Implementation and Validation
of the Coupled UnSWAN+ADCIRC Model

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ADCIRC

ADvanced CIRCulation (ADCIRC):

- 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

ADvanced CIRCulation (ADCIRC):

- Solves the vertically-integrated momentum equations:

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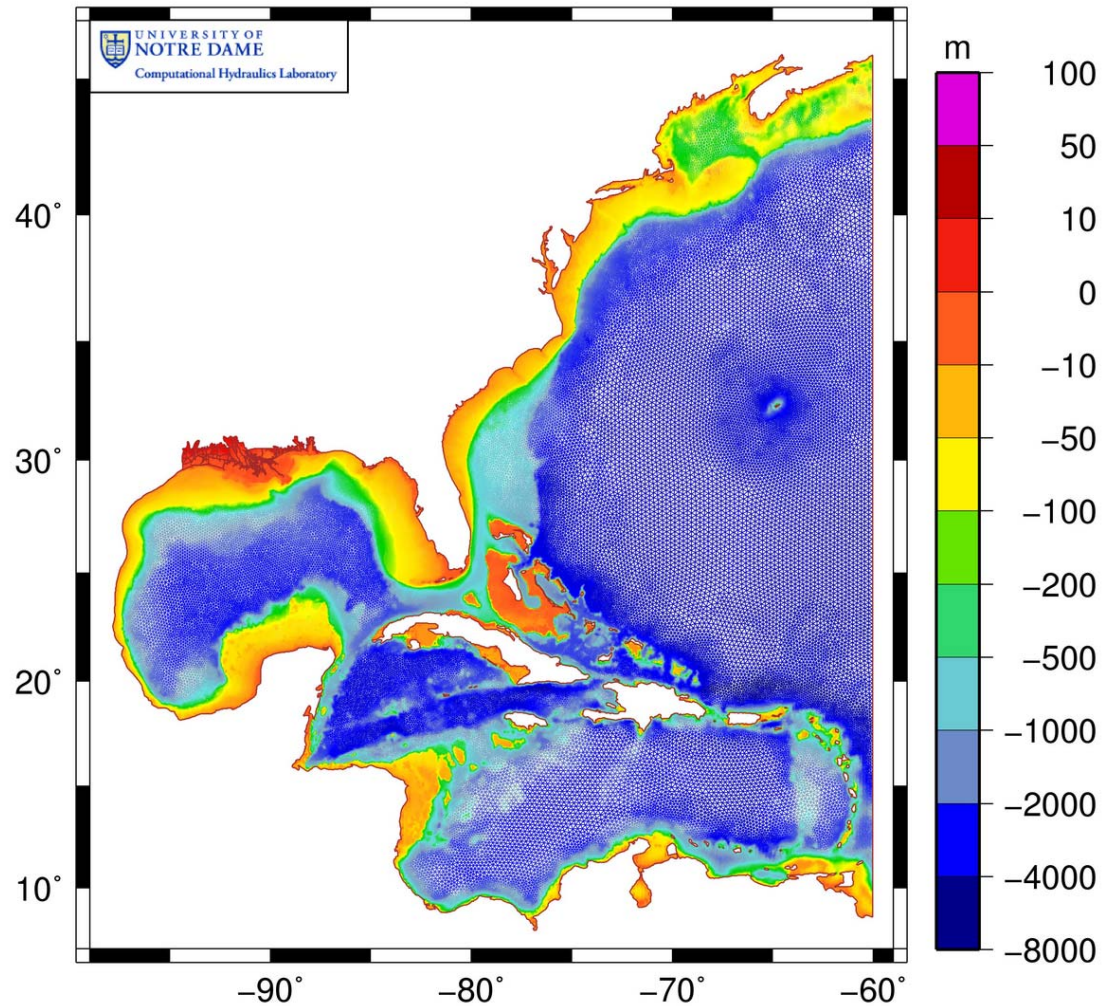
and:

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

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

ADCIRC

Example: Louisiana Storm Surge Modeling

ADCIRC
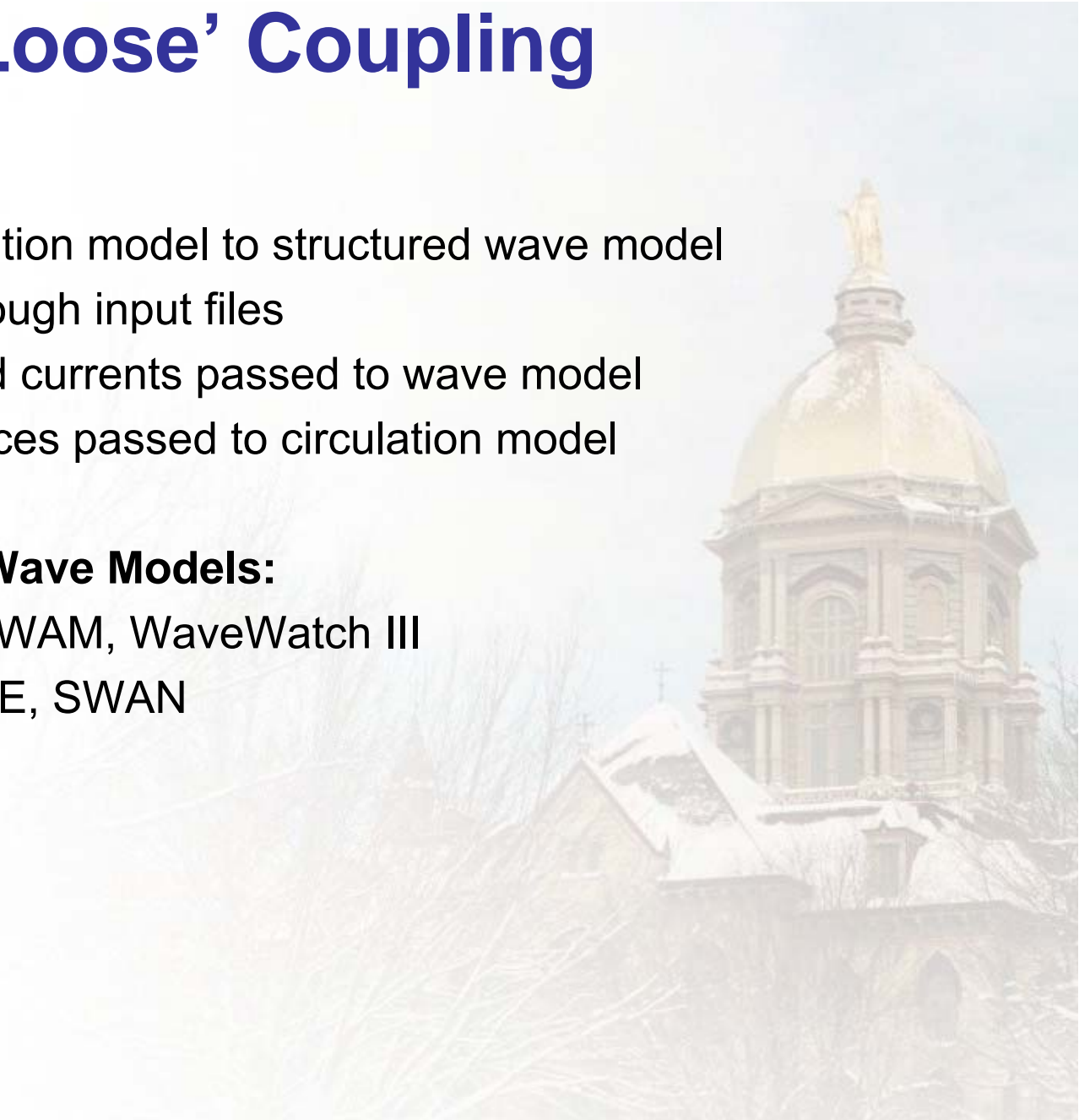
Example: Louisiana Storm Surge Modeling

'Loose' Coupling

'Loose' Coupling:

- Unstructured circulation model to structured wave model
- Models coupled through input files
  - Water levels and currents passed to wave model
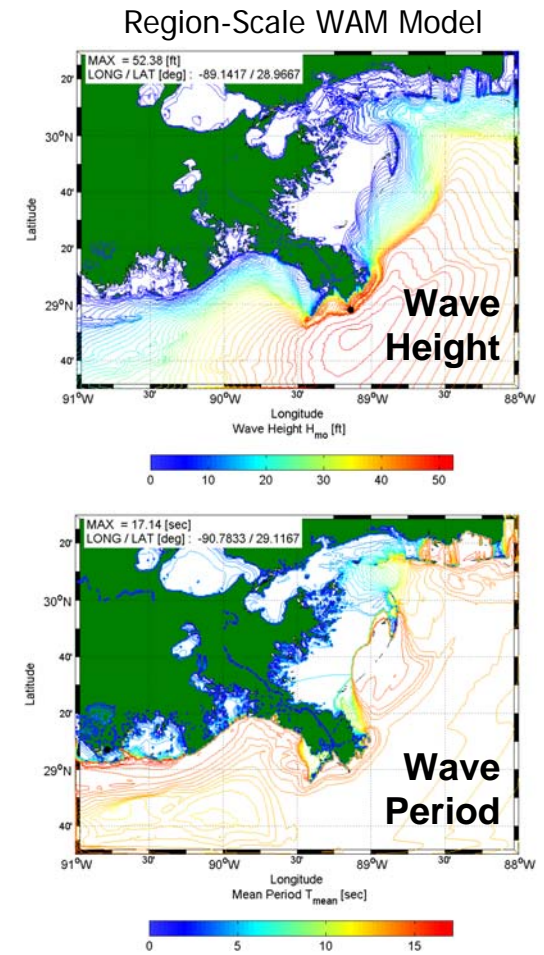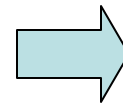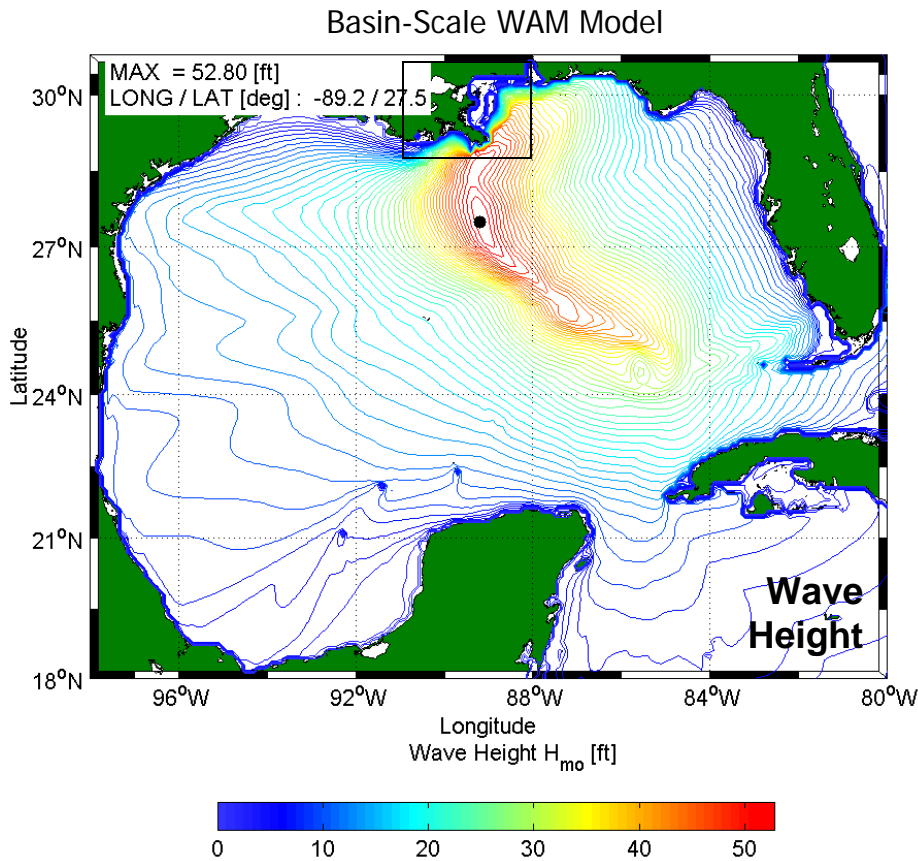 - Wave-driven forces passed to circulation model

ADCIRC Coupled to Wave Models:

- Basin/region scale: WAM, WaveWatch III
- Nearshore: STWAVE, SWAN

'Loose' Coupling

Example: Louisiana Storm Surge Modeling

Basin-Scale WAM Model

Region-Scale WAM Model

'Loose' Coupling

Example: Louisiana Storm Surge Modeling

Nearshore STWAVE Model

'Loose' Coupling

It Works!

- Maximum significant wave heights in Hurricane Katrina
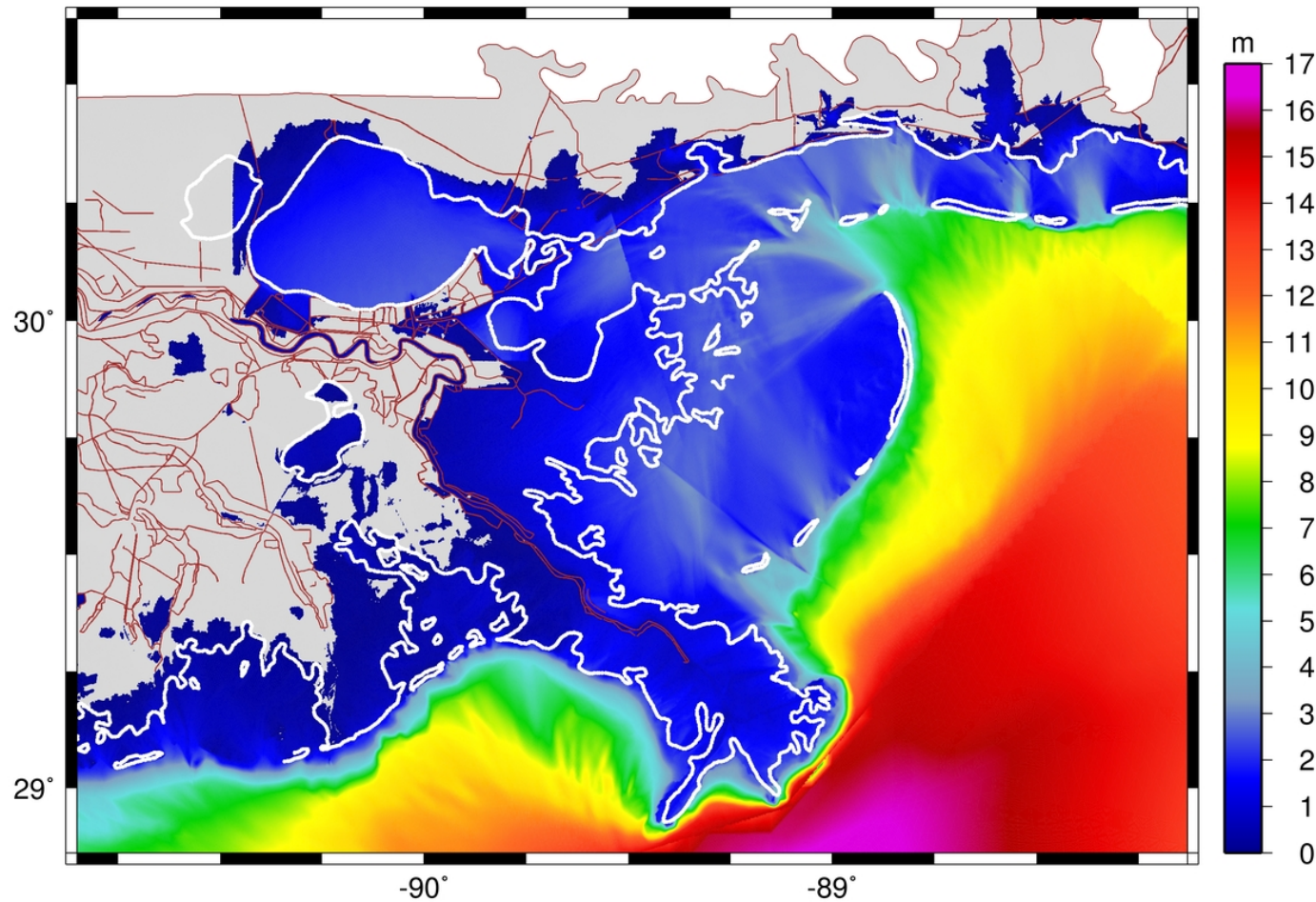
'Loose' Coupling

It Works!

- Maximum wave-driven forces in Hurricane Katrina
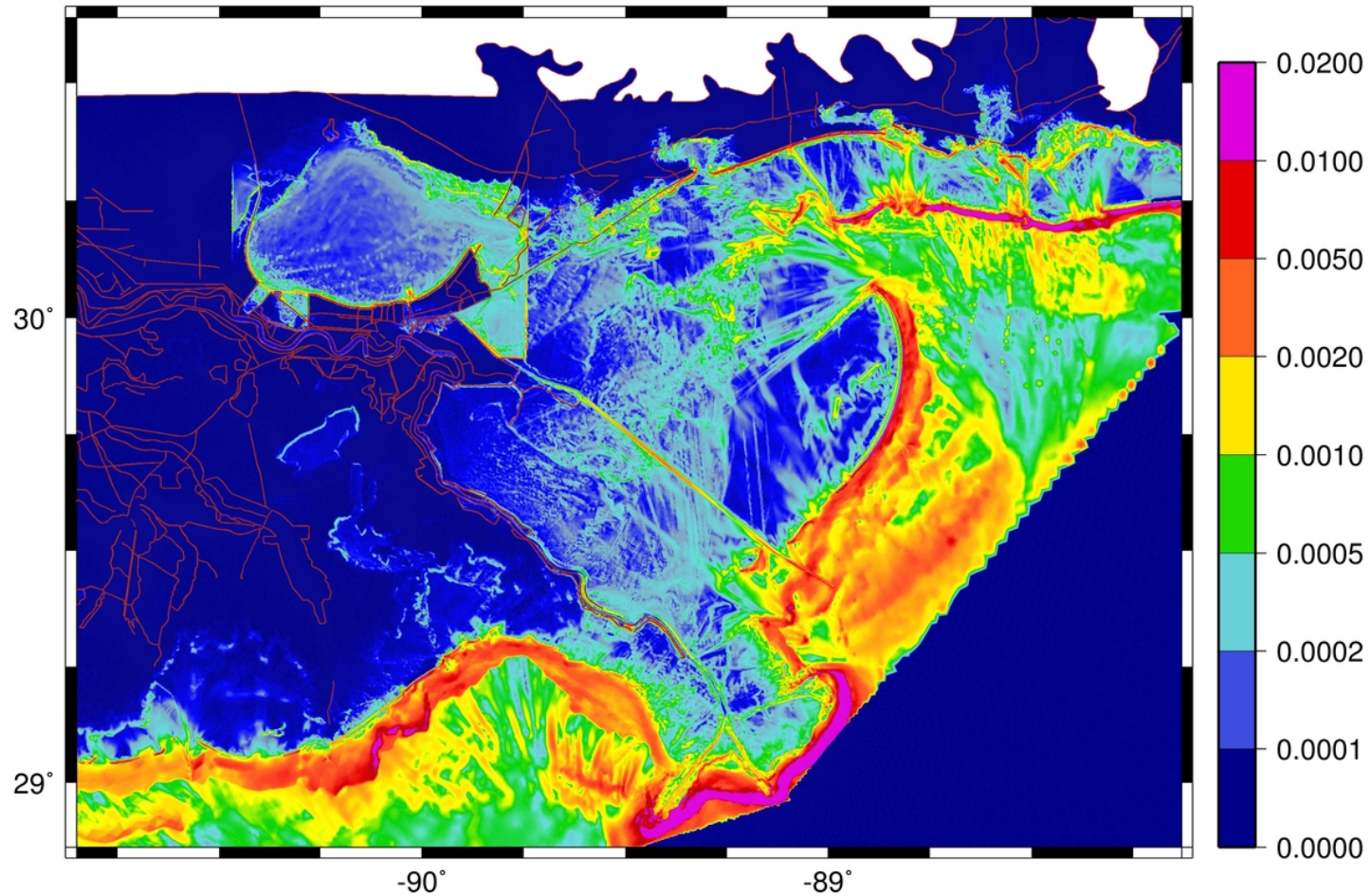
'Loose' Coupling

It Works!

• Effect of waves on water levels in Hurricane Katrina
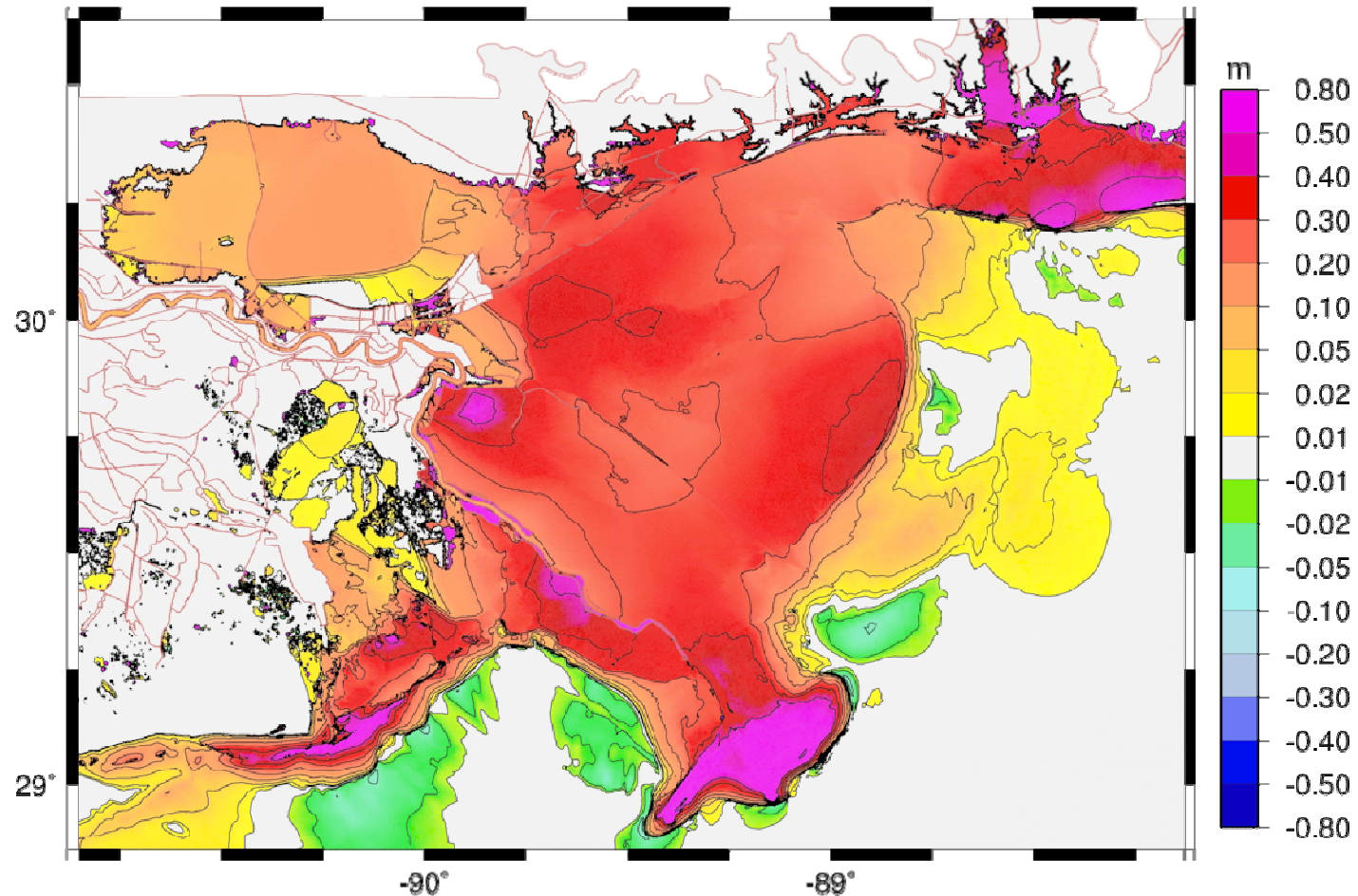
Disadvantages of 'Loose' Coupling

1. **Iteration:**

   - Models coupled through input files
     - Water levels and currents passed to wave model
     - Wave-driven forces passed to circulation model
   - Process can be automated, but is still inefficient

$\zeta,\ u,\ v$

ADCIRC ⟷ Wave Model

$F_x,\ F_y$
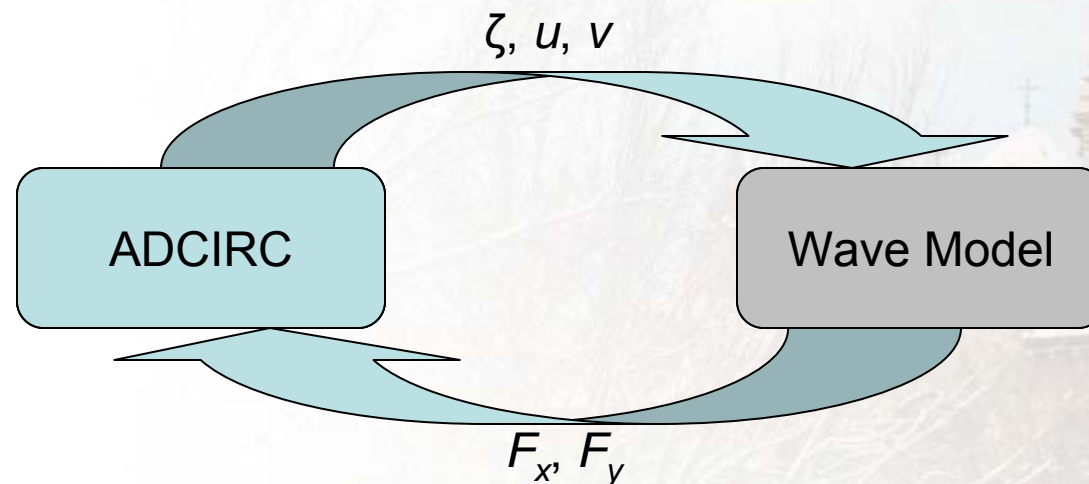
Disadvantages of 'Loose' Coupling

2. **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
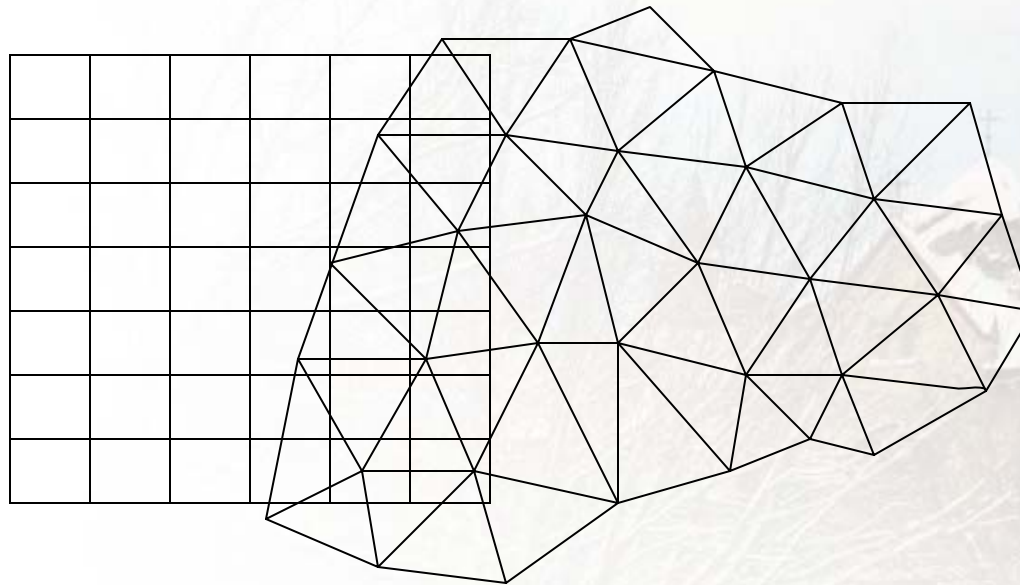
Disadvantages of 'Loose' Coupling

3. **Resolution in wave breaking zones:**

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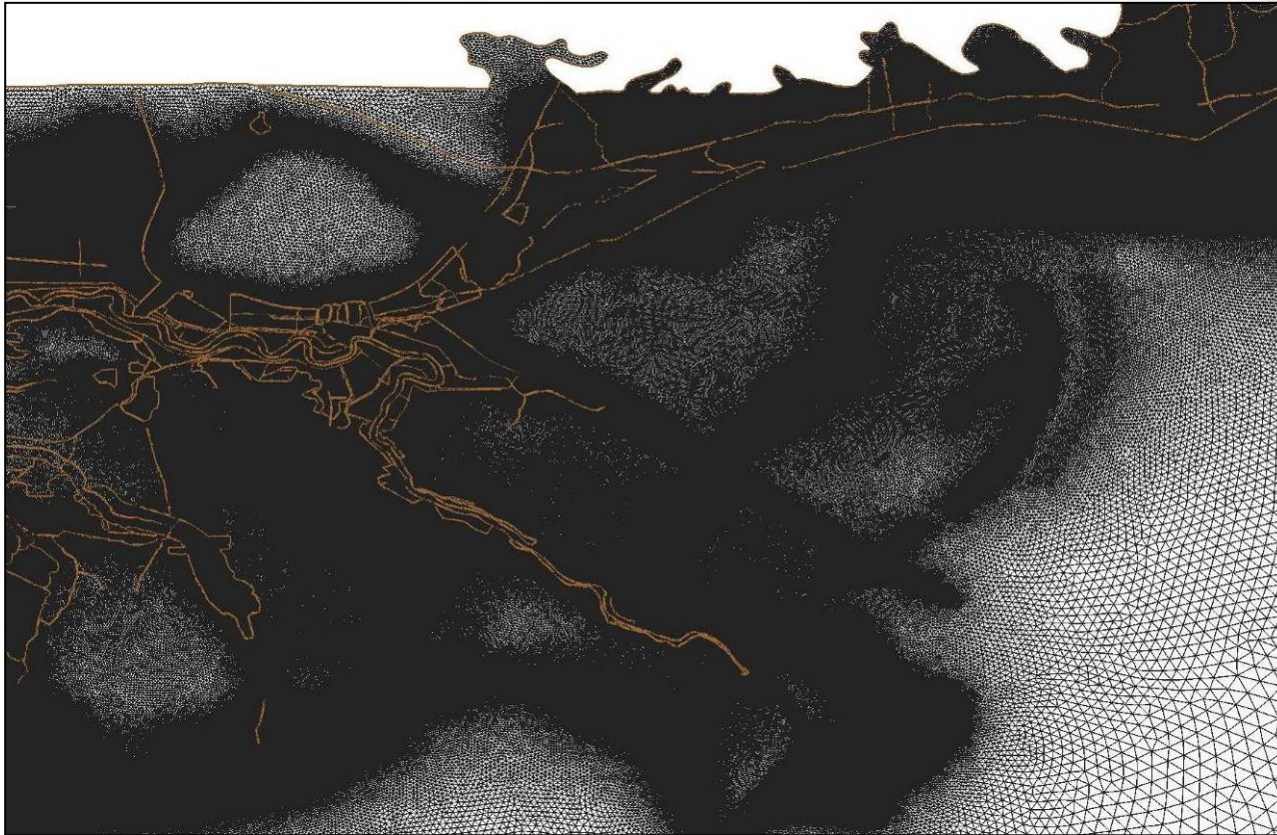
'Tight' Coupling

Advantages:

- ADCIRC and wave model run on the same mesh
  - No nesting of meshes
  - No overlapping of meshes
- ADCIRC and wave model 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 waves model
  - Dynamic h- and p-adaptivity

'Tight' Coupling

Introducing … UnSWAN+ADCIRC

- ADCIRC coupled to Simulating WAves Near-shore (SWAN)
- SWAN:
  - Developed at Delft University
  - Non-phase-resolving, wave energy propagation model

Progress:

- SWAN converted to unstructured meshes (UnSWAN)
- UnSWAN implemented in parallel (PUnSWAN)
- ADCIRC and PUnSWAN compiled into PAdcSwan
  - Pass node-based information between models
  - Run on same local mesh
  - Leapfrog through time

UnSWAN+ADCIRC

Shared Local Meshes:

- Example of Mesh Decomposition on 256 Cores
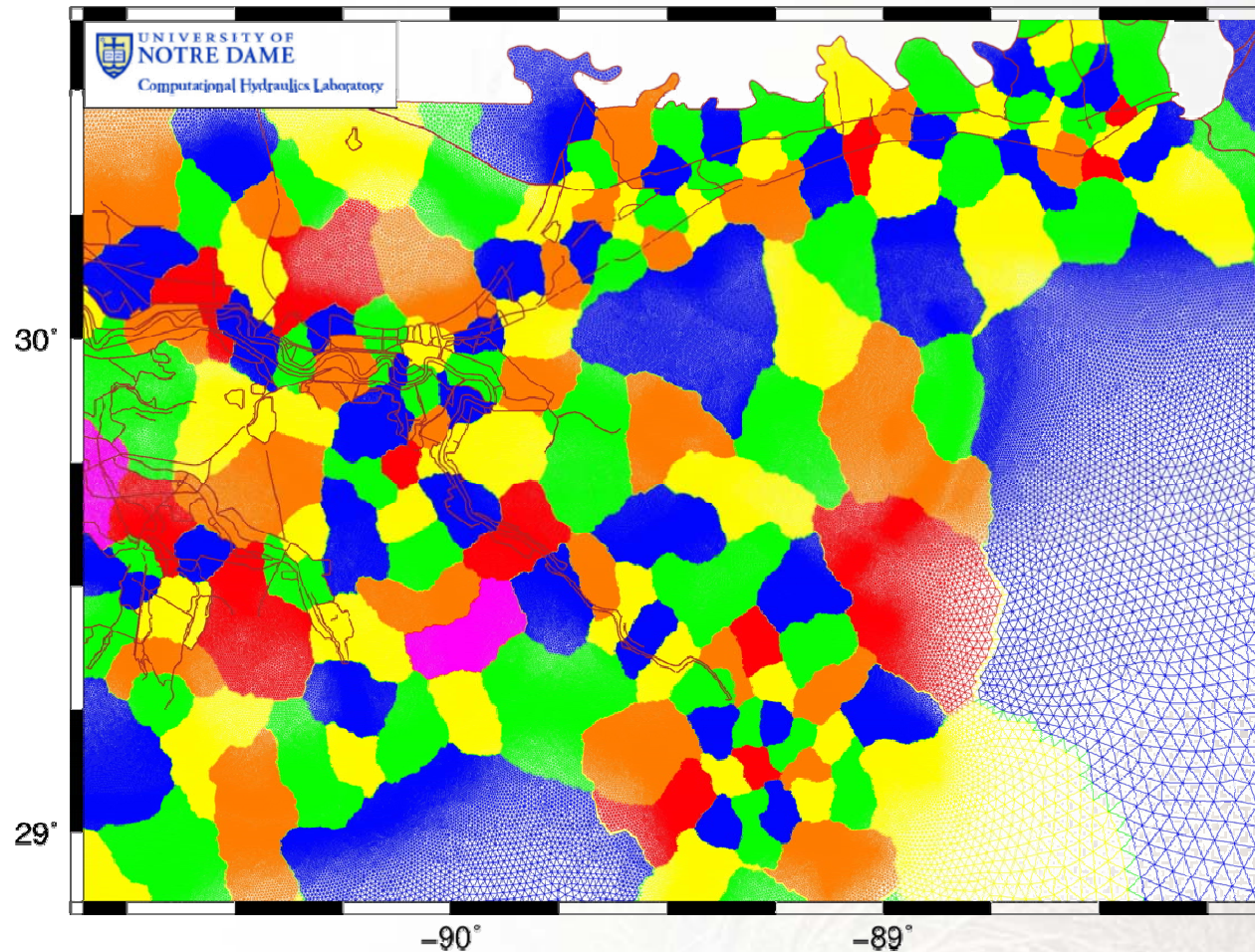
UnSWAN+ADCIRC

