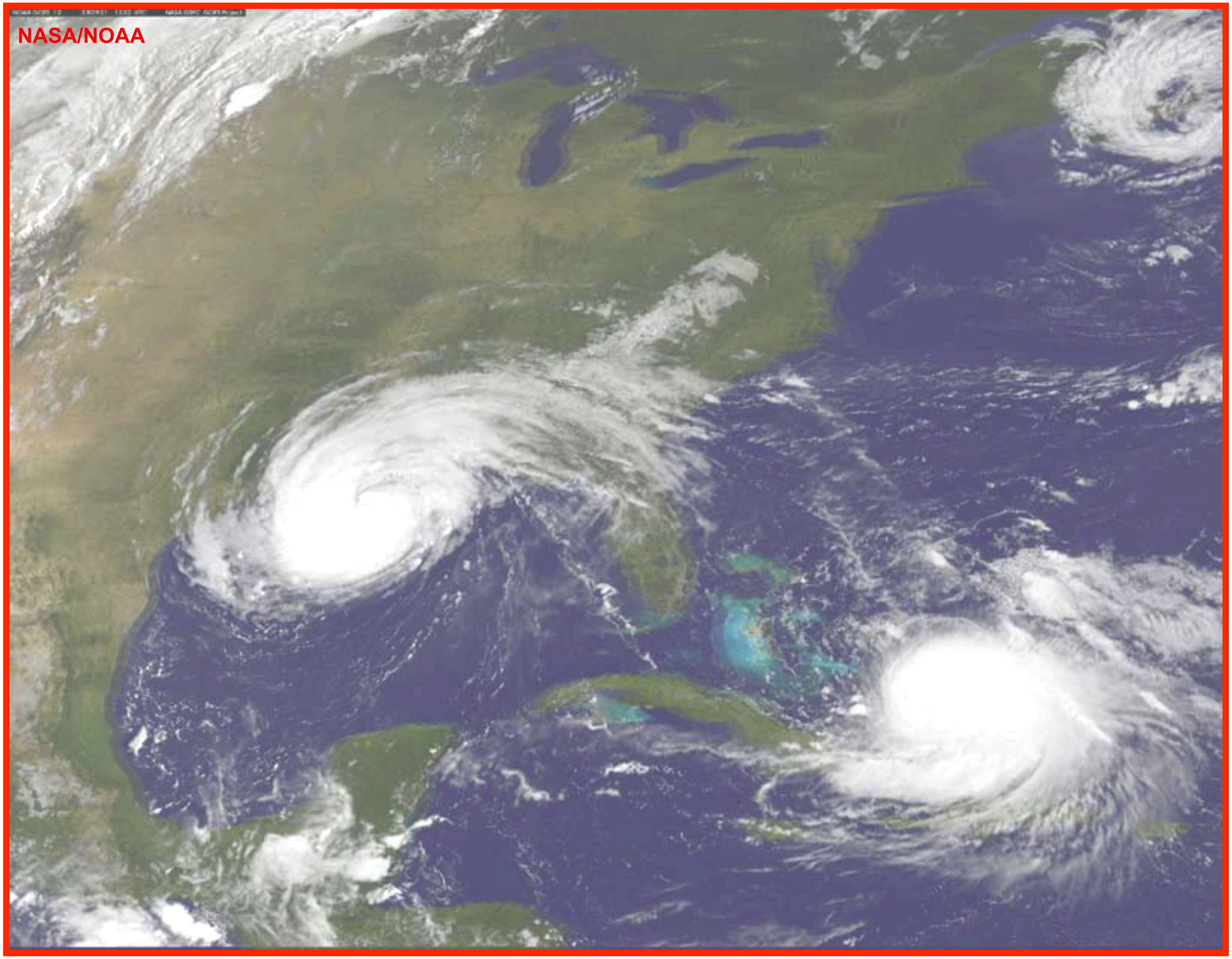
Coupled Physics



Coupled Physics

