Coupled, Unstructured Grid, Wave and Circulation Models: Validation and Resolution Requirements

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'Loose' Coupling

ADvanced CIRCulation (ADCIRC):

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

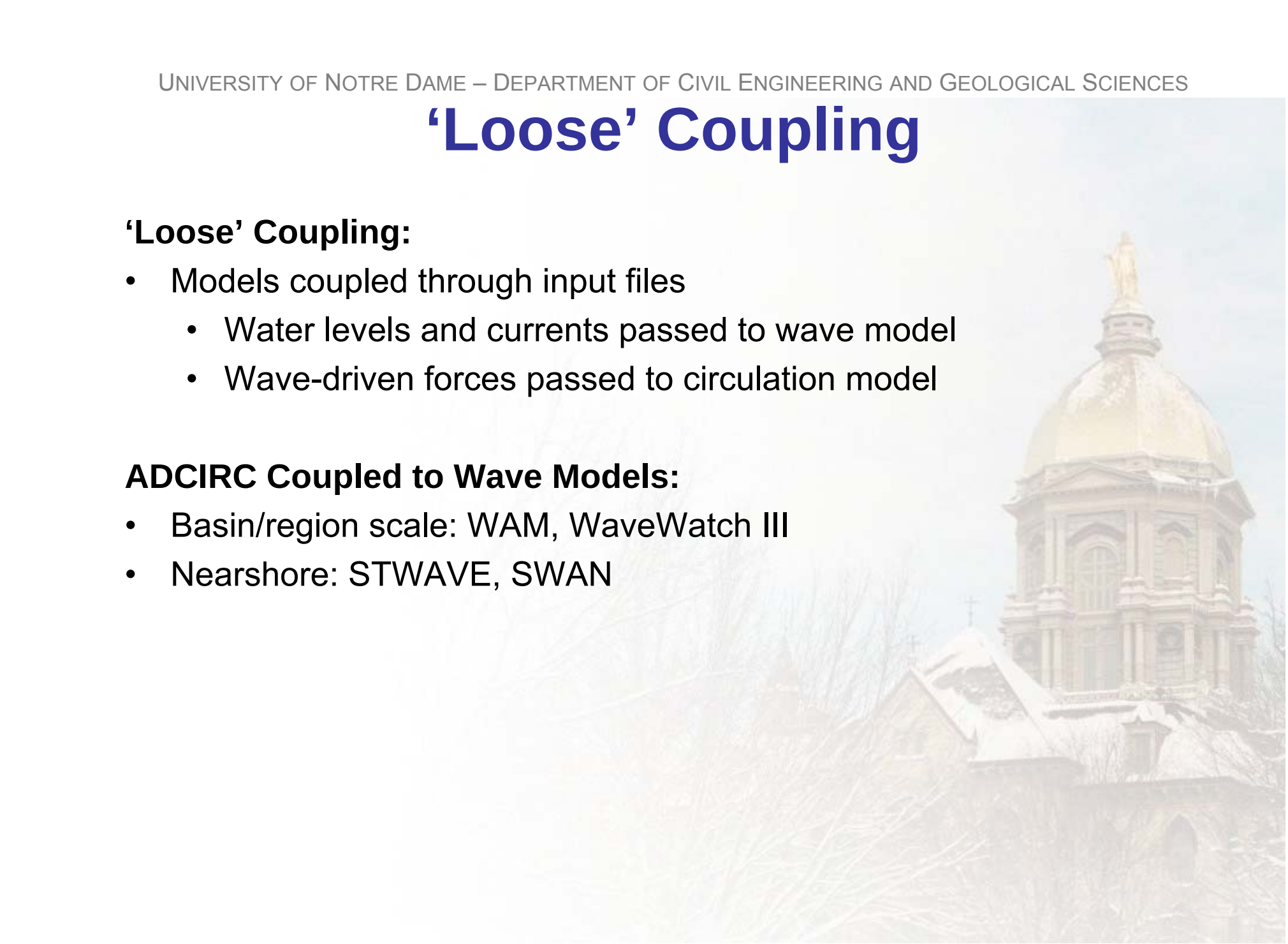
'Loose' Coupling

'Loose' Coupling:

- 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:

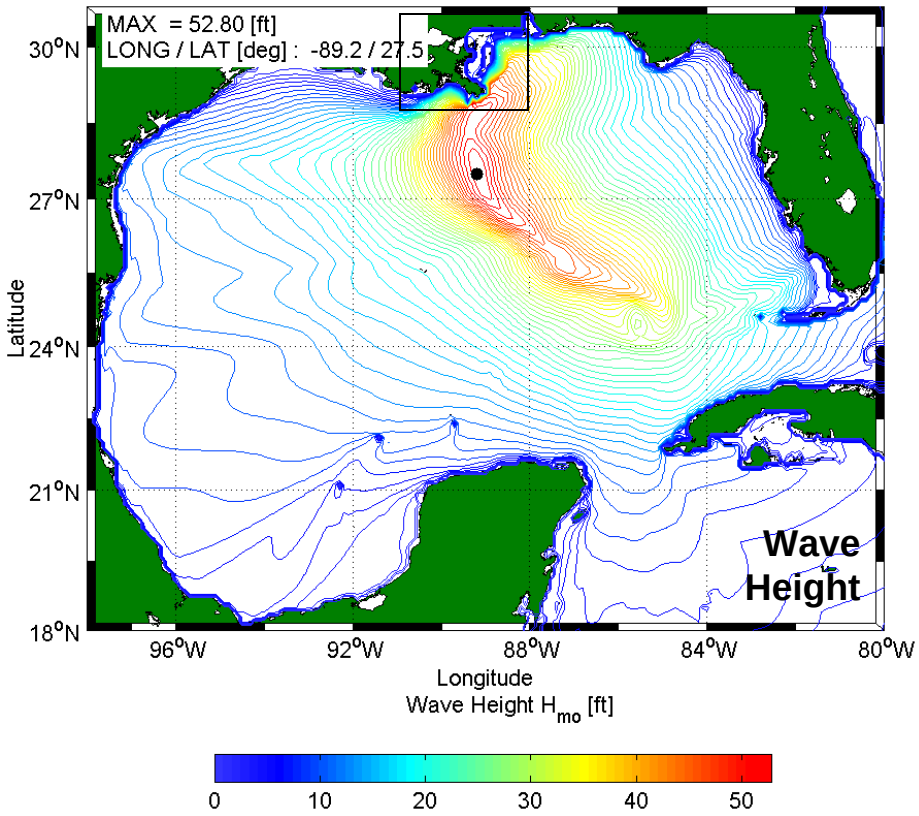
- Basin/region scale: WAM, WaveWatch III
- Nearshore: STWAVE, SWAN



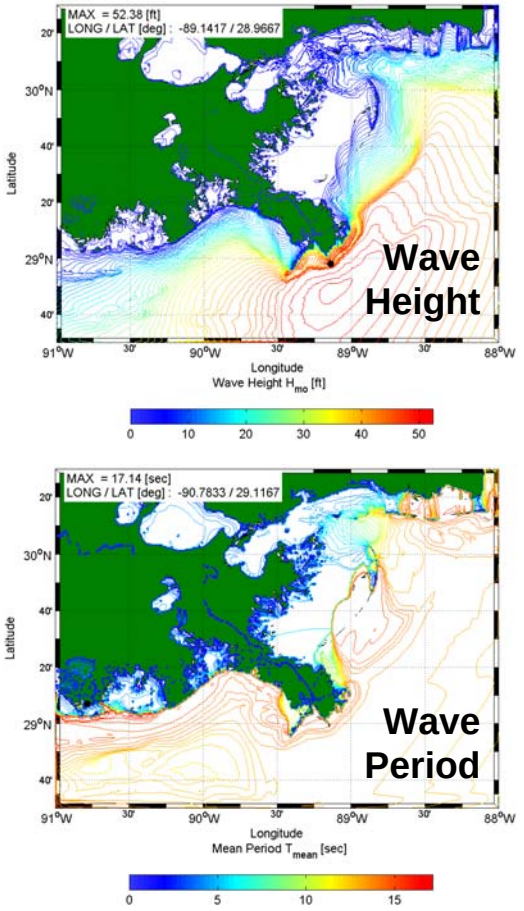
'Loose' Coupling

Example: Louisiana Storm Surge Modeling

Basin-Scale WAM Model



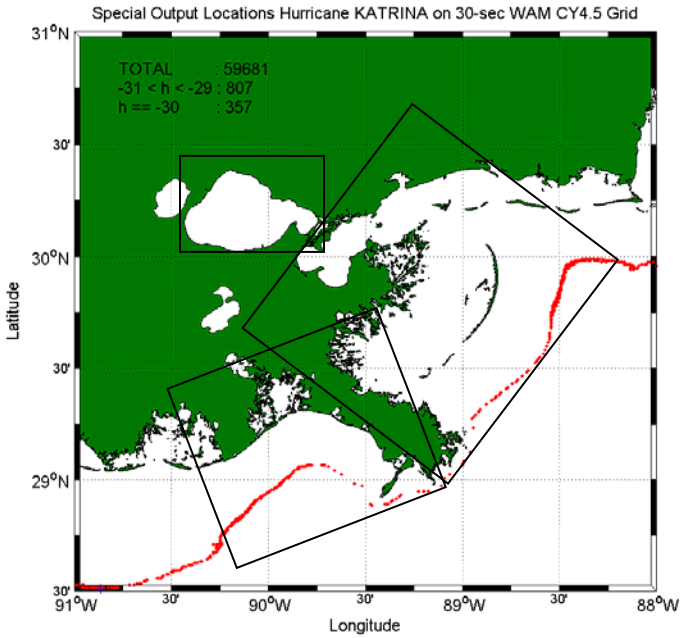
Region-Scale WAM Model

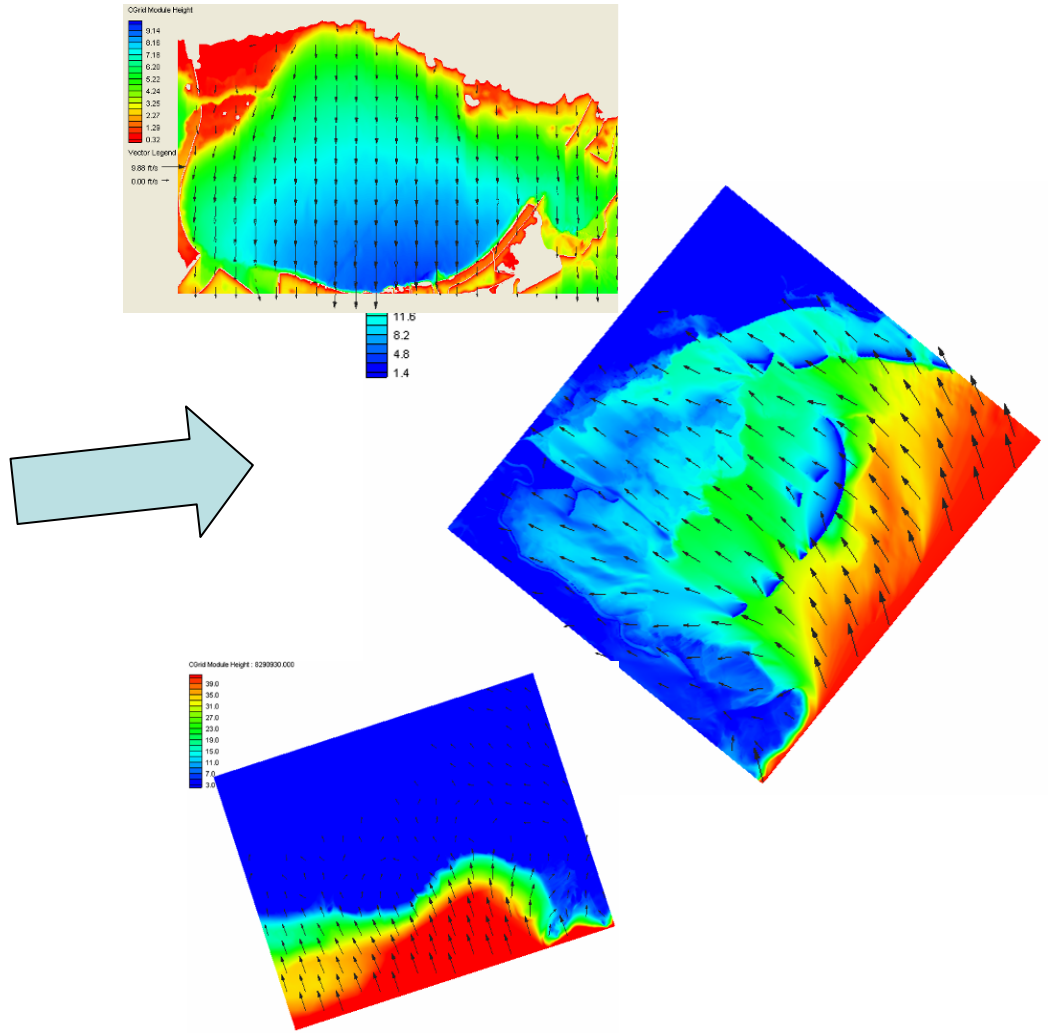


‘Loose’ Coupling

Example: Louisiana Storm Surge Modeling

Nearshore STWAVE Model

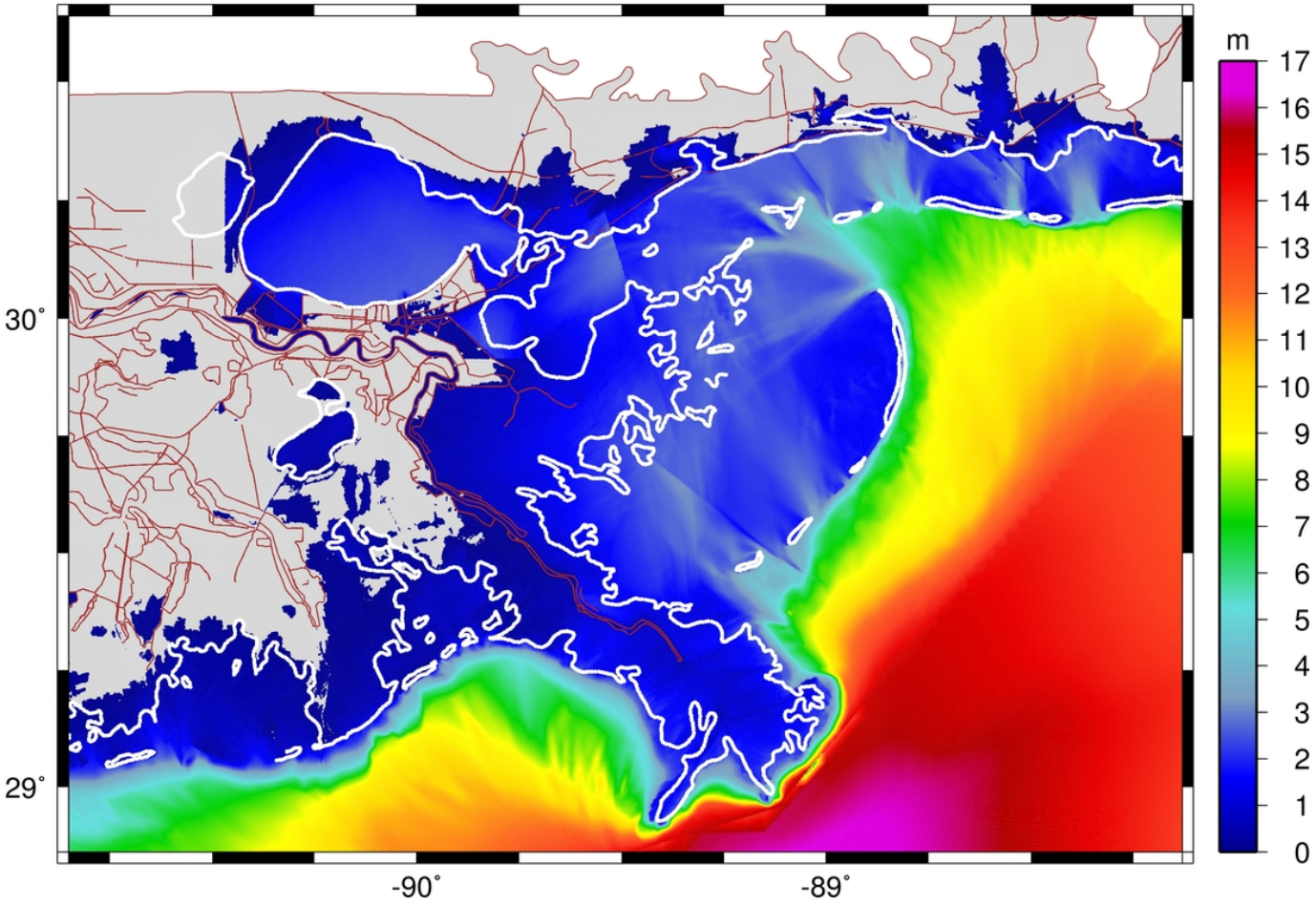




‘Loose’ Coupling

It Works!

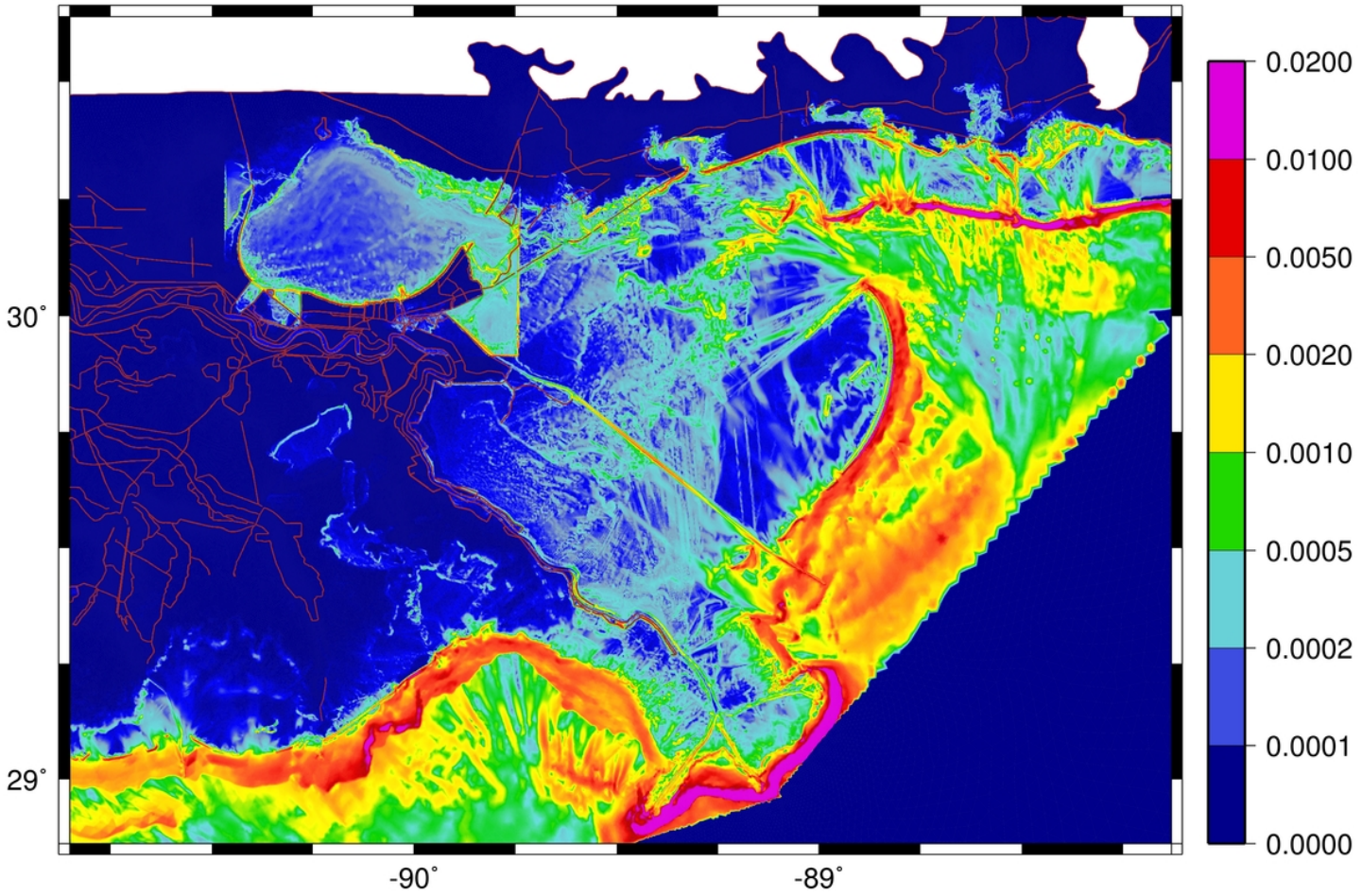
- Maximum significant wave heights in Hurricane Katrina



‘Loose’ Coupling

It Works!