Passing Information:

- ADCIRC to UnSWAN:
  - Water levels, currents, and wind speeds
- UnSWAN to ADCIRC:
  - Wave-driven forces:

$$F_x = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y} \quad \text{and} \quad F_y = -\frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y}$$

where the wave radiation stresses are:

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

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

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

UnSWAN+ADCIRC

Schematic of Coupling:

- ADCIRC is run for 600 seconds ($\Delta t = 1$ sec)
- Water levels (ζ) and currents (u,v) are passed to Swan
- UnSWAN is run for 600 seconds ($\Delta t = 600$ sec)
- Radiation stresses (S_{xx}, S_{xy}, S_{yy}) and wave-driven forces (F_x, F_y) are computed; forces are passed to ADCIRC
- Repeat
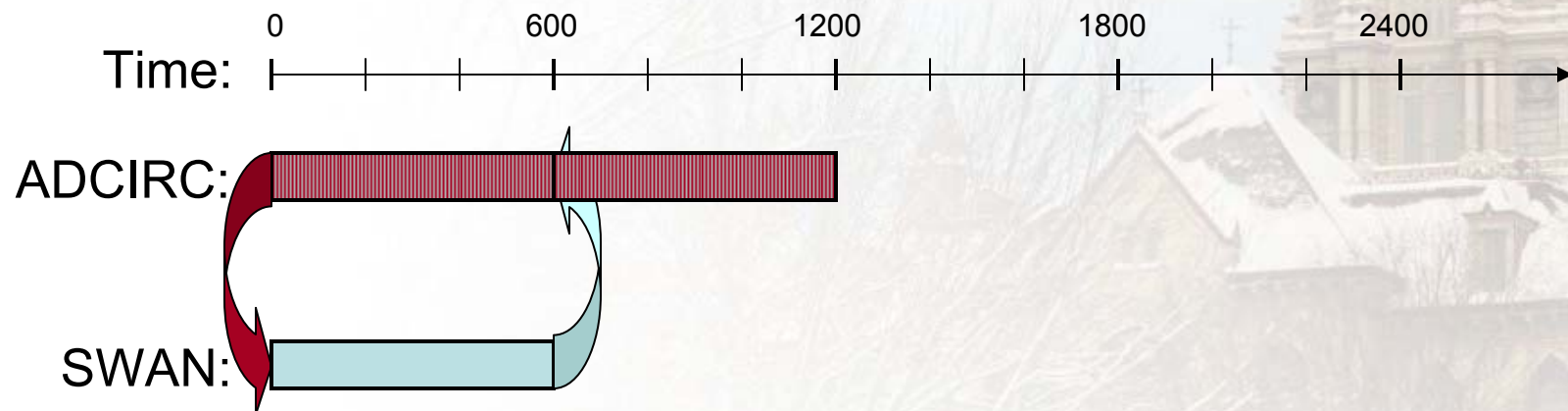
- UnSWAN and ADCIRC are always extrapolating in time

Hurricane Katrina

Preliminary Results

- Synoptic histories in Gulf of Mexico and in SE Louisiana:
    - Wave heights
    - Wave-driven forces
    - Wave setup
- Comparison to WAM-STWAVE setup
- Comparison to measured data:
    - NDBC buoy data
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- Computational performance

Hurricane Katrina

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Hurricane Katrina

Wave Heights

- 2005/08/28/0000Z

SL15 (090306) Wave Heights (HS) and Winds
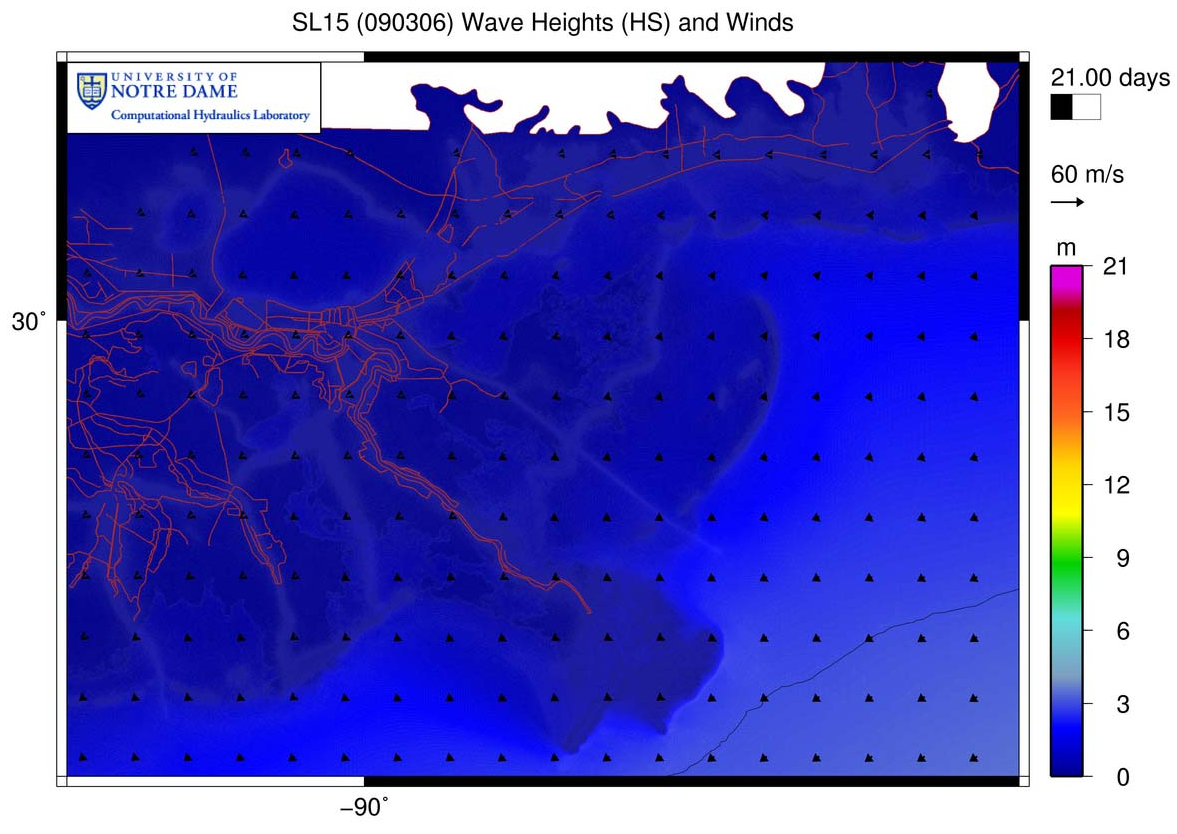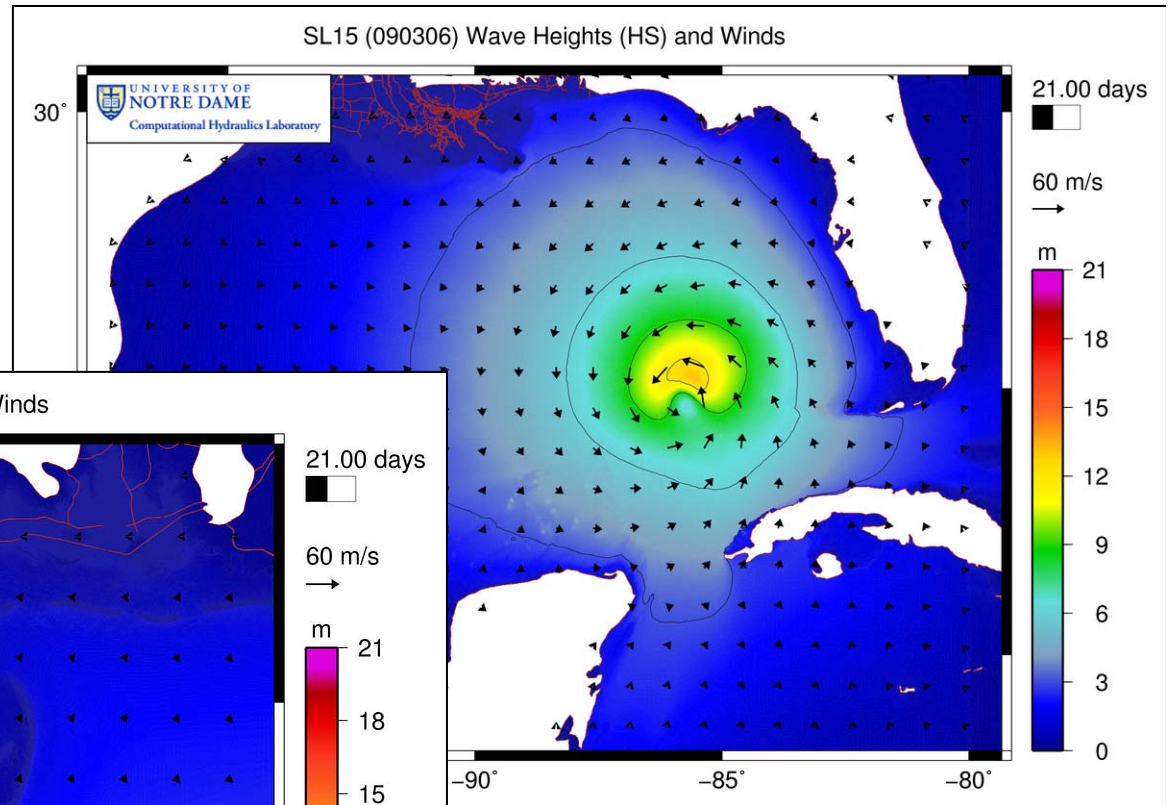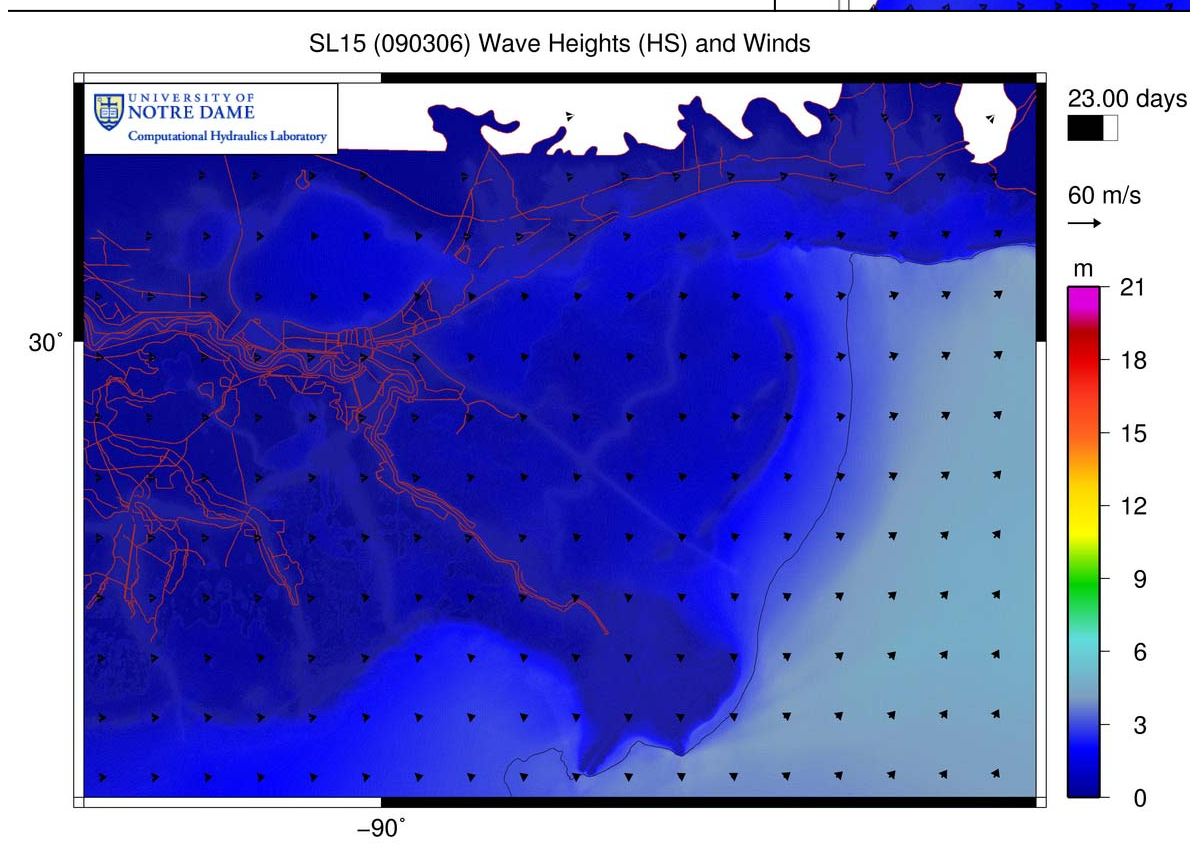
Hurricane Katrina

Wave Heights

- 2005/08/28/0400Z

Hurricane Katrina

Wave Heights

- 2005/08/28/0800Z
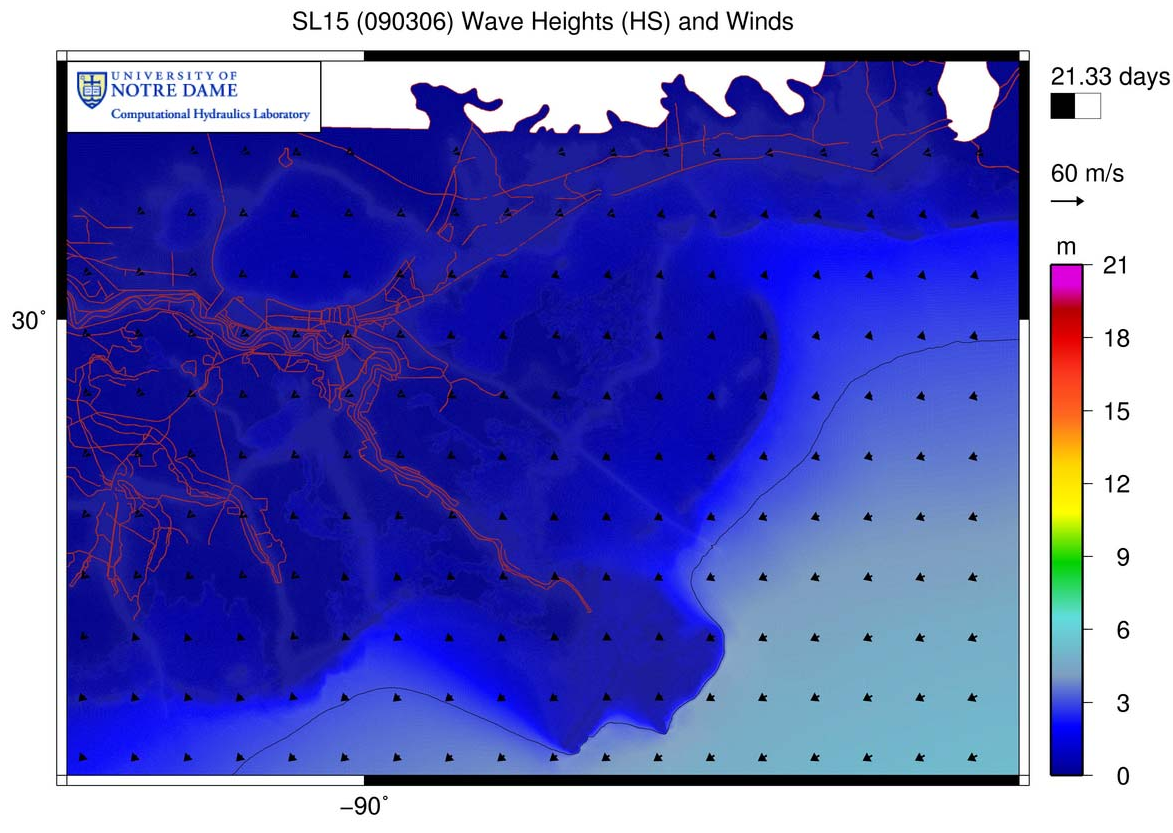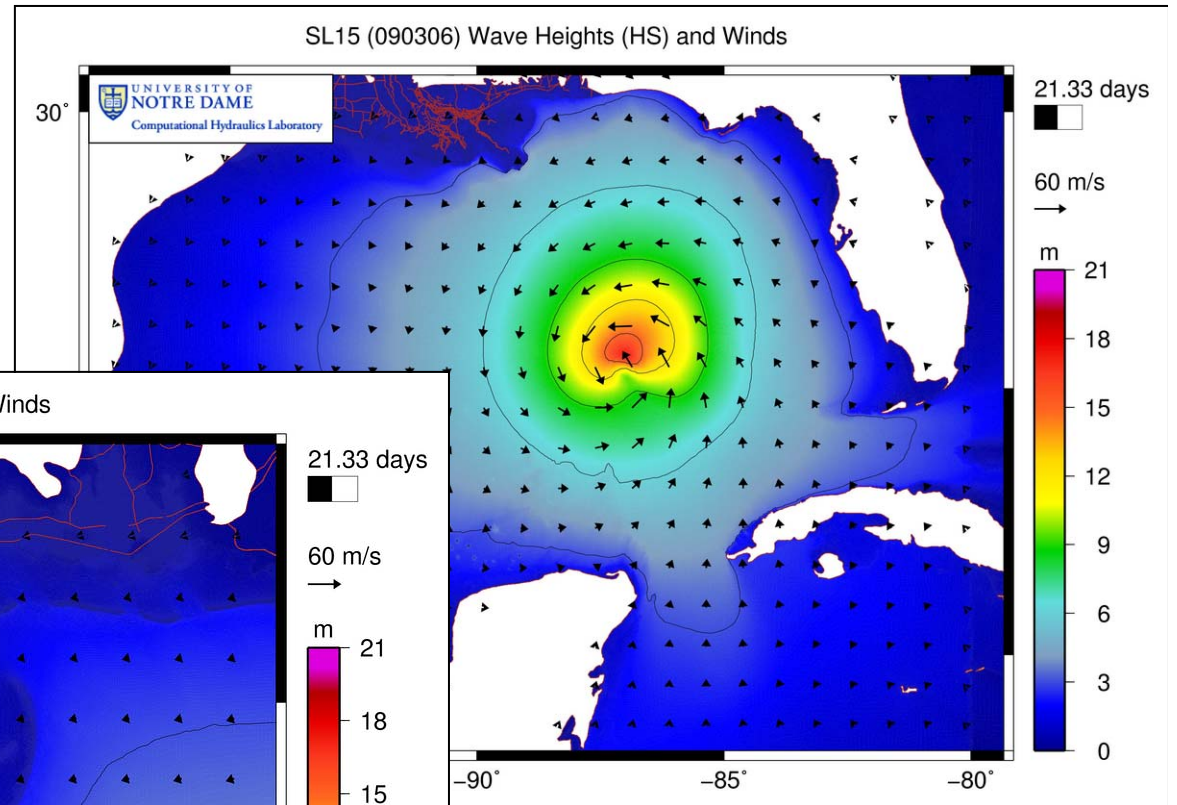
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Wave Heights

- 2005/08/28/1200Z
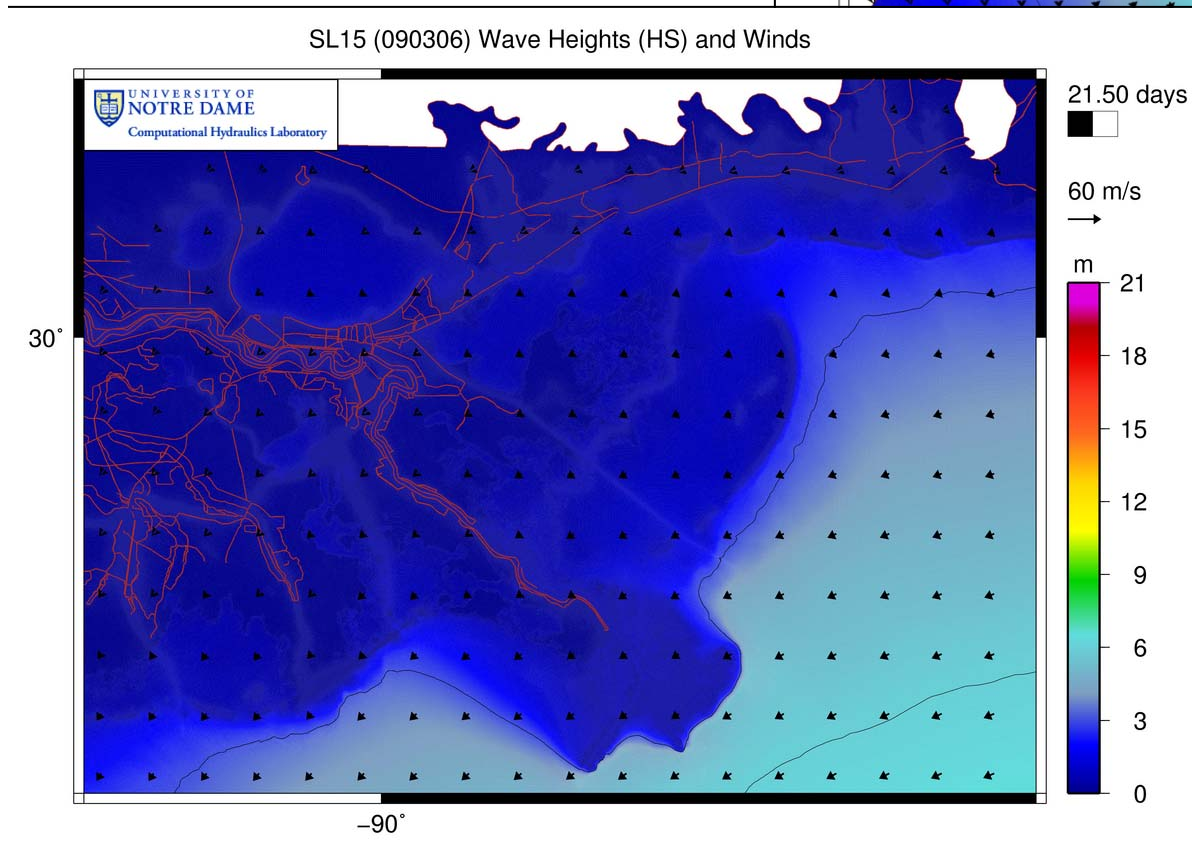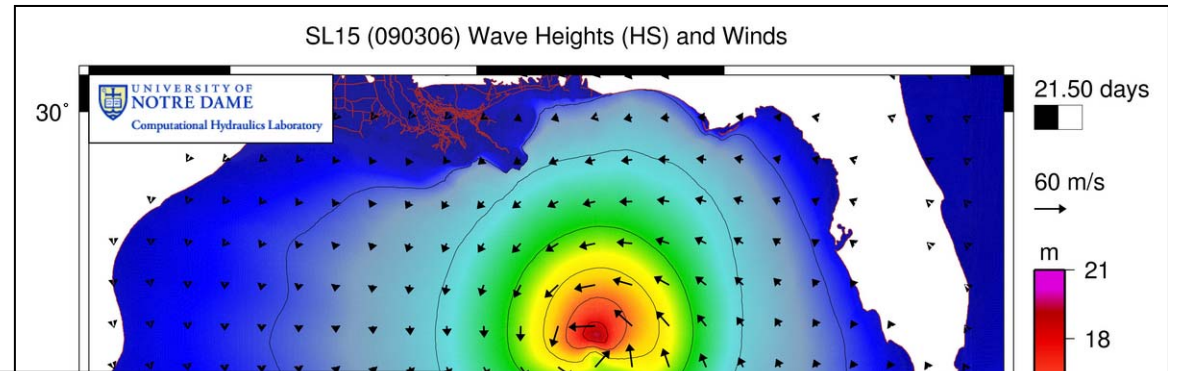
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Wave Heights
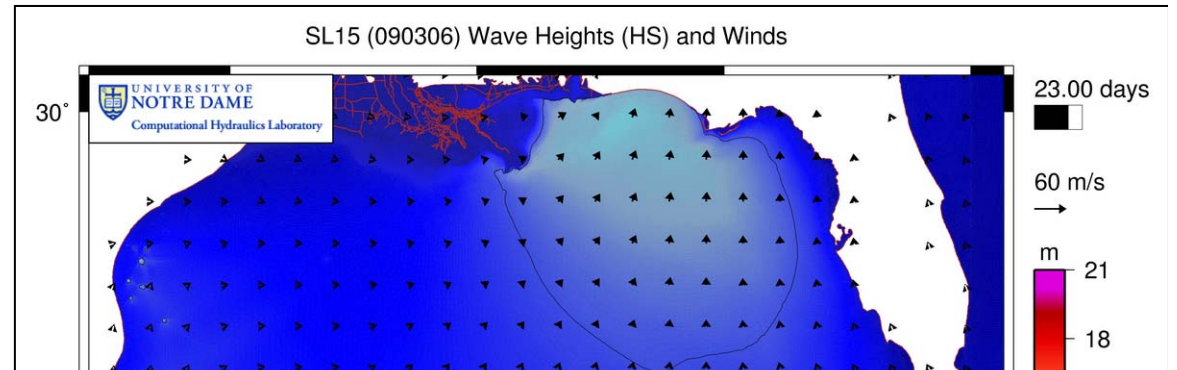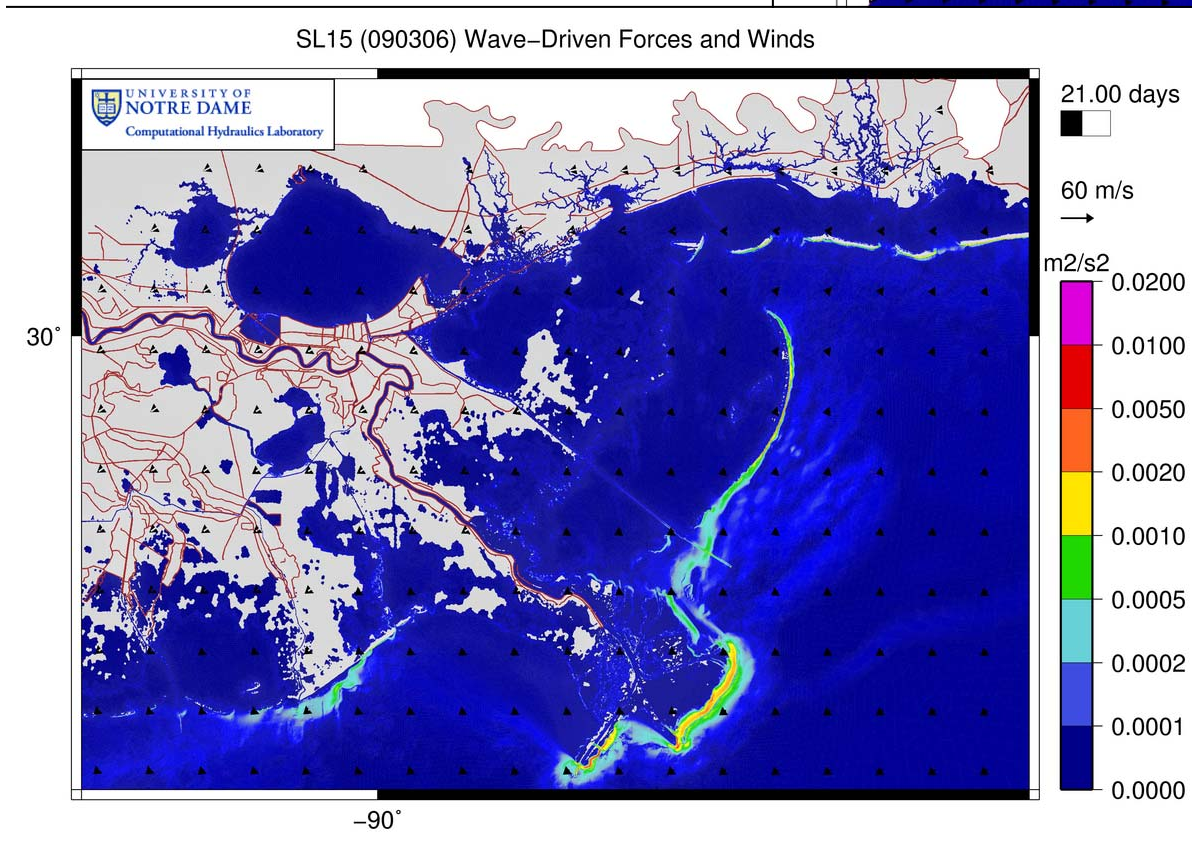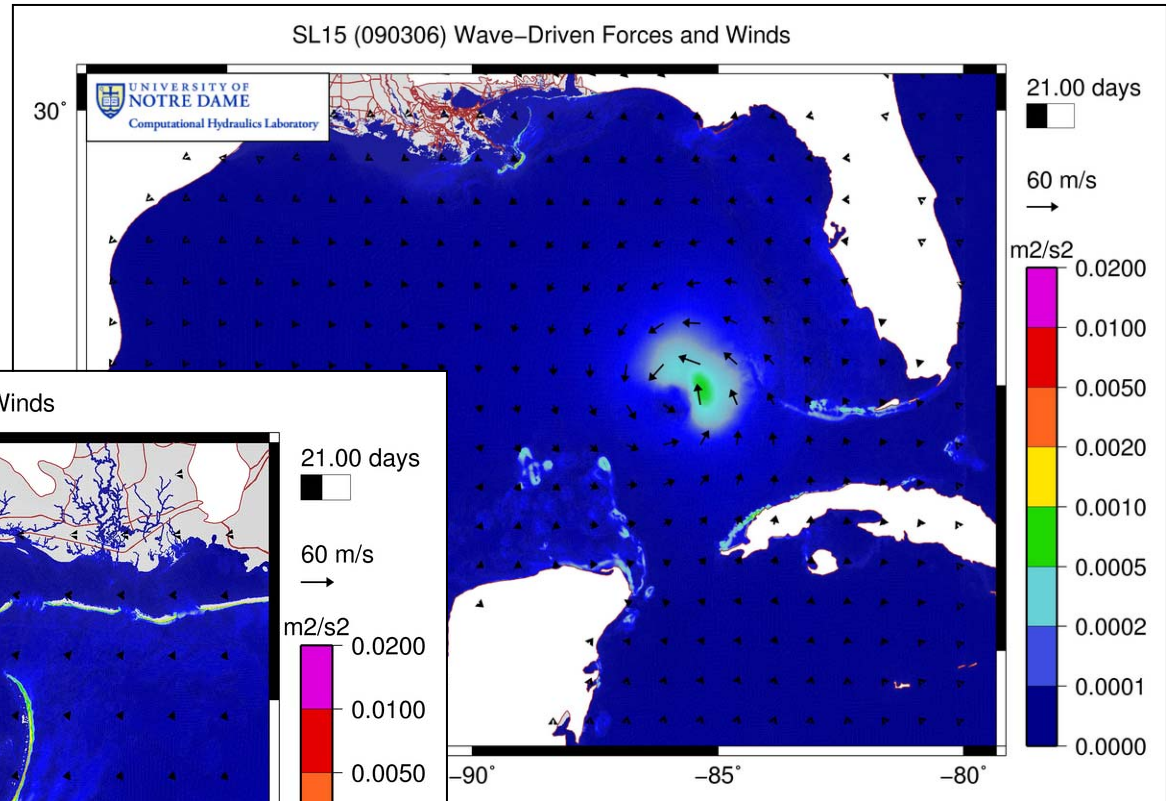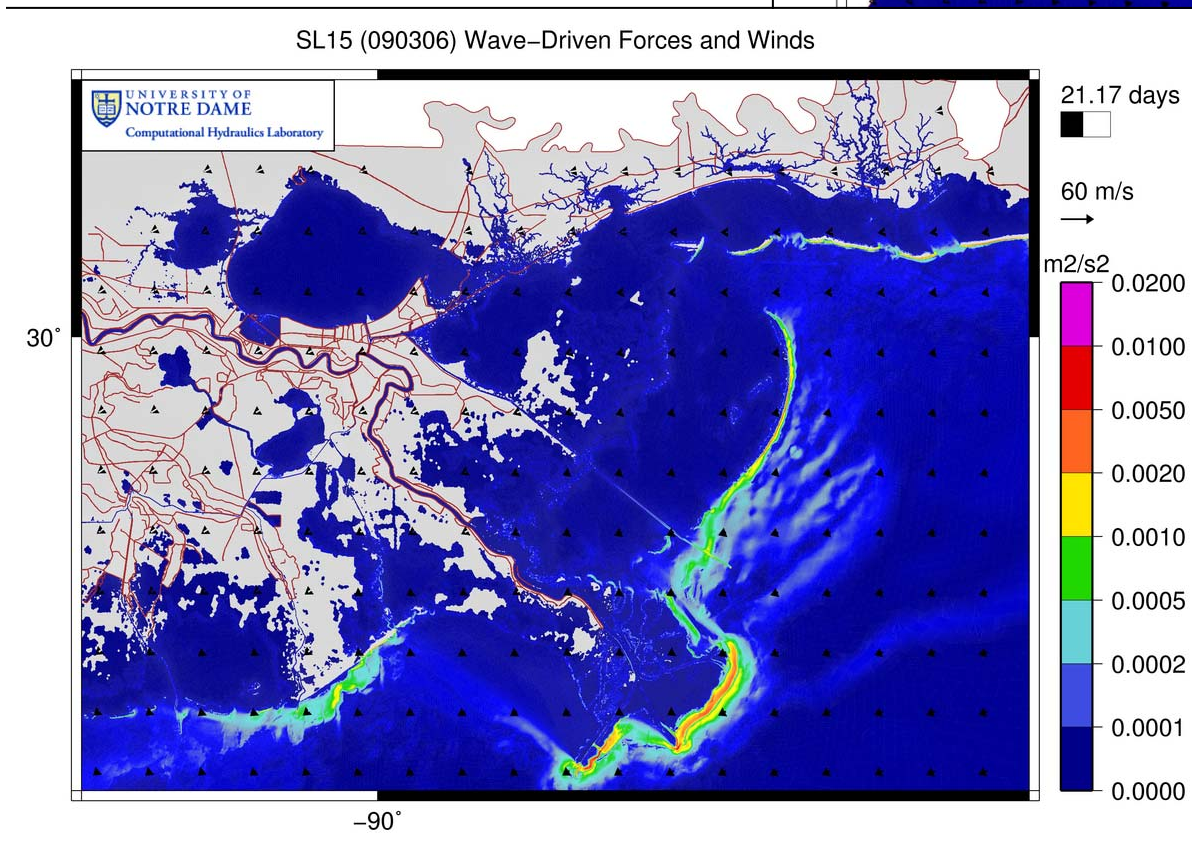
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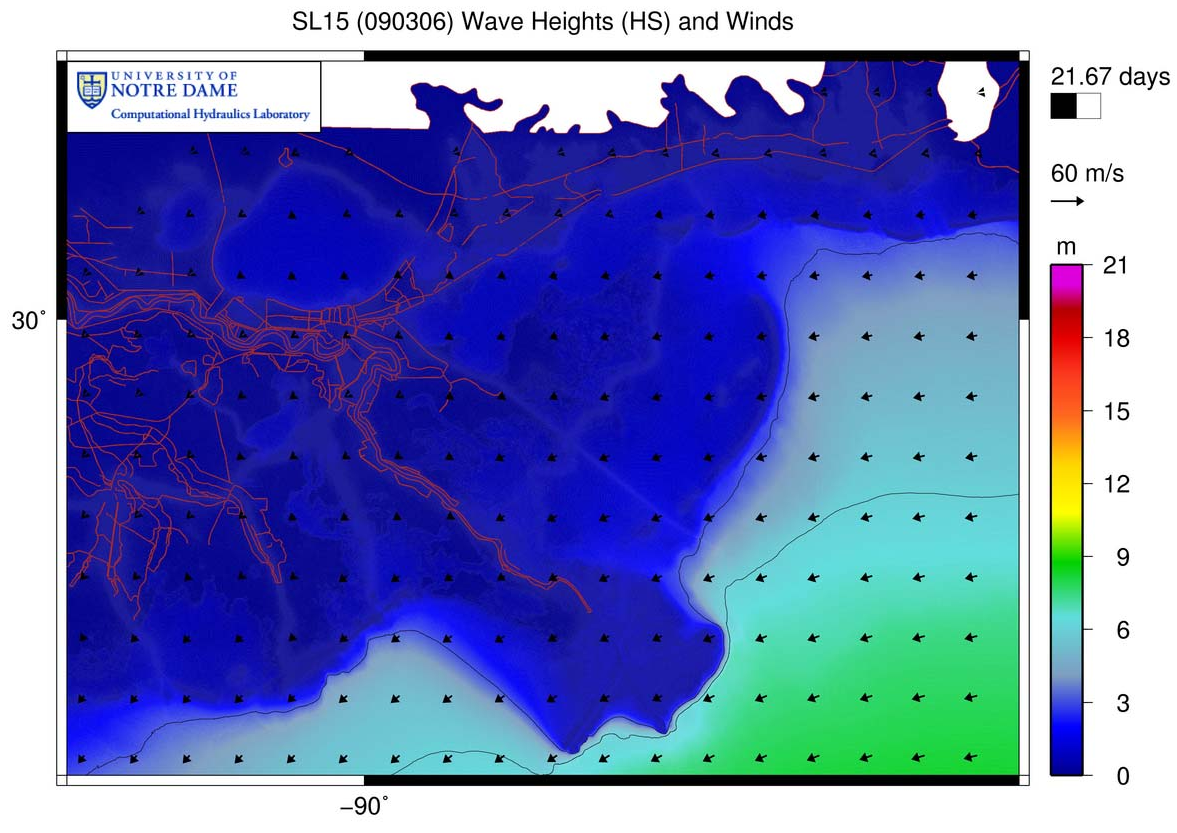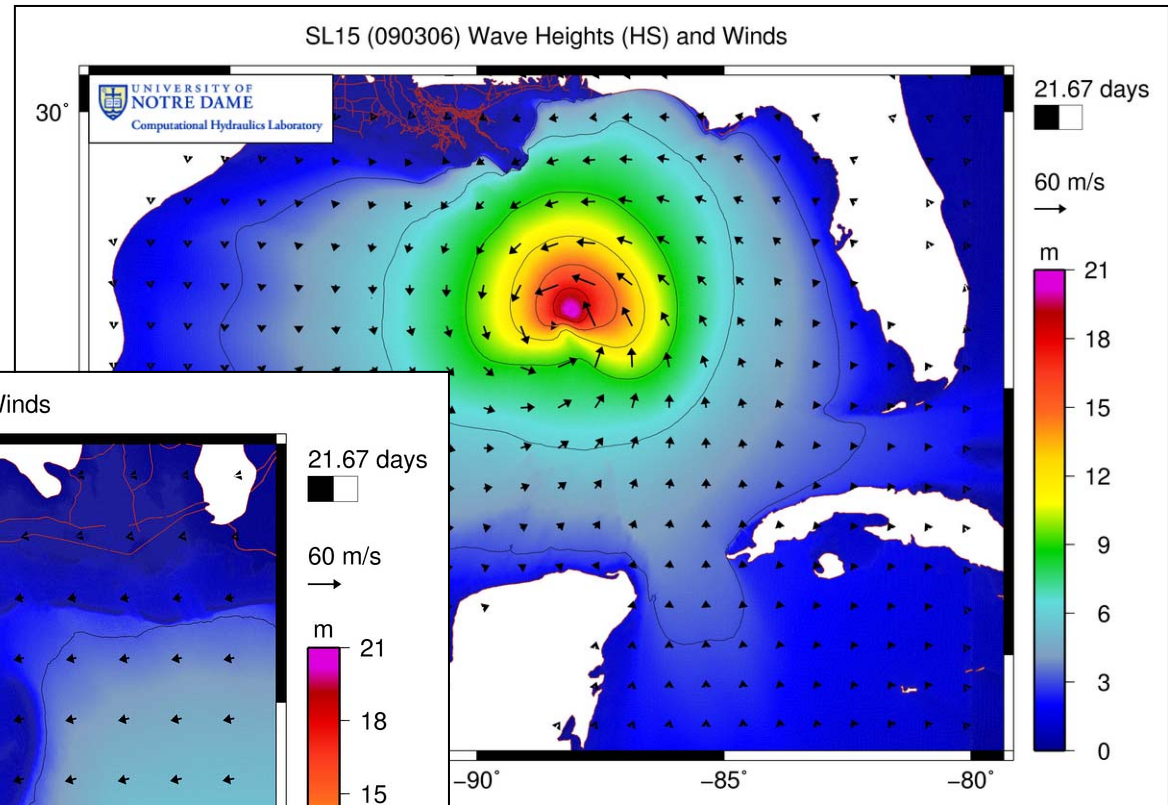
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Wave Heights