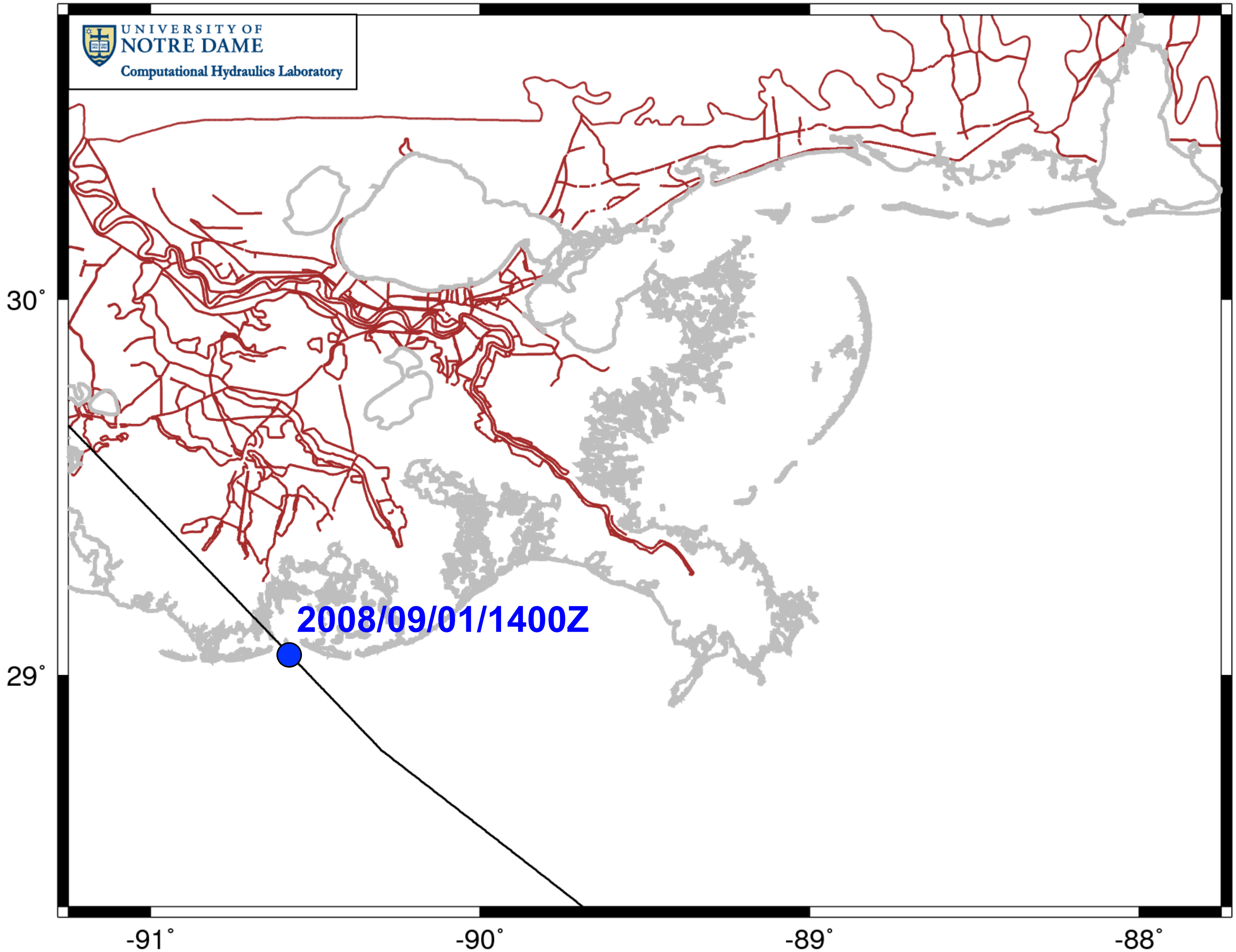


Hurricane Season 2008