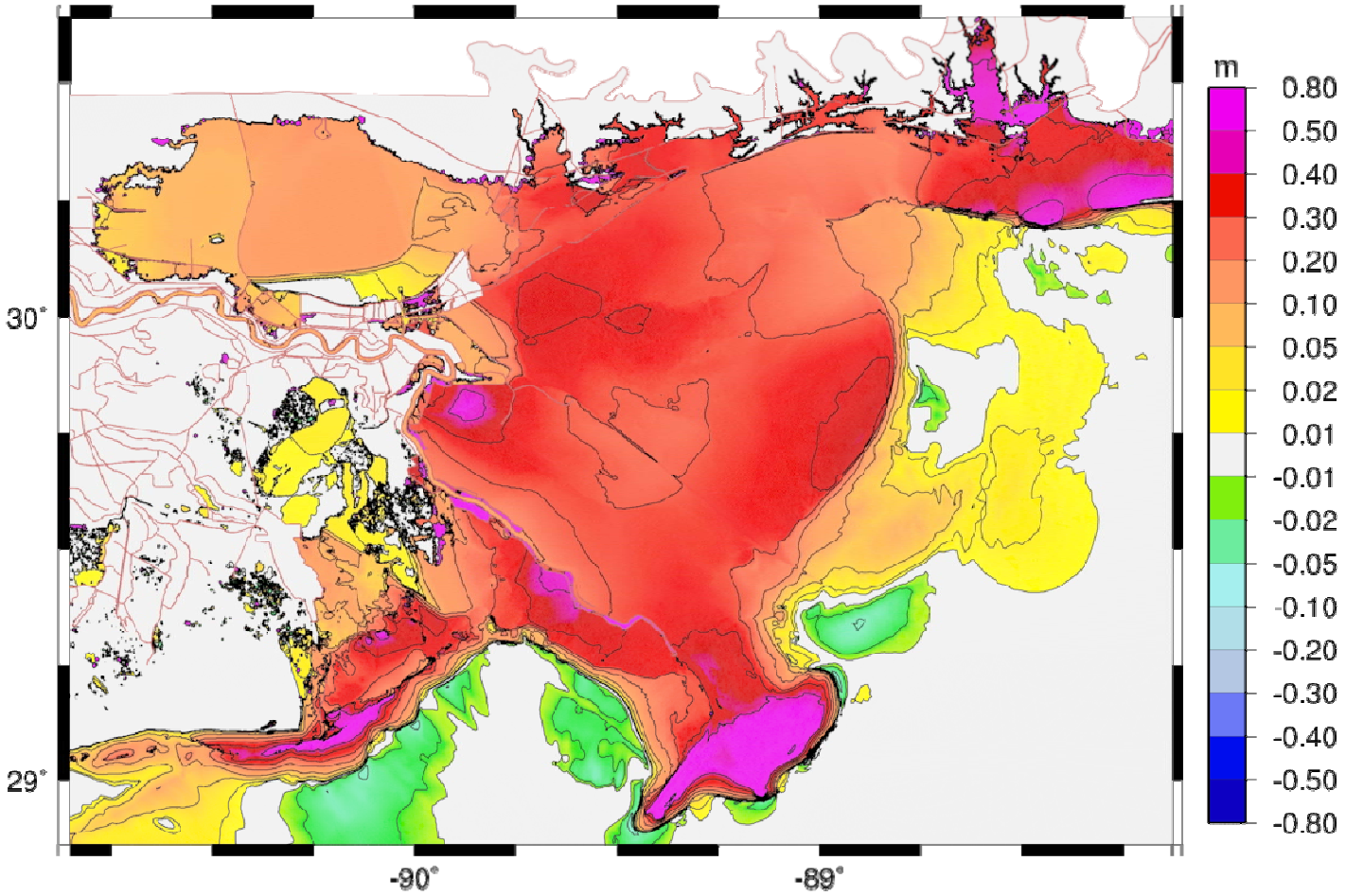
- Maximum wave-driven forces in Hurricane Katrina



‘Loose’ Coupling

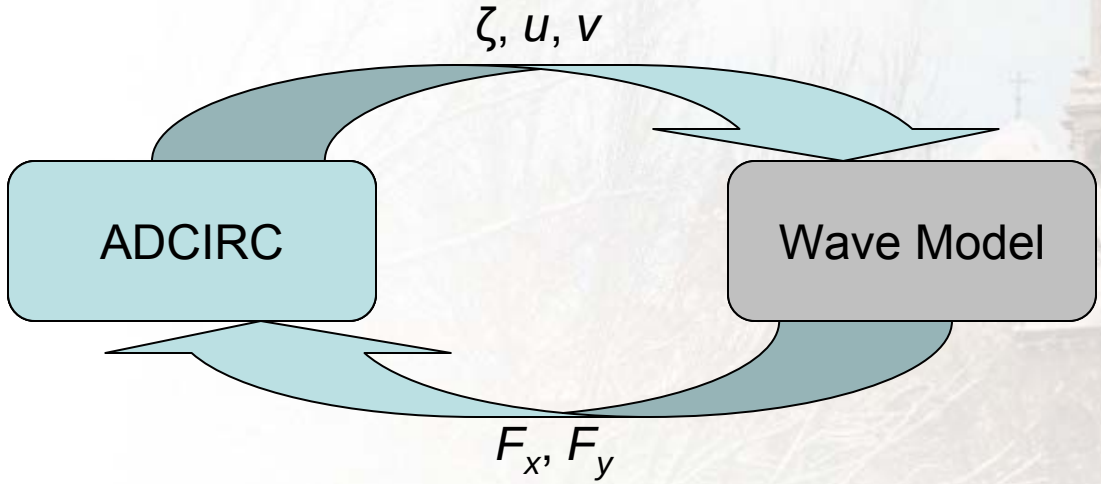
It Works!

- Effect of waves on water levels in Hurricane Katrina



Disadvantages of 'Loose' Coupling

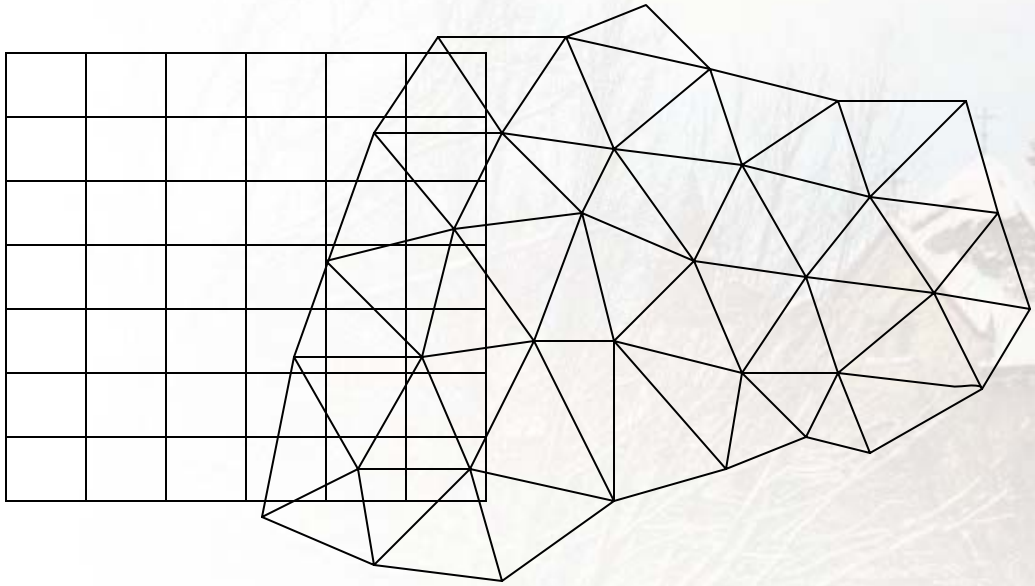
1. **Iteration:**
   - Models coupled through input files
     - Water levels and currents passed to wave model
     - Wave-driven forces passed to circulation model
   - Process can be automated, but is still inefficient



Disadvantages of 'Loose' Coupling

2. Interpolation:

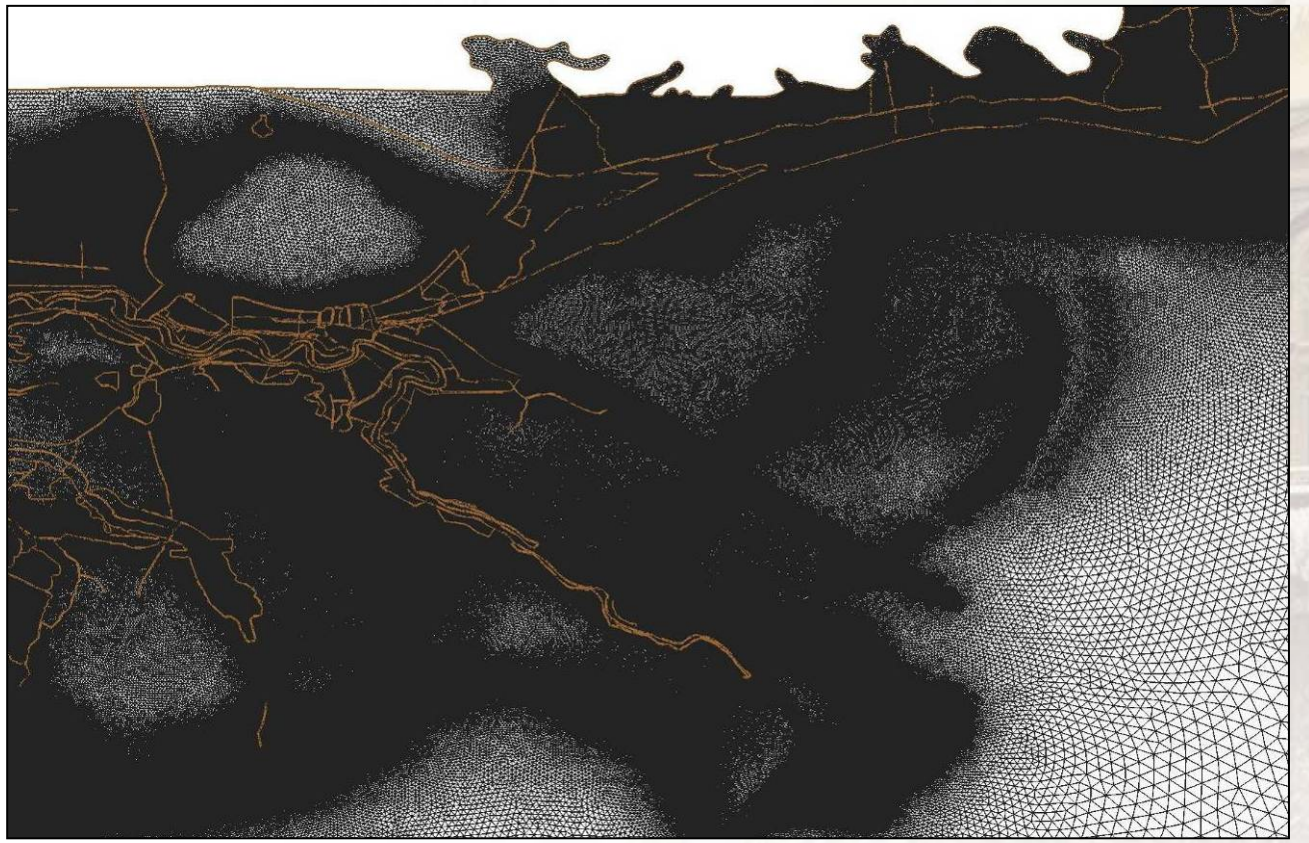
- Wave and circulation models run on different grids
  - Wave models on structured meshes
  - ADCIRC on unstructured, finite element mesh
- Results must be interpolated onto each mesh



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 processor
  - No interpolation
  - No global message passing
  - Information is passed through memory
- Optimization of code
  - 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 … AdcSwan! (Or SwAdcirc?)

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

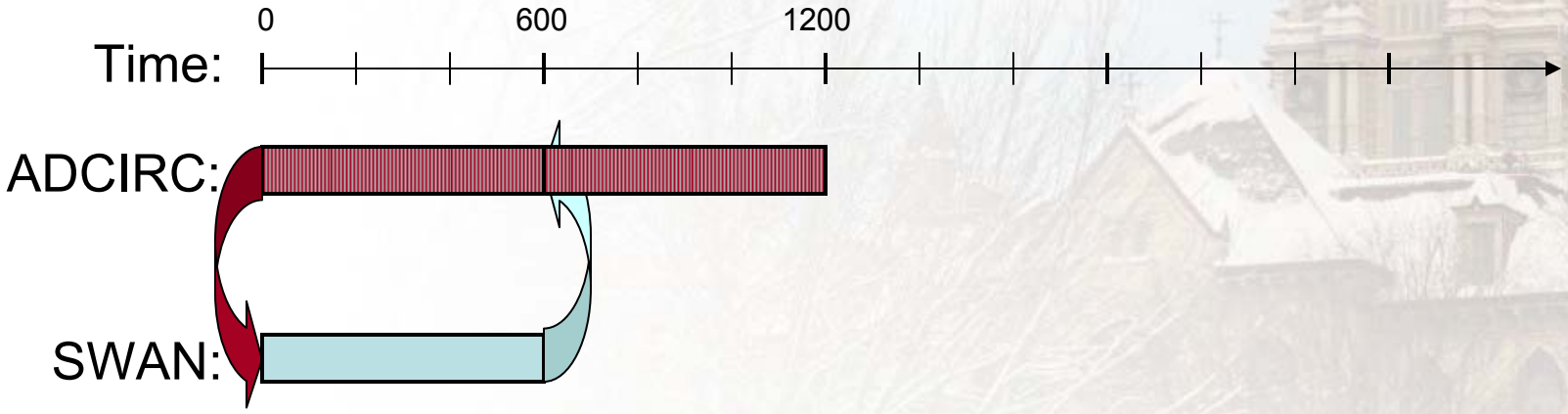
Progress:

- 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

'Tight' Coupling

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 wave-driven forces (F_x, F_y) are computed; forces are passed to ADCIRC
- Repeat

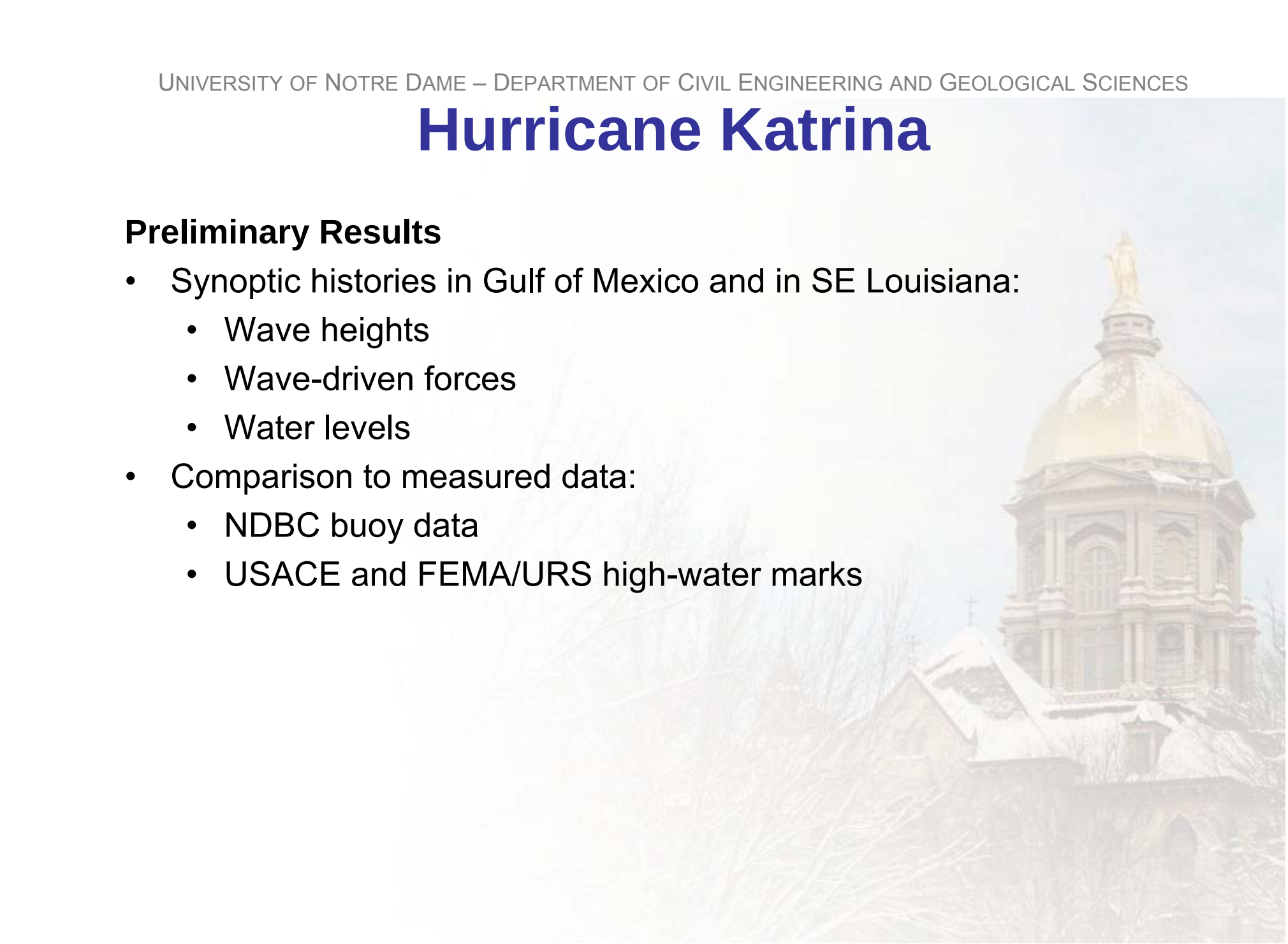


- SWAN and ADCIRC are always extrapolating in time

Hurricane Katrina

Preliminary Results

- Synoptic histories in Gulf of Mexico and in SE Louisiana:
  - Wave heights
  - Wave-driven forces
  - Water levels
- Comparison to measured data:
  - NDBC buoy data
  - USACE and FEMA/URS high-water marks