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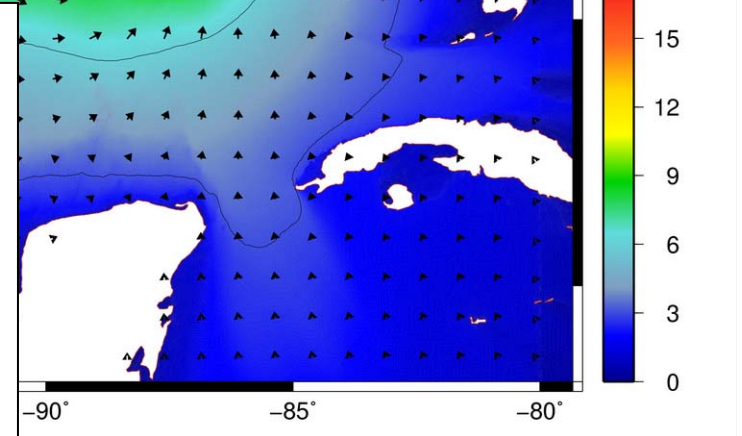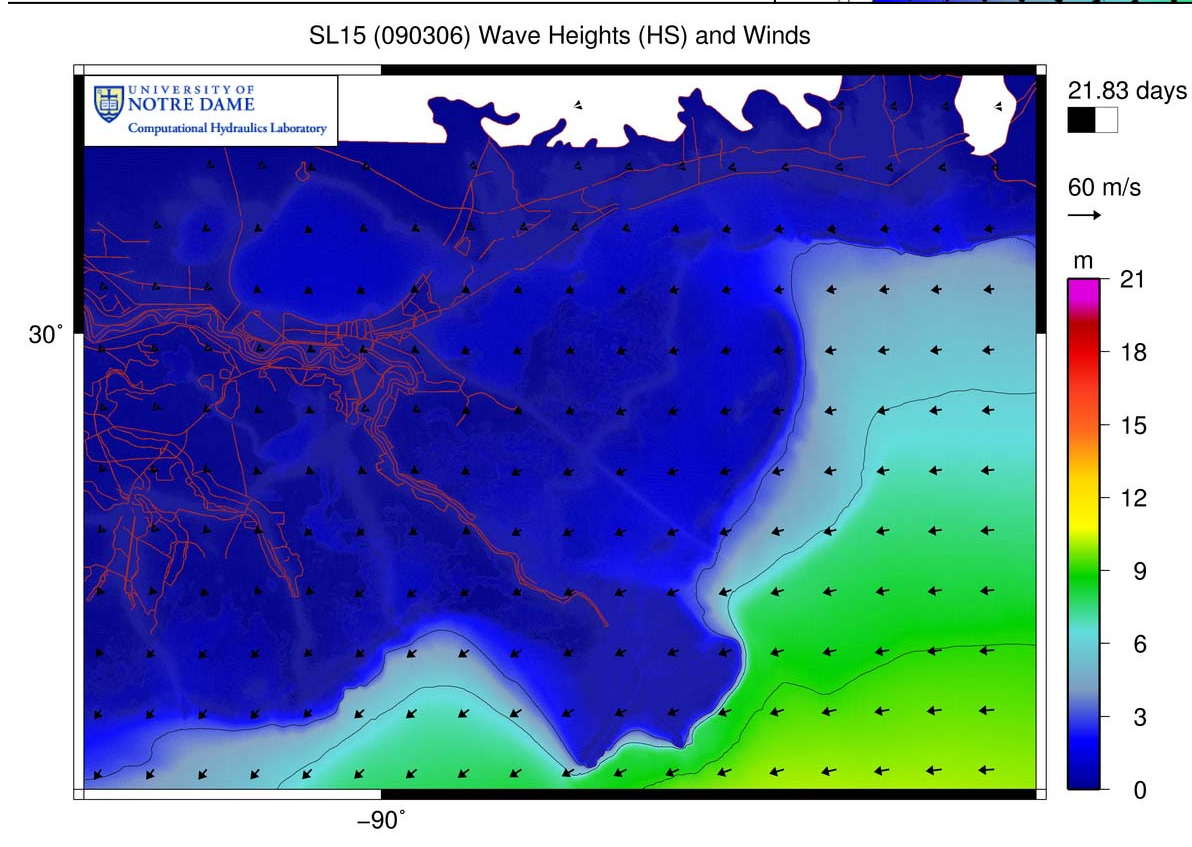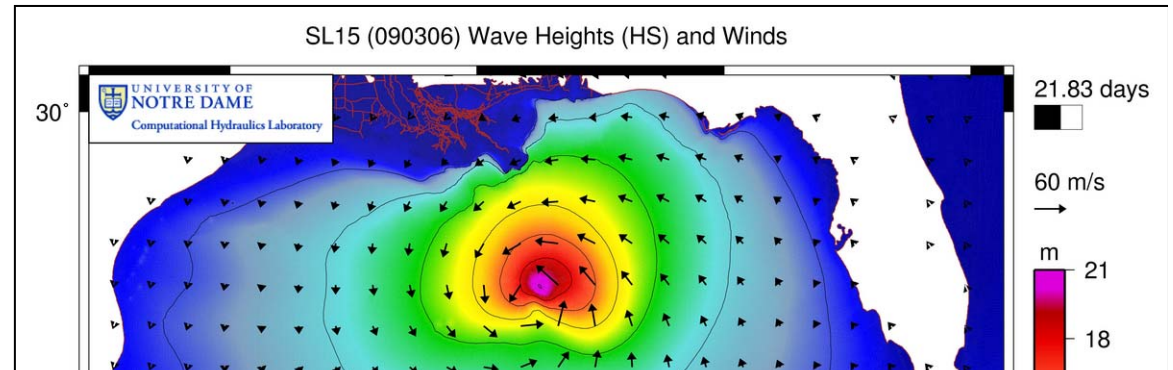
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Wave Heights

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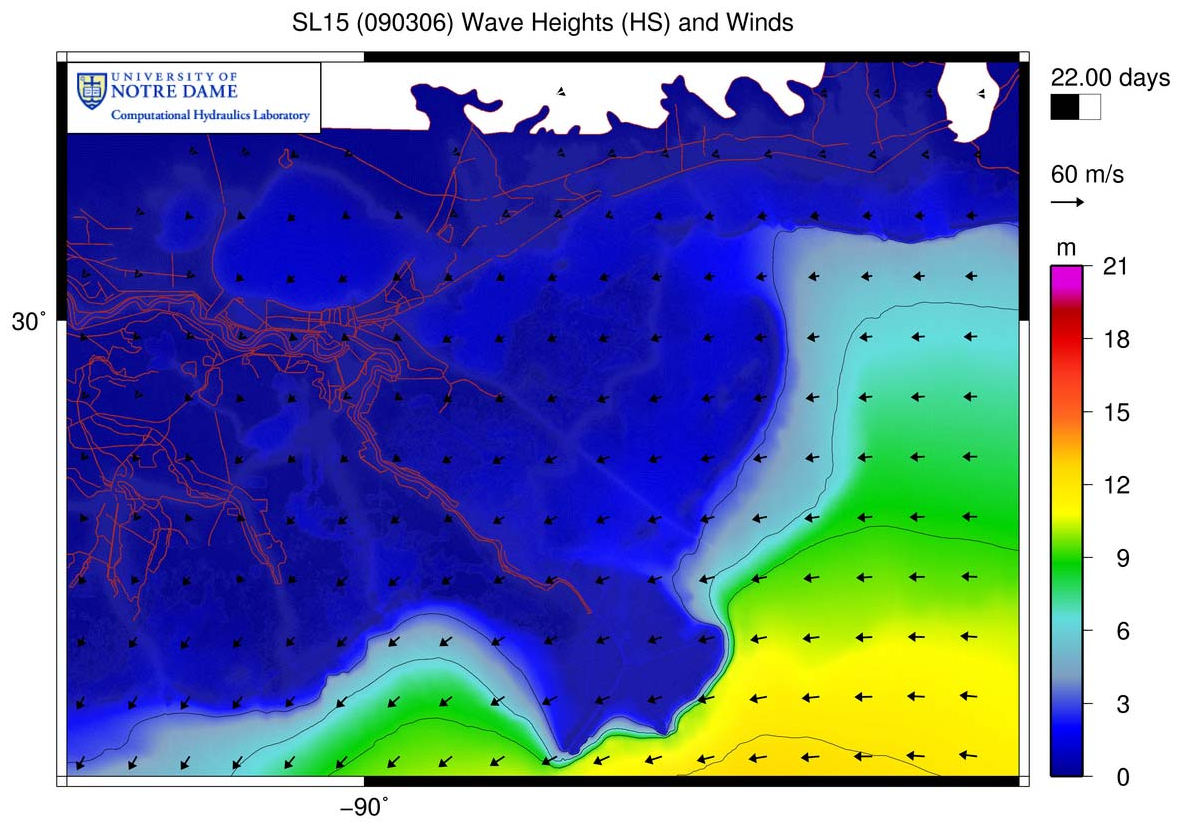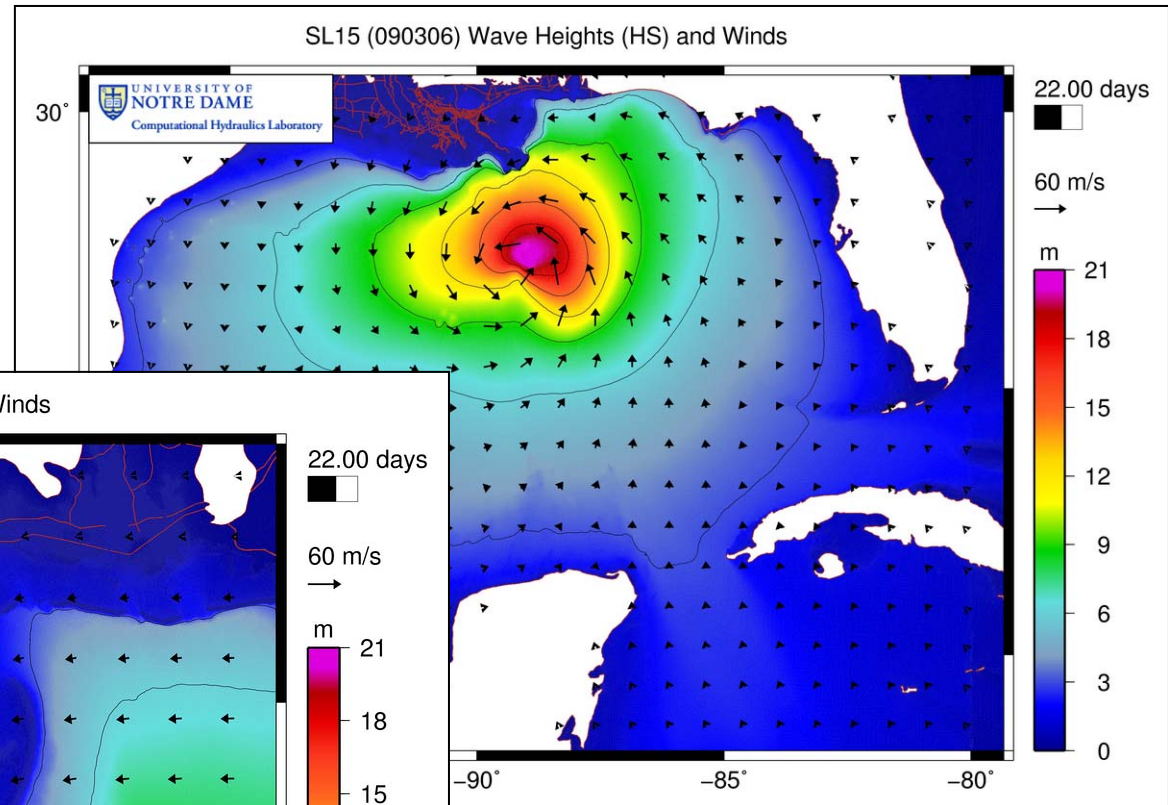
Hurricane Katrina

Wave Heights

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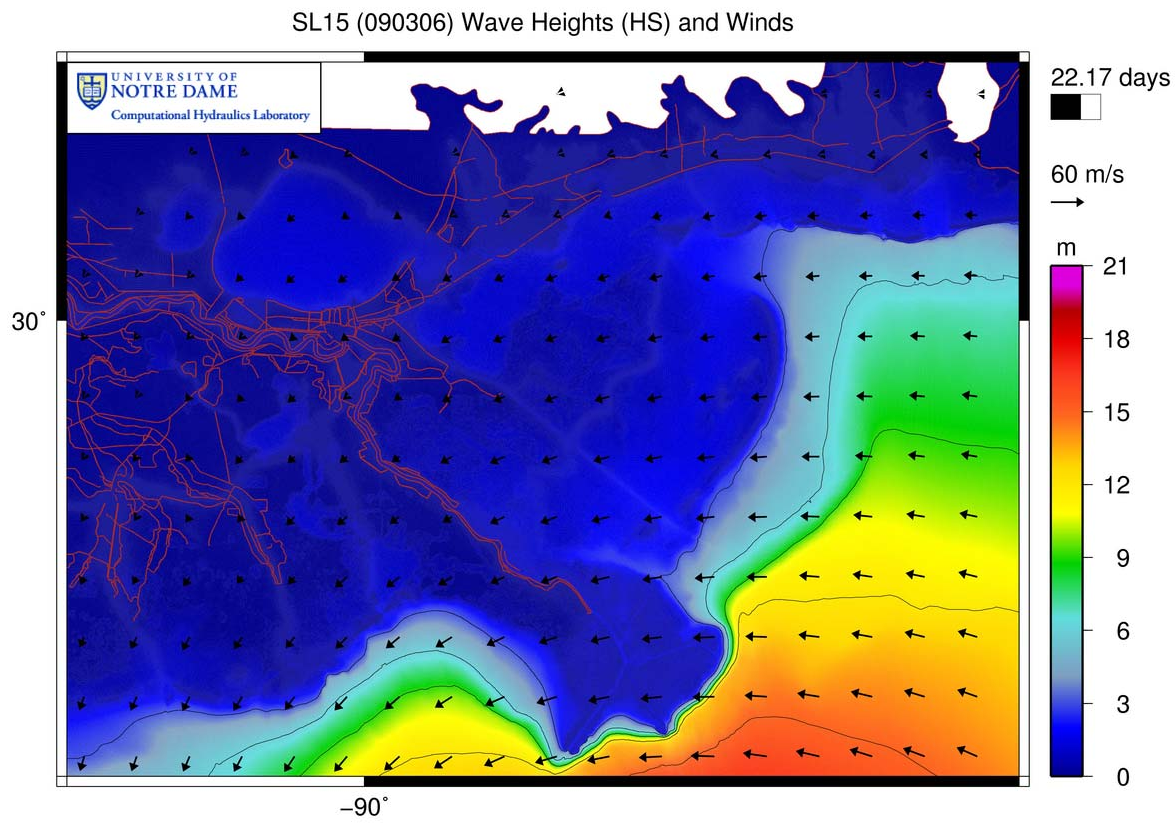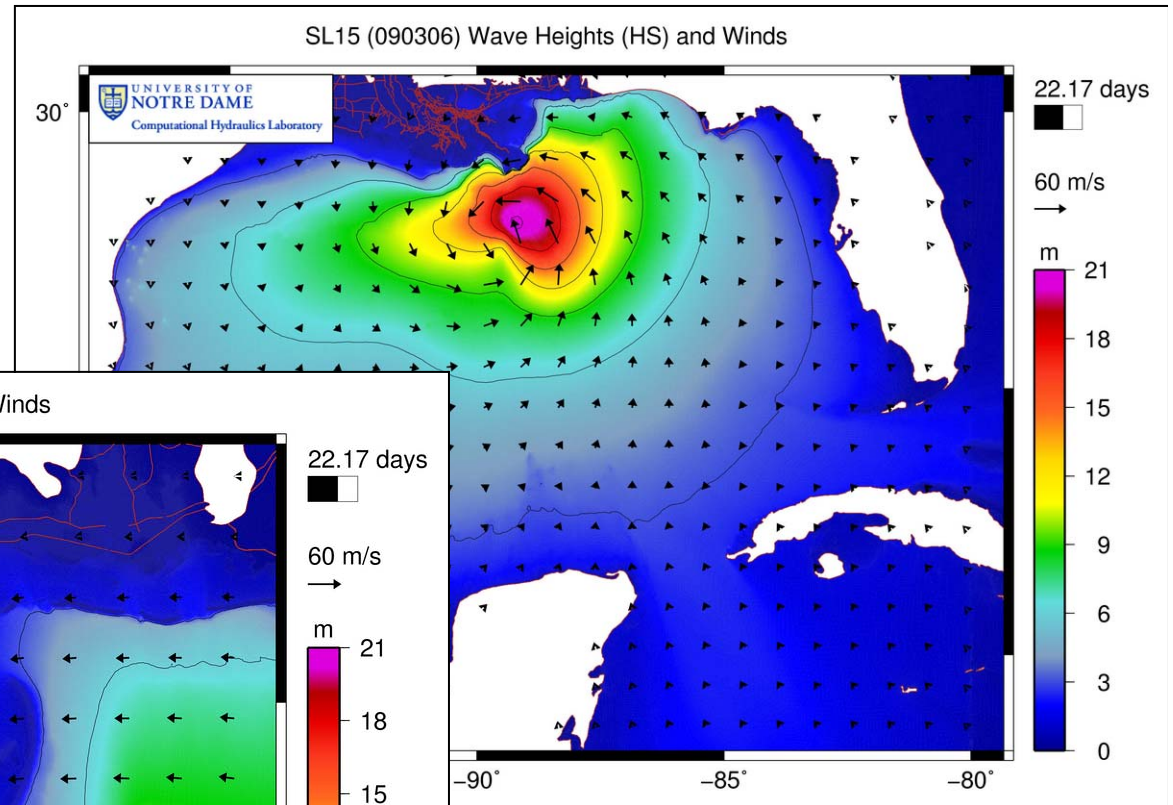
Hurricane Katrina

Wave Heights

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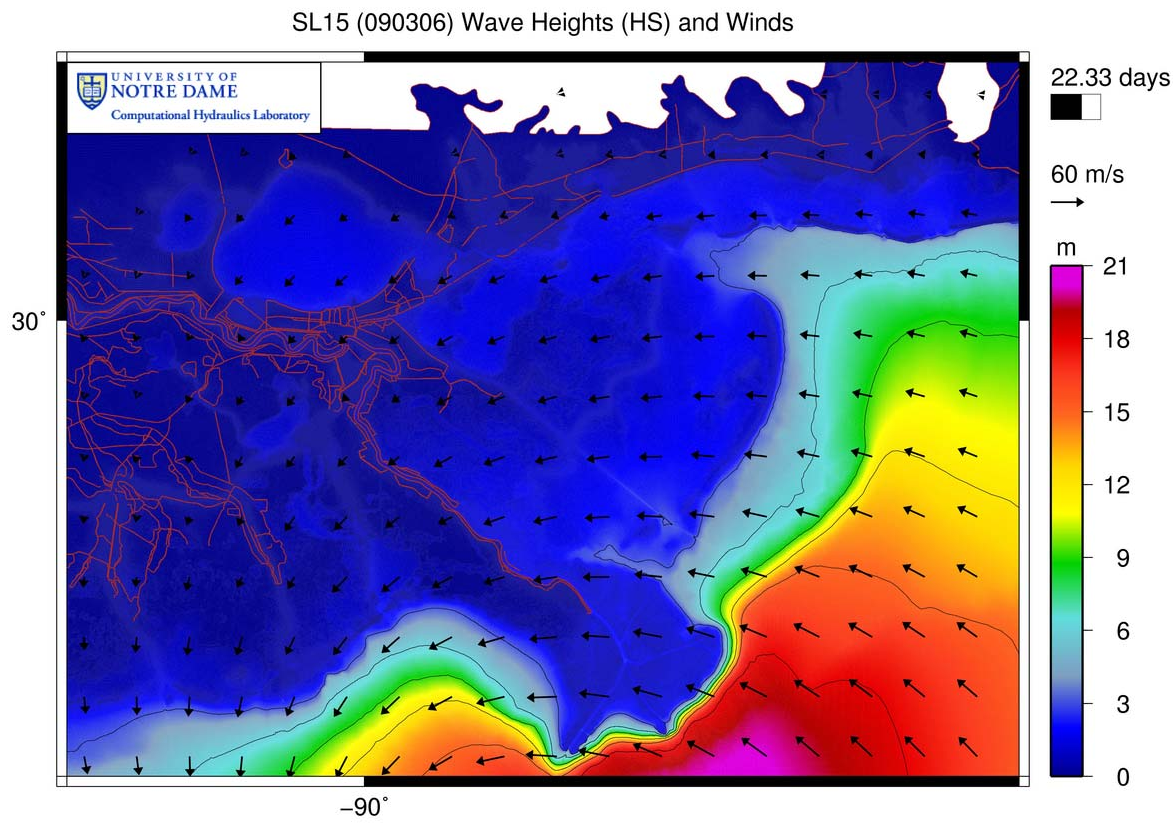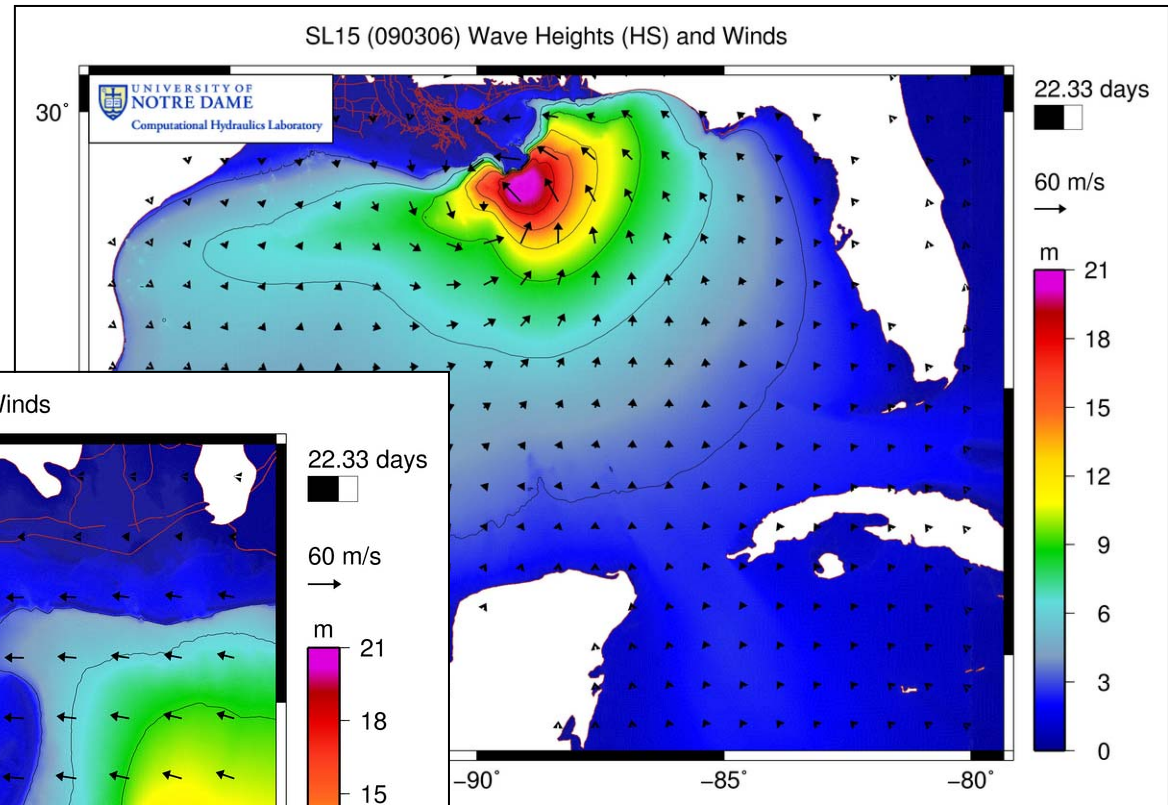
Hurricane Katrina

Wave Heights

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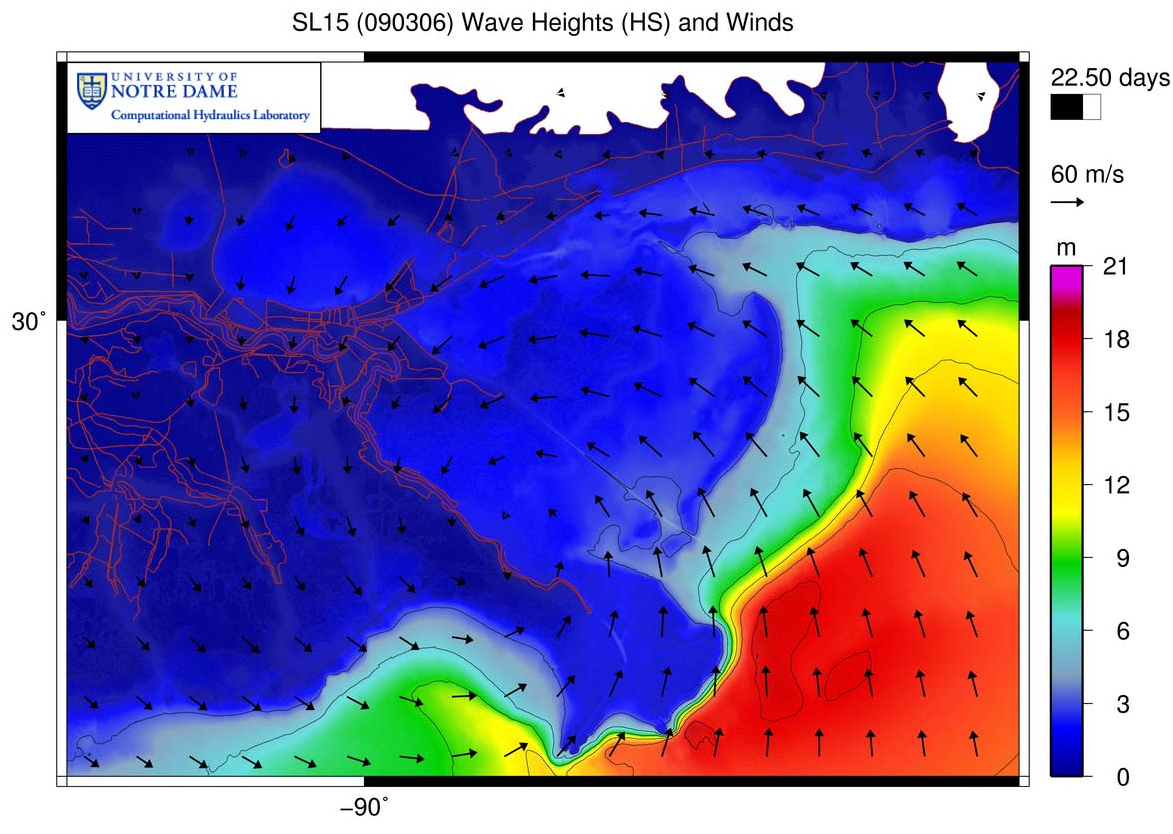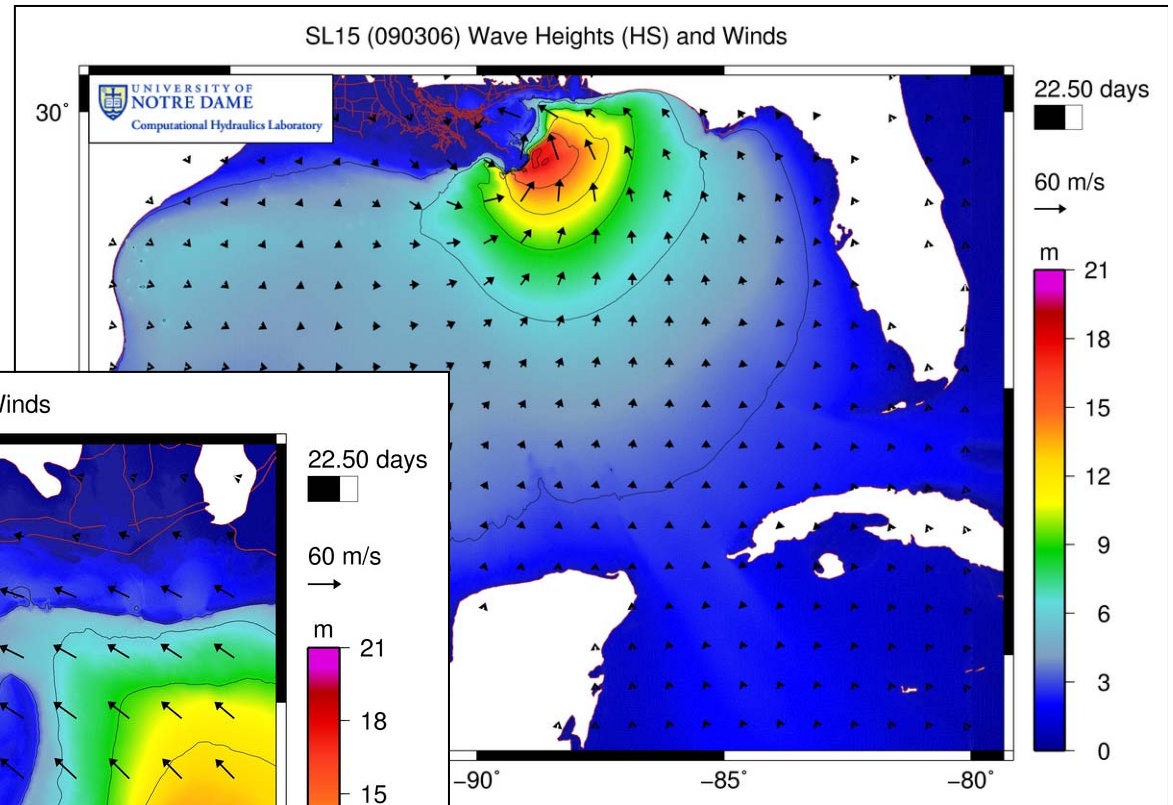
Hurricane Katrina