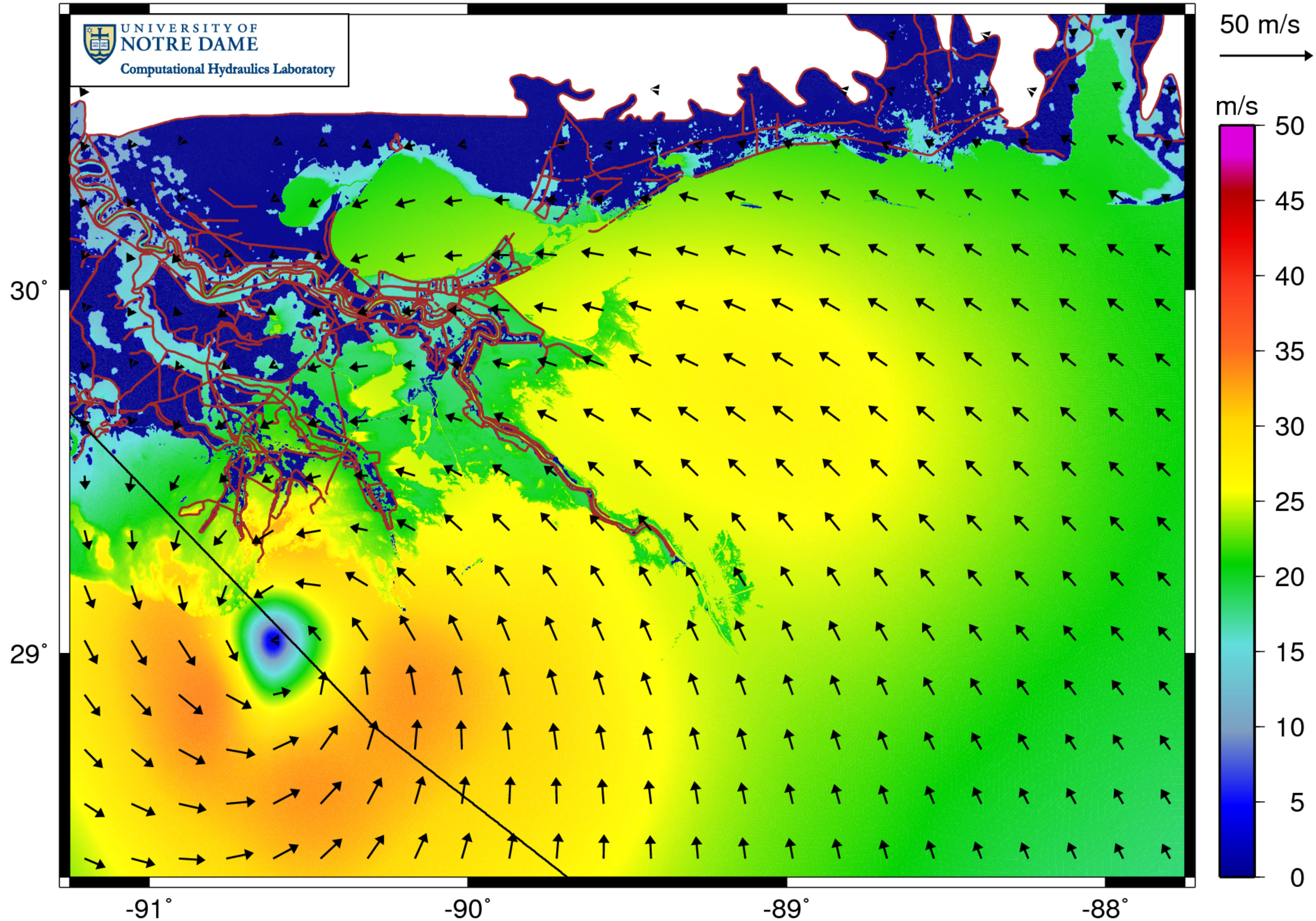


Gustav : Storm Surge near New Orleans