Hurricane Katrina

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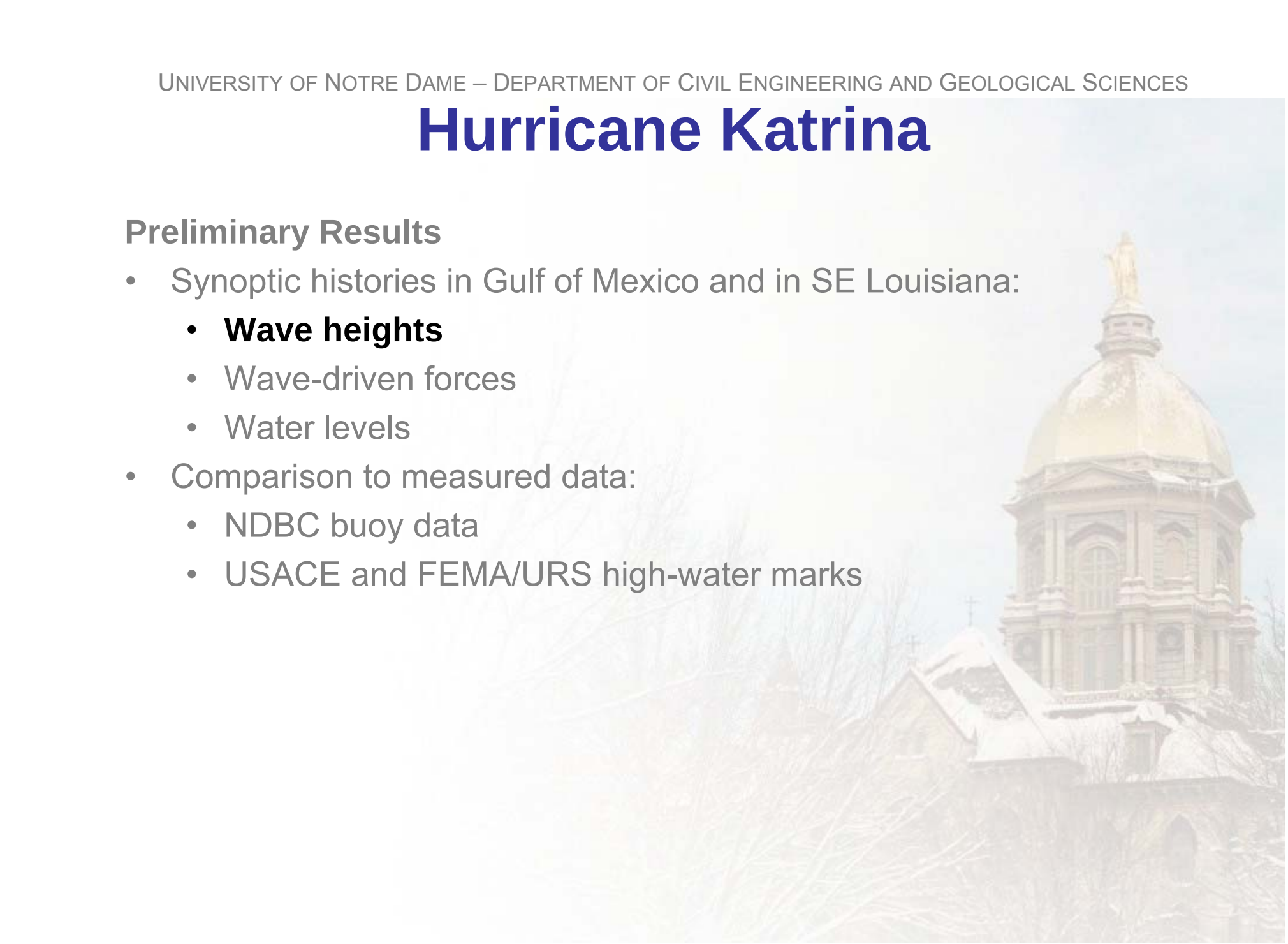
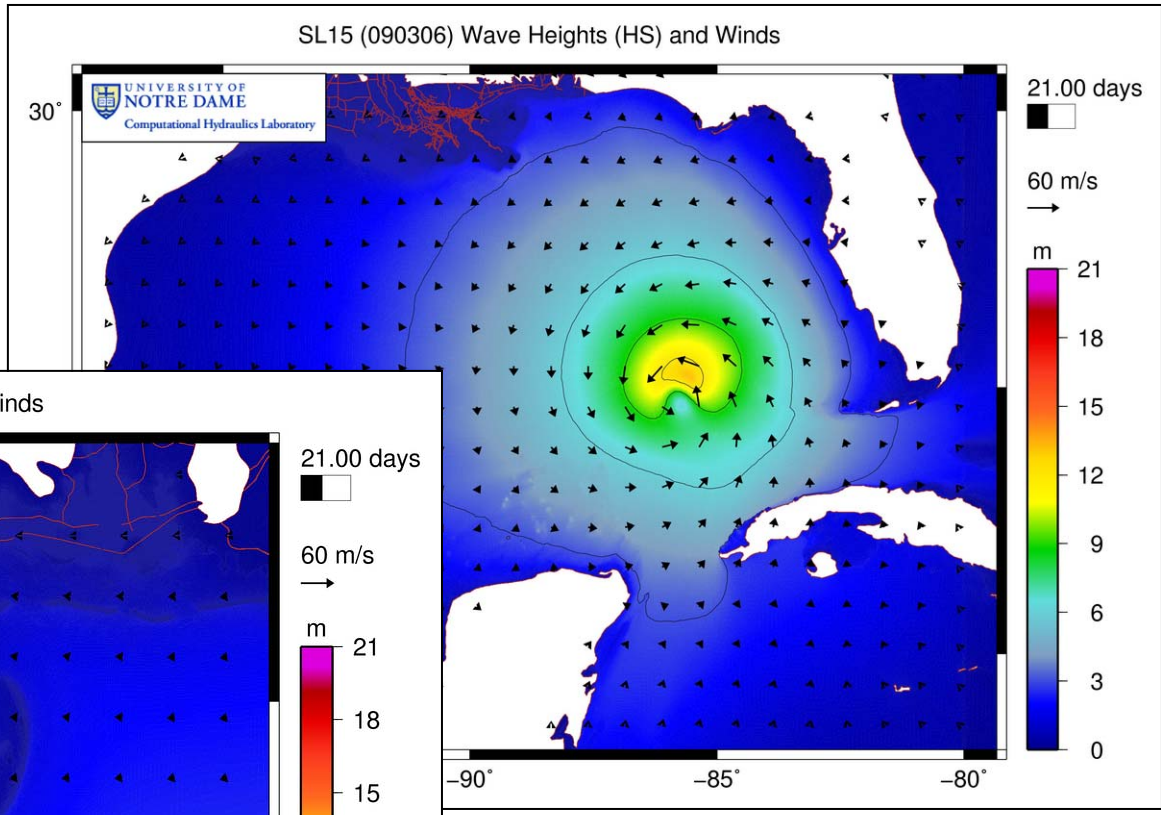
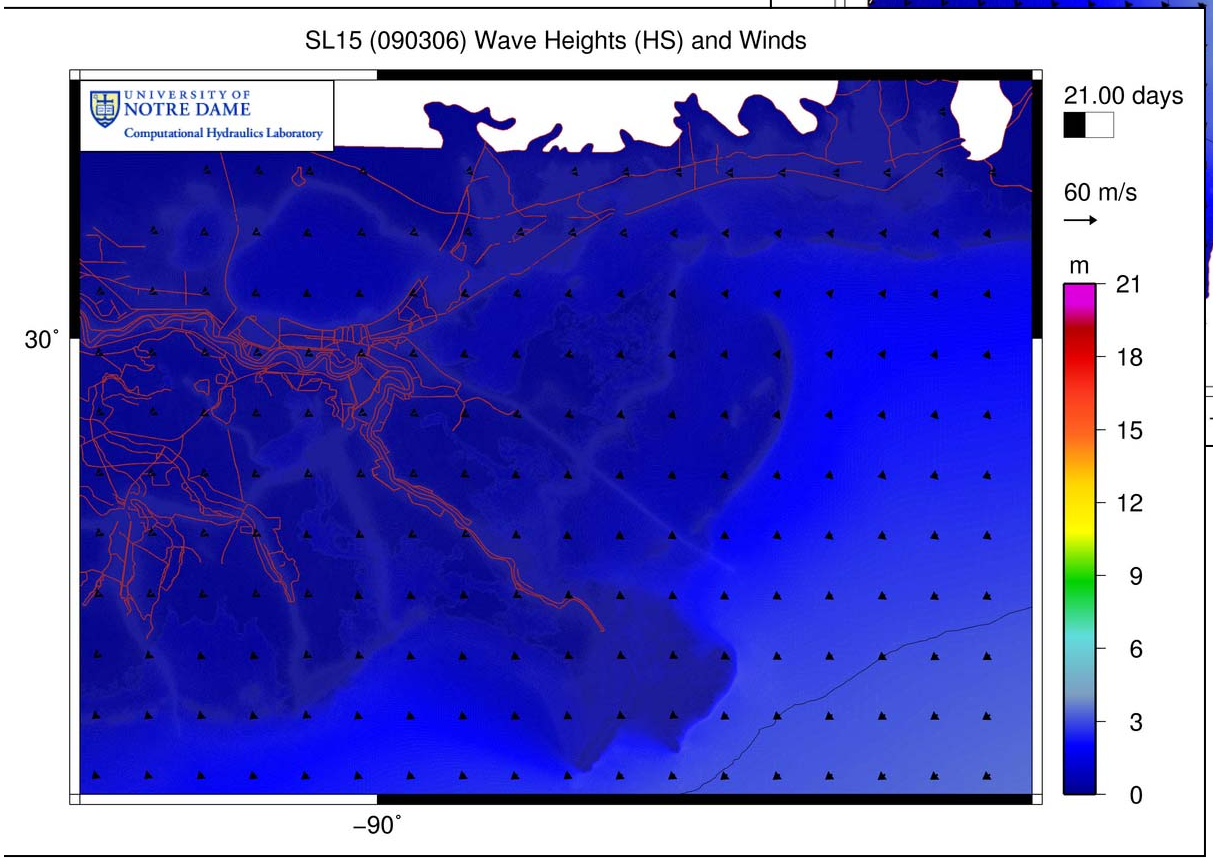


