Coupled Waves and Storm Surge in Southern Louisiana

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Environmental Fluid Dynamics Seminar Series
Tuesday, 23 March 2010

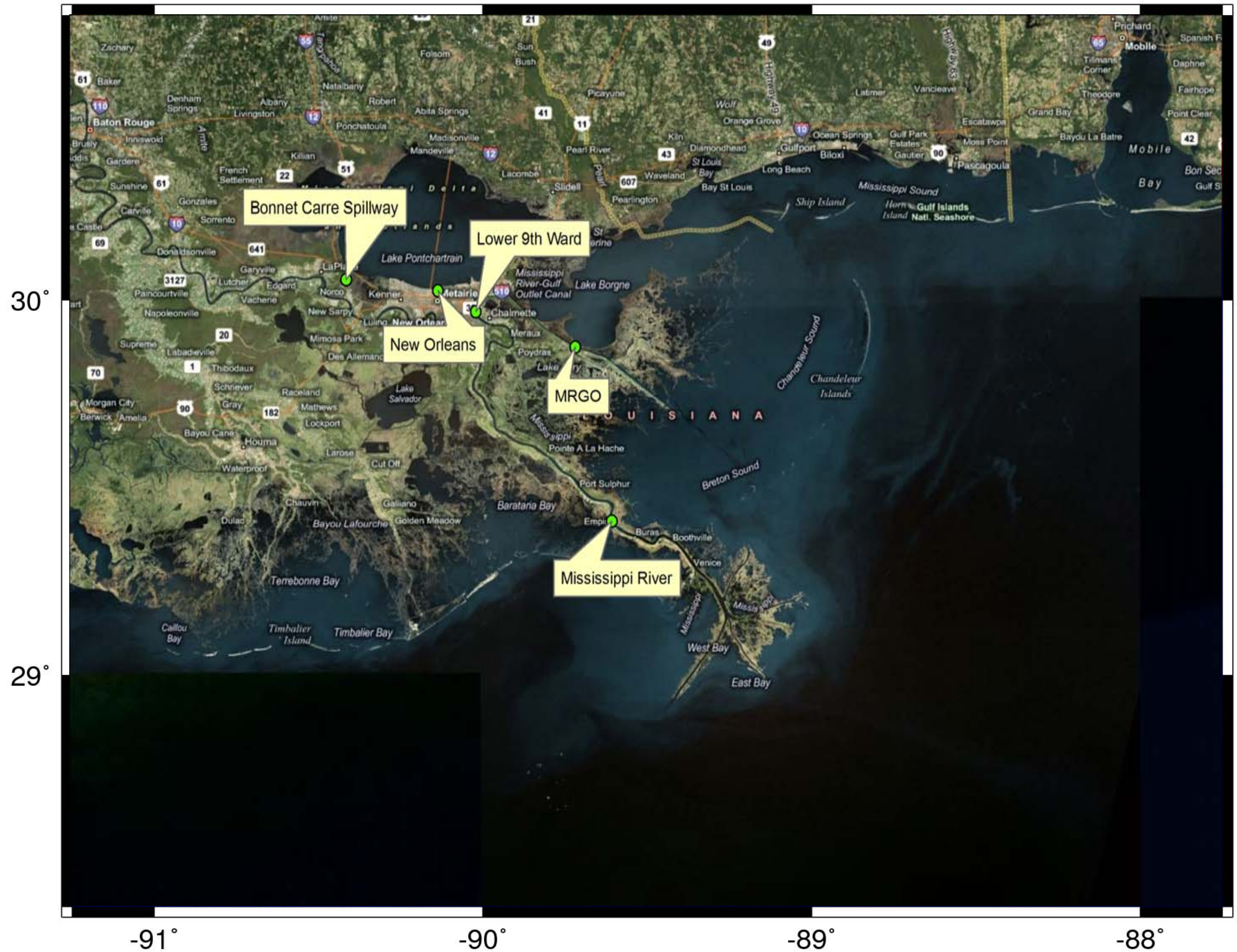
The Original:

‘Loose’ Coupling of Waves and Surge during Katrina

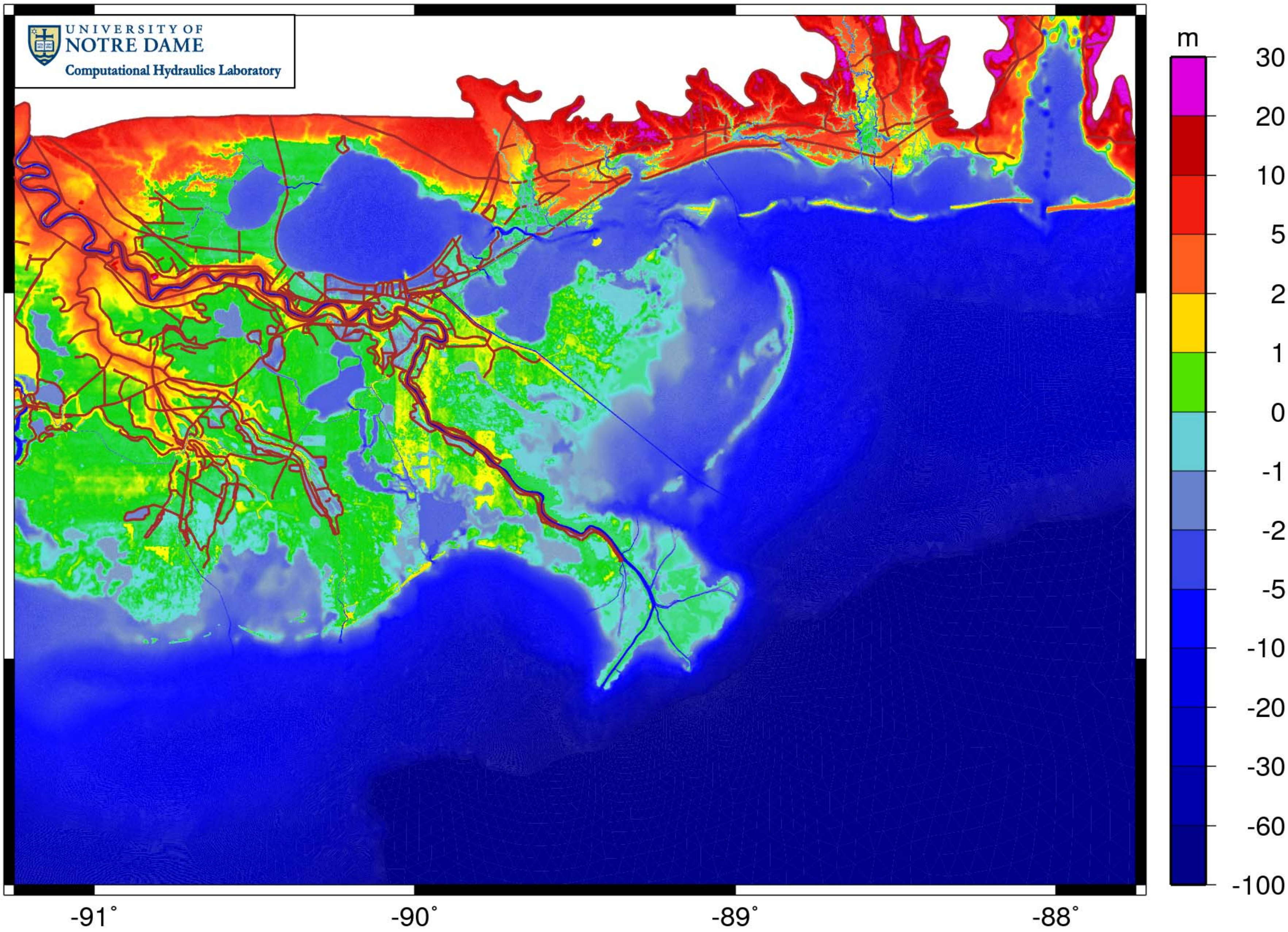
S. Bunya, *et al*. (2010). "A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi, Part I: Model Development and Validation." *Monthly Weather Review* 138, 345-377.

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.

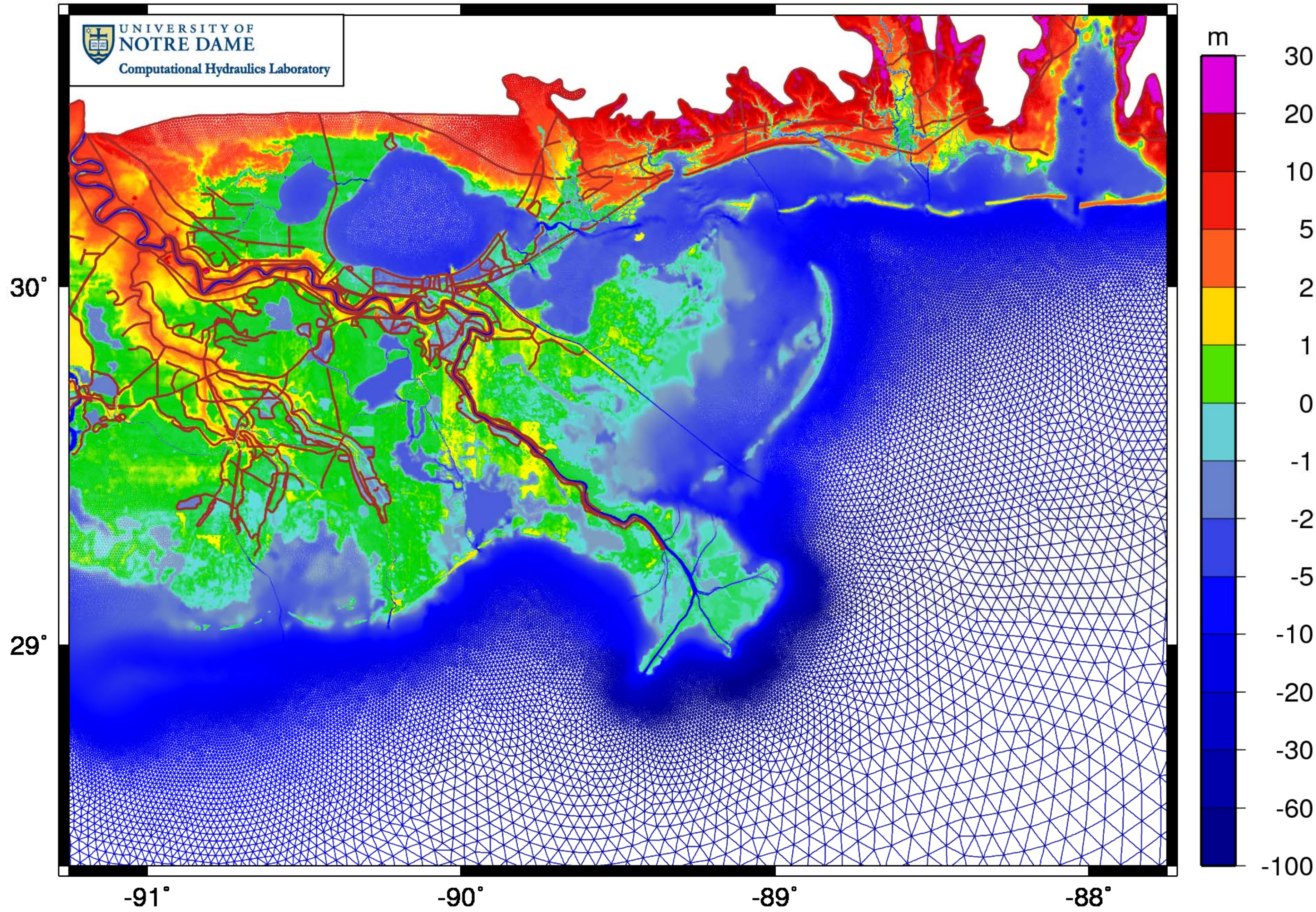
Southern Louisiana



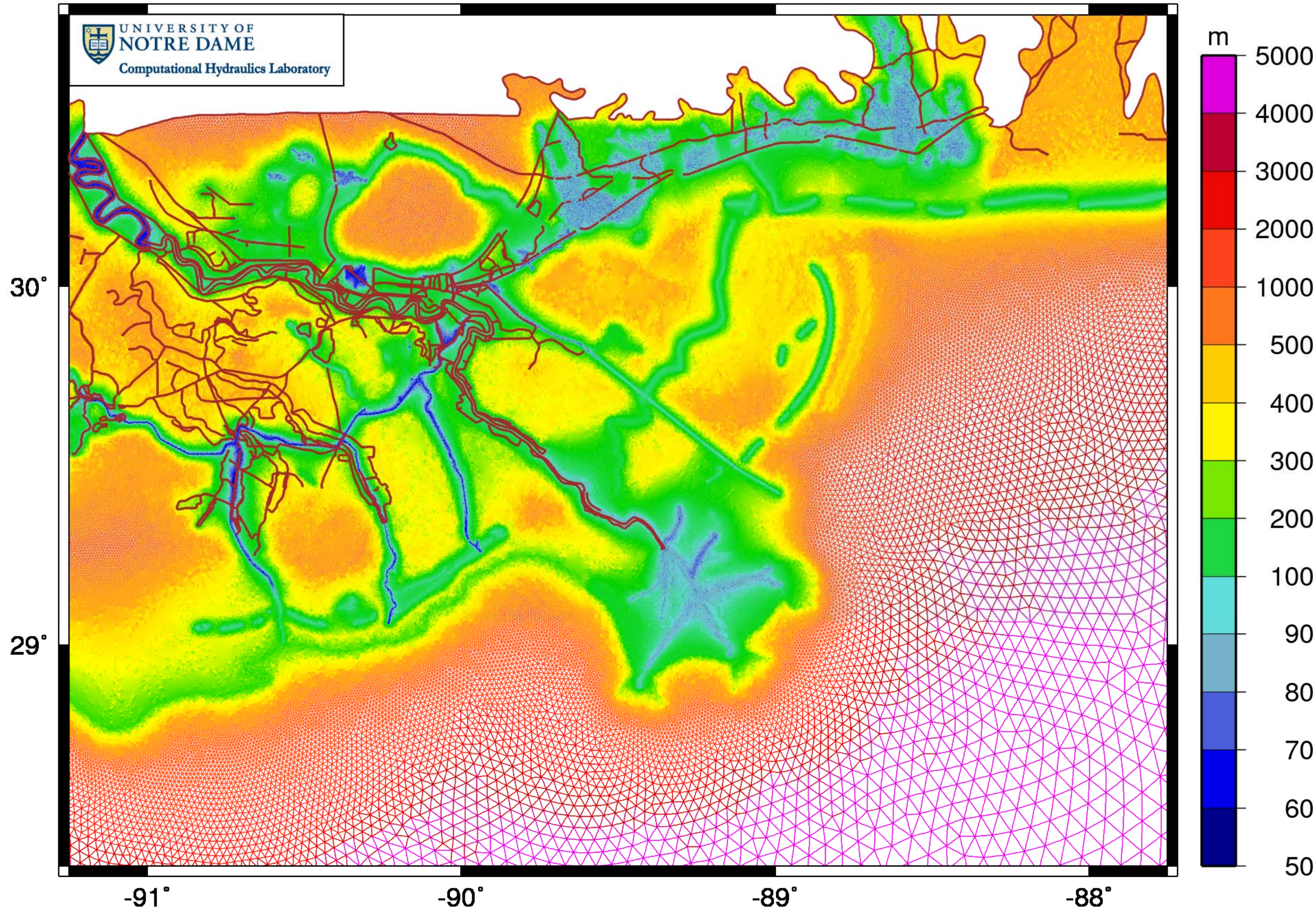
SL15v7l : Bathymetry and Topography



SL15v7l : Bathymetry and Topography



SL15v7l : Mesh Sizes



ADCIRC : Background and Governing Equations

ADvanced CIRCulation:

- Developed by Westerink, Luettich, and many others
- Continuous-Galerkin, finite-element, shallow-water model
- Solves for water levels and currents at a range of scales
  - From rivers and tides to wind-driven storm surge
  - Resolution can vary from 20-30km to 30-50m
- Solves the Generalized Wave Continuity Equation (GWCE):

$$\frac{\partial}{\partial t}\left[\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) + \frac{\partial}{\partial y}(VH)\right] + \tau_0\left[\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) + \frac{\partial}{\partial y}(VH)\right] = 0$$

where: $H = \zeta + h$ is the total water depth, U and V are the depth-averaged velocities, and τ_0 is a numerical parameter

ADCIRC : Background and Governing Equations

ADvanced CIRCulation:

- Solves the vertically-integrated momentum equations:

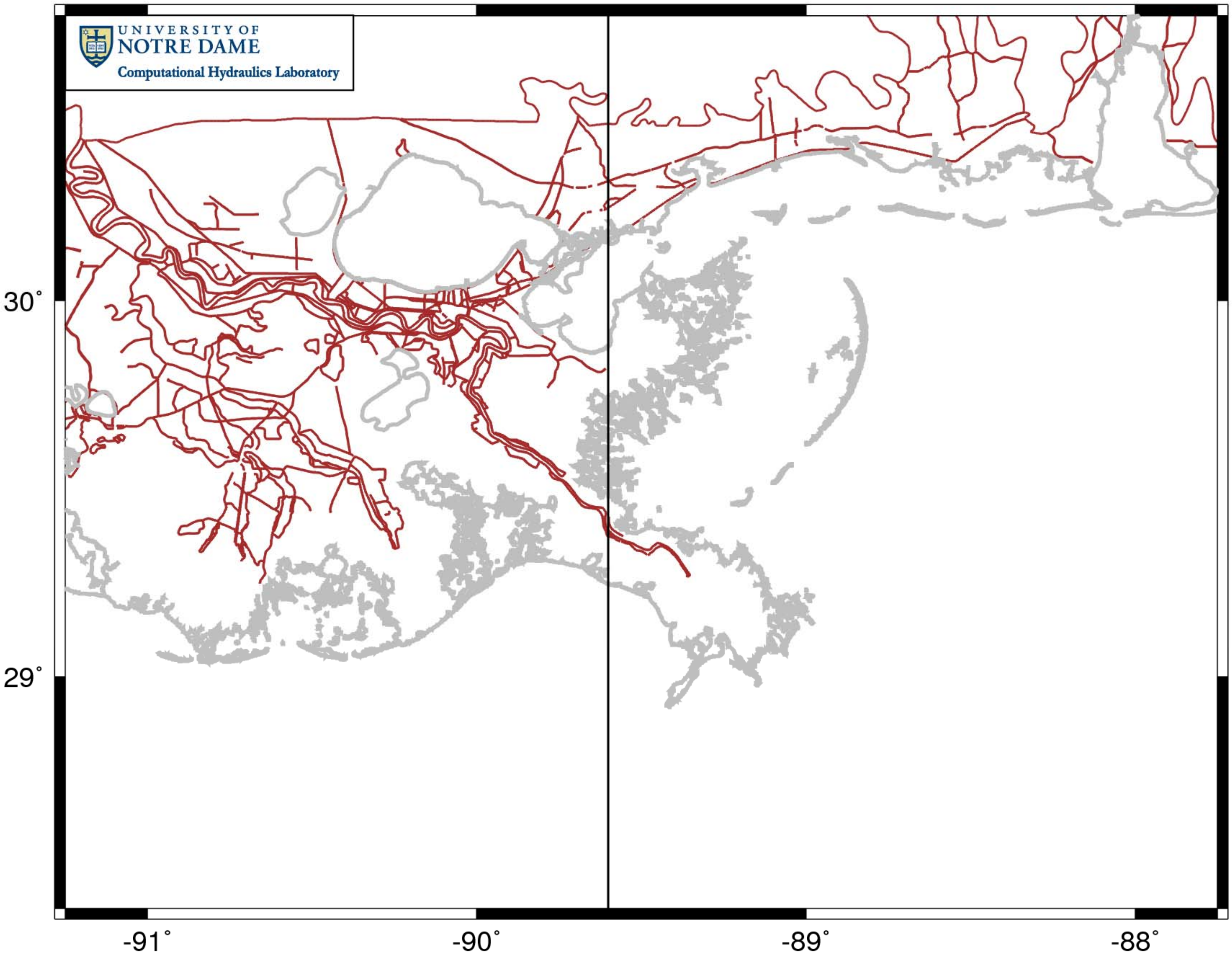
$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -g\frac{\partial}{\partial x}\left[\zeta + \frac{P_s}{\rho_0 g} - \alpha\eta\right] + \frac{\tau_{sx}}{H\rho_0} - \frac{\tau_{bx}}{H\rho_0} + \frac{M_x}{H} - \frac{D_x}{H} - \frac{B_x}{H}$$

and:

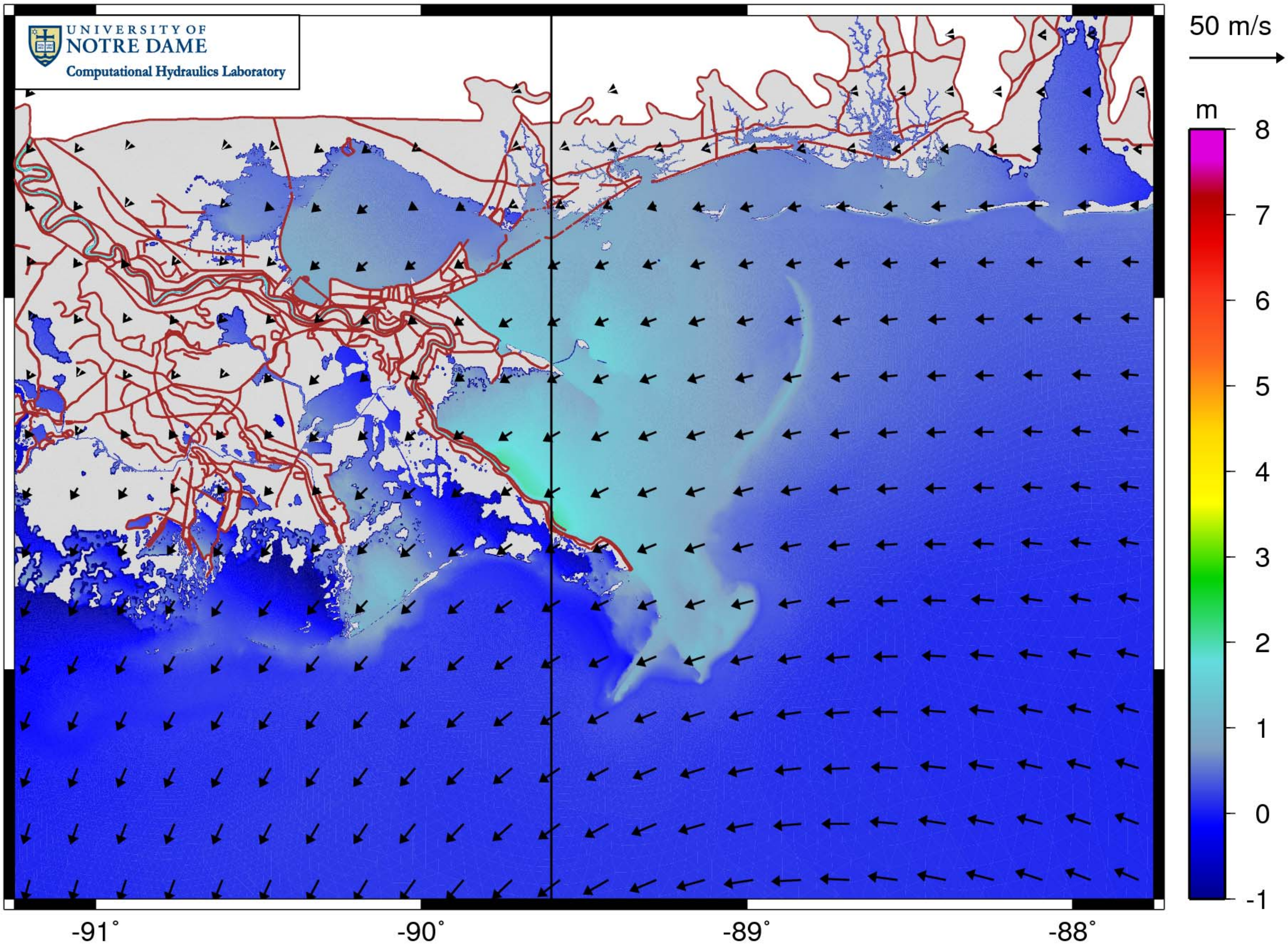
$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU = -g\frac{\partial}{\partial x}\left[\zeta + \frac{P_s}{\rho_0 g} - \alpha\eta\right] + \frac{\tau_{sy}}{H\rho_0} - \frac{\tau_{by}}{H\rho_0} + \frac{M_y}{H} - \frac{D_y}{H} - \frac{B_y}{H}$$

where: f is the Coriolis parameter, P_s is atmospheric pressure, ρ_0 is the reference density of water, τ_s and τ_b are stresses at the surface and bottom, M is a lateral stress gradient, B is a baroclinic pressure gradient, and D is momentum dispersion

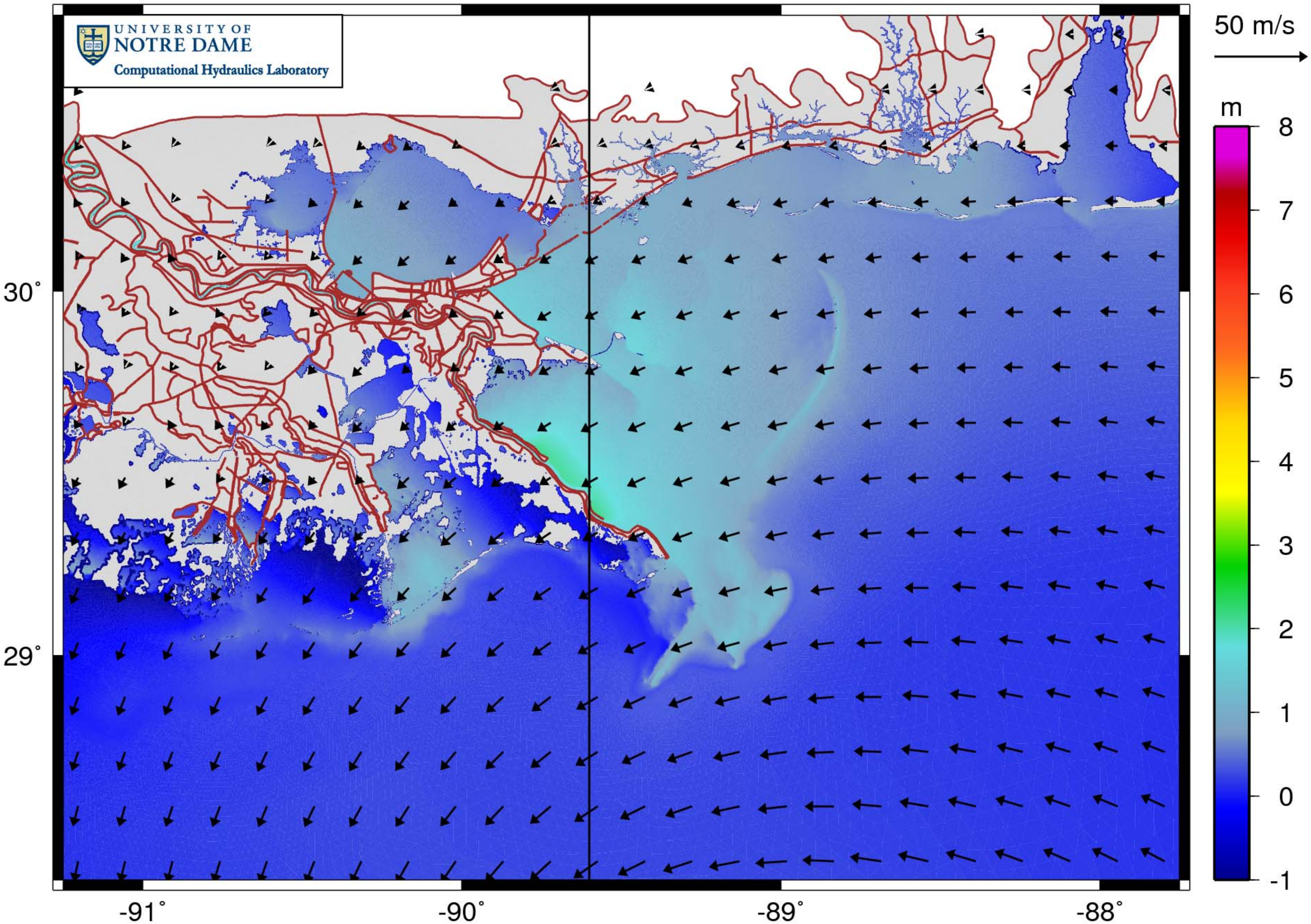
Katrina : Track



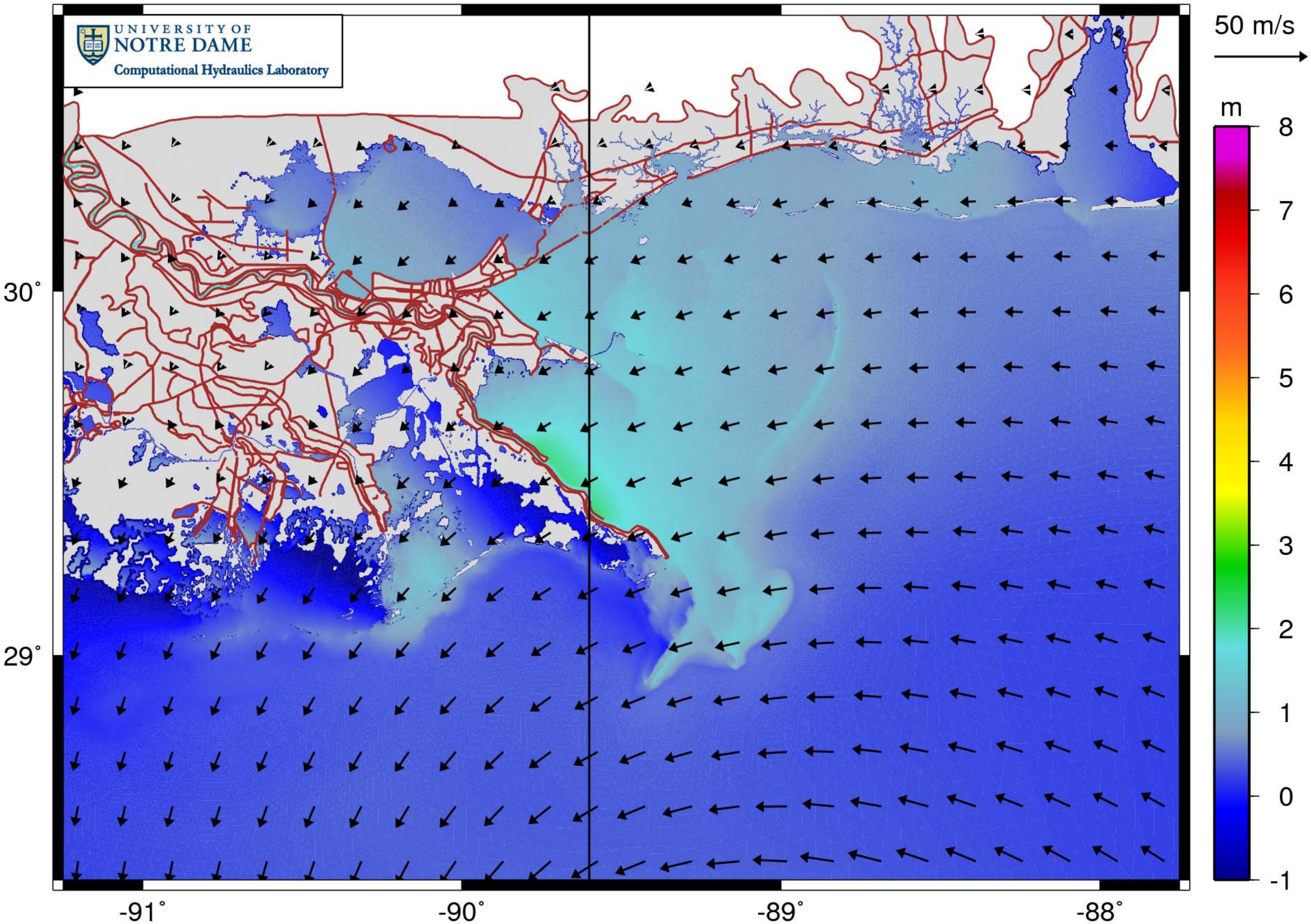
Katrina : Water Levels : 2005/08/29/0000Z



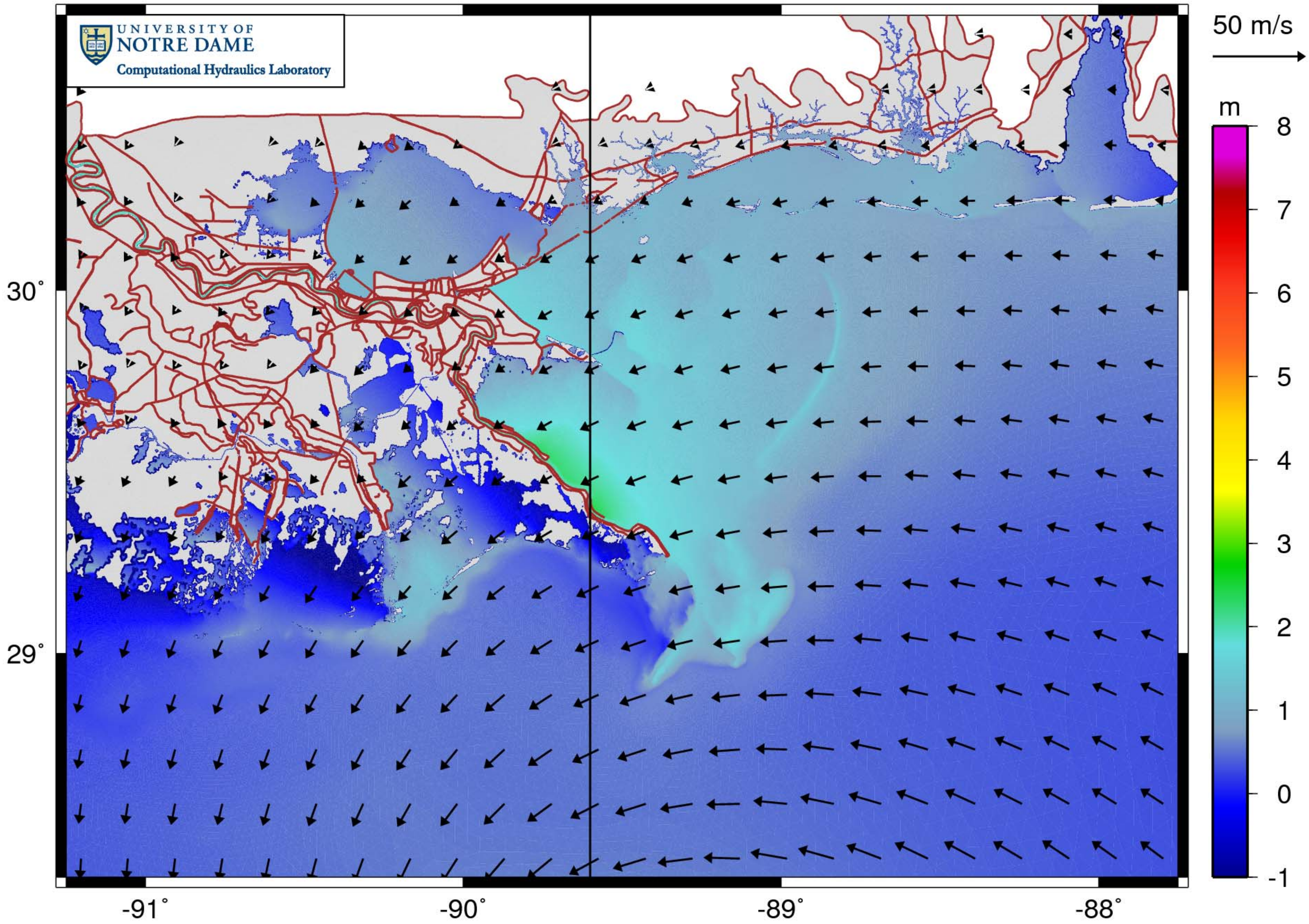
Katrina : Water Levels : 2005/08/29/0100Z



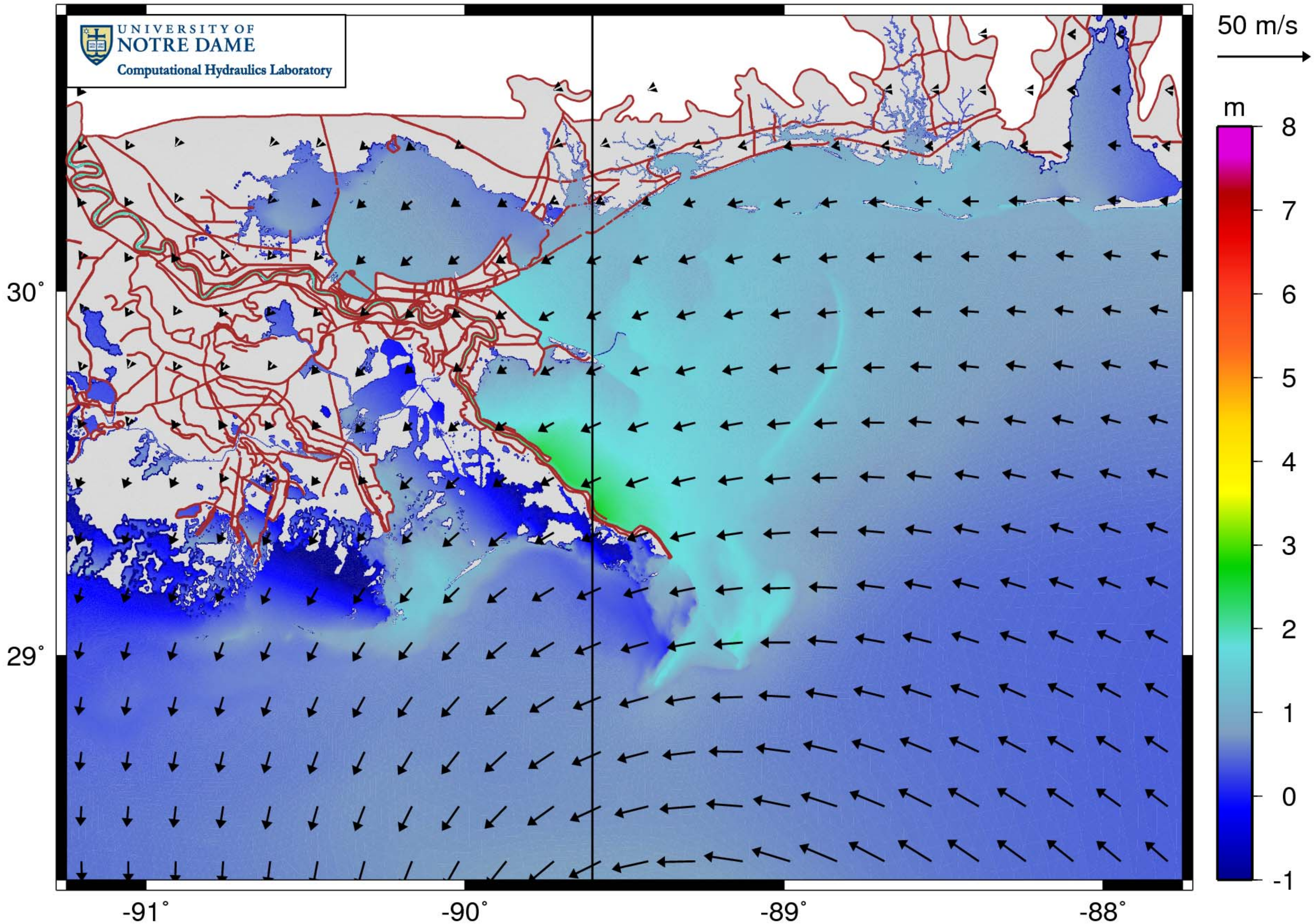
Katrina : Water Levels : 2005/08/29/0200Z



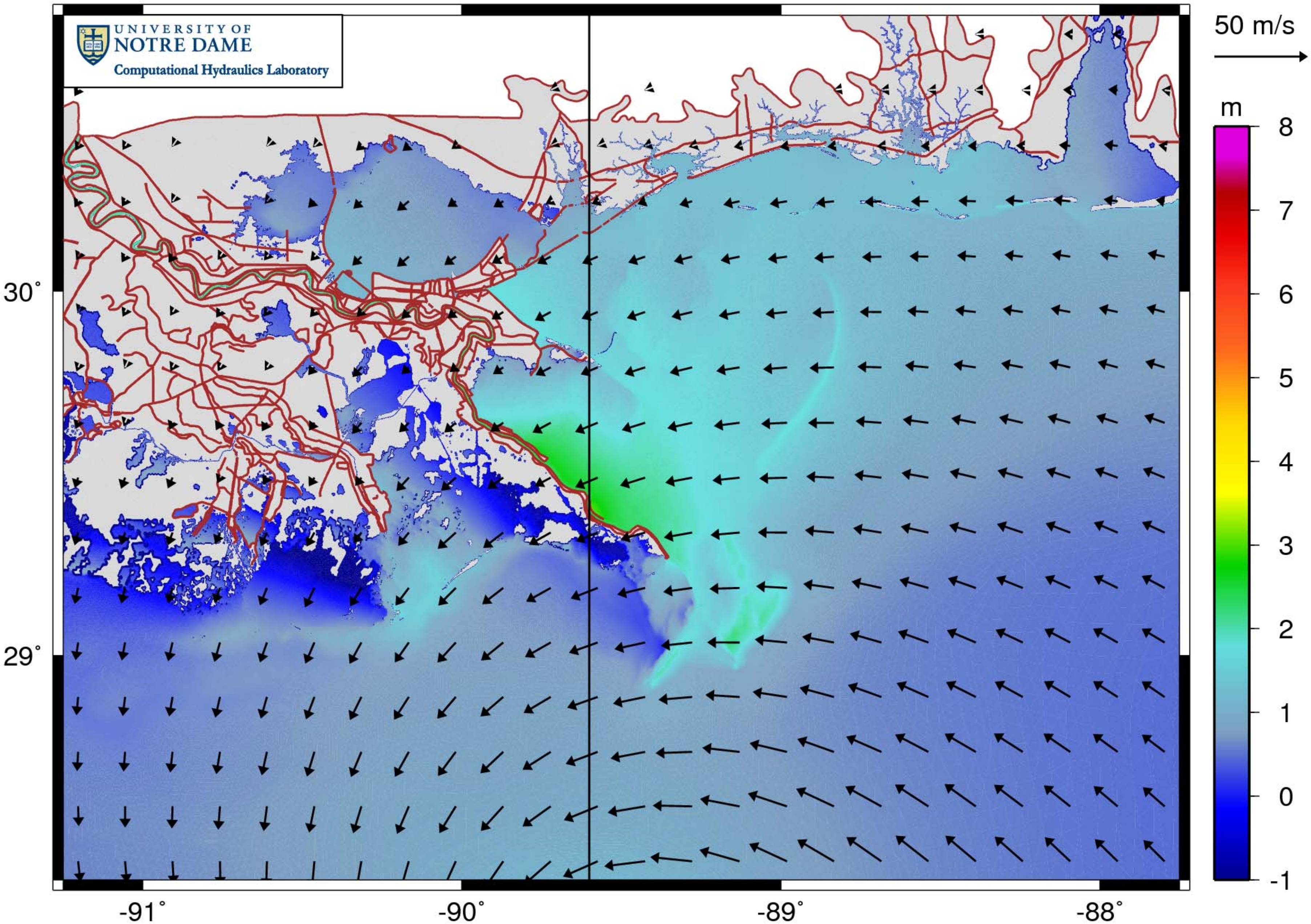
Katrina : Water Levels : 2005/08/29/0300Z



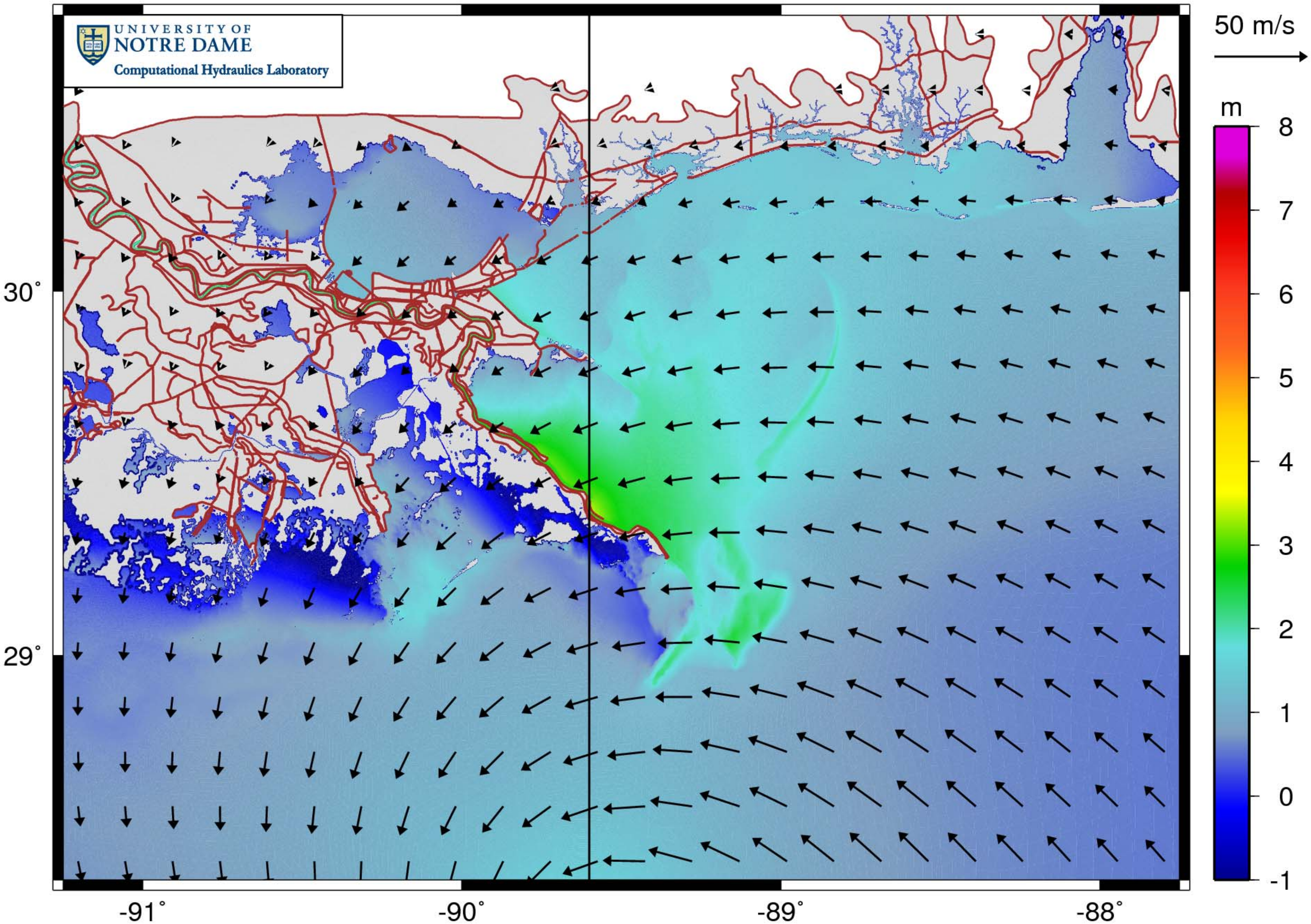
Katrina : Water Levels : 2005/08/29/0400Z



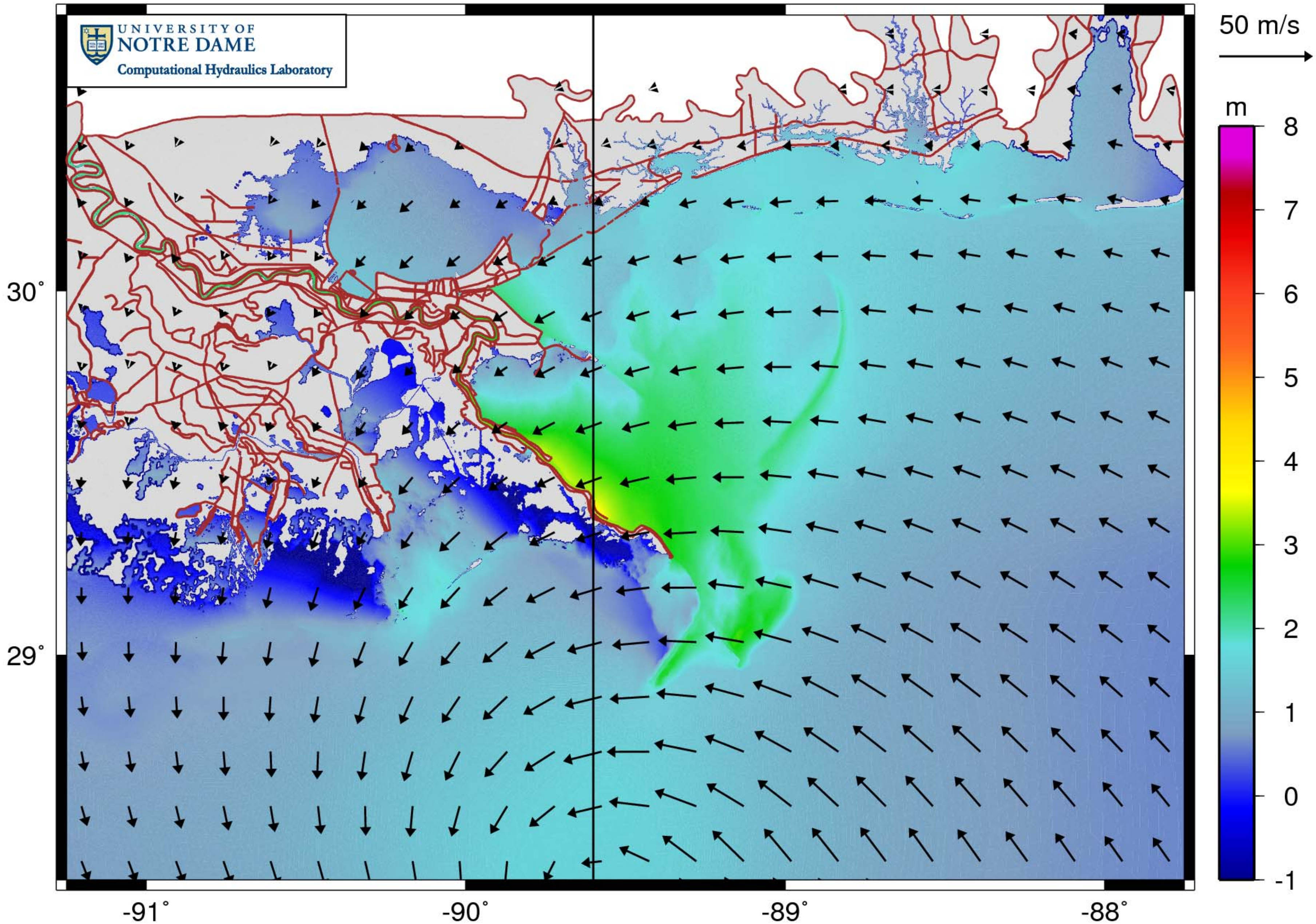
Katrina : Water Levels : 2005/08/29/0500Z