Wave Heights

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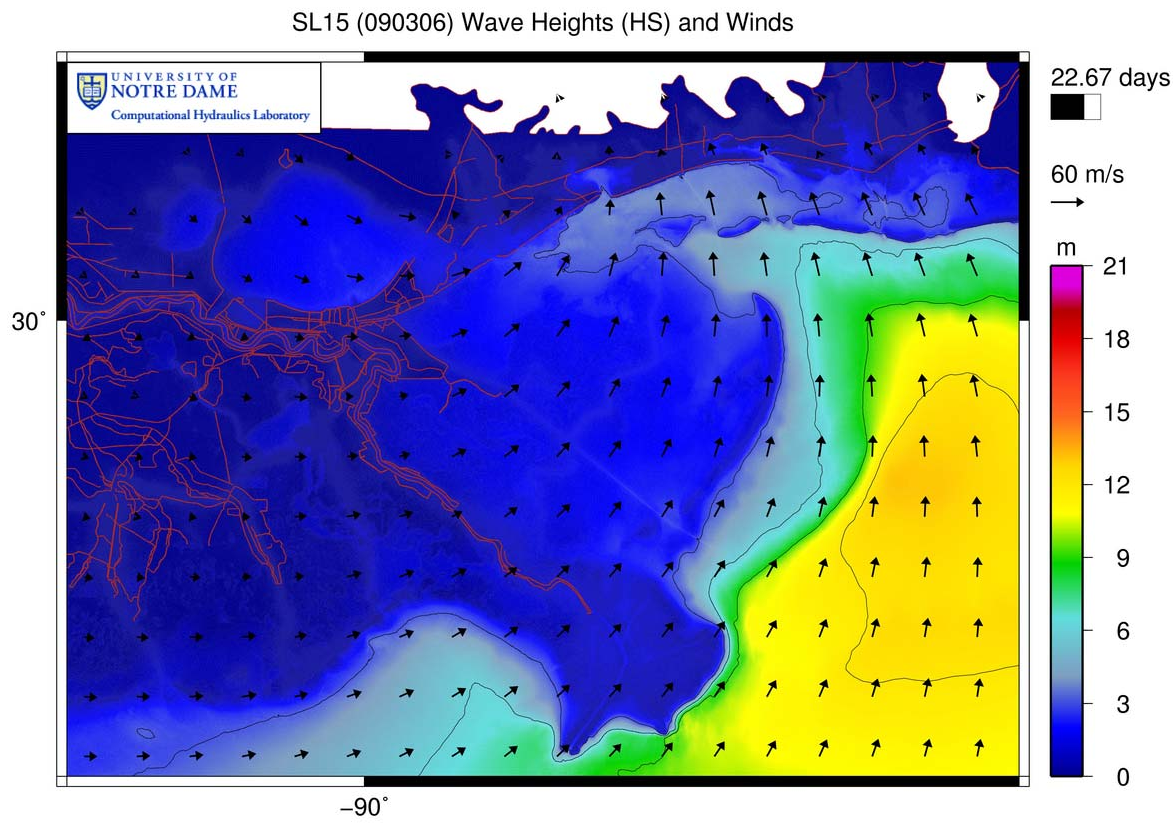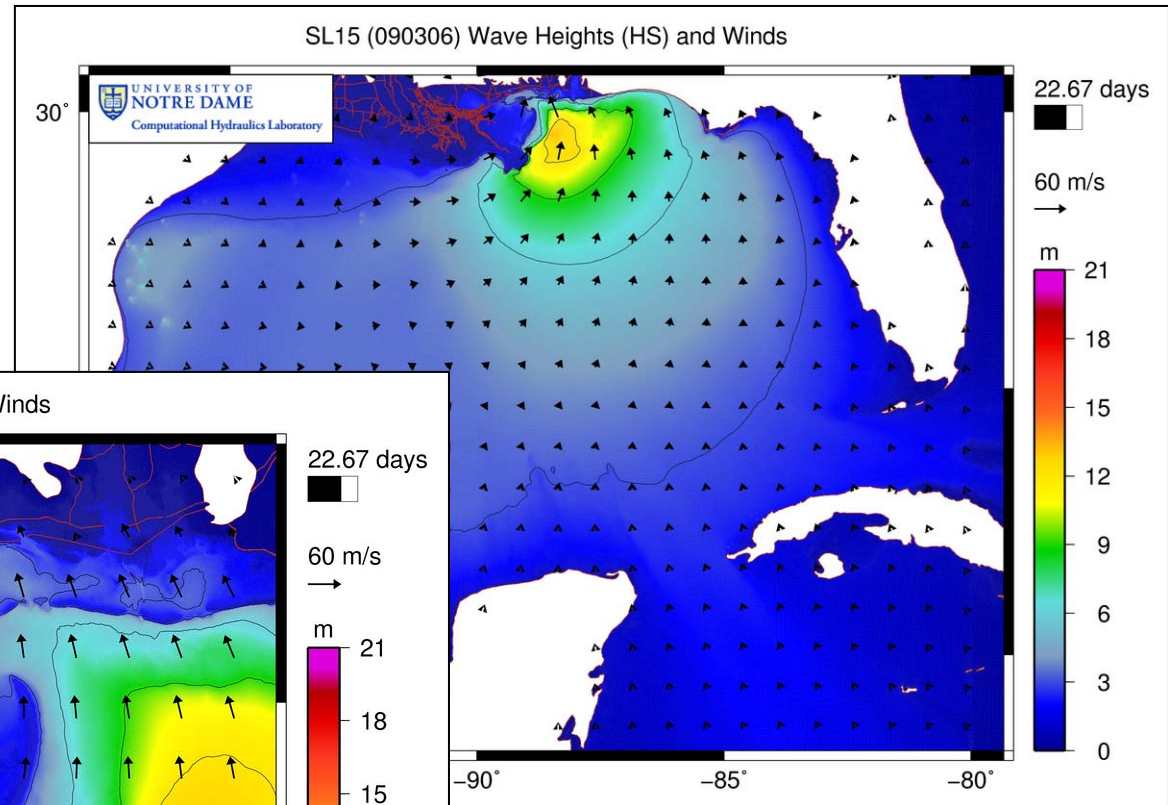
Hurricane Katrina

Wave Heights

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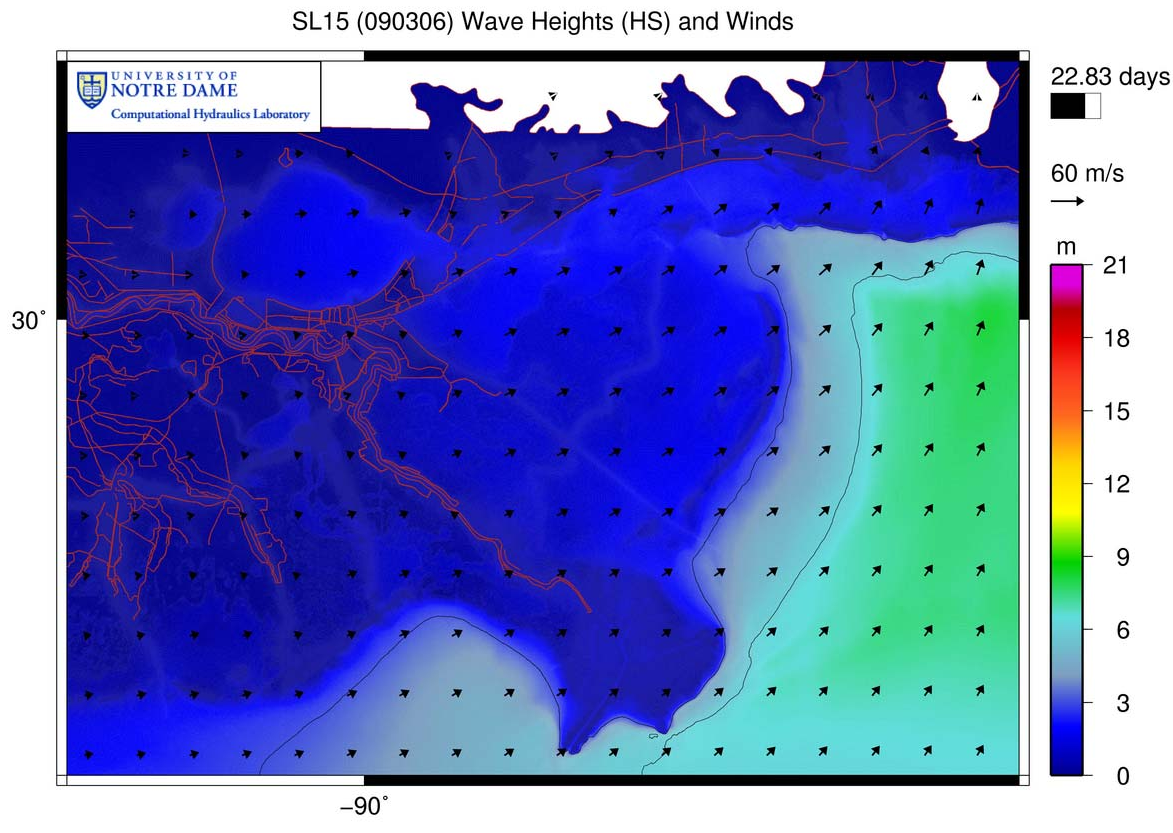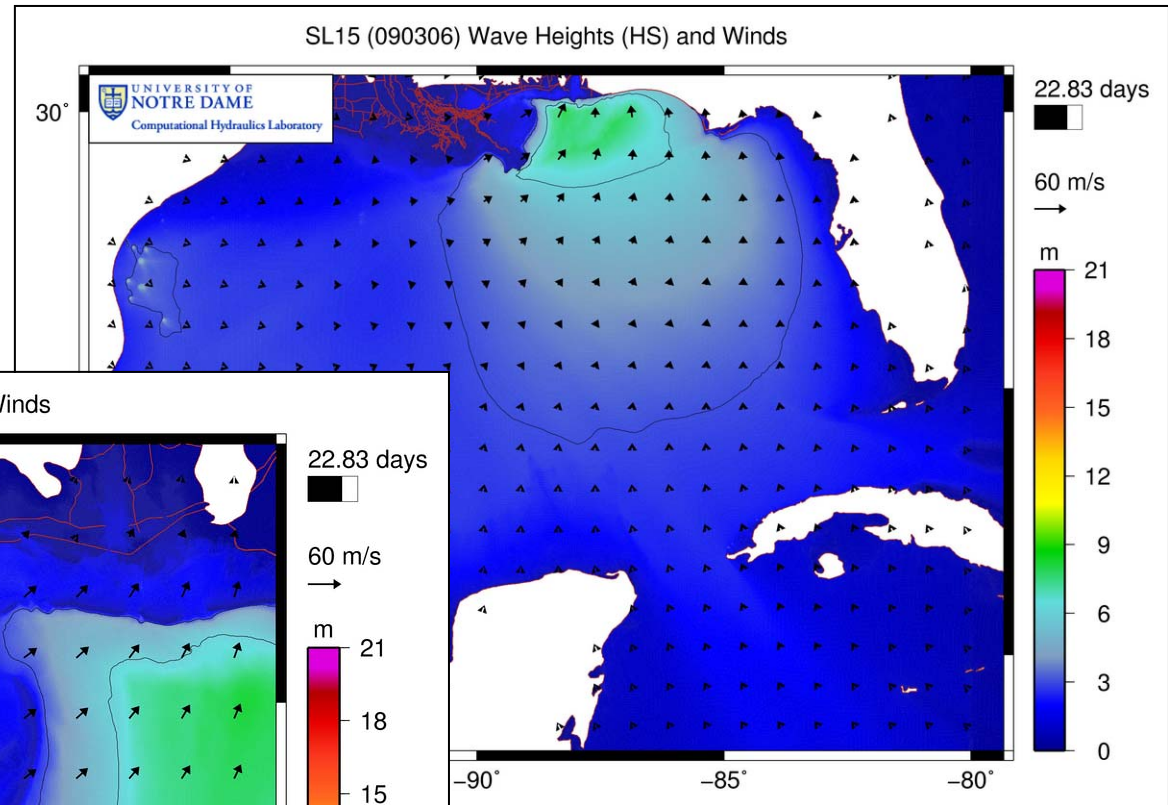
Hurricane Katrina

Wave Heights

- 2005/08/30/0000Z

Hurricane Katrina

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Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/0000Z

Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/0400Z
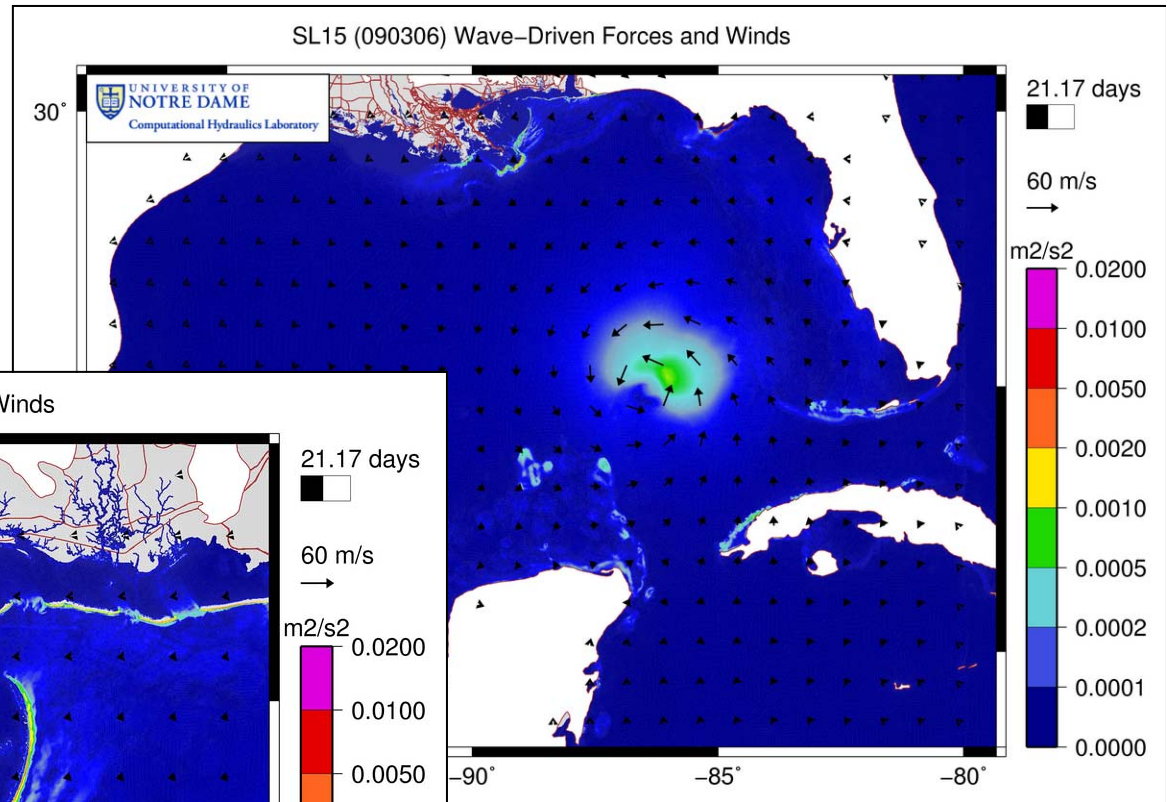
Hurricane Katrina

Wave-Driven Forces
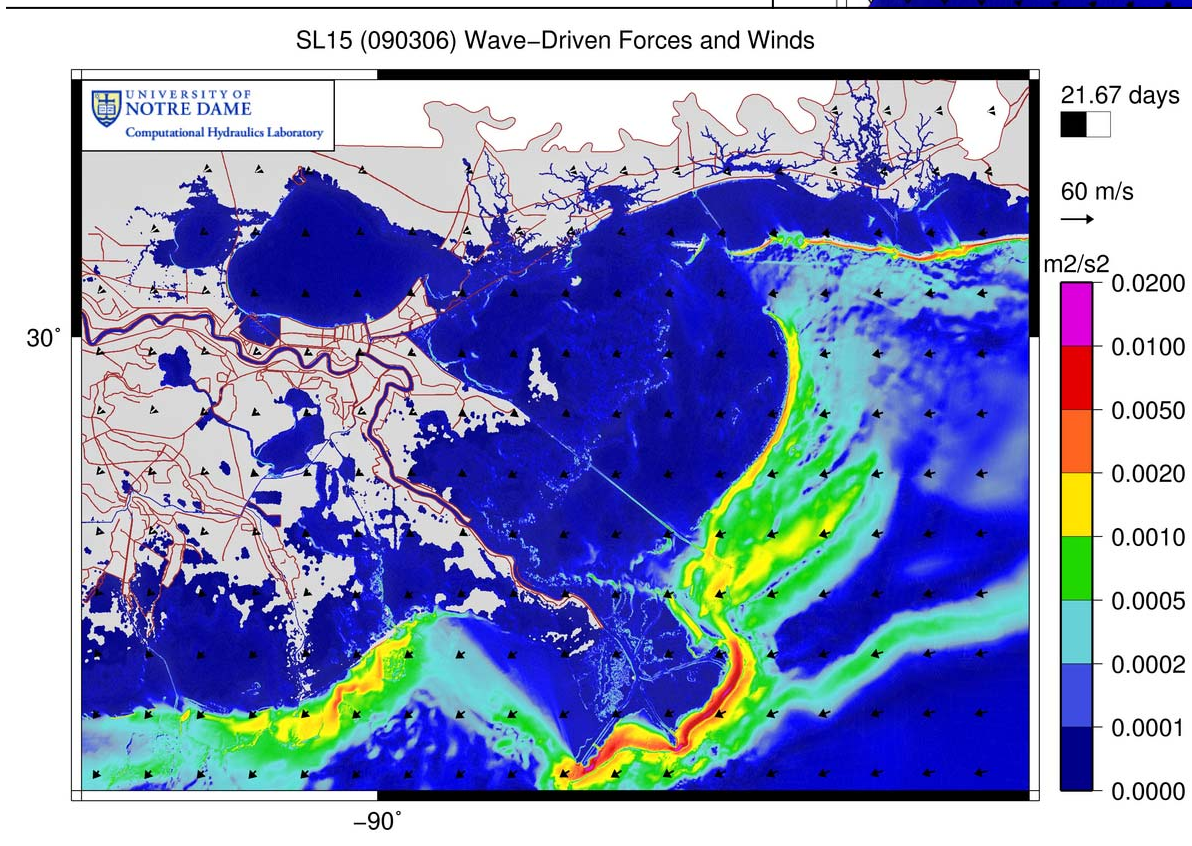
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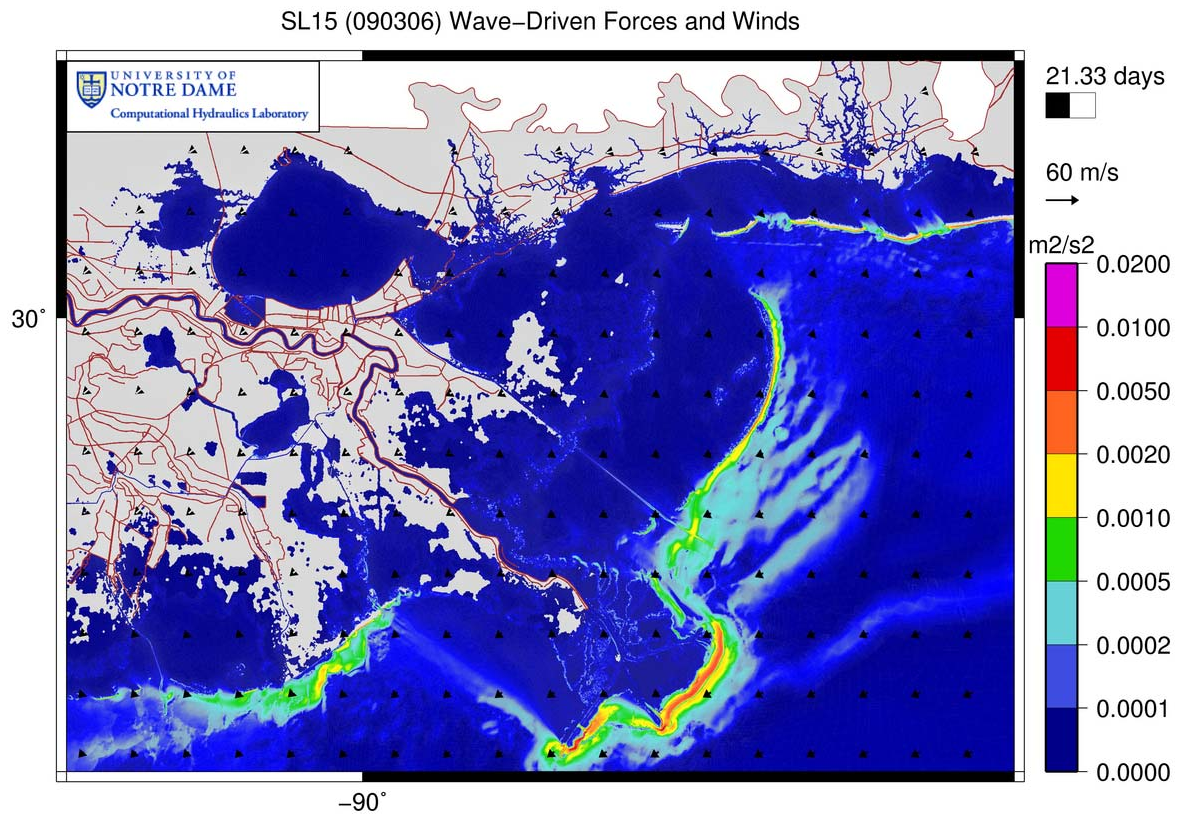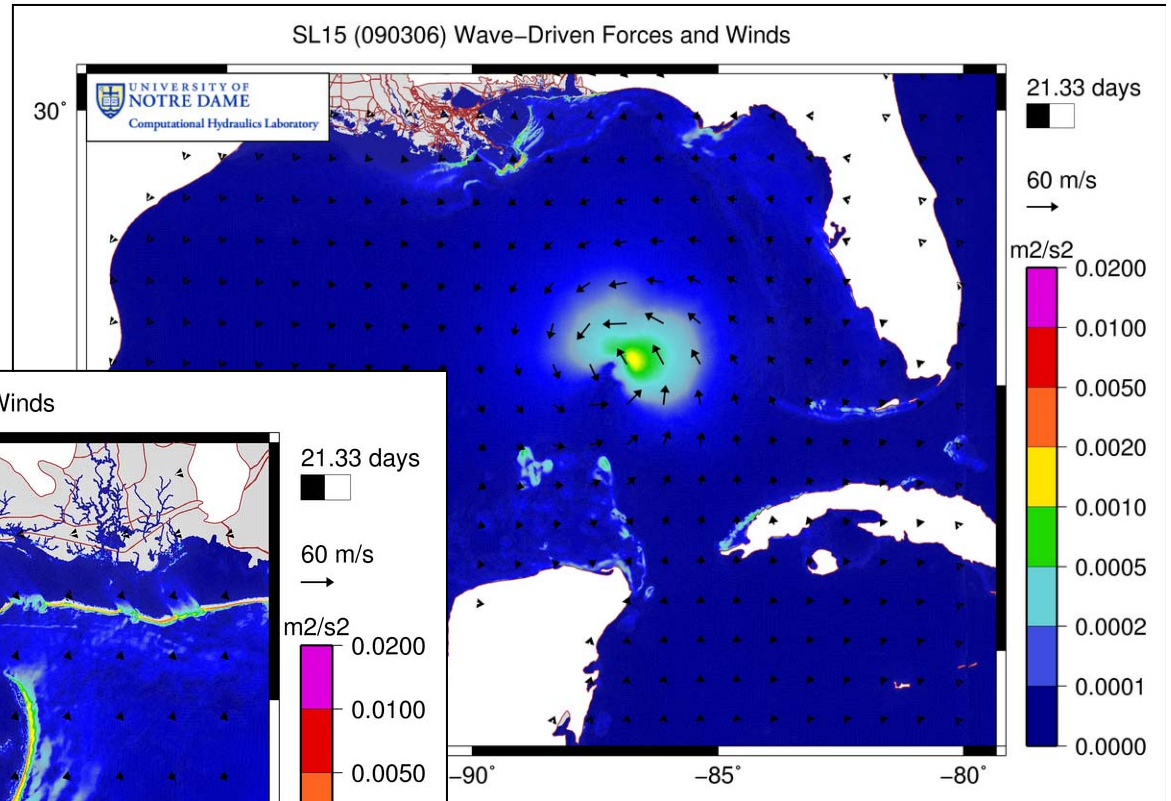
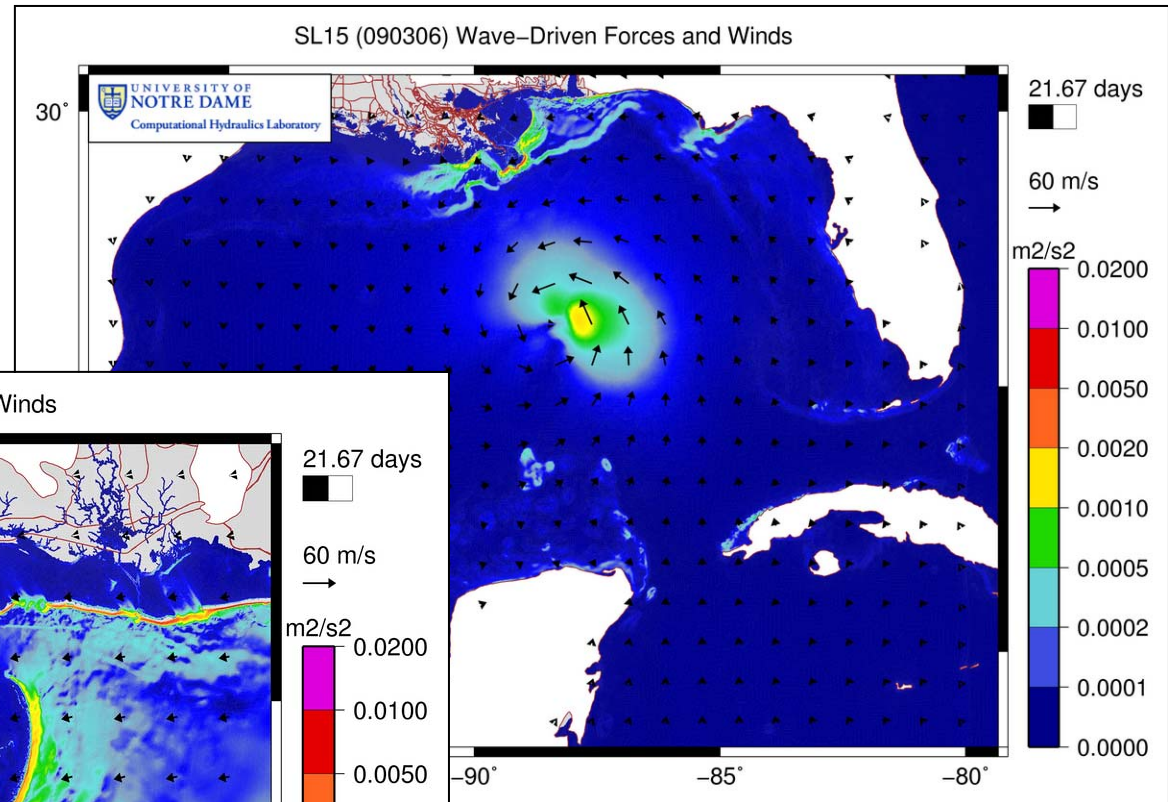# Hurricane Katrina