Hurricane Katrina

Wave Heights

- 2005/08/28/0000Z

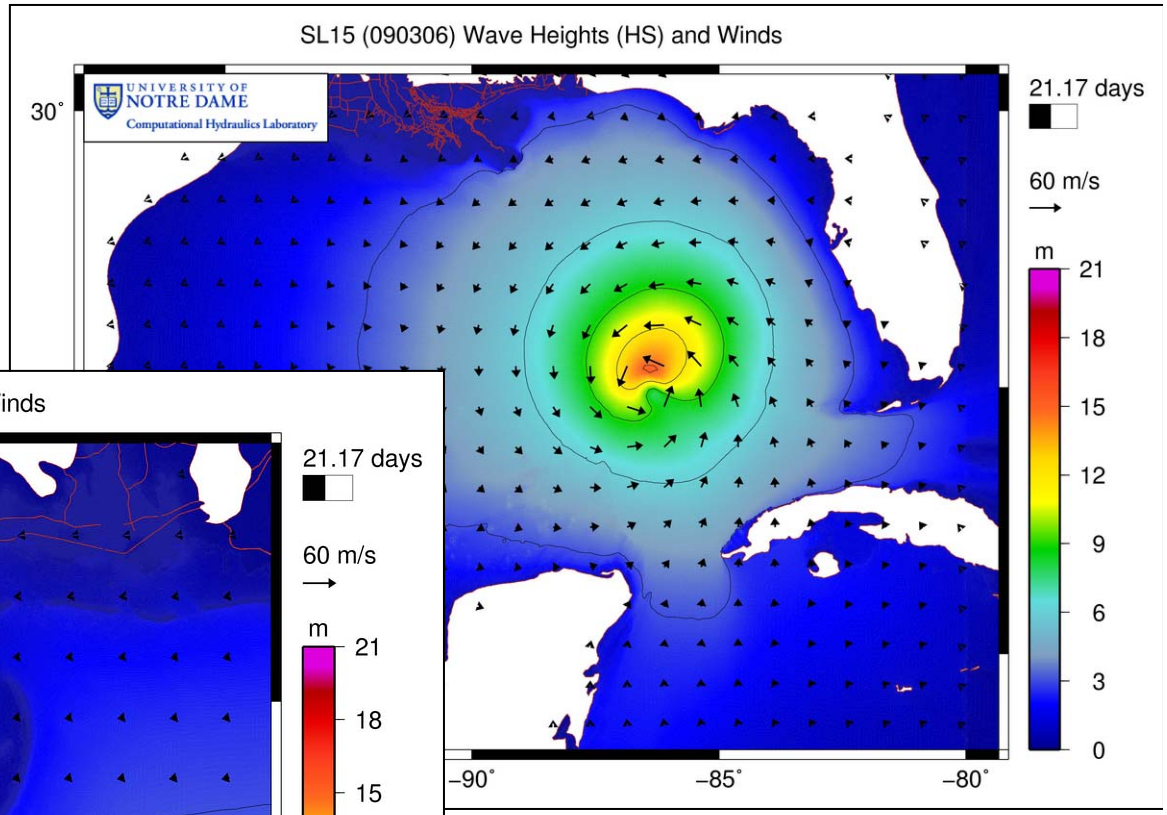


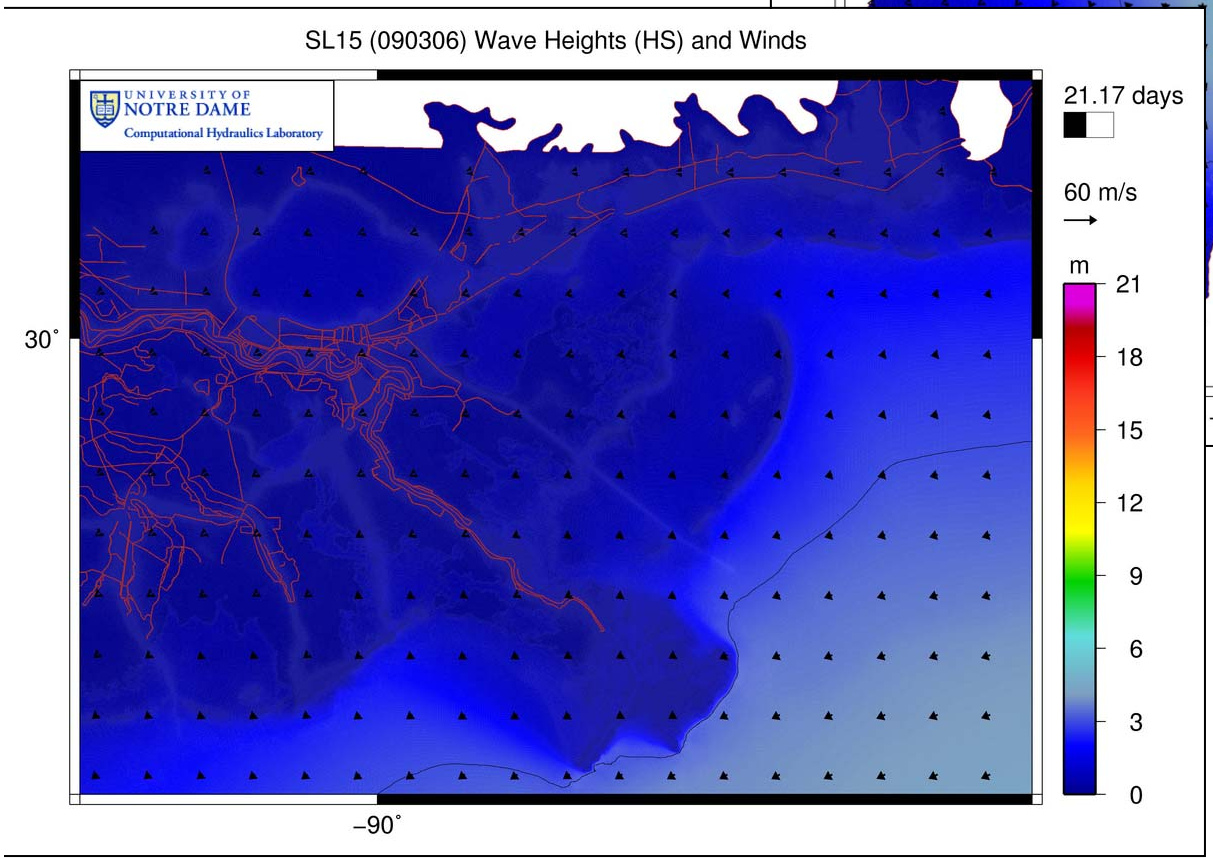


Hurricane Katrina

Wave Heights

- 2005/08/28/0400Z





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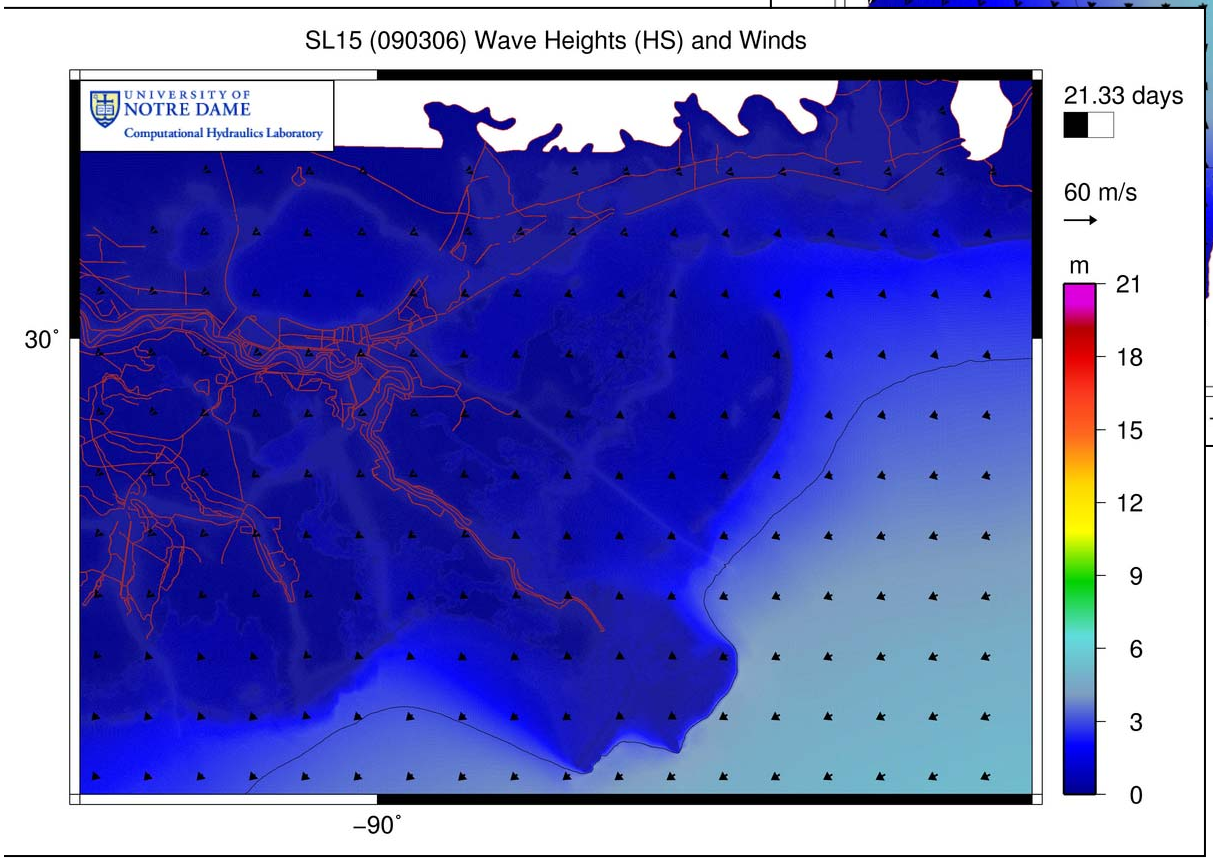
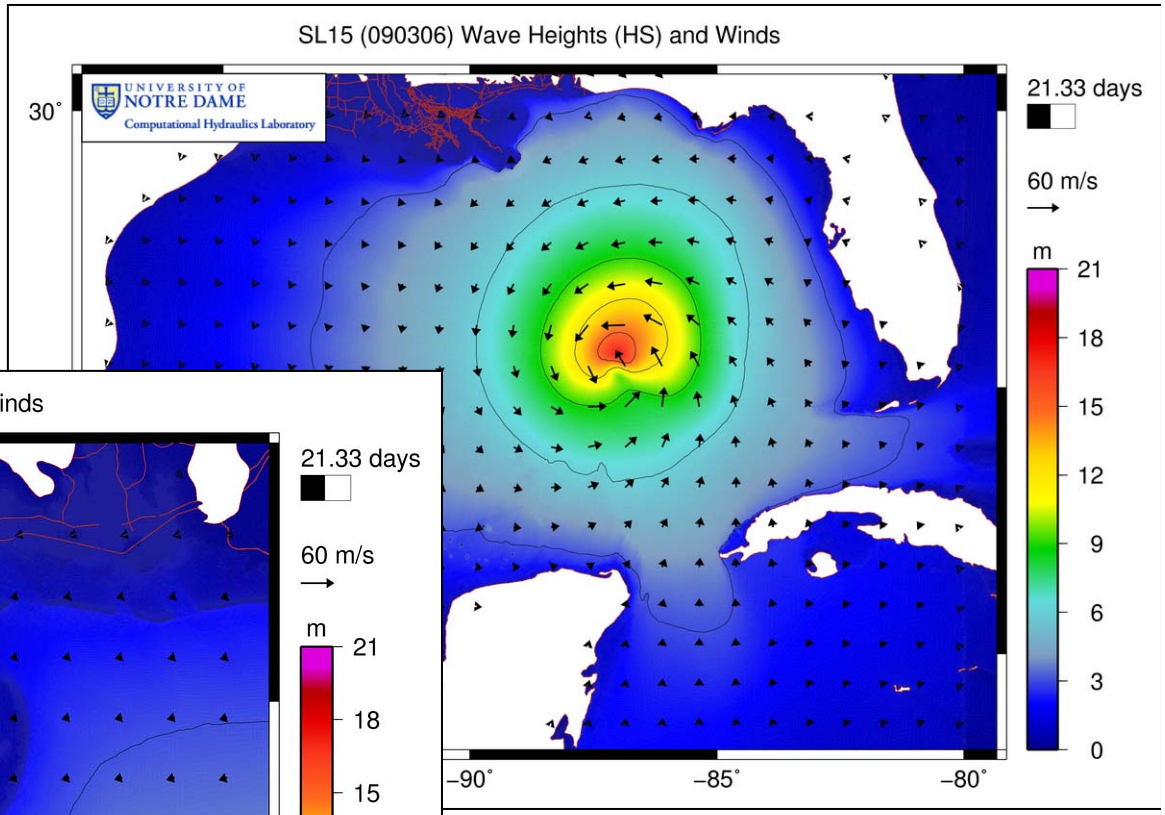
Wave Heights

- 2005/08/28/0800Z

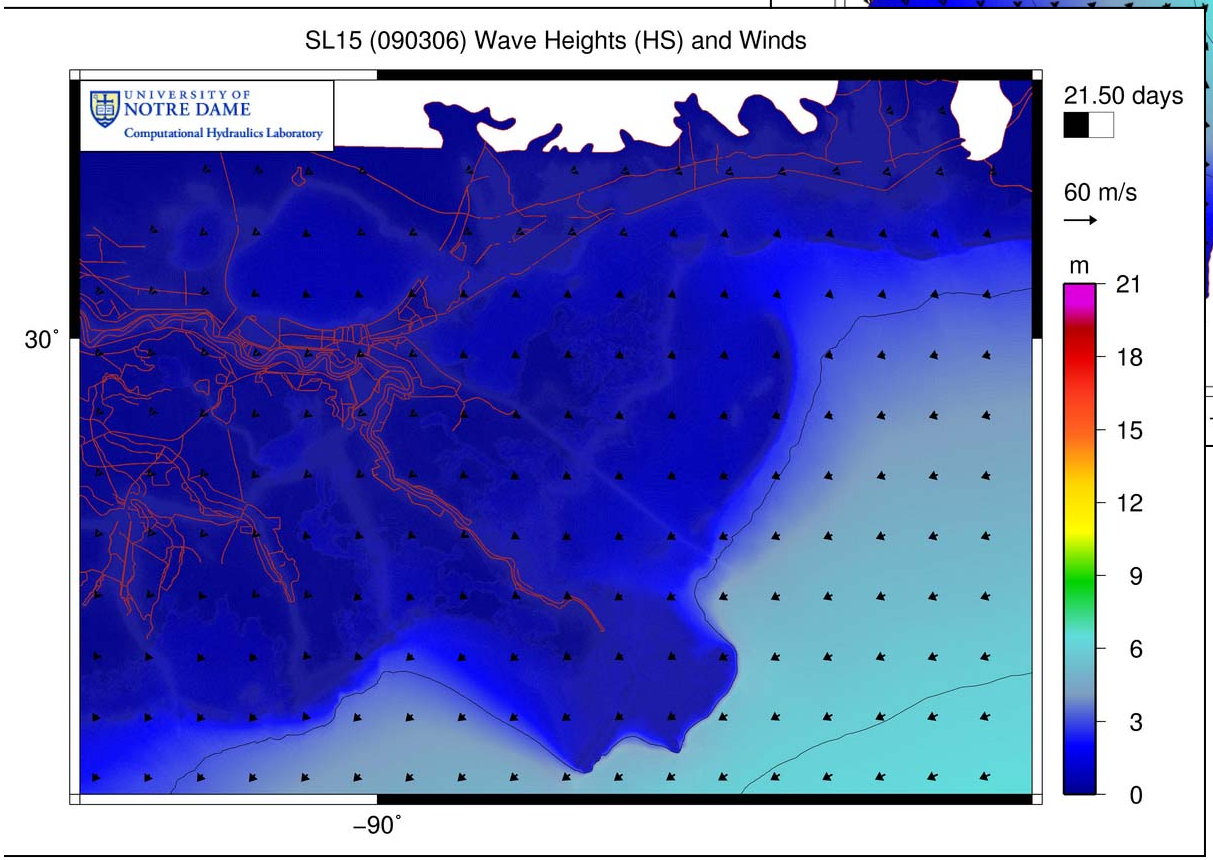


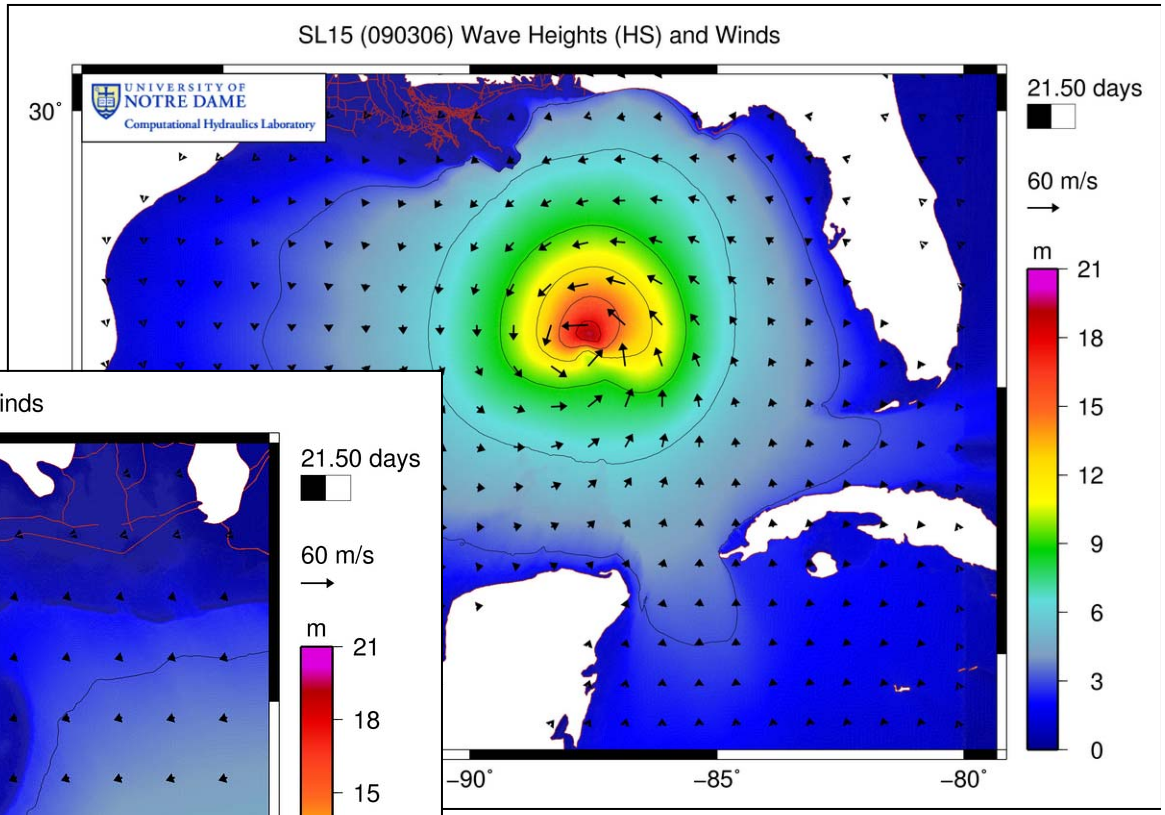


Hurricane Katrina

Wave Heights

- 2005/08/28/1200Z

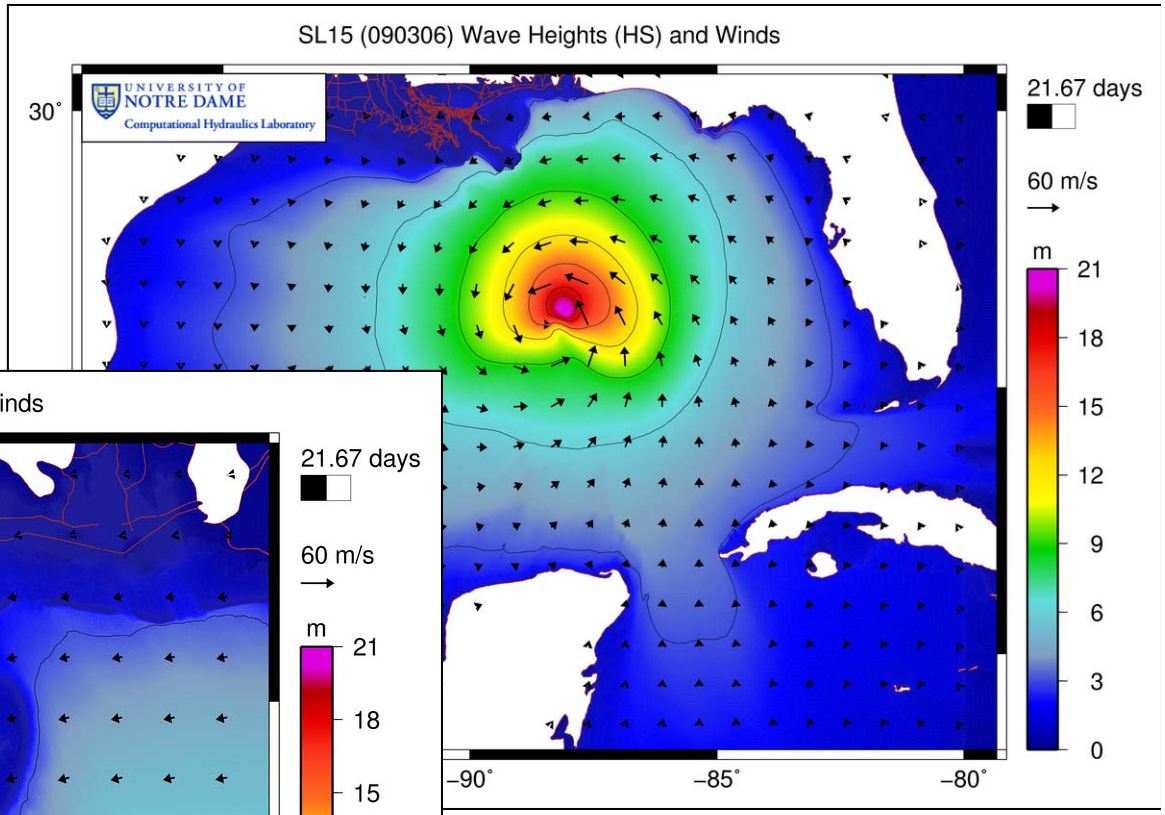


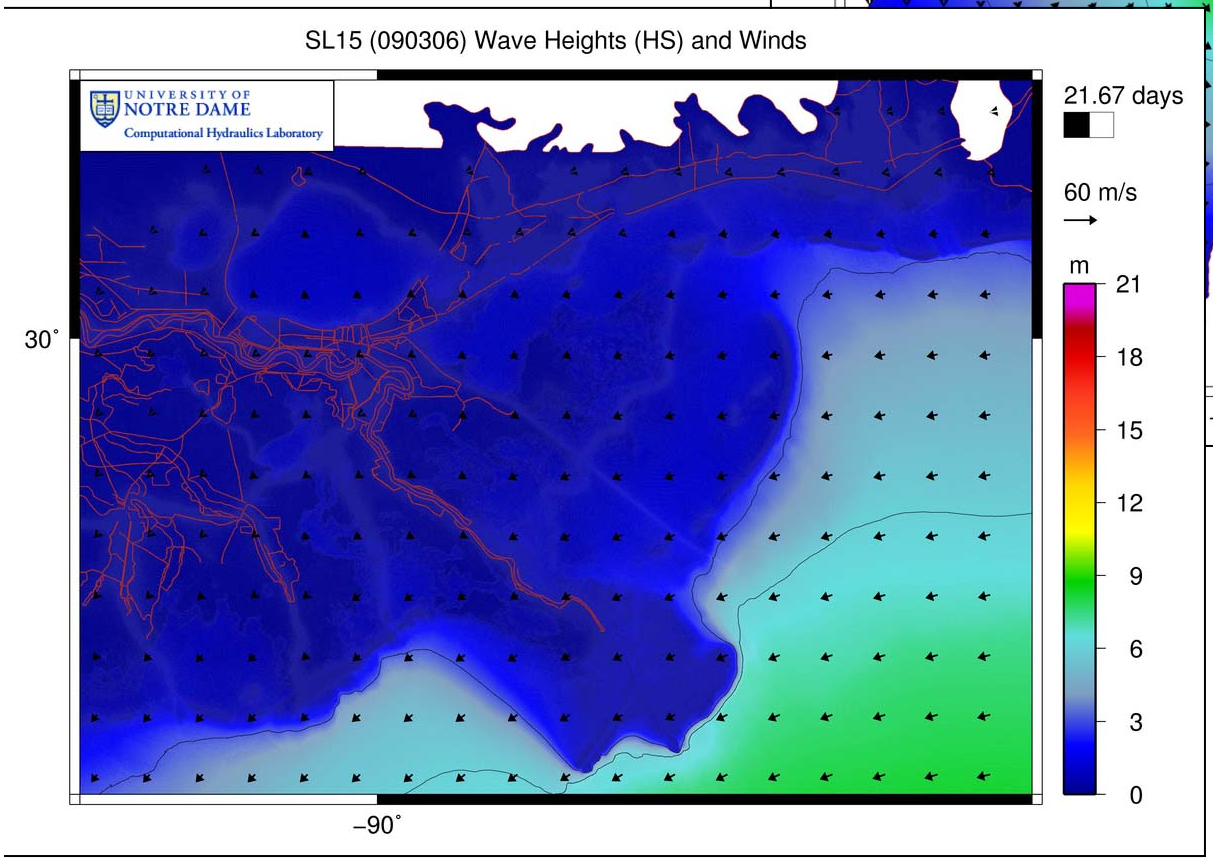


Hurricane Katrina

Wave Heights

- 2005/08/28/1600Z





Hurricane Katrina

Wave Heights

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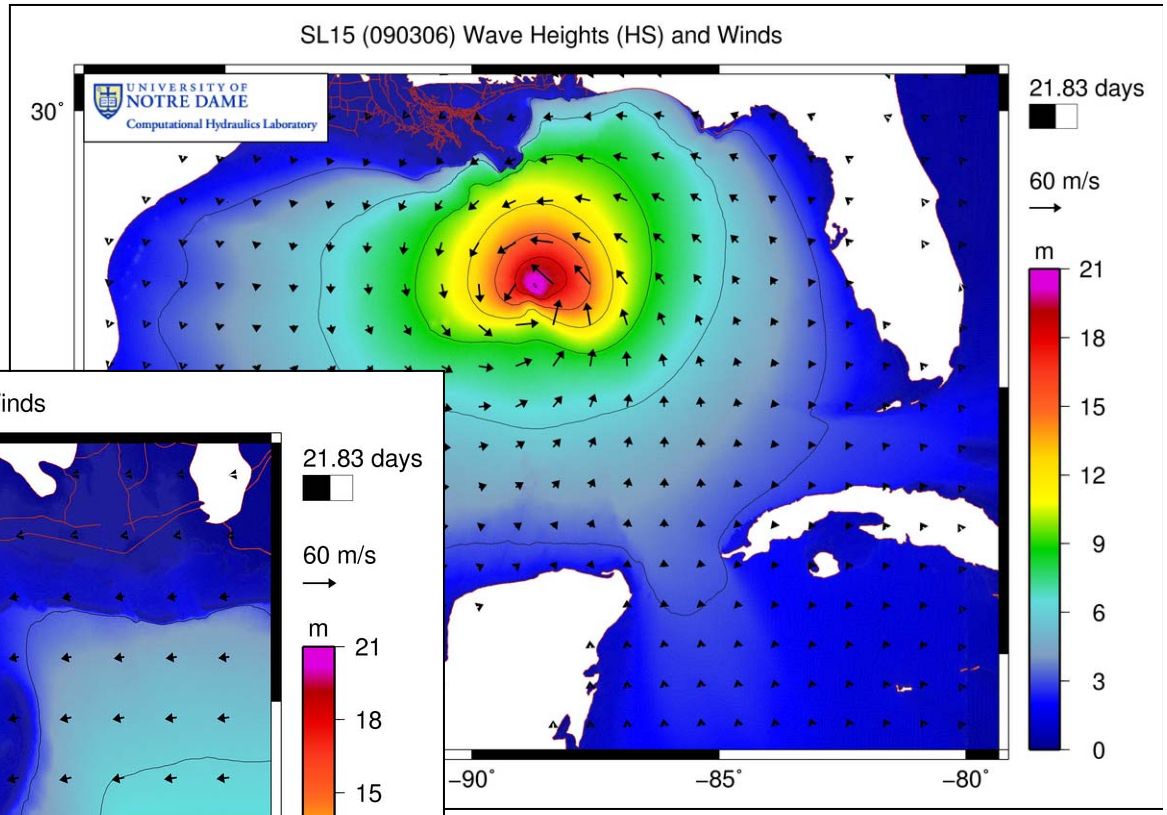