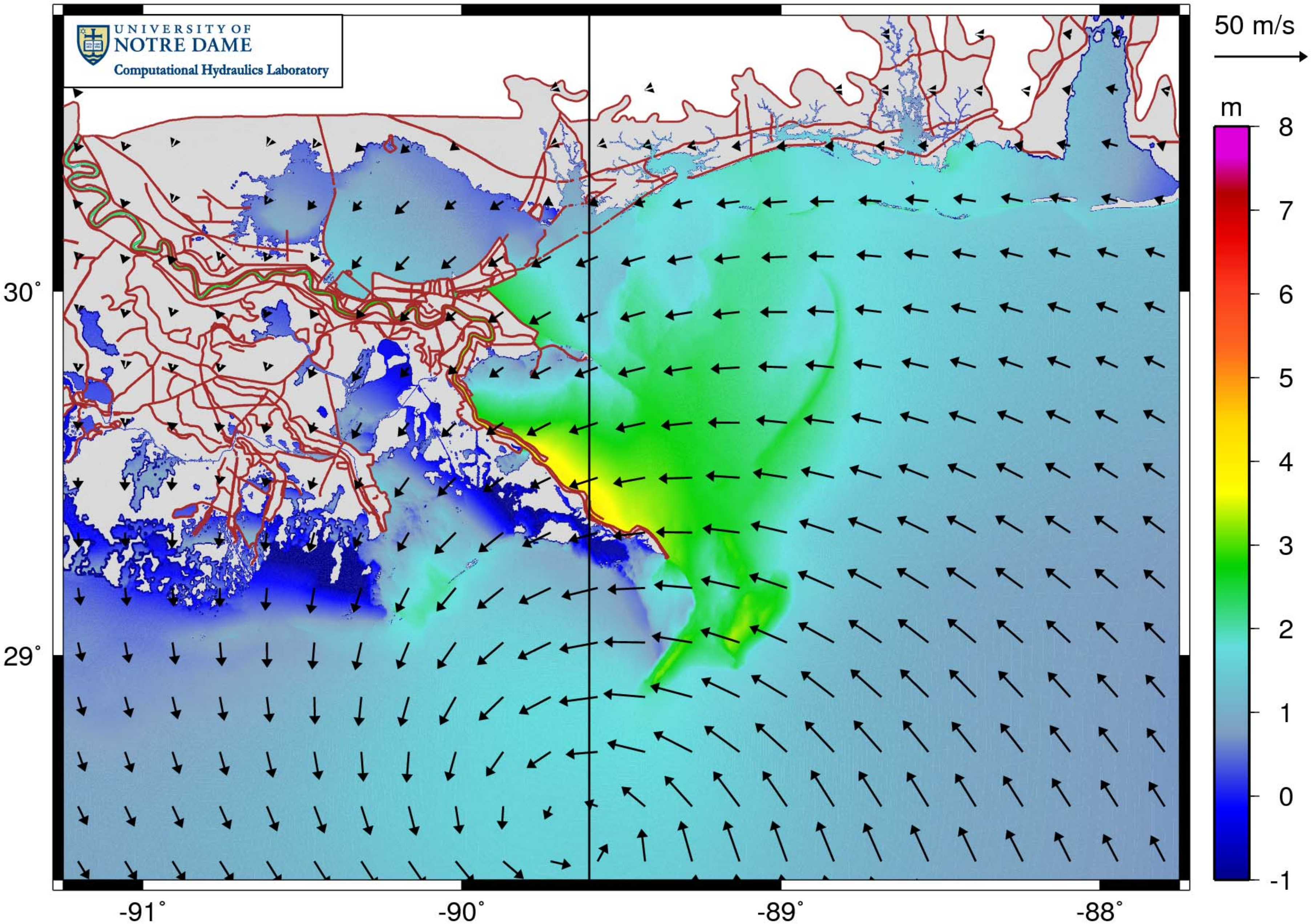
Katrina : Water Levels : 2005/08/29/0600Z



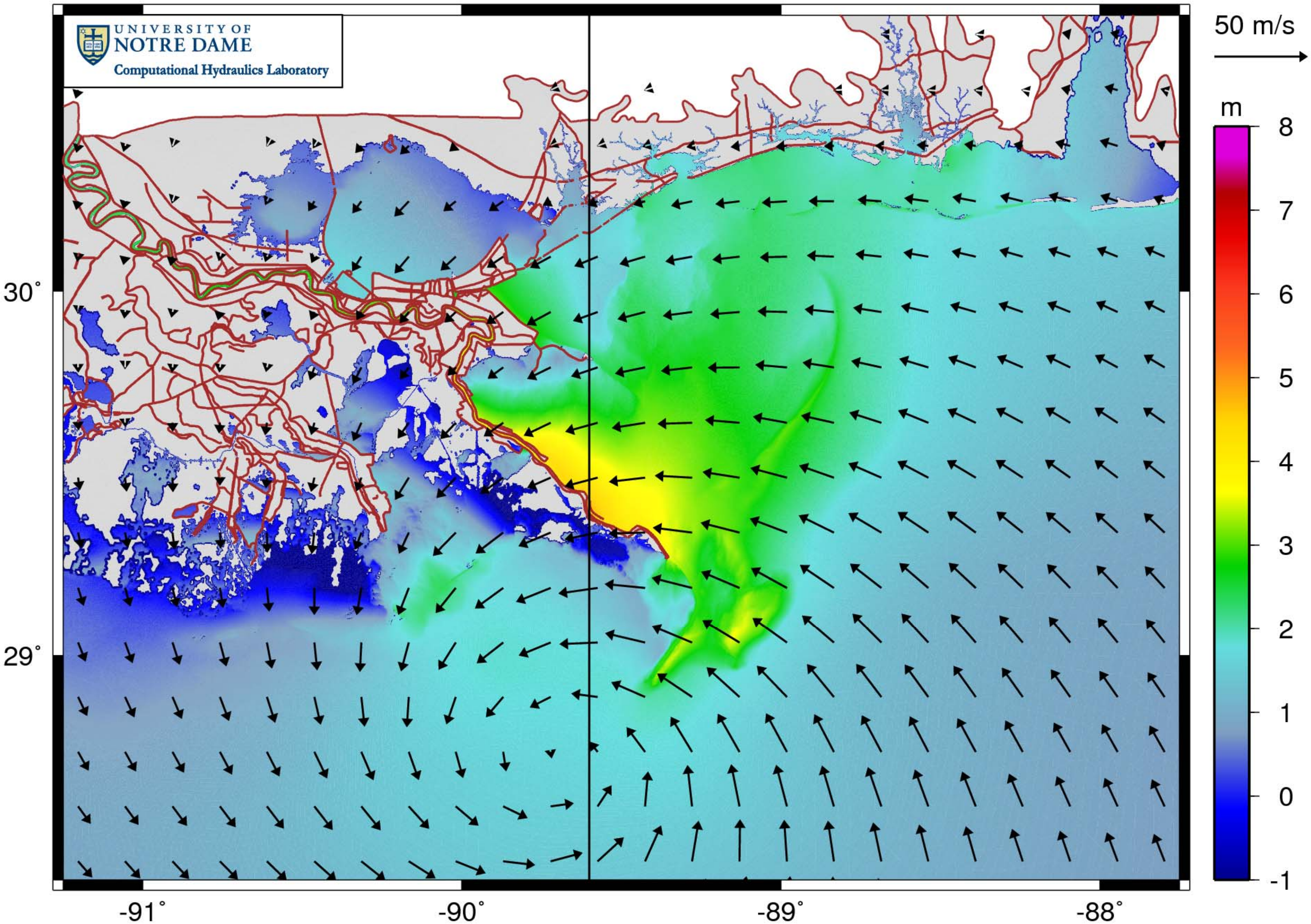
Katrina : Water Levels : 2005/08/29/0700Z



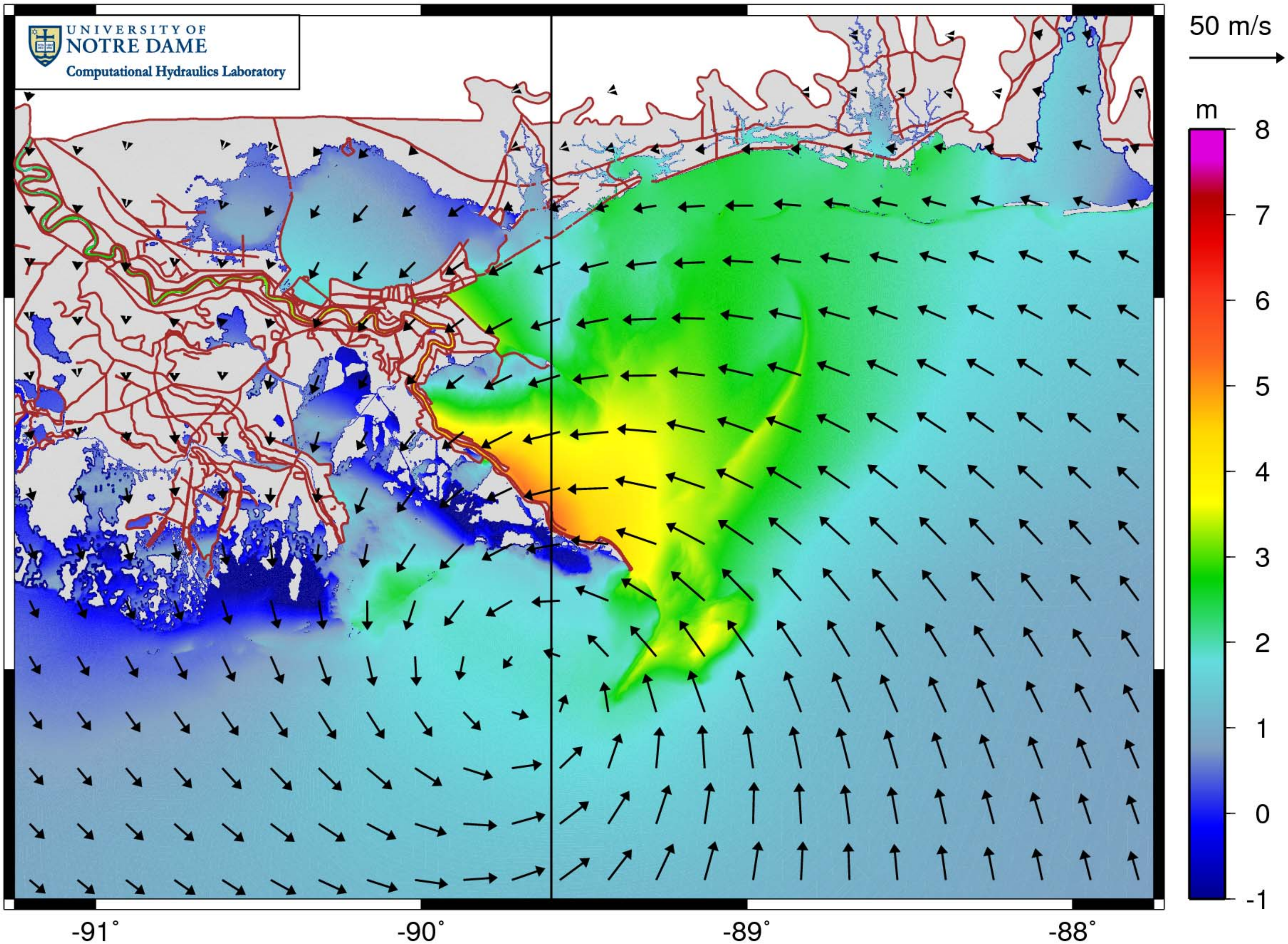
Katrina : Water Levels : 2005/08/29/0800Z



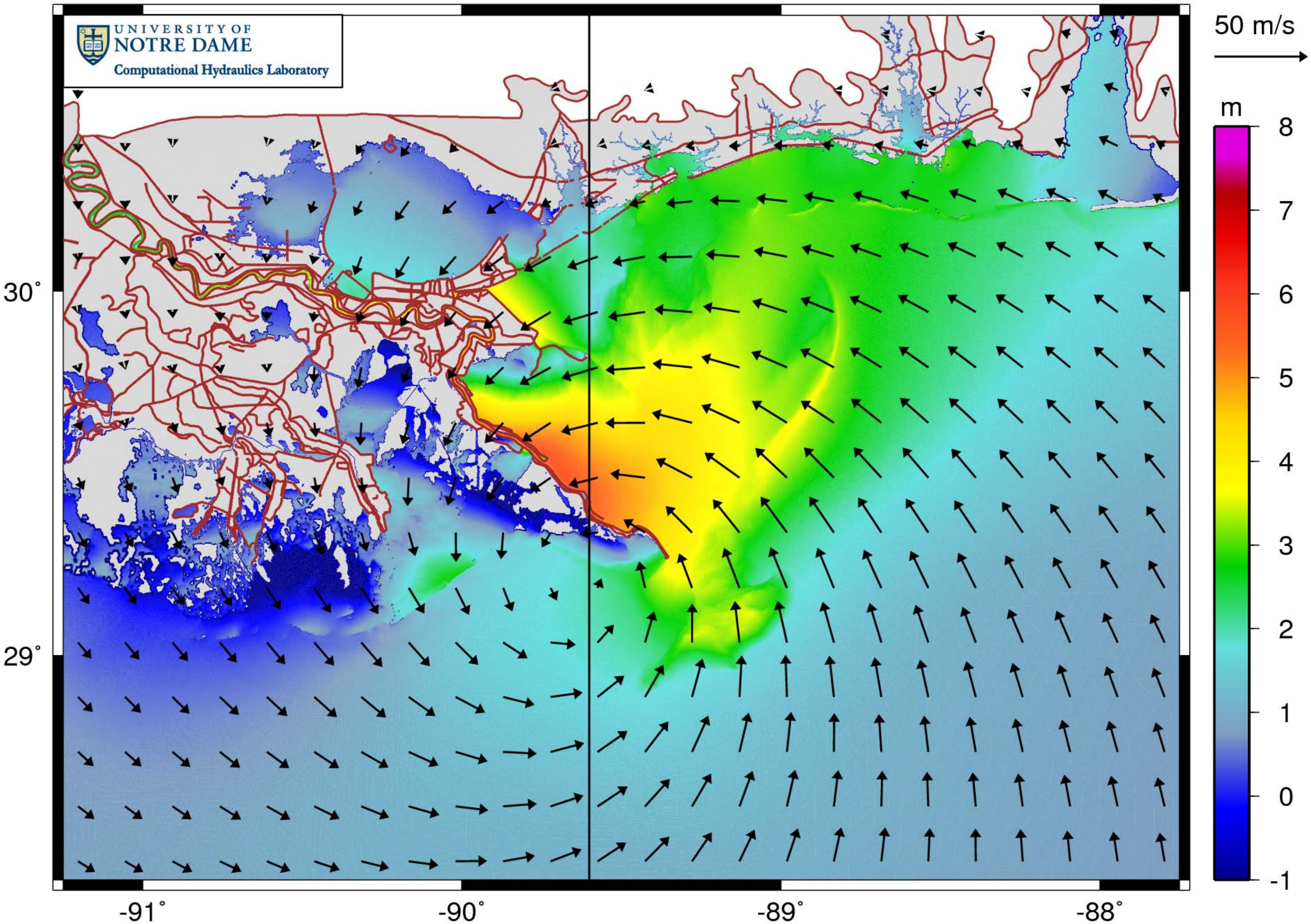
Katrina : Water Levels : 2005/08/29/0900Z



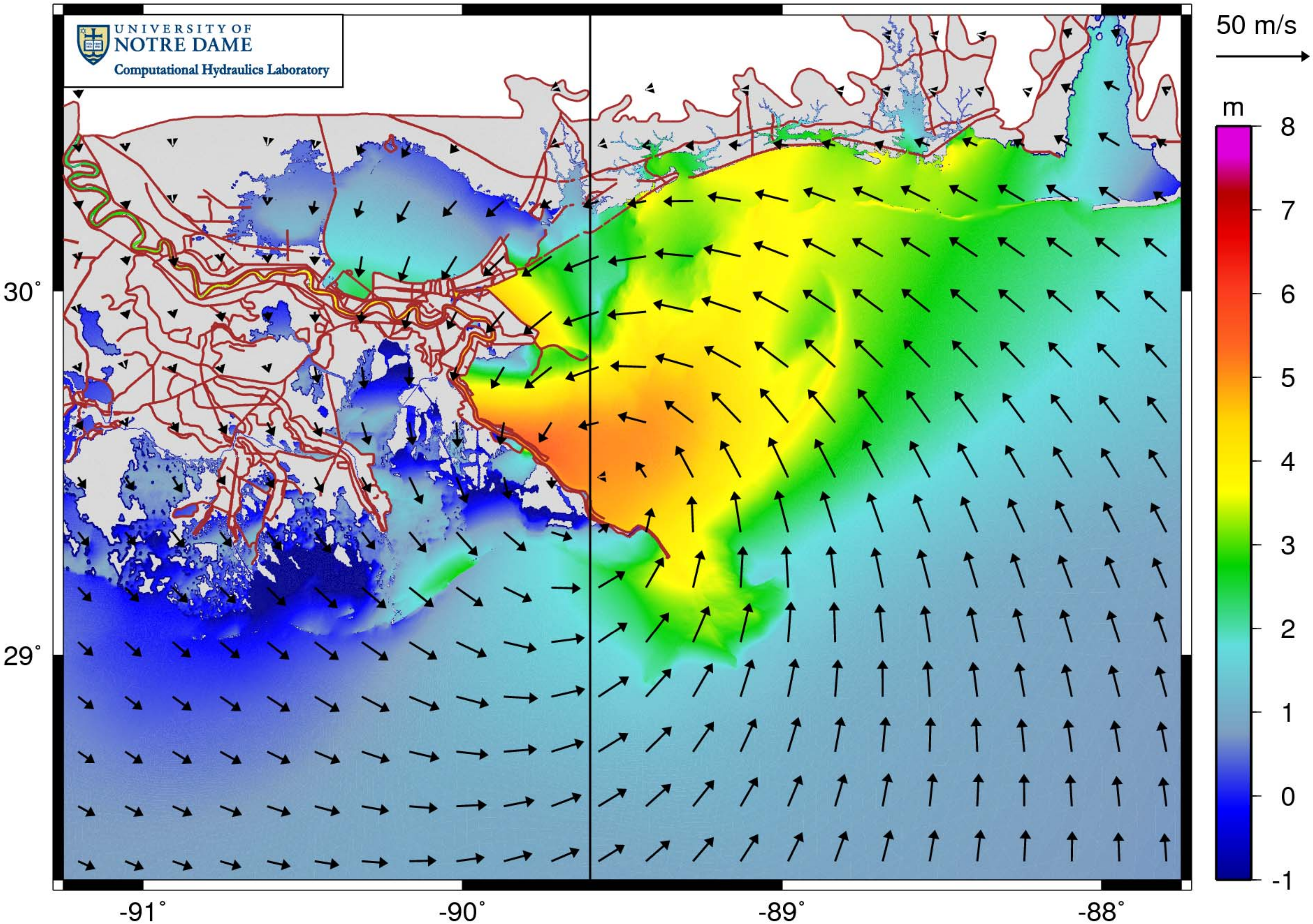
Katrina : Water Levels : 2005/08/29/1000Z



Katrina : Water Levels : 2005/08/29/1100Z



Katrina : Water Levels : 2005/08/29/1200Z



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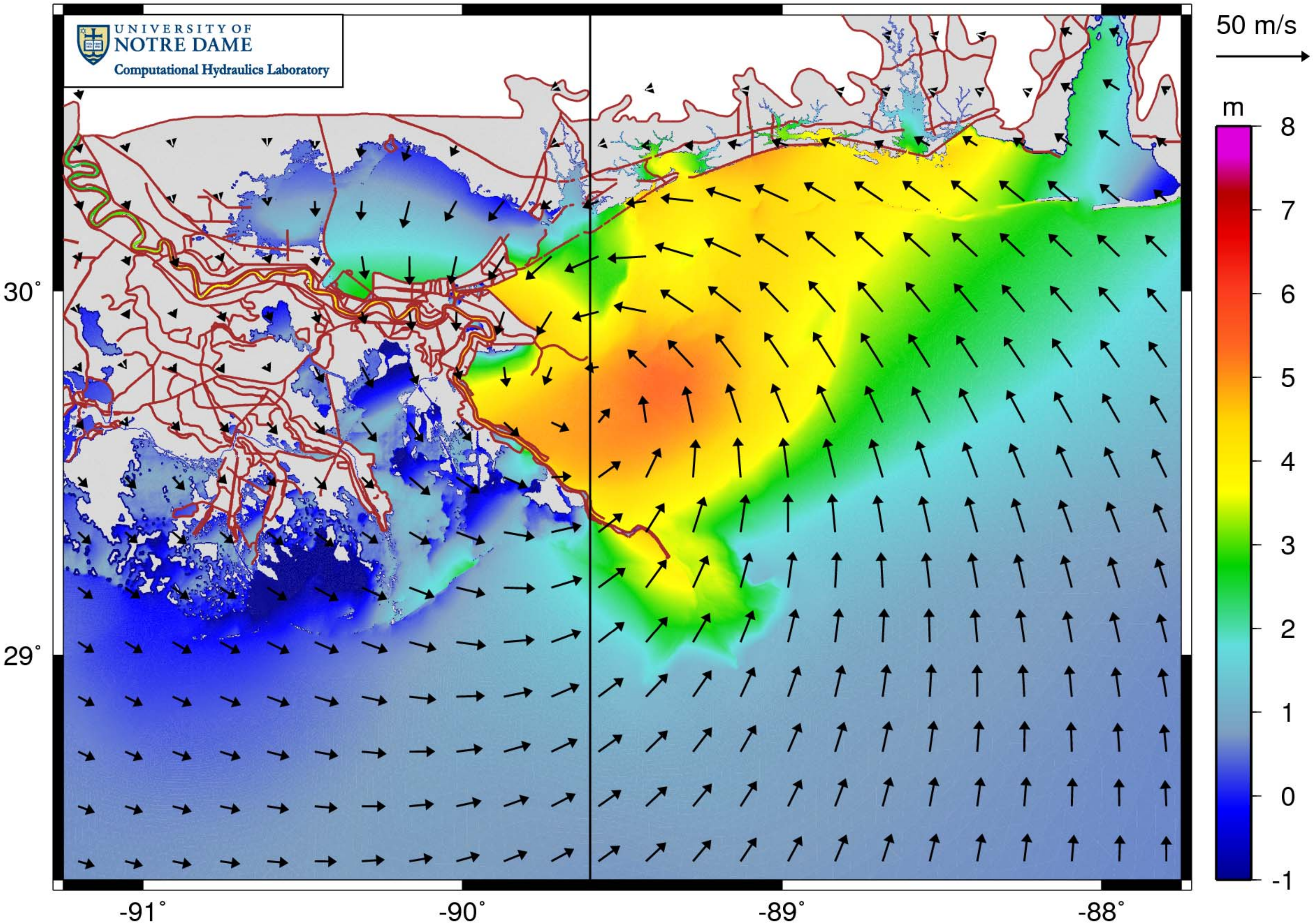
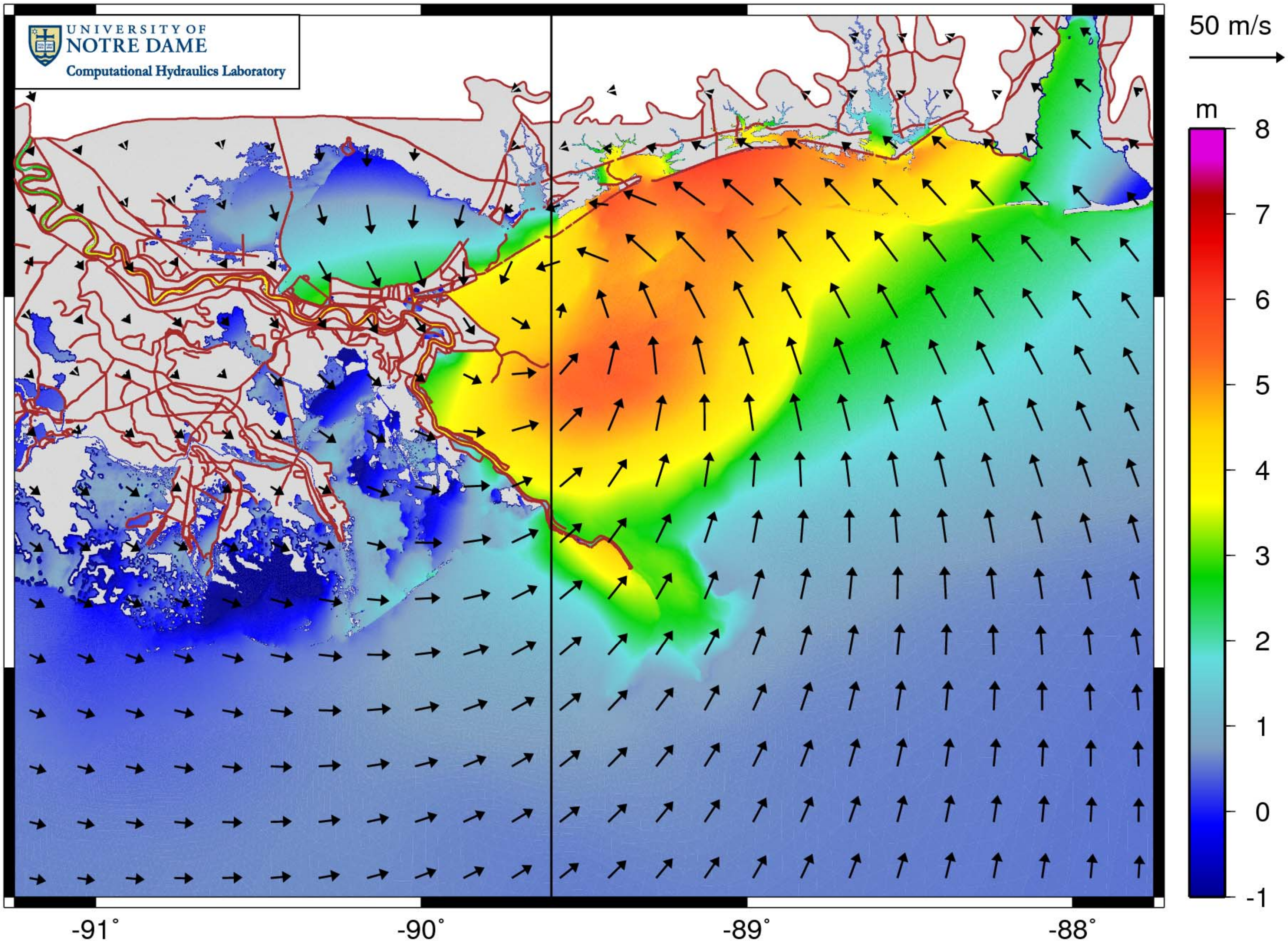
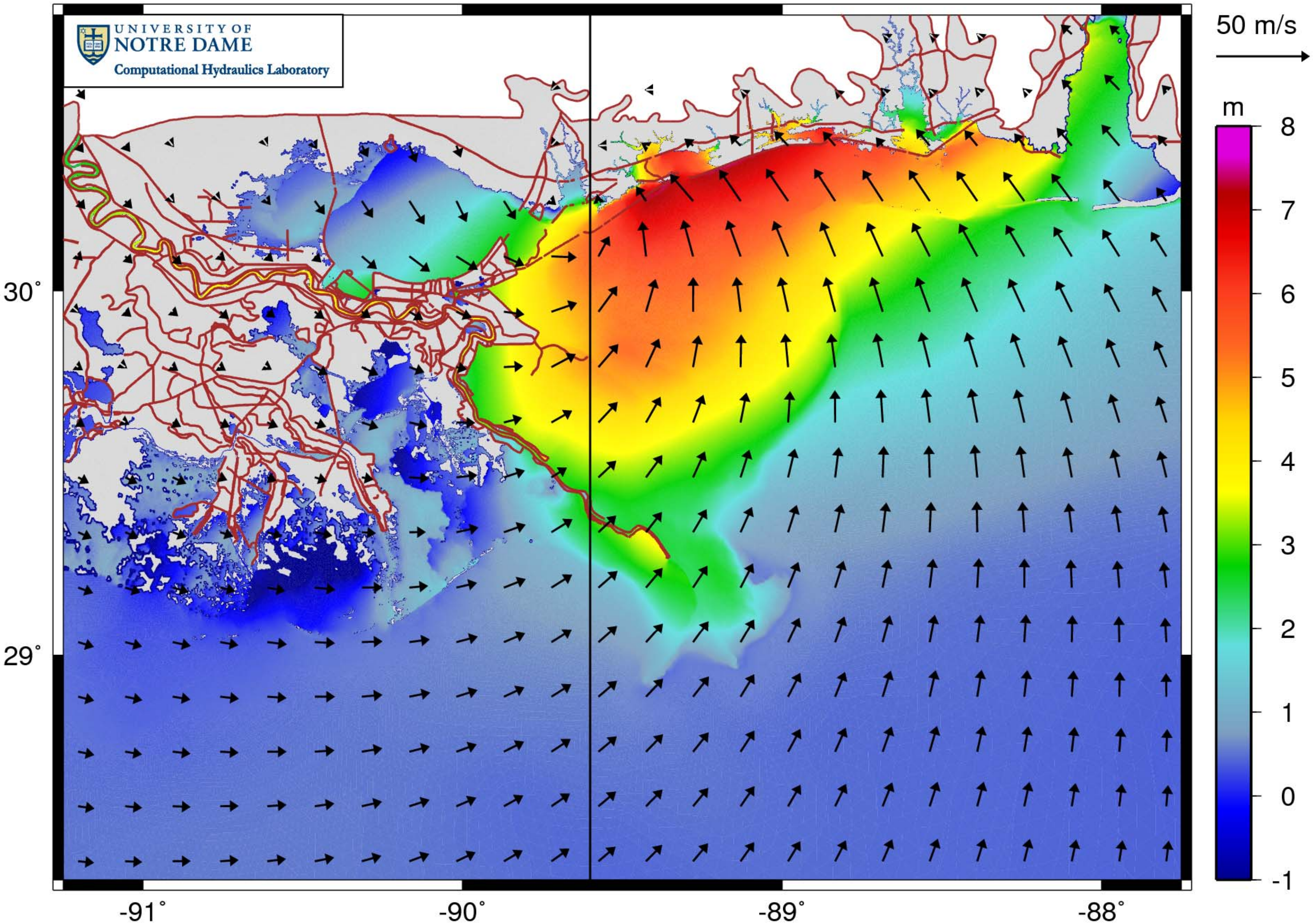


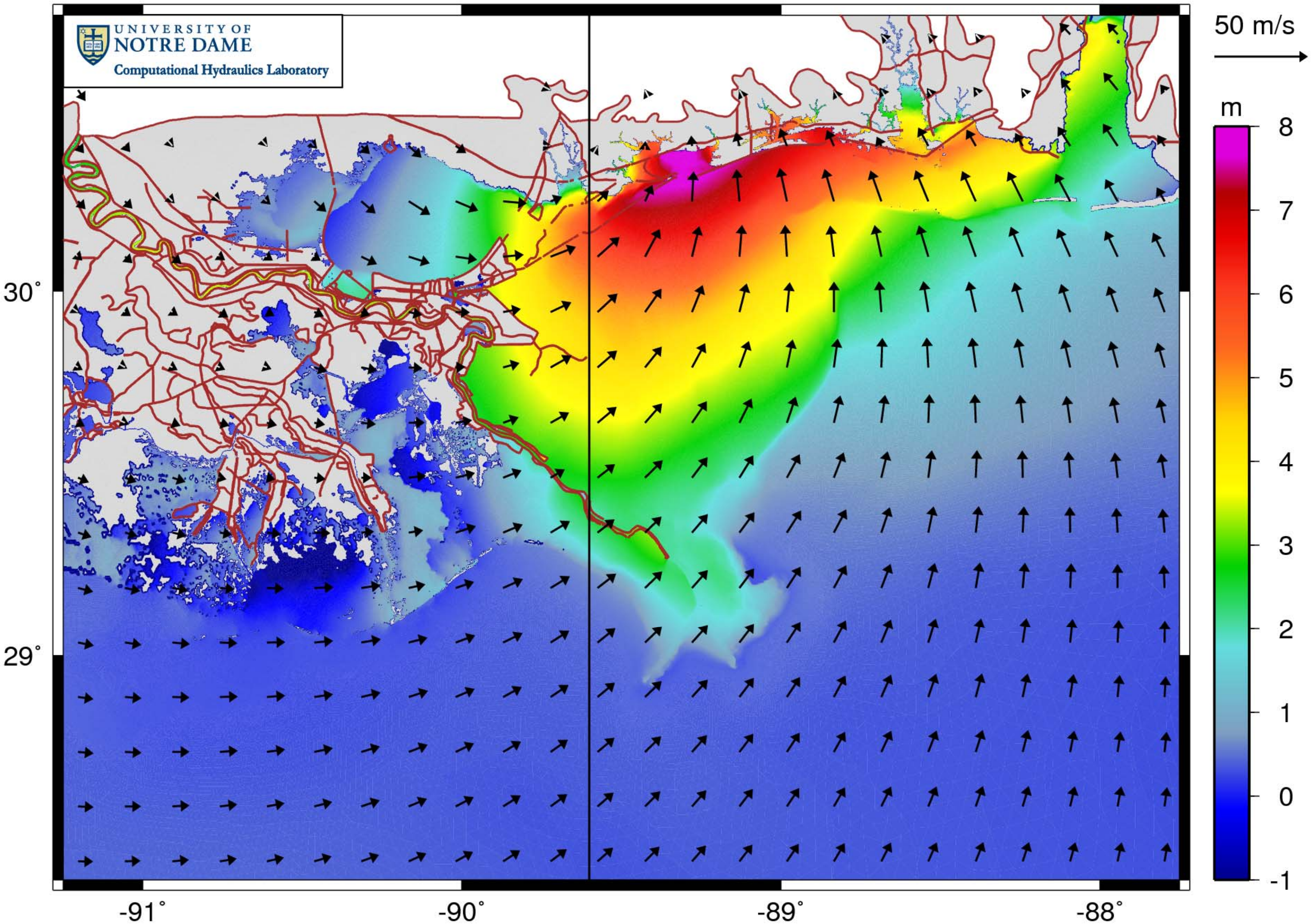
Katrina : Water Levels : 2005/08/29/1400Z



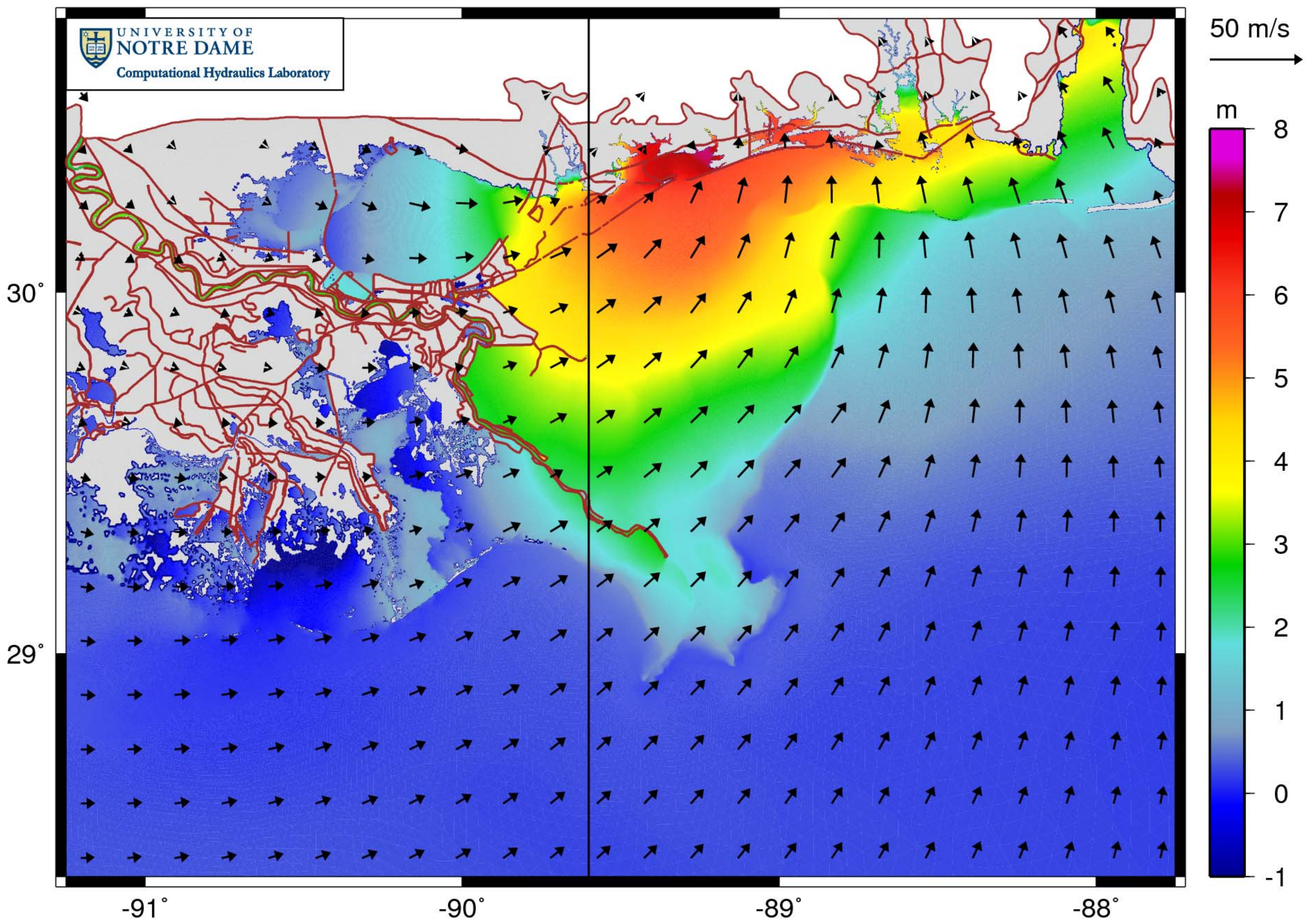
Katrina : Water Levels : 2005/08/29/1500Z



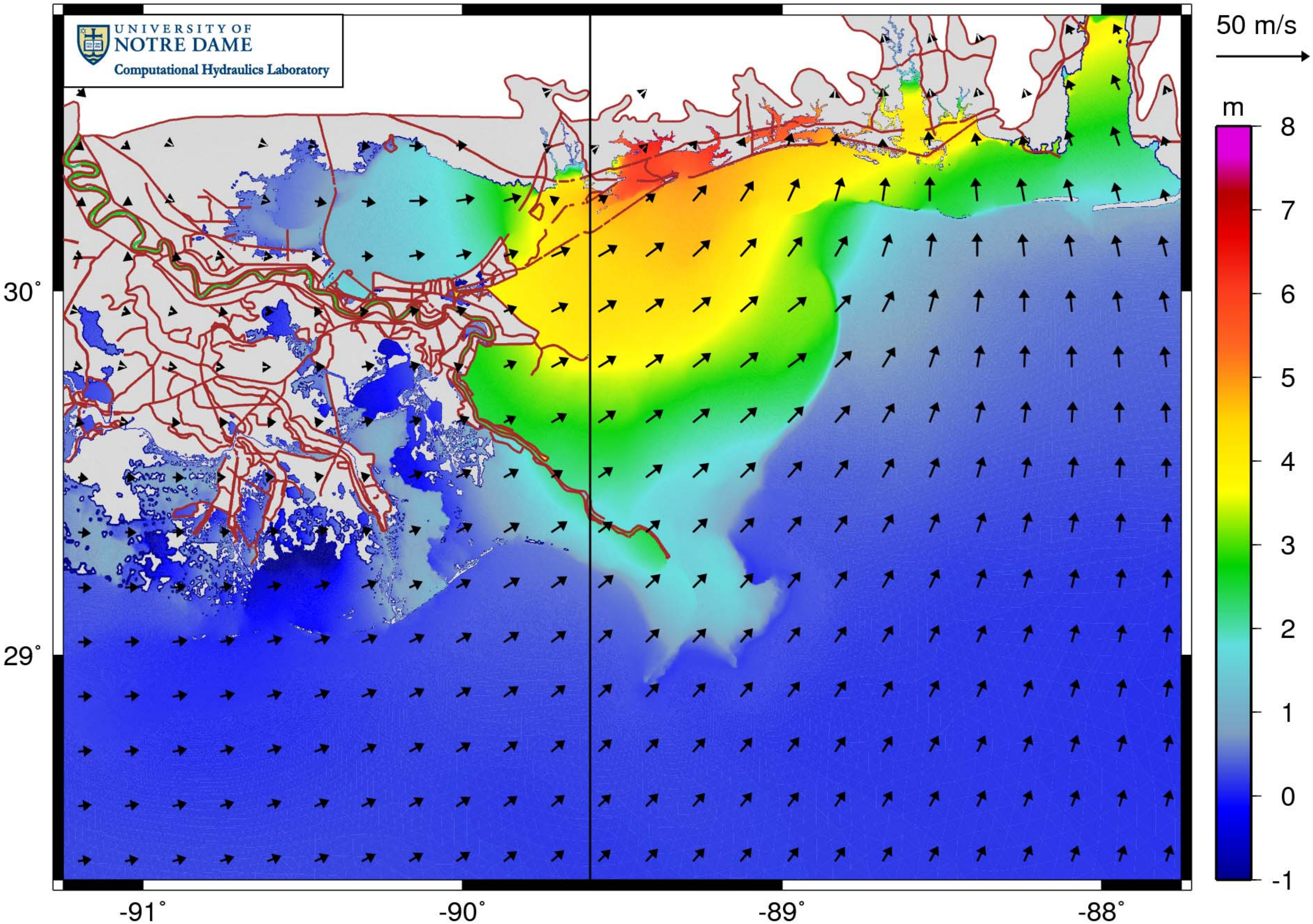
Katrina : Water Levels : 2005/08/29/1600Z



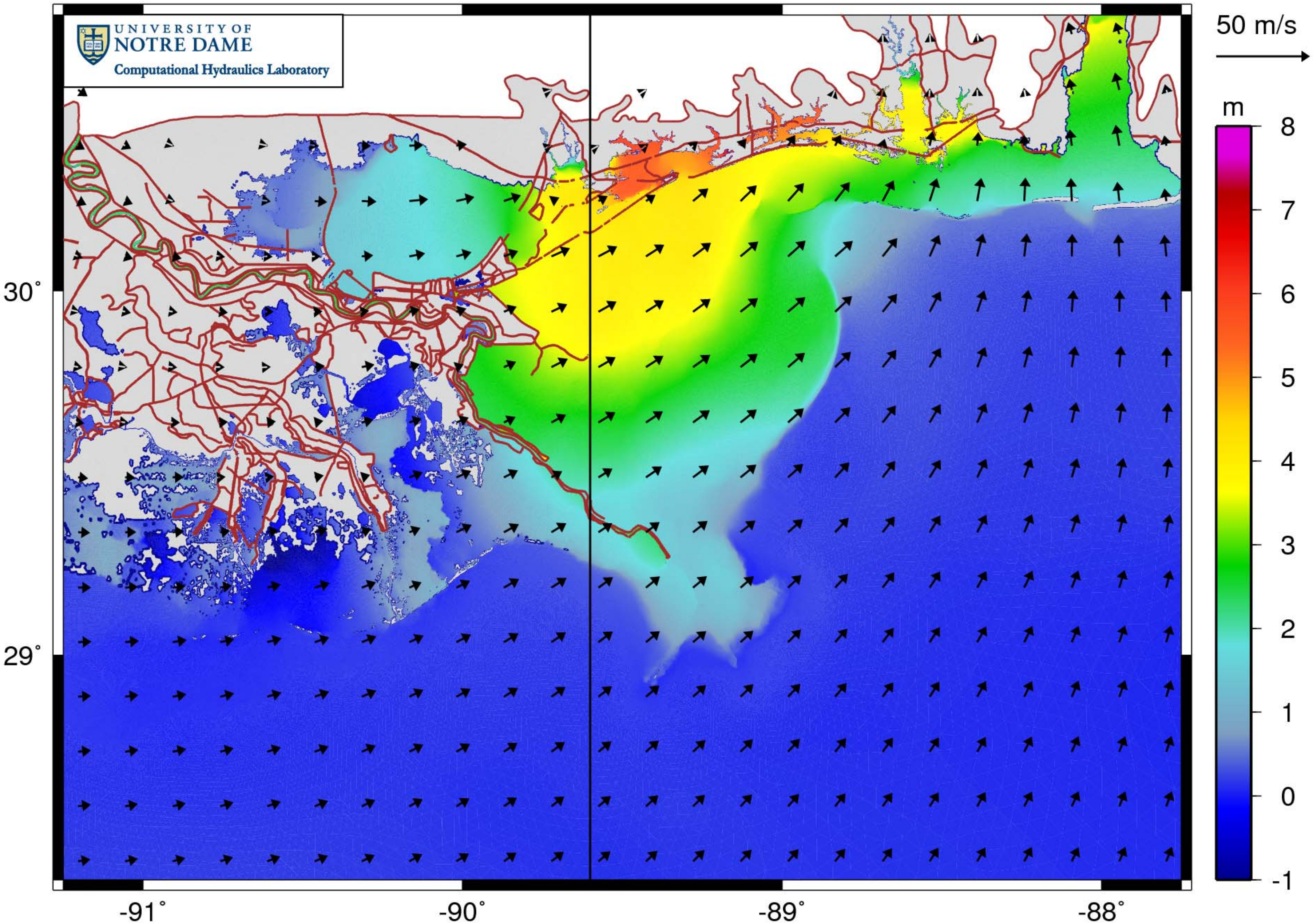
Katrina : Water Levels : 2005/08/29/1700Z



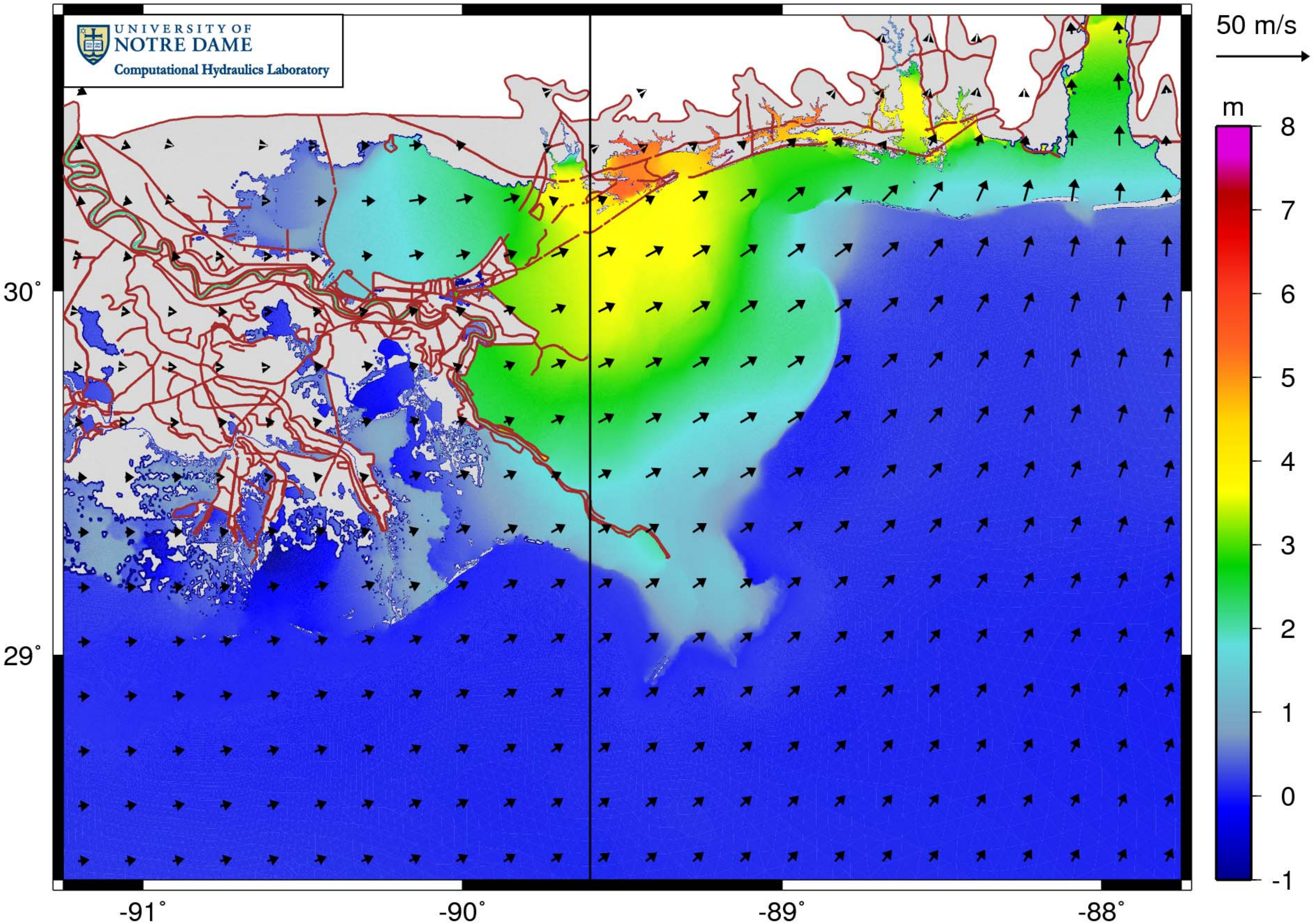
Katrina : Water Levels : 2005/08/29/1800Z



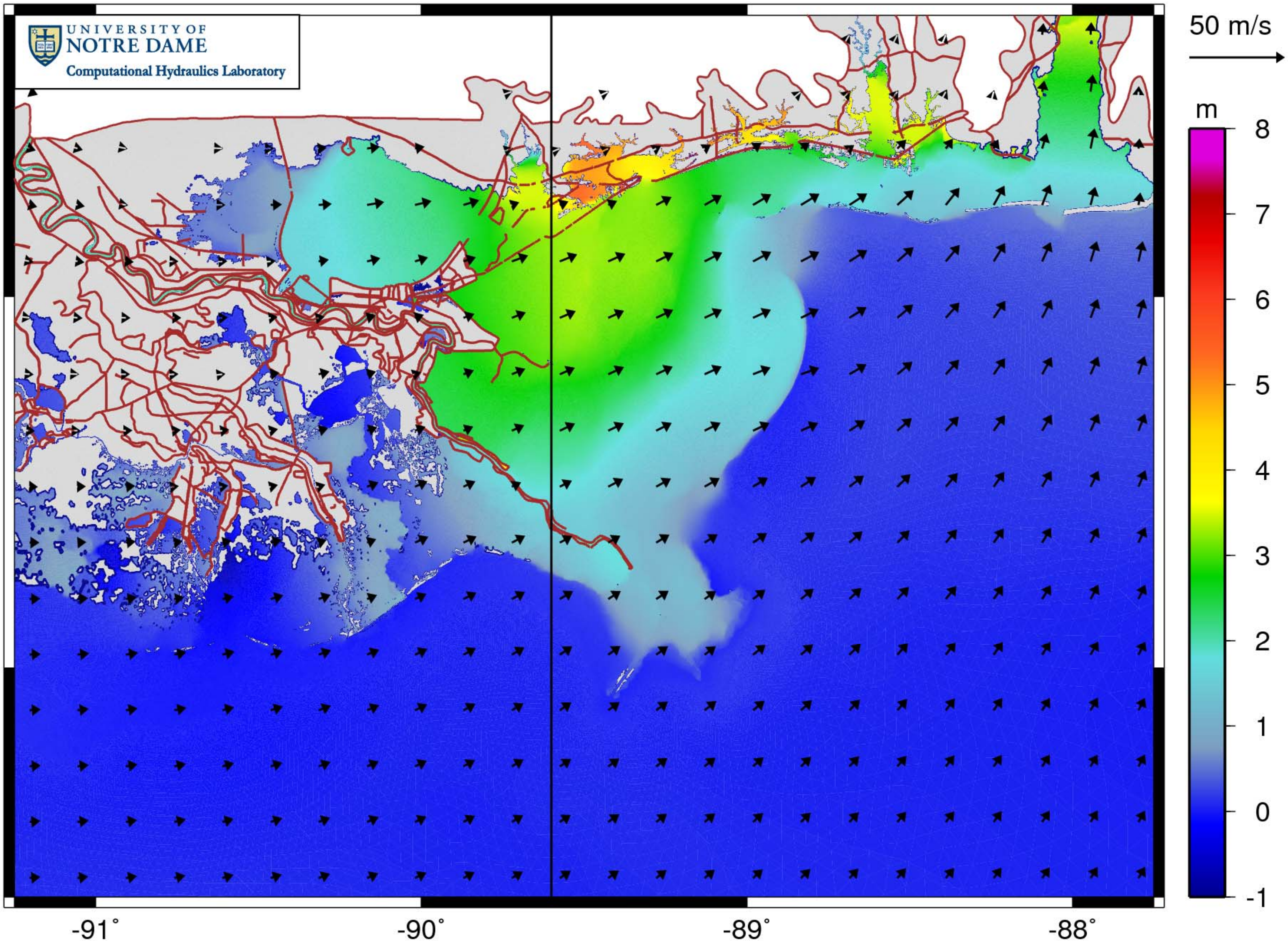
Katrina : Water Levels : 2005/08/29/1900Z