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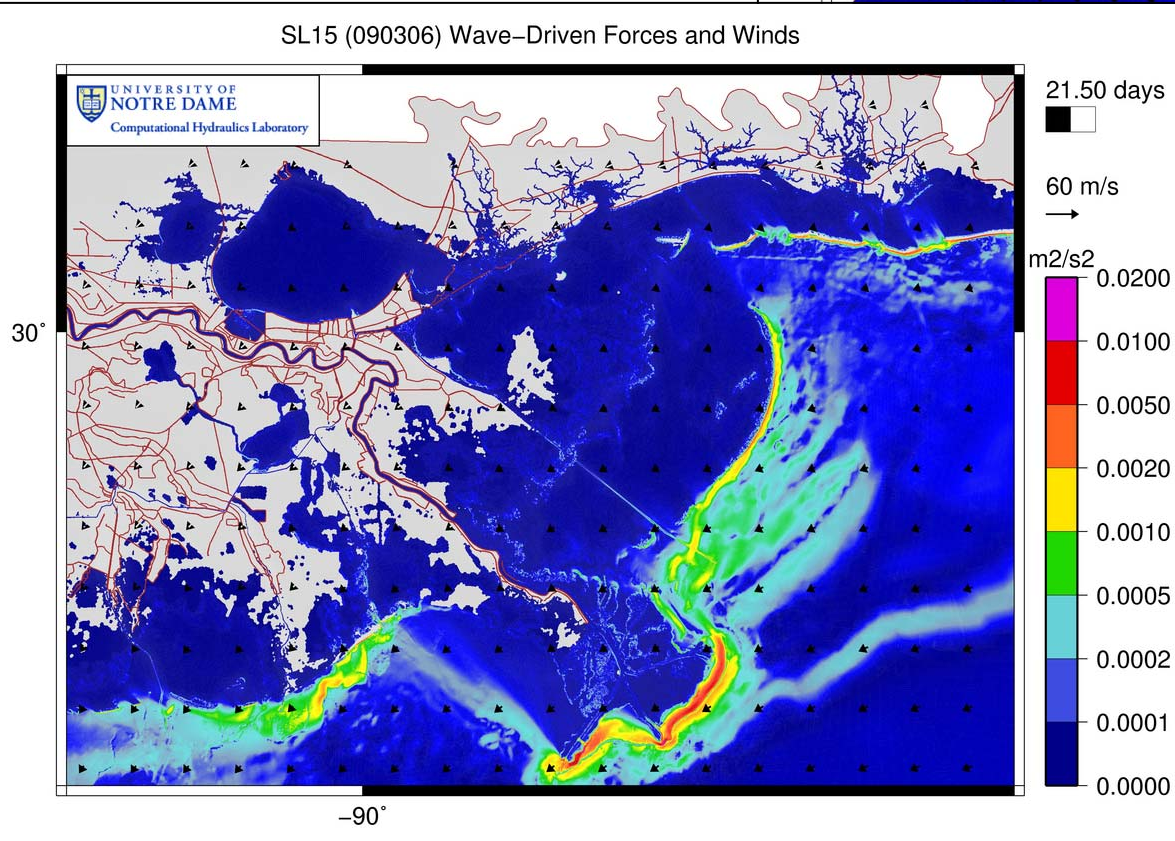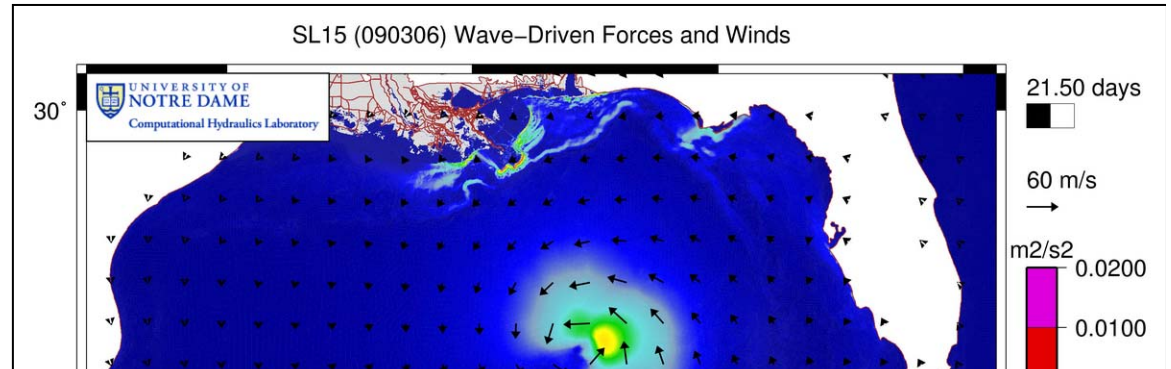
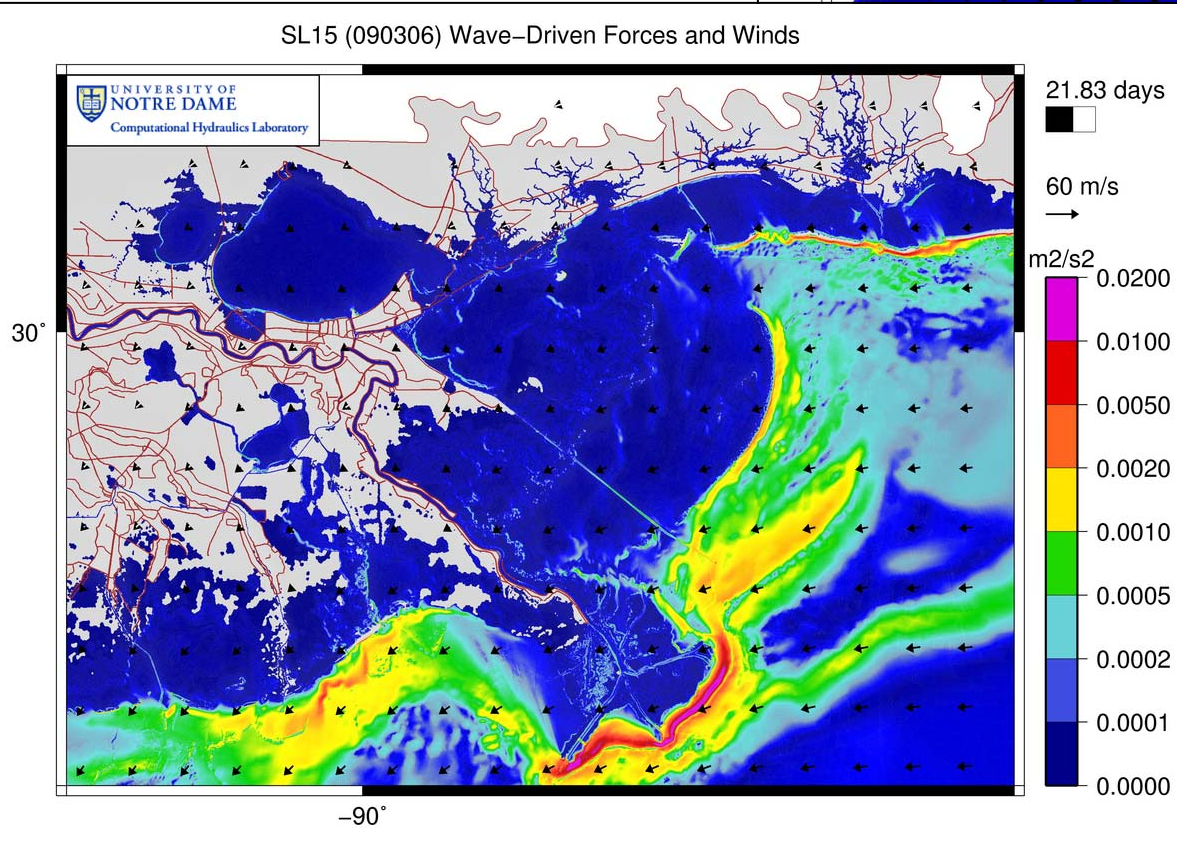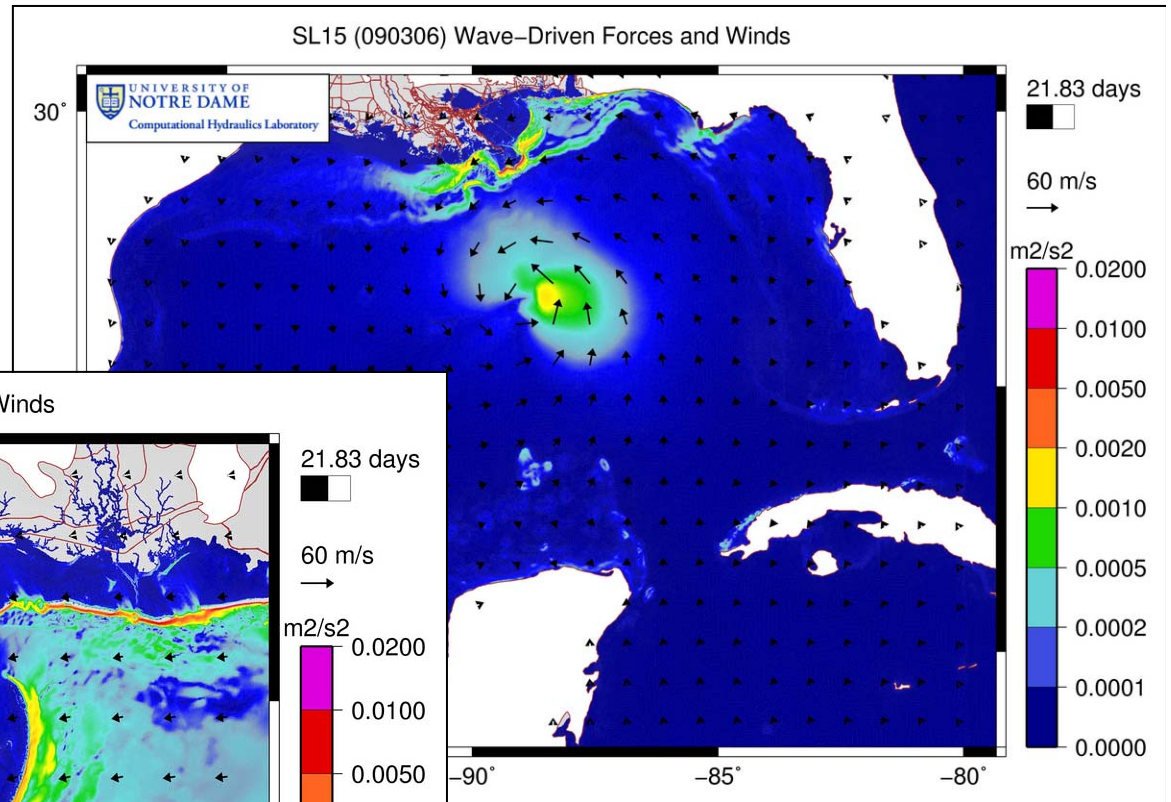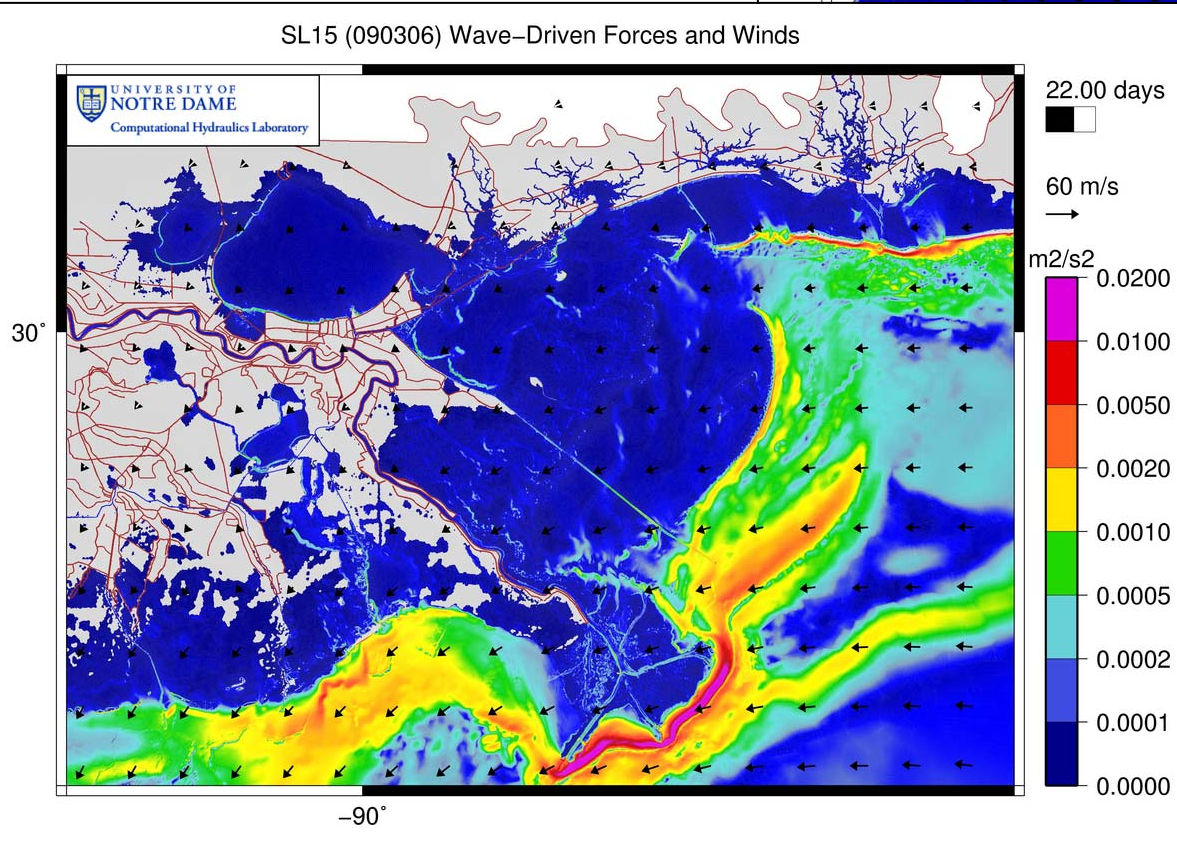# Hurricane Katrina

Wave-Driven Forces

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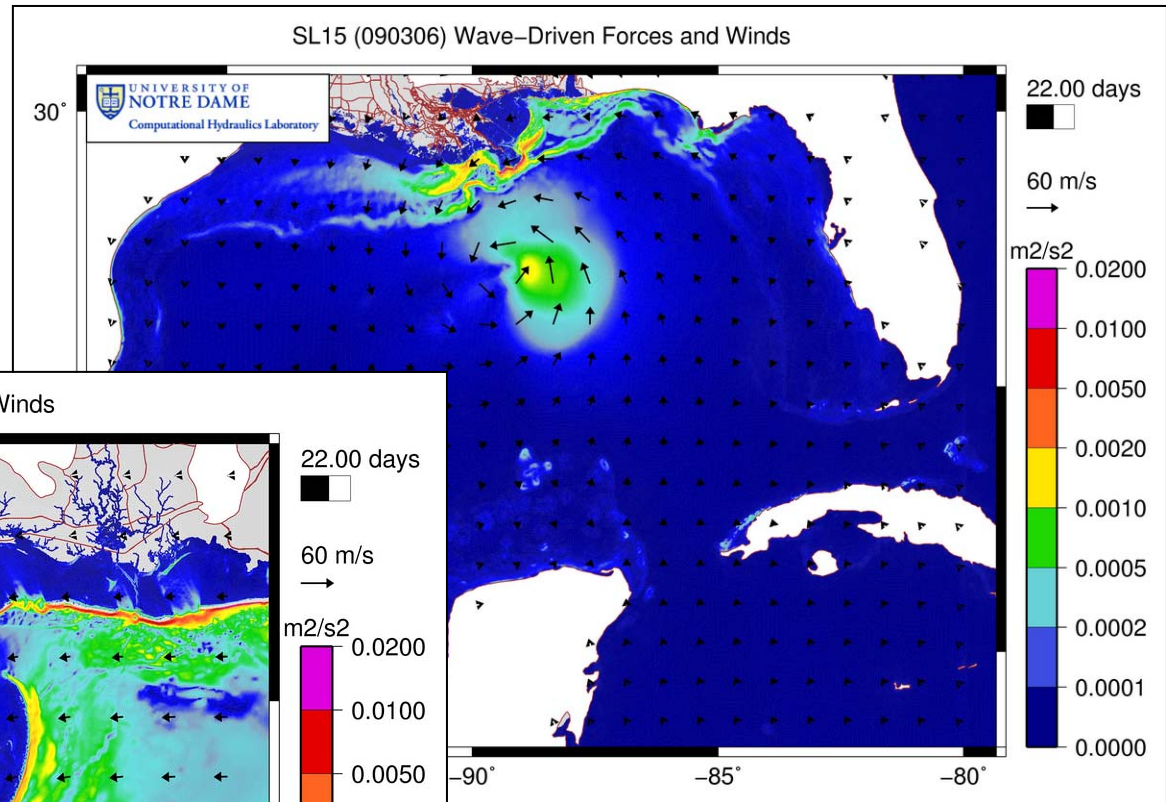# Hurricane Katrina

Wave-Driven Forces

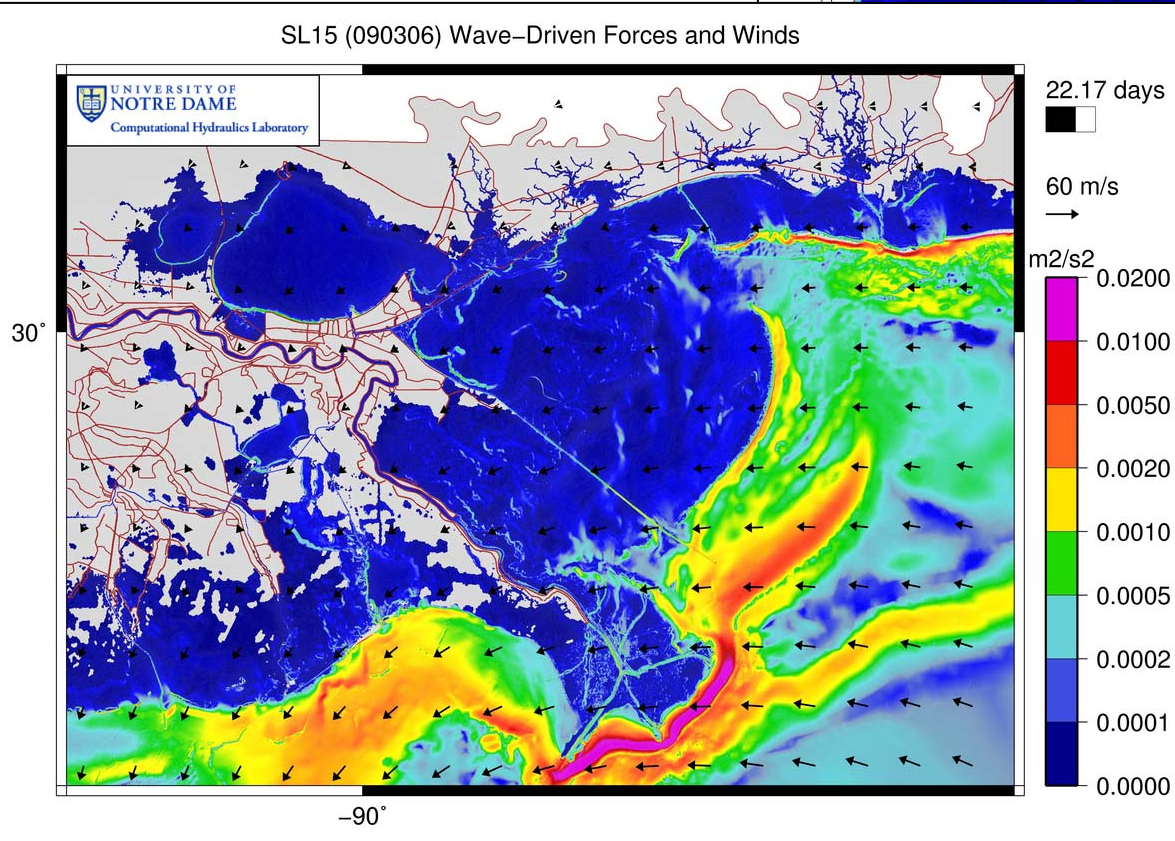- 2005/08/28/2000Z
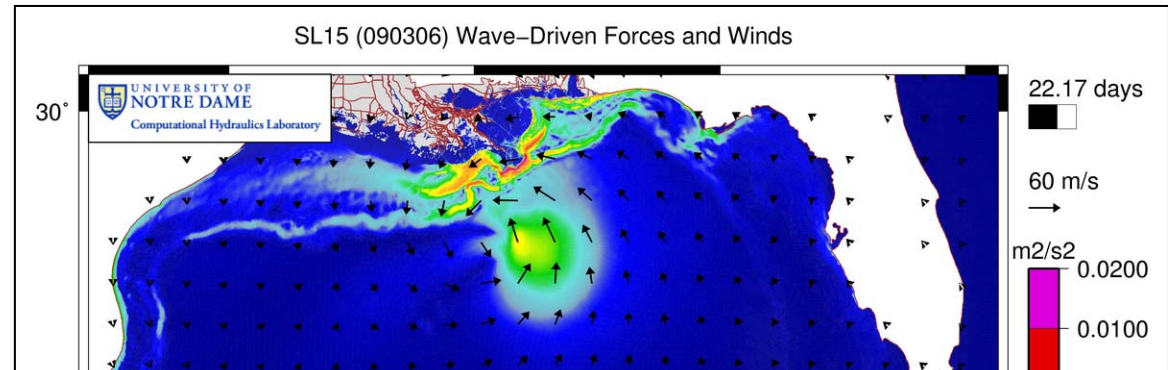
Hurricane Katrina

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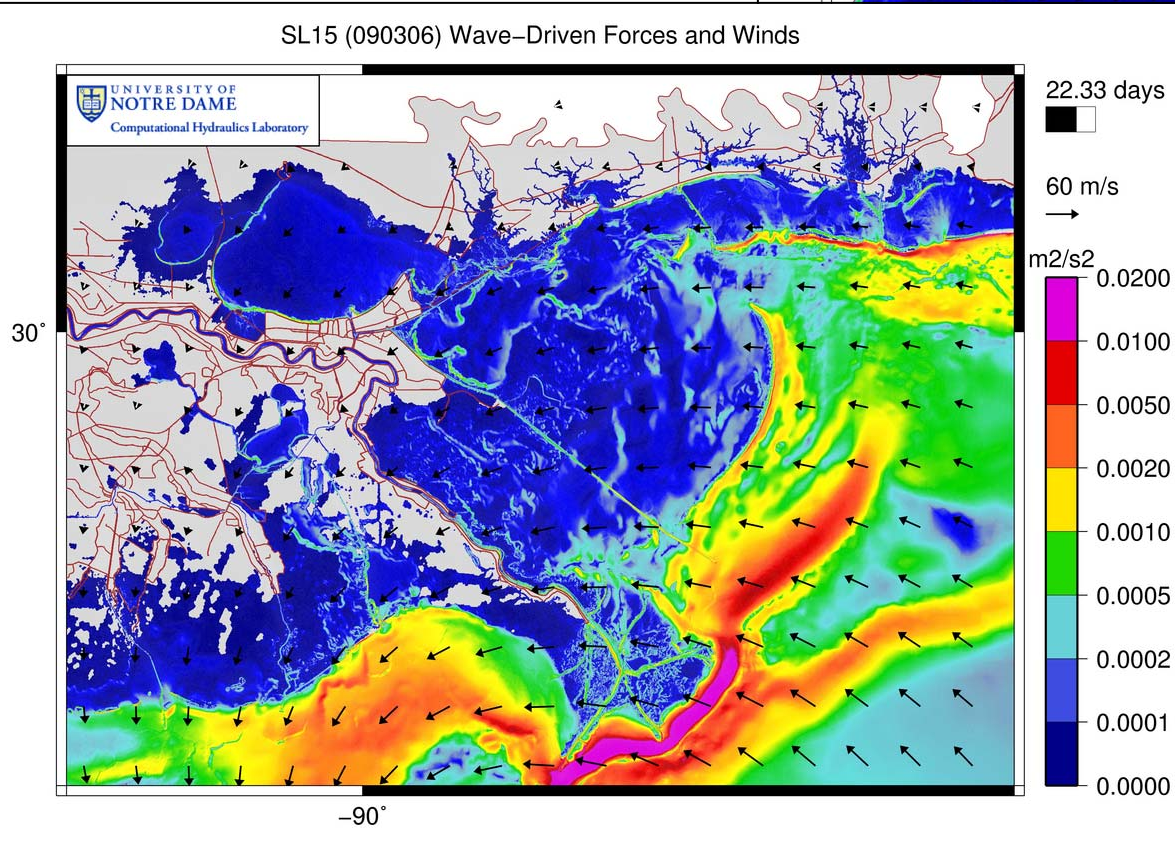
Hurricane Katrina

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Hurricane Katrina

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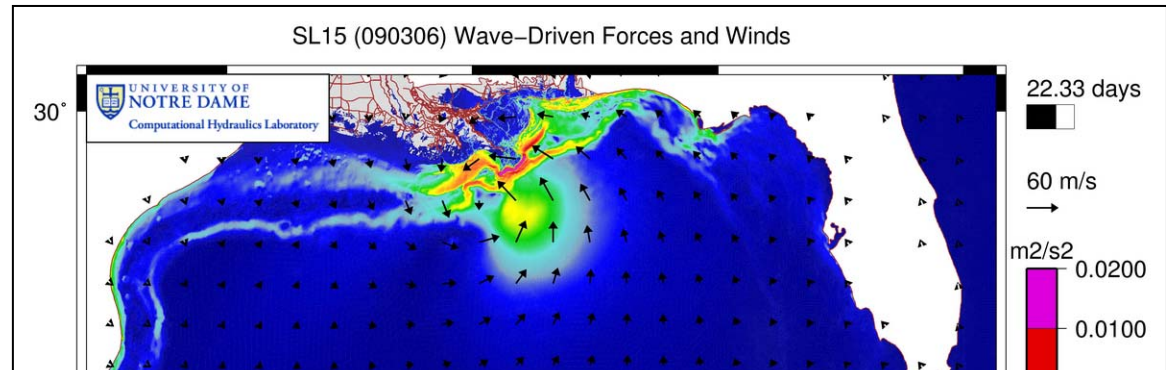
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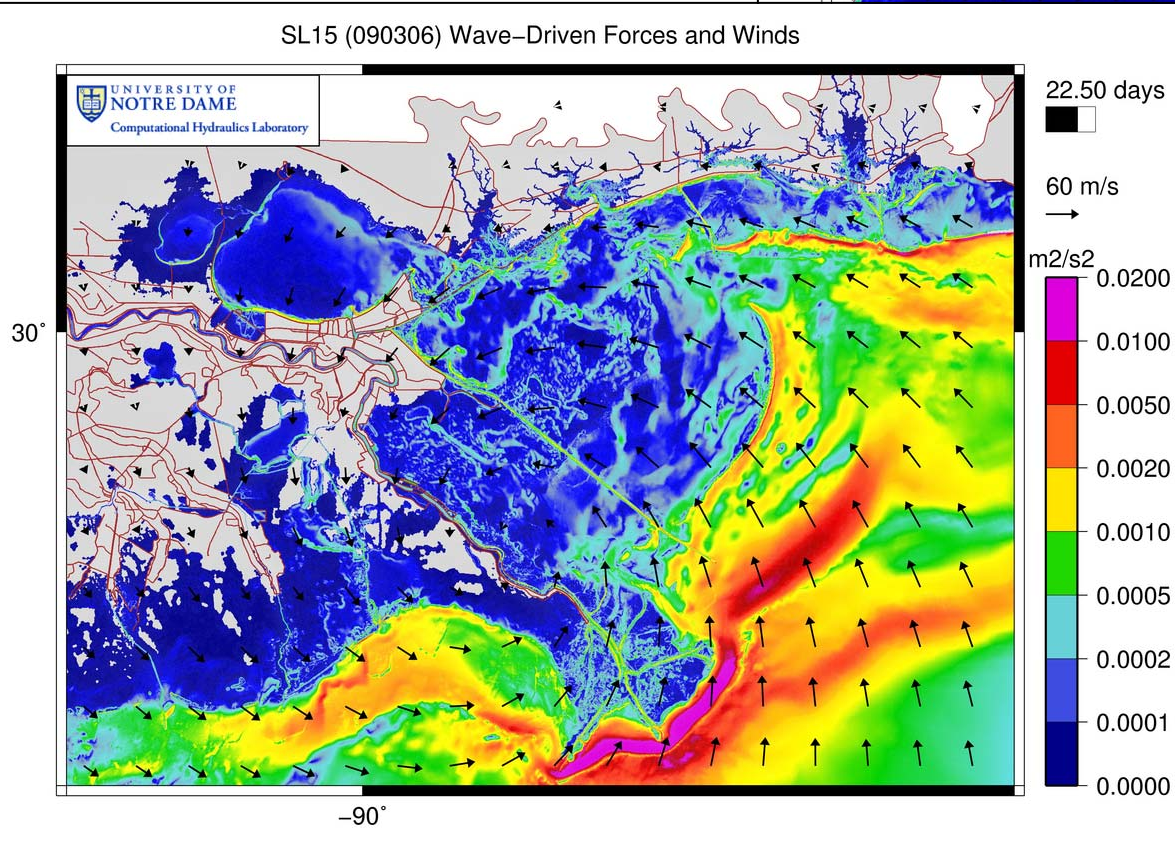
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Hurricane Katrina

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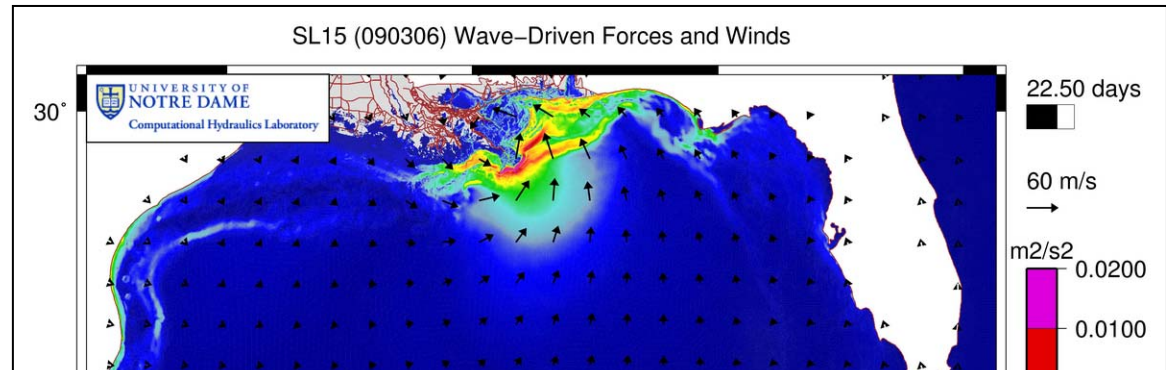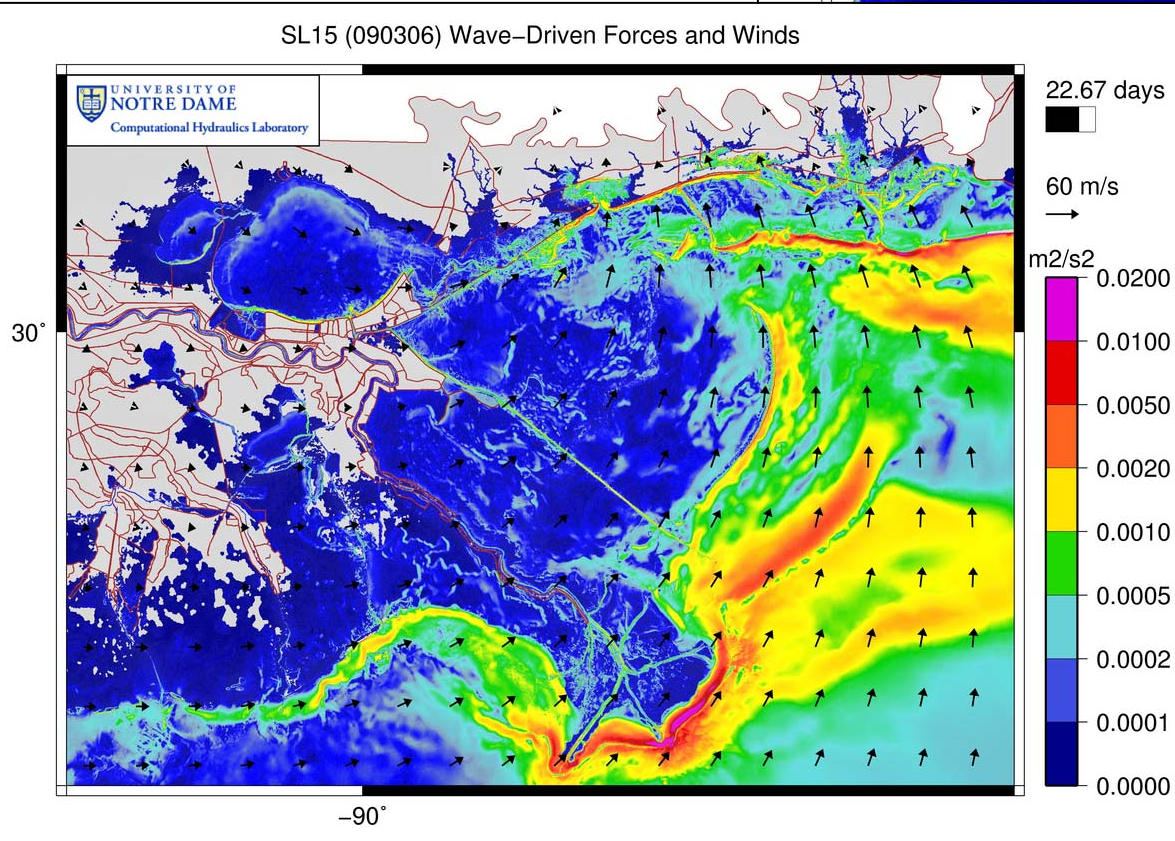
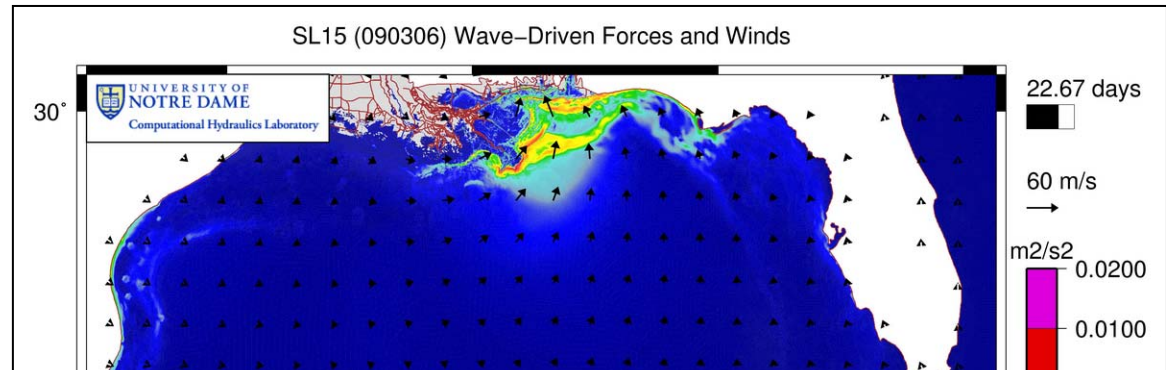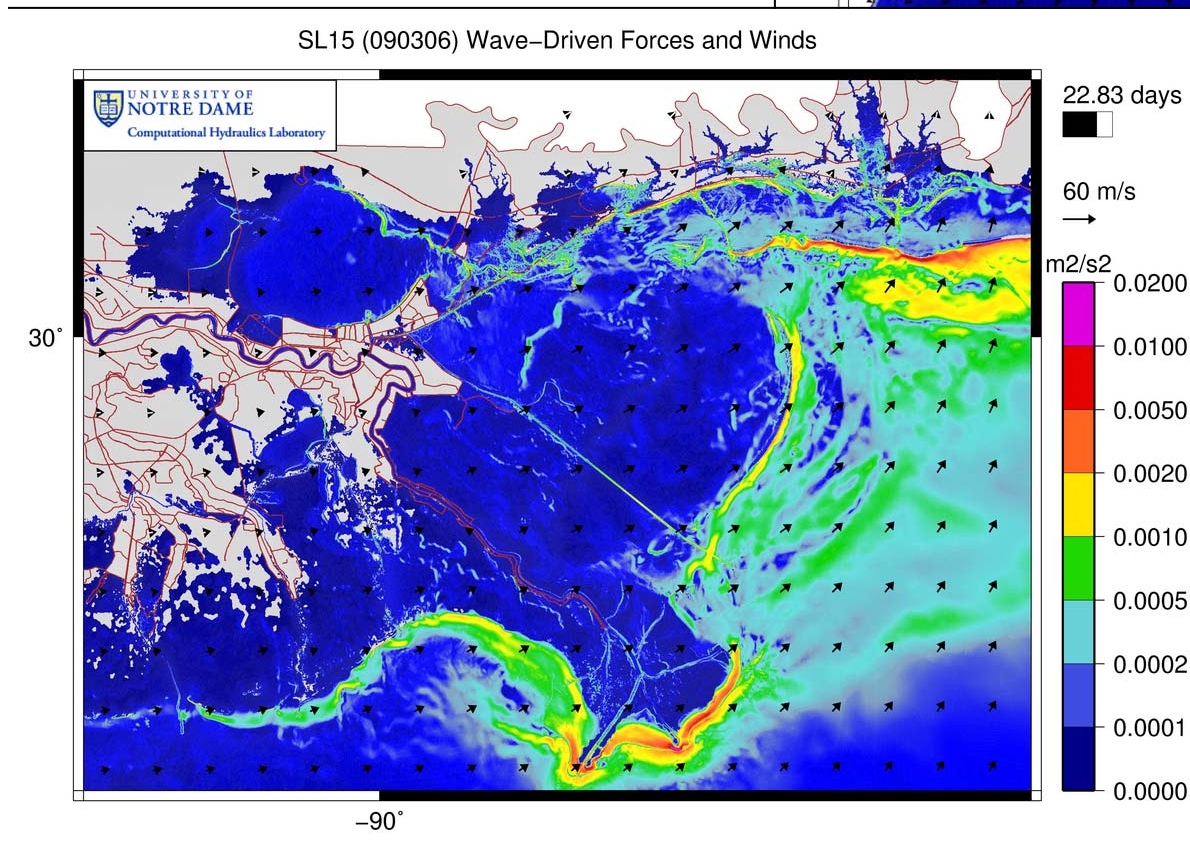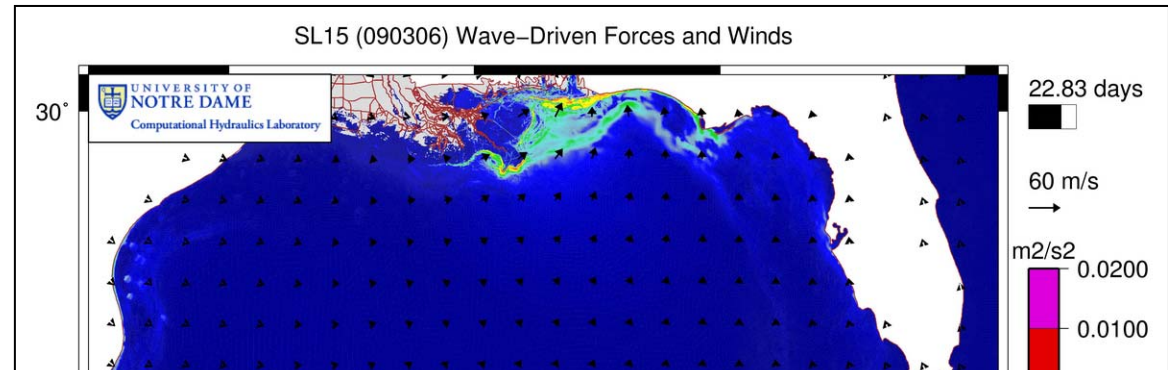# Hurricane Katrina