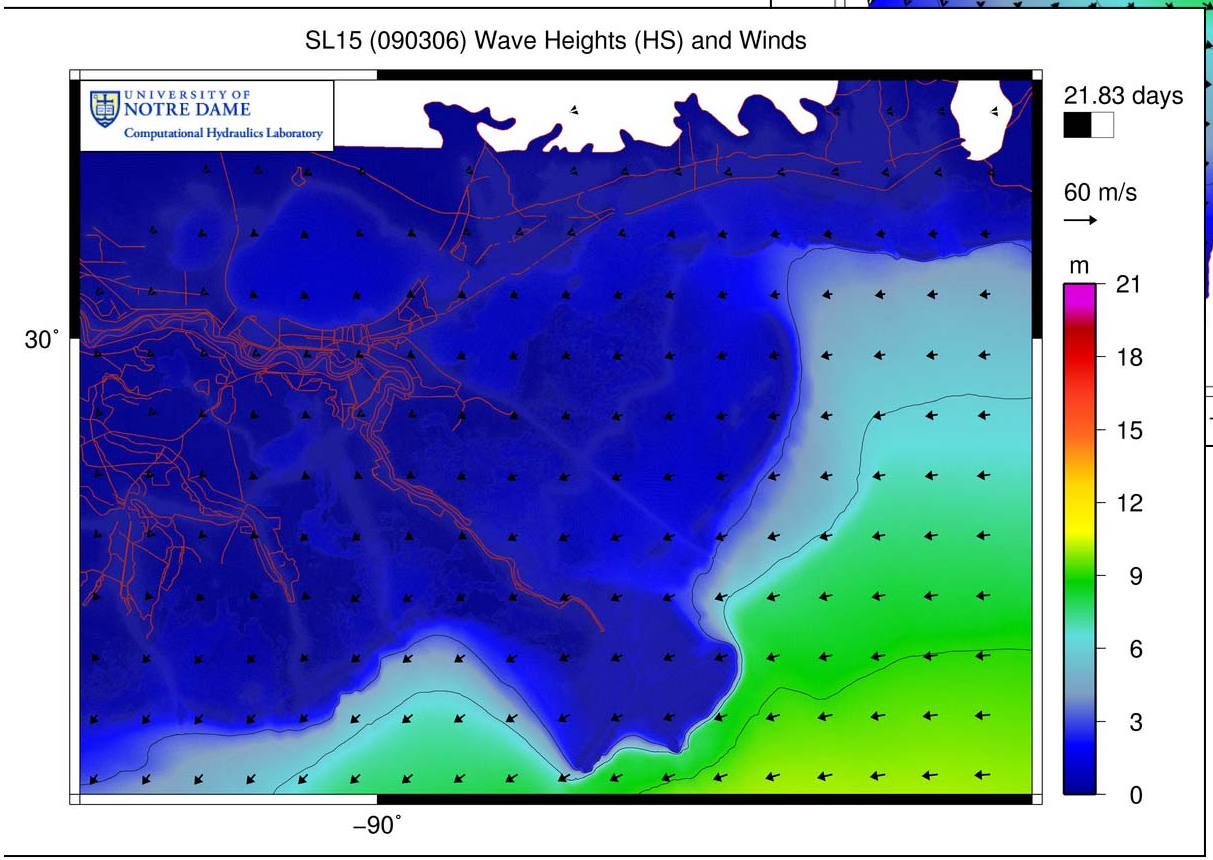

Hurricane Katrina

Wave Heights

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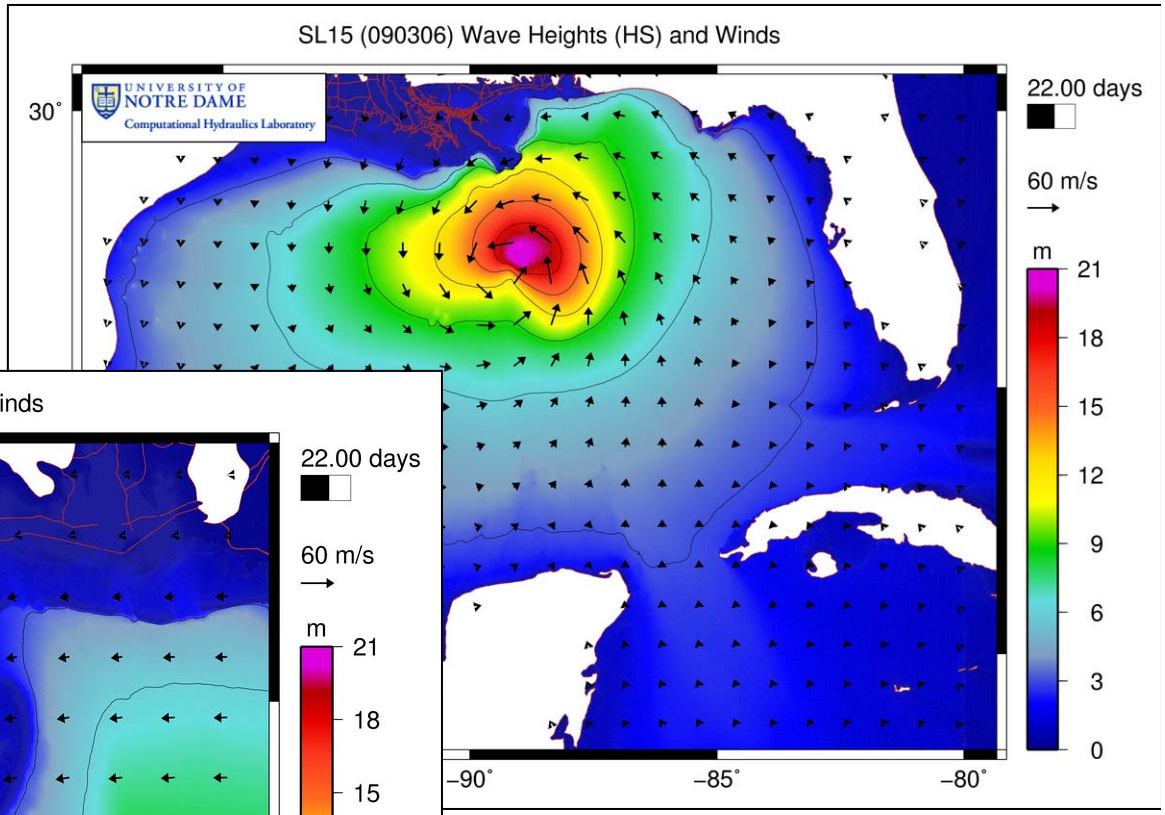

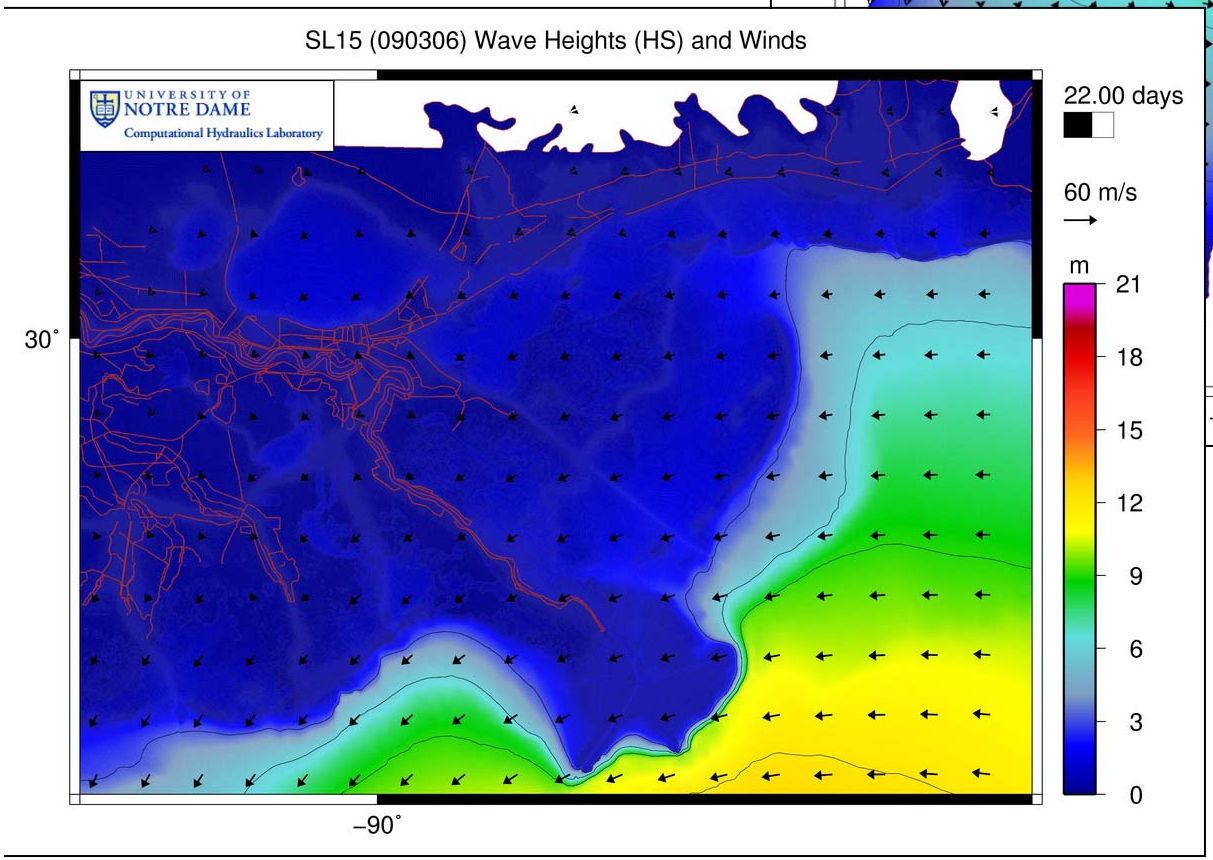

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Wave Heights

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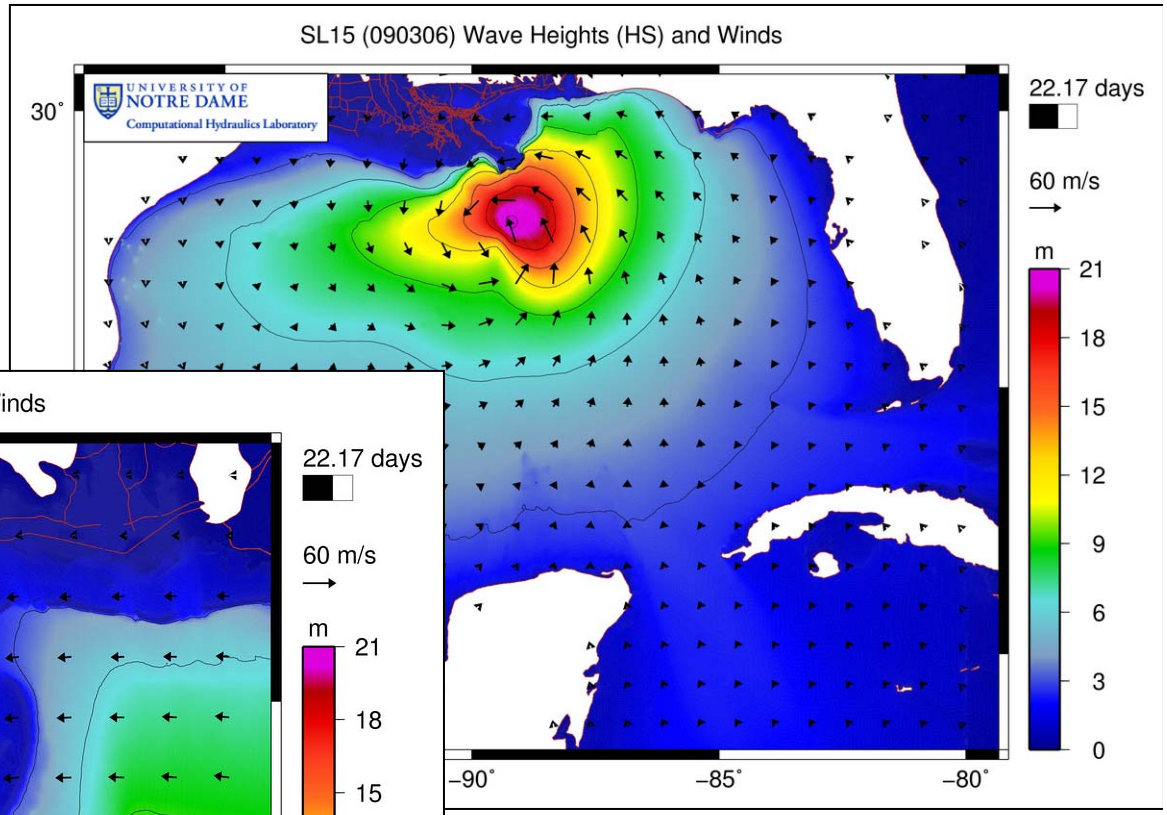

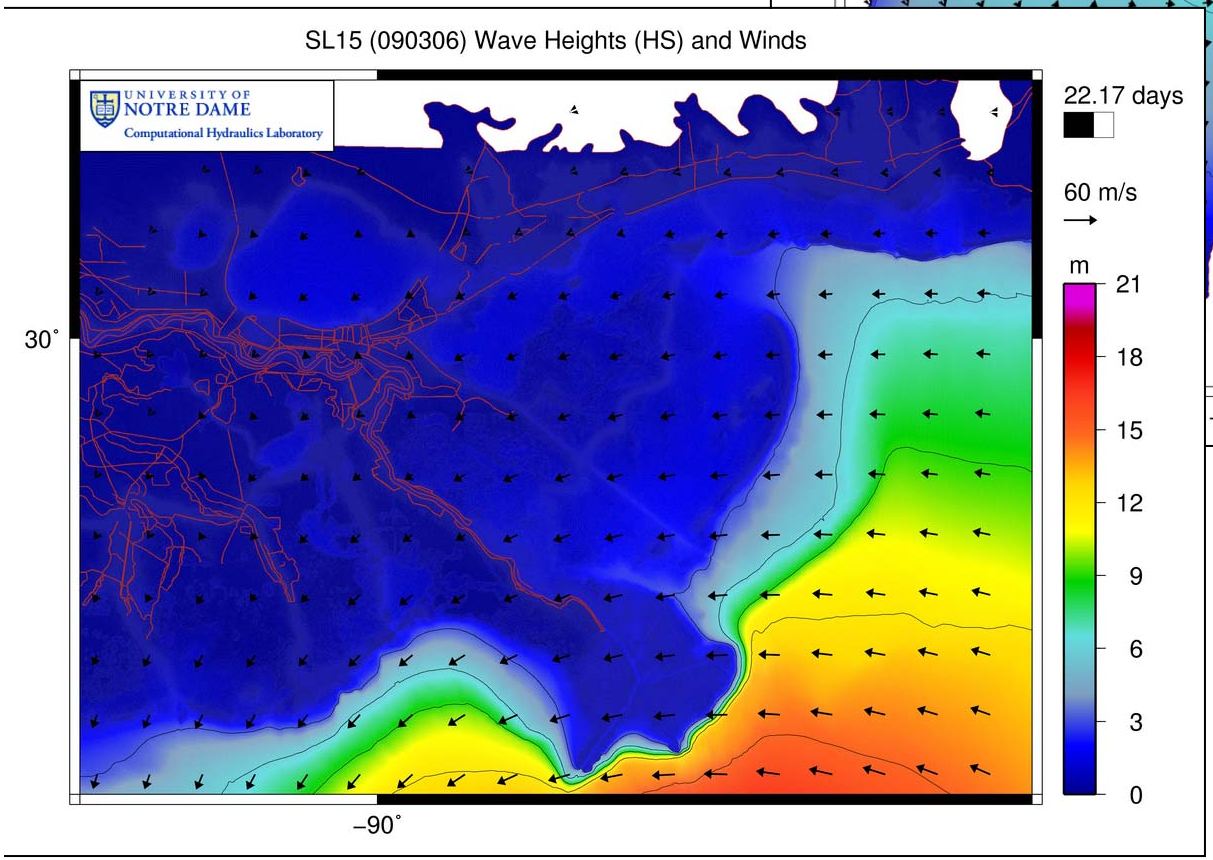

Hurricane Katrina

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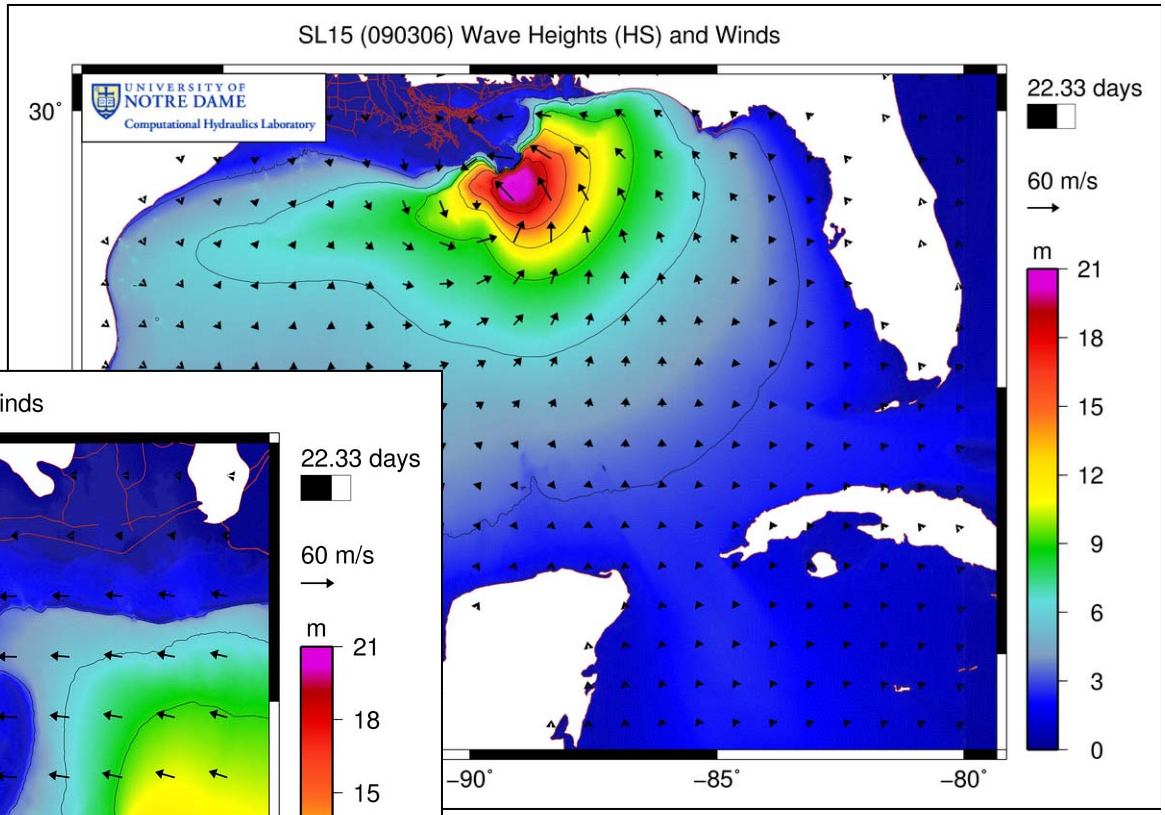