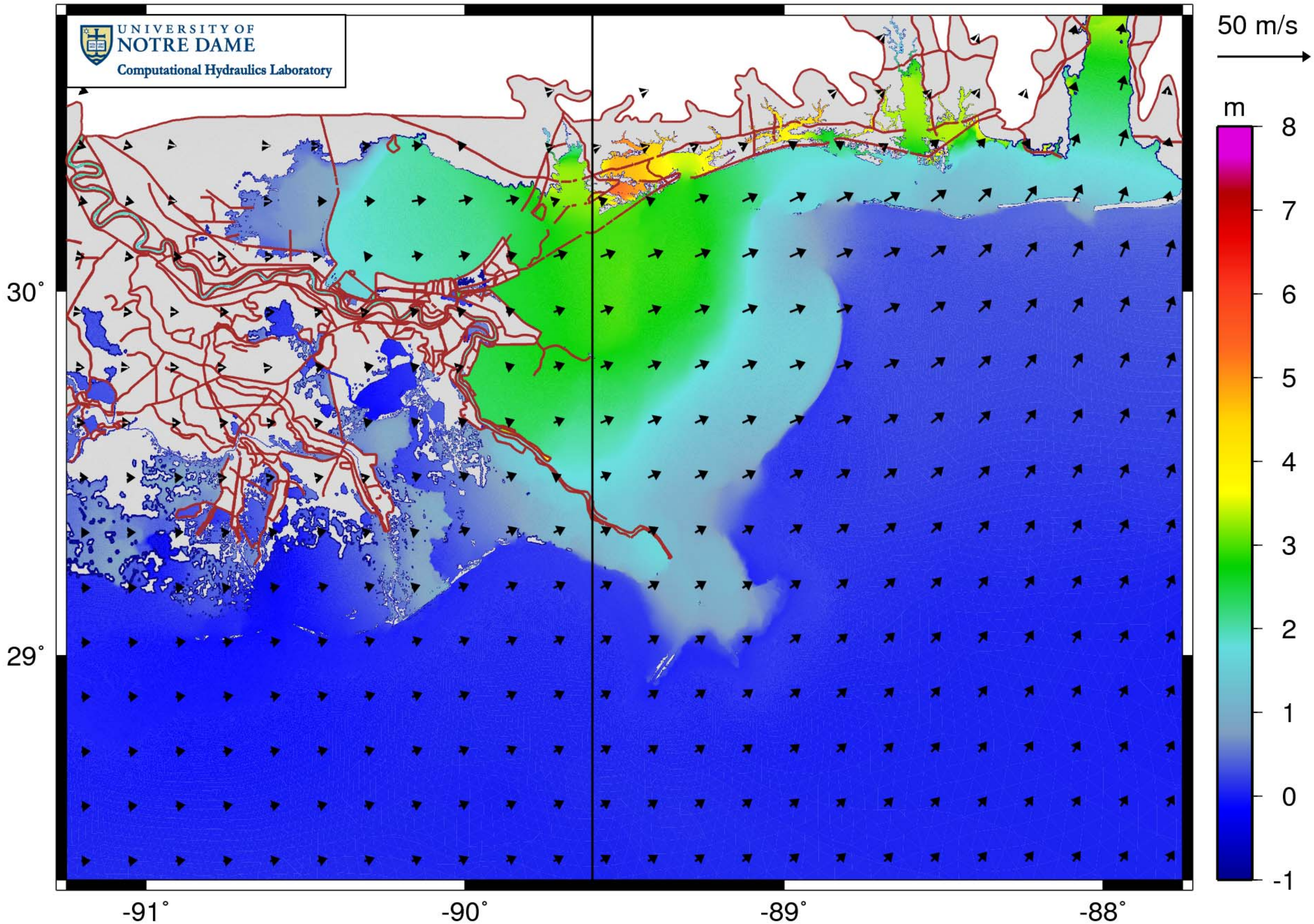
Katrina : Water Levels : 2005/08/29/2000Z



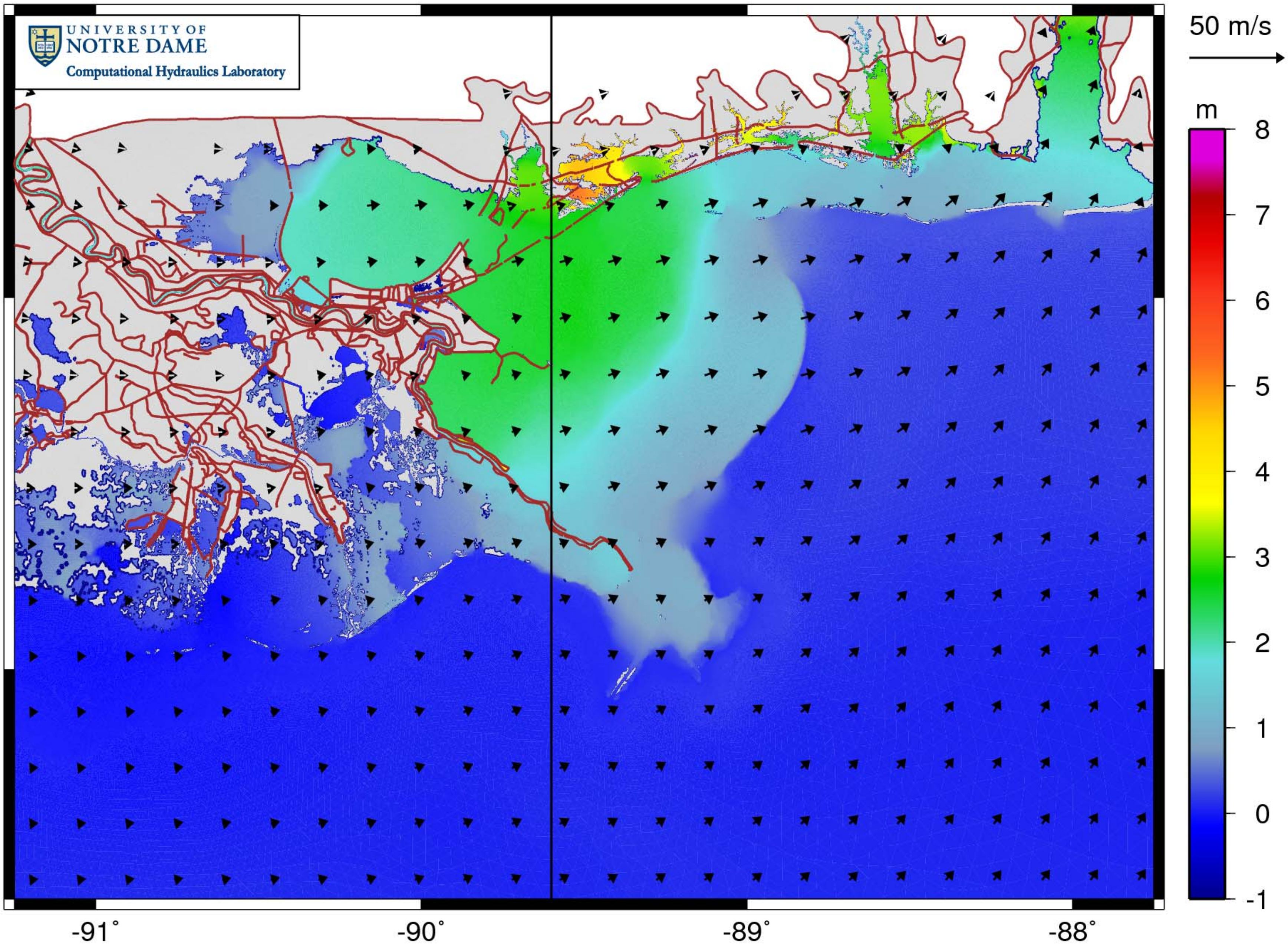
Katrina : Water Levels : 2005/08/29/2100Z



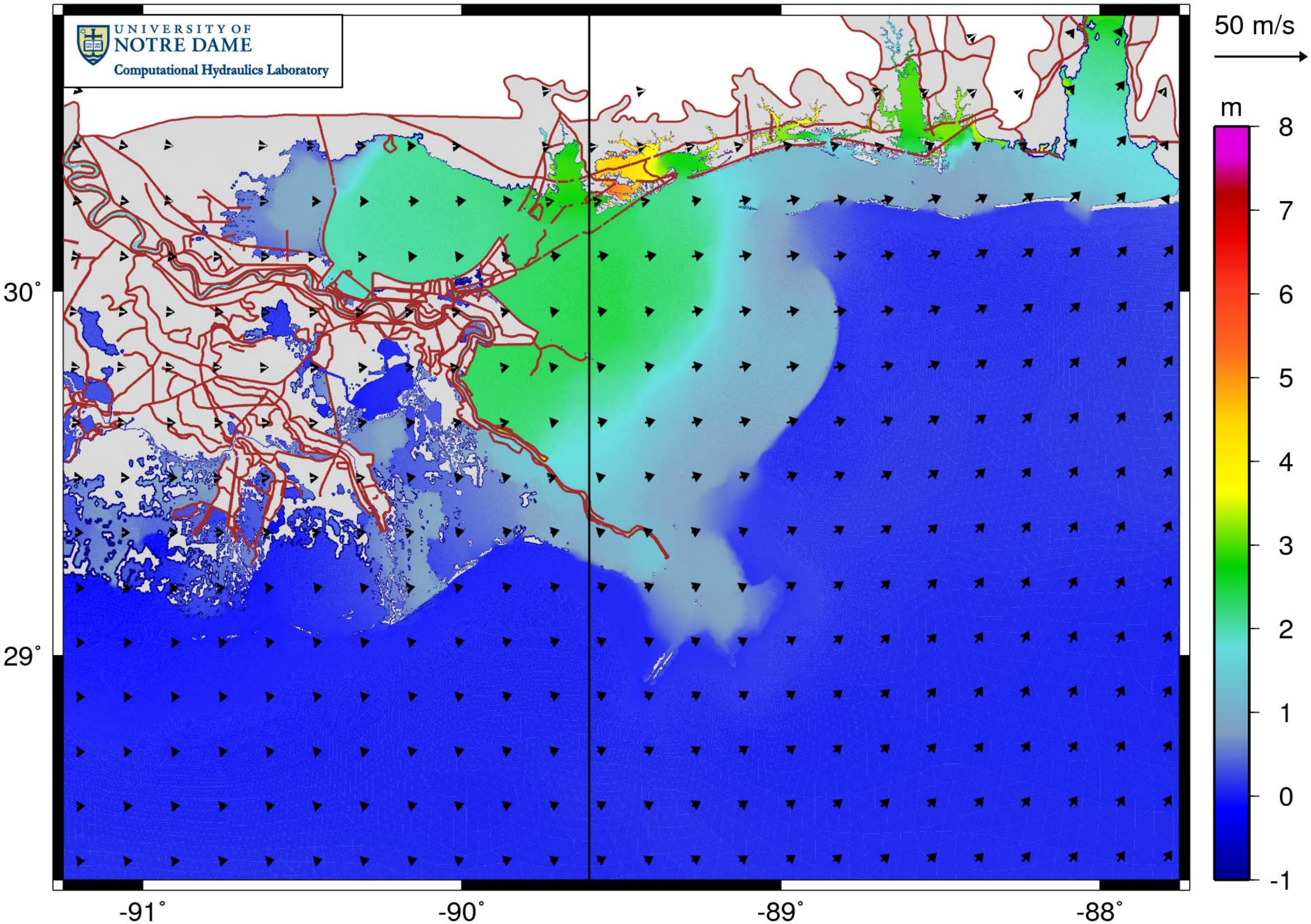
Katrina : Water Levels : 2005/08/29/2200Z



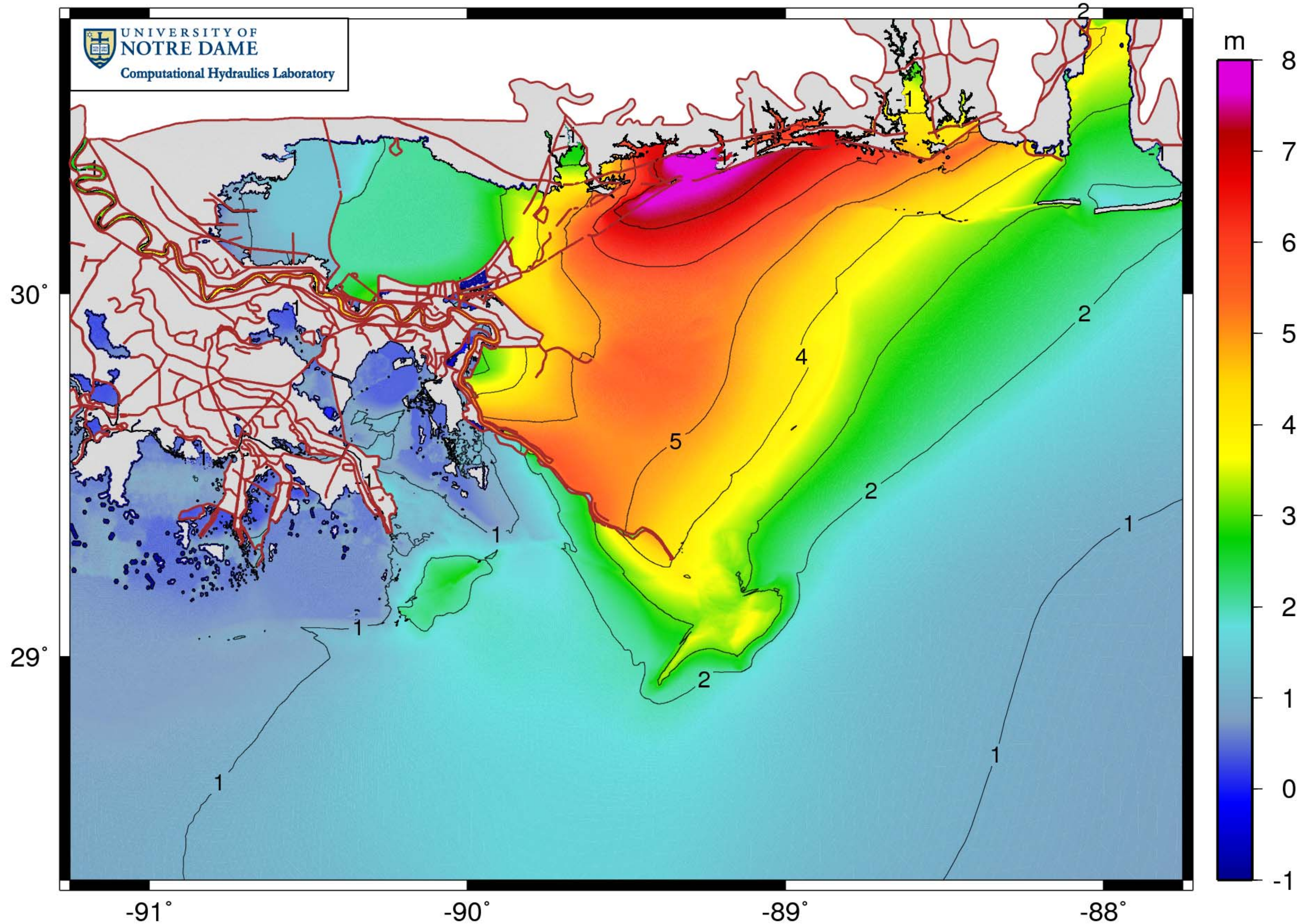
Katrina : Water Levels : 2005/08/29/2300Z



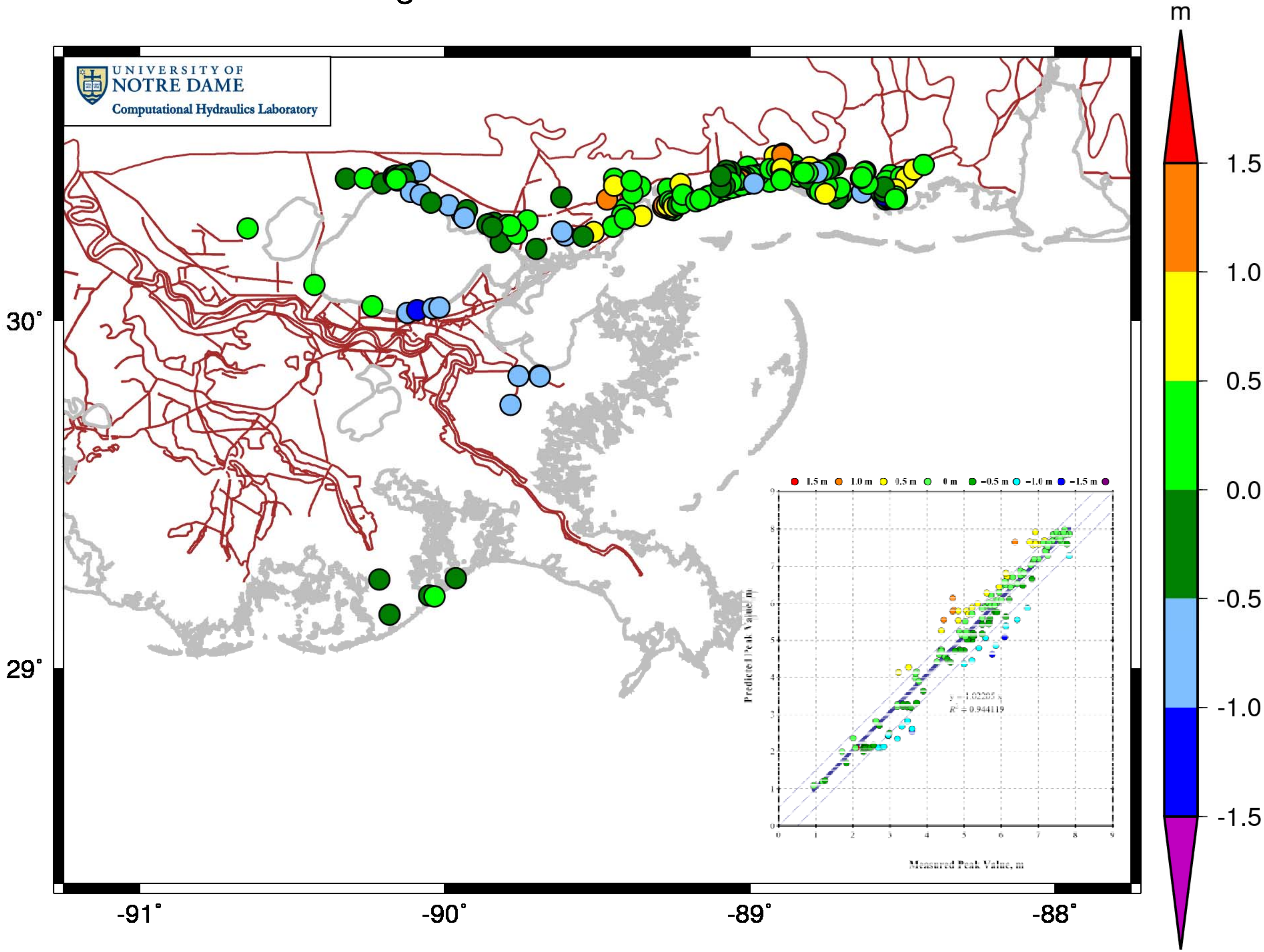
Katrina : Water Levels : 2005/08/30/0000Z



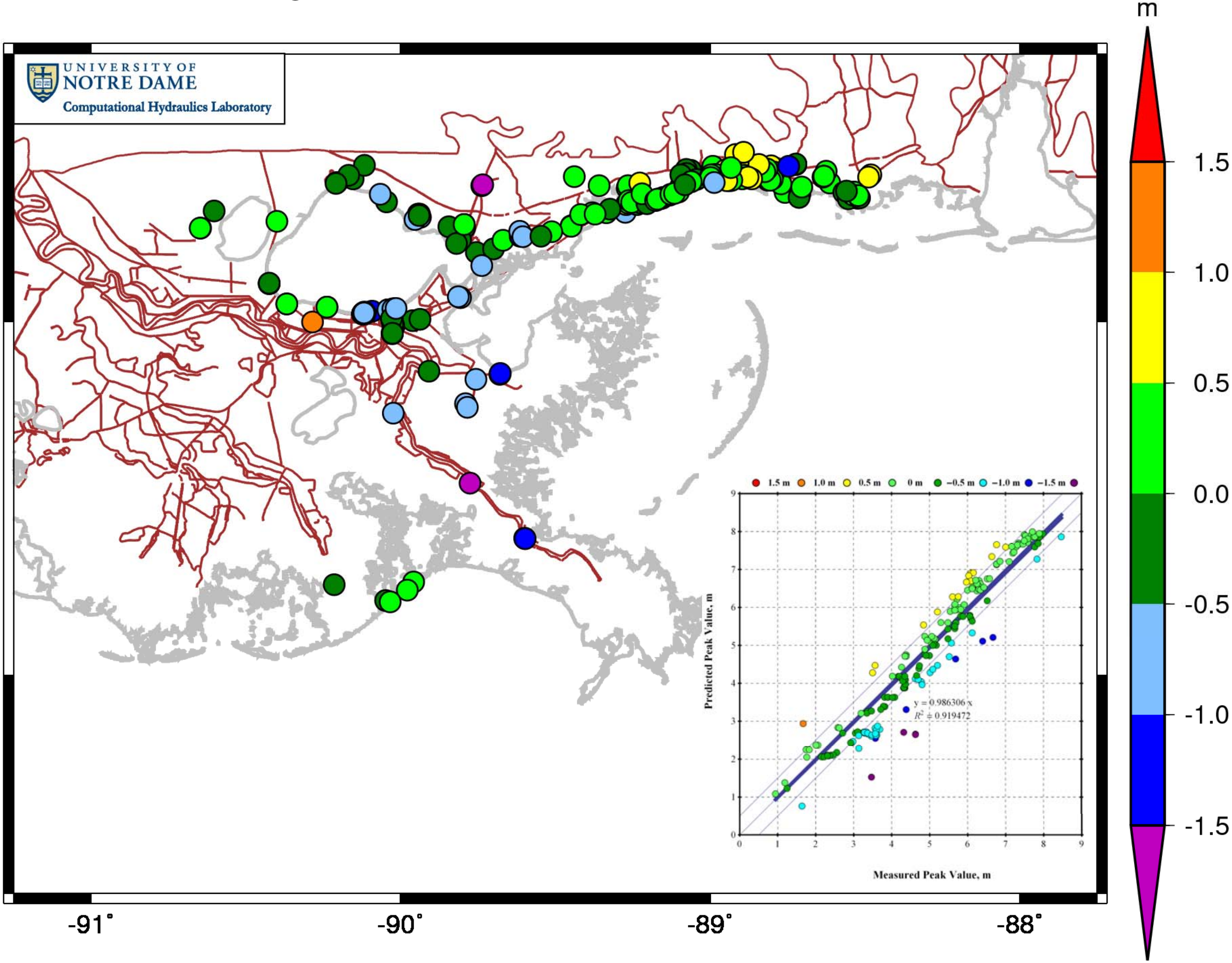
Katrina : Water Levels : Maximum



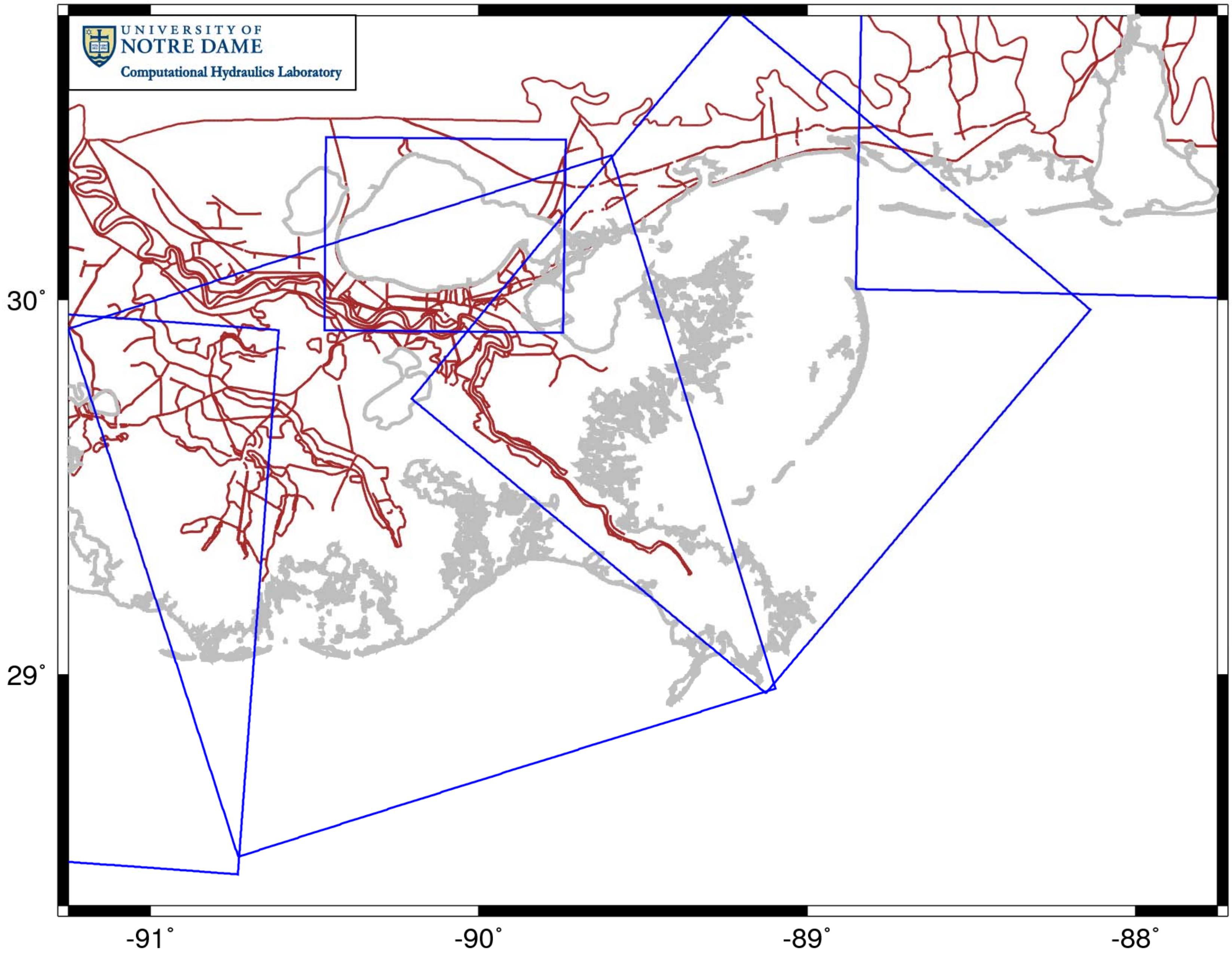
Katrina : URS/FEMA High-Water Marks



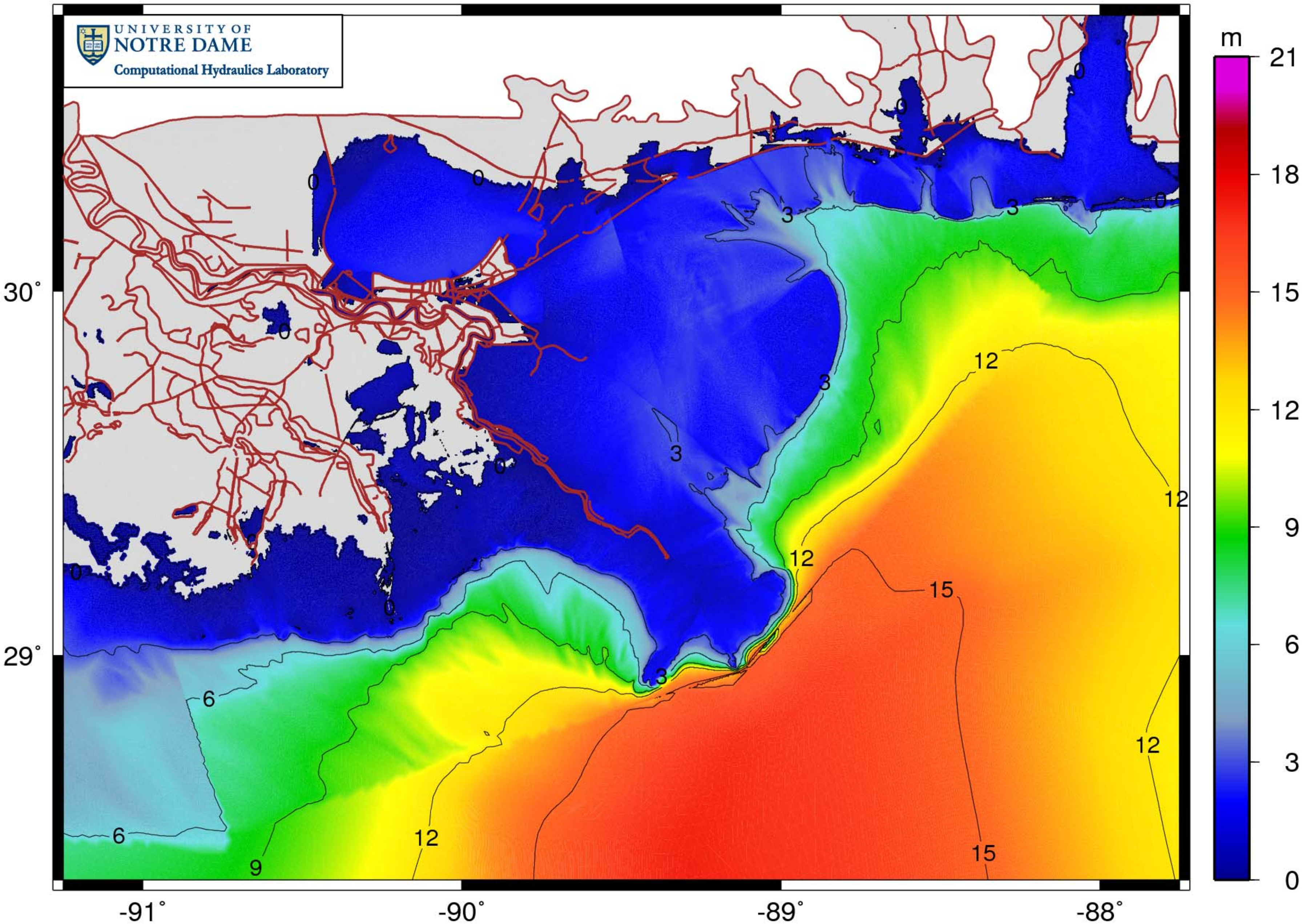
Katrina : USACE High-Water Marks



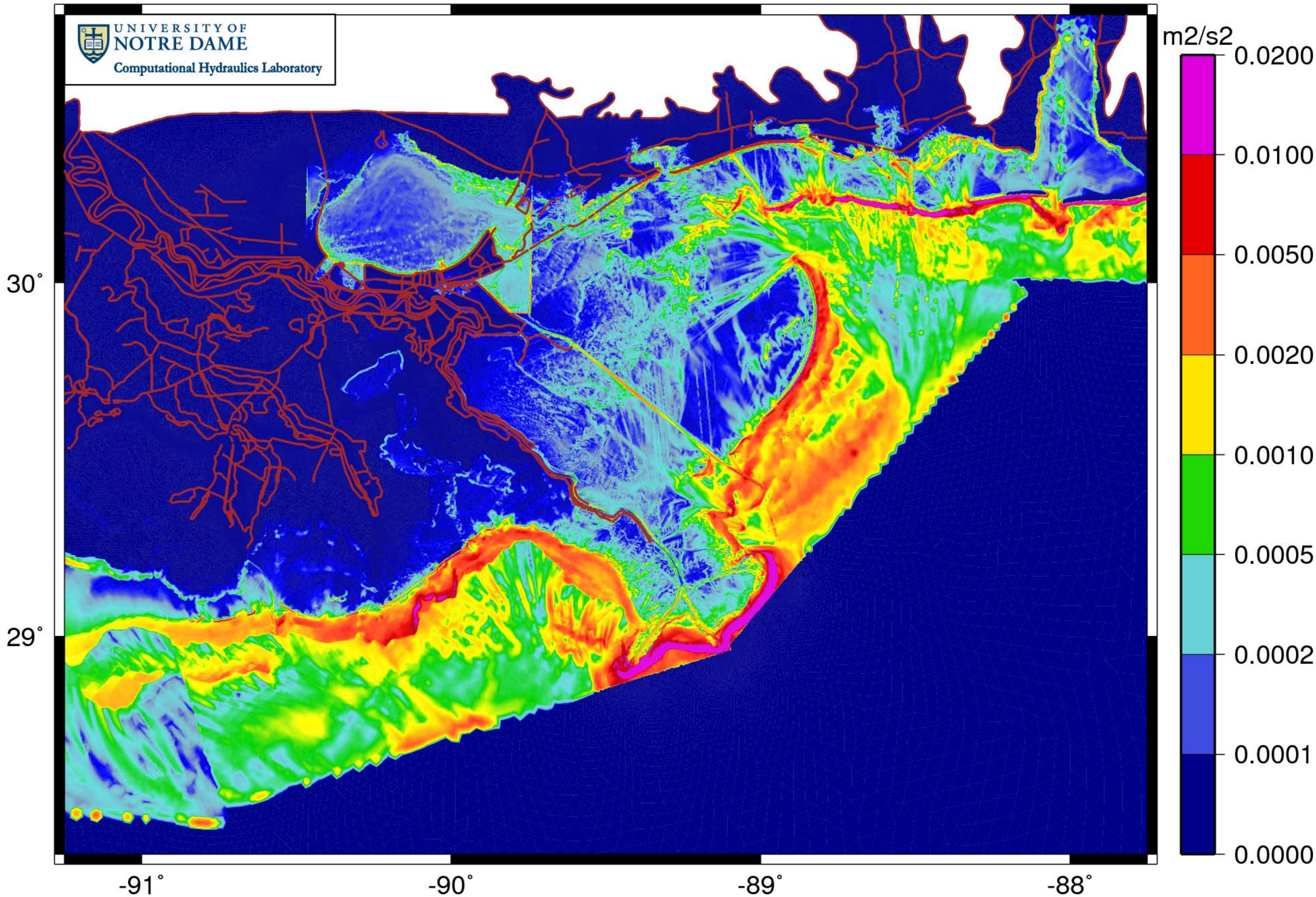
Katrina : Nearshore STWAVE Domains



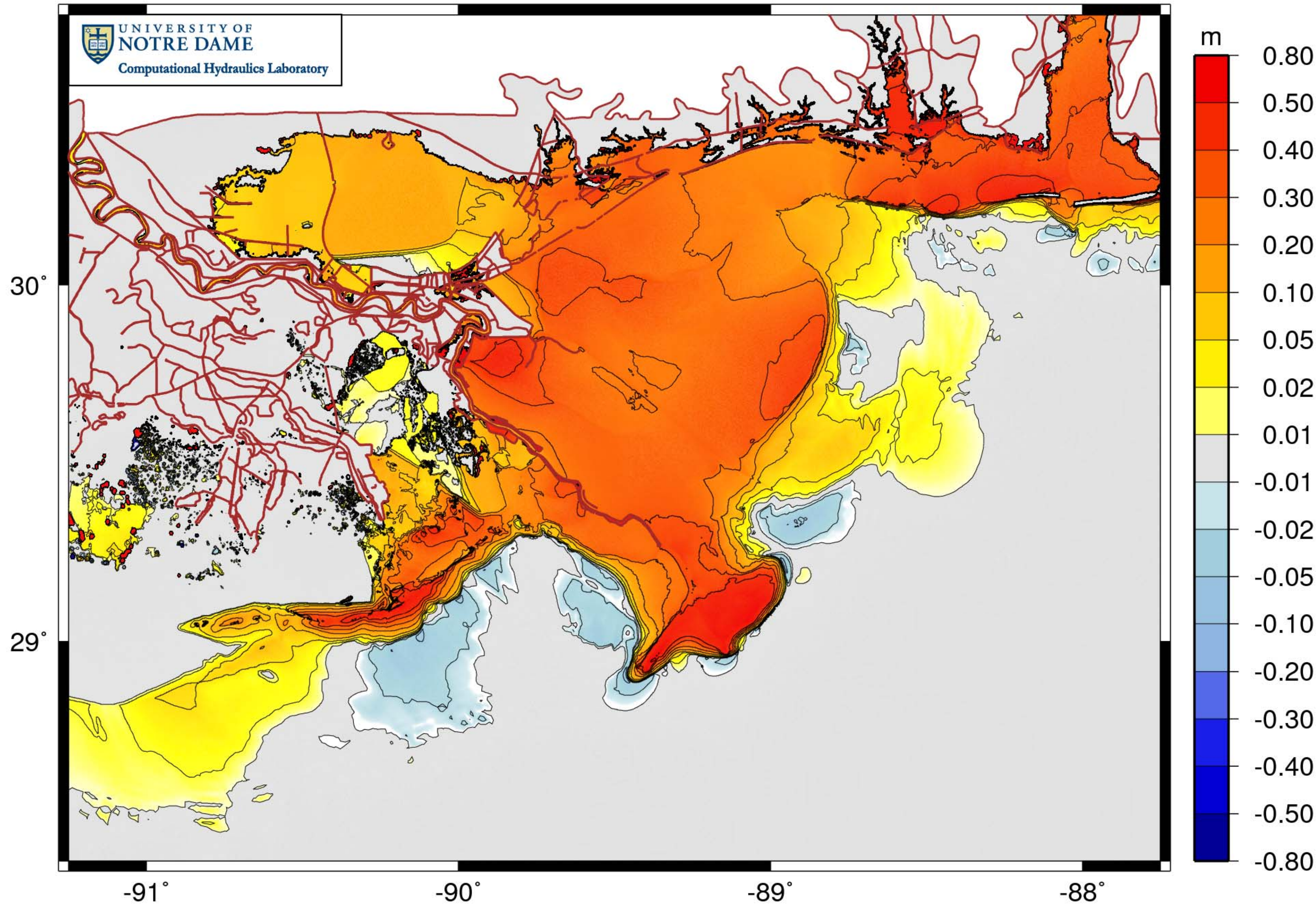
Katrina : Significant Wave Heights : Maximum



Katrina : Radiation Stress Gradients : Maximum



Katrina : Wave-Driven Setup : Maximum

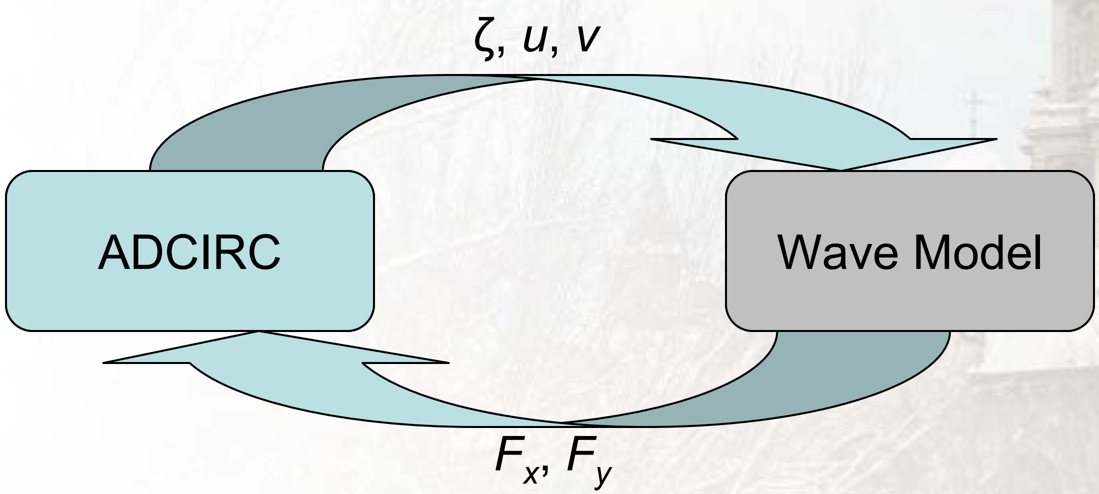


The Change:
‘Tight’ Coupling of SWAN+ADCIRC

J.C. Dietrich, *et al*. (2010). "Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations." *Journal of Atmospheric and Oceanic Technology*, in review.

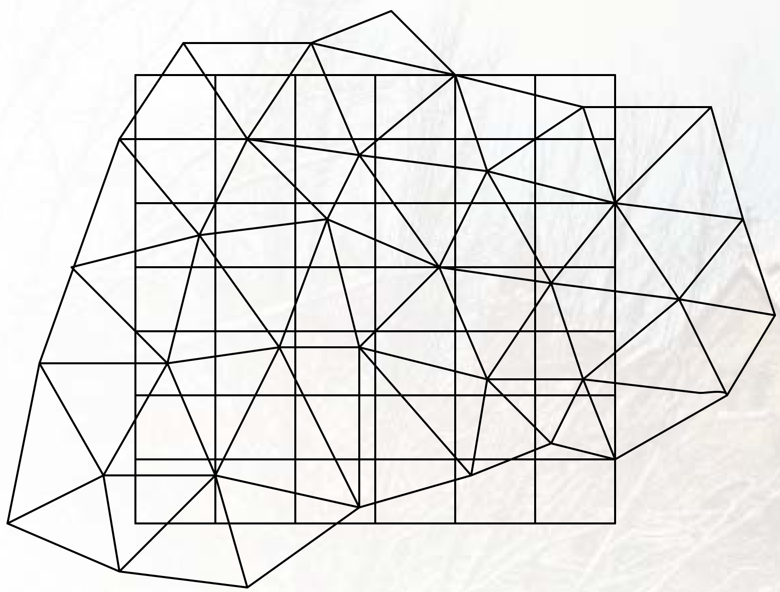
Disadvantages of ‘Loose’ Coupling

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



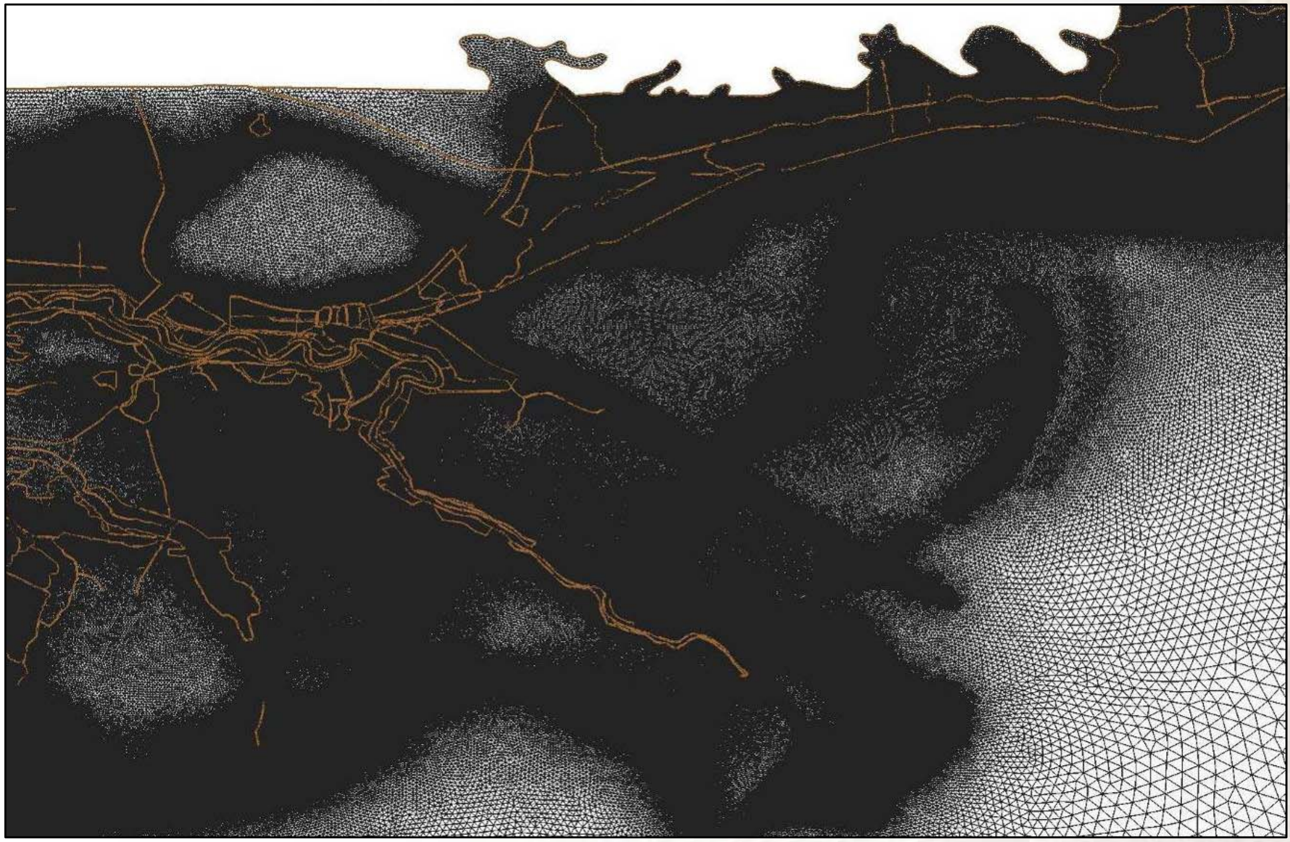
Disadvantages of 'Loose' Coupling

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:

- Developed by Booij, Holthuijsen, Zijlema at Delft University
- Non-phase-resolving, wave energy propagation model
- Solves the action balance equation:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \lambda}(c_{\lambda} N) + \frac{\partial}{\partial \varphi}(c_{\varphi} N) + \frac{\partial}{\partial \sigma}(c_{\sigma} N) + \frac{\partial}{\partial \theta}(c_{\theta} N) = \frac{S_{tot}}{\sigma}$$

where: $N(\sigma,\theta)$ is the action density; c_{λ} and c_{φ} are the propagation velocities in geographic space (λ,φ); c_{σ} and c_{θ} are the propagation velocities in spectral space (σ,θ); and S_{tot} is the source/sink term that represents wave generation, dissipation, etc.

‘Tight’ Coupling of SWAN+ADCIRC

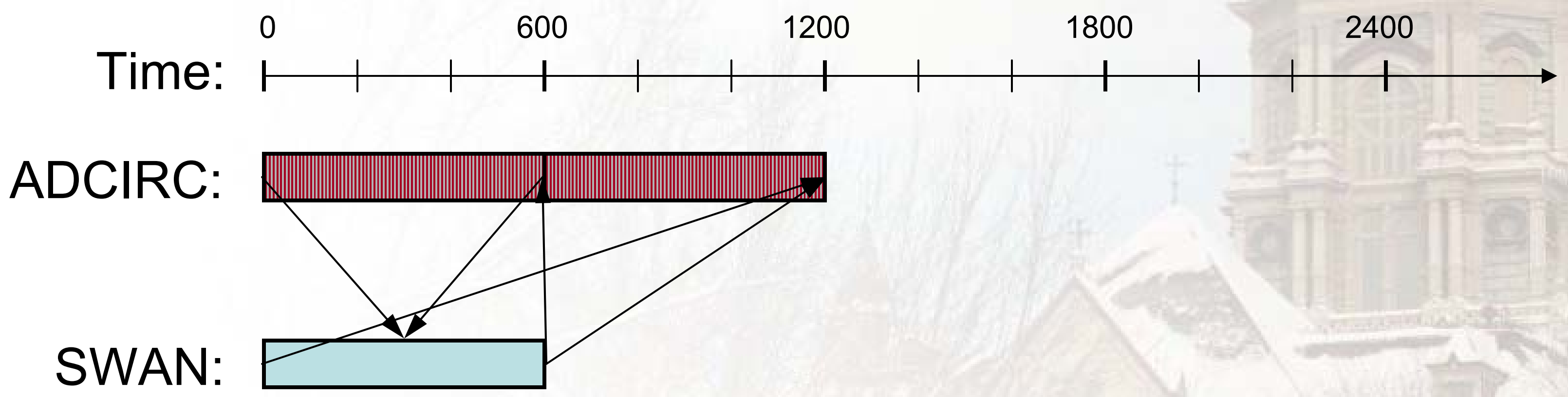
Advantages:

- SWAN and ADCIRC run on the same mesh
  - No nesting of meshes
  - No overlapping of meshes
- SWAN and ADCIRC run on the same core
  - No interpolation
  - No global message passing
- Optimization of code
  - No iteration of models
  - No overhead for coupling modeling framework
  - Utilize shared memory on multi-core processors
- Optimization of physics
  - No need for directionality in wave model
  - Dynamic *h*- and *p*-adaptivity

‘Tight’ Coupling of SWAN+ADCIRC

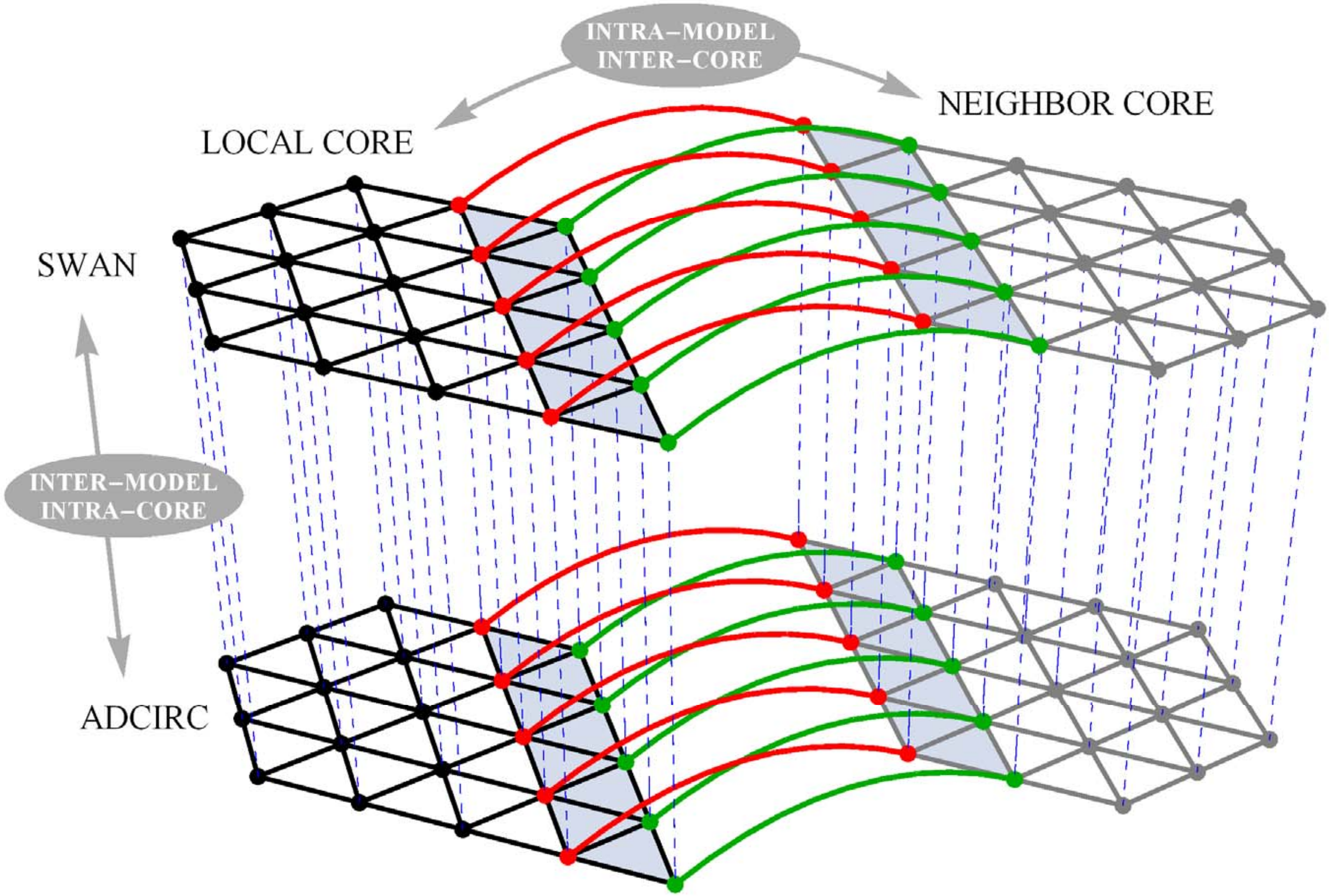
Schematic of Coupling:

- 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_{xx}, S_{xy}, S_{yy}) and their gradients (F_x, F_y) are computed; gradients are passed to ADCIRC
- Repeat