Wave-Driven Forces

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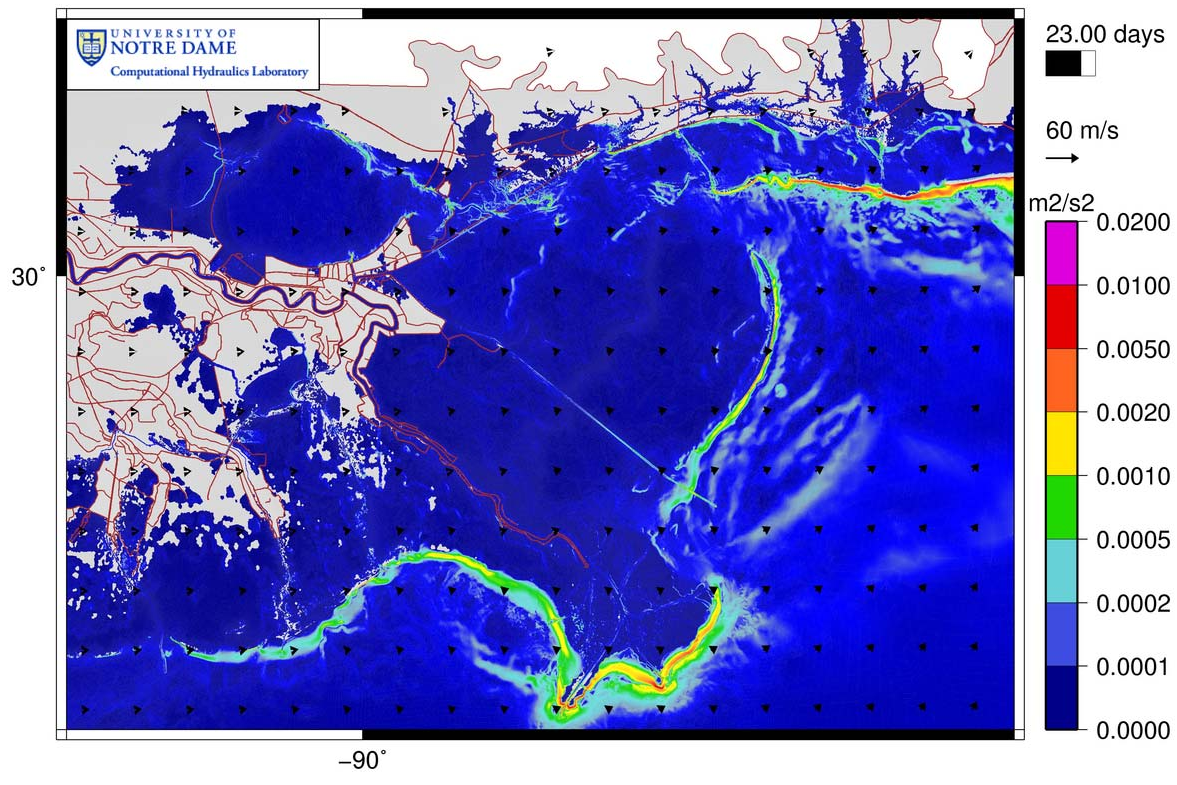
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Hurricane Katrina

Wave Setup

- 2005/08/28/0000Z

Hurricane Katrina

Wave Setup

- 2005/08/28/0400Z
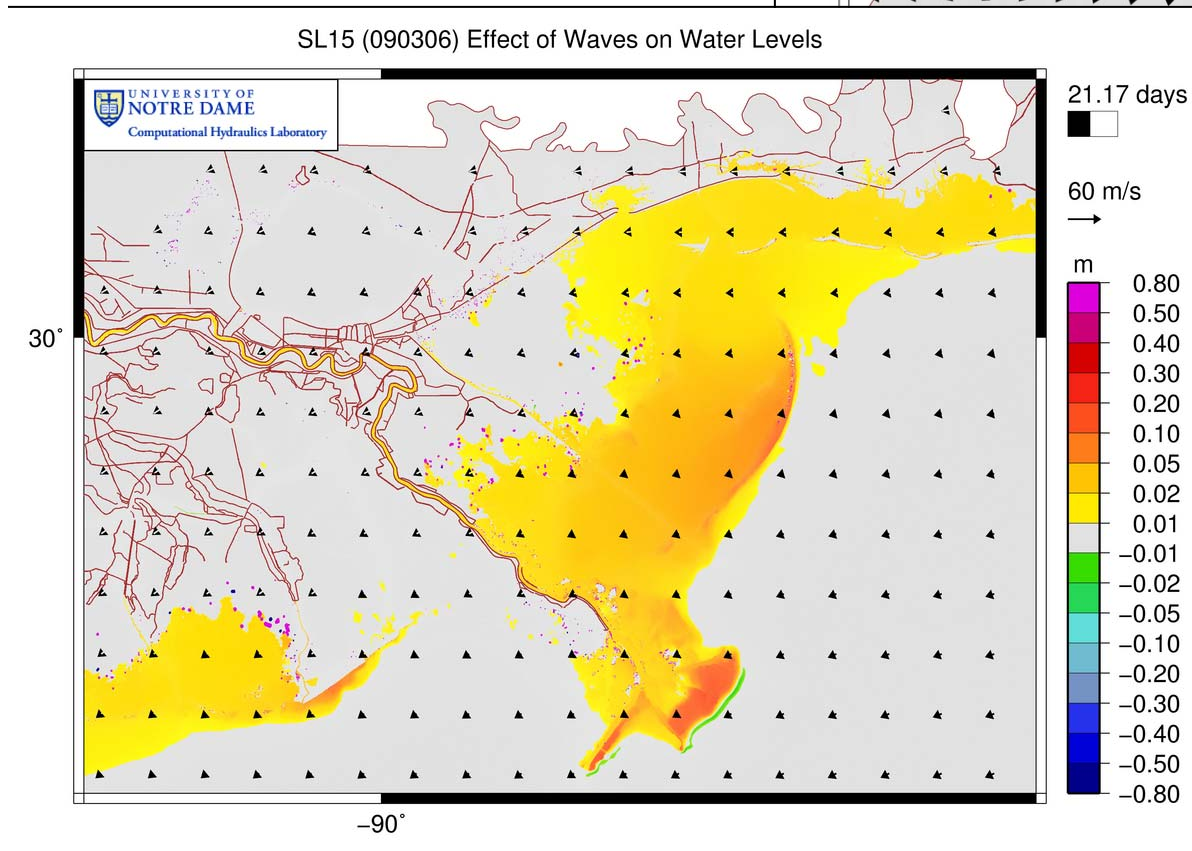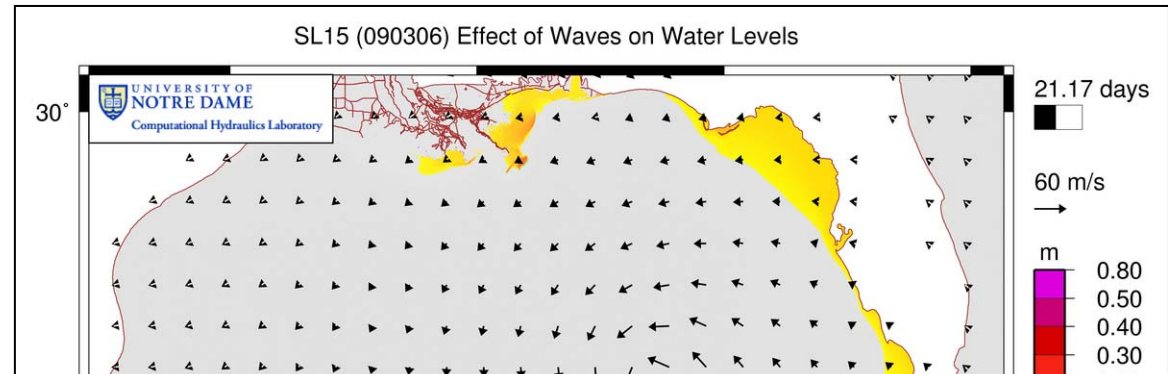
Hurricane Katrina

Wave Setup

- 2005/08/28/0800Z
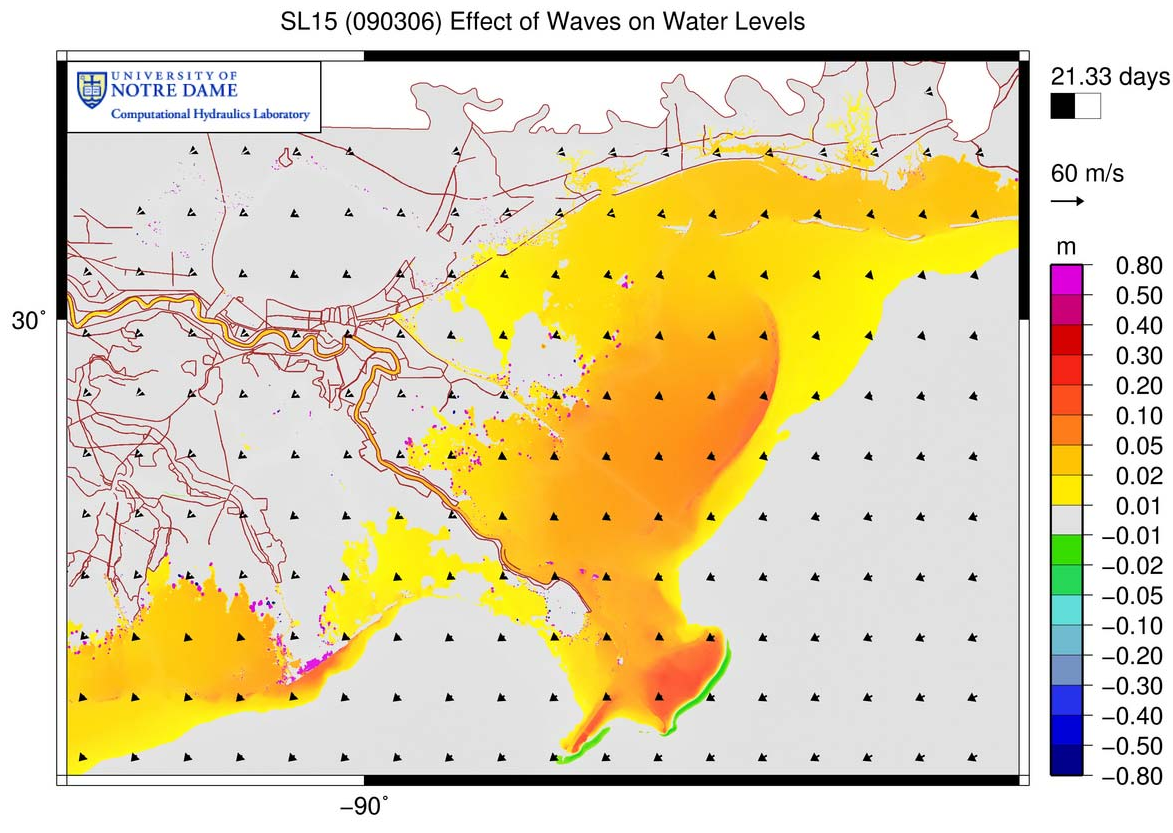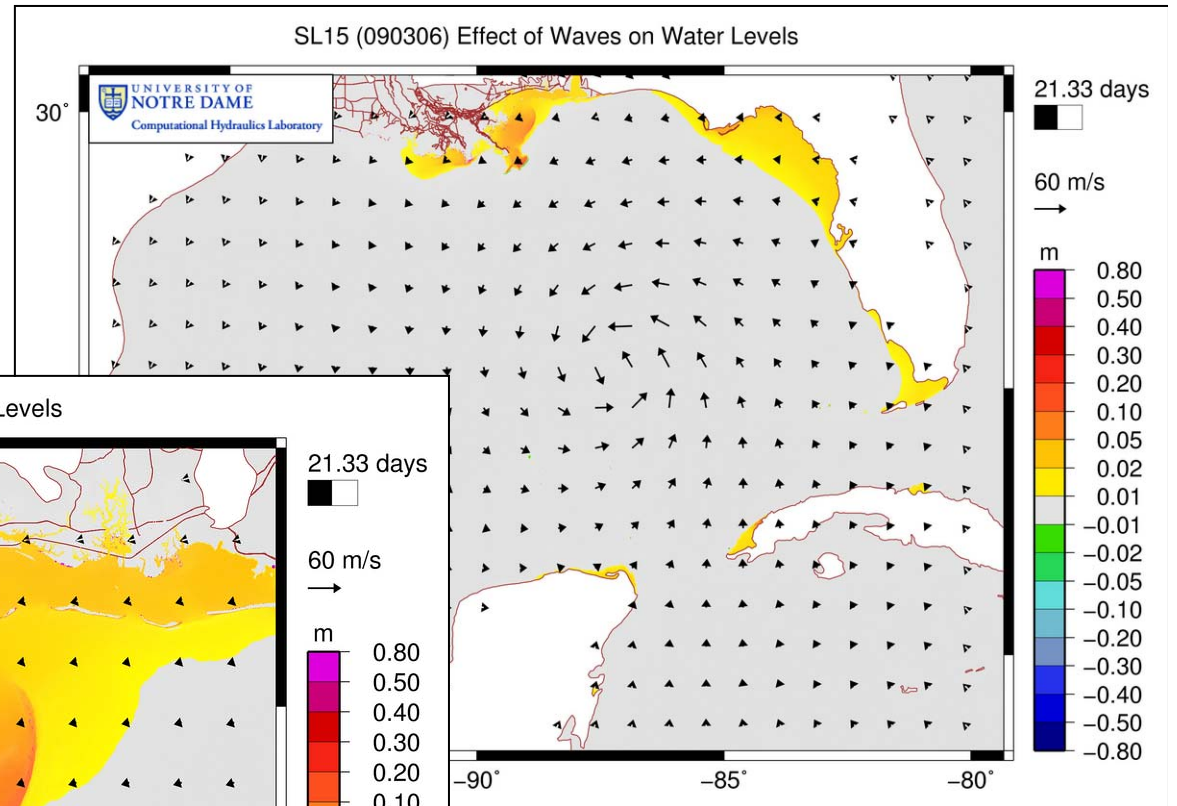
Hurricane Katrina

Wave Setup

- 2005/08/28/1200Z
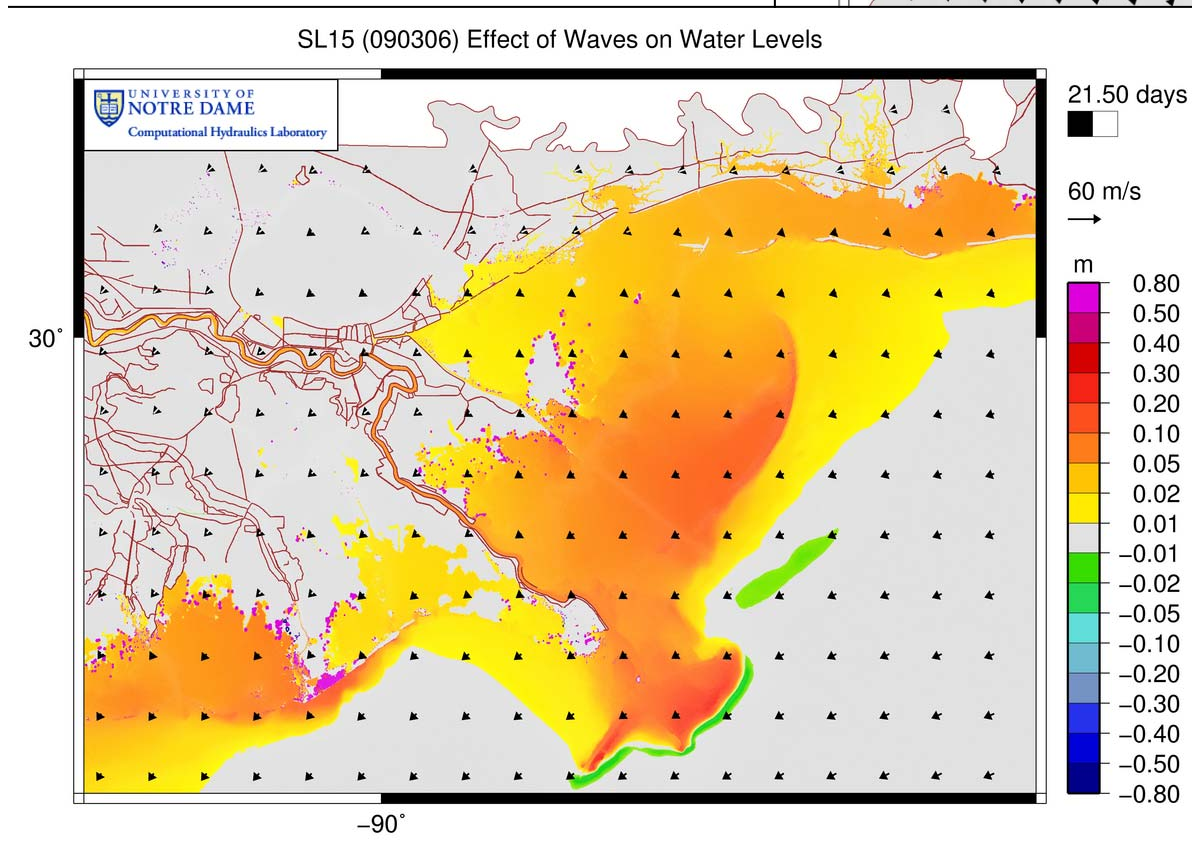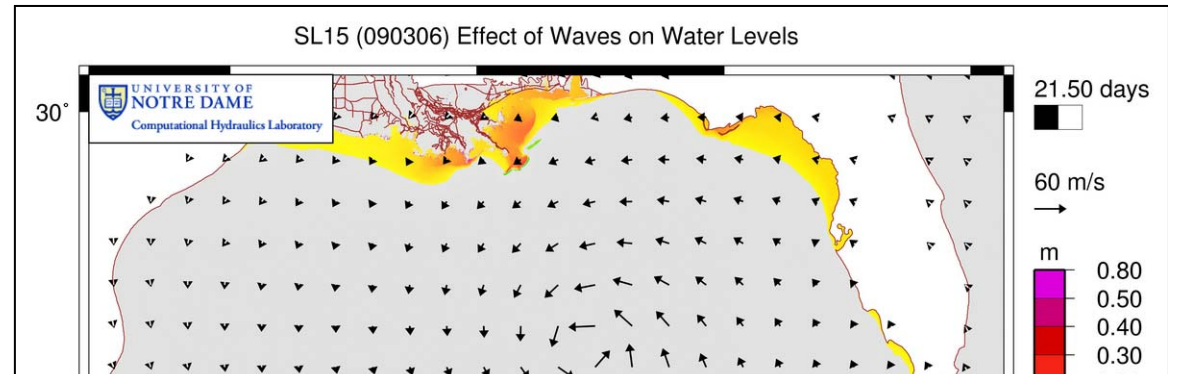
Hurricane Katrina

Wave Setup

- 2005/08/28/1600Z
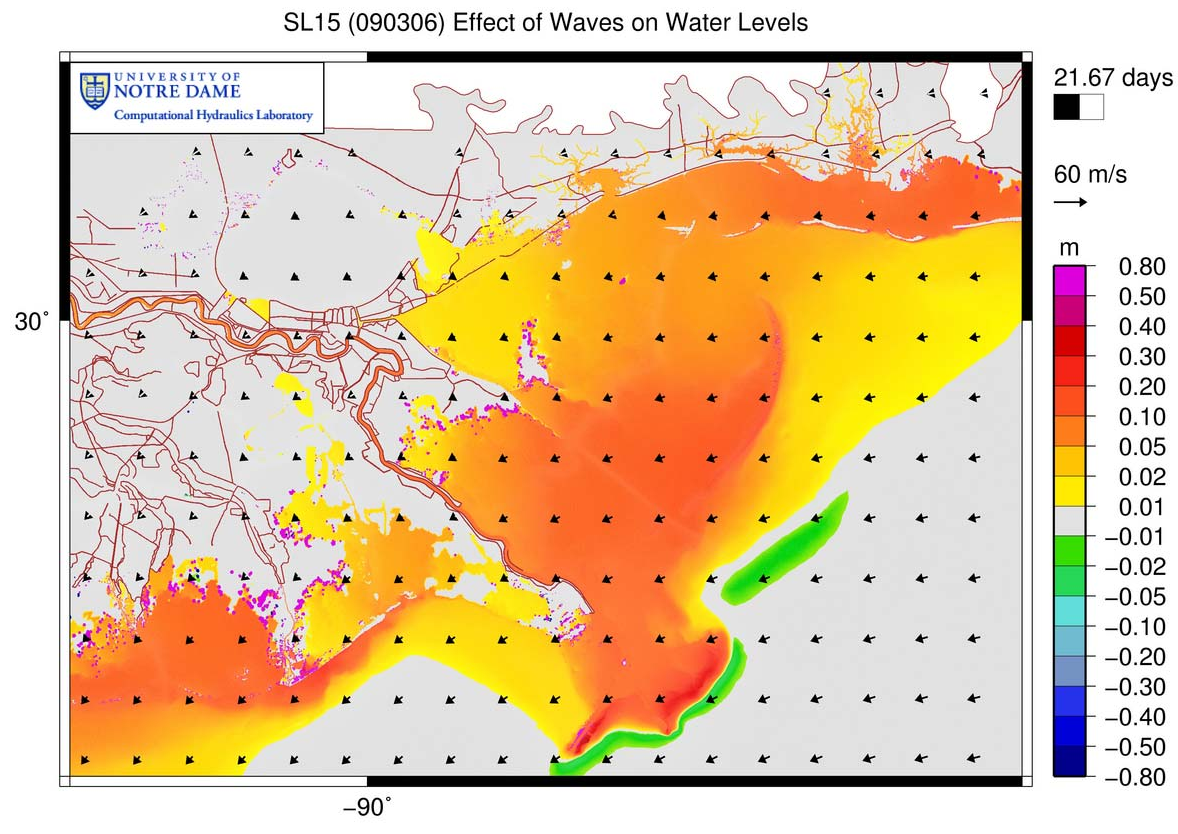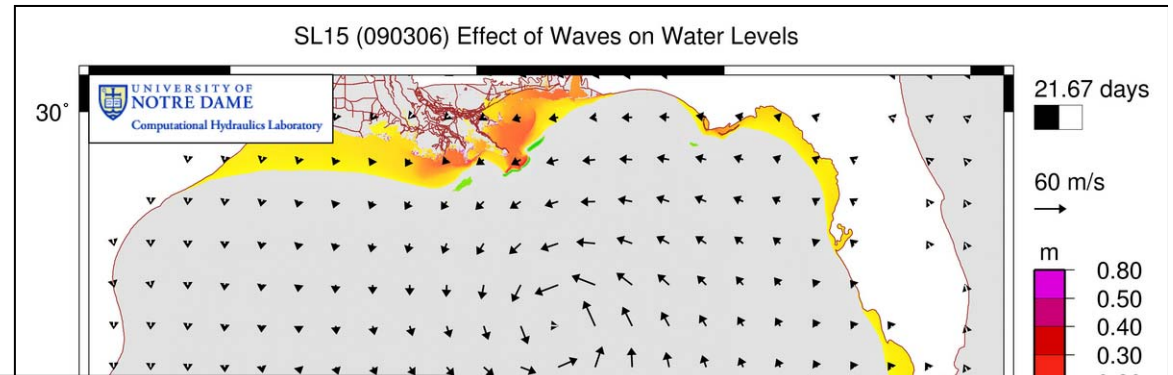
Hurricane Katrina

Wave Setup

- 2005/08/28/2000Z
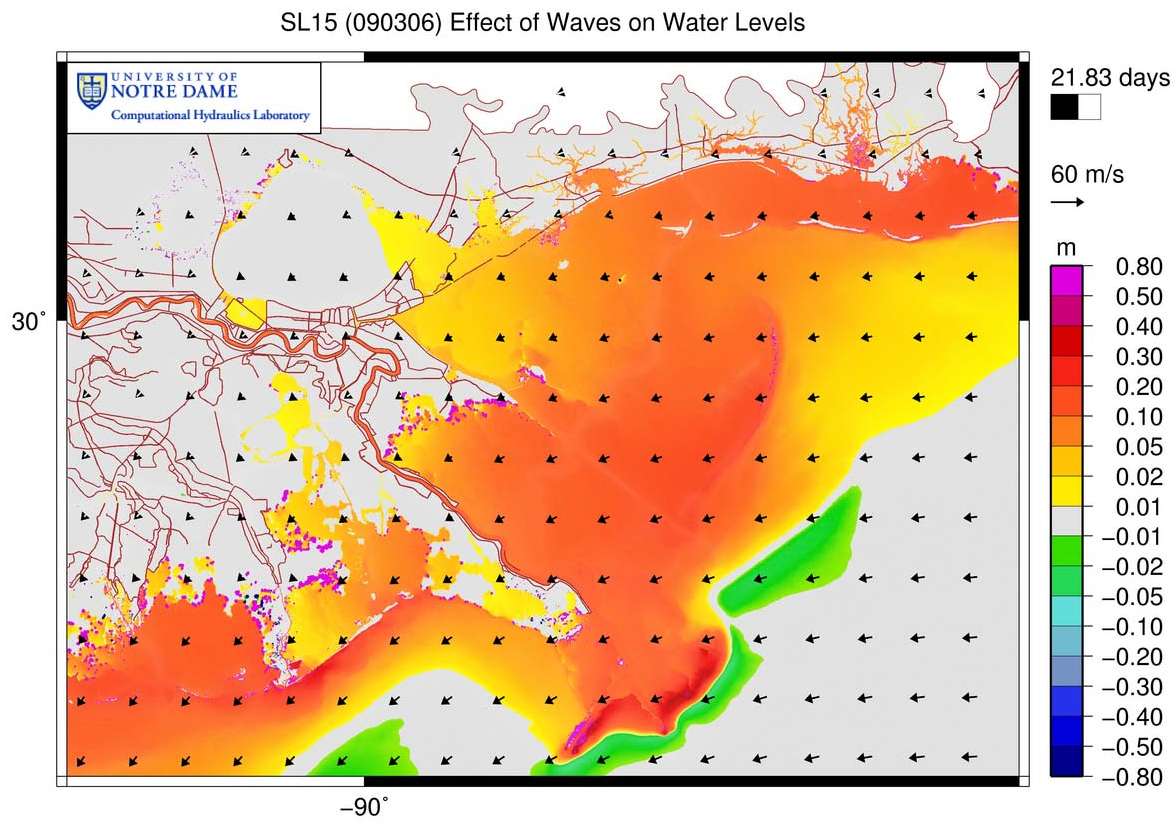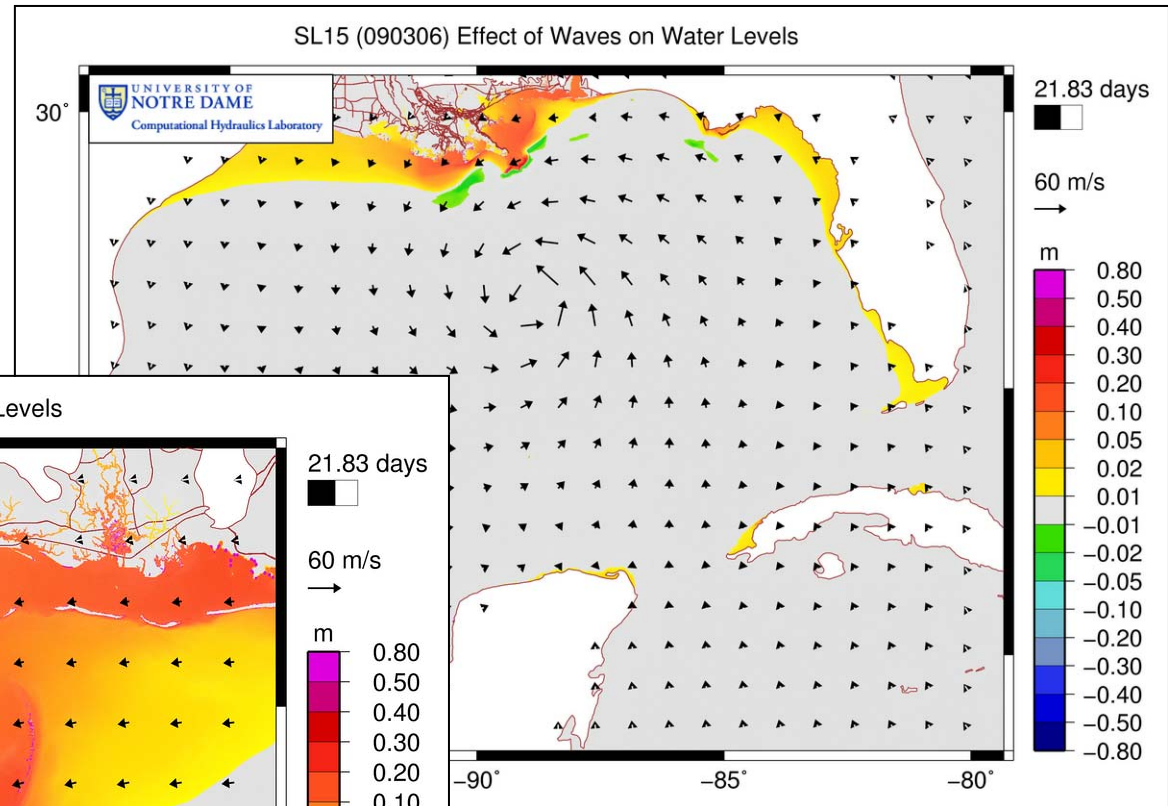
Hurricane Katrina

Wave Setup

- 2005/08/29/0000Z
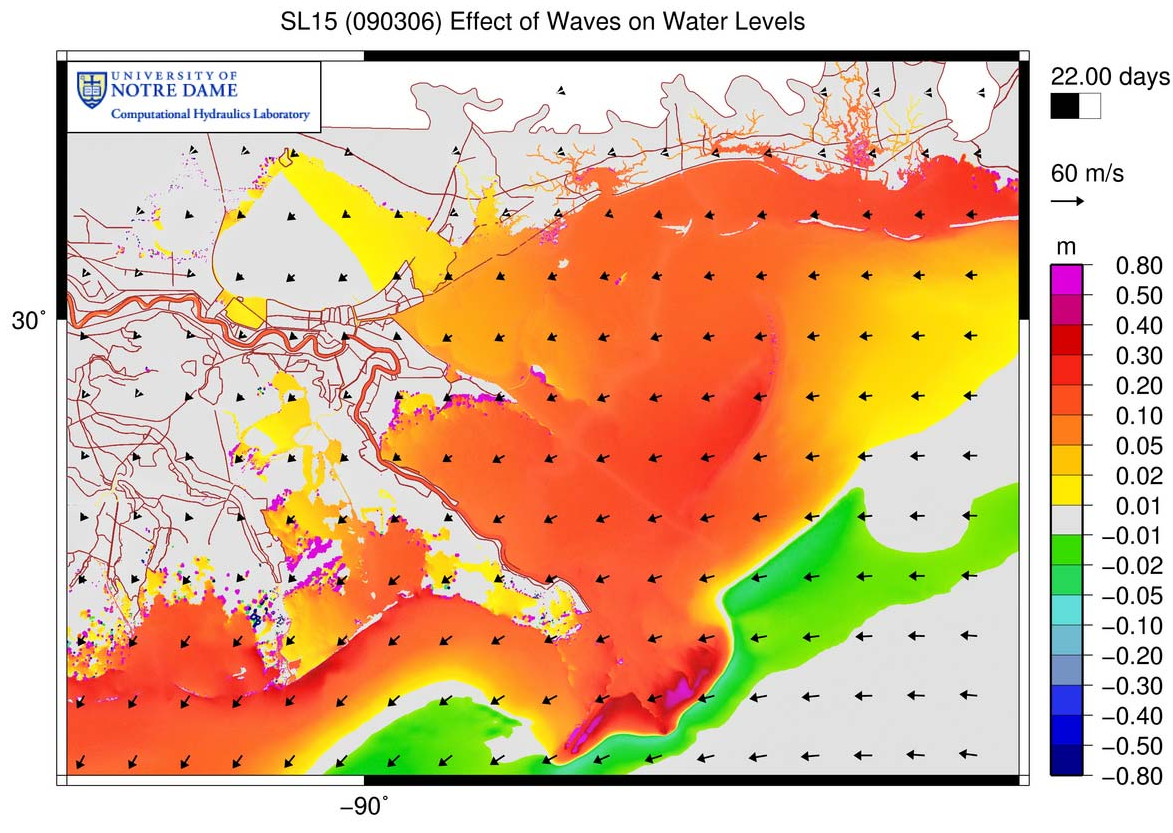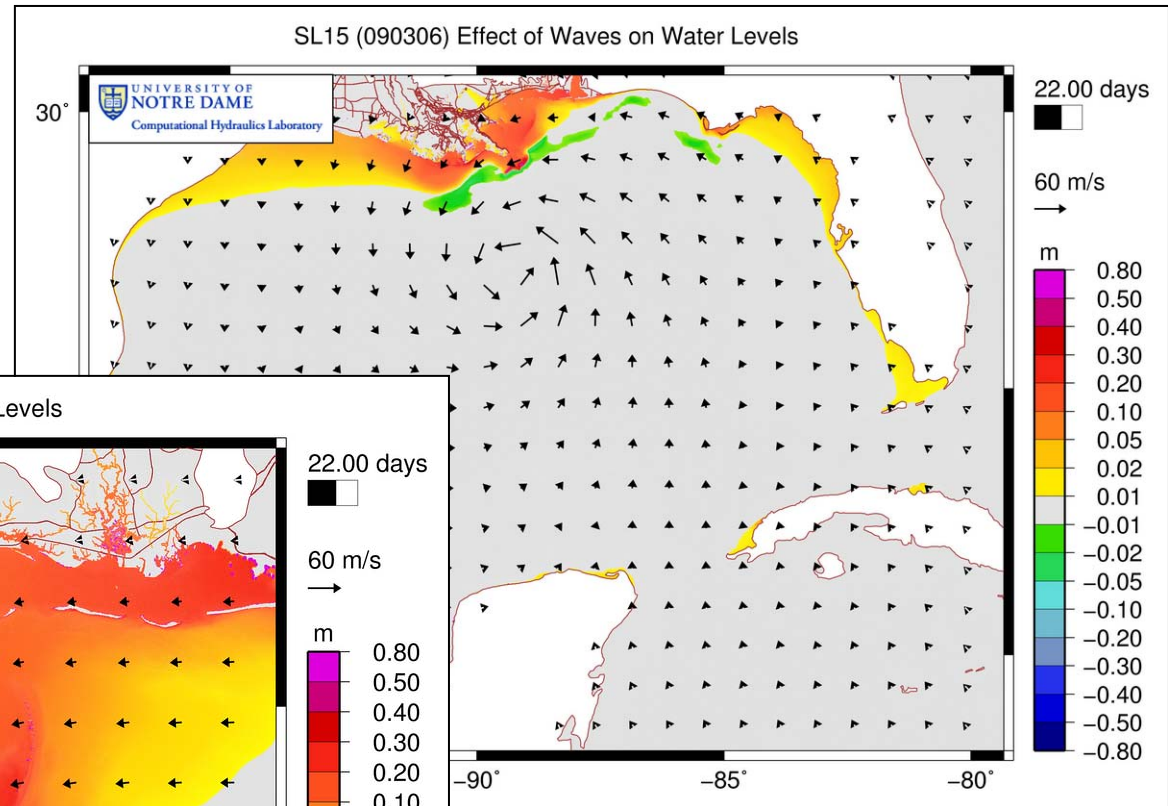
Hurricane Katrina