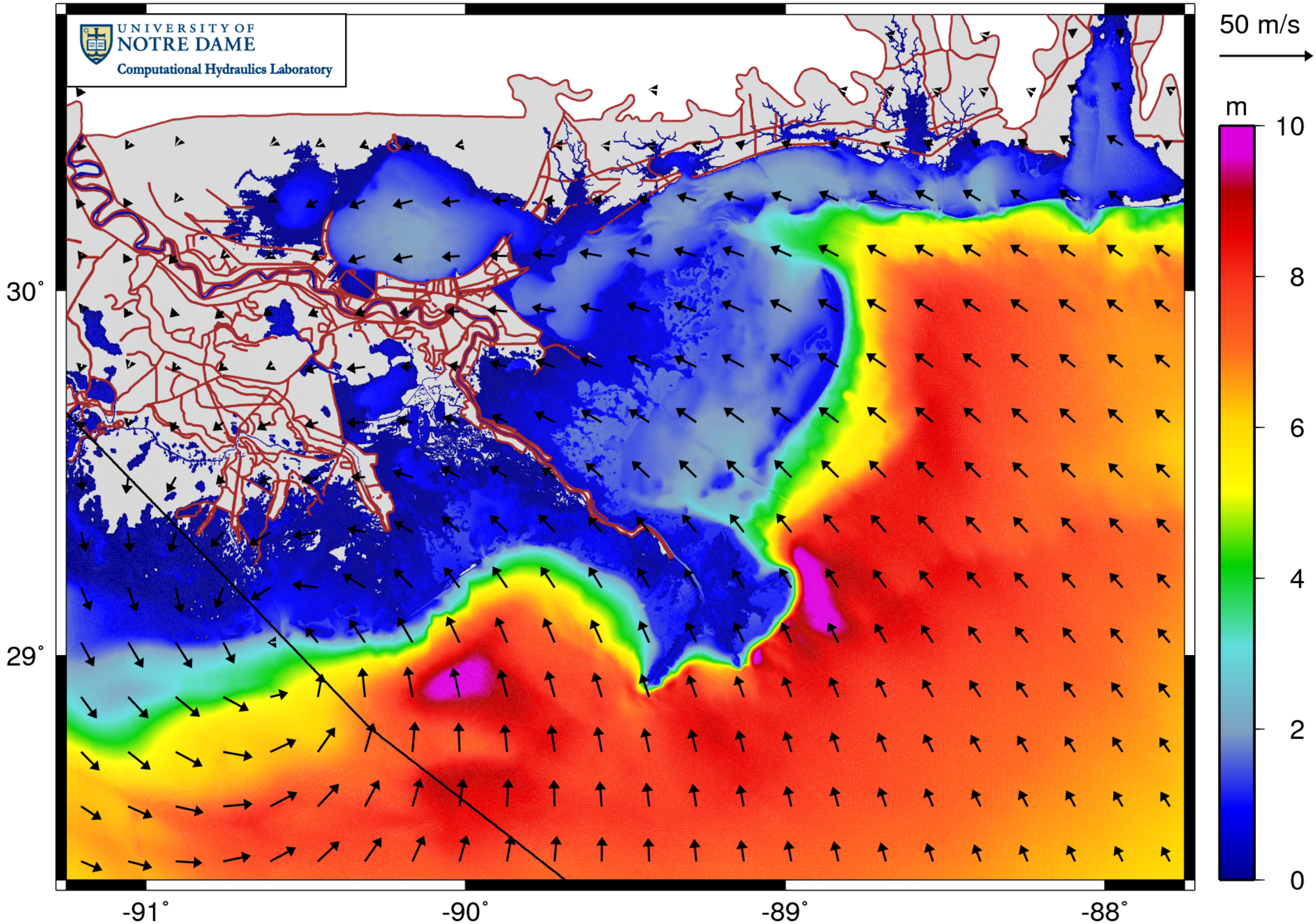
Gustav : Track



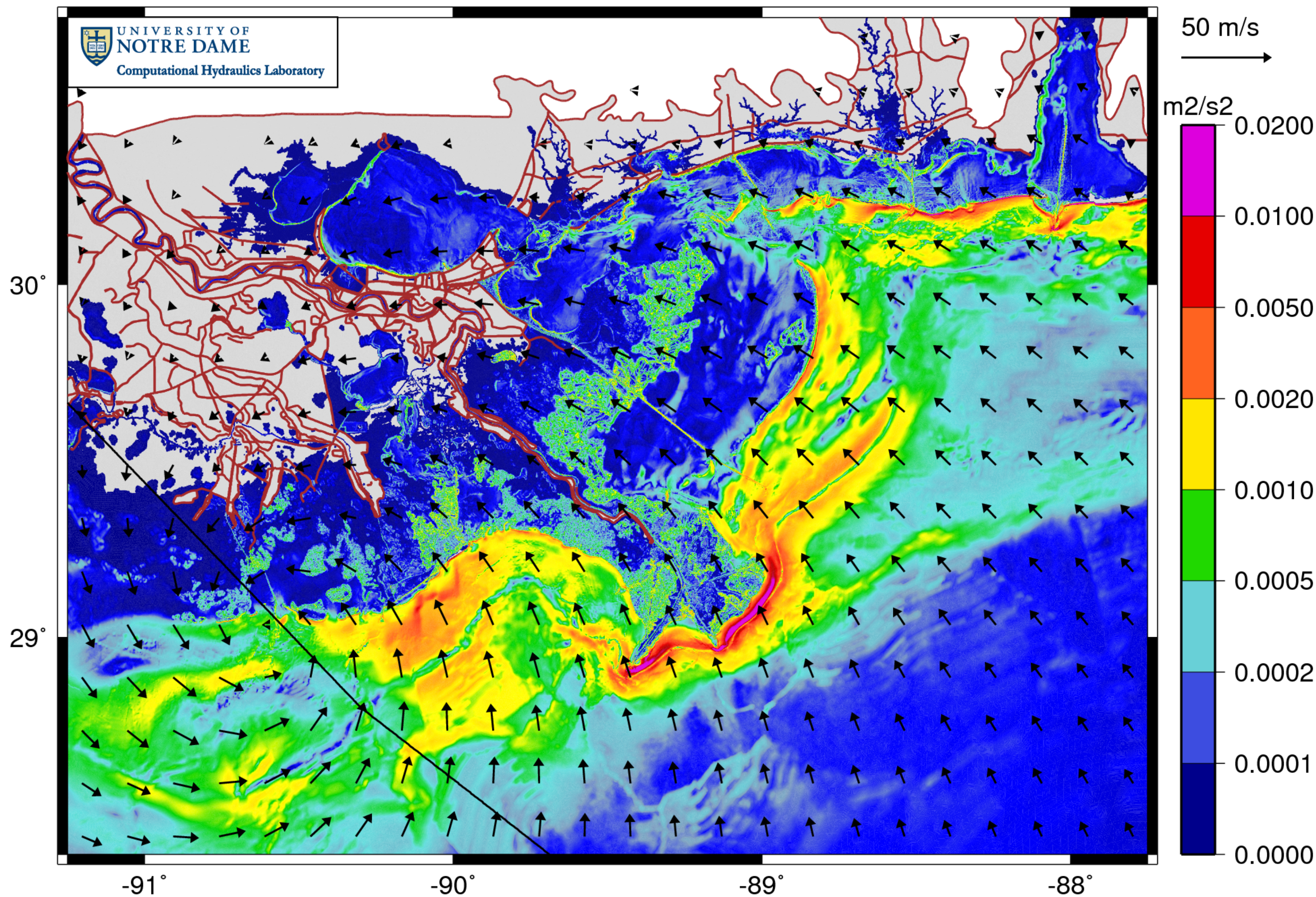