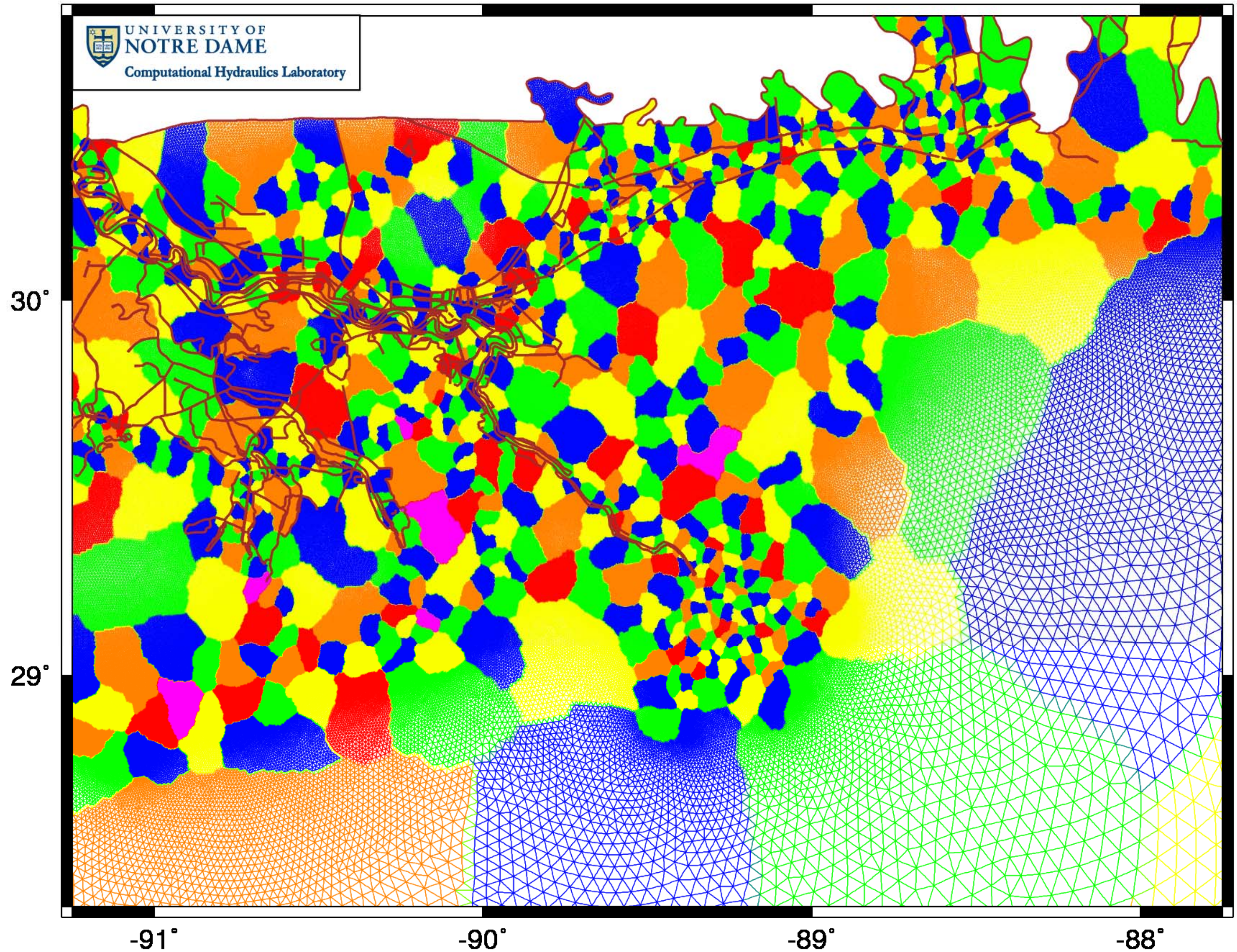


- SWAN and ADCIRC are always extrapolating in time

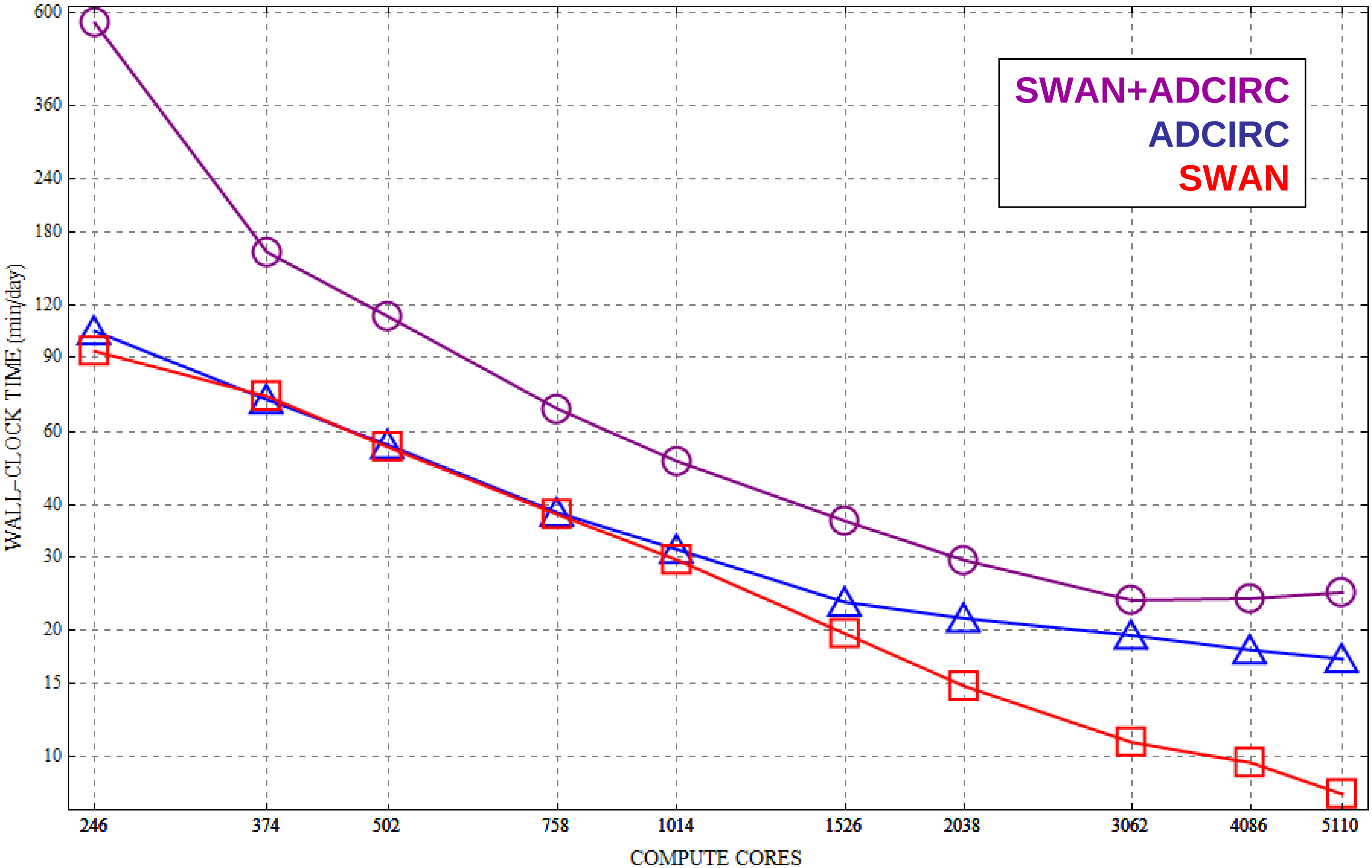
'Tight' Coupling of SWAN+ADCIRC



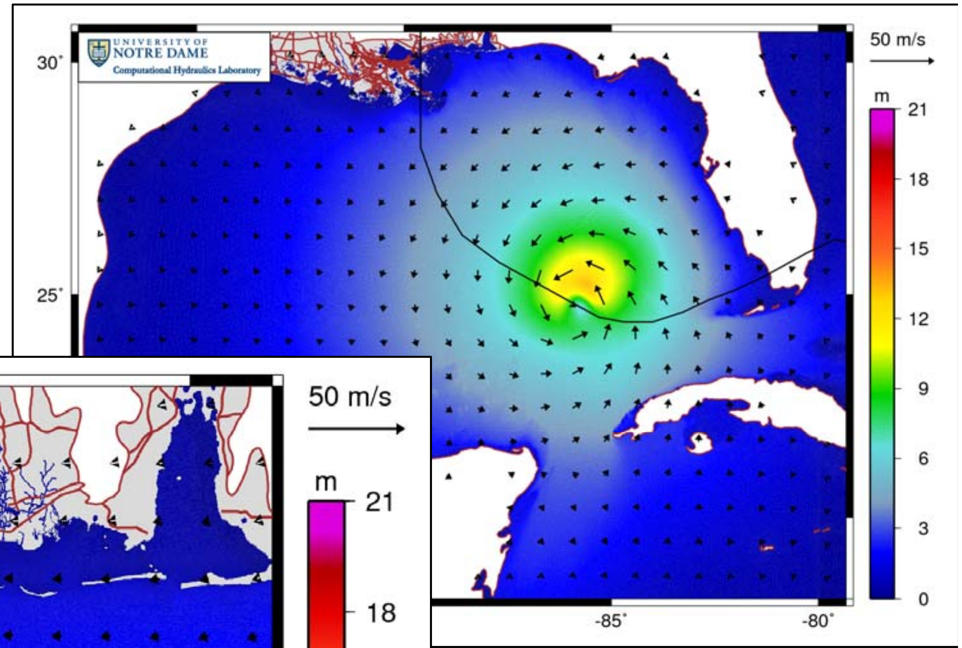
‘Tight’ Coupling of SWAN+ADCIRC

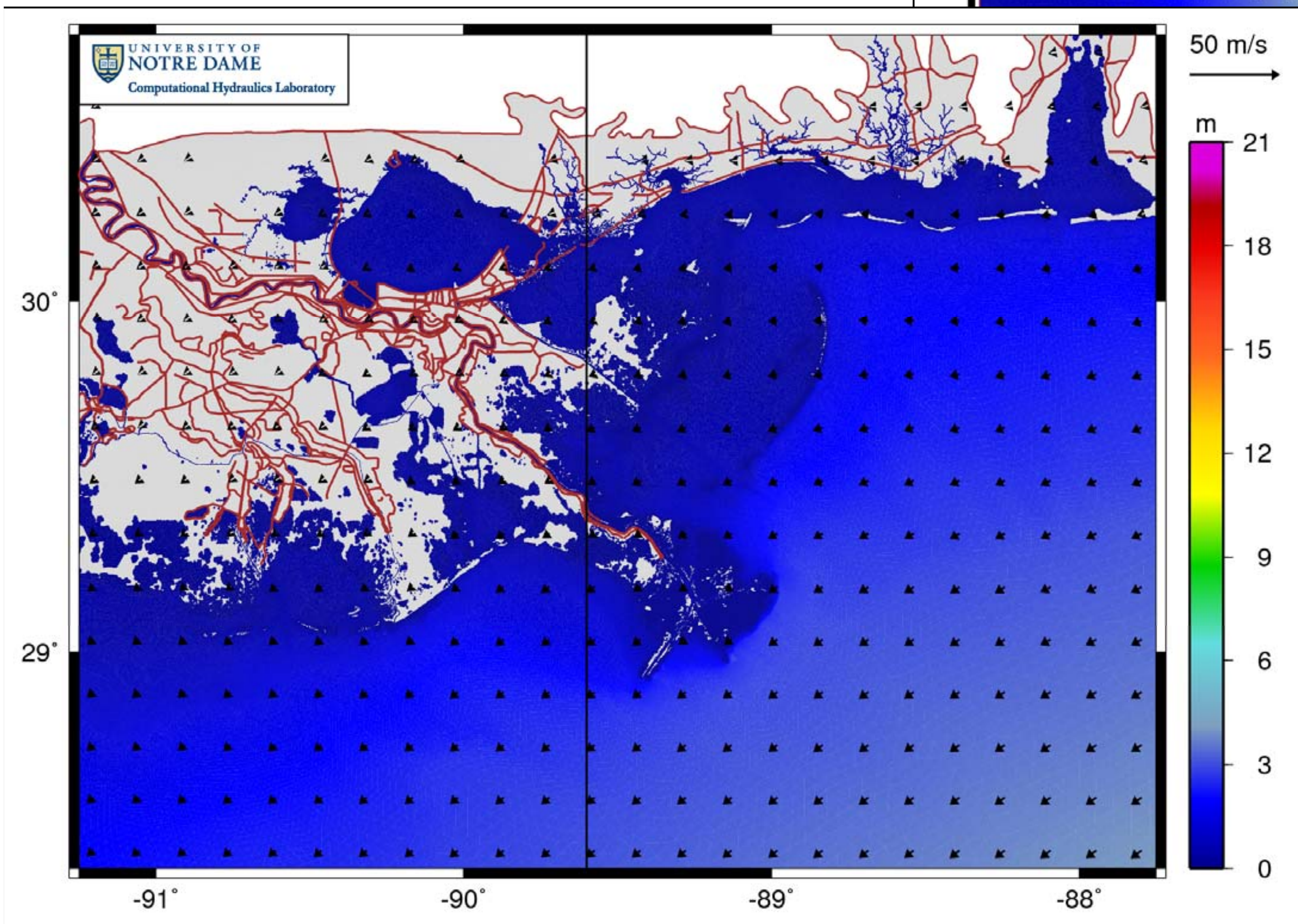


‘Tight’ Coupling of SWAN+ADCIRC

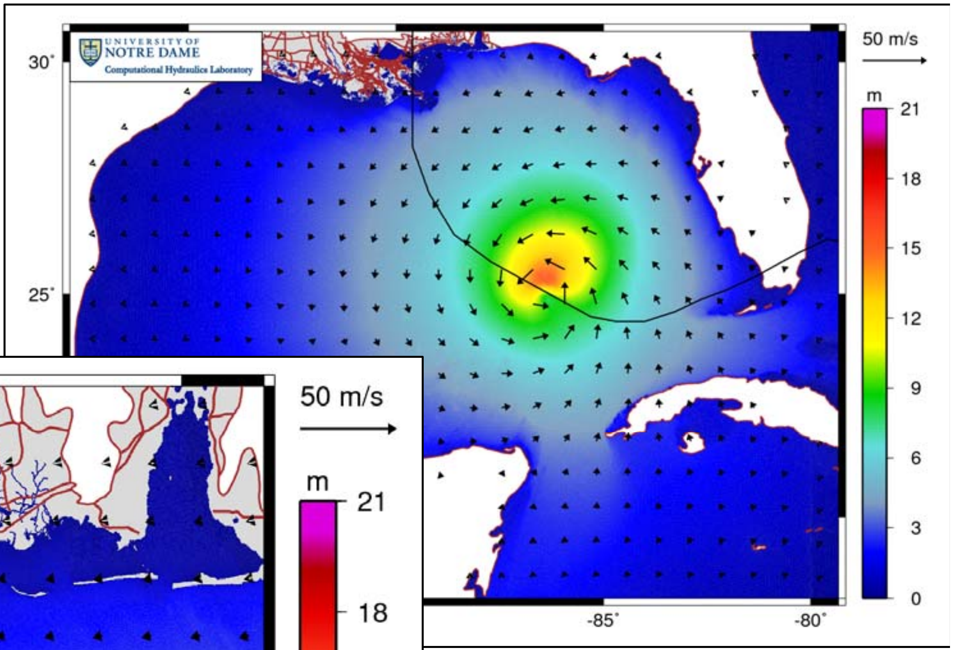


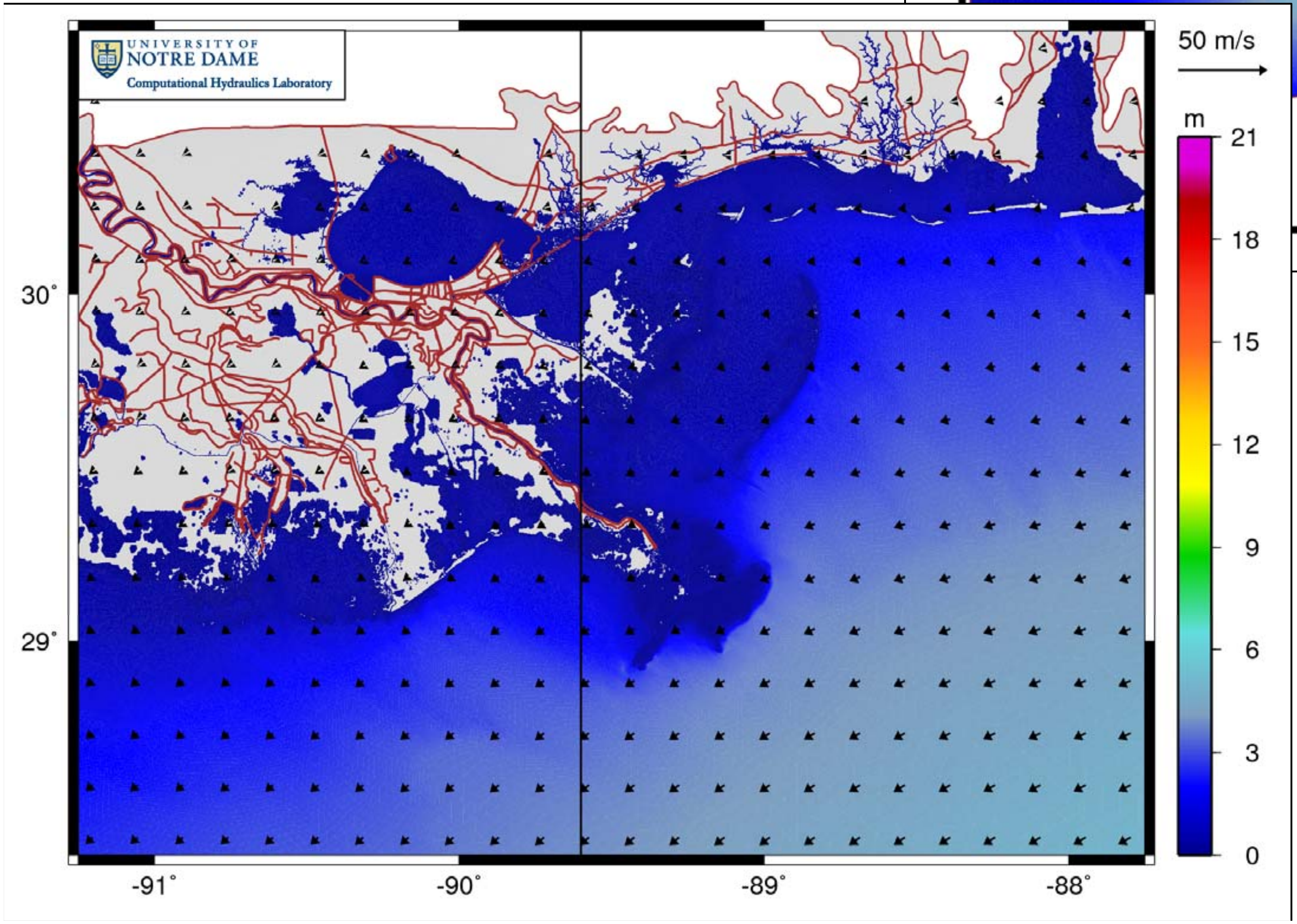
Katrina : Significant Wave Heights : 2005/09/28/0000Z



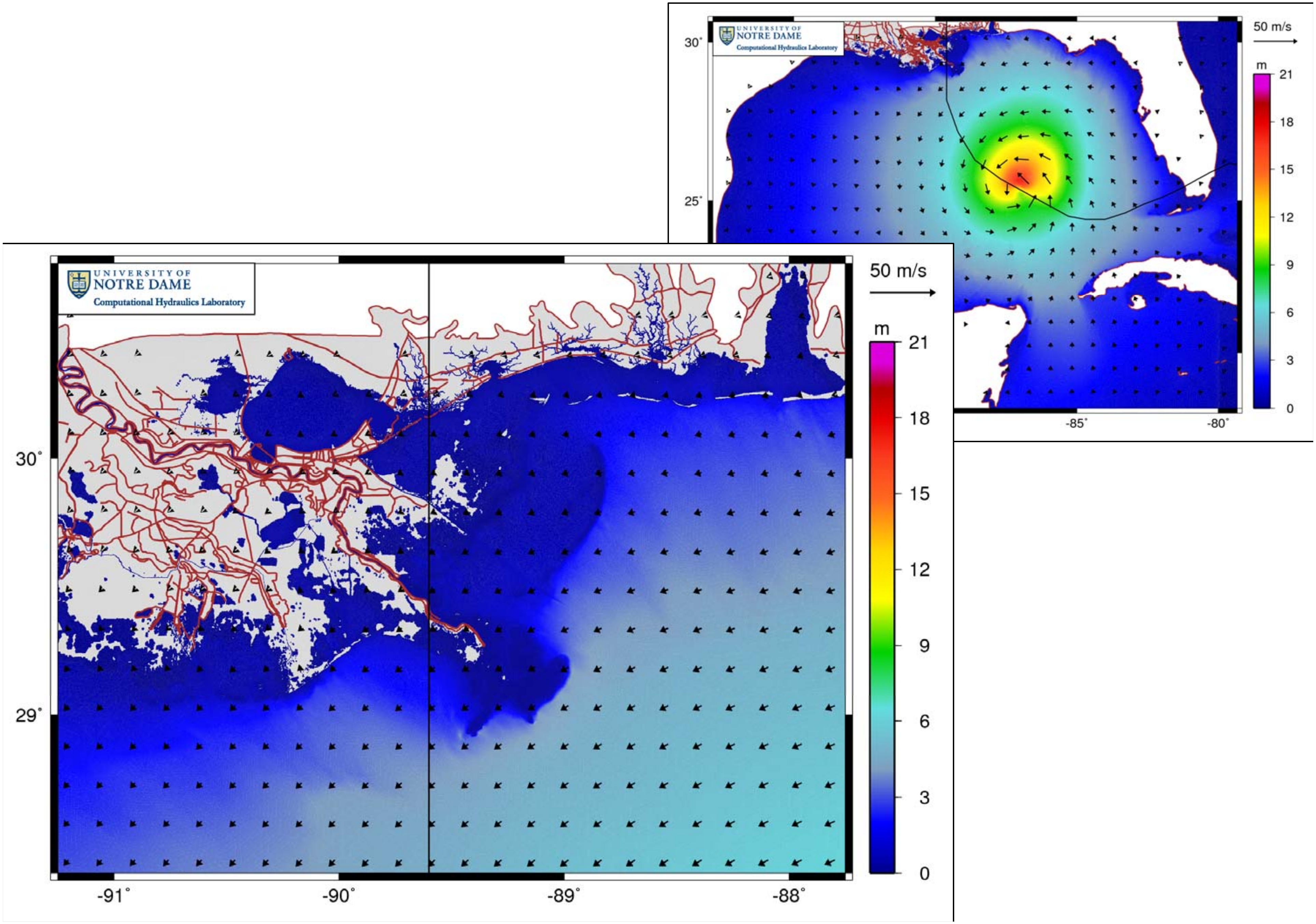


Katrina : Significant Wave Heights : 2005/09/28/0400Z

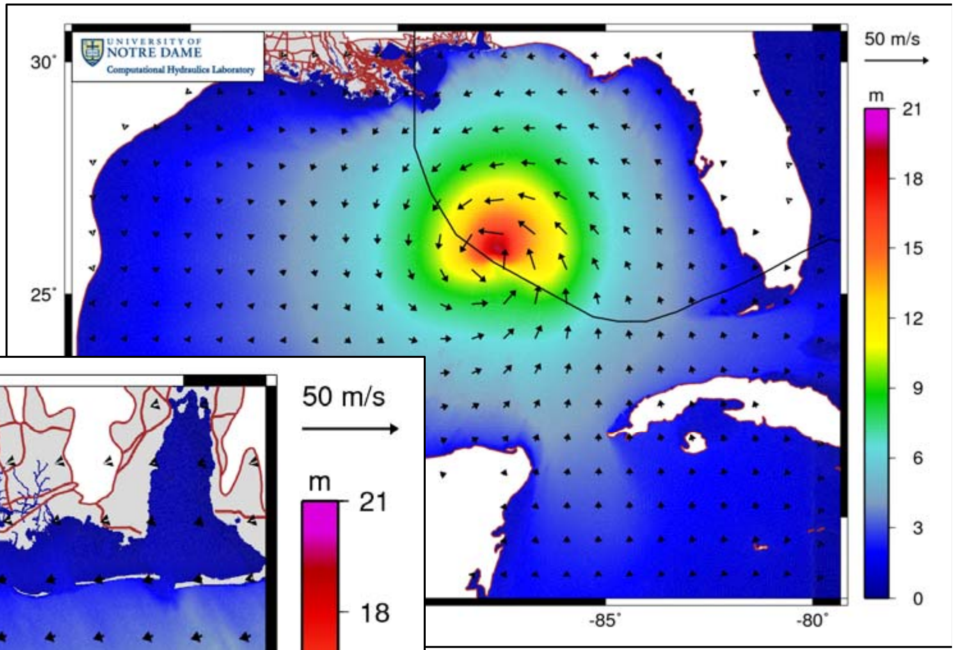


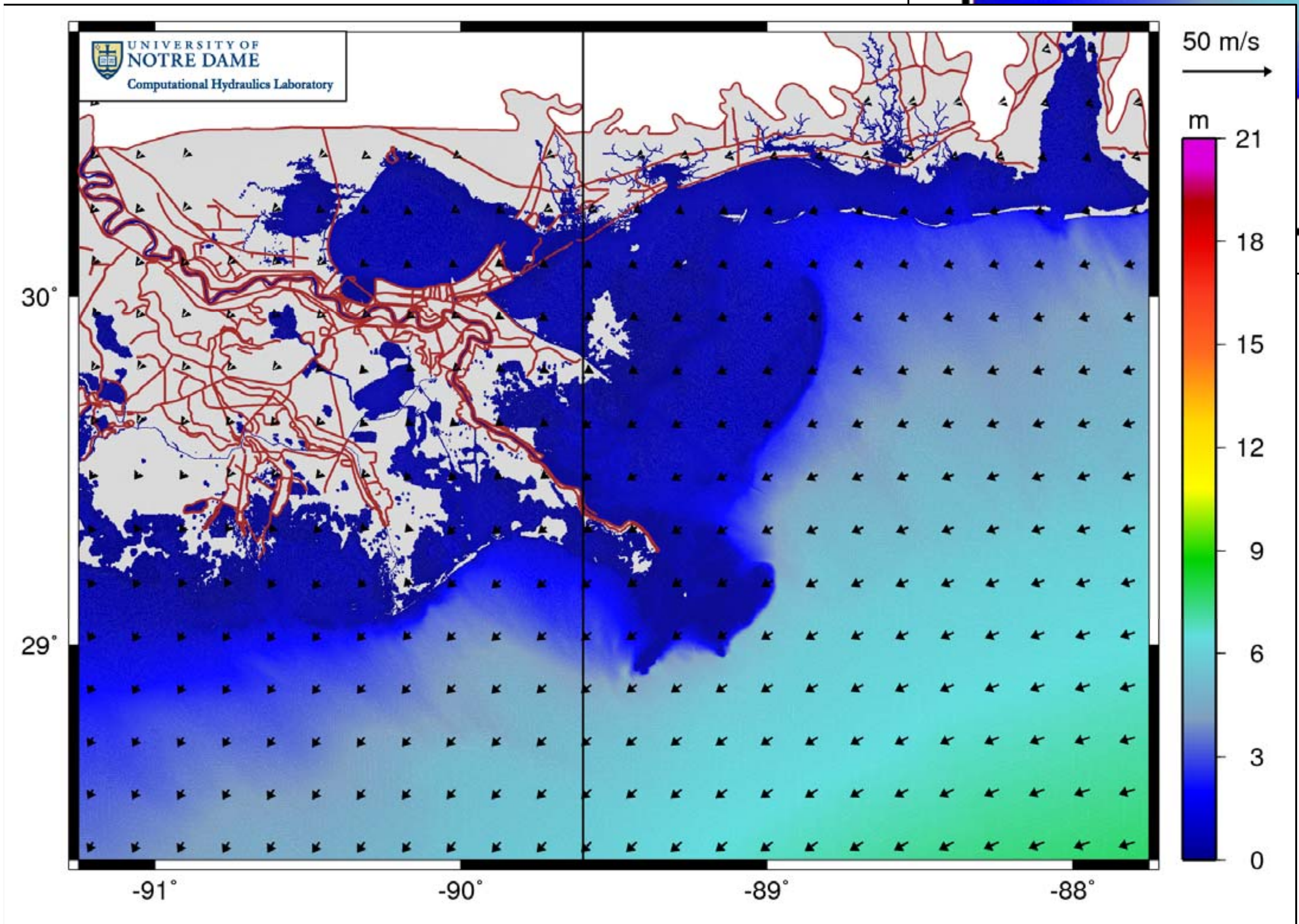


Katrina : Significant Wave Heights : 2005/09/28/0800Z



Katrina : Significant Wave Heights : 2005/09/28/1200Z





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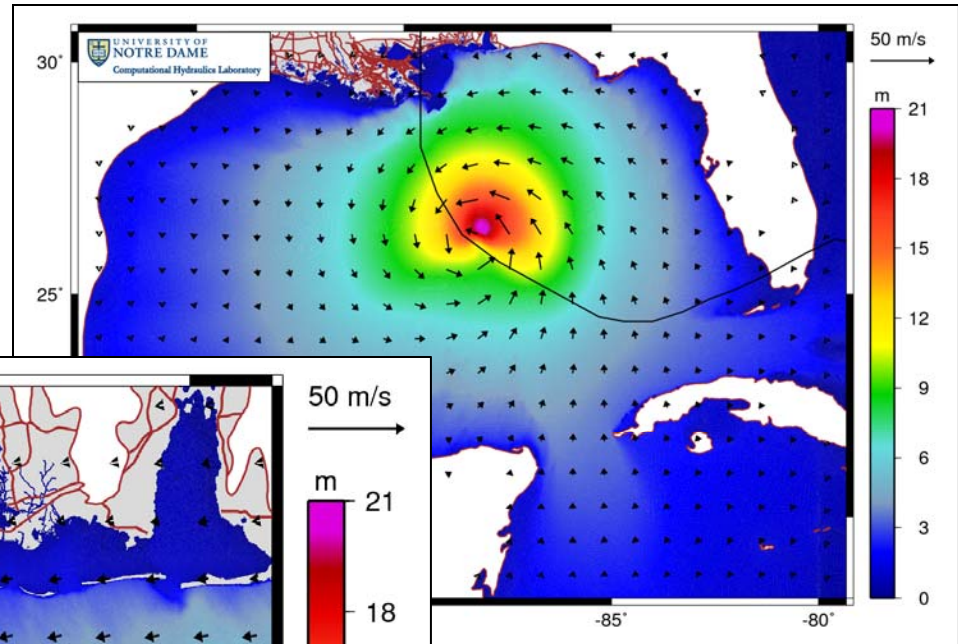
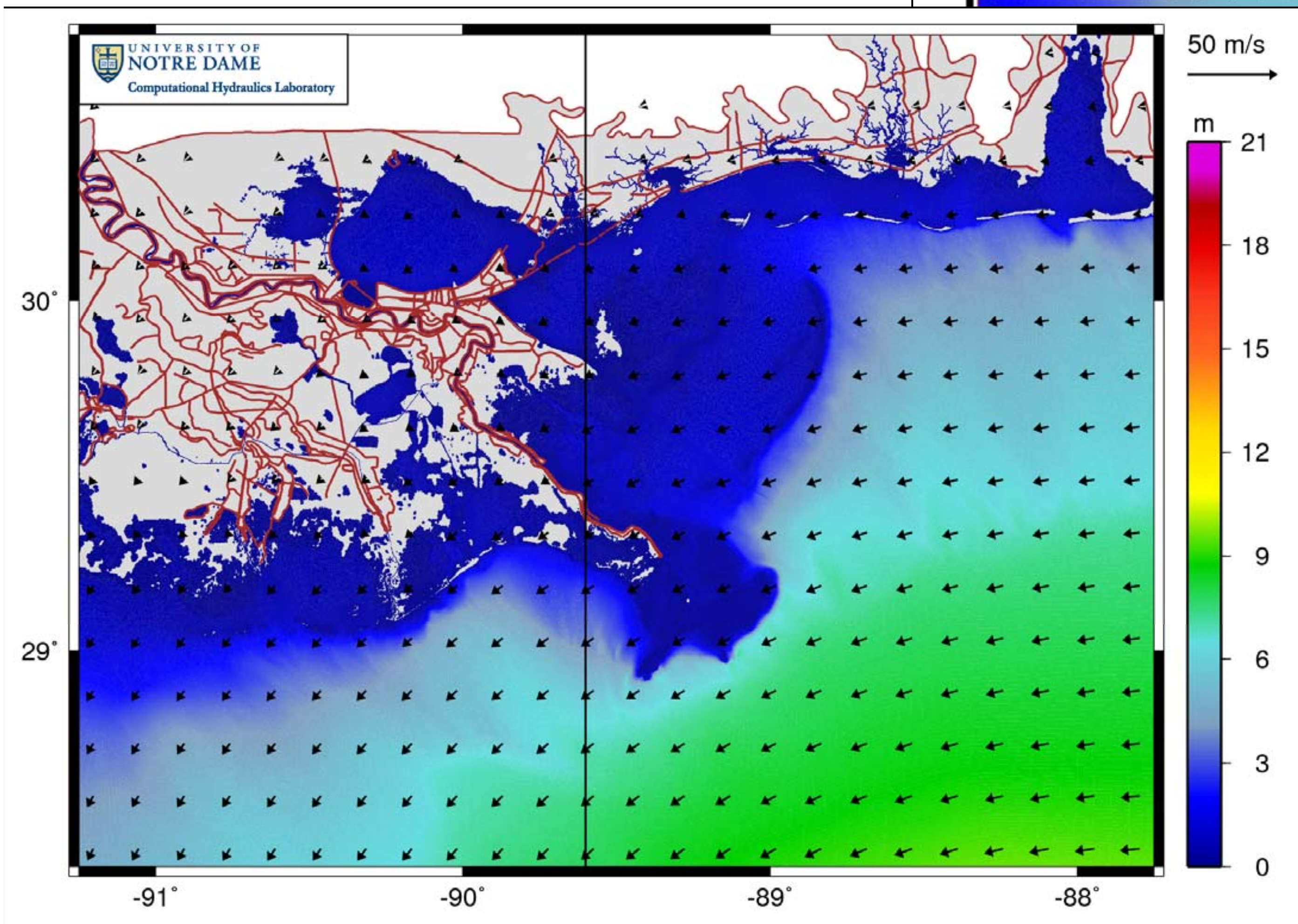
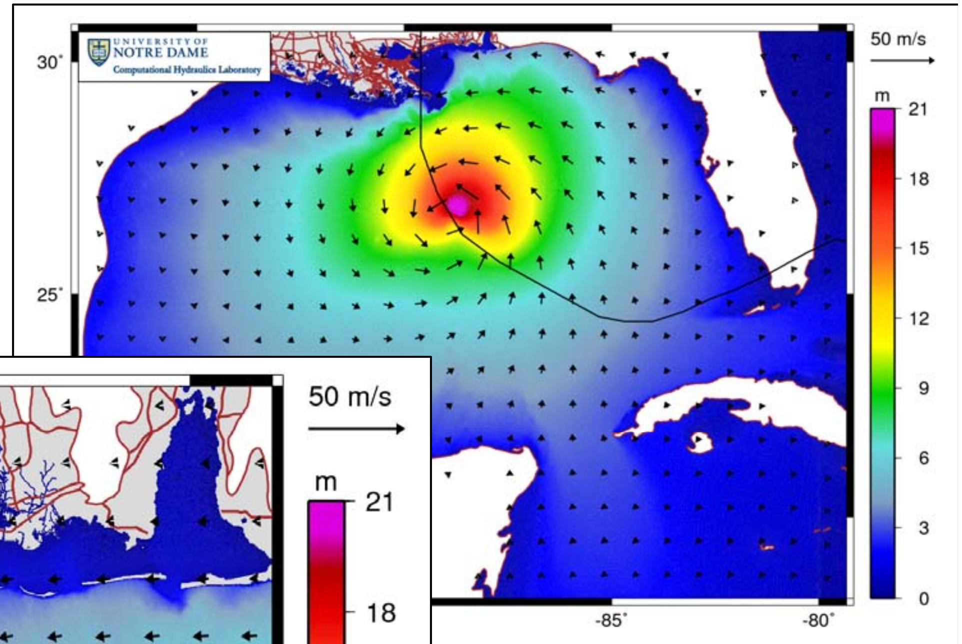
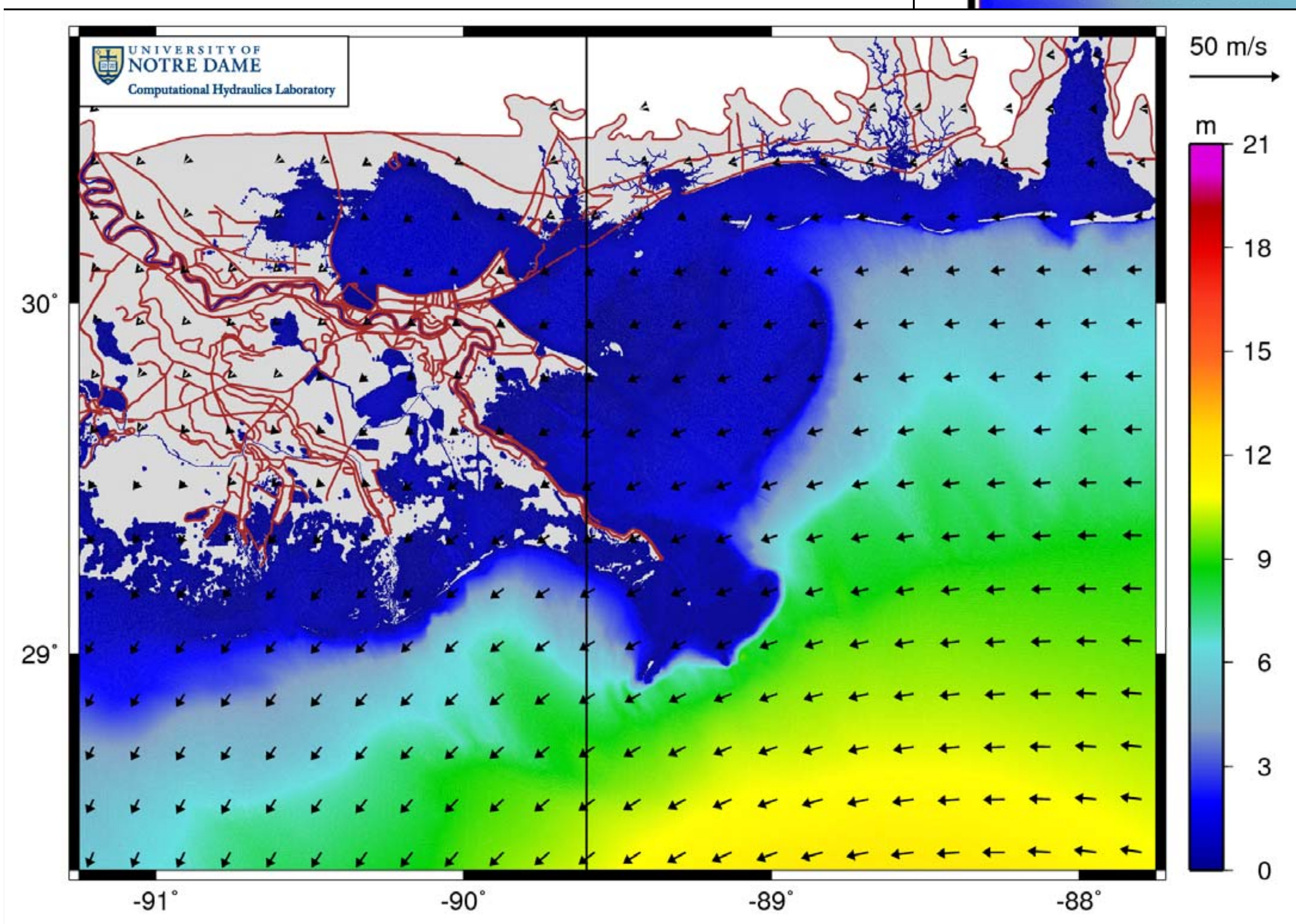


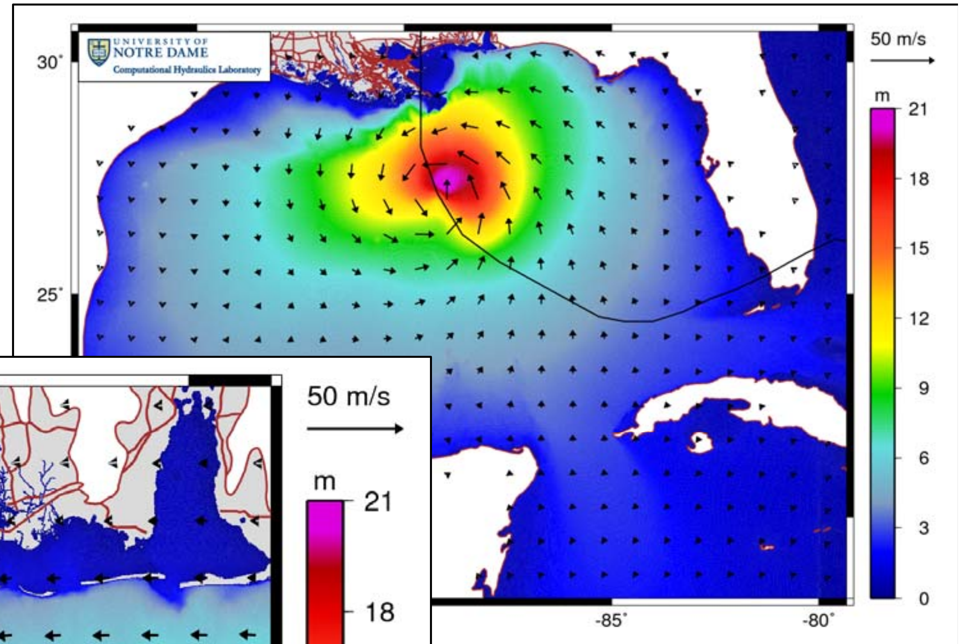


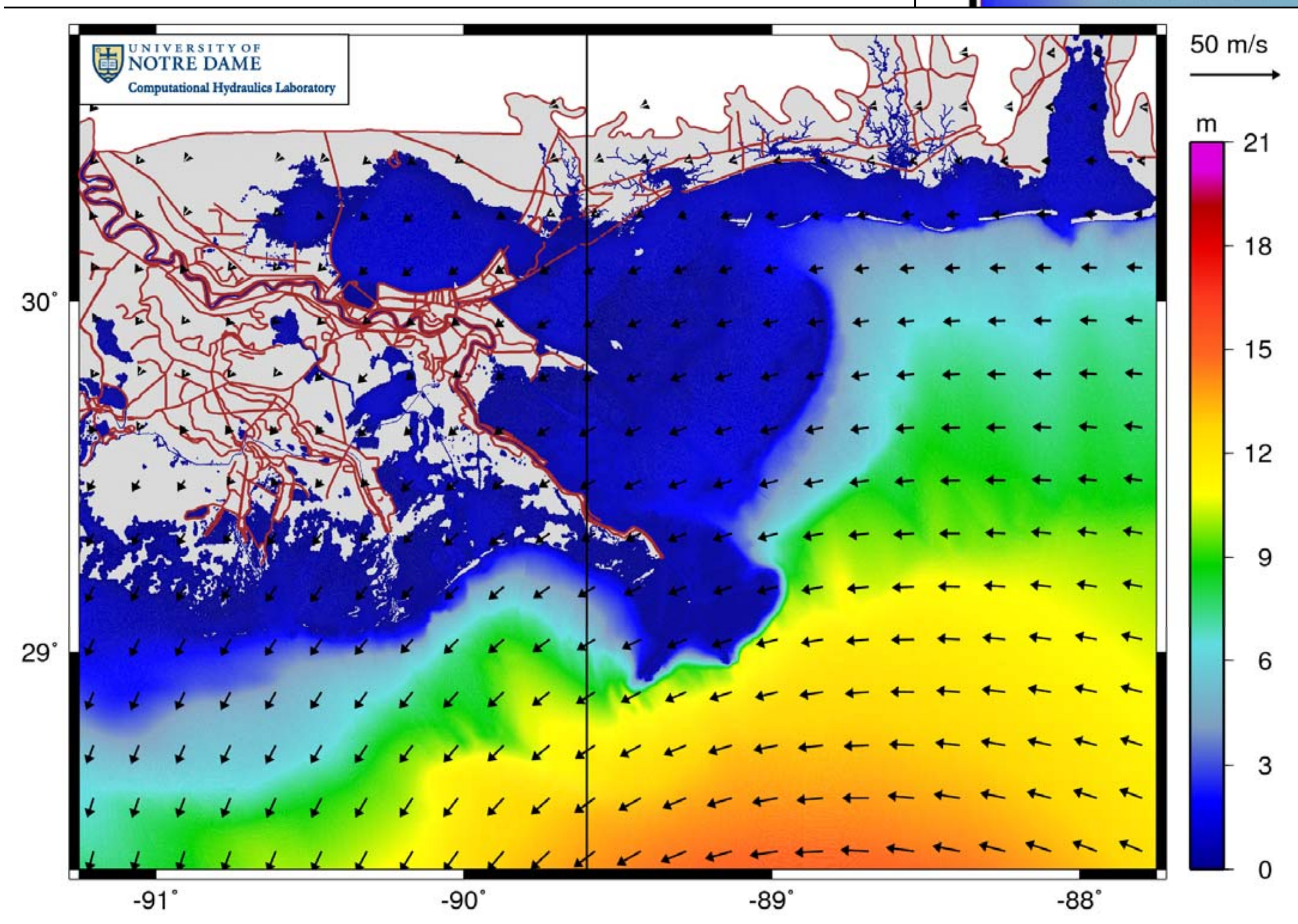
Katrina : Significant Wave Heights : 2005/09/28/2000Z



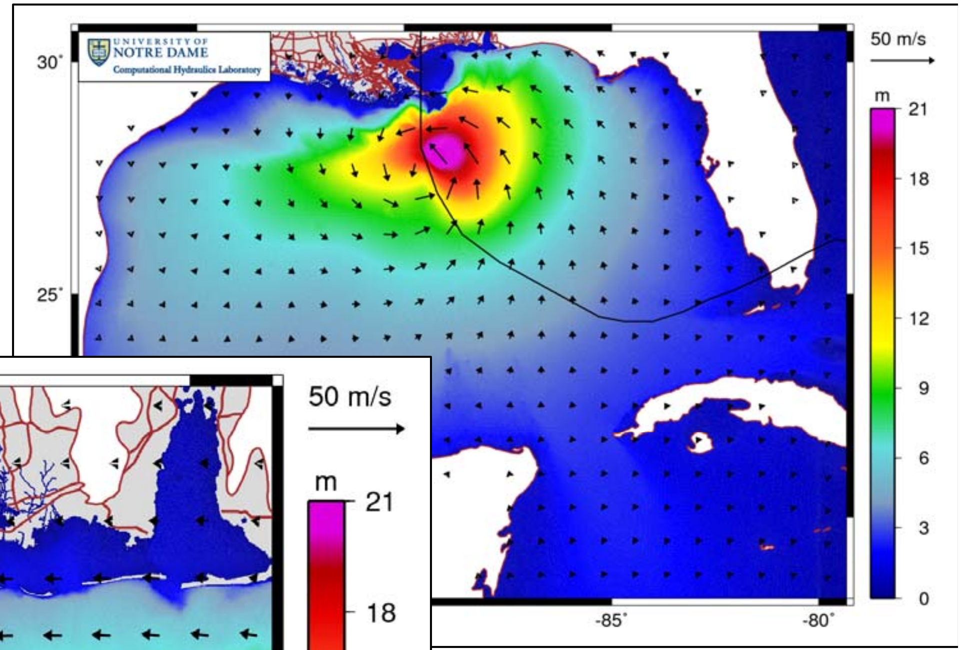


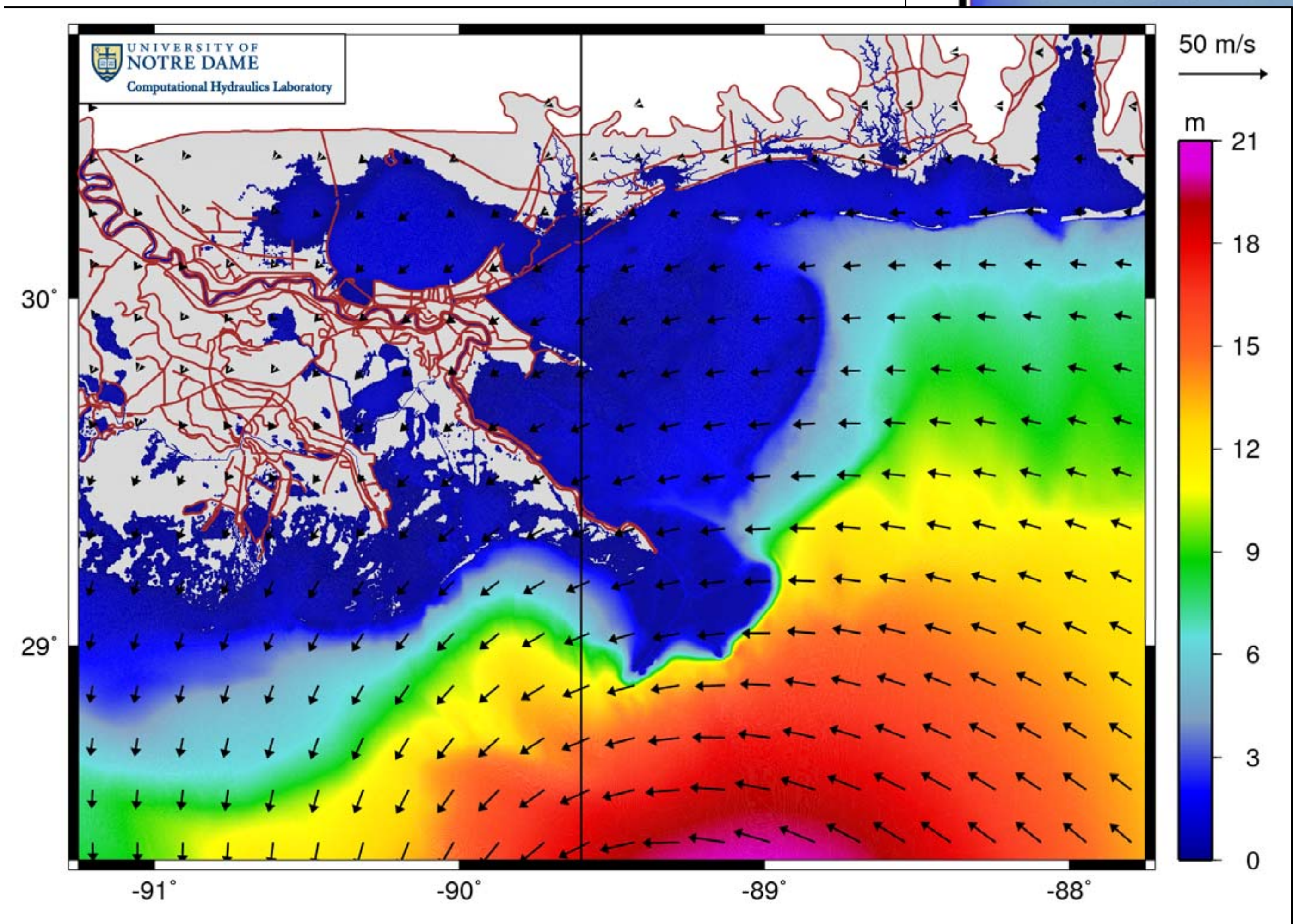
Katrina : Significant Wave Heights : 2005/09/29/0000Z



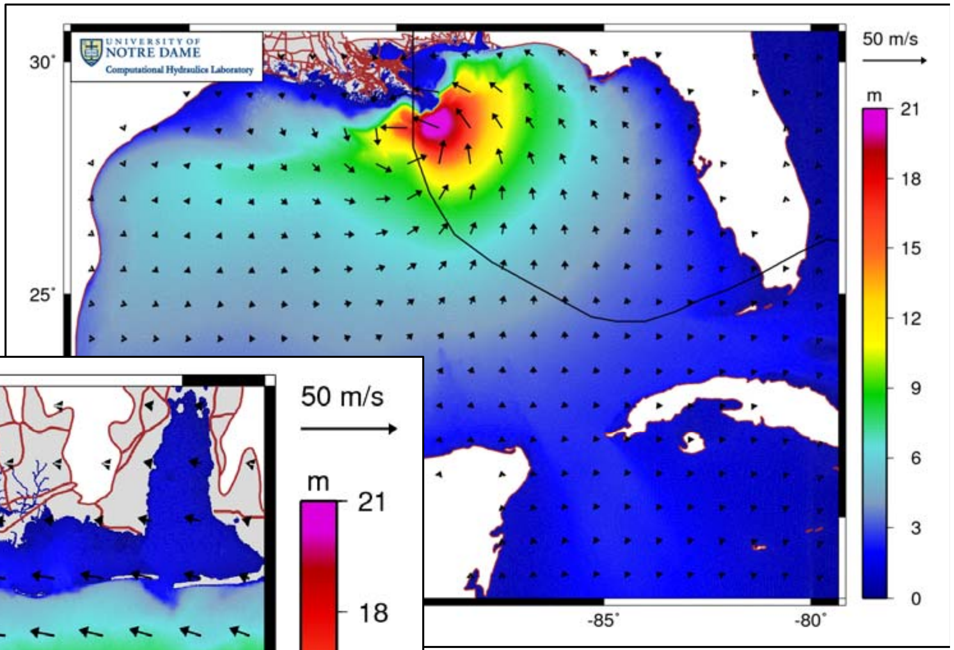


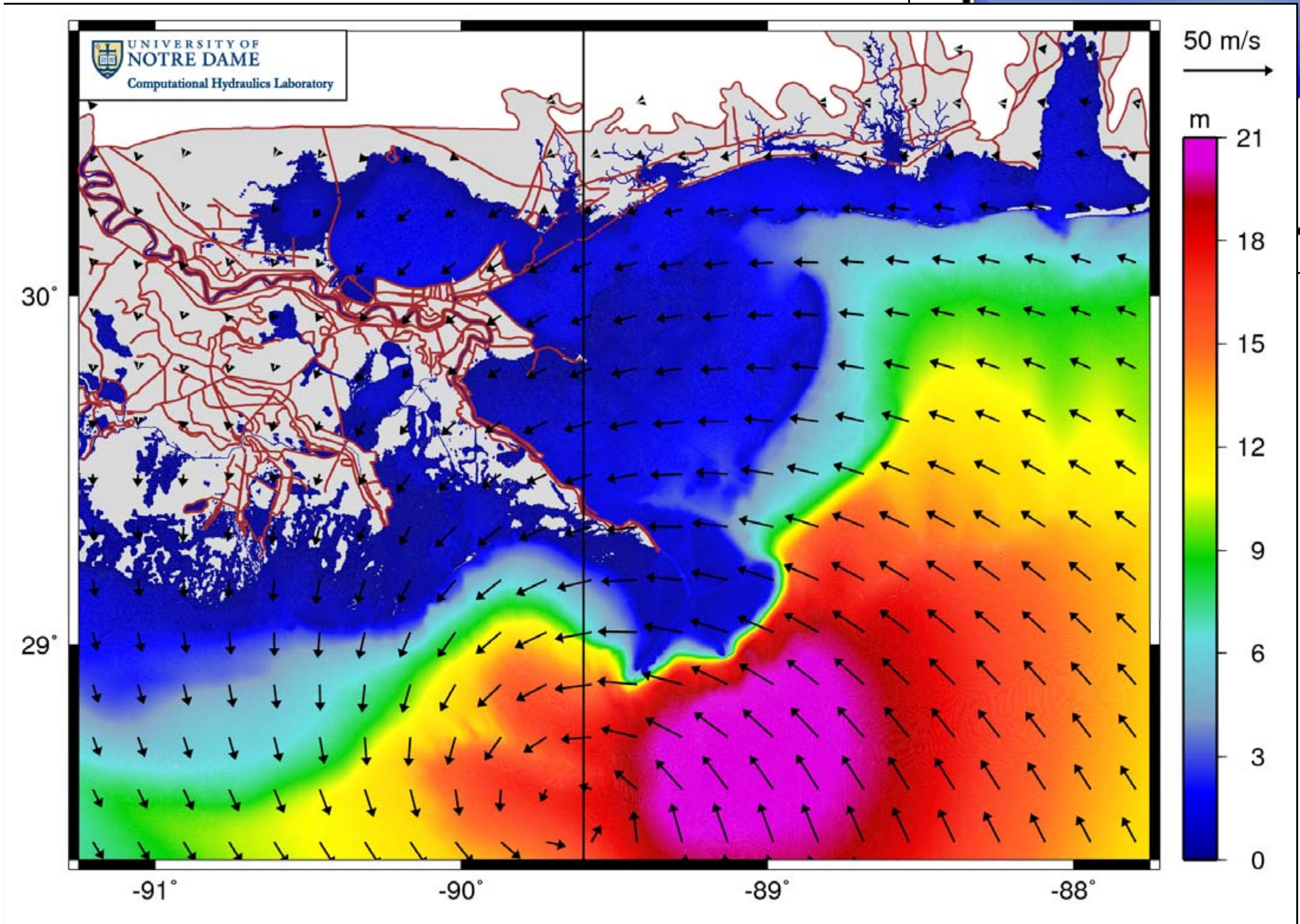
Katrina : Significant Wave Heights : 2005/09/29/0400Z