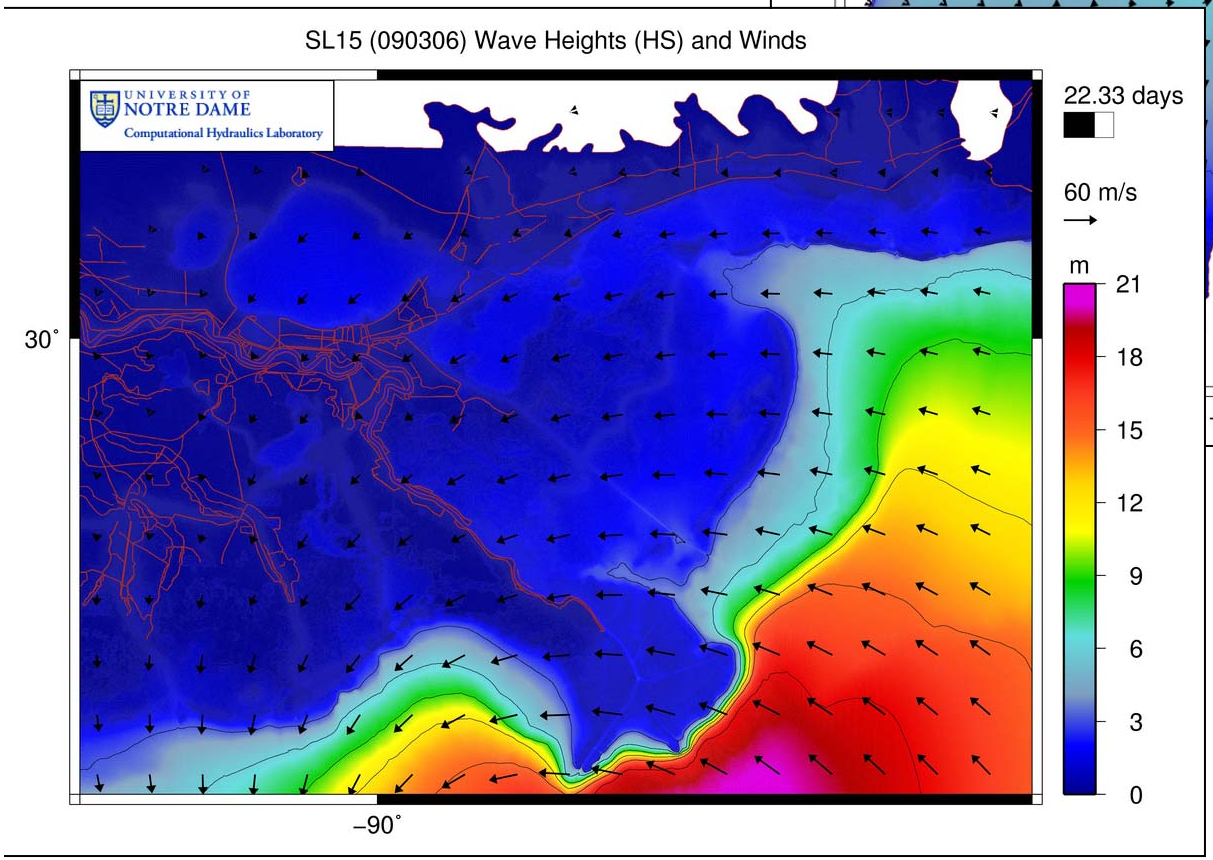

Hurricane Katrina

Wave Heights

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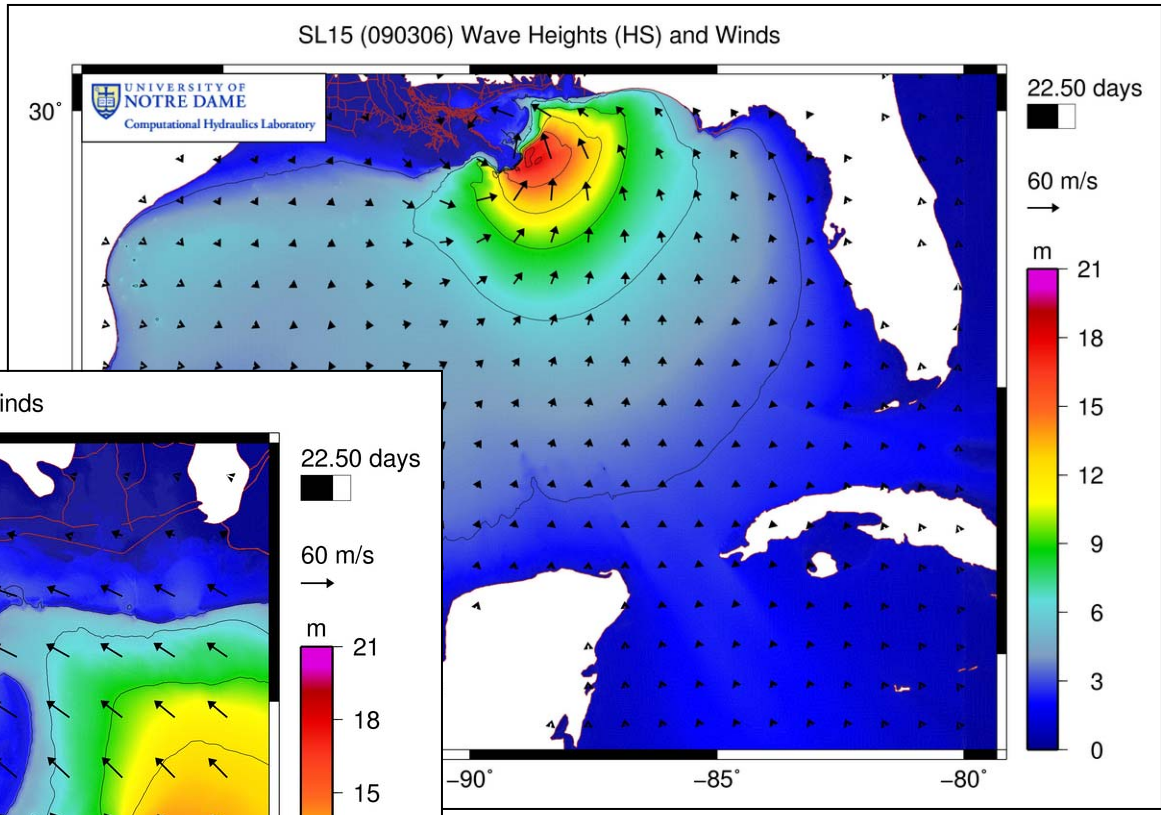

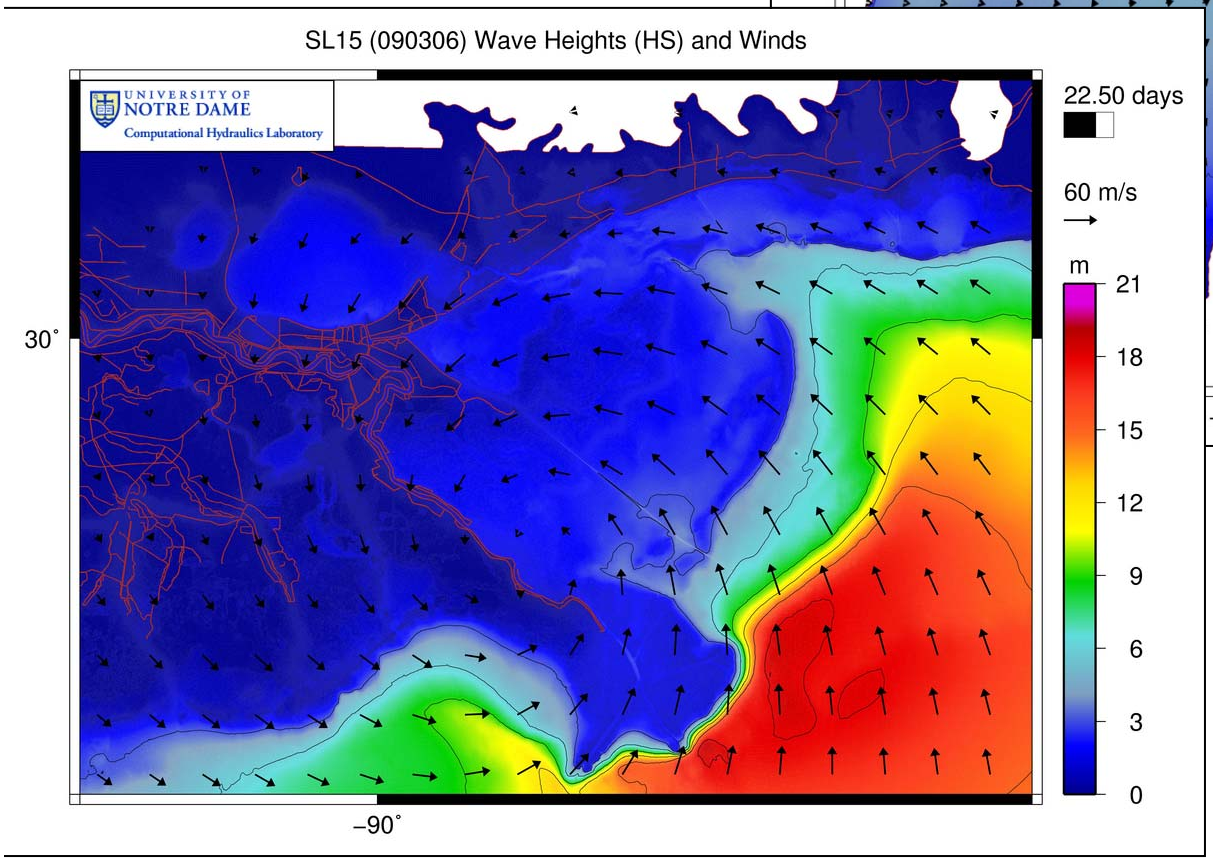

Hurricane Katrina

Wave Heights

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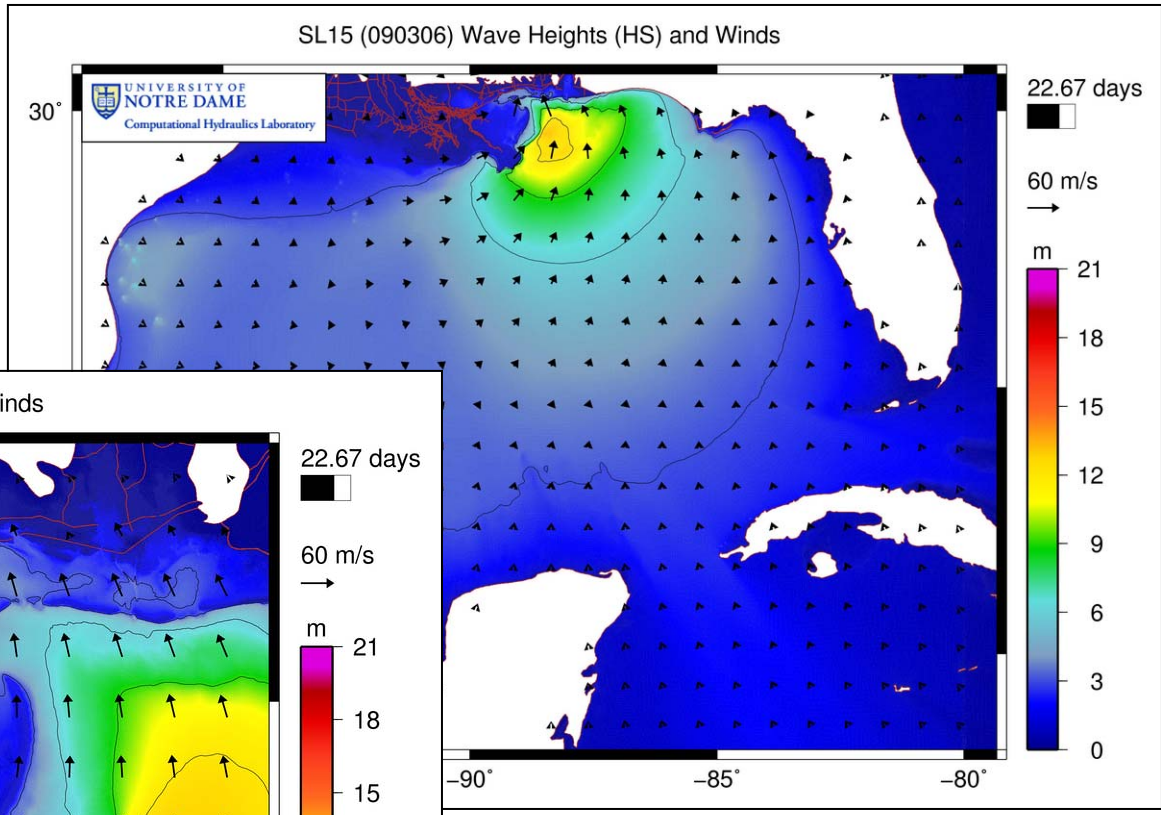

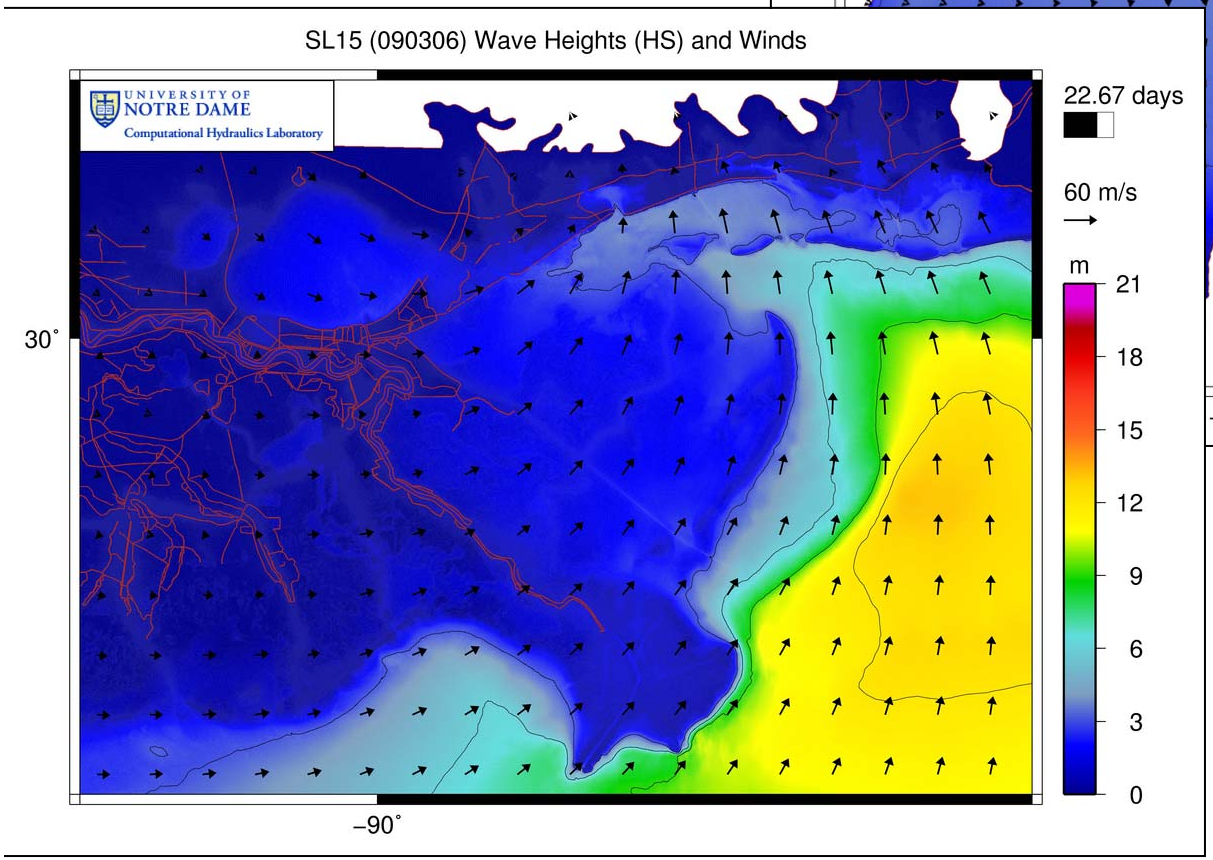

Hurricane Katrina

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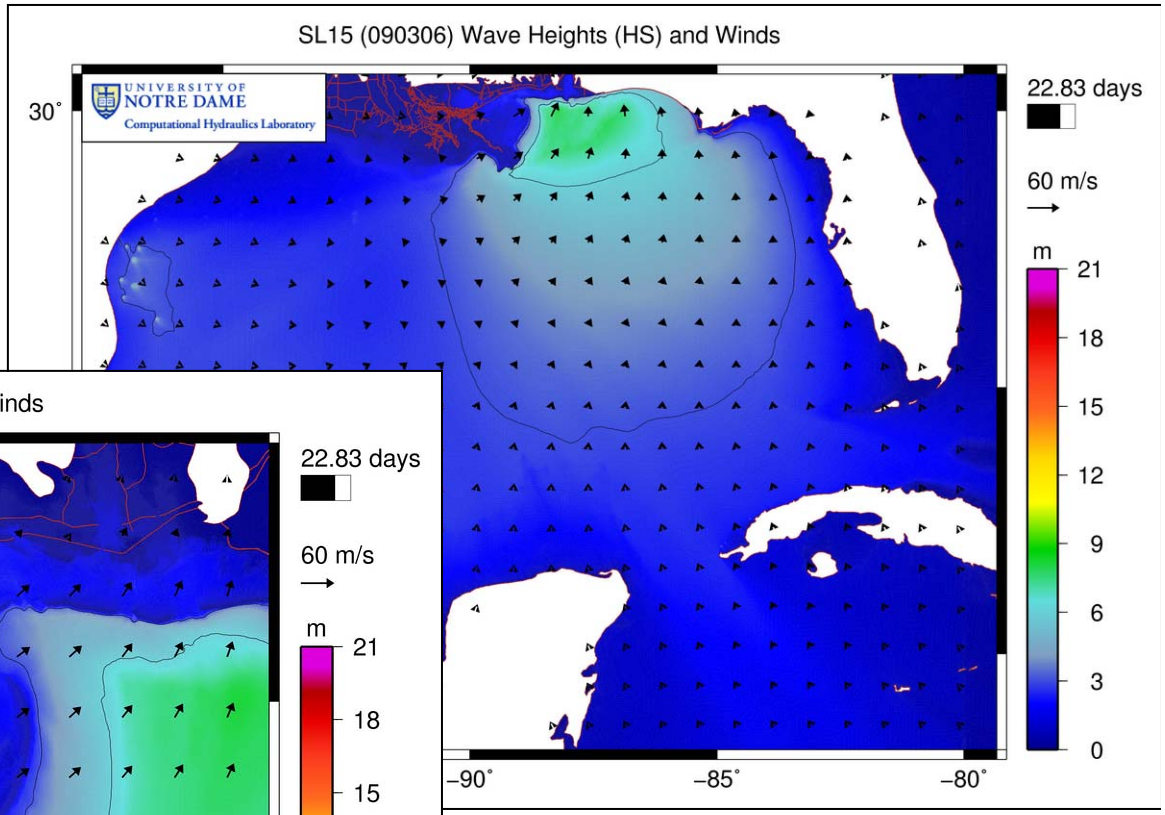