Wave Setup

- 2005/08/29/0400Z
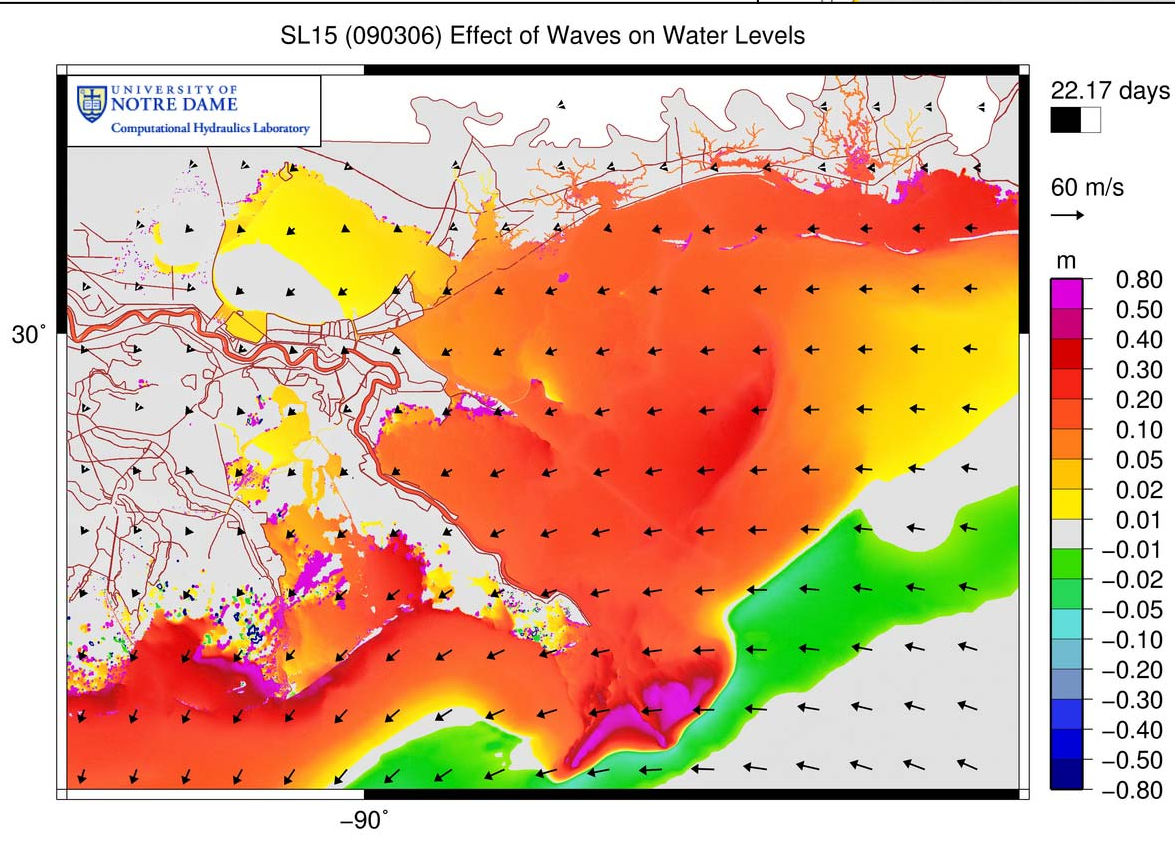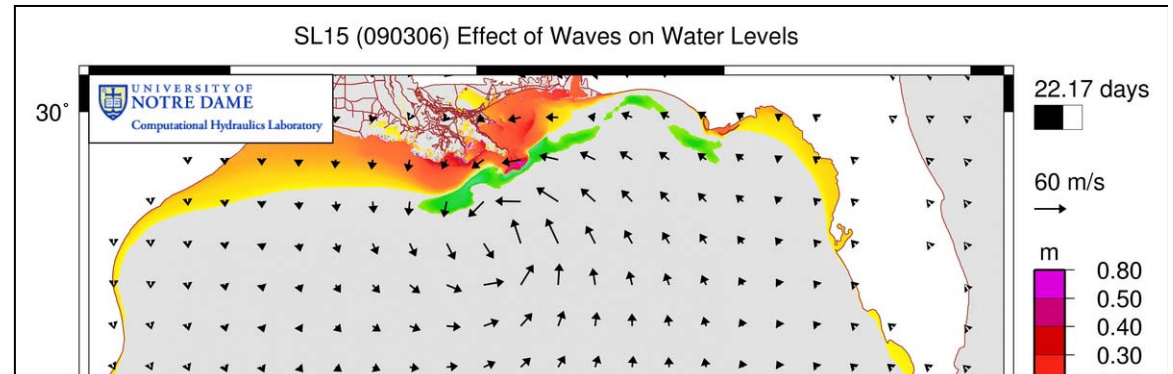
Hurricane Katrina

Wave Setup

- 2005/08/29/0800Z
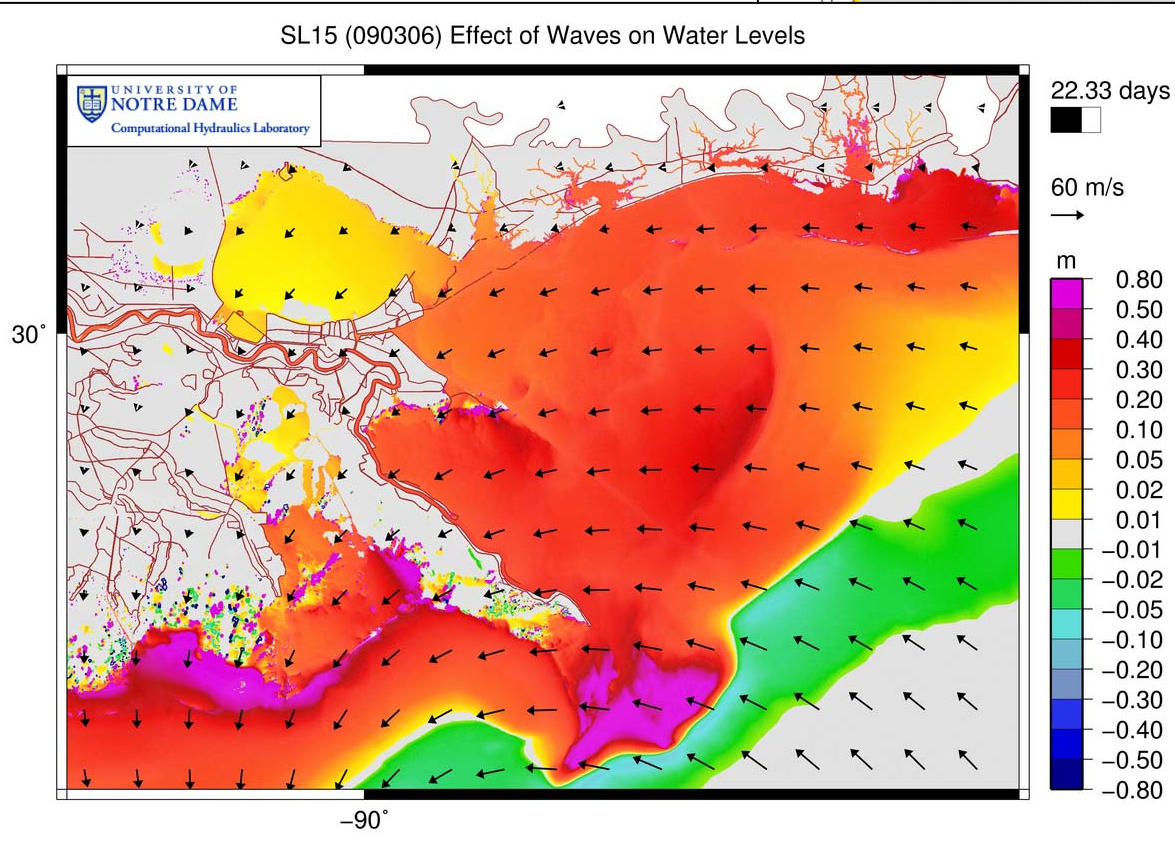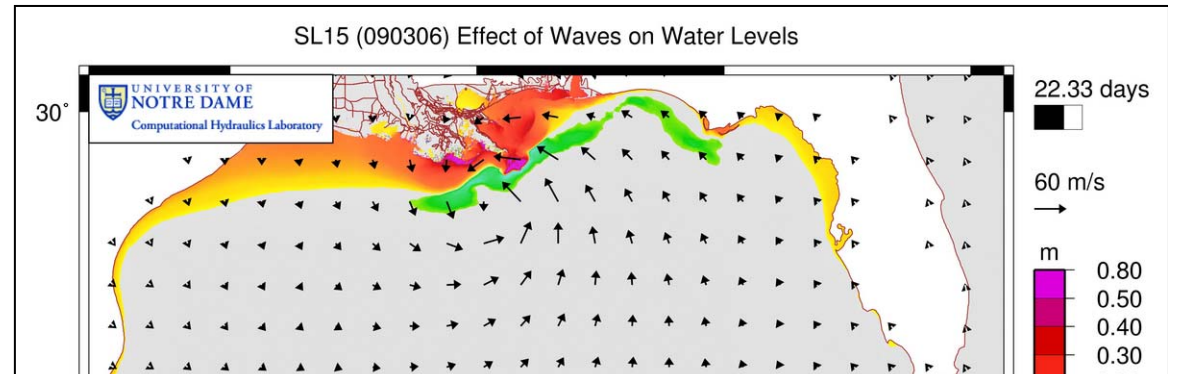
Hurricane Katrina

Wave Setup

- 2005/08/29/1200Z
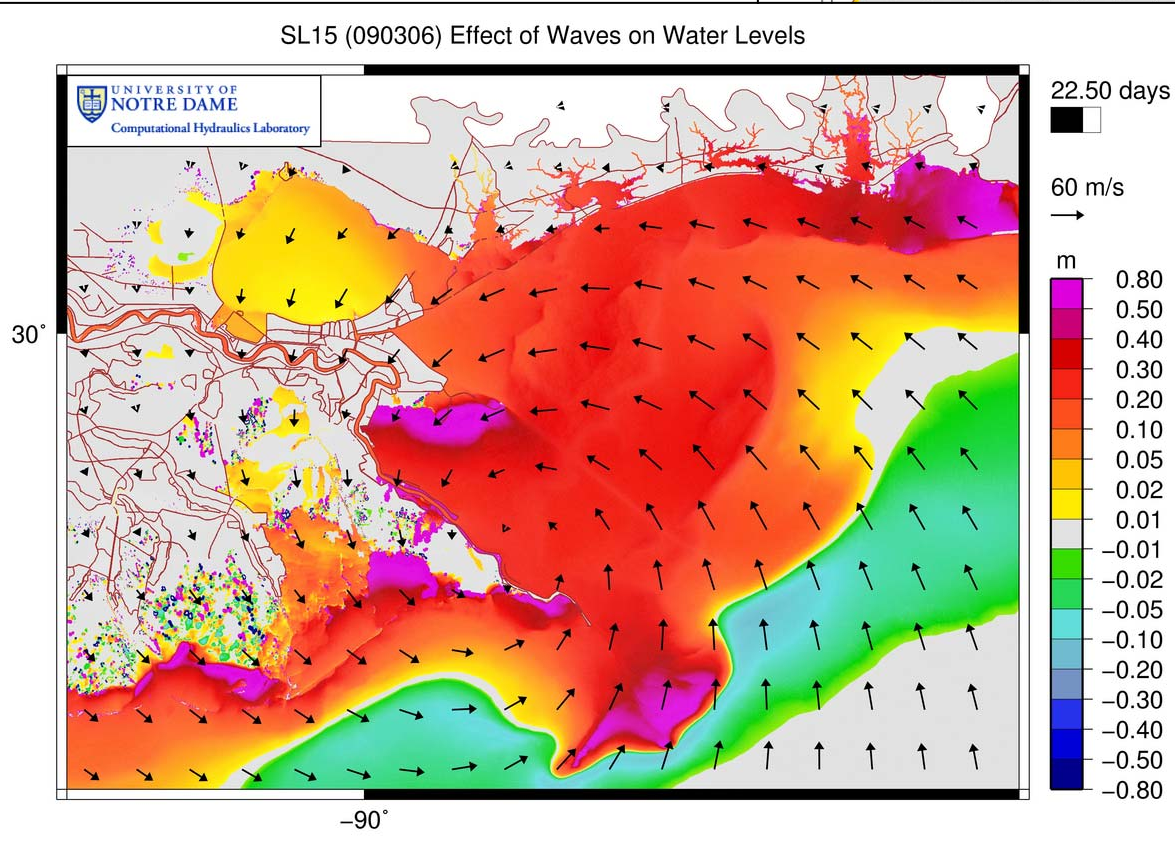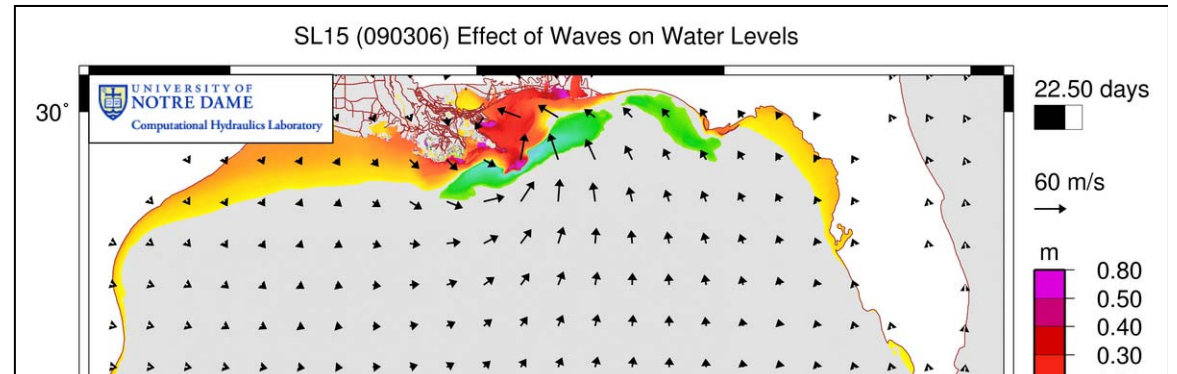
Hurricane Katrina

Wave Setup

- 2005/08/29/1600Z
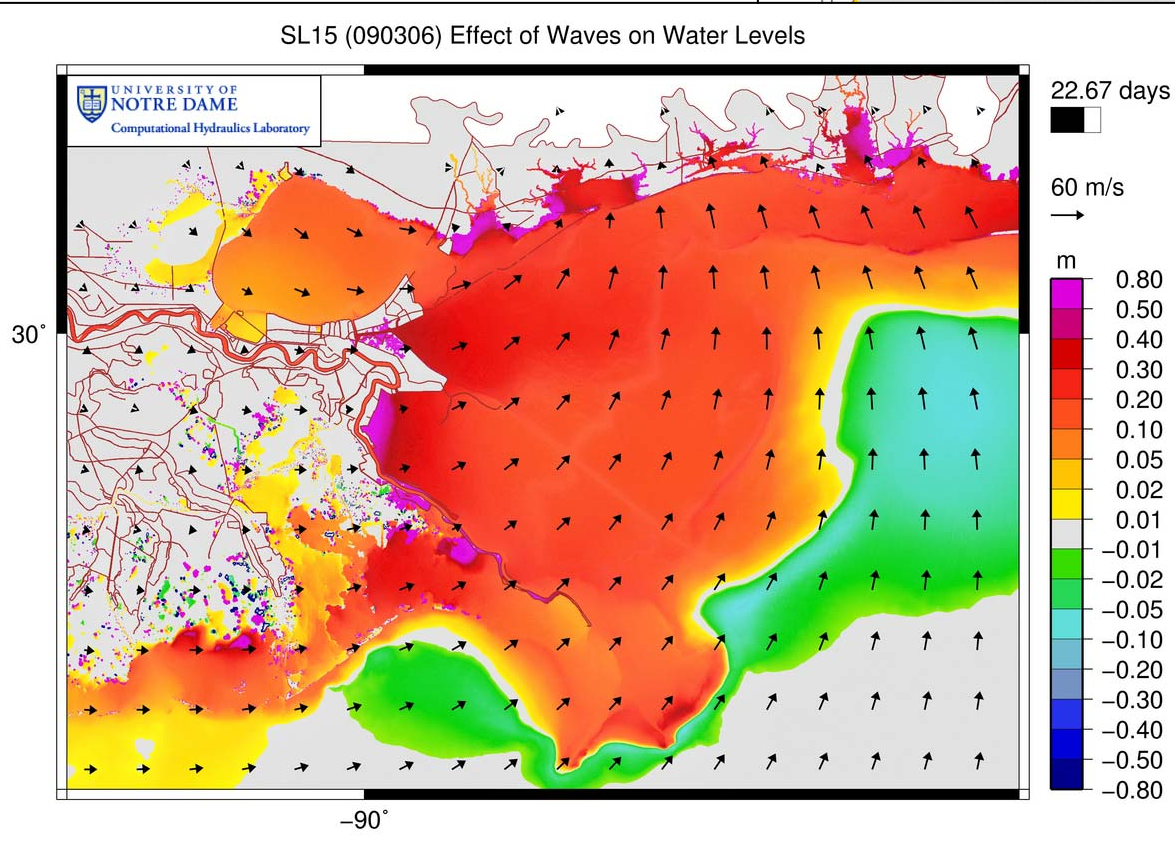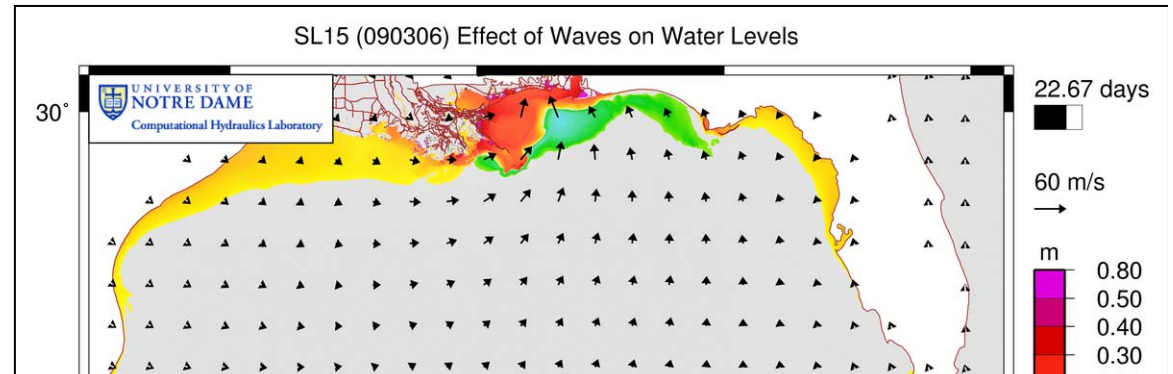
Hurricane Katrina

Wave Setup

- 2005/08/29/2000Z
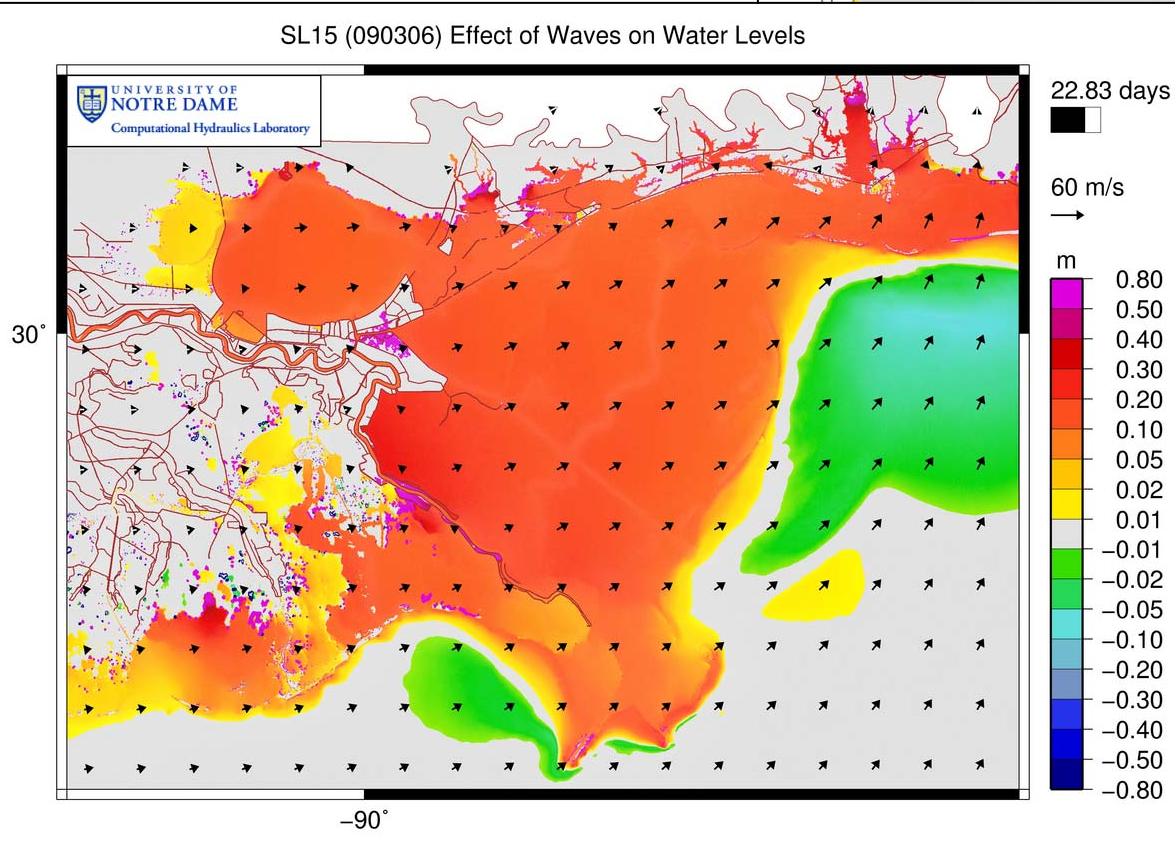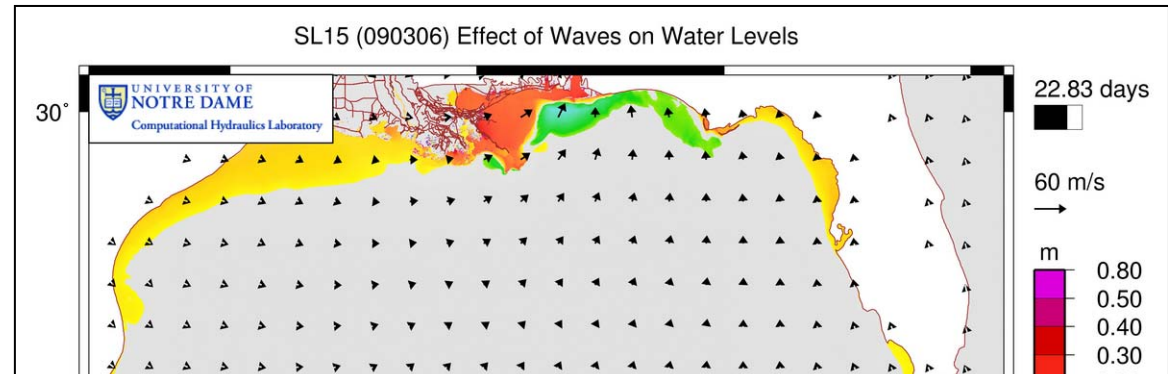
Hurricane Katrina

Wave Setup

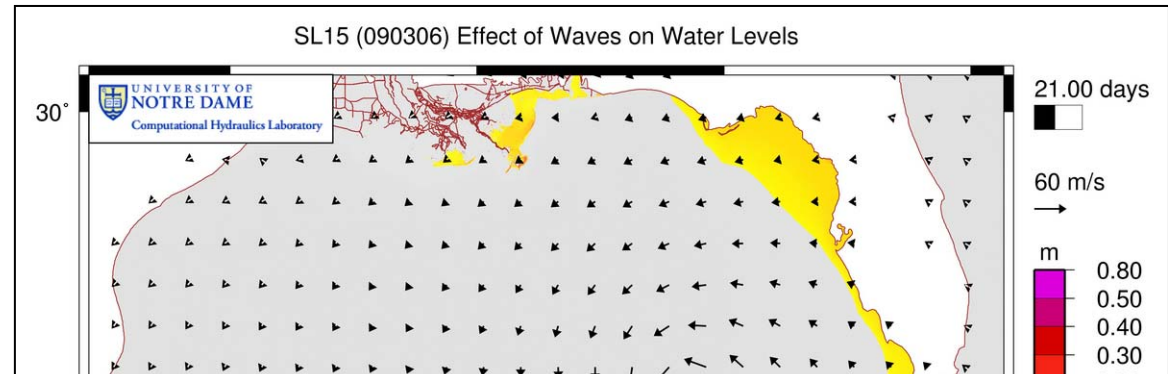- 2005/08/30/0000Z
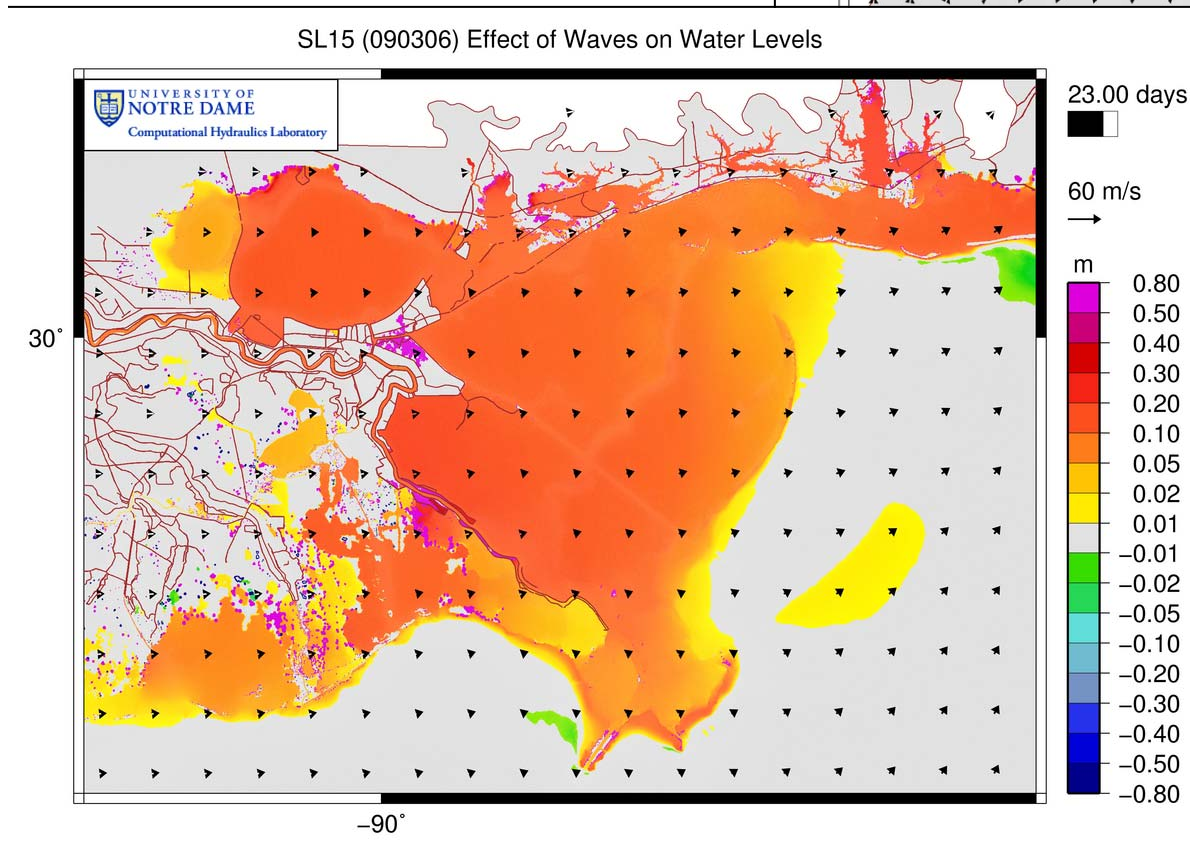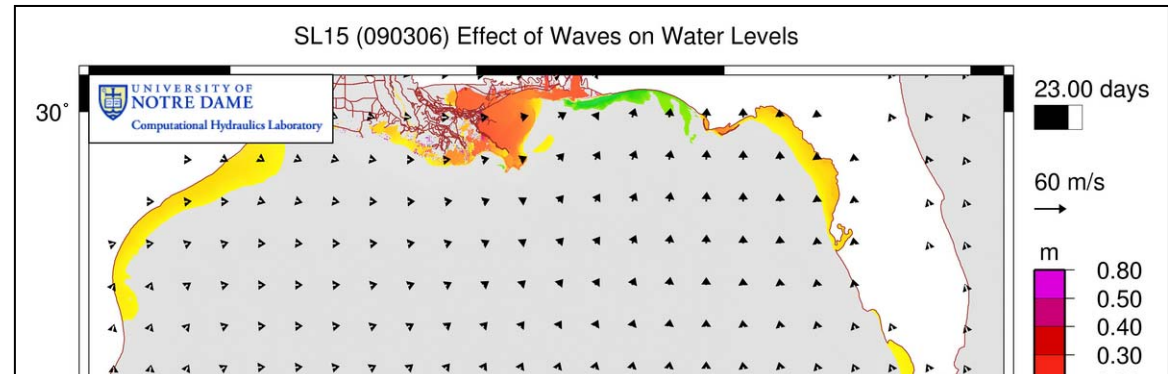
Hurricane Katrina

Preliminary Results

- Synoptic histories in Gulf of Mexico and in SE Louisiana:
  - Wave heights
  - Wave-driven forces
  - Wave setup
- **Comparison to WAM-STWAVE setup**
- Comparison to measured data:
  - NDBC buoy data
  - USACE and FEMA/URS high-water marks
- Computational performance