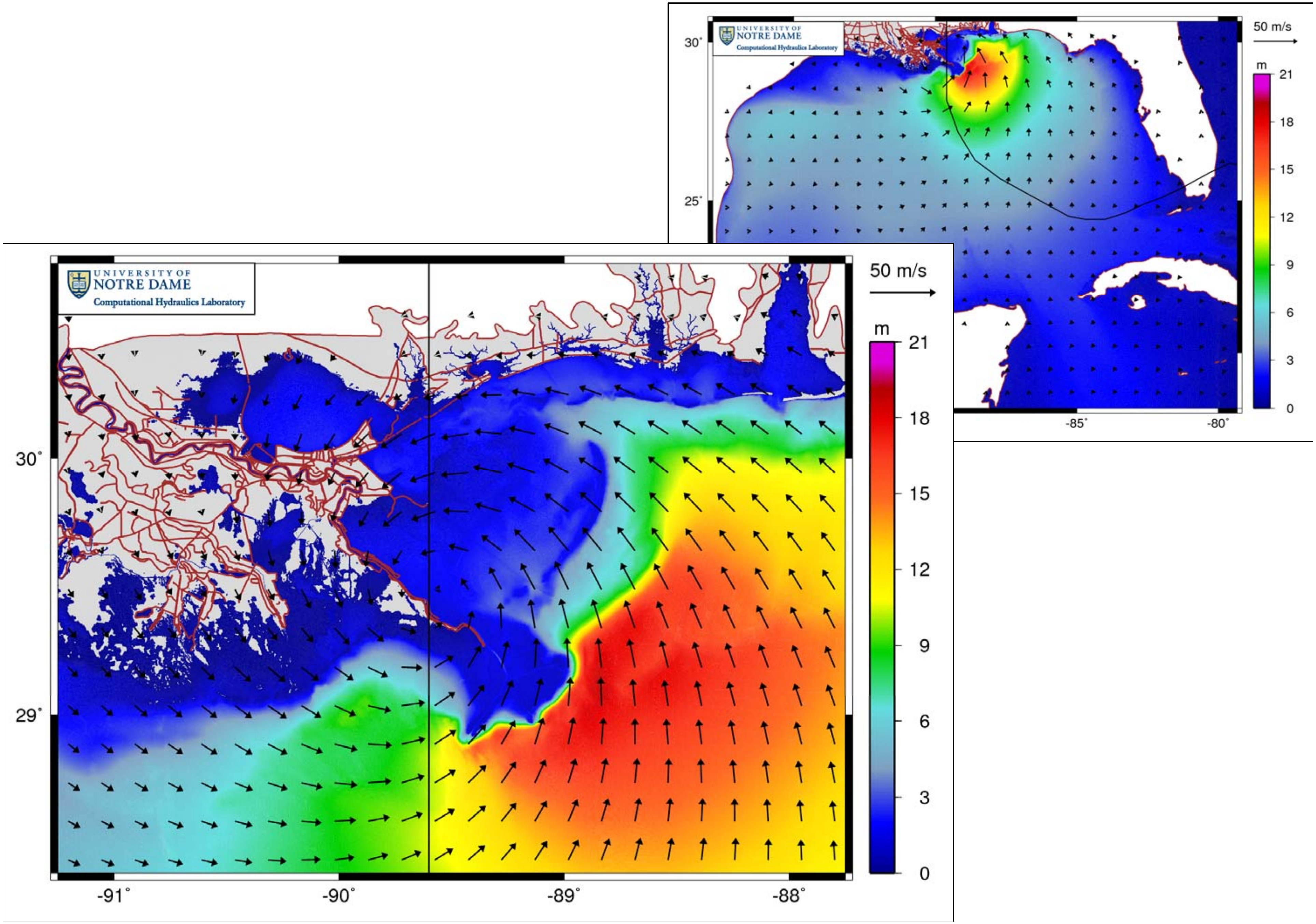


Katrina : Significant Wave Heights : 2005/09/29/0800Z

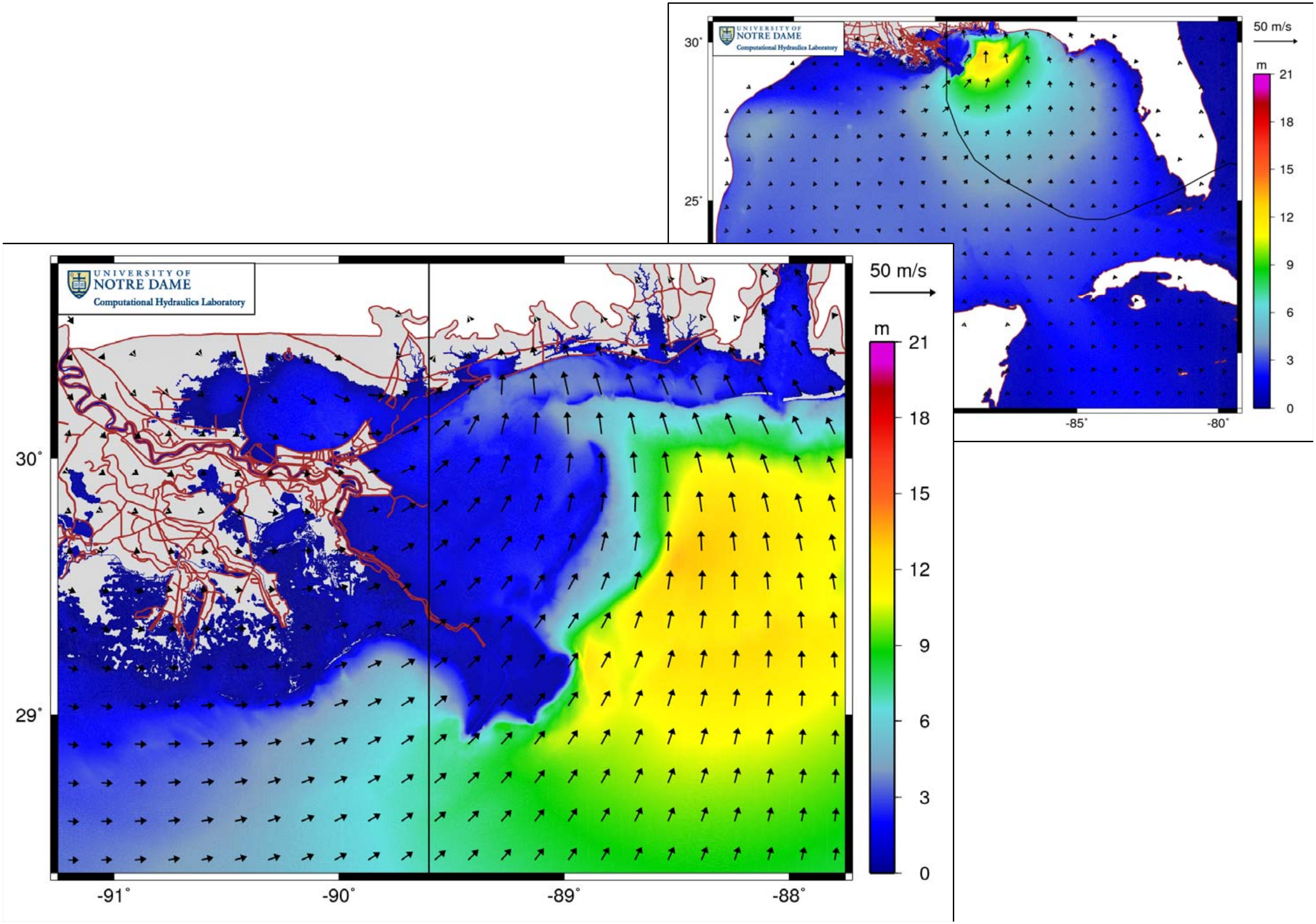




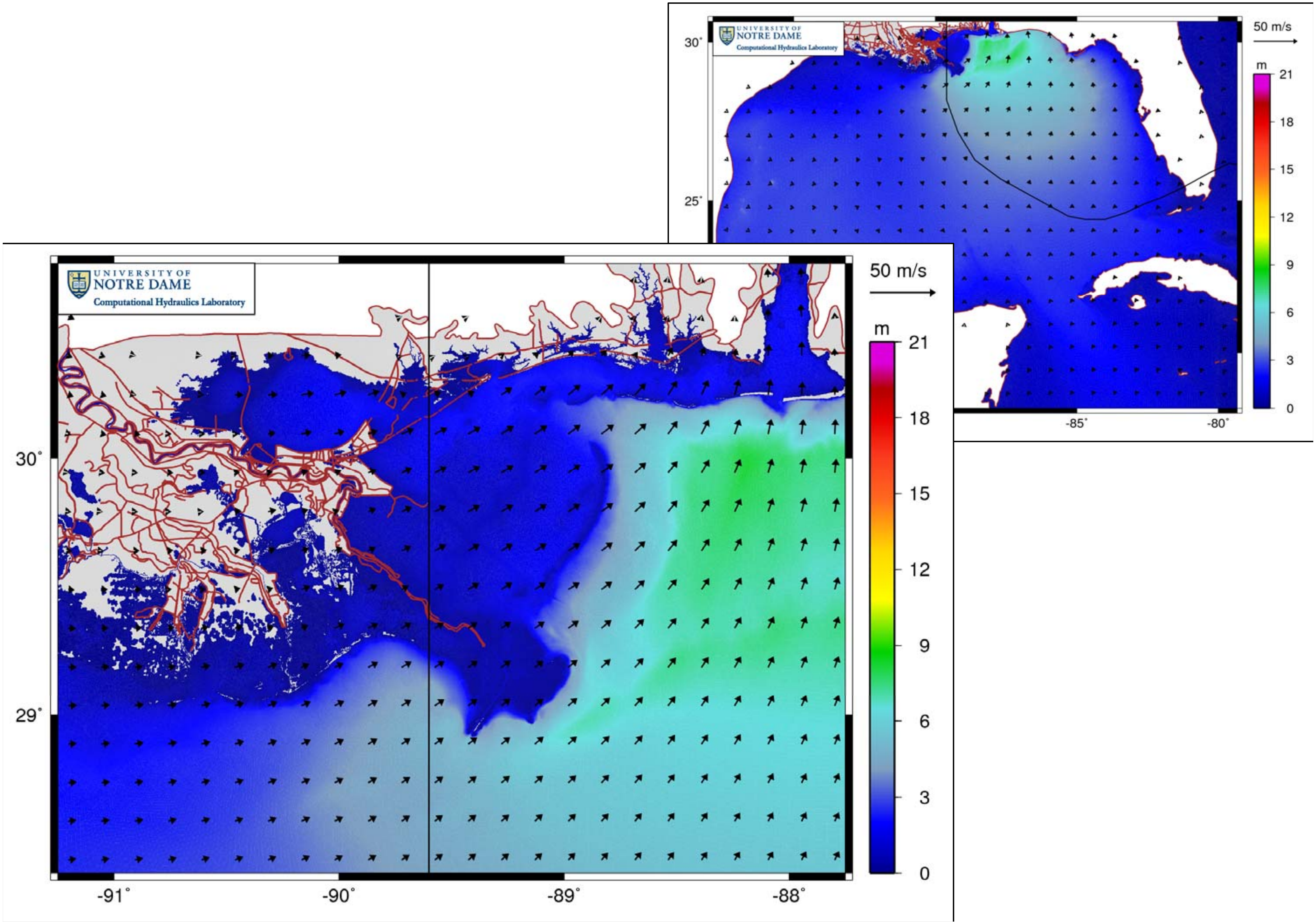
Katrina : Significant Wave Heights : 2005/09/29/1200Z



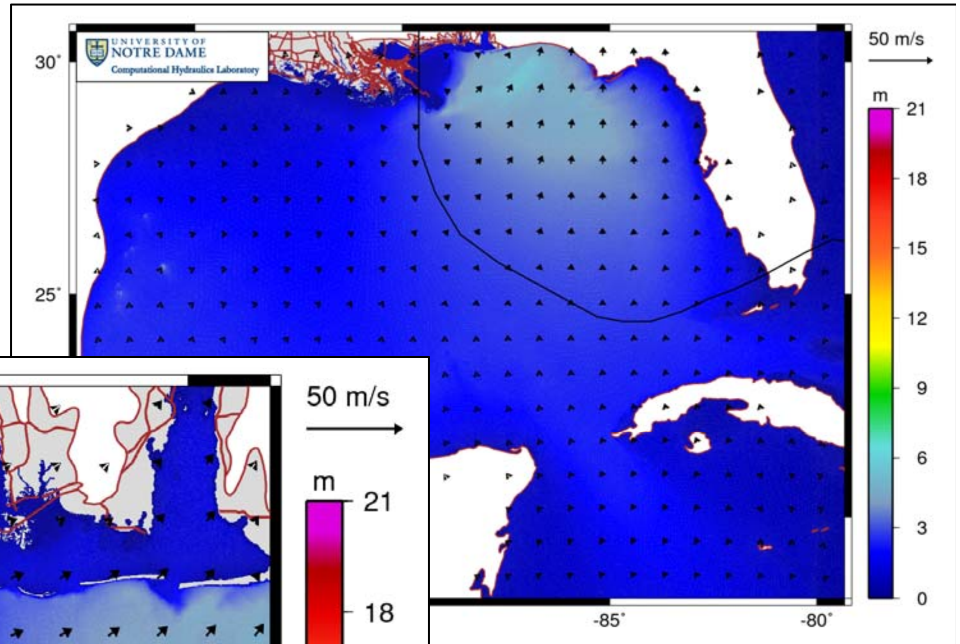
Katrina : Significant Wave Heights : 2005/09/29/1600Z

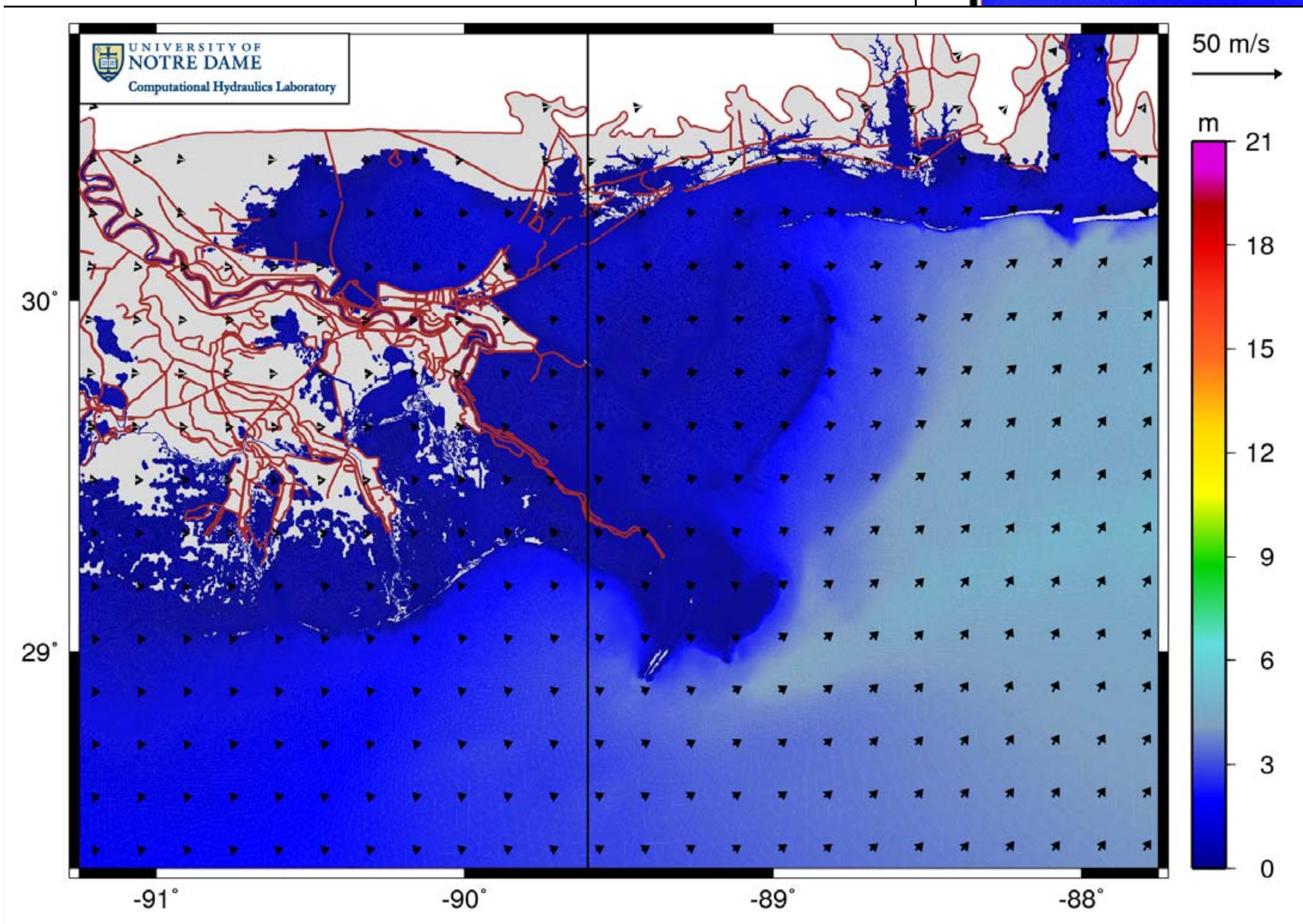


Katrina : Significant Wave Heights : 2005/09/29/2000Z

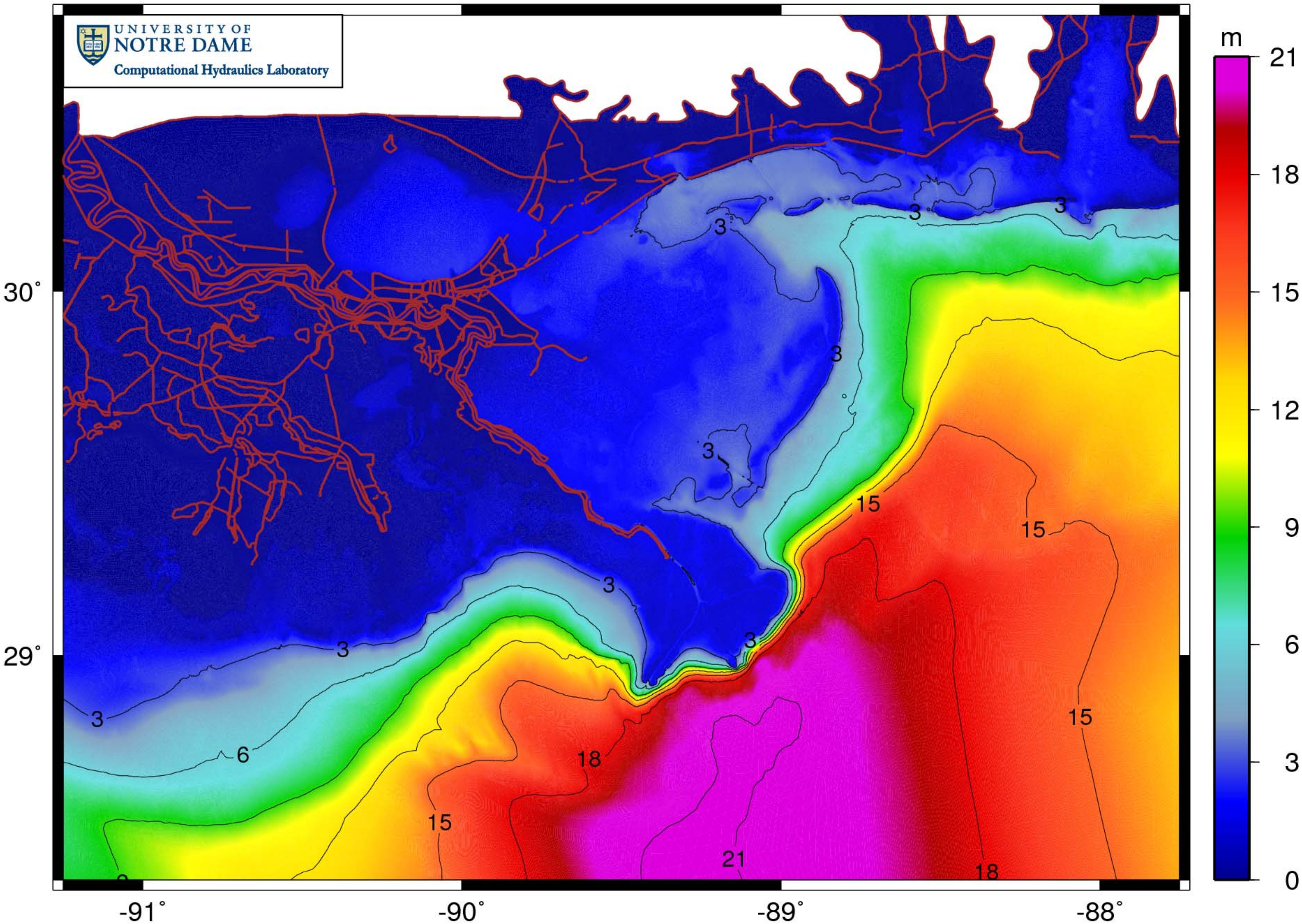


Katrina : Significant Wave Heights : 2005/09/30/0000Z

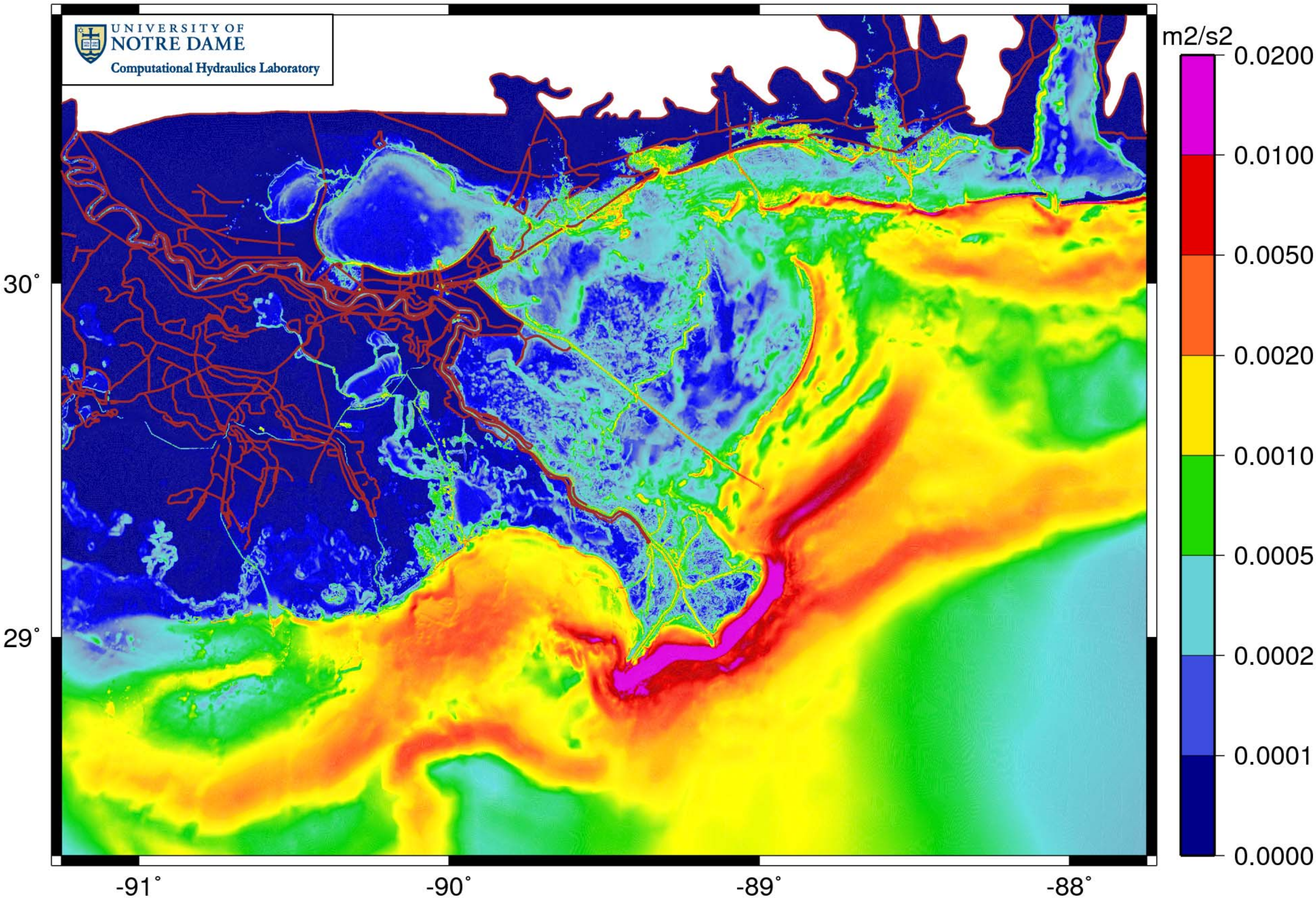




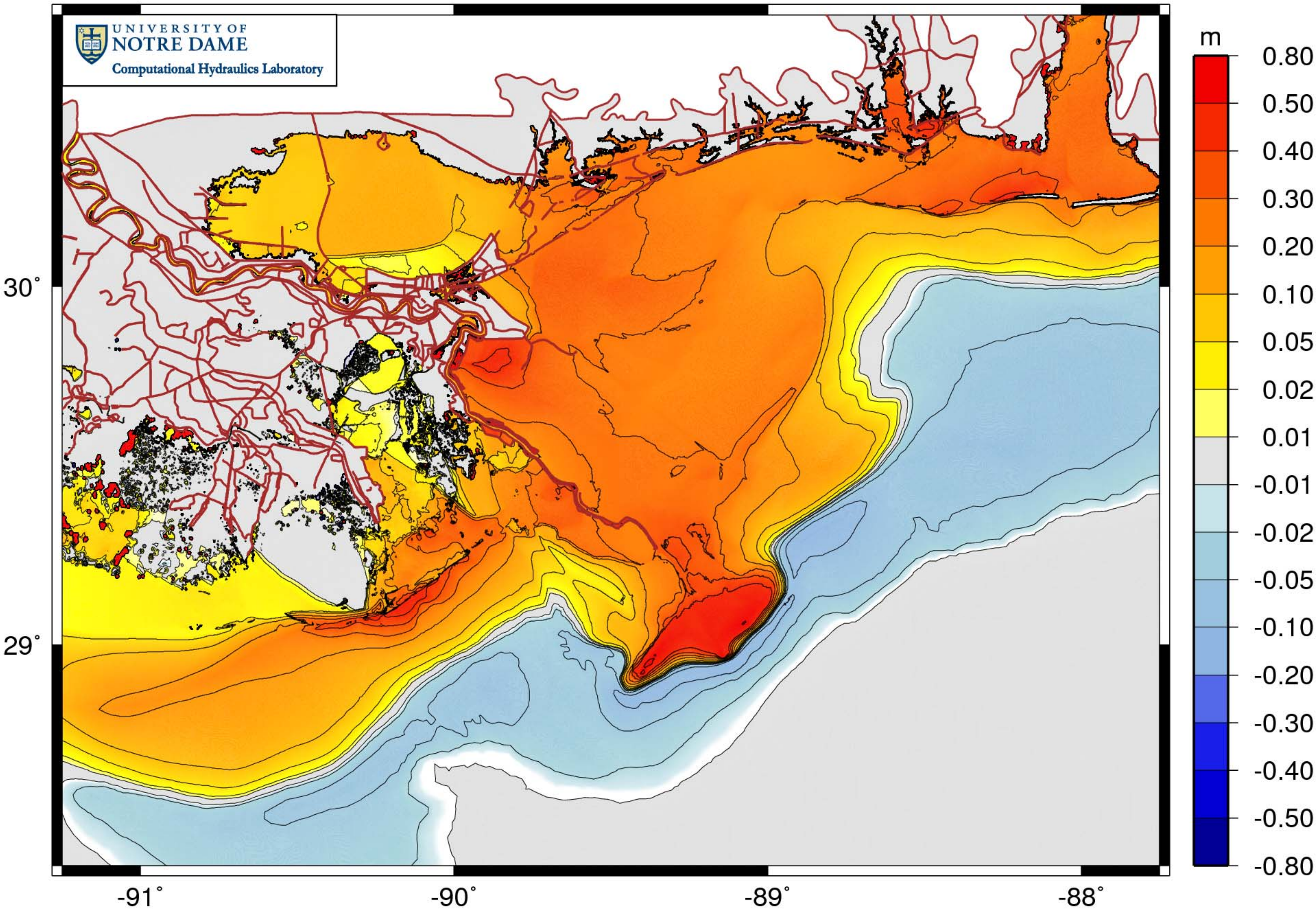
Katrina : Significant Wave Heights : Maximum



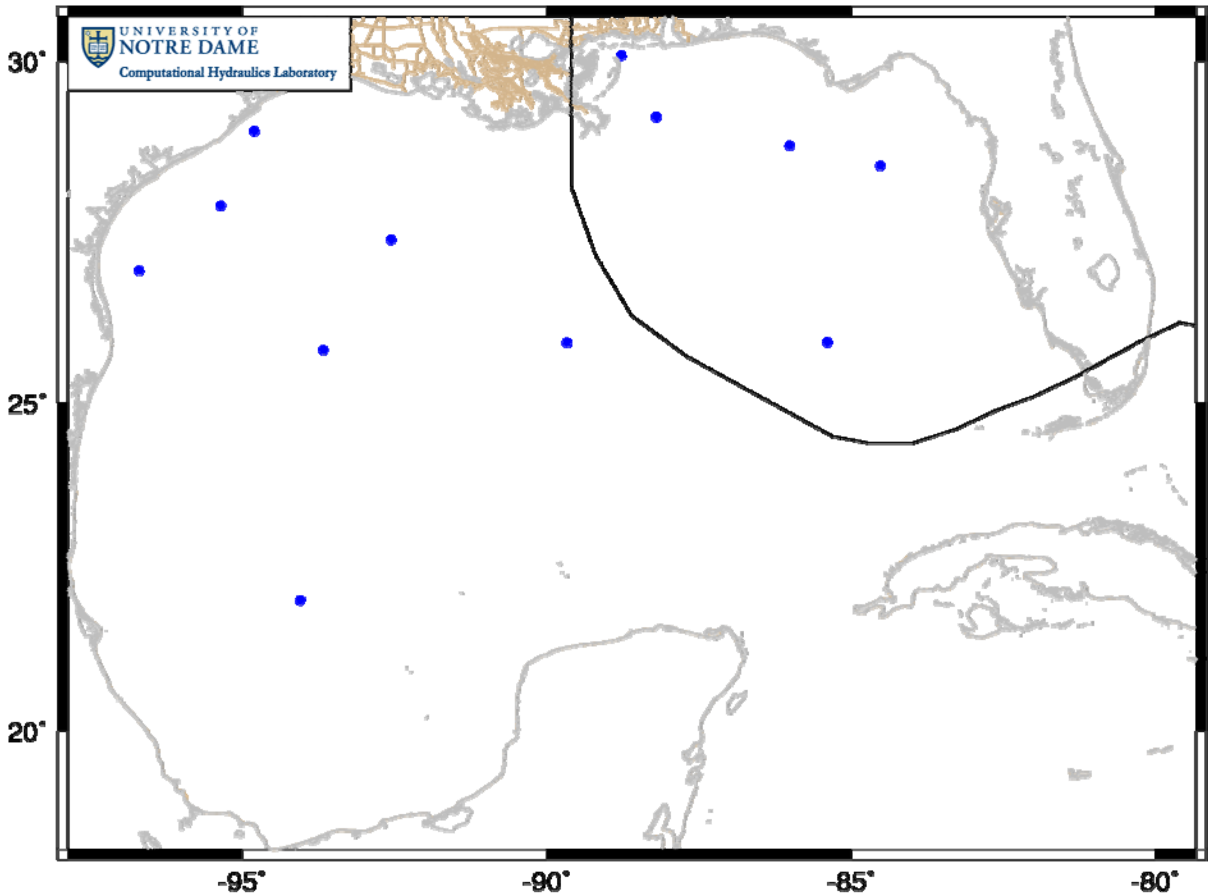
Katrina : Radiation Stress Gradients : Maximum



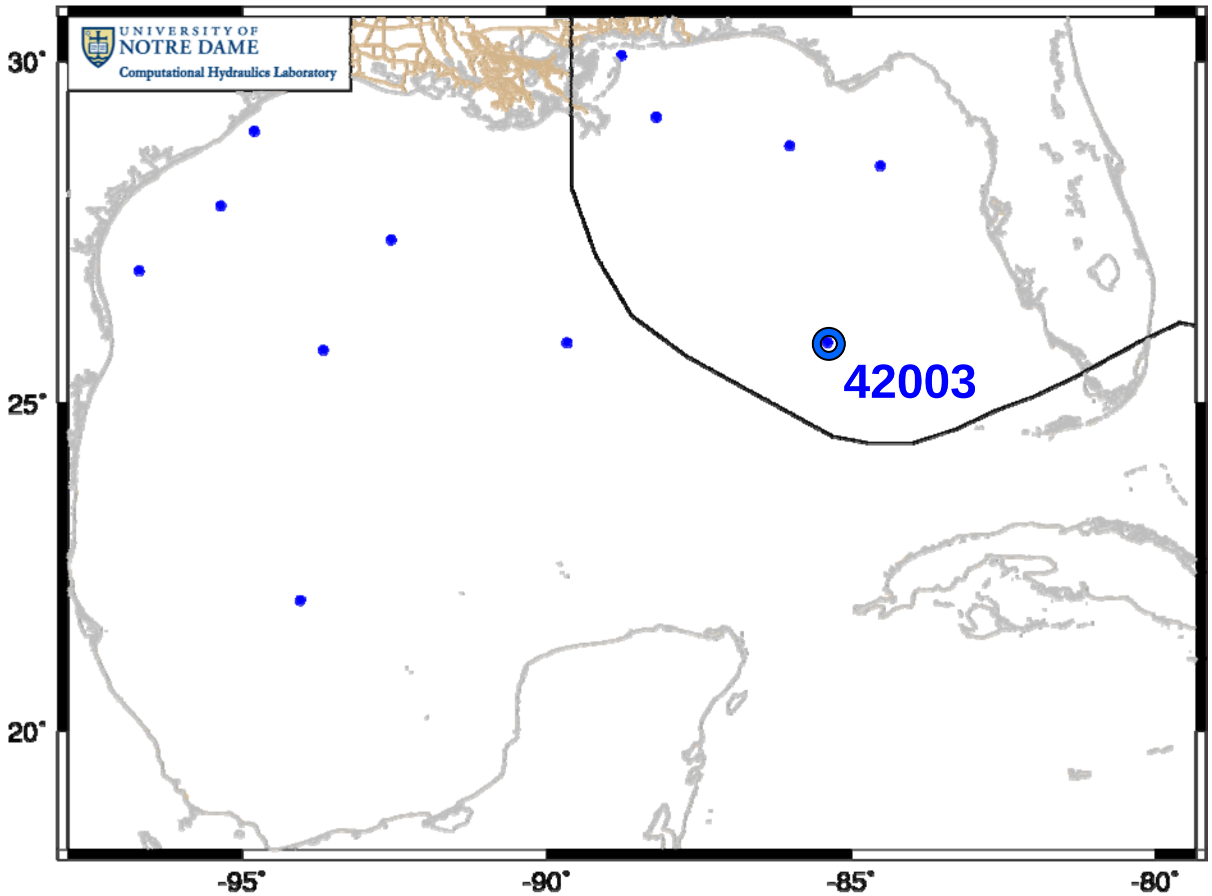
Katrina : Wave-Driven Setup : Maximum

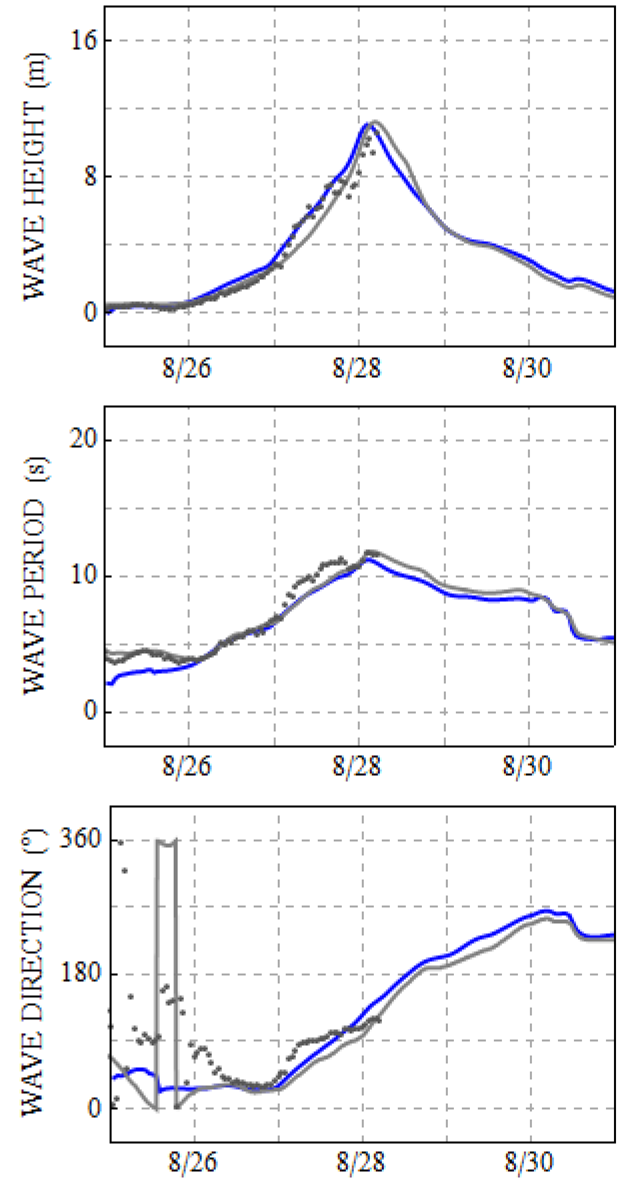


Katrina : Validation of Wave Parameters : NDBC

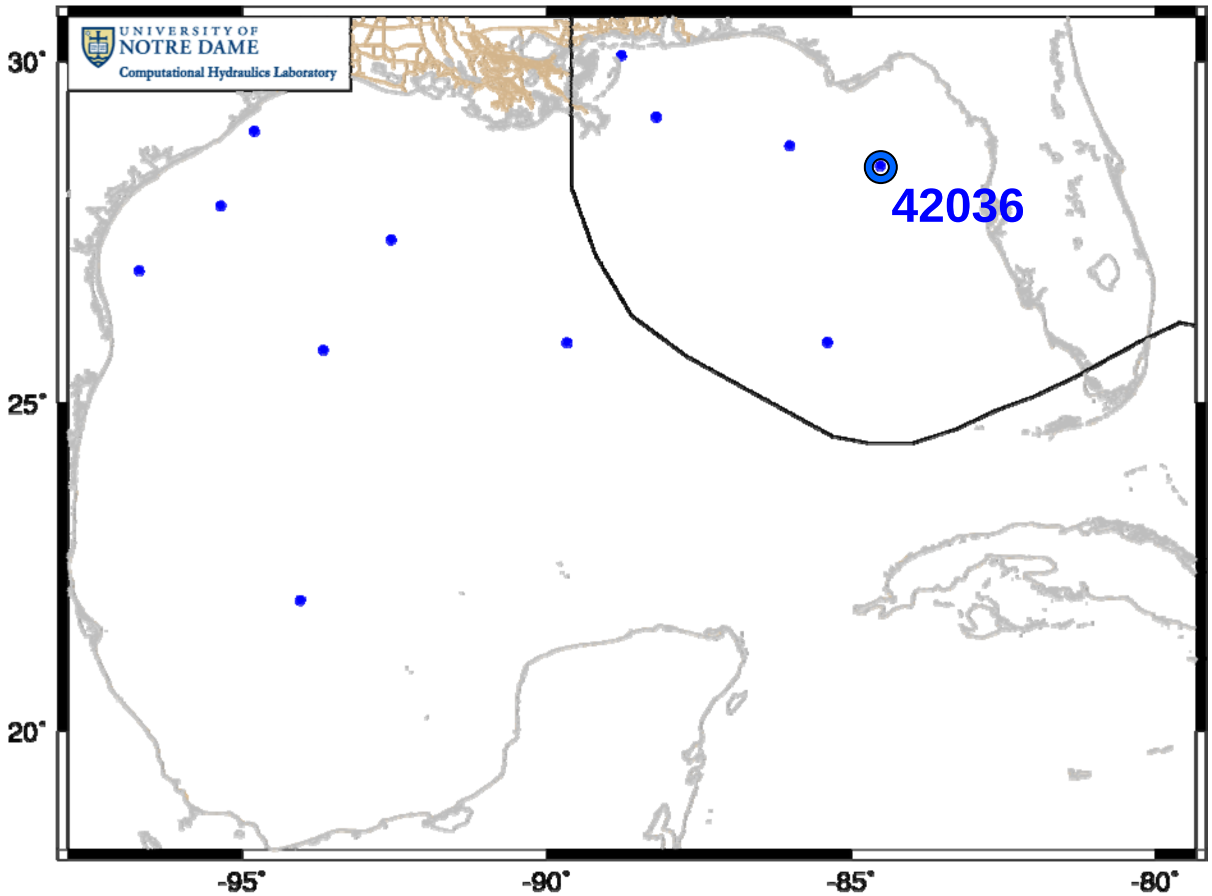


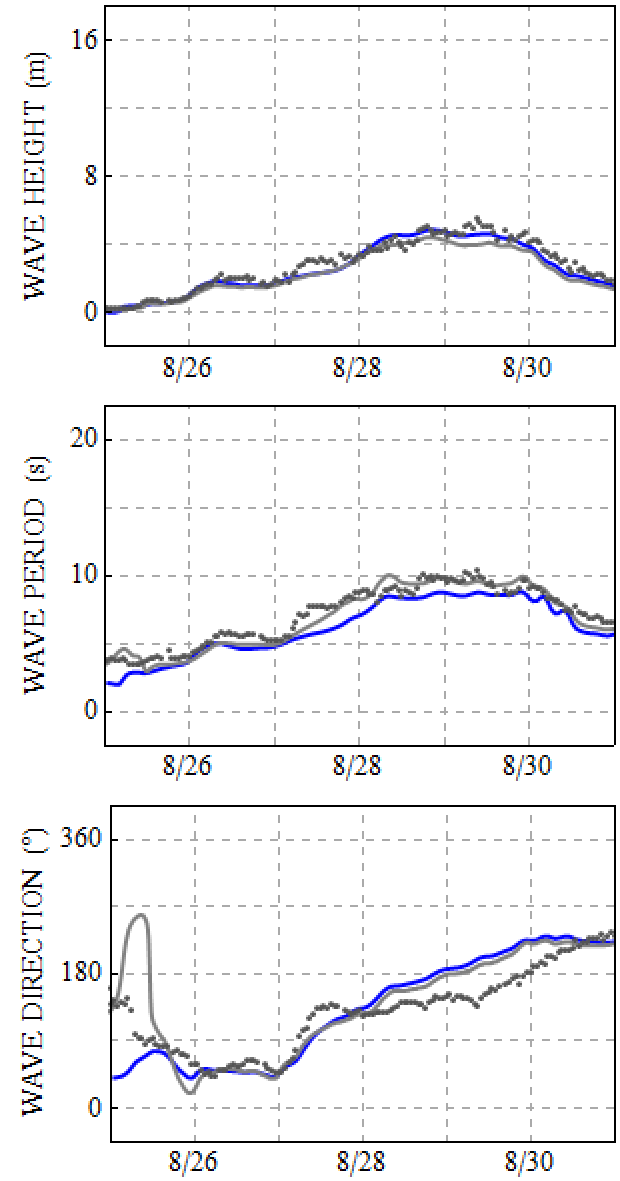
Katrina : Validation of Wave Parameters : NDBC 42003