Gustav : 2008/09/01/1400Z : Winds



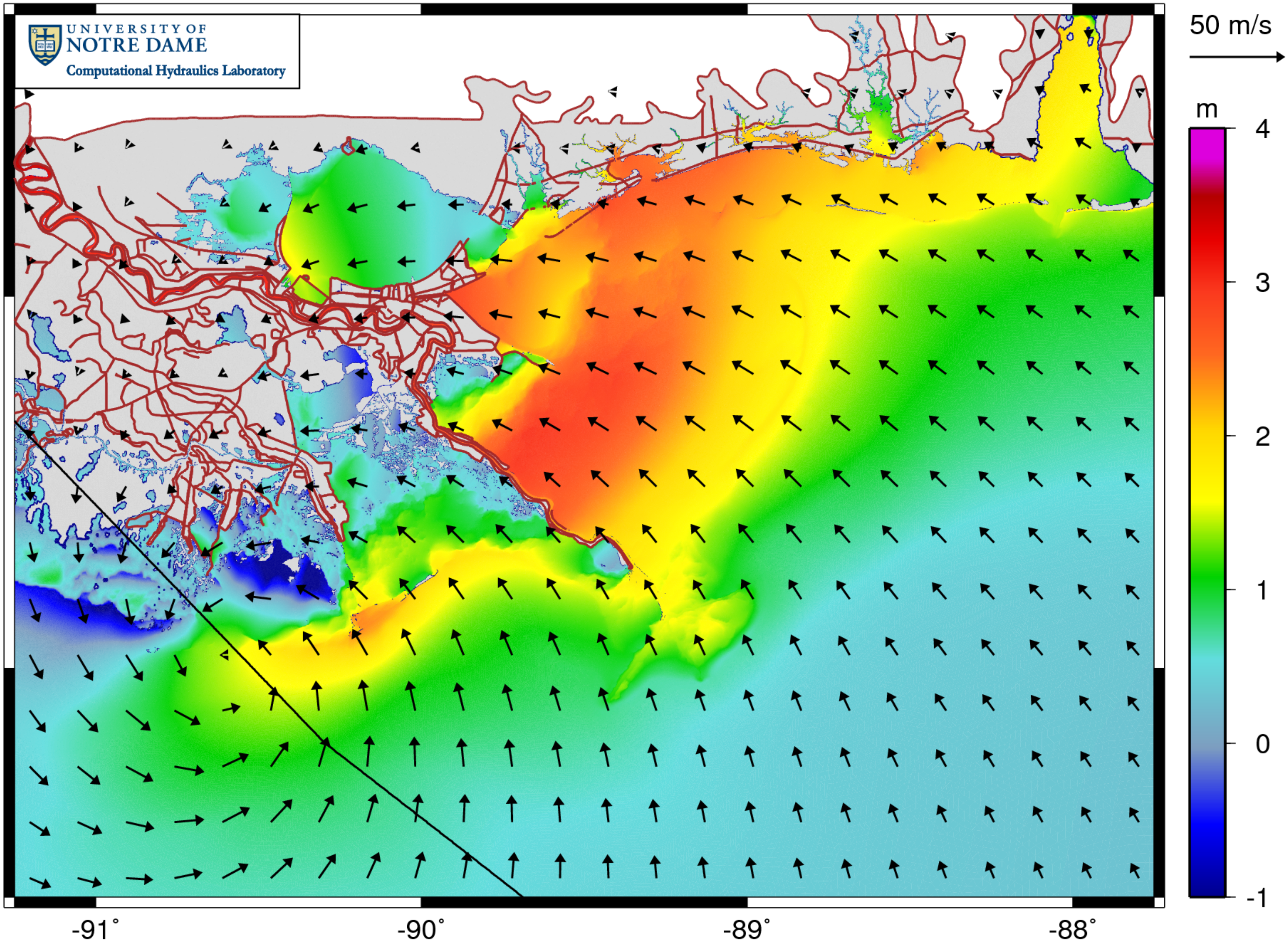
Gustav : 2008/09/01/1400Z : Significant Wave Heights