Hurricane Katrina

Maximum Wave Setup

- WAM-STWAVE

Hurricane Katrina

Maximum Wave Setup

- UnSWAN
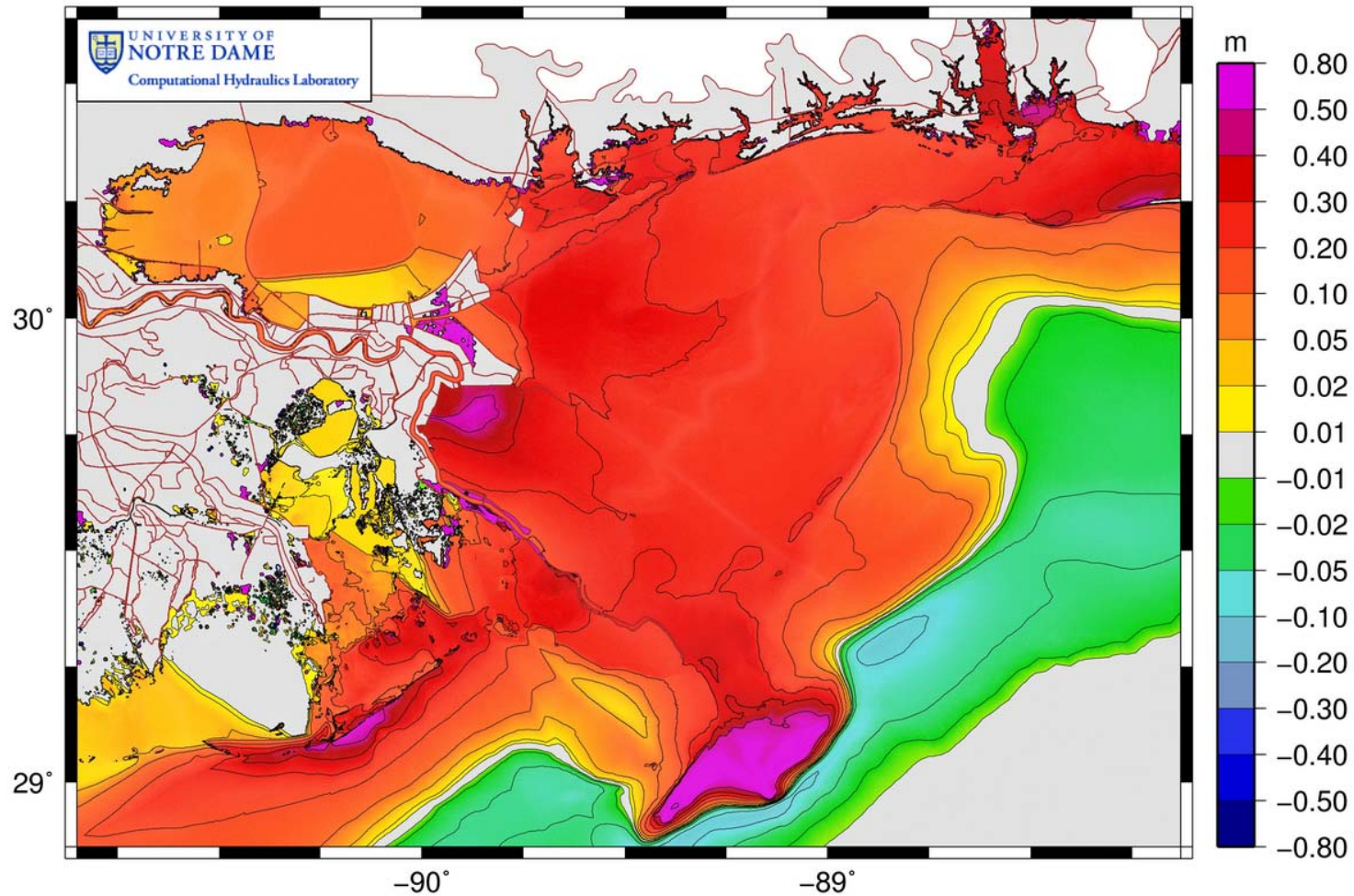
Hurricane Katrina

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Hurricane Katrina

SIGNIFICANT WAVE HEIGHTS (HS) AT NDBC BUOYS

BUOY	SWAN		WAM	
	RMS	L_∞	RMS	L_∞
42001	1.07	3.78	0.71	2.30
42002	1.18	3.88	0.63	2.50
42003	0.65	2.24	0.60	1.82
42007	0.34	1.41	0.34	1.14
42019	0.59	1.84	0.33	1.23
42020	0.76	2.83	0.48	2.12
42035	0.32	1.12	0.46	1.42
42036	0.39	0.98	0.54	1.52
42038	0.57	2.43	0.59	1.38
42039	0.56	1.59	0.71	2.22
42040	0.86	3.28	0.61	2.95
42055	0.44	1.33	0.30	0.82

Hurricane Katrina

MEAN WAVE DIRECTIONS (DIR) AT NDBC BUOYS

BUOY	SWAN RMS	SWAN L_∞	WAM RMS	WAM L_∞
42001	85.07	179.85	92.90	179.83
42002	110.77	178.81	119.20	173.40
42003	99.87	179.40	90.06	174.93
42007	25.14	135.99	30.75	106.00
42019	53.69	174.57	56.59	176.40
42020	41.81	144.56	41.90	144.50
42035	51.31	154.29	56.90	177.90
42036	37.39	104.49	48.05	176.00
42038	–	–	–	–
42039	25.13	63.71	29.97	95.80
42040	38.14	176.37	44.81	172.80
42055	57.37	179.51	49.24	175.30

Hurricane Katrina

PEAK WAVE PERIODS (TPS) AT NDBC BUOYS
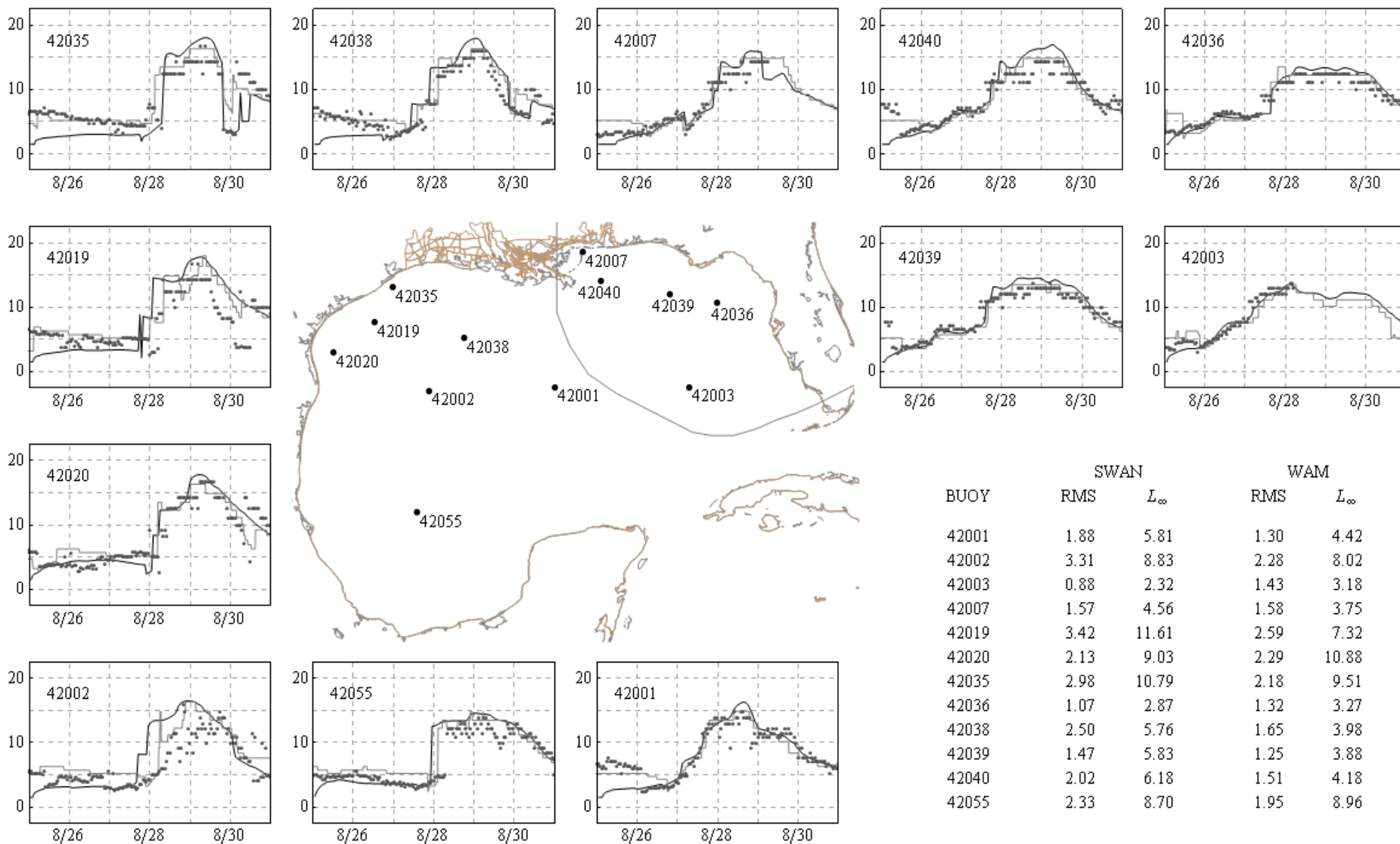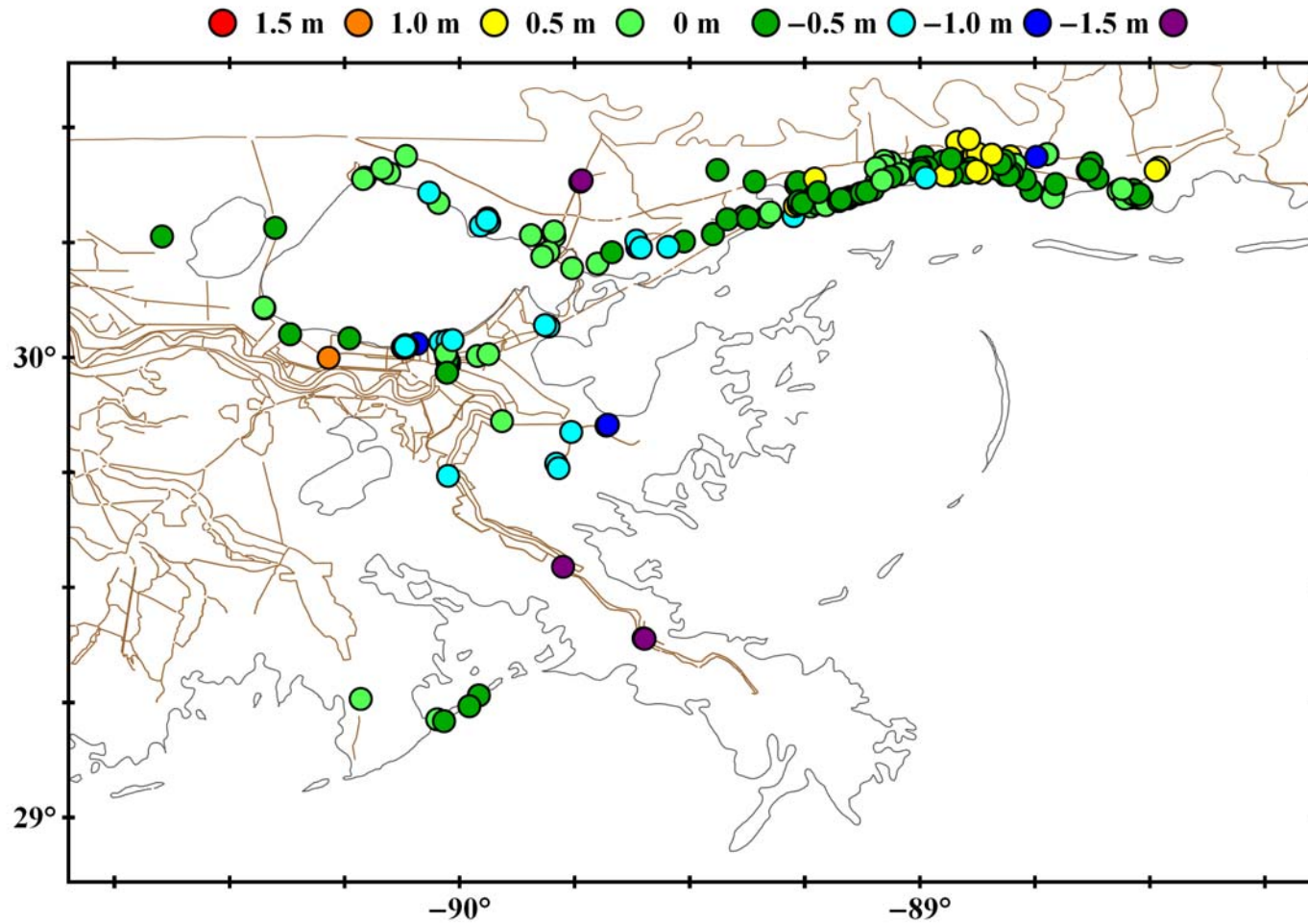
BUOY	SWAN		WAM	
	RMS	L_∞	RMS	L_∞
42001	1.88	5.81	1.30	4.42
42002	3.31	8.83	2.28	8.02
42003	0.88	2.32	1.43	3.18
42007	1.57	4.56	1.58	3.75
42019	3.42	11.61	2.59	7.32
42020	2.13	9.03	2.29	10.88
42035	2.98	10.79	2.18	9.51
42036	1.07	2.87	1.32	3.27
42038	2.50	5.76	1.65	3.98
42039	1.47	5.83	1.25	3.88
42040	2.02	6.18	1.51	4.18
42055	2.33	8.70	1.95	8.96

Hurricane Katrina

USACE High-Water Marks

Hurricane Katrina

USACE High-Water Marks

Hurricane Katrina

FEMA/URS High-Water Marks
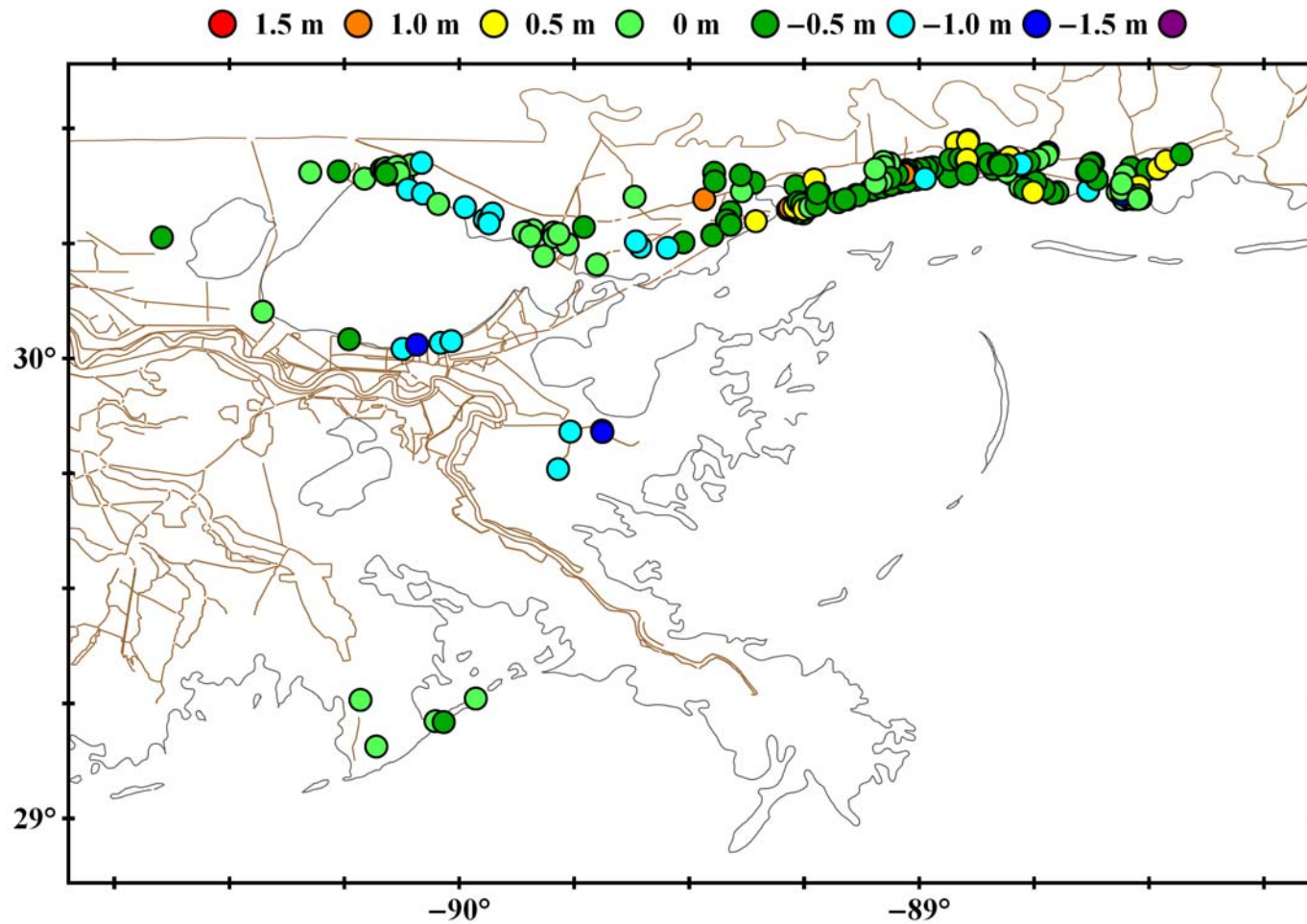
Hurricane Katrina

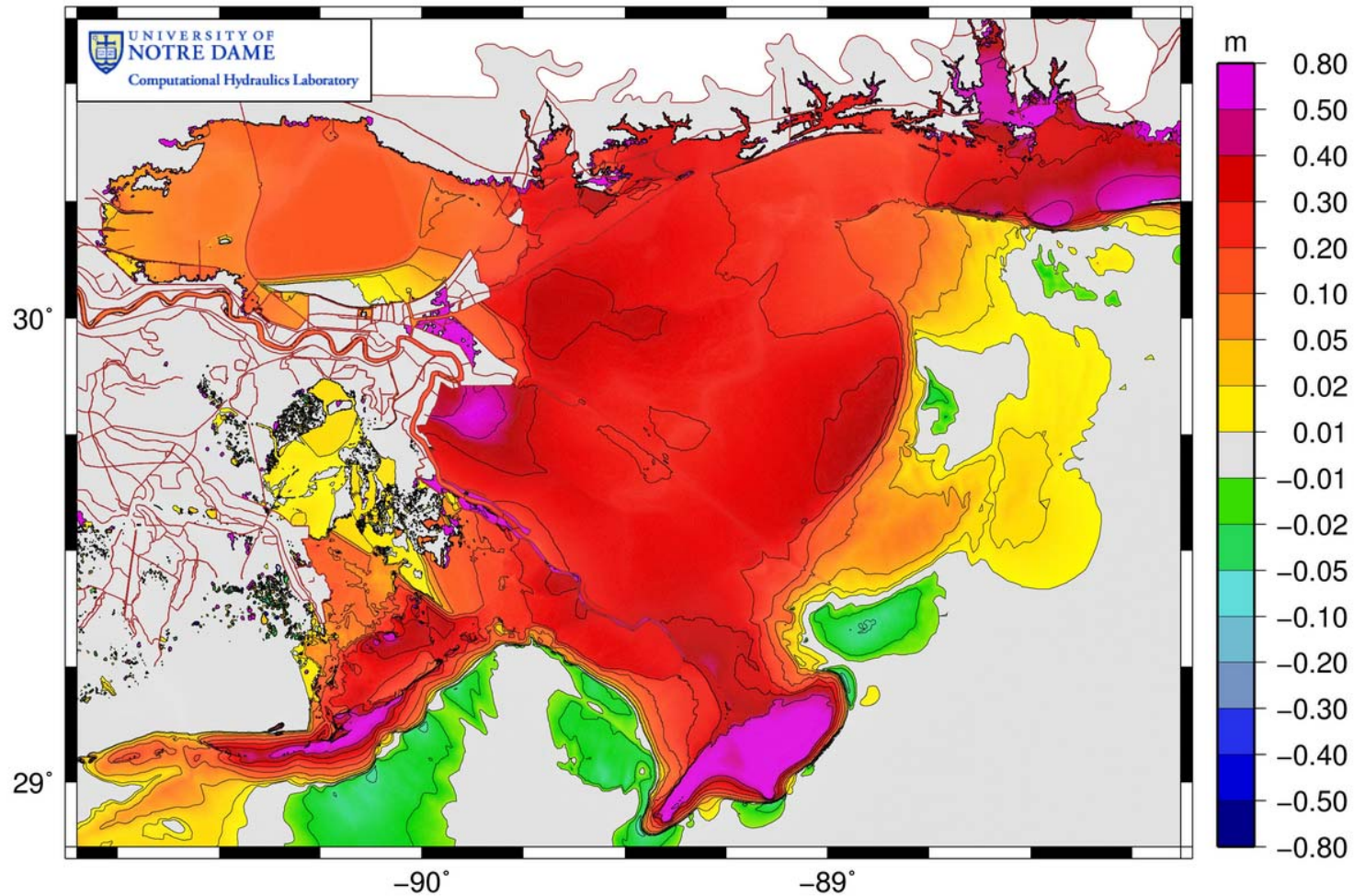**FEMA/URS High-Water Marks**
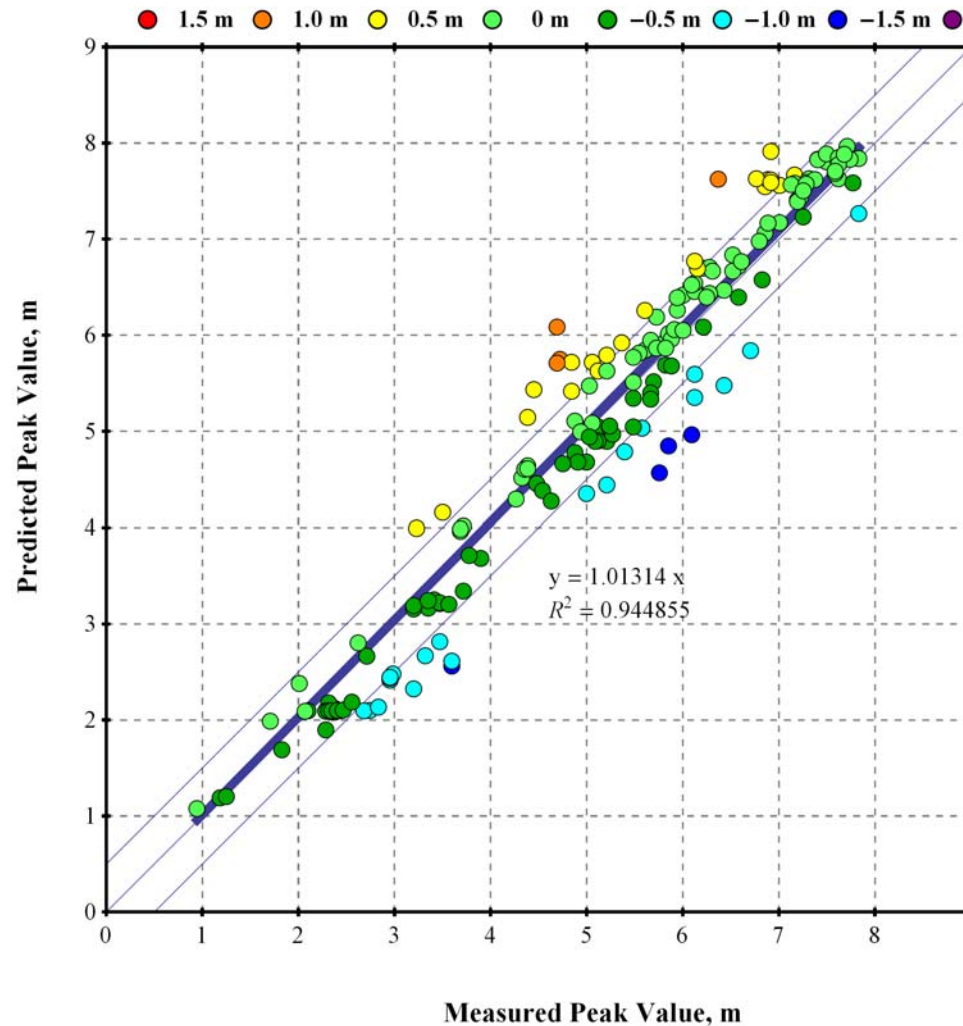
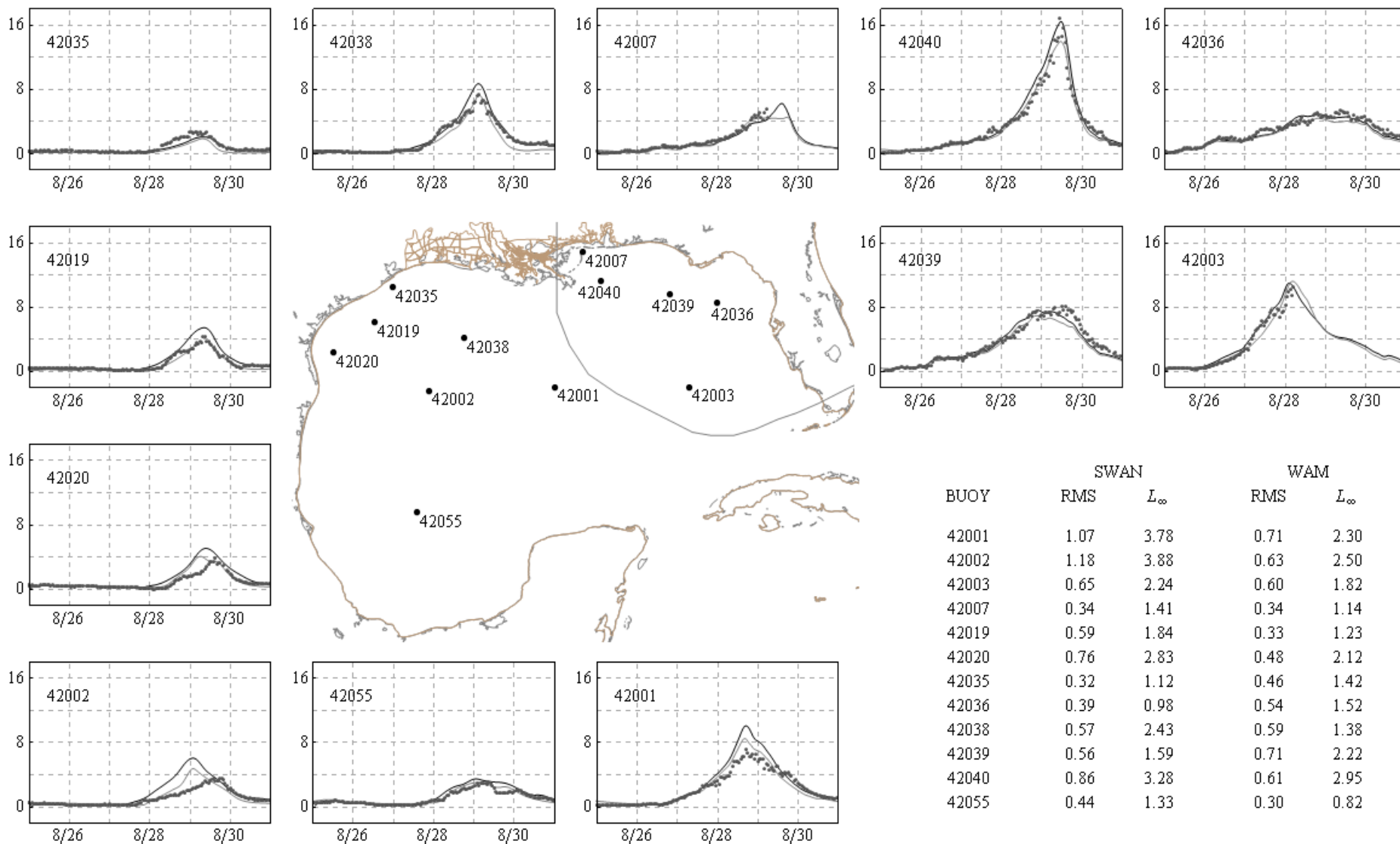# Hurricane Katrina

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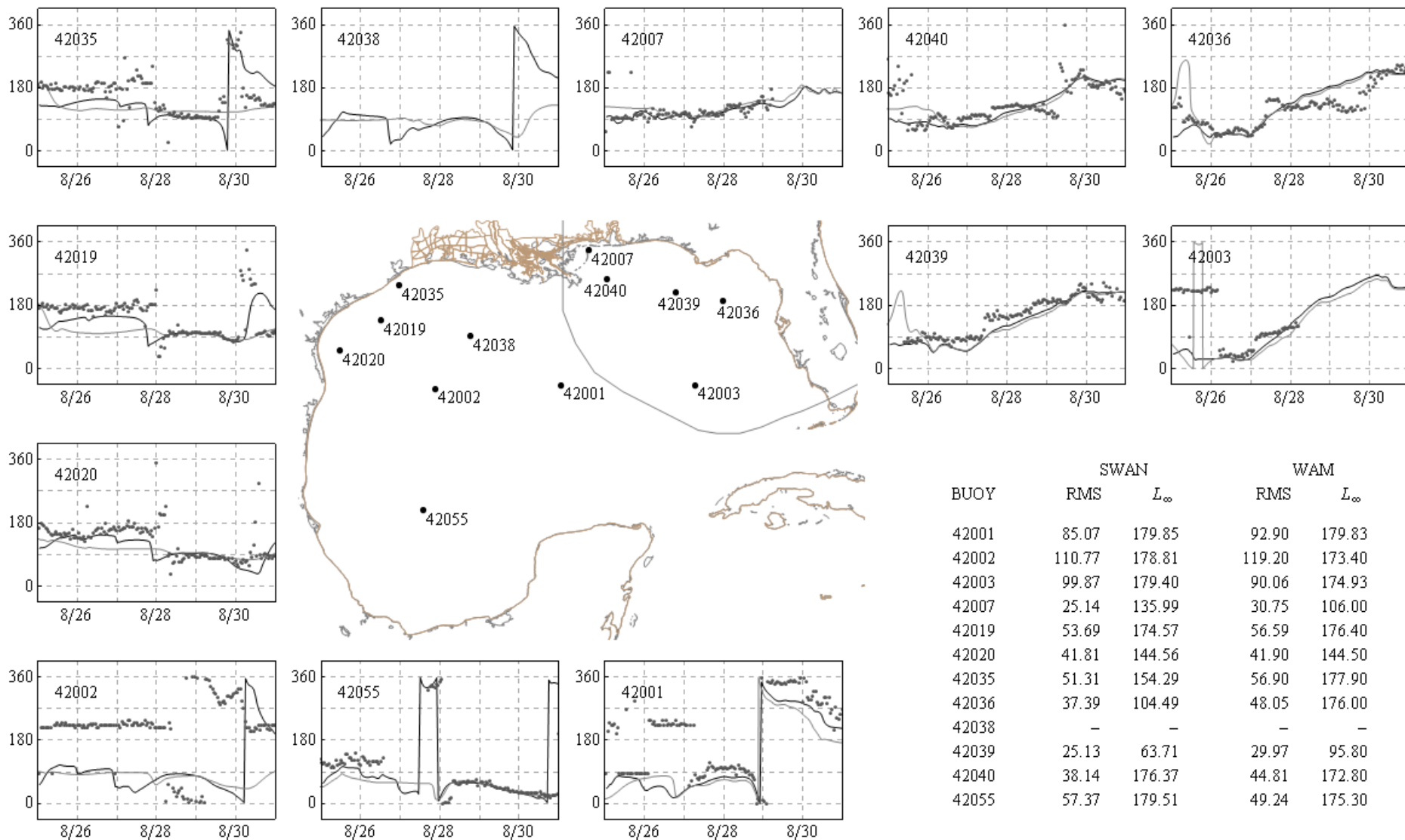 - USACE and FEMA/URS high-water marks
- **Computational performance**

Hurricane Katrina

Computational Performance

- Timings on TACC Ranger

Conclusions

Implementation:

- ADCIRC and SWAN have been coupled so that they:
  - Run on the same processor
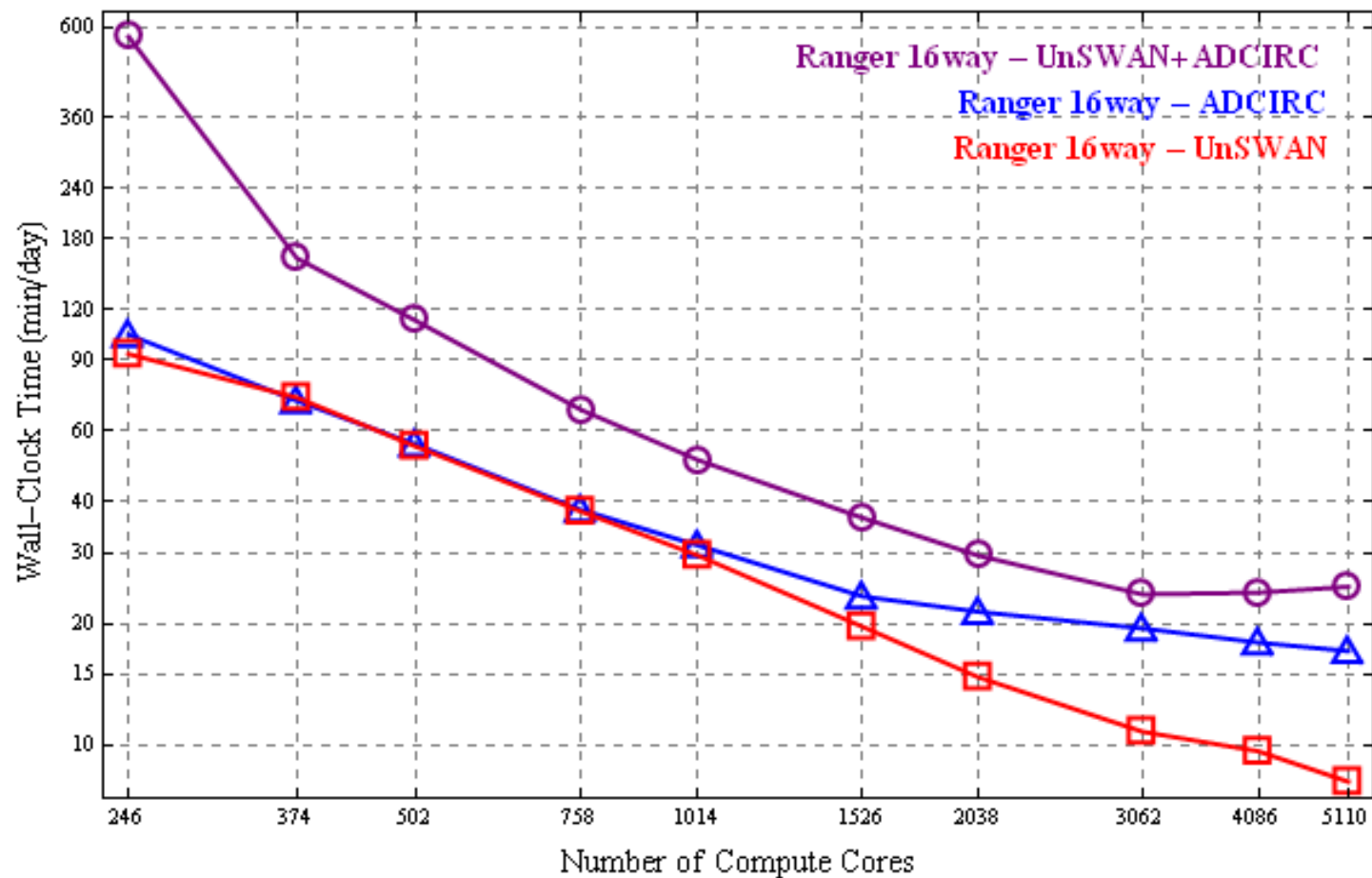 - Run on the same local mesh
  - Share information through memory
- The coupled model is efficient and scalable

Validation:

- Performed for Katrina (shown) and Rita (not shown)
- The coupled model performs surprisingly well, especially in deep water
- More resolution is needed in the Gulf of Mexico
- More physics (warm-core eddies?) may also be needed

Future Work

Implementation:

- Experiment with different methods of coupling in time
- Utilize multi-core programming environments

Verification:

- Study convergence in geographic space
- Study convergence in all other parameters (σ, θ, Δt, *etc.*)

Validation:

- Next generation of meshes
- Next generation of measured data
  - Gustav (2008)
  - Ike (2008)