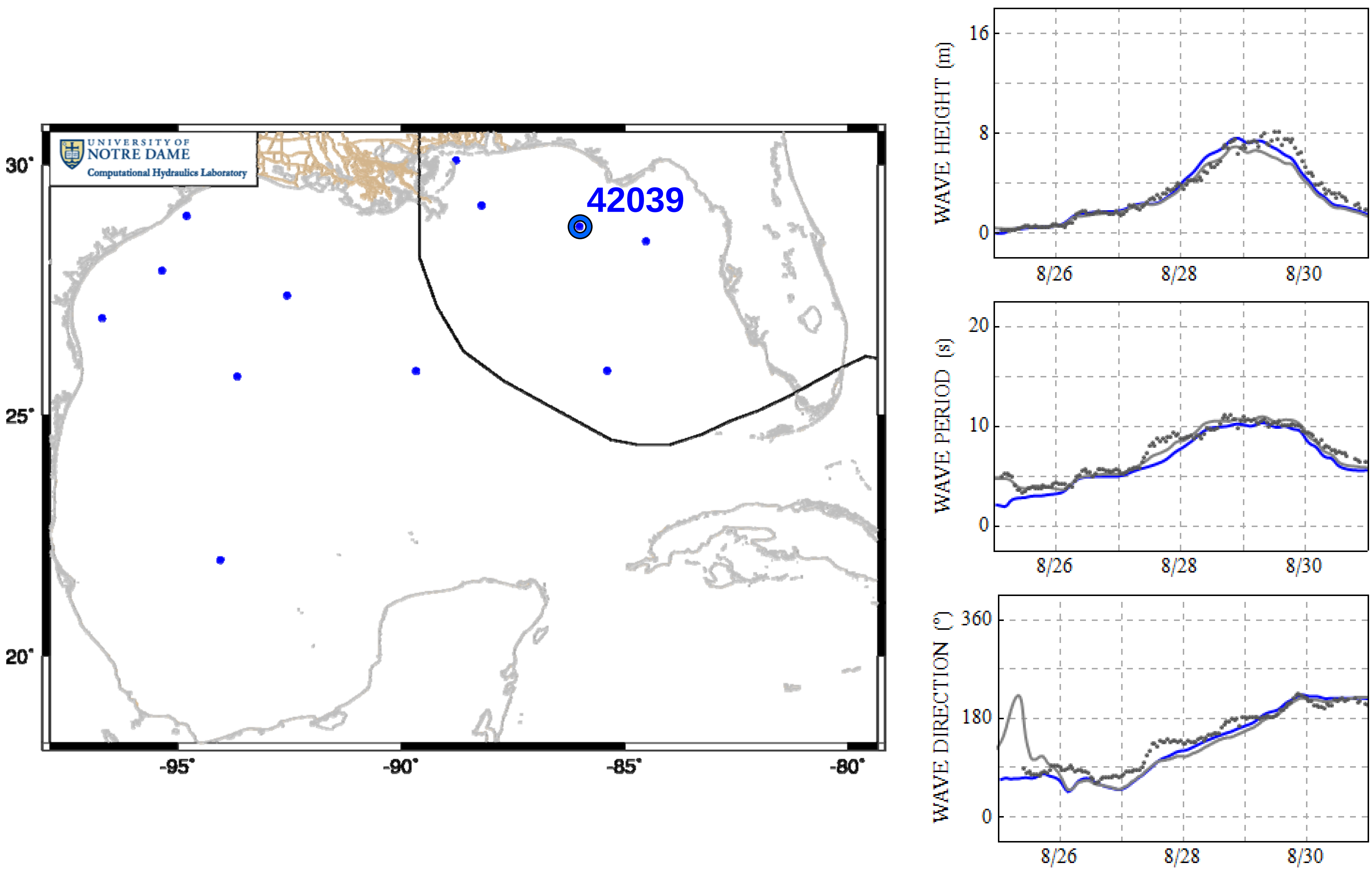


Katrina : Validation of Wave Parameters : NDBC 42036

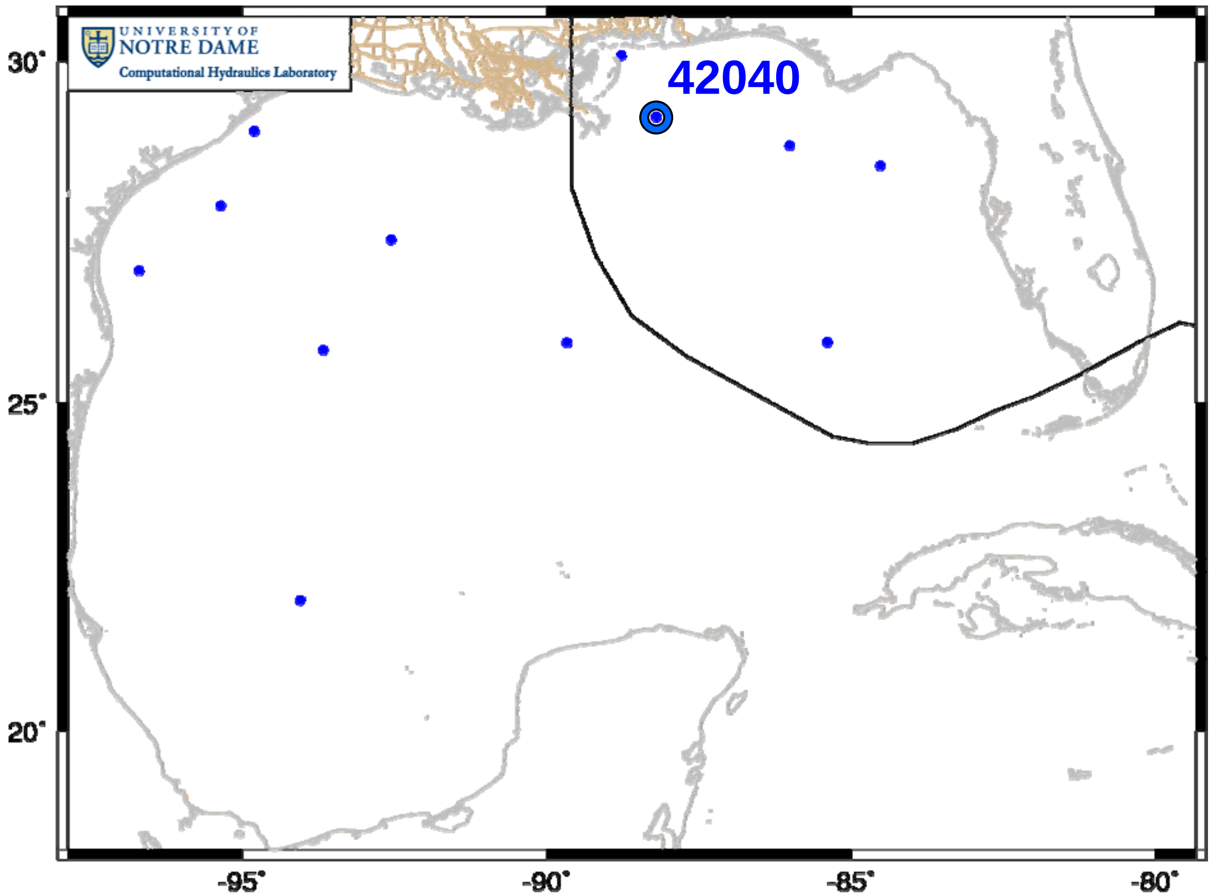


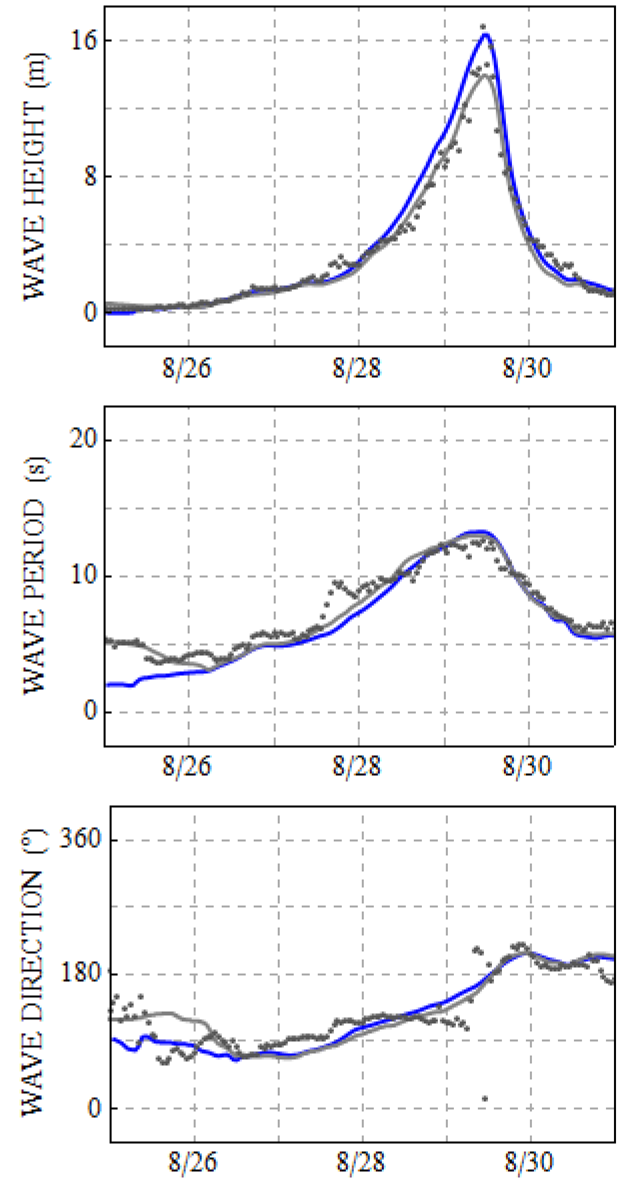


Katrina : Validation of Wave Parameters : NDBC 42039

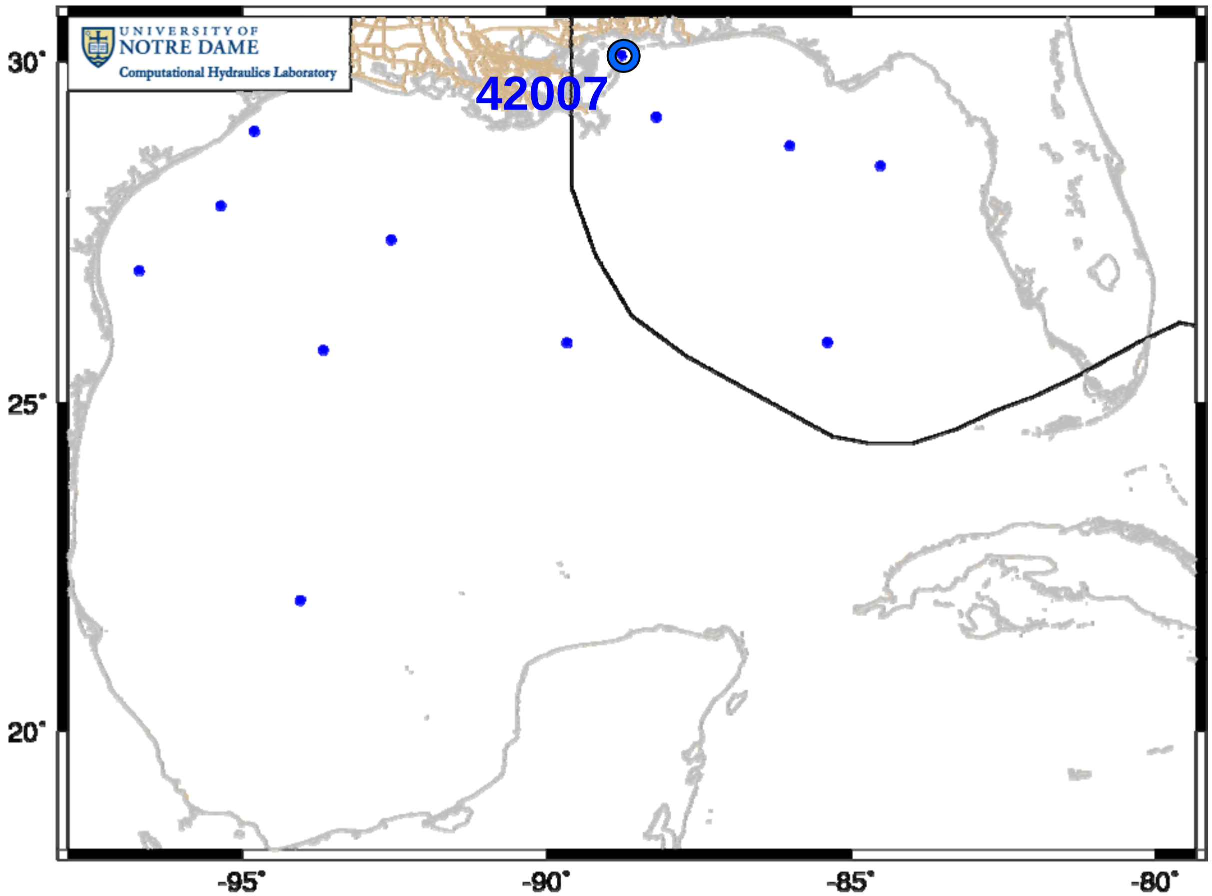


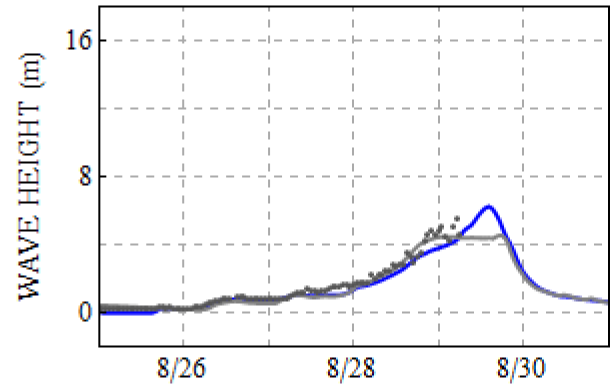
Katrina : Validation of Wave Parameters : NDBC 42040

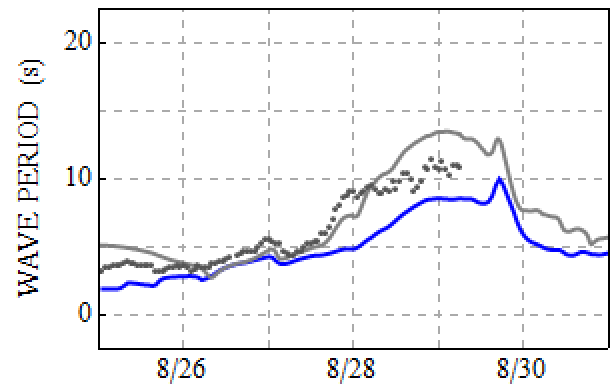


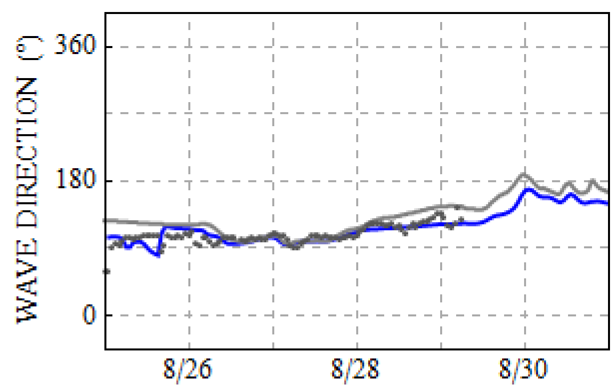


Katrina : Validation of Wave Parameters : NDBC 42007

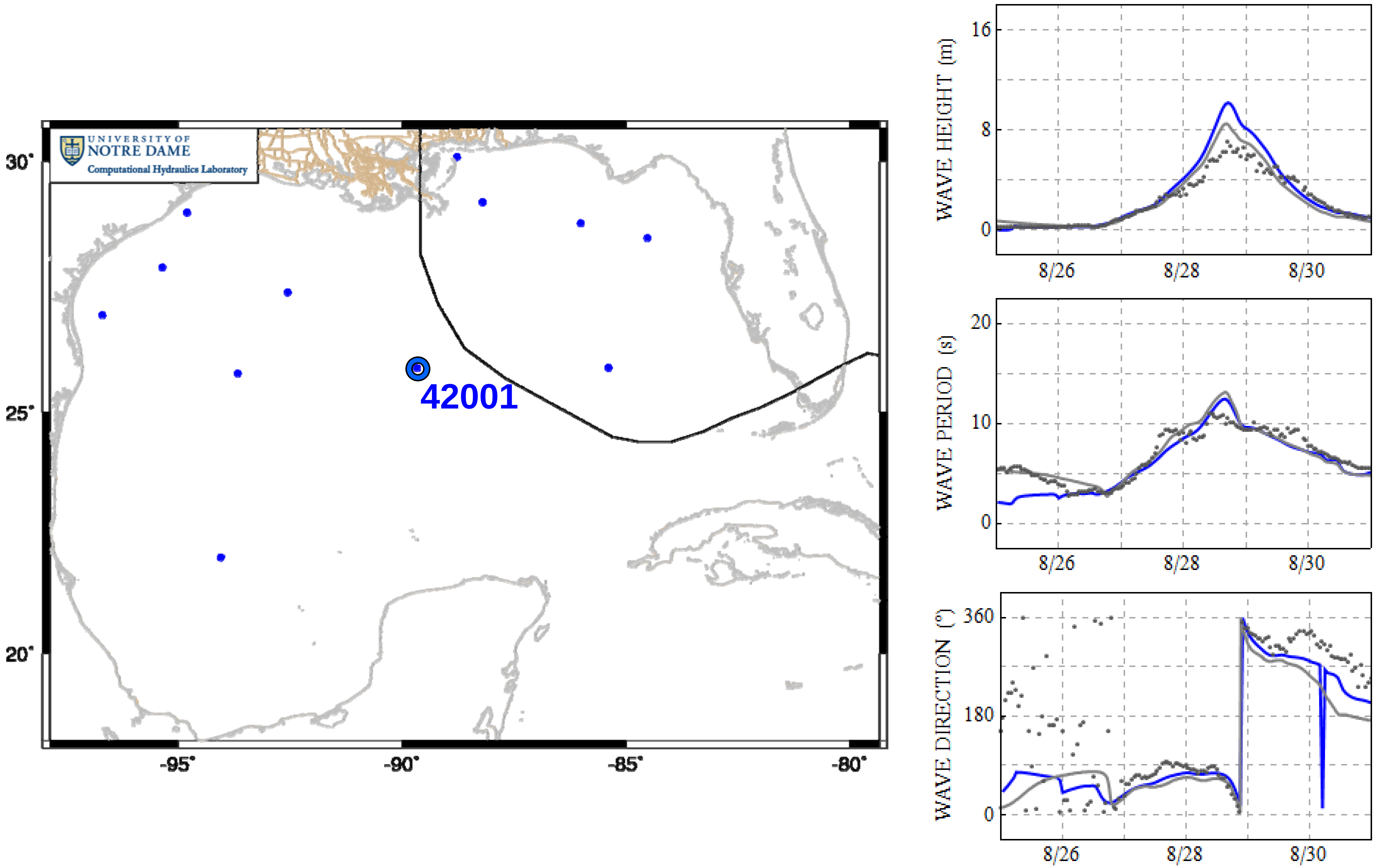




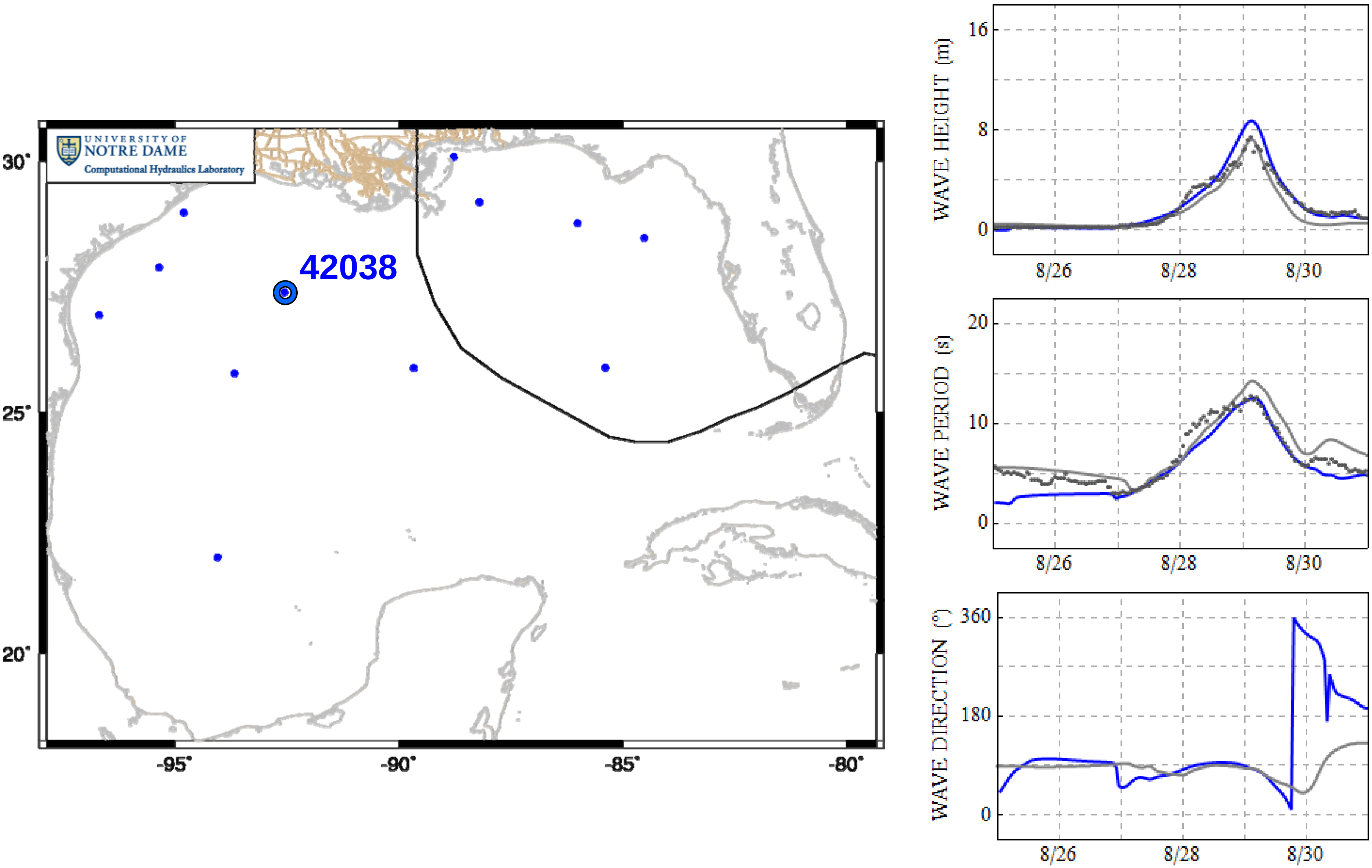




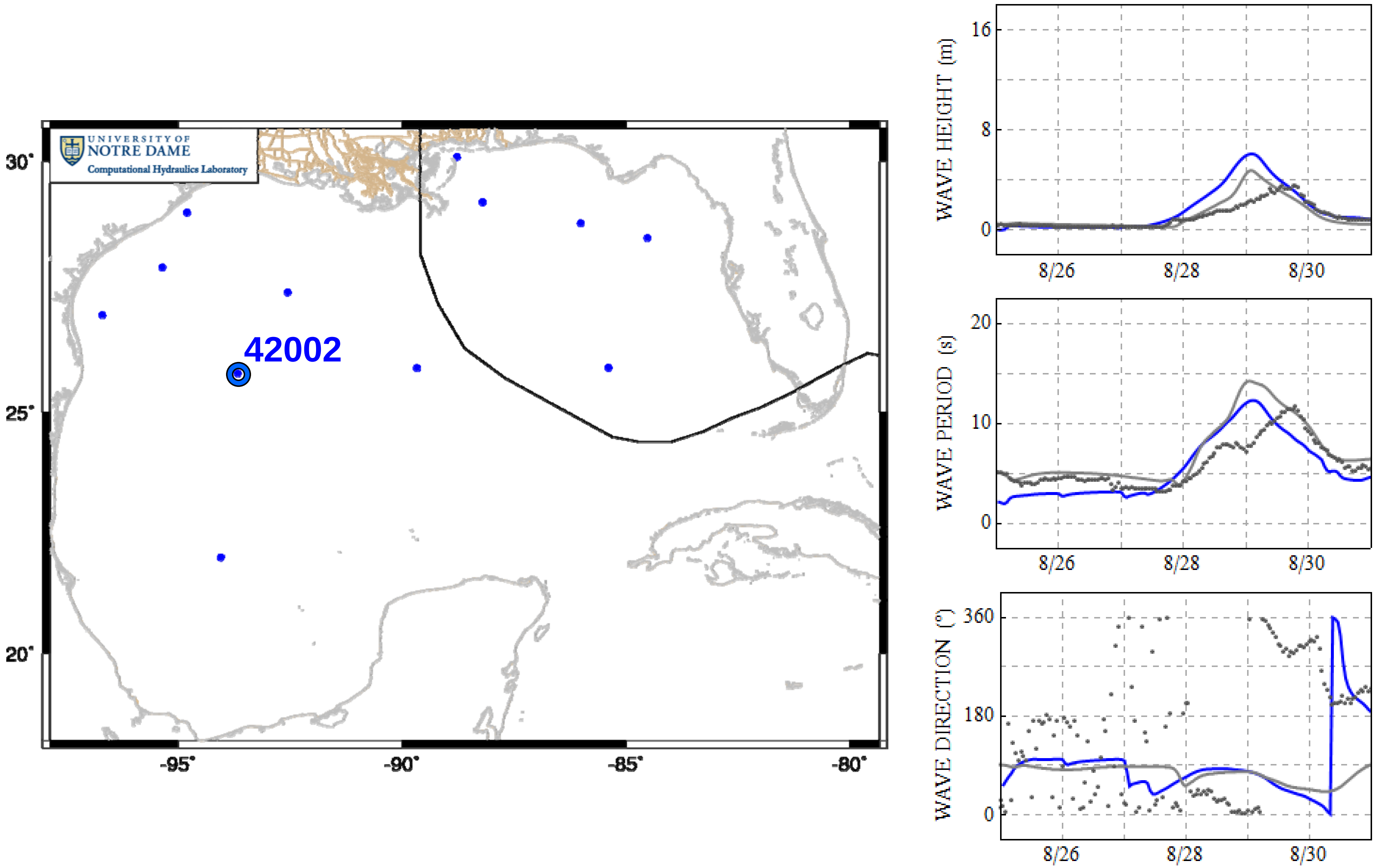
Katrina : Validation of Wave Parameters : NDBC 42001



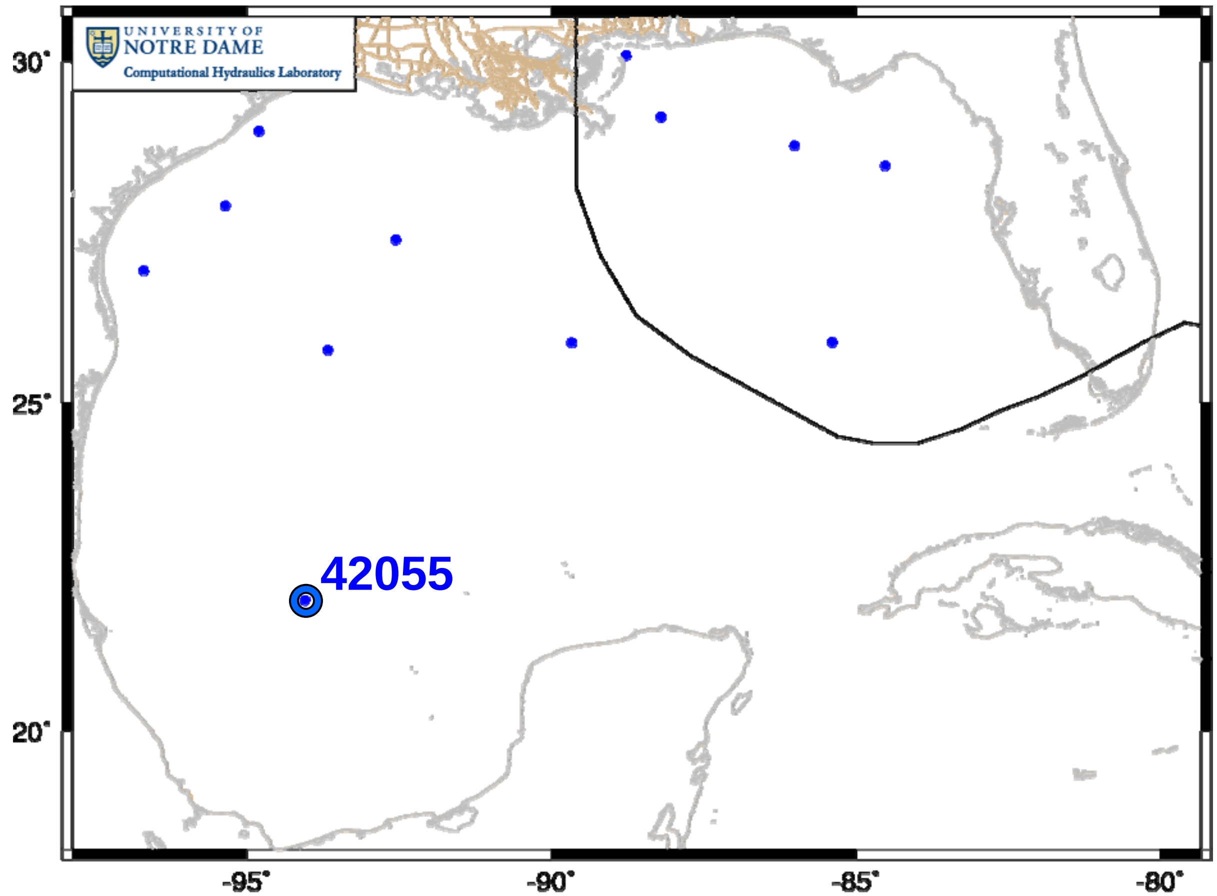
Katrina : Validation of Wave Parameters : NDBC 42038

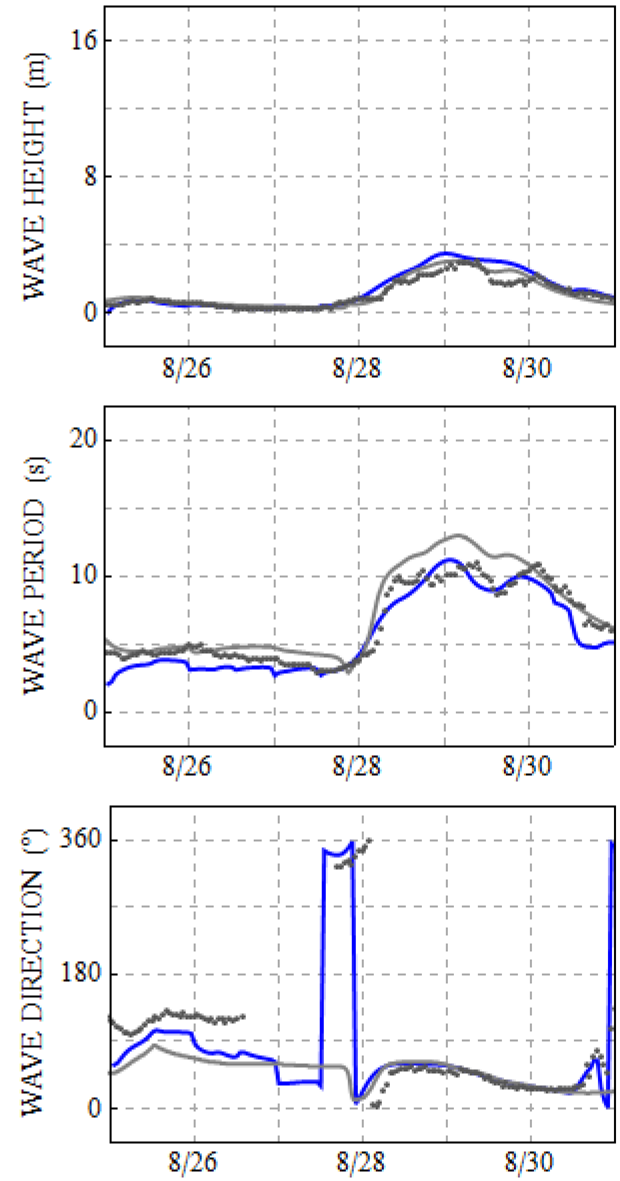


Katrina : Validation of Wave Parameters : NDBC 42002

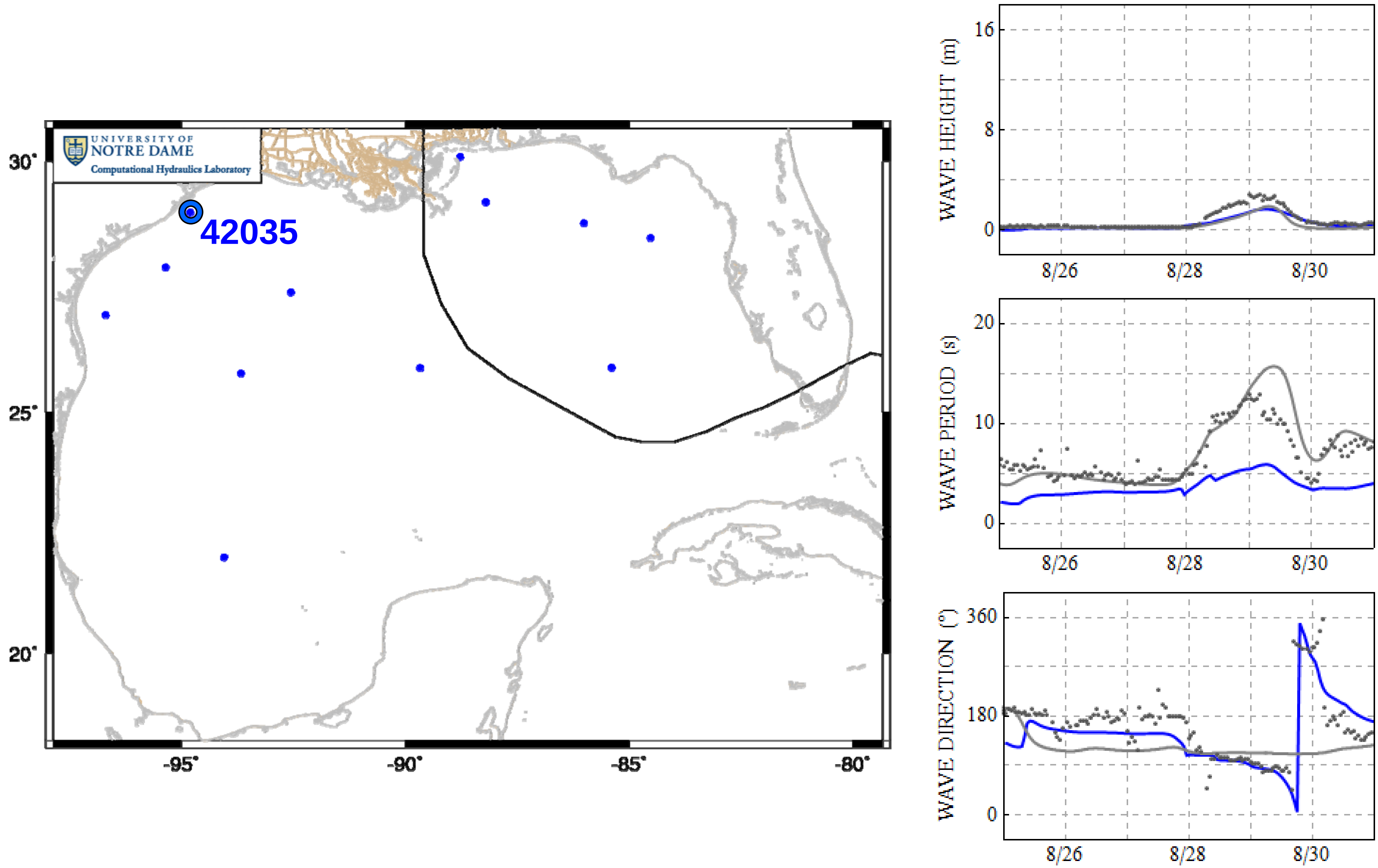


Katrina : Validation of Wave Parameters : NDBC 42055

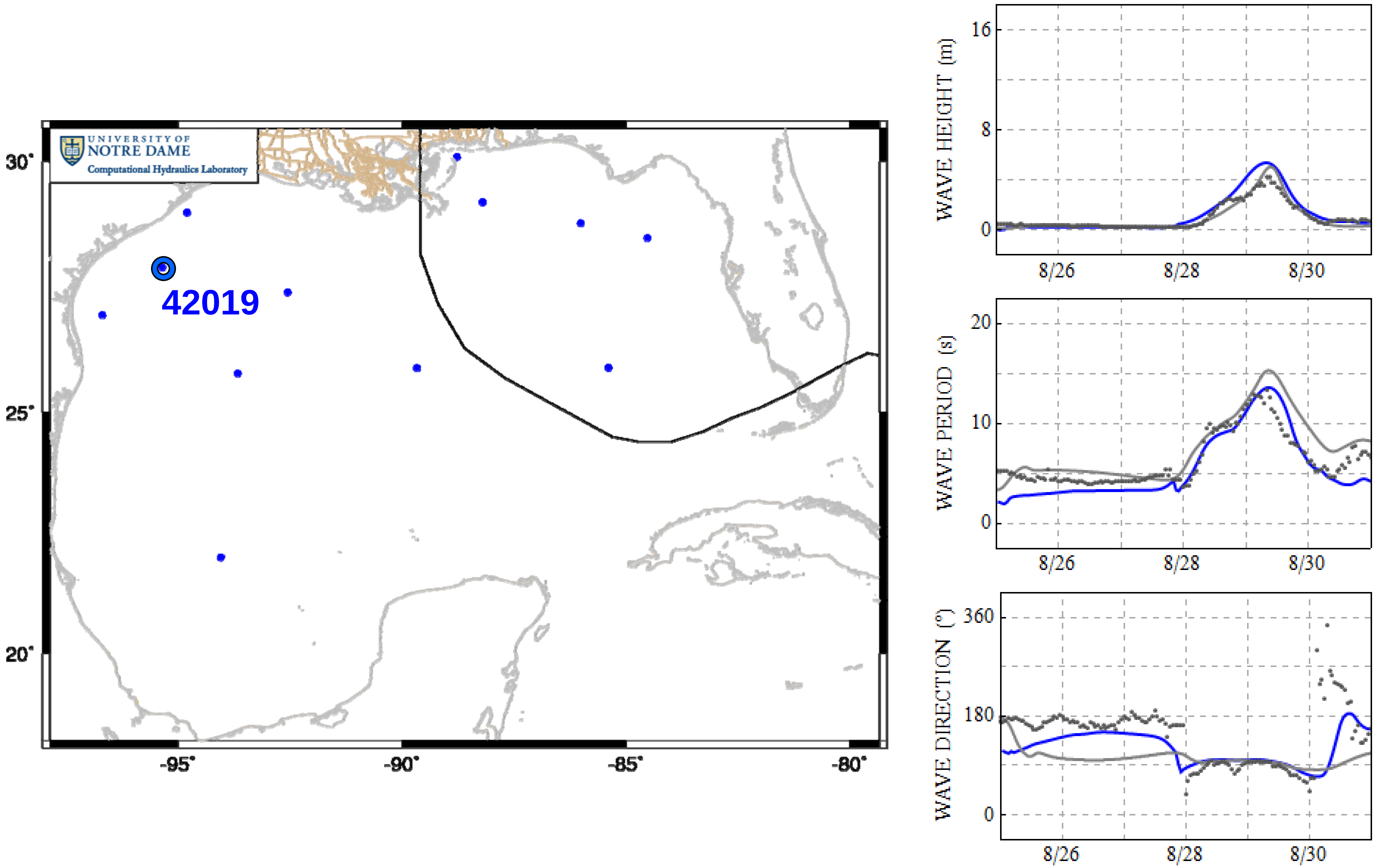




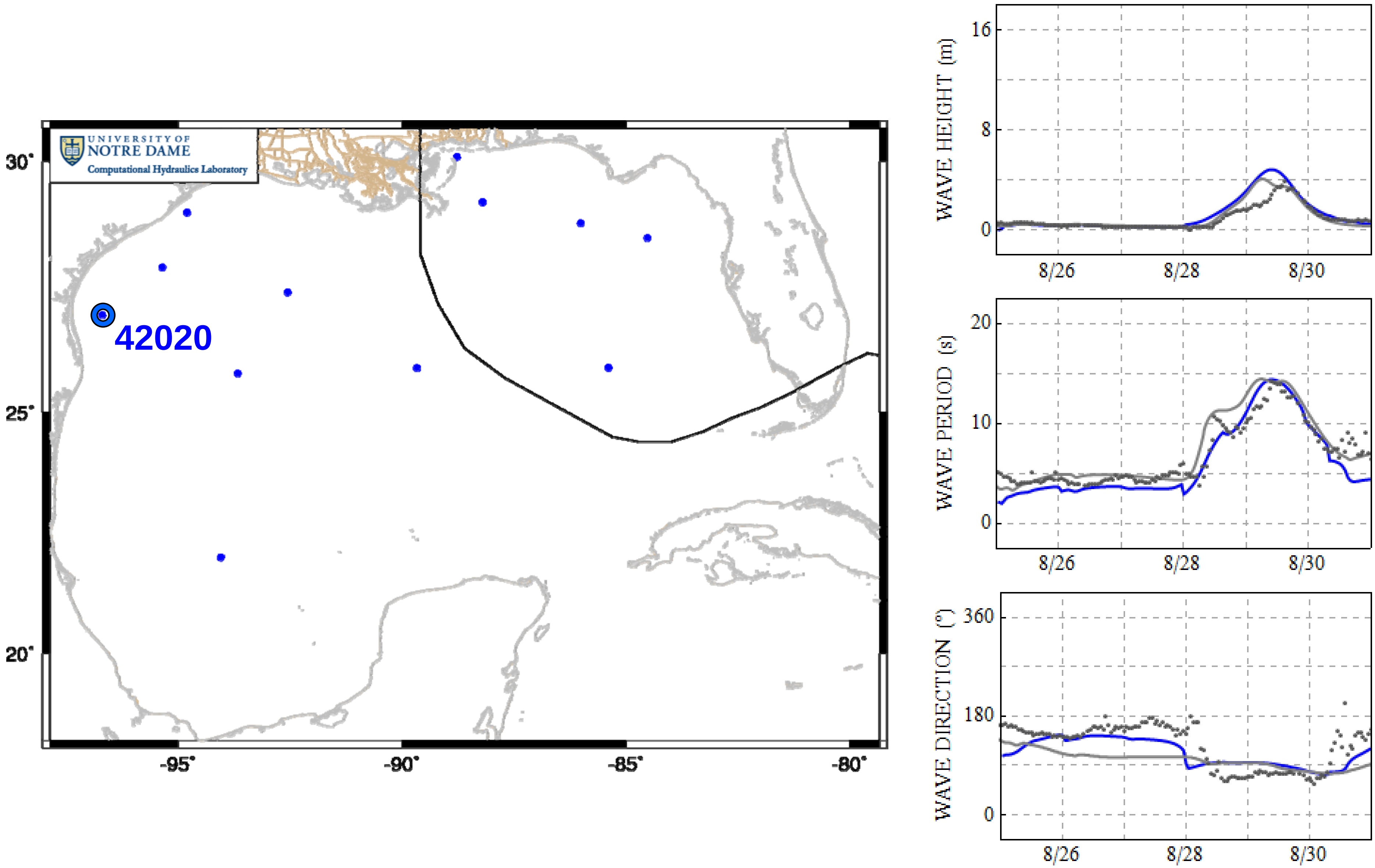
Katrina : Validation of Wave Parameters : NDBC 42035



Katrina : Validation of Wave Parameters : NDBC 42019



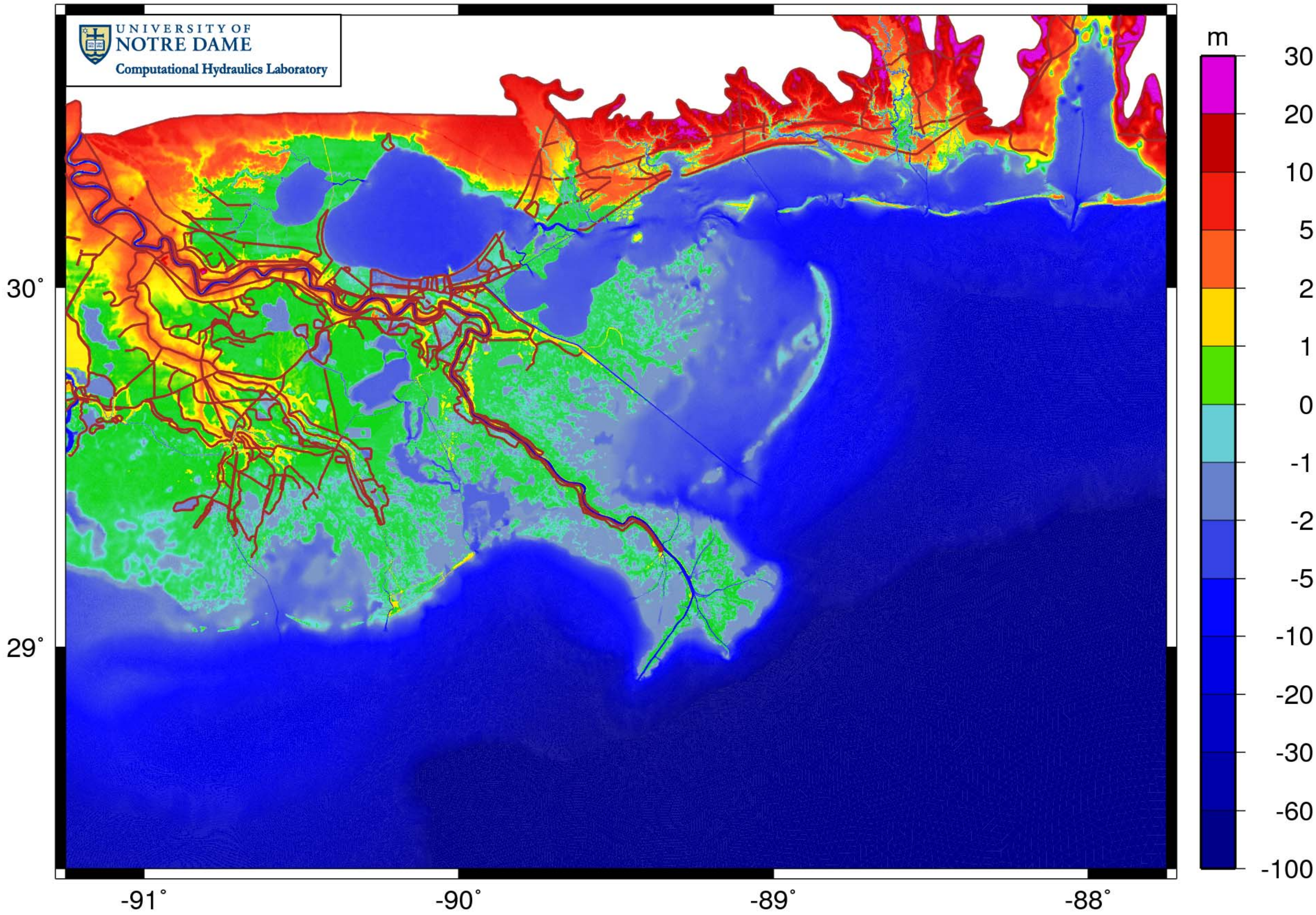
Katrina : Validation of Wave Parameters : NDBC 42020



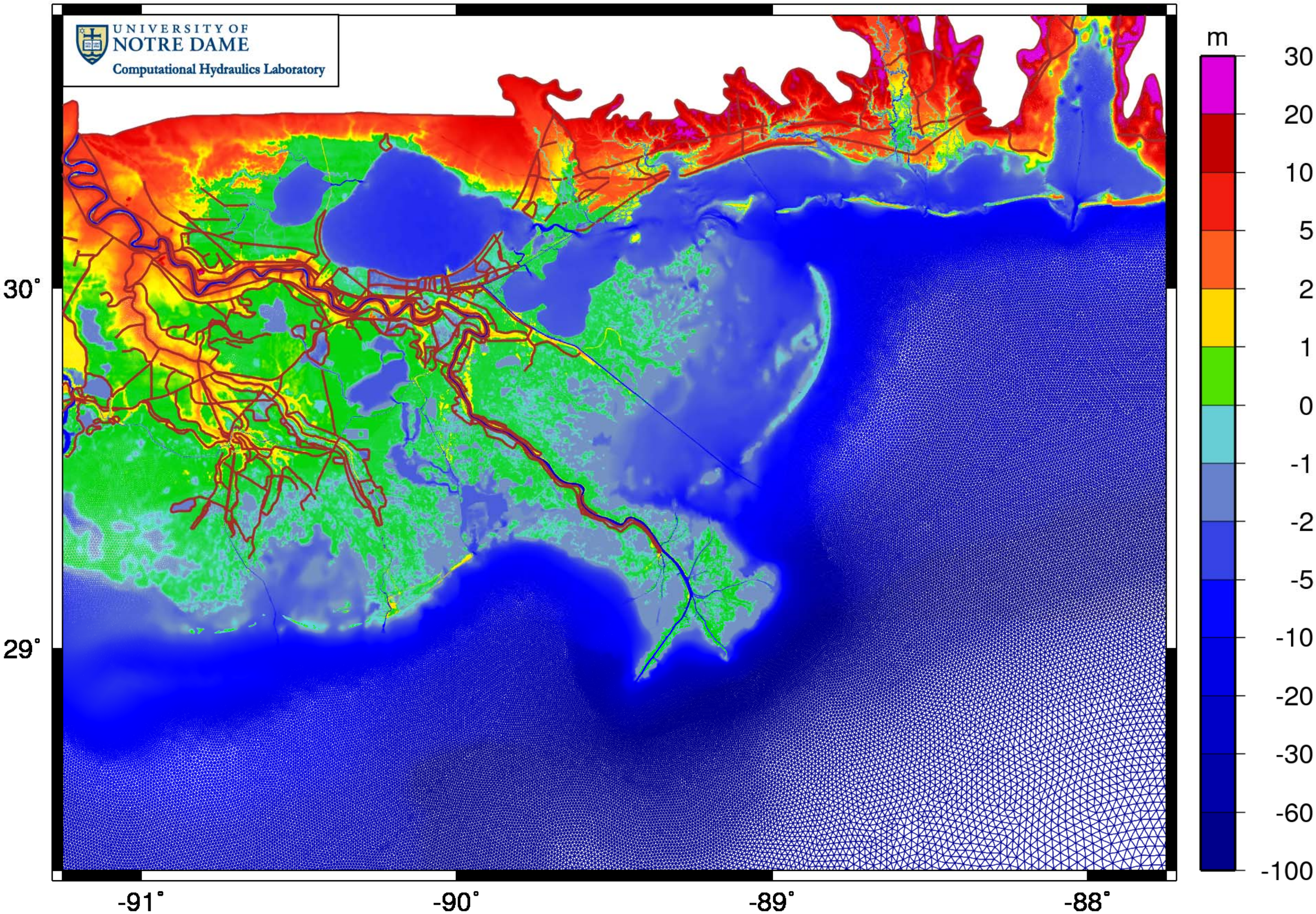
The New:
SWAN+ADCIRC Hindcast of Gustav

J.C. Dietrich, *et al*. (2010). "Hurricane Gustav (2008) Waves, Storm Surge and Currents: Hindcast and Synoptic Analysis in Southern Louisiana." *Monthly Weather Review*, in preparation.