Gustav : 2008/09/01/1400Z : Radiation Stress Gradients



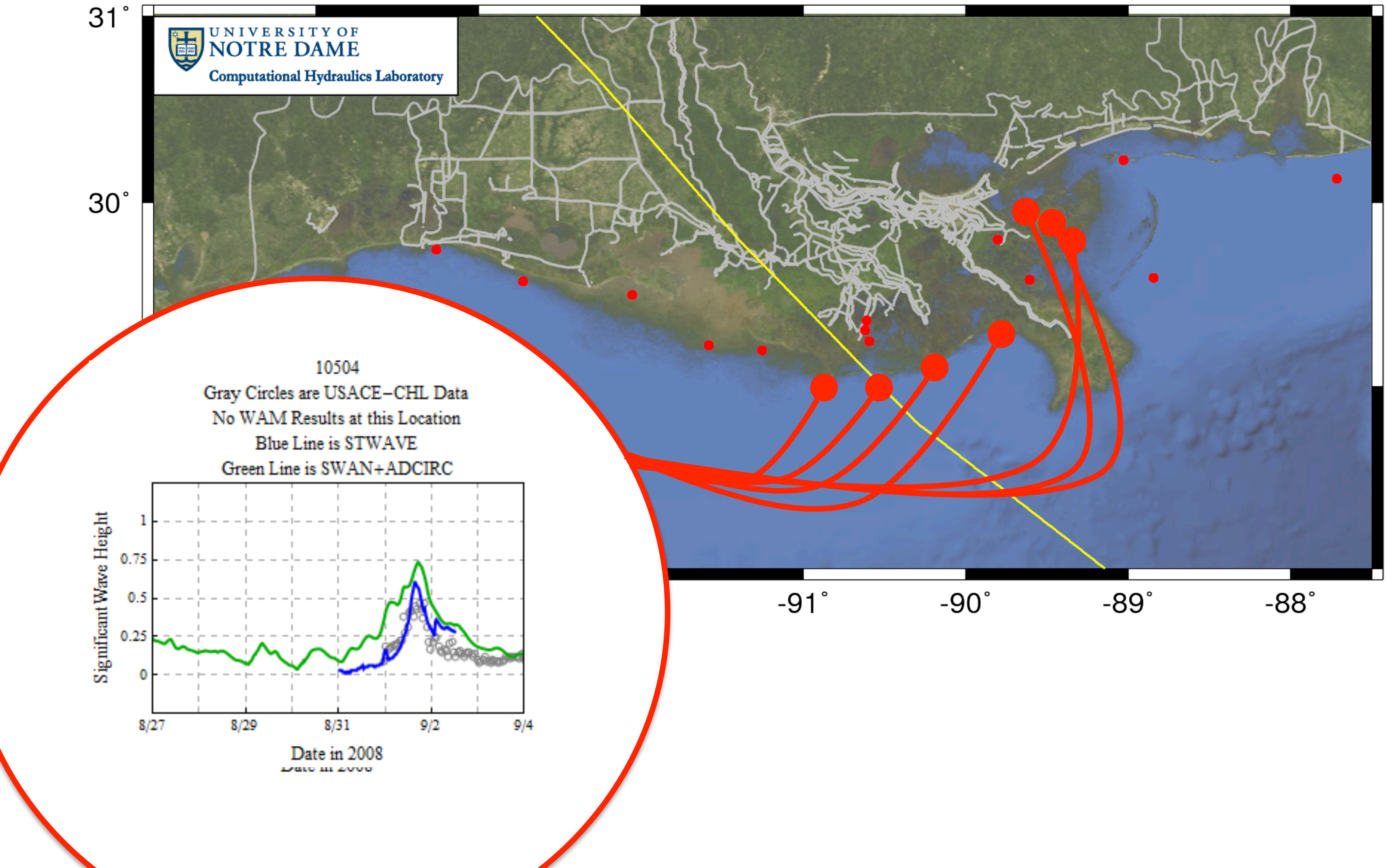
Gustav : 2008/09/01/1400Z : Water Levels