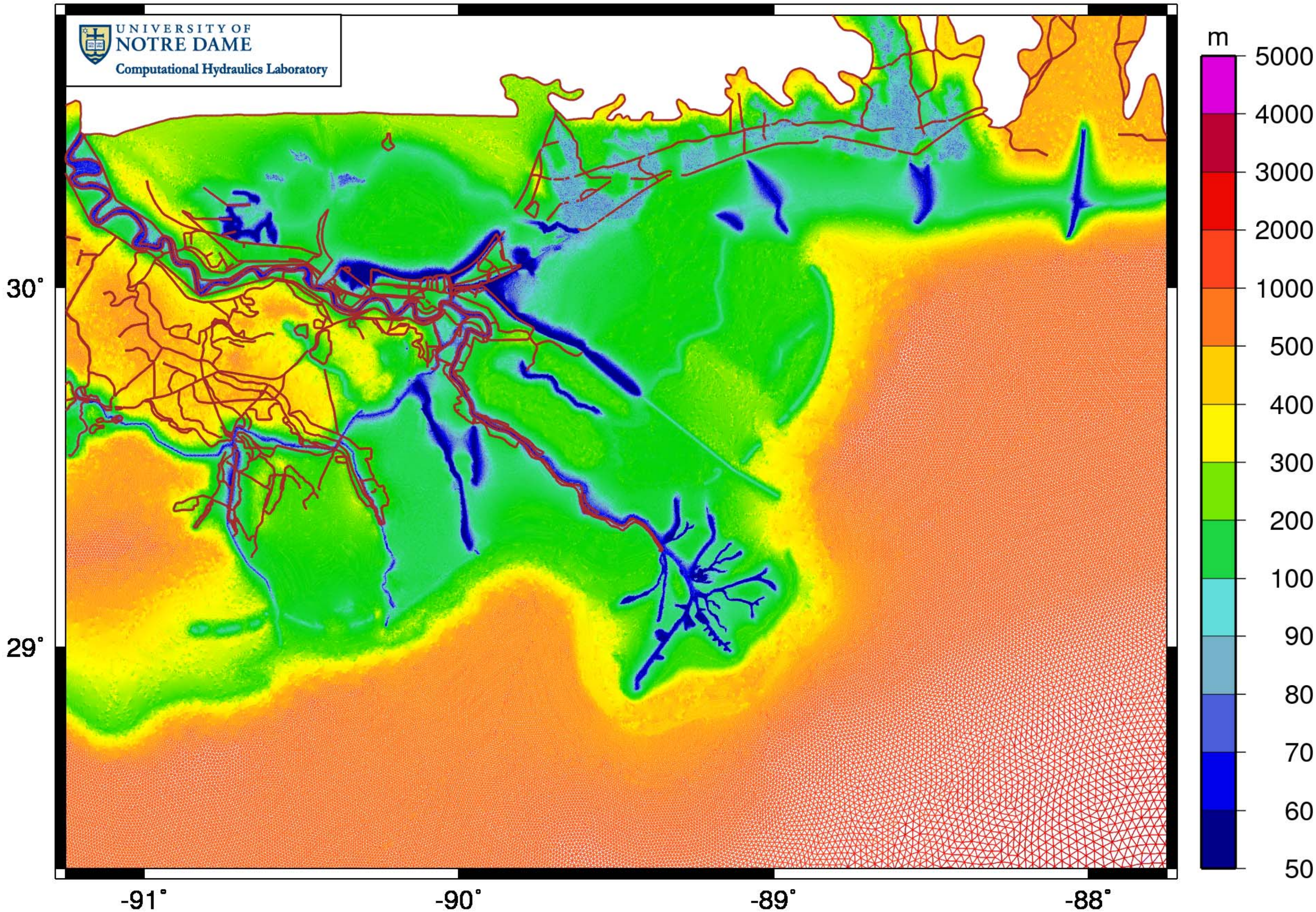
SL16v18c3 : Bathymetry and Topography



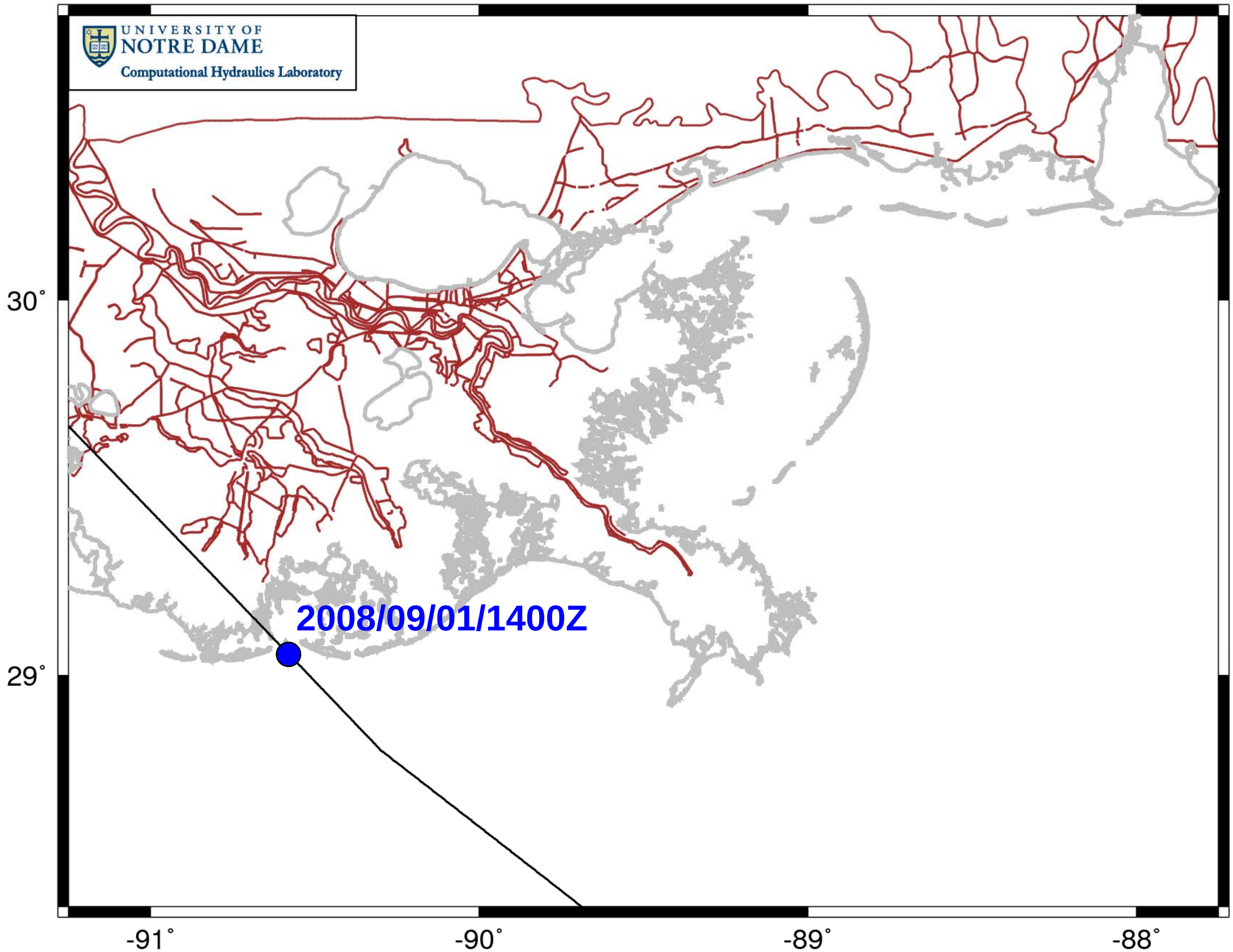
SL16v18c3 : Bathymetry and Topography



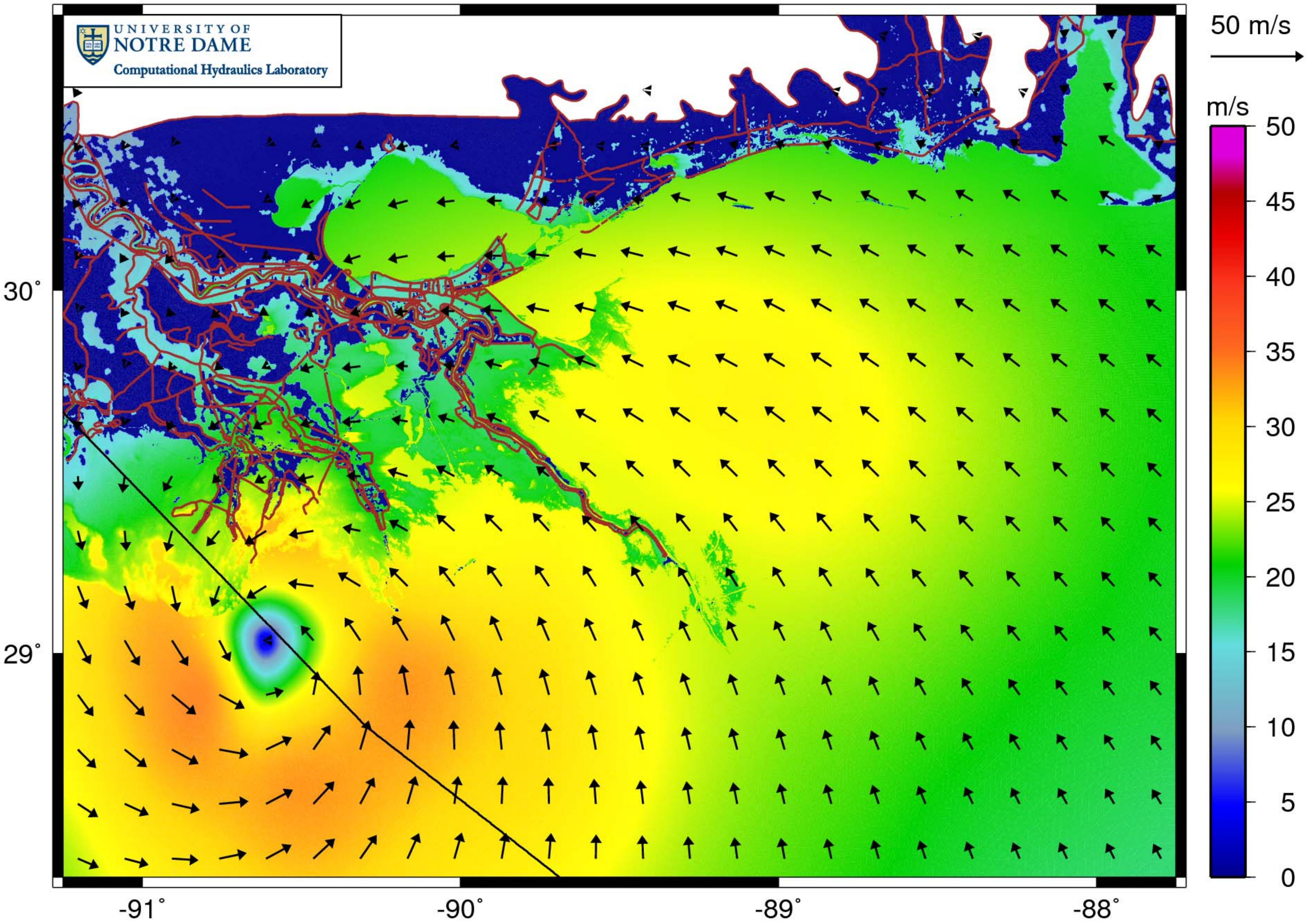
SL16v18c3 : Mesh Sizes



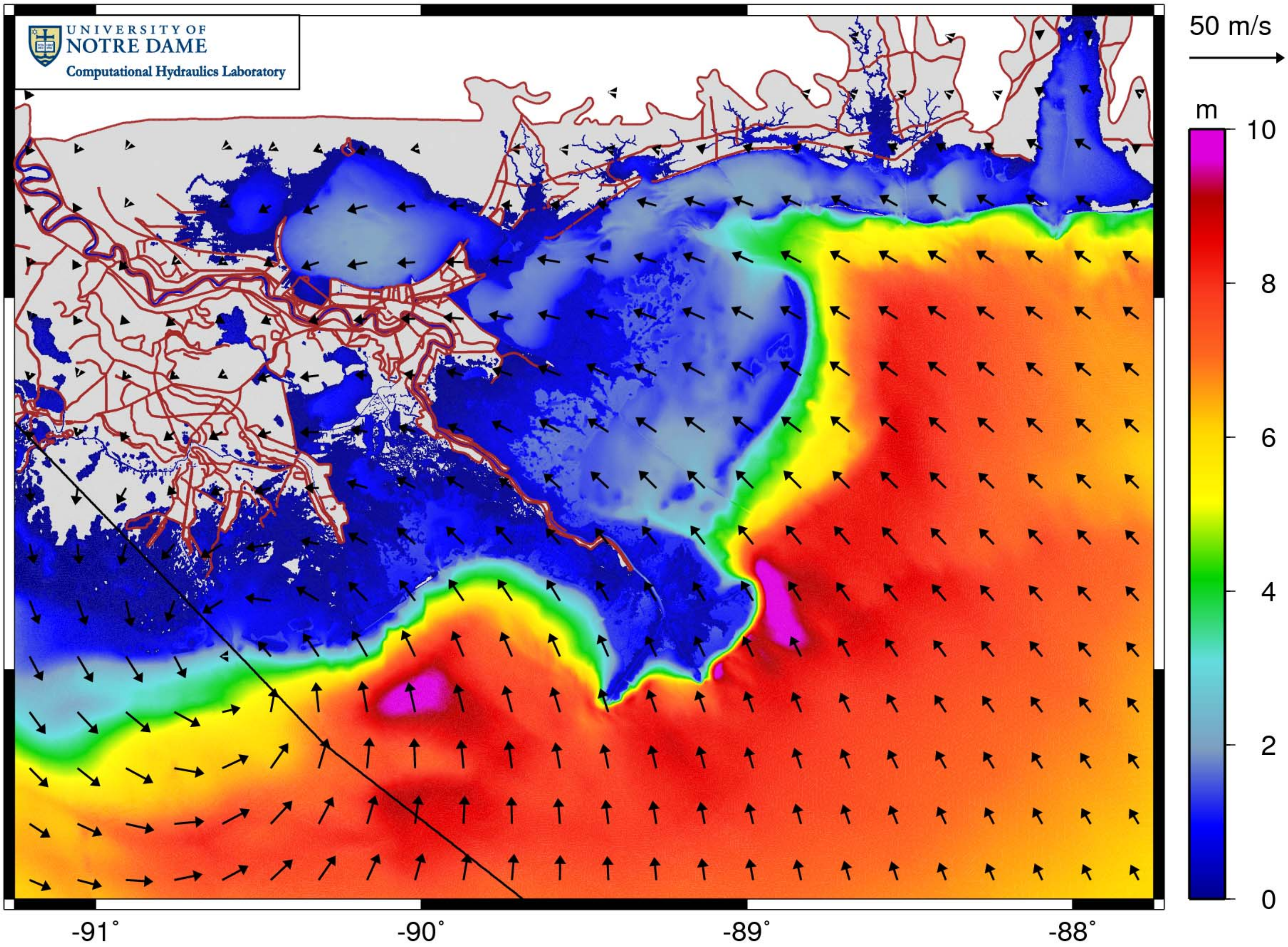
Gustav : Track



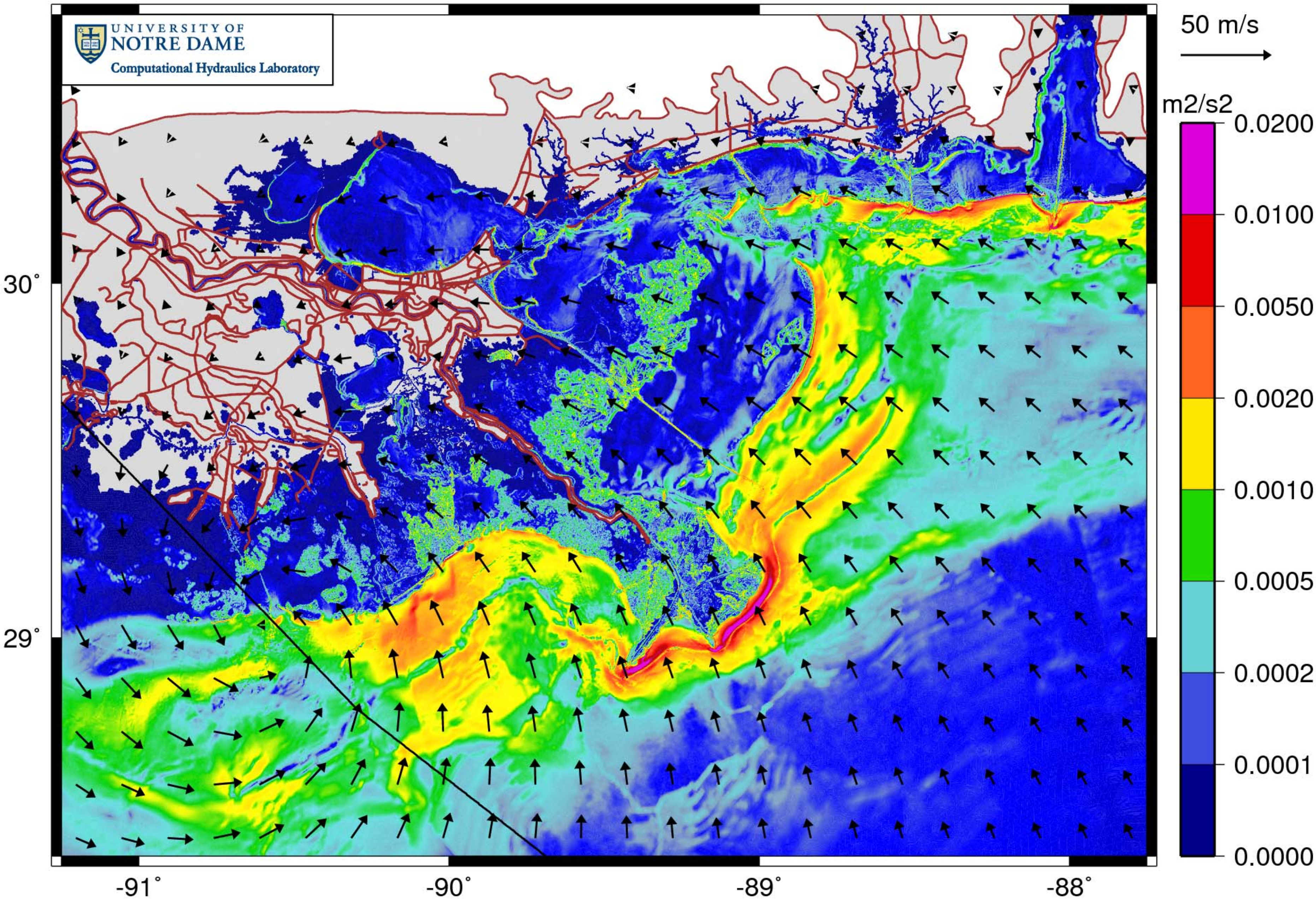
Gustav : Winds : 2008/09/01/1400Z



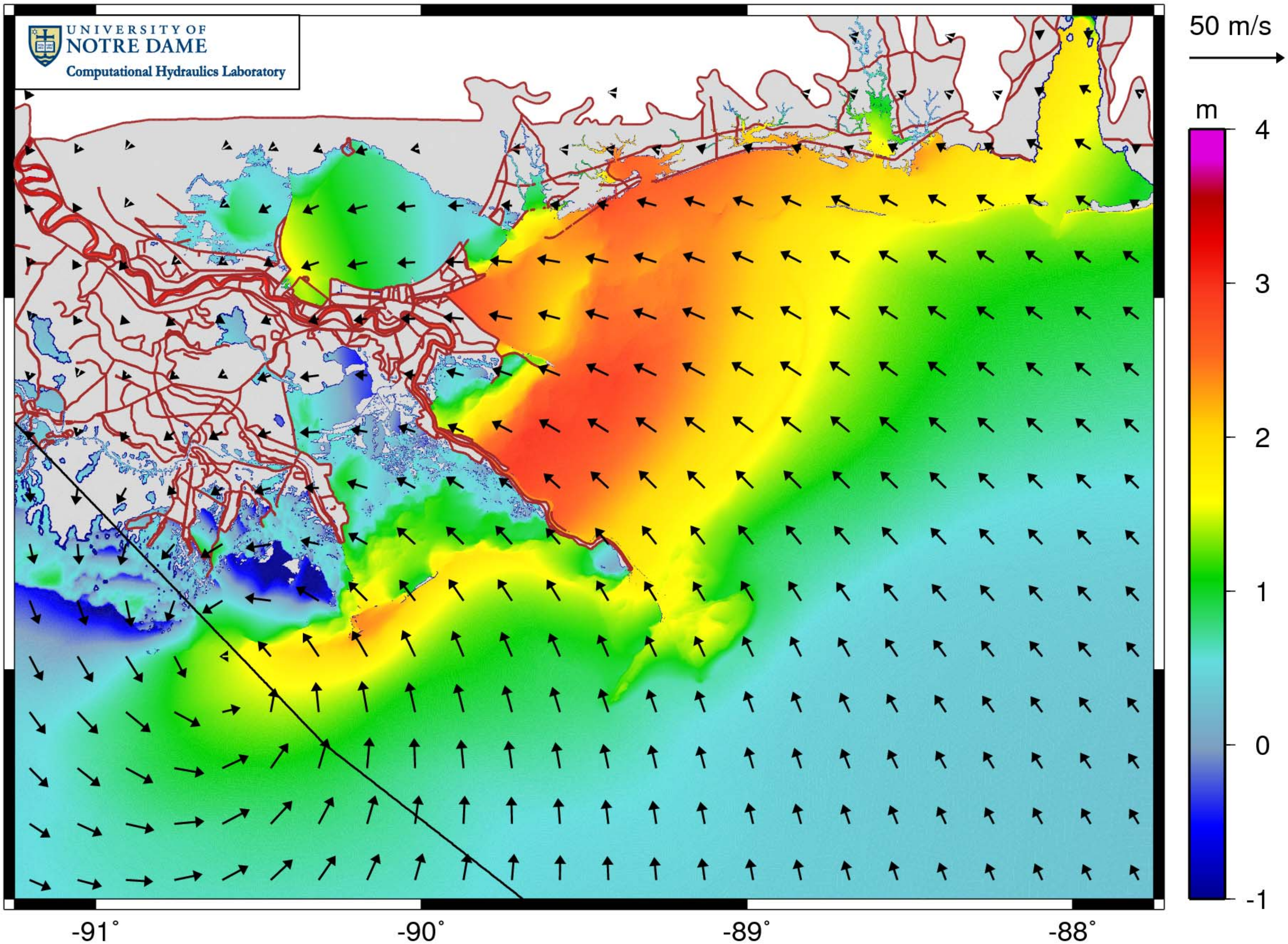
Gustav : Significant Wave Heights : 2008/09/01/1400Z



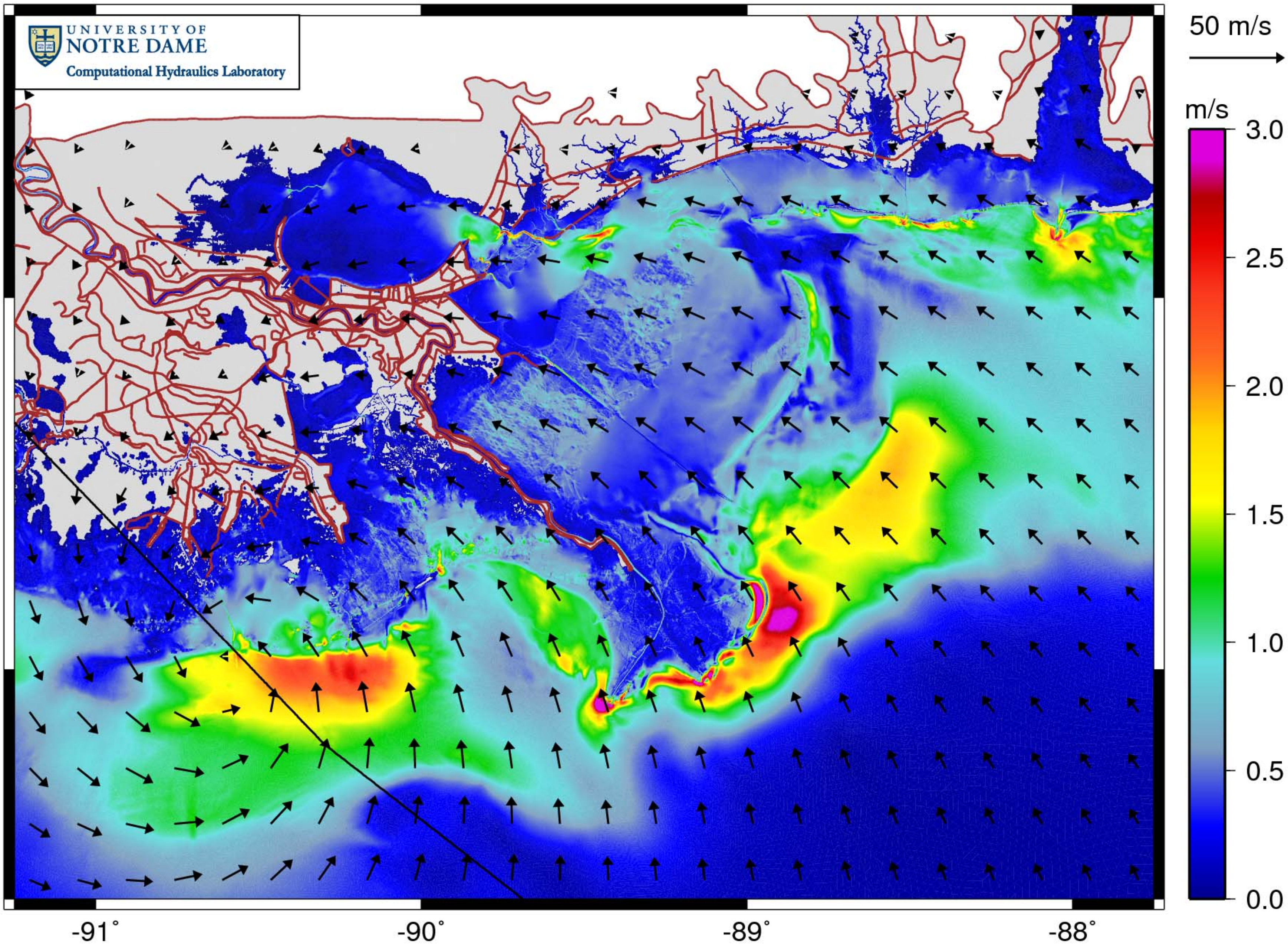
Gustav : Radiation Stress Gradients : 2008/09/01/1400Z



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



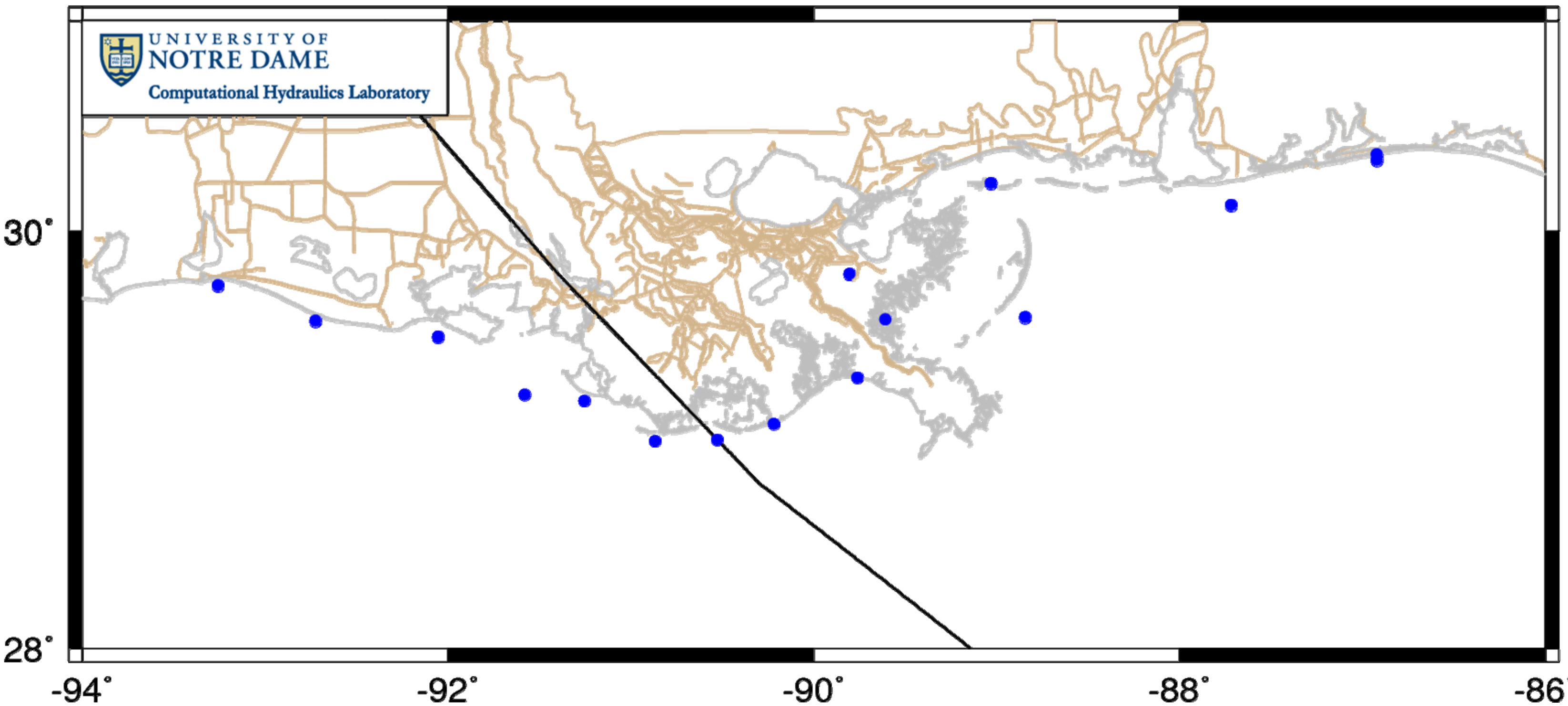
Gustav : Currents : 2008/09/01/1400Z



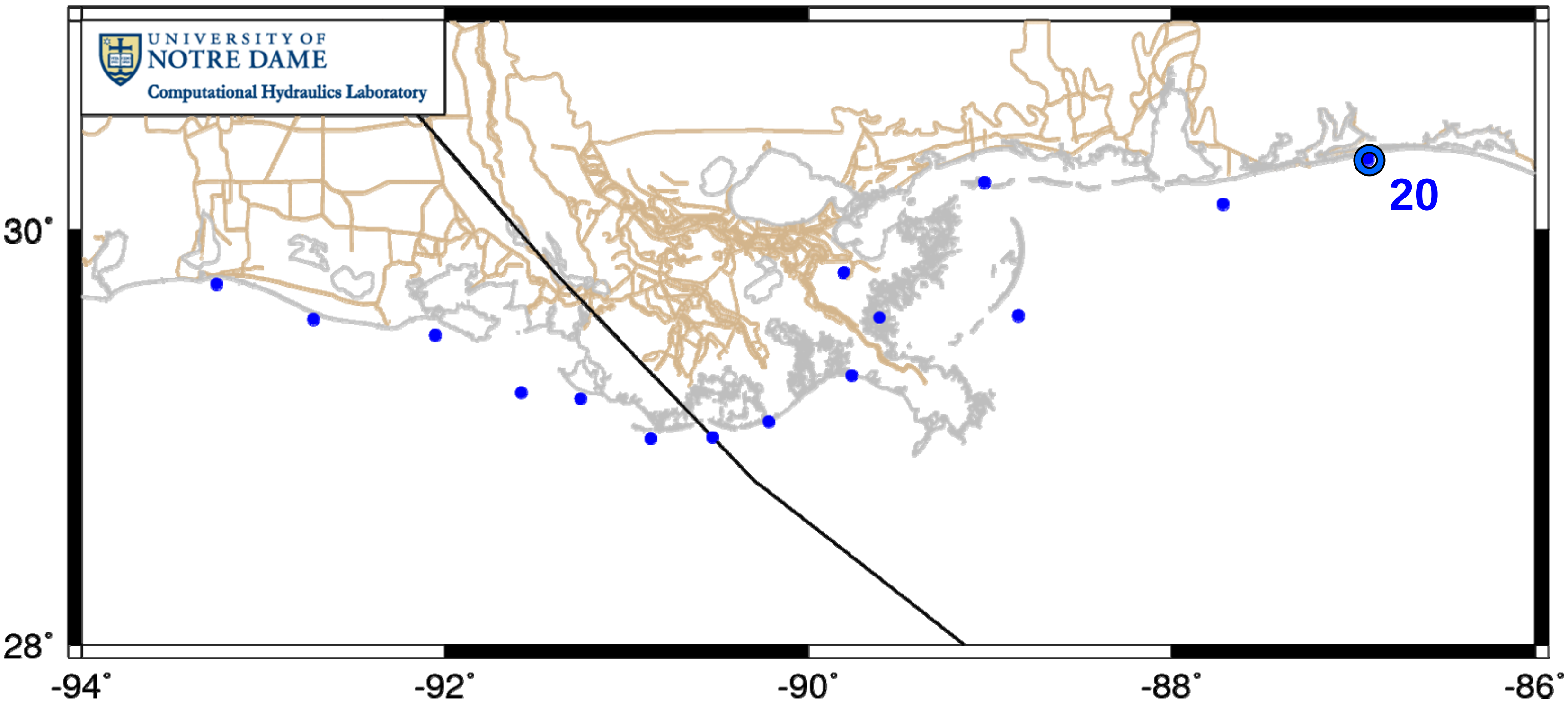
Increased Availability of Measurement Data

	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:**	**184**
	NOS	2		
	NWS	1		
	USGS (Permanent)	6	USGS (Permanent)	44
			USGS (Deployable)	42
			NOAA	26
			USACE	46
			ND (Kennedy)	16
			USACE (Smith)	6
	Wave Parameters:	**14**	**Wave Parameters:**	**39**
	NDBC	12	NDBC	12
	CSI	2	CSI	5
			ND (Kennedy)	16
			USACE (Smith)	6

Gustav : Validation of Wave Parameters : AK

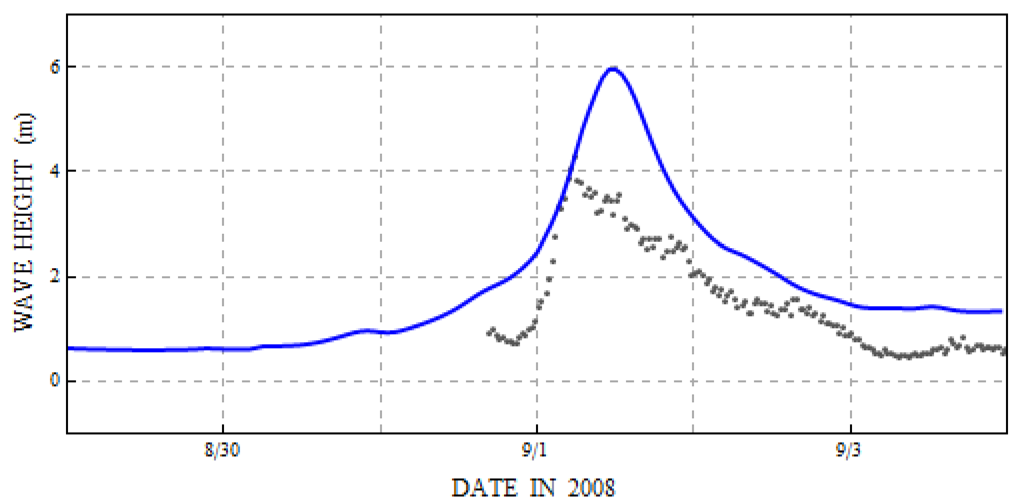


Gustav : Validation of Wave Parameters : AK 20

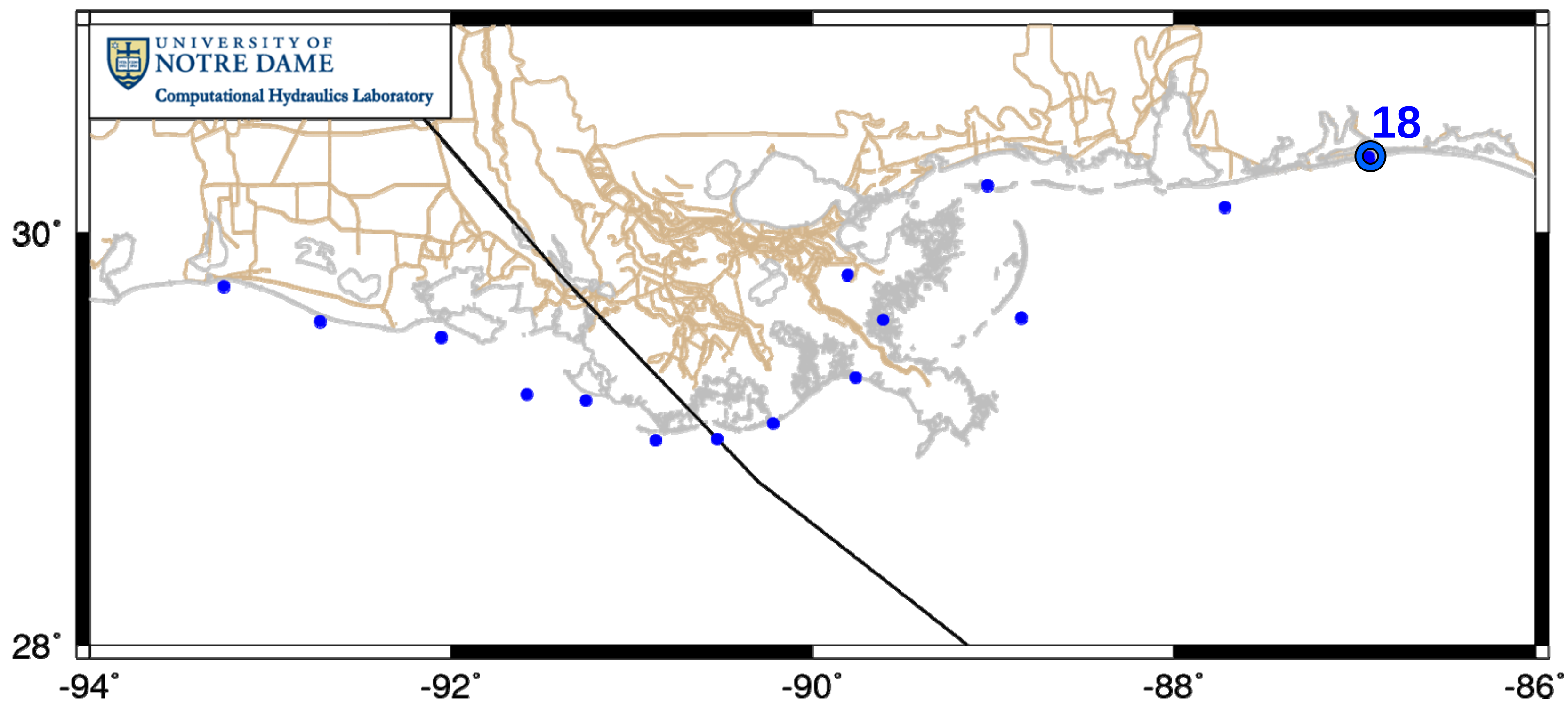


Bathymetry at Gage:

Kennedy:	23.1
ADCIRC:	18.7

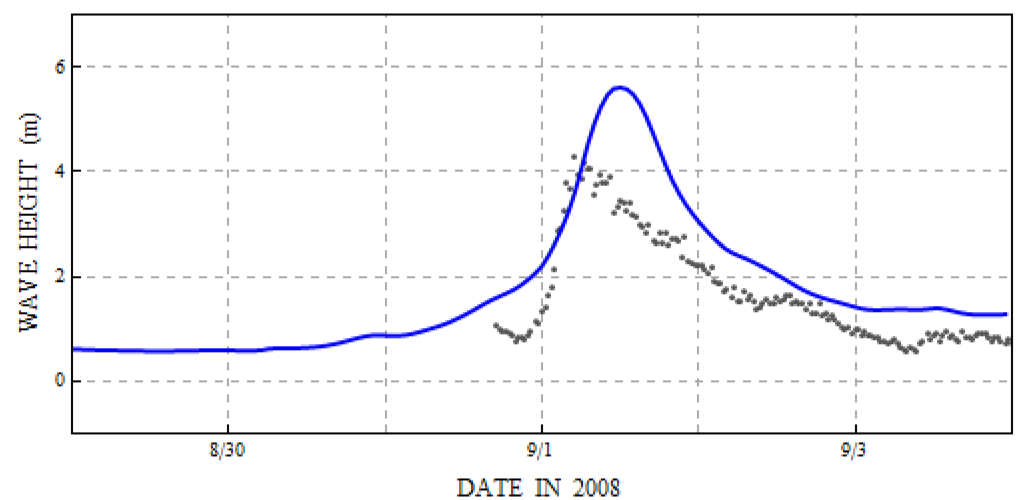


Gustav : Validation of Wave Parameters : AK 18

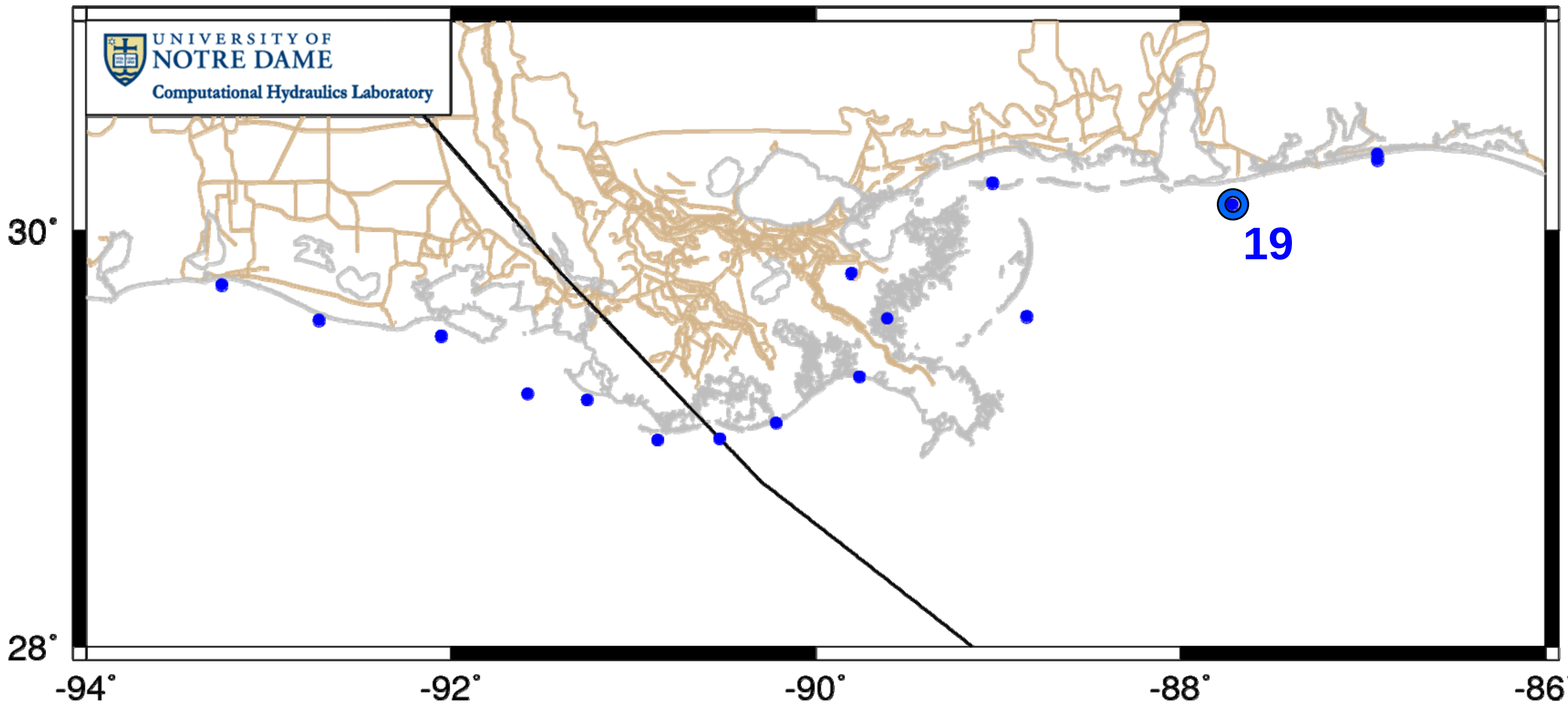


Bathymetry at Gage:

Kennedy:	10.7
ADCIRC:	17.4

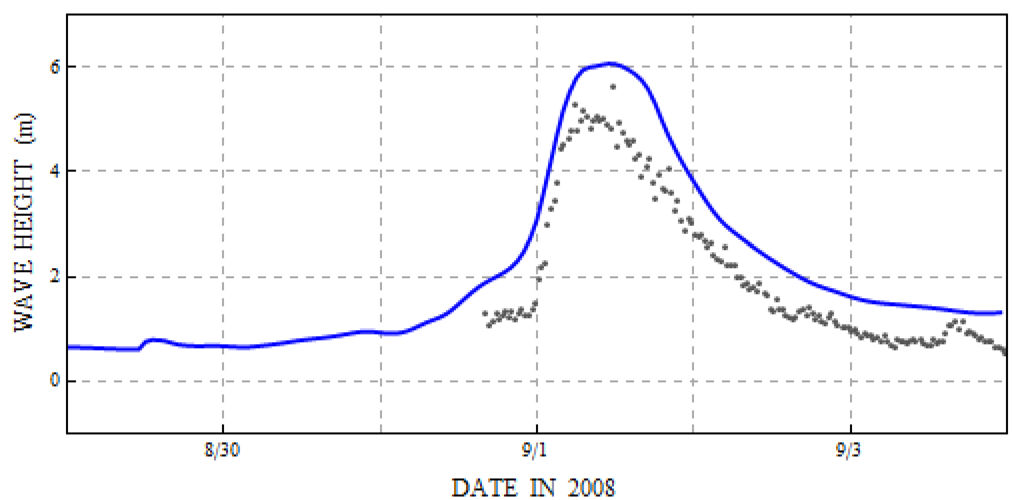


Gustav : Validation of Wave Parameters : AK 19

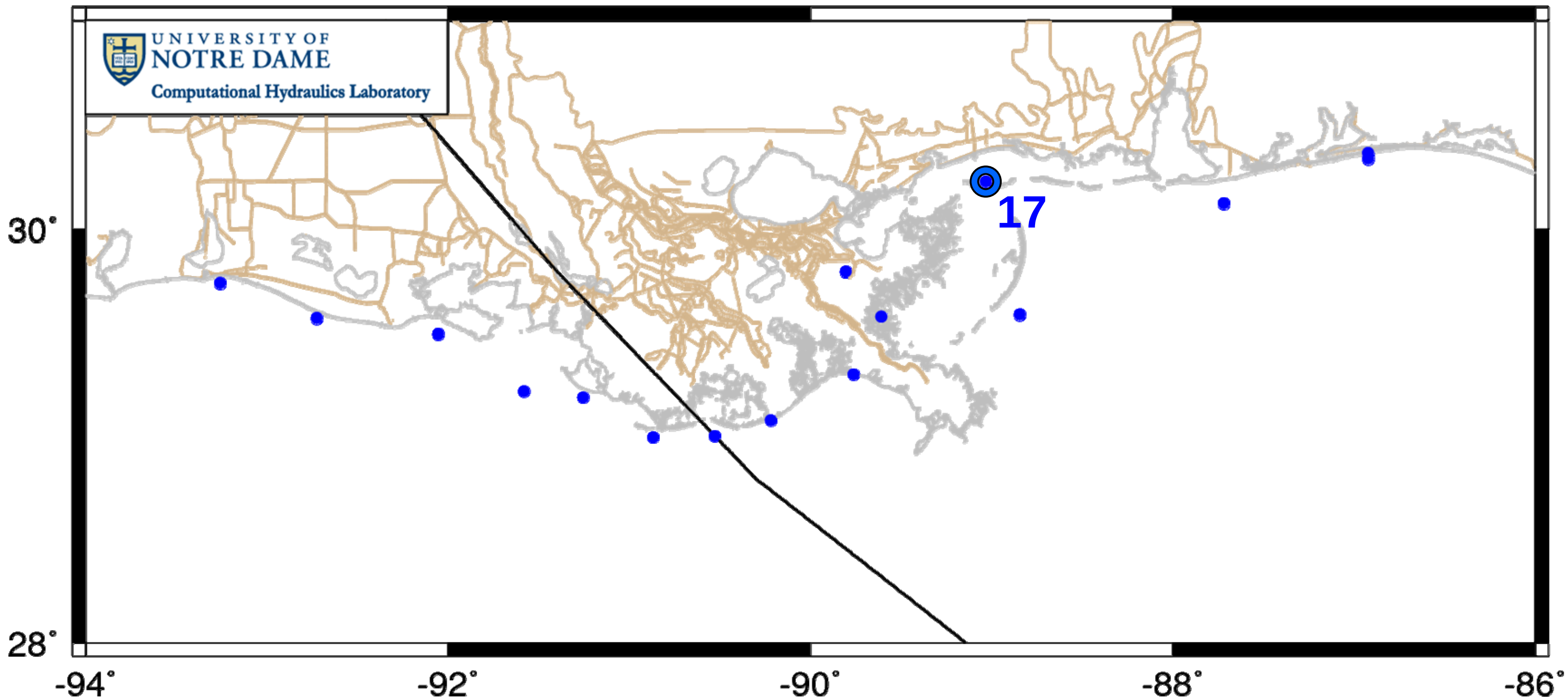


Bathymetry at Gage:

Kennedy:	15.4
ADCIRC:	14.8

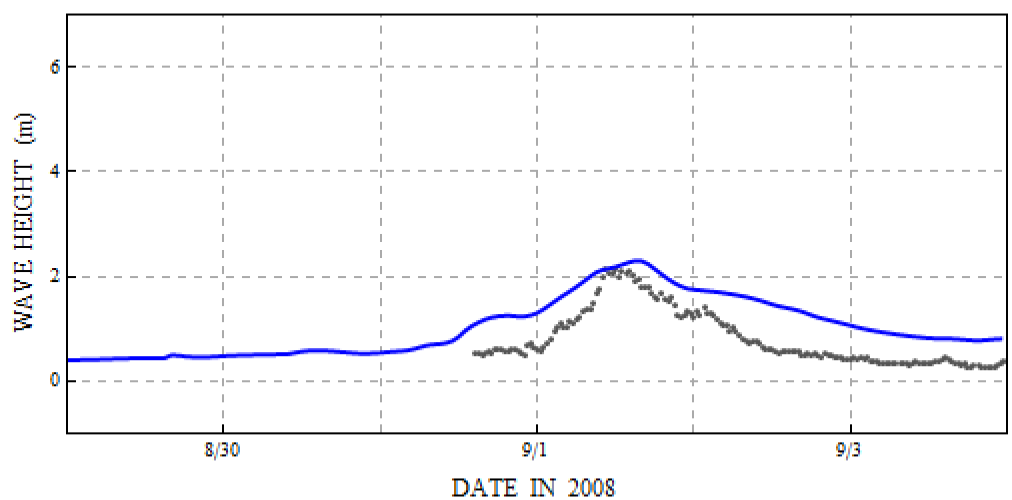


Gustav : Validation of Wave Parameters : AK 17

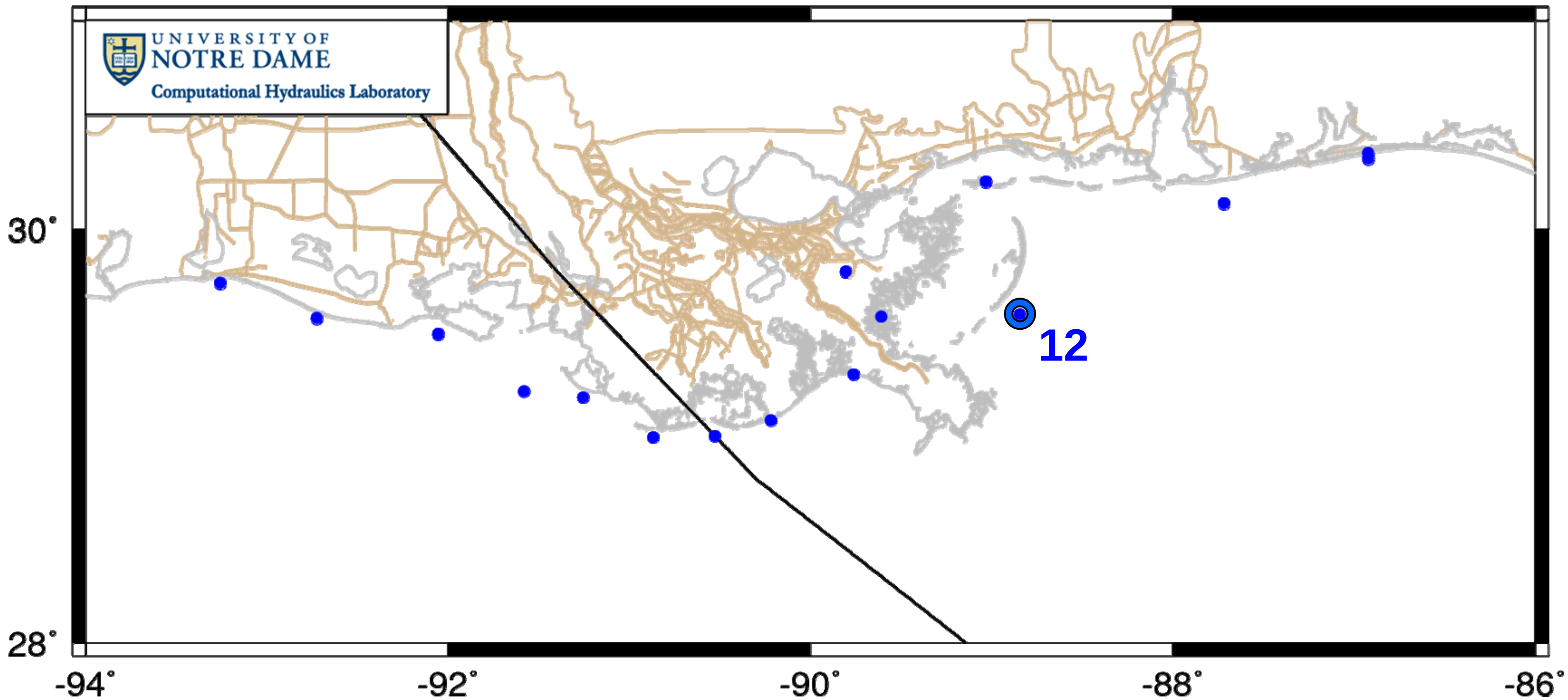


Bathymetry at Gage:

Kennedy:	4.6
ADCIRC:	3.2

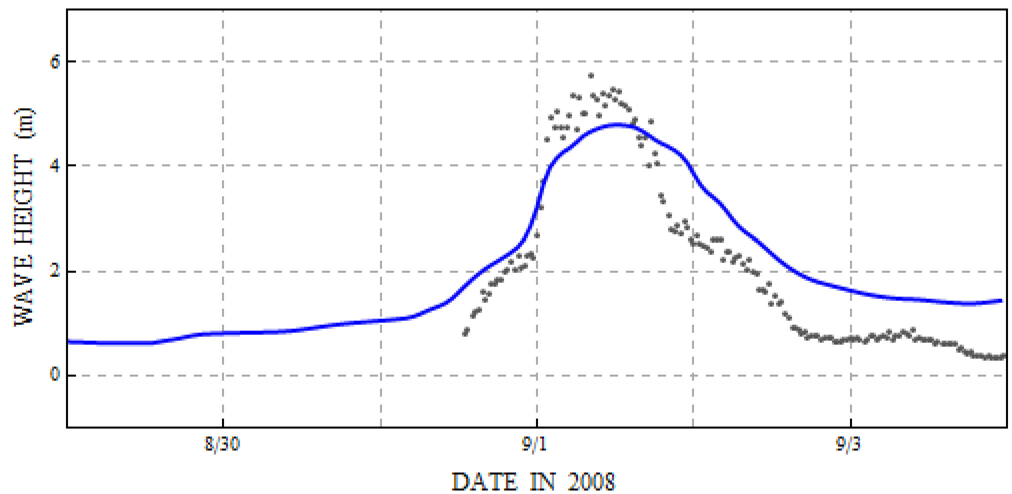


Gustav : Validation of Wave Parameters : AK 12

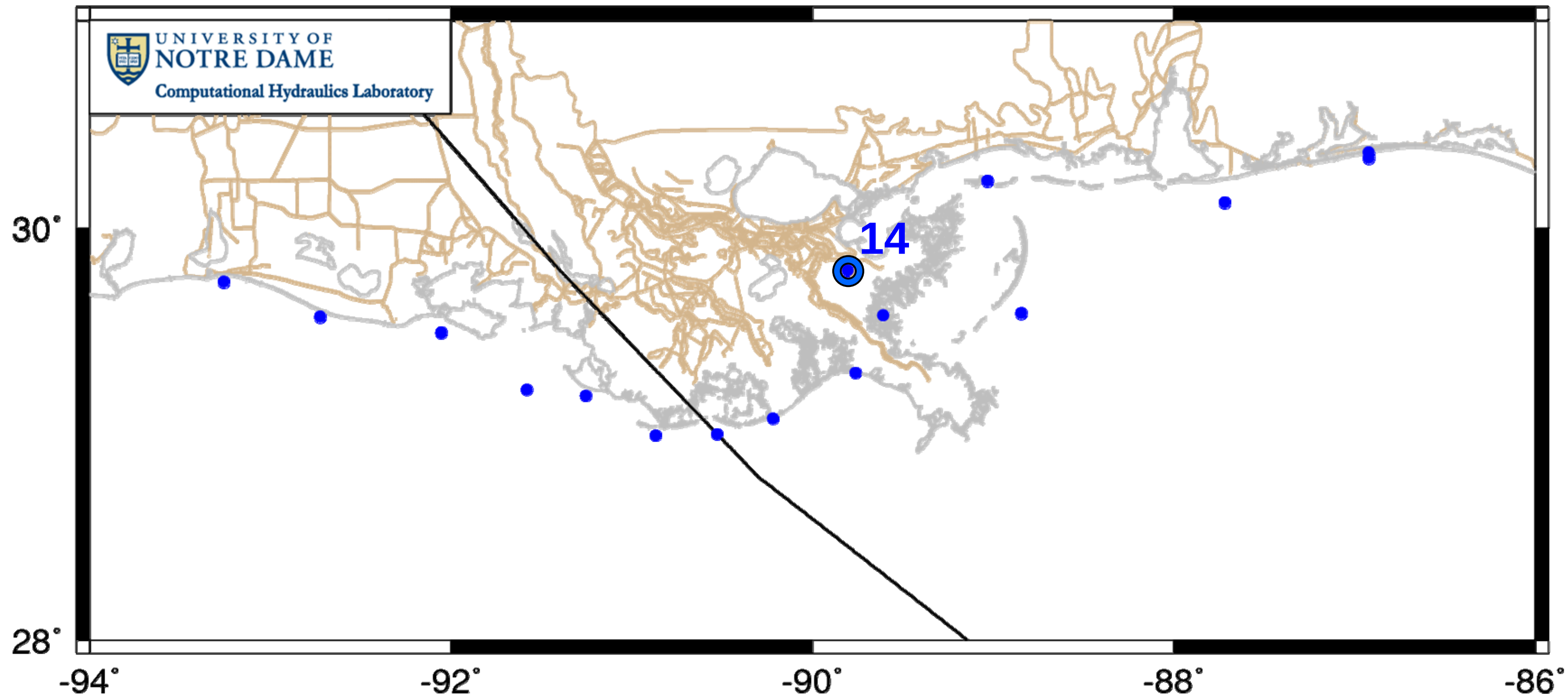


Bathymetry at Gage:

Kennedy:	14.0
ADCIRC:	11.1



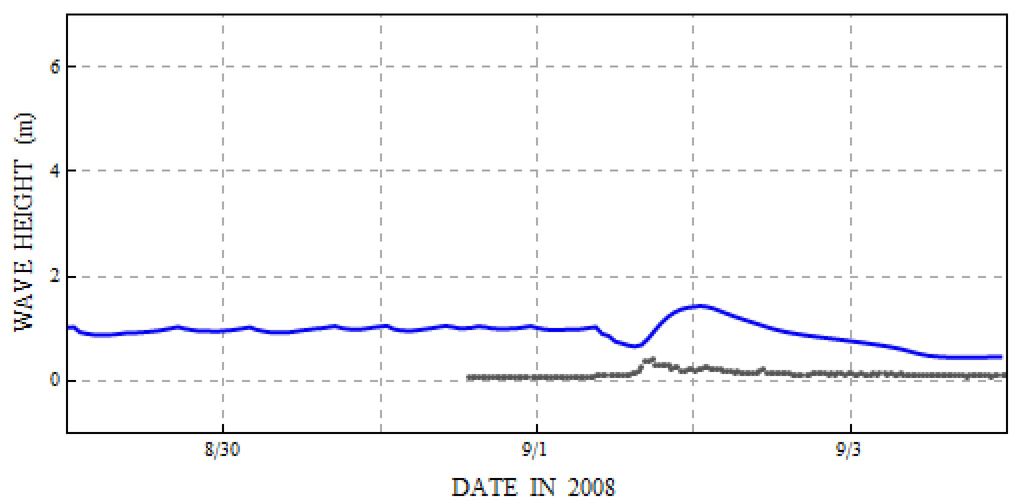
Gustav : Validation of Wave Parameters : AK 14



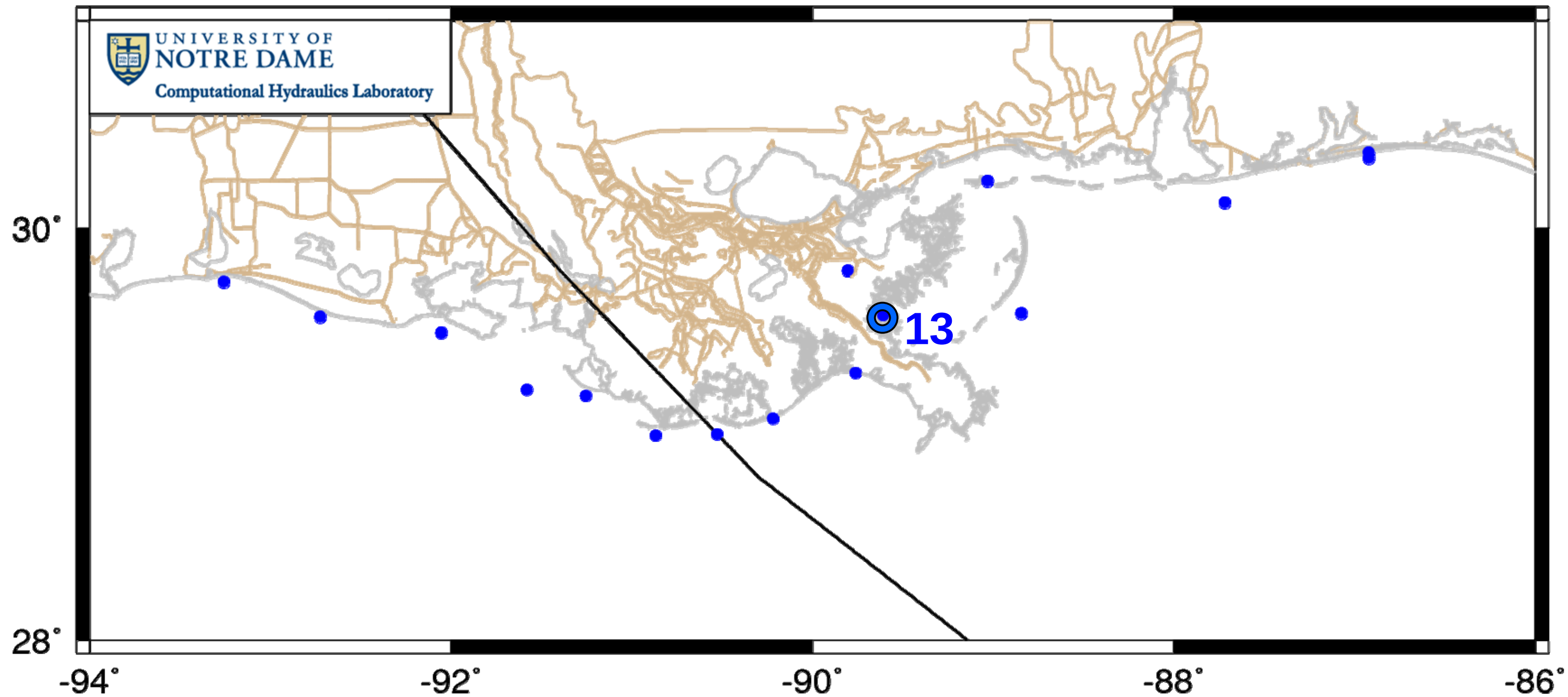
Bathymetry at Gage:

Kennedy: 1.4

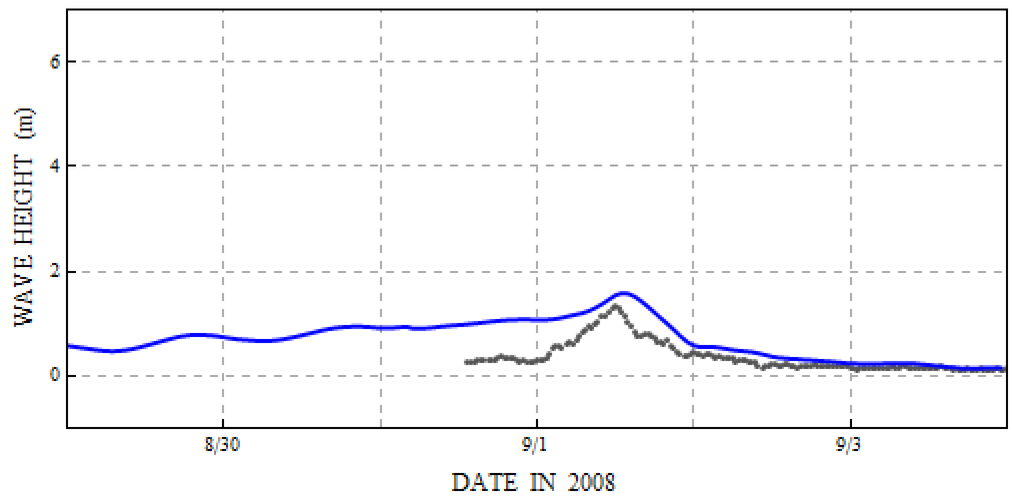
ADCIRC: 1.2



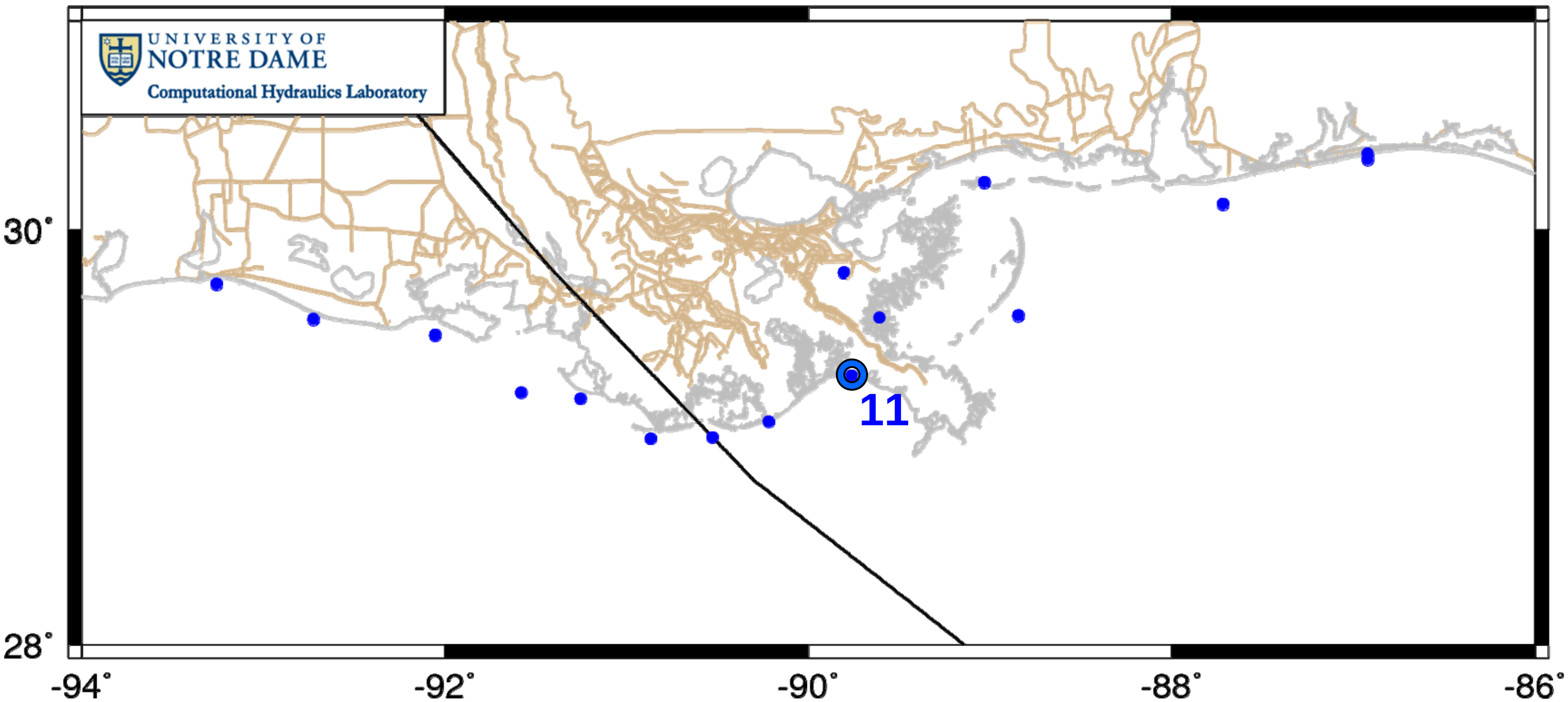
Gustav : Validation of Wave Parameters : AK 13



Bathymetry at Gage:	
Kennedy:	1.8
ADCIRC:	1.2

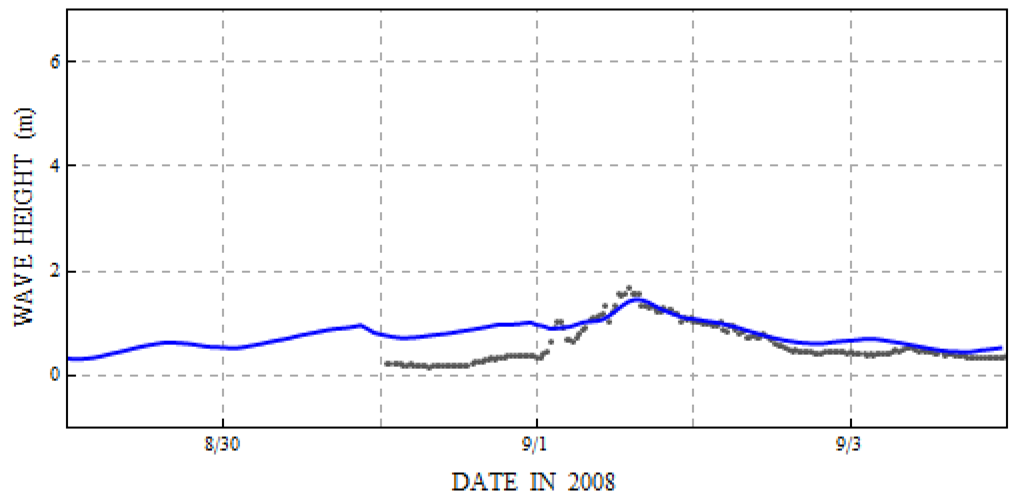


Gustav : Validation of Wave Parameters : AK 11

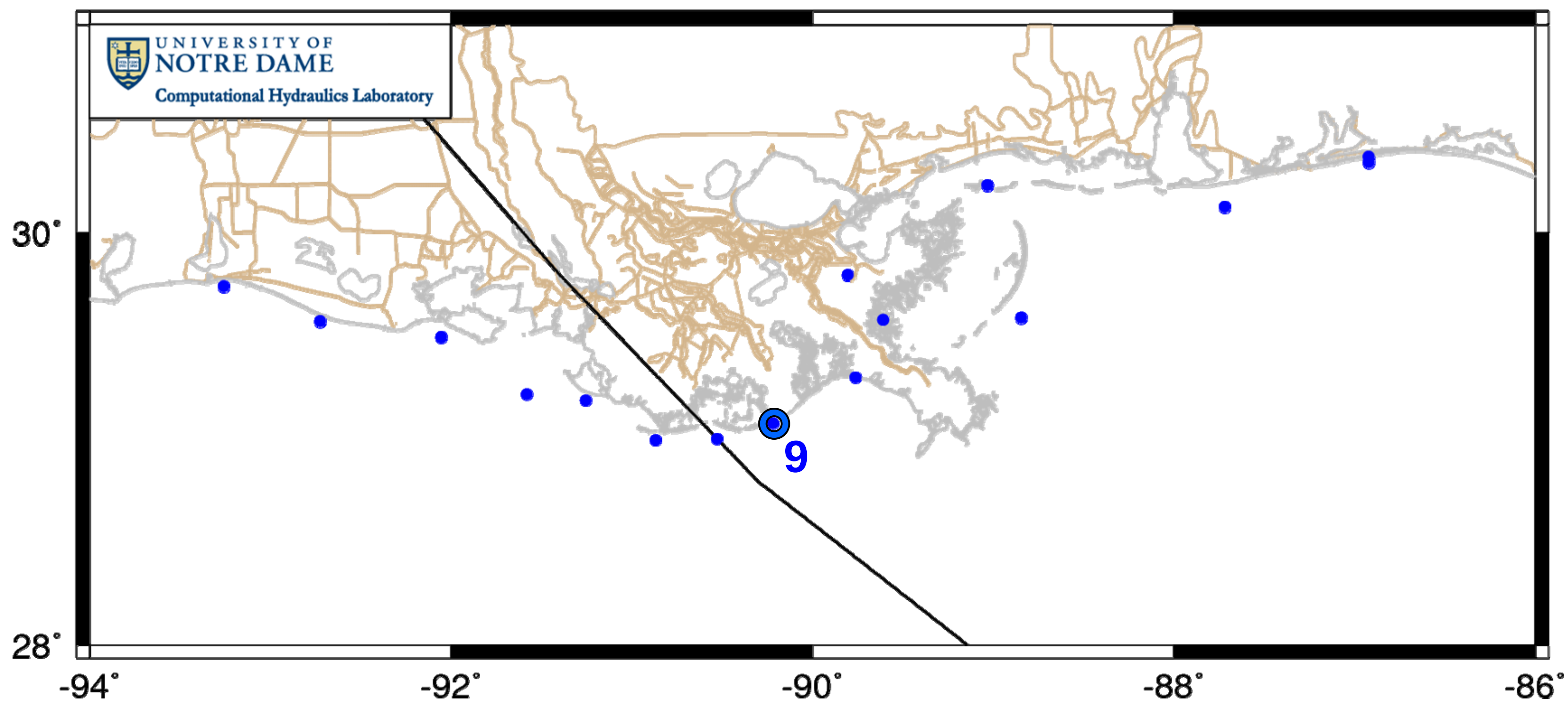


Bathymetry at Gage:

Kennedy:	3.5
ADCIRC:	1.2

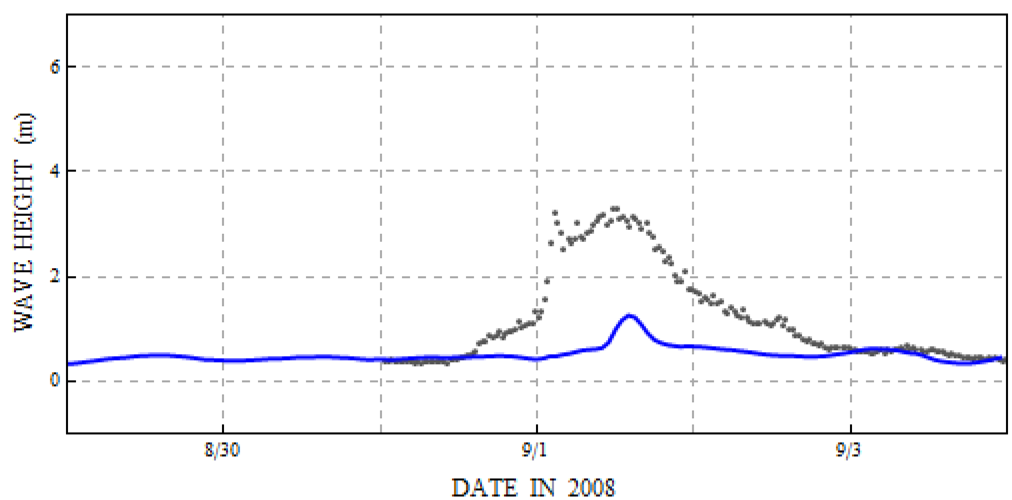


Gustav : Validation of Wave Parameters : AK 9

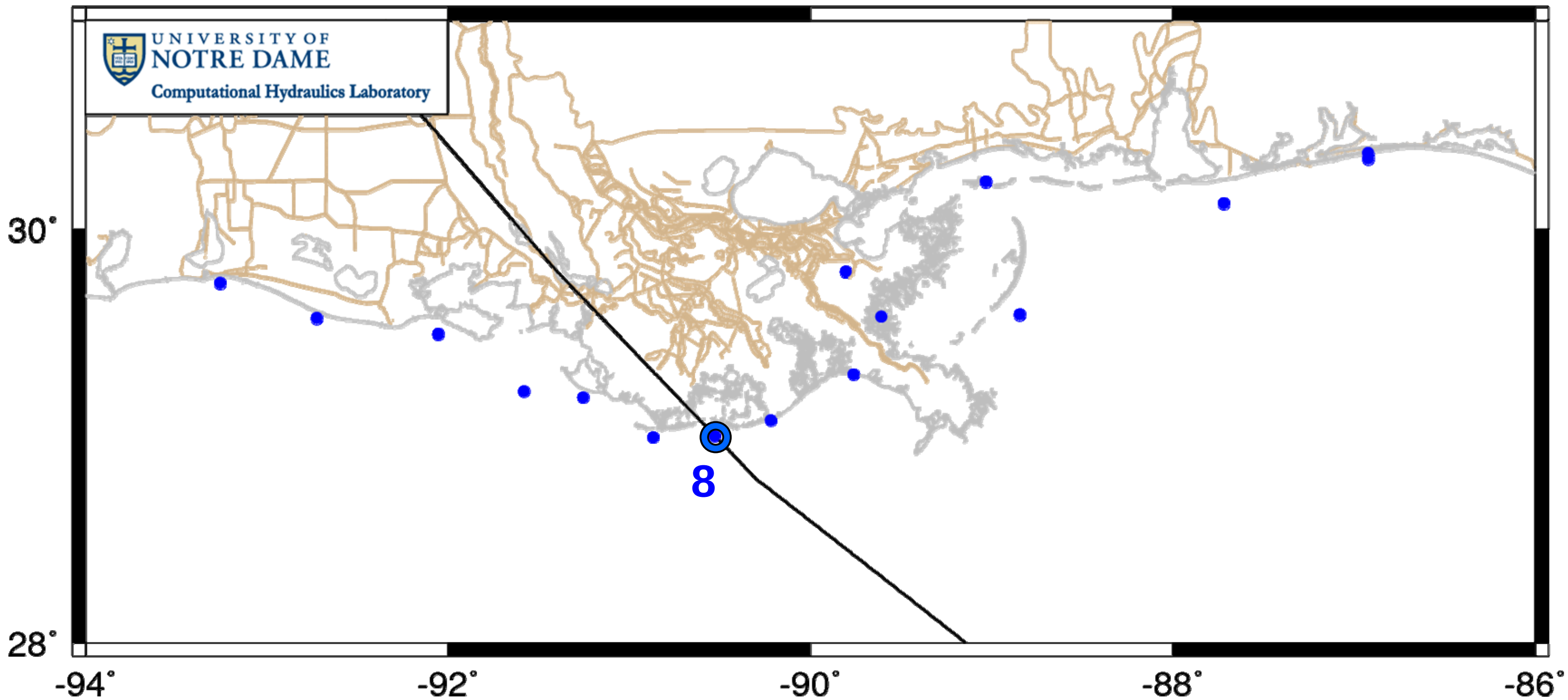


Bathymetry at Gage:

Kennedy:	6.9
ADCIRC:	1.0

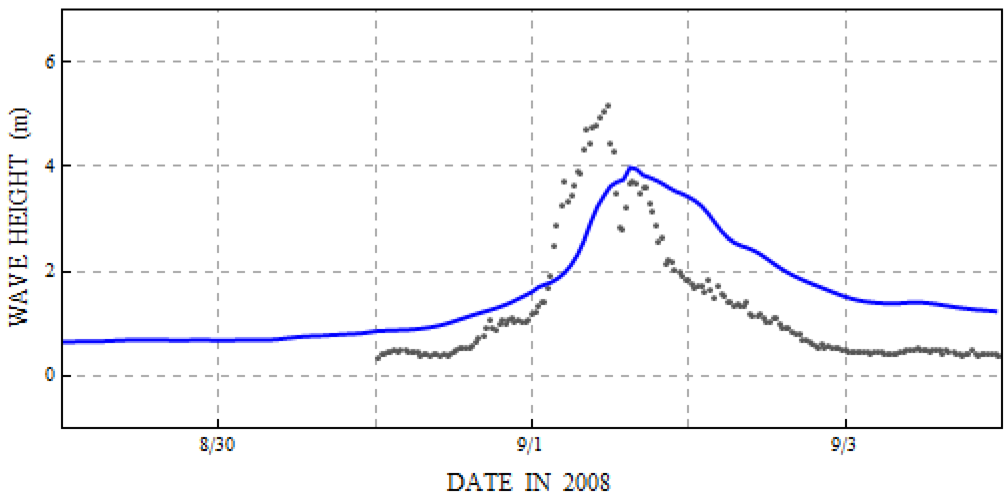


Gustav : Validation of Wave Parameters : AK 8

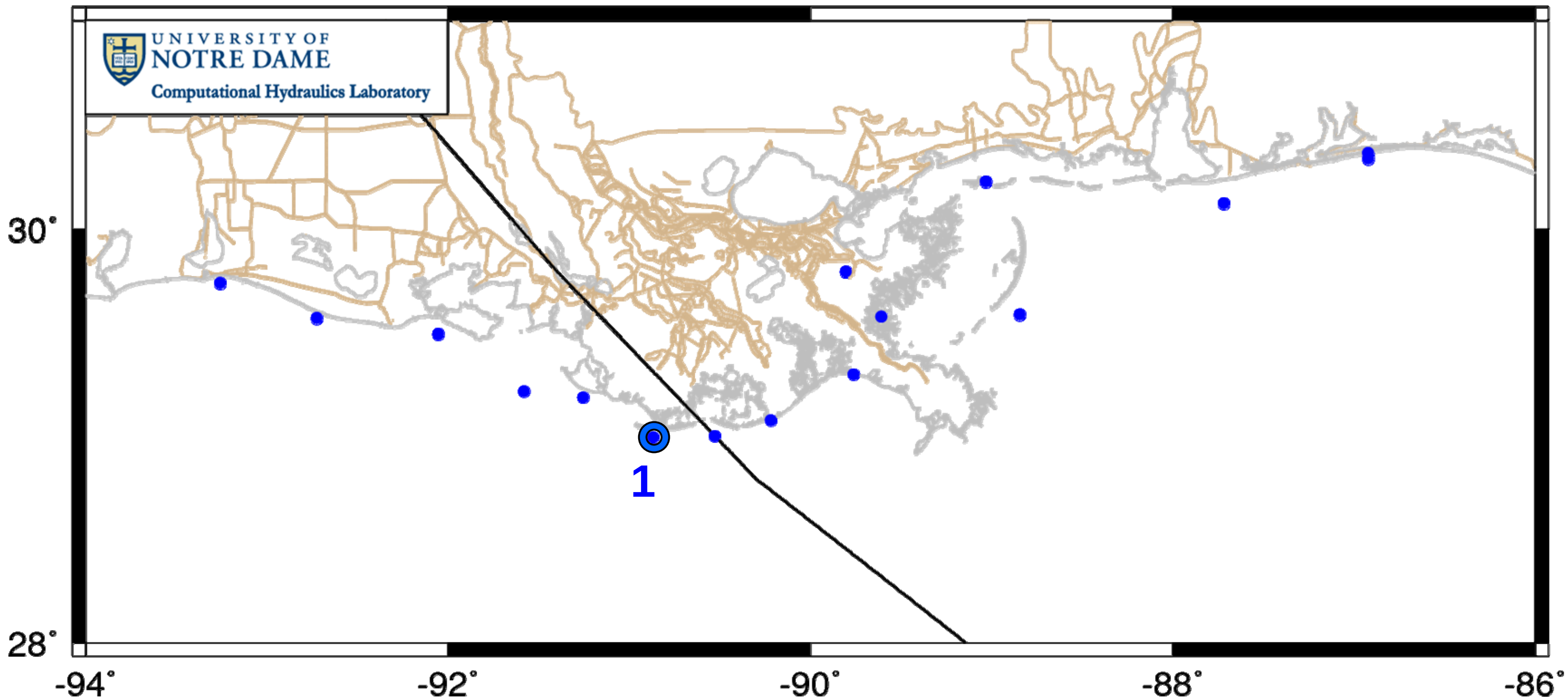


Bathymetry at Gage:

Kennedy:	10.6
ADCIRC:	9.4

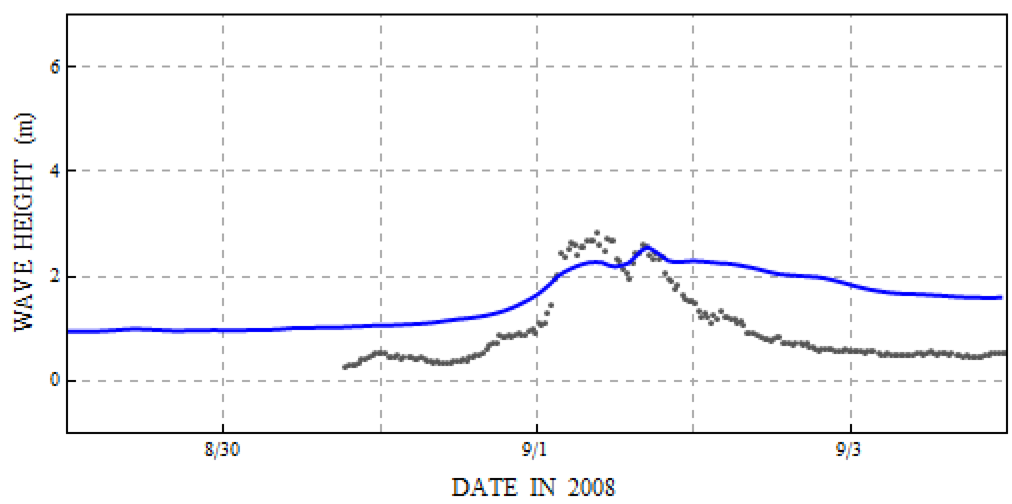


Gustav : Validation of Wave Parameters : AK 1

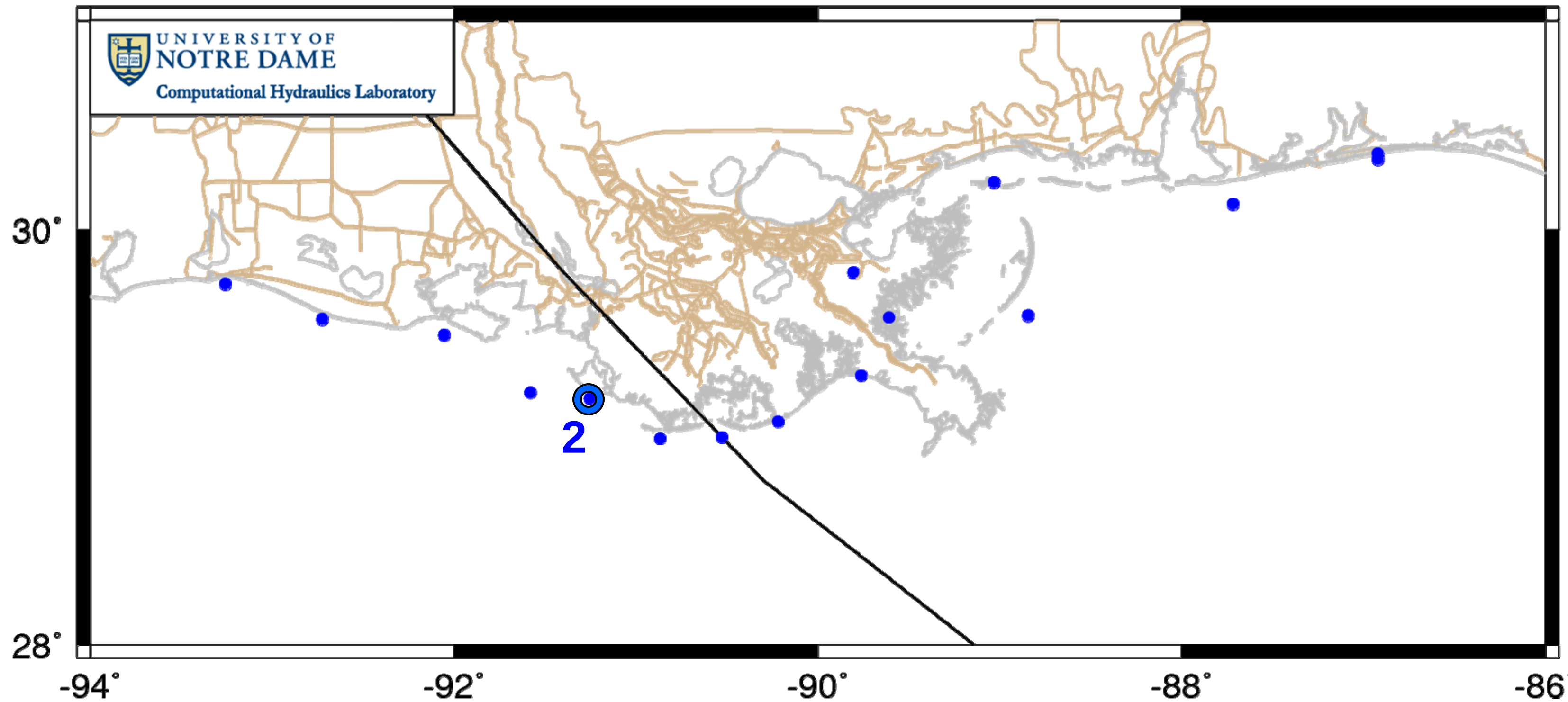


Bathymetry at Gage:

Kennedy:	7.0
ADCIRC:	5.5

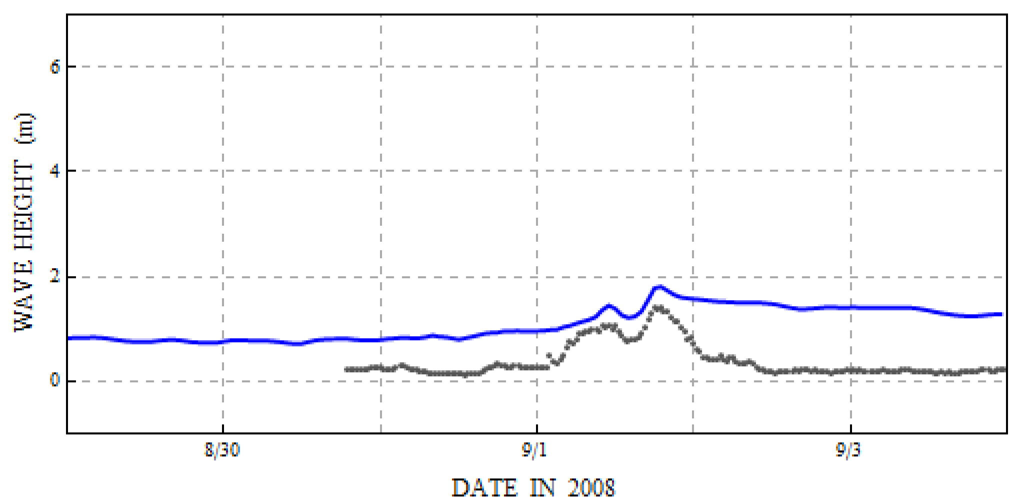


Gustav : Validation of Wave Parameters : AK 2

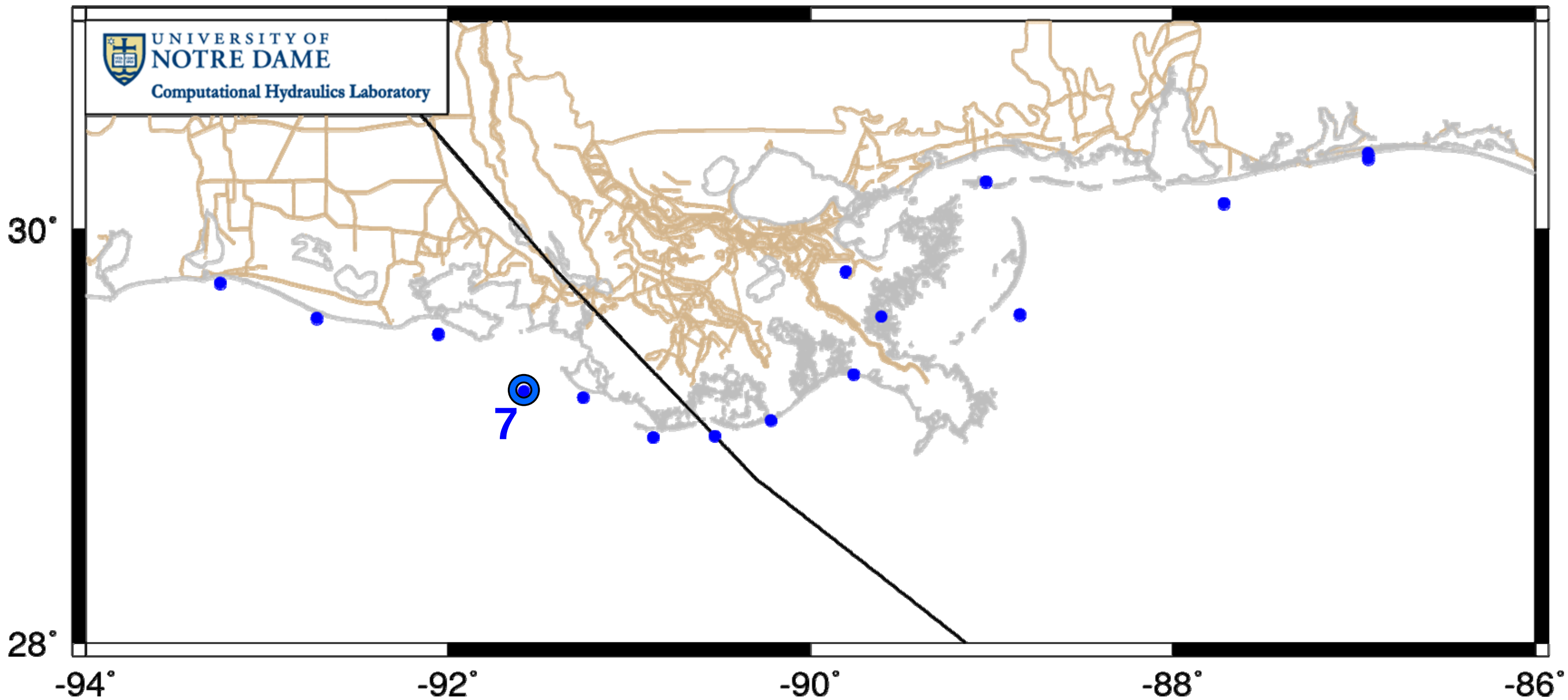


Bathymetry at Gage:

Kennedy:	3.7
ADCIRC:	3.9

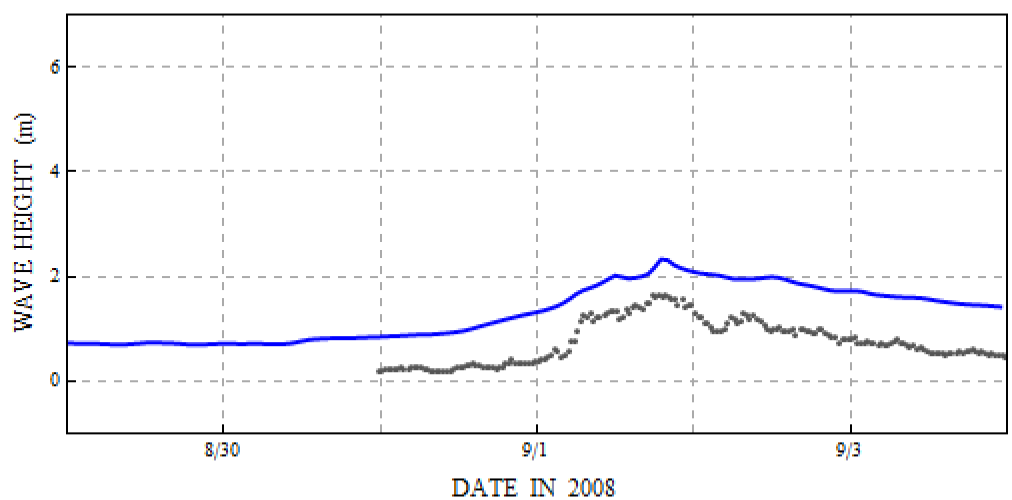


Gustav : Validation of Wave Parameters : AK 7

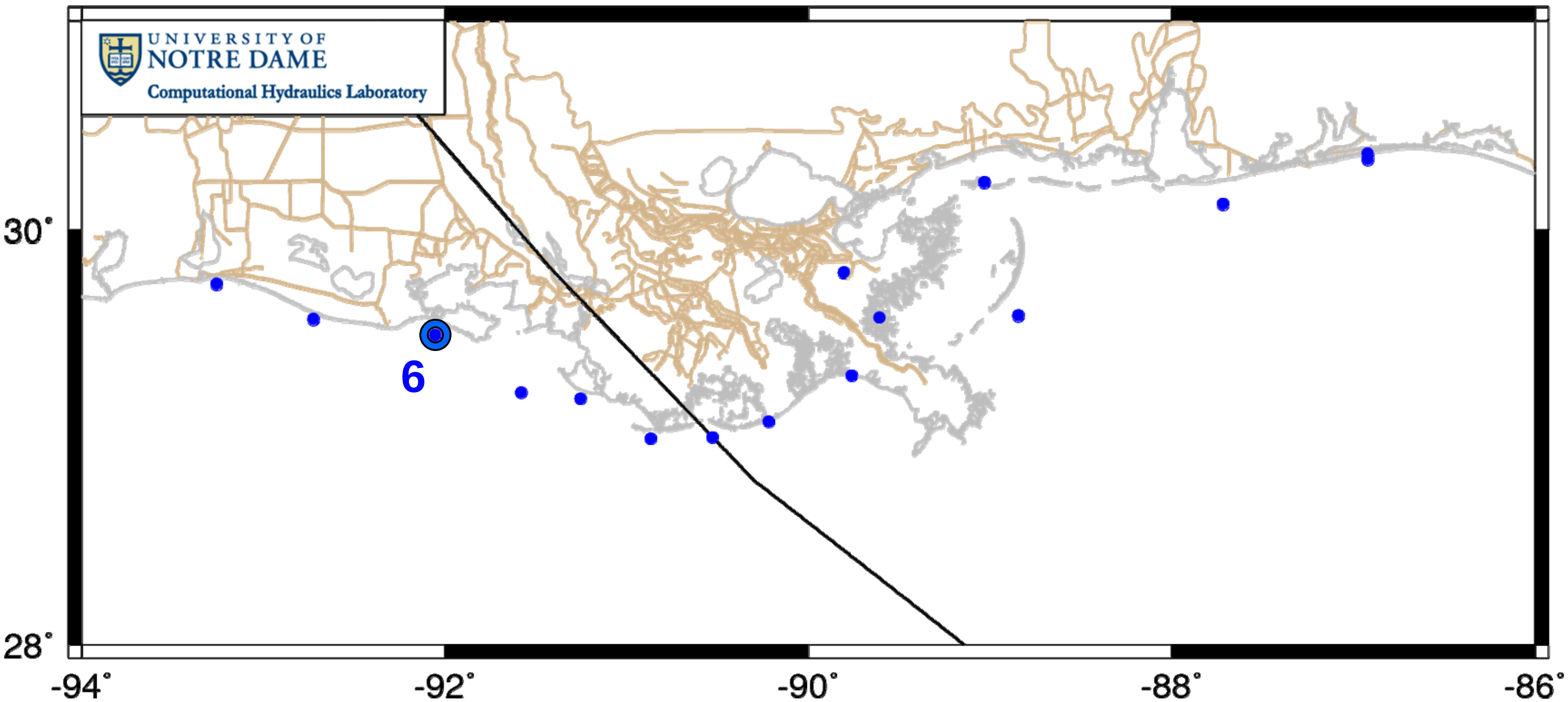


Bathymetry at Gage:

Kennedy:	5.1
ADCIRC:	6.3

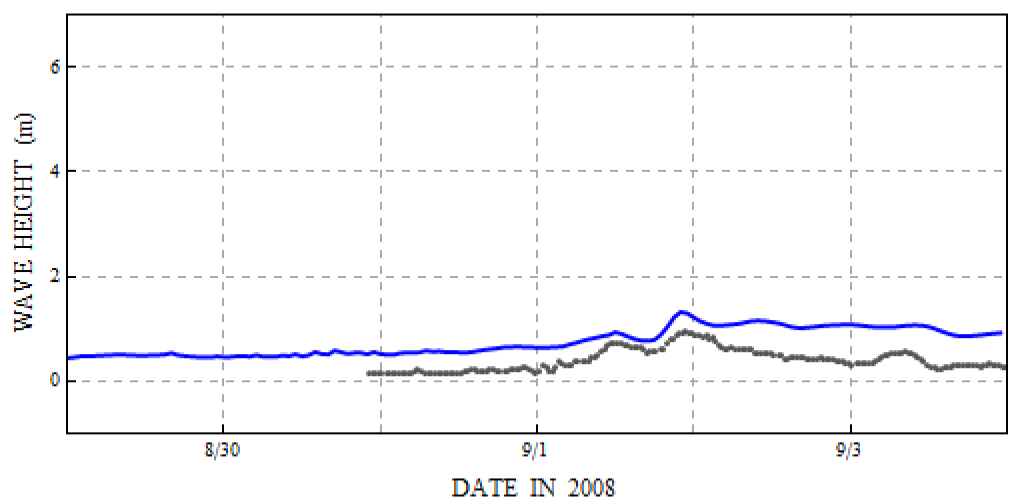


Gustav : Validation of Wave Parameters : AK 6

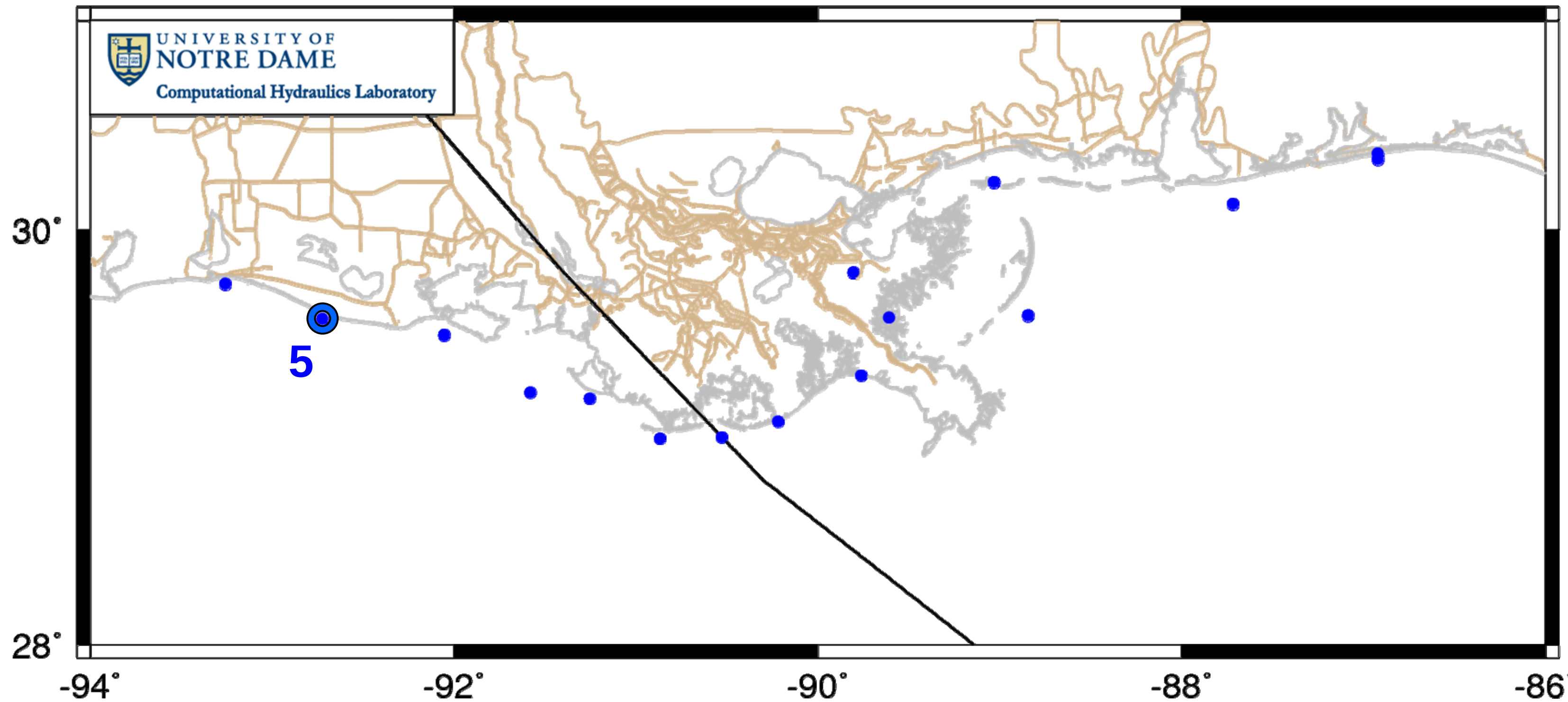


Bathymetry at Gage:

Kennedy:	3.2
ADCIRC:	2.9

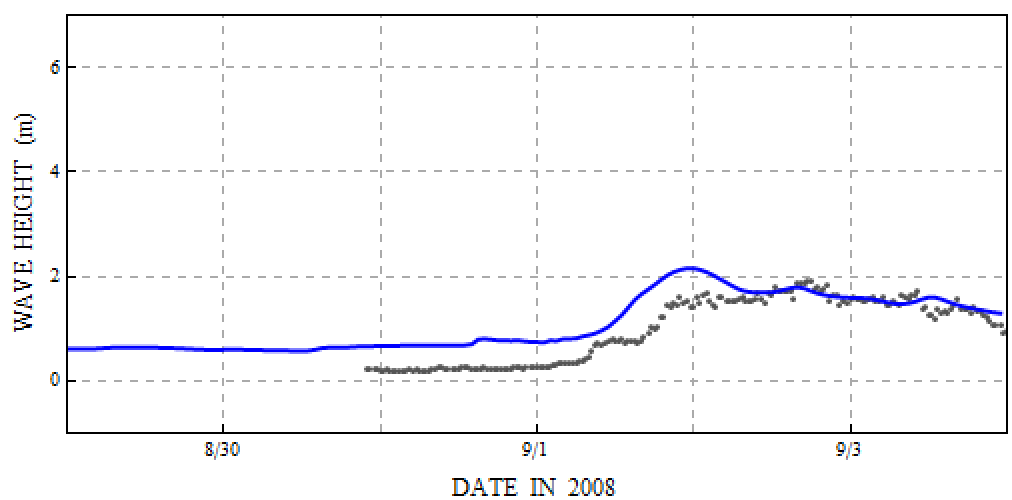


Gustav : Validation of Wave Parameters : AK 5

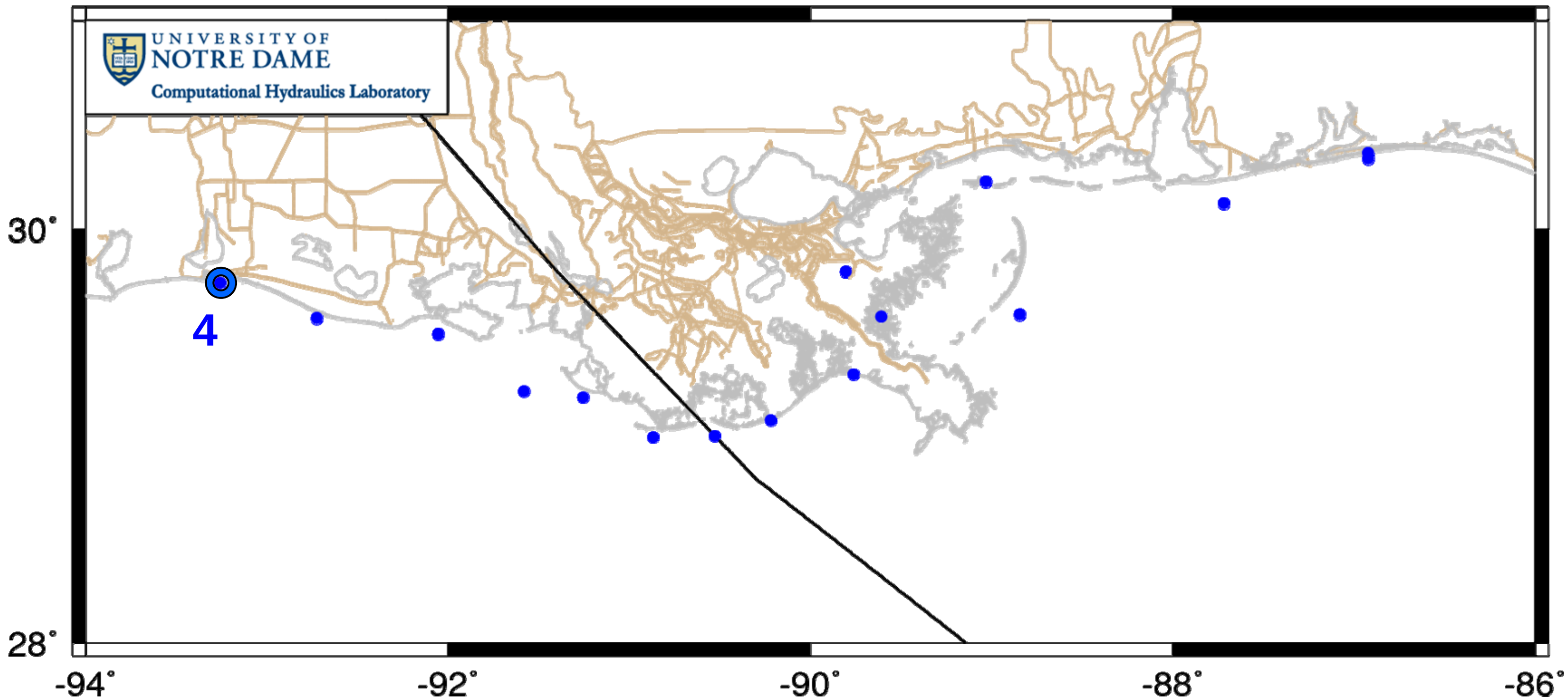


Bathymetry at Gage:

Kennedy:	7.7
ADCIRC:	6.1

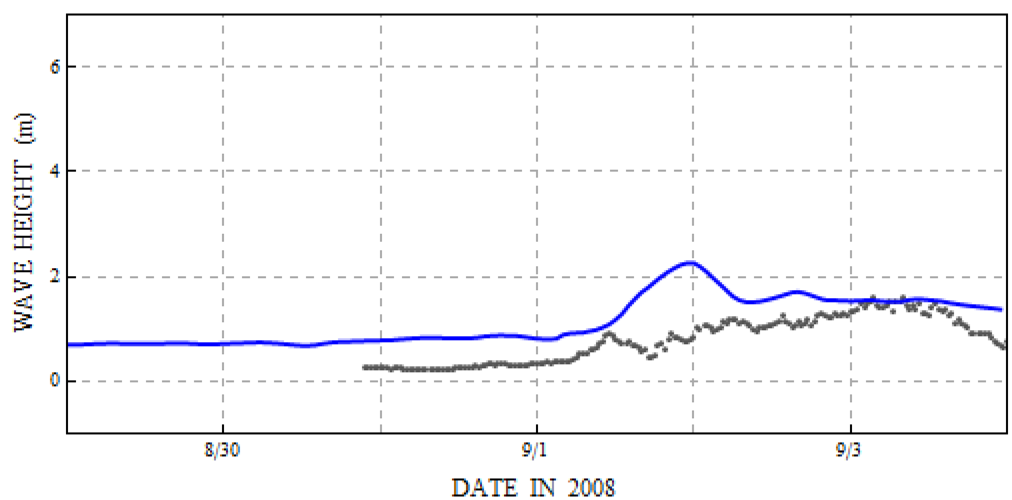


Gustav : Validation of Wave Parameters : AK 4



Bathymetry at Gage:

Kennedy:	6.2
ADCIRC:	6.0



The Way Ahead:
Conclusions and Future Work

Conclusions and Future Work

‘Loose’ Coupling of Waves and Surge during Katrina

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

‘Tight’ Coupling of SWAN+ADCIRC

- Wave model uses the 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
- Must create meshes with both models in mind