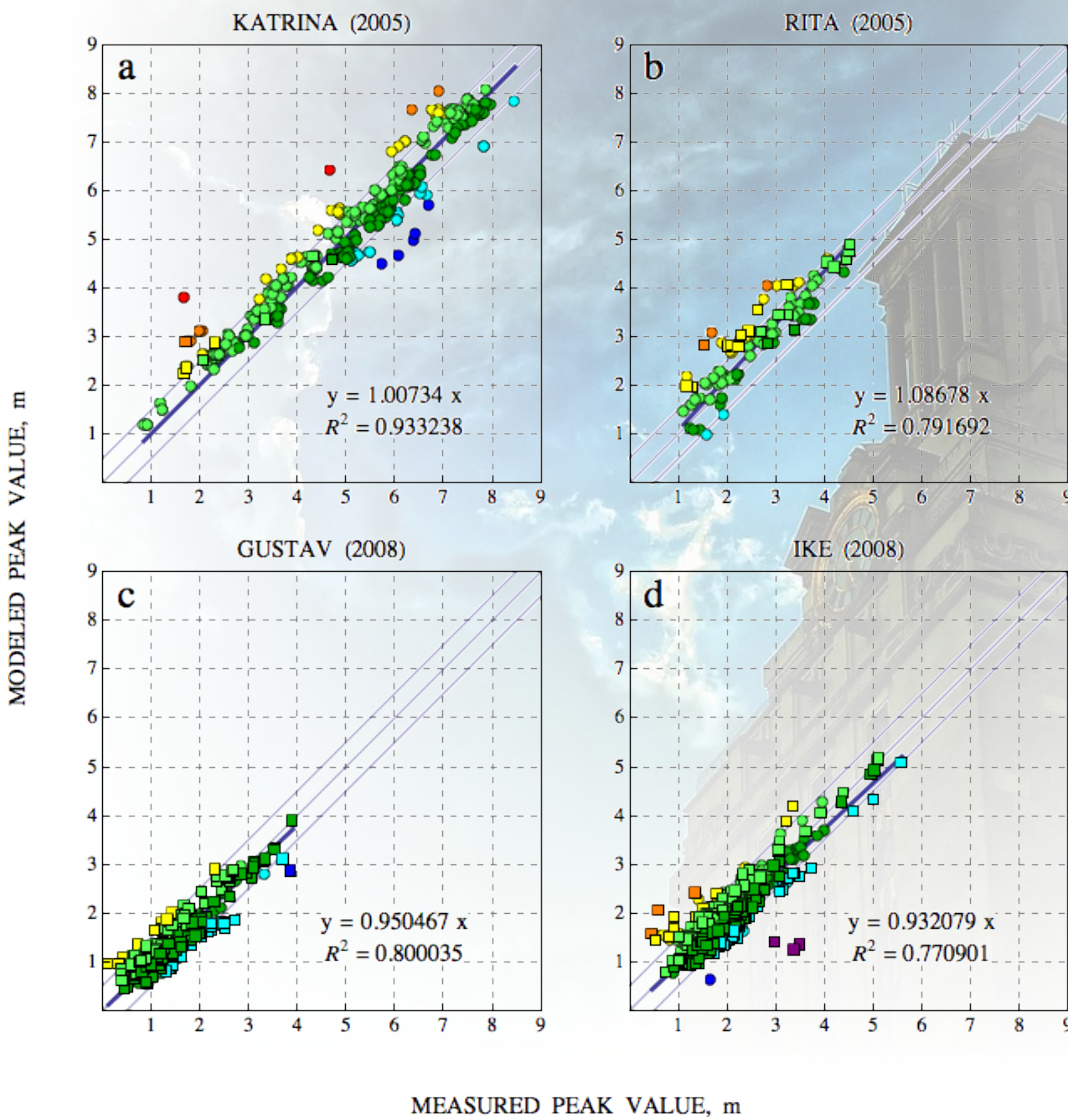
Increased Availability of Measurement Data

	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

Gustav : Validation : Significant Wave Heights



Validation : High-Water Marks



Validation : Error Statistics

Error Norms for Time Series Data:

- Scatter Index (SI):

$$SI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(E_i - \overline{E}\right)^2}}{\frac{1}{N}\sum_{i=1}^{N}\left|O_i\right|}$$

- Bias:

$$Bias = \frac{\frac{1}{N}\sum_{i=1}^{N}E_i}{\frac{1}{N}\sum_{i=1}^{N}\left|O_i\right|}$$

where: N is the number of observations, $E_i = S_i - O_i$ is the error between the modeled (S_i) and measured (O_i) values, and $\overline{E}$ is the mean error.

Validation : Error Statistics

			Katrina	Rita	Gustav	Ike
Water Levels	ς	*m*	1.01	1.09	0.95	0.93
		R^2	0.93	0.79	0.80	0.77
		SI	0.19	0.28	0.24	0.16
		Bias	0.14	0.15	0.14	-0.07
Waves	H_s	*SI*	0.23	0.23	0.34	0.29
		Bias	0.05	0.43	0.35	0.09
	T_p	*SI*	0.22	0.25	0.53	0.57
		Bias	0.07	0.25	-0.03	0.02
	T_{m-10}	*SI*	0.15	0.12	0.22	0.16
		Bias	0.09	0.18	-0.03	0.13

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

Couple SWAN with ADCIRC(DG):

- Preliminary work is promising