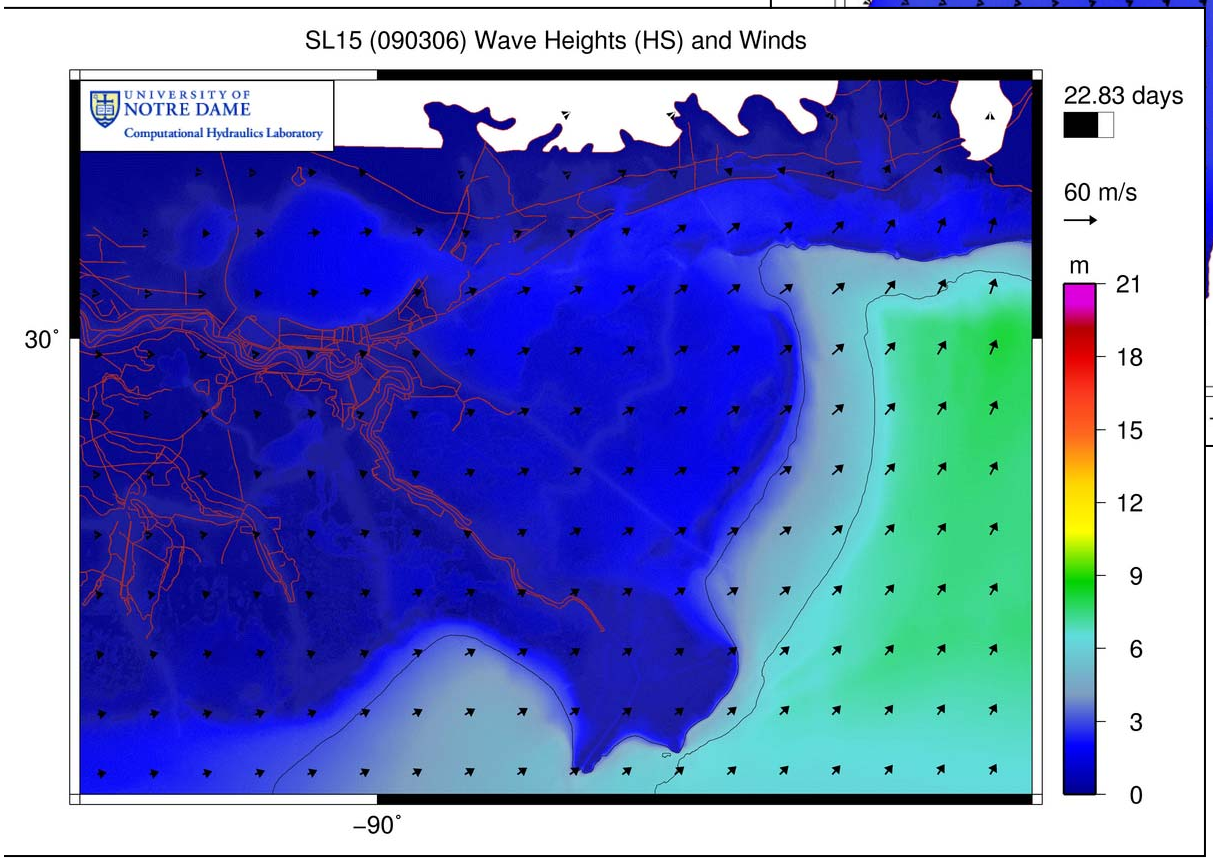

Hurricane Katrina

Wave Heights

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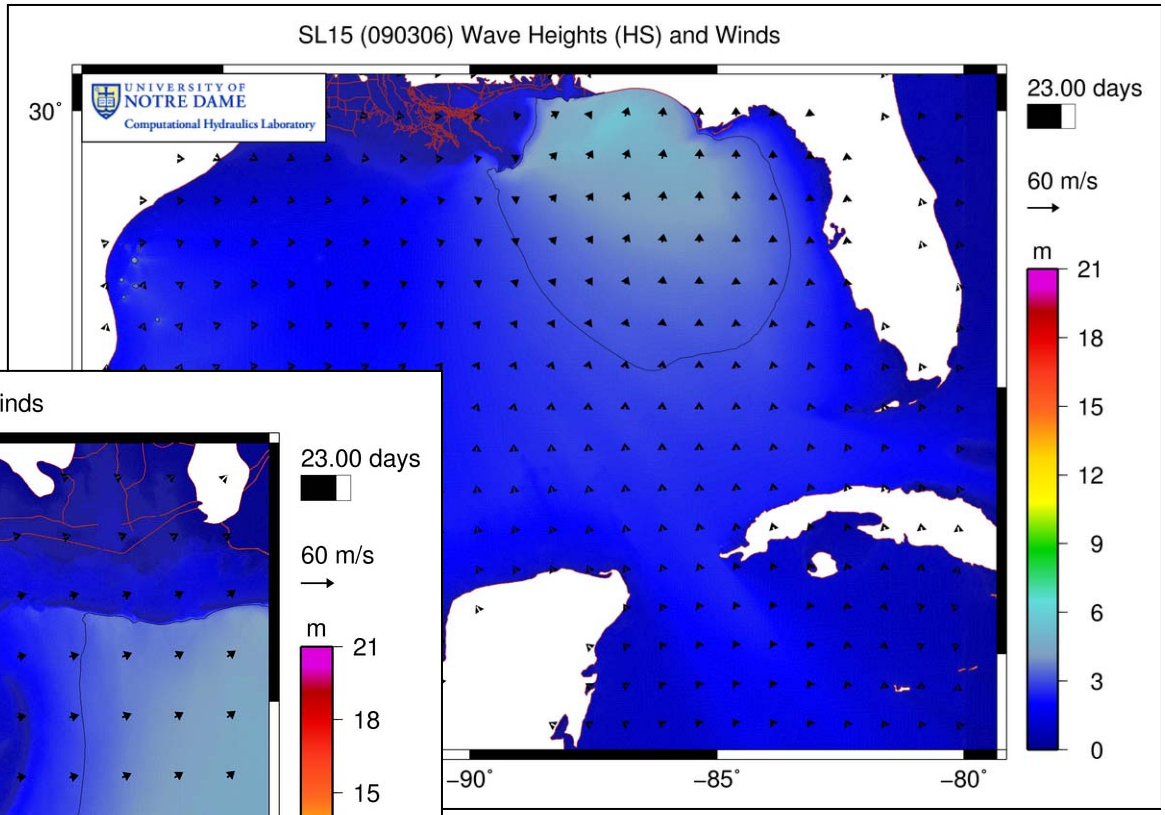

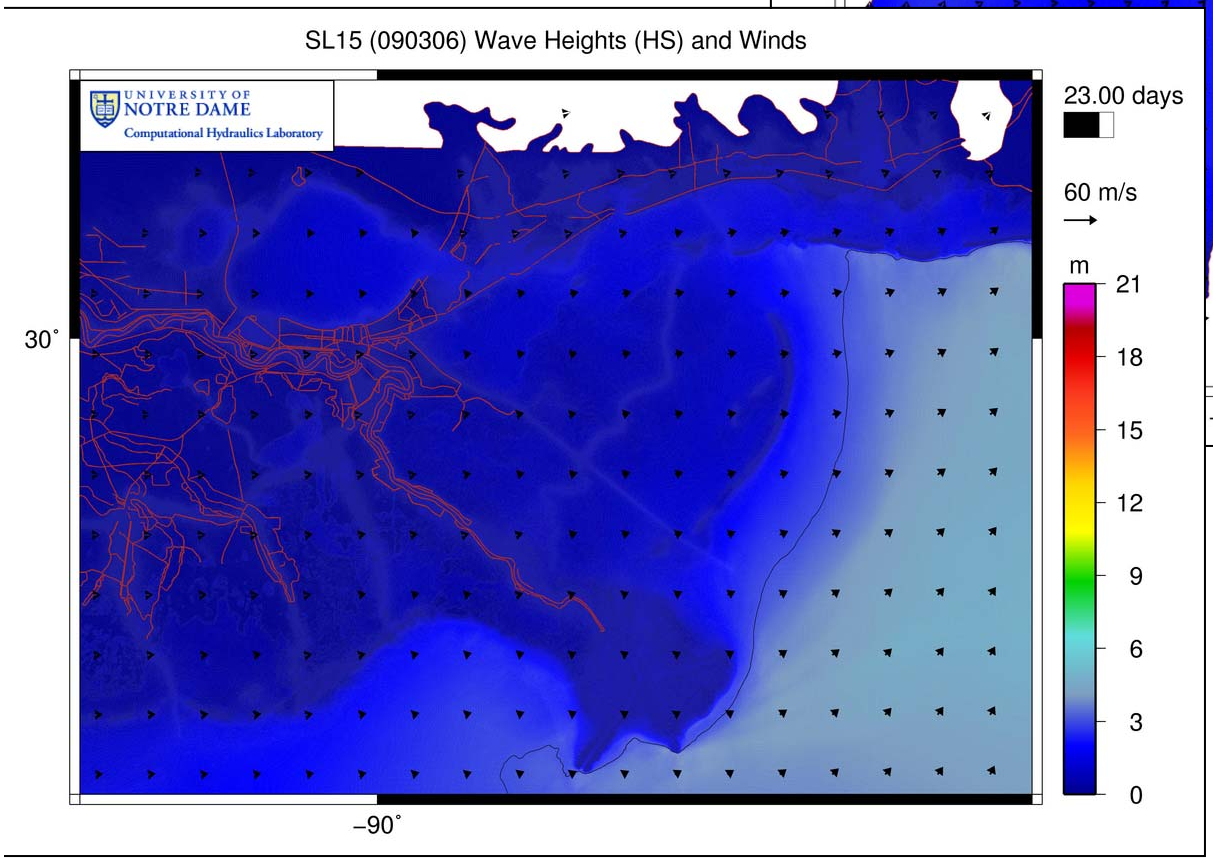

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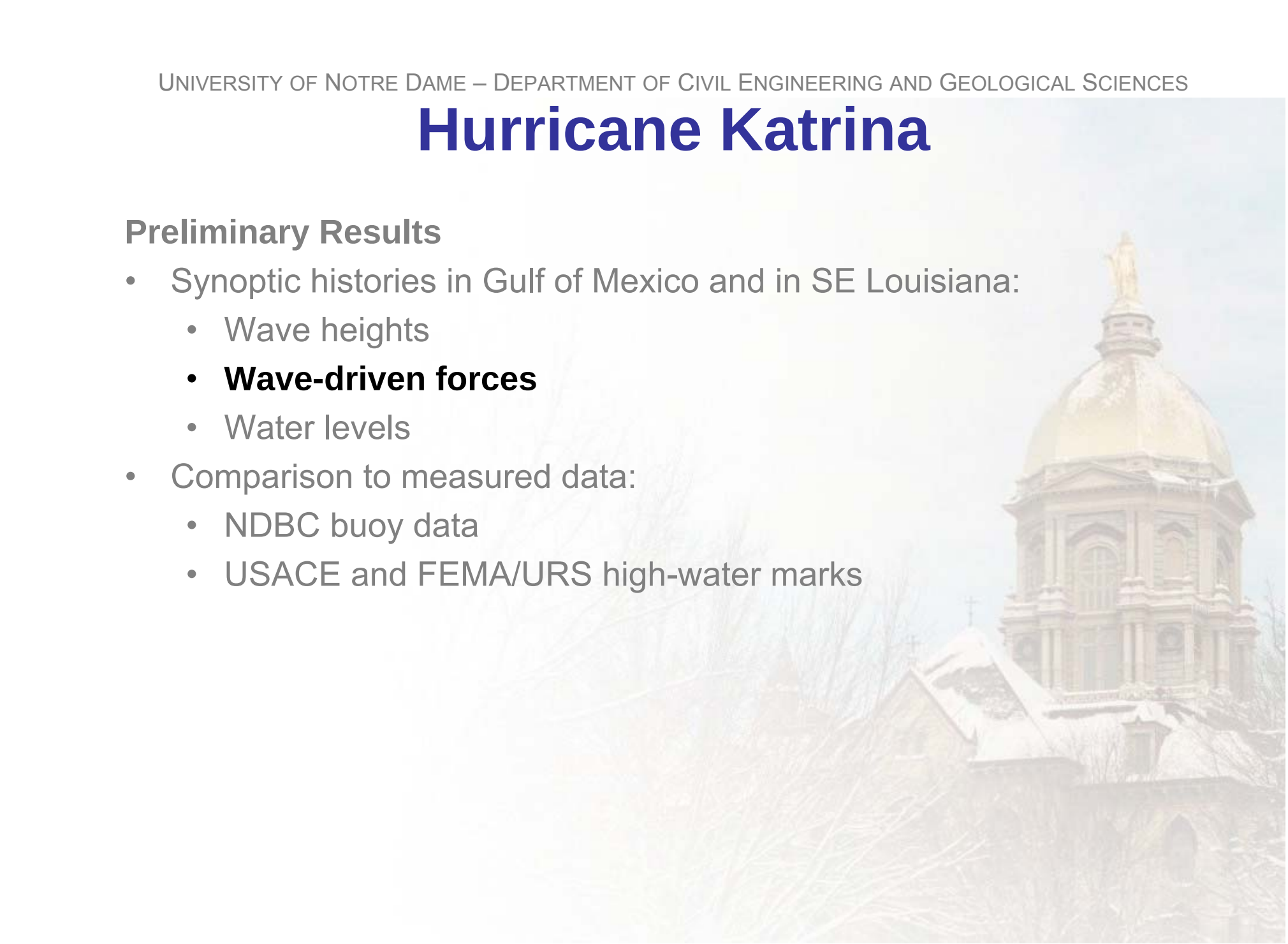
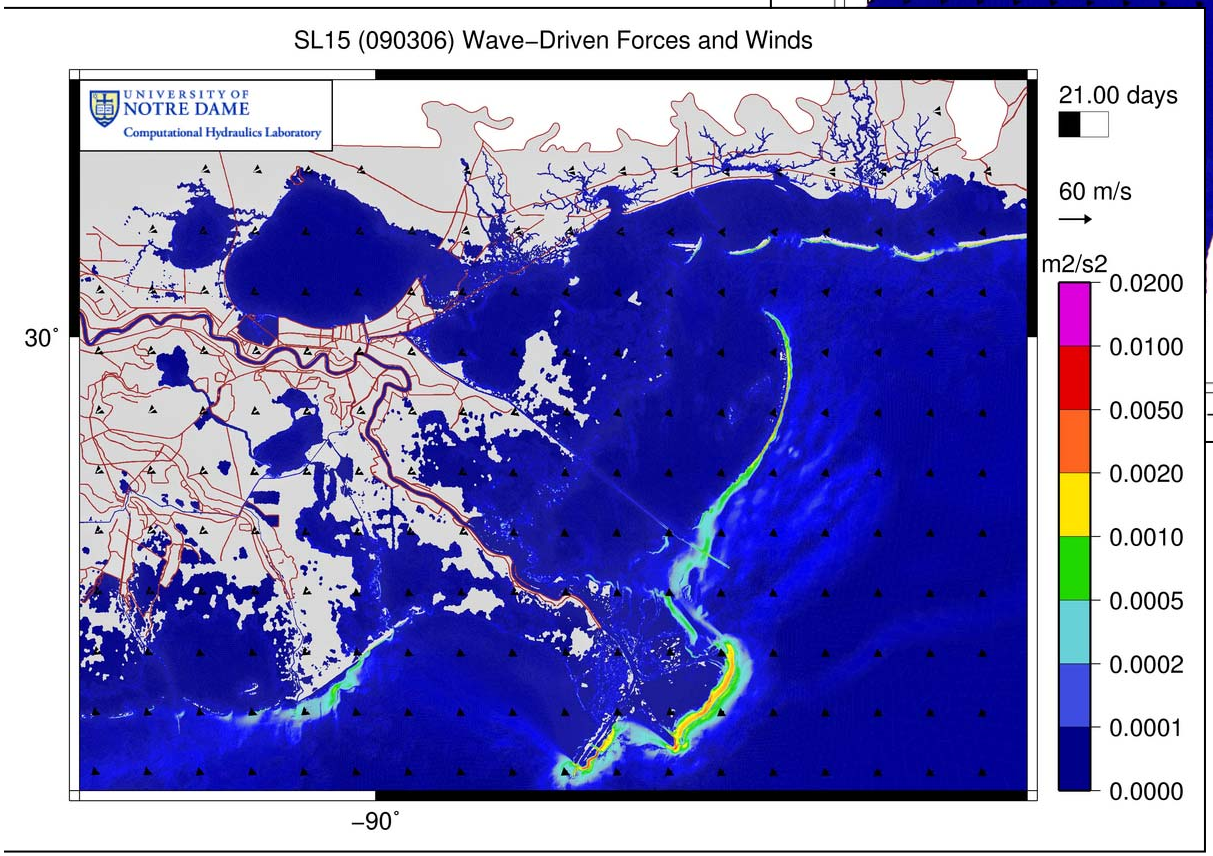
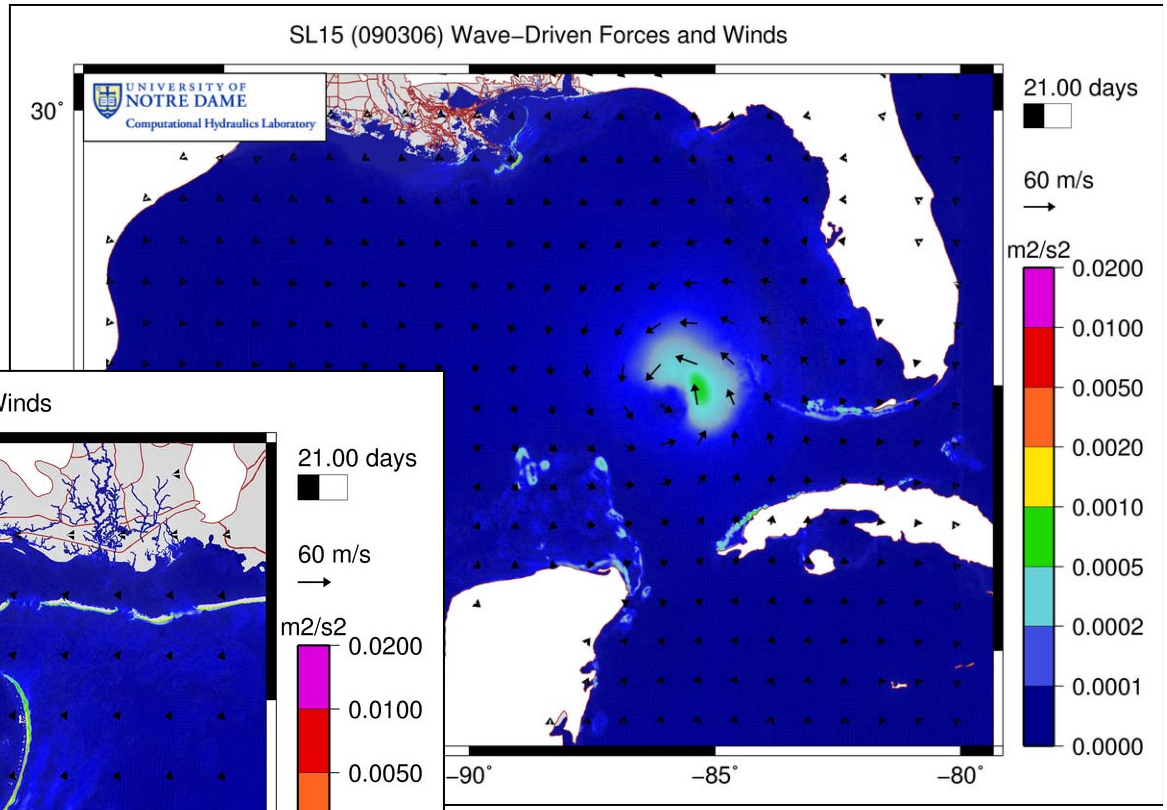


Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/0000Z





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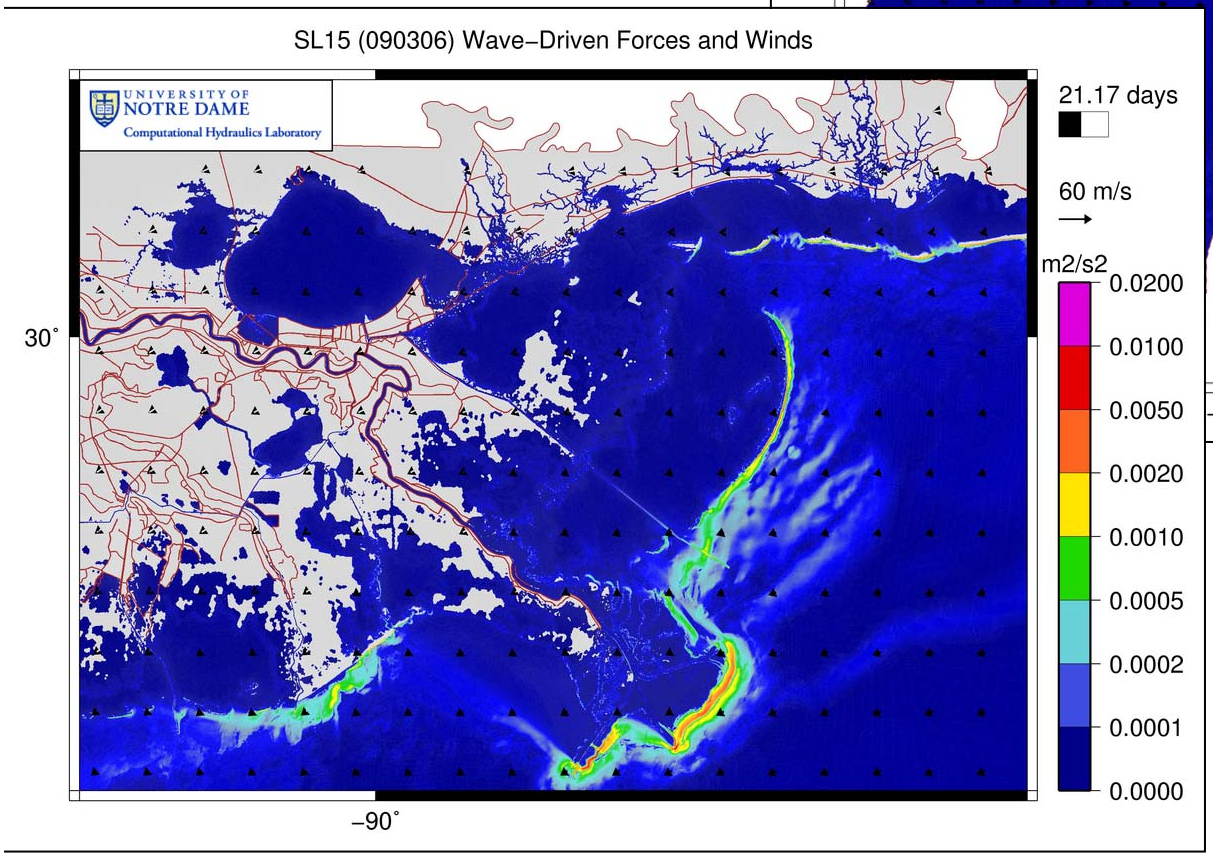
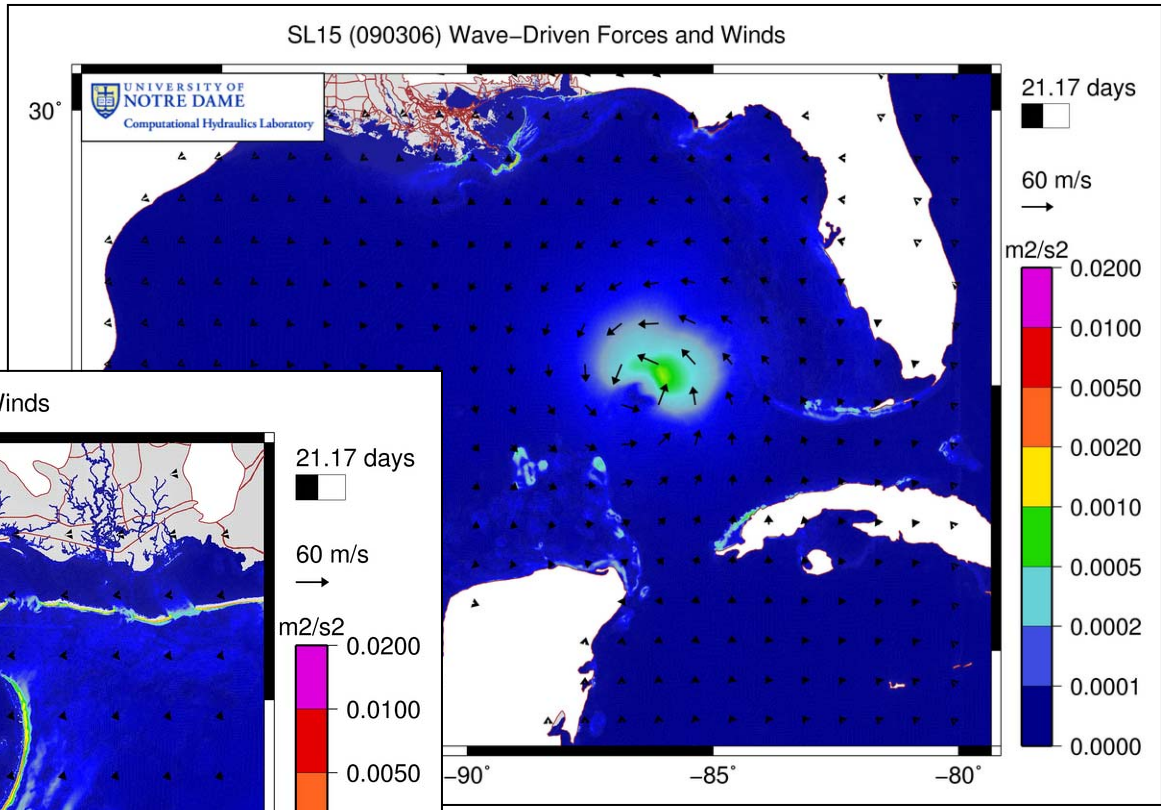
Wave-Driven Forces

- 2005/08/28/0400Z





Hurricane Katrina

Wave-Driven Forces

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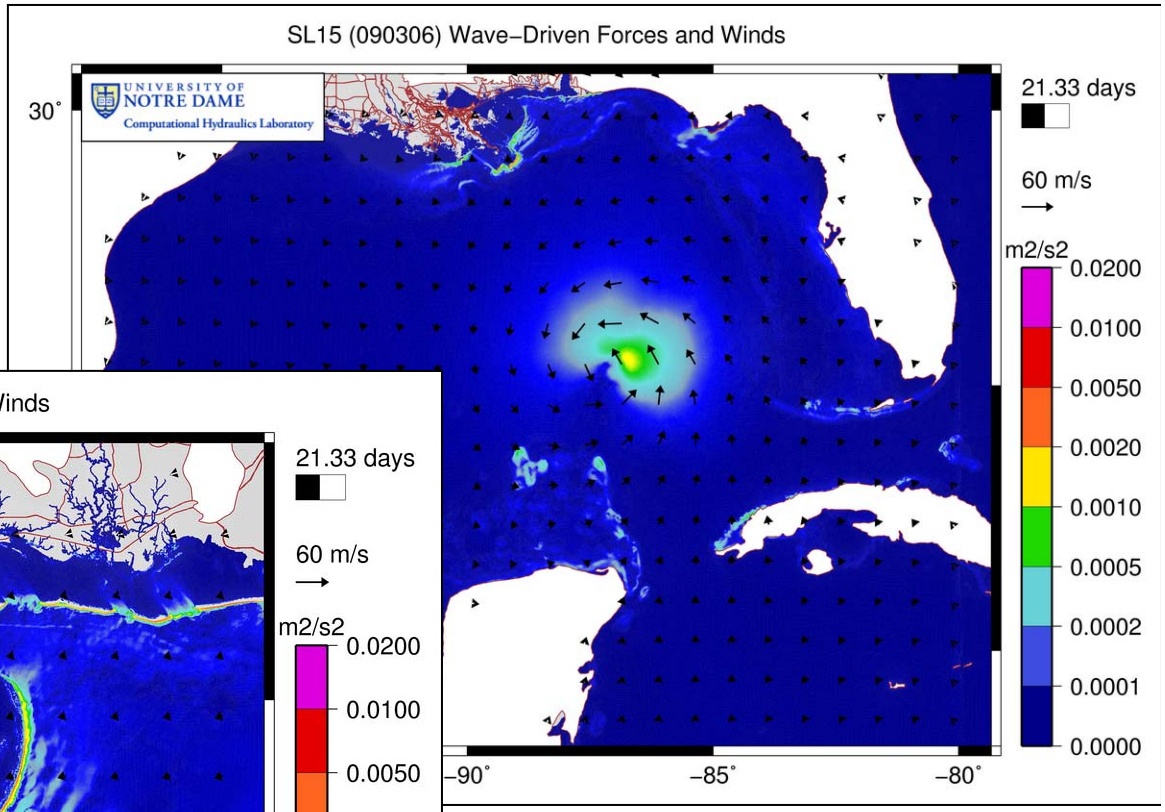
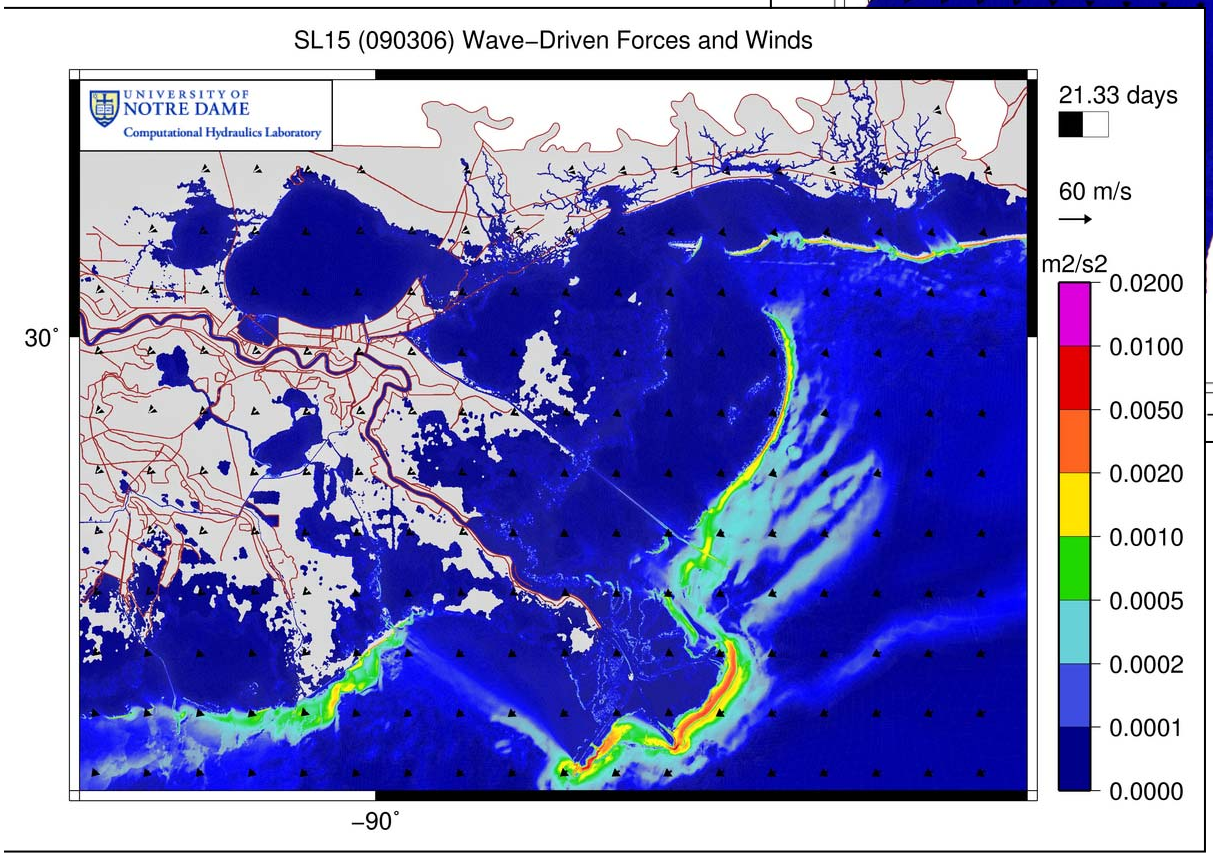
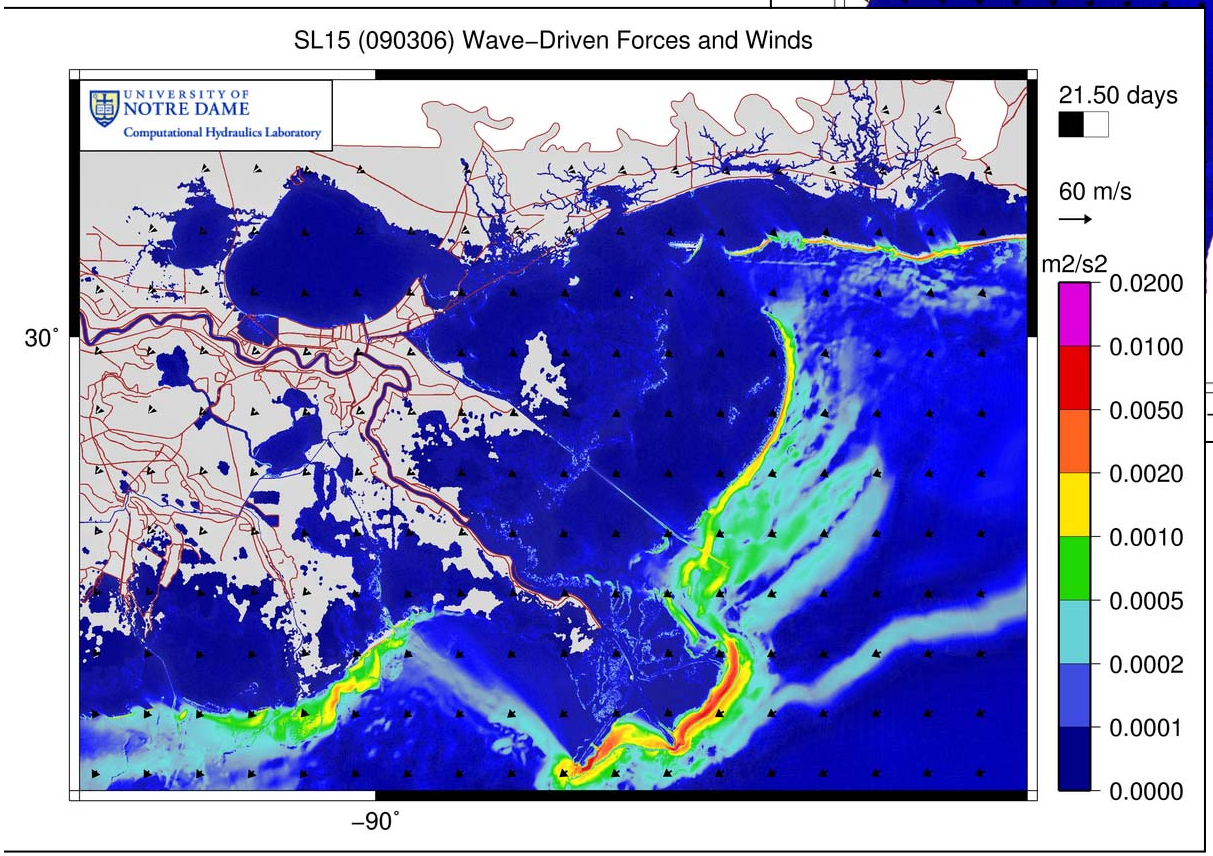


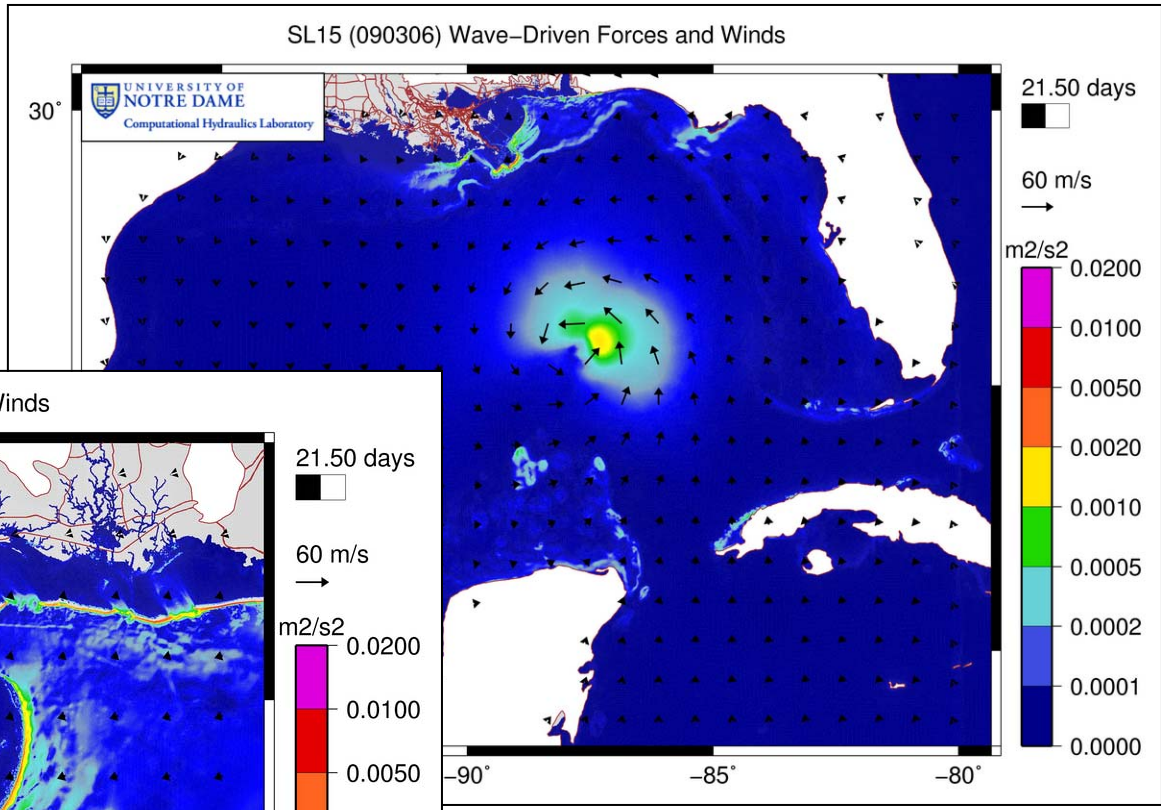


Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/1200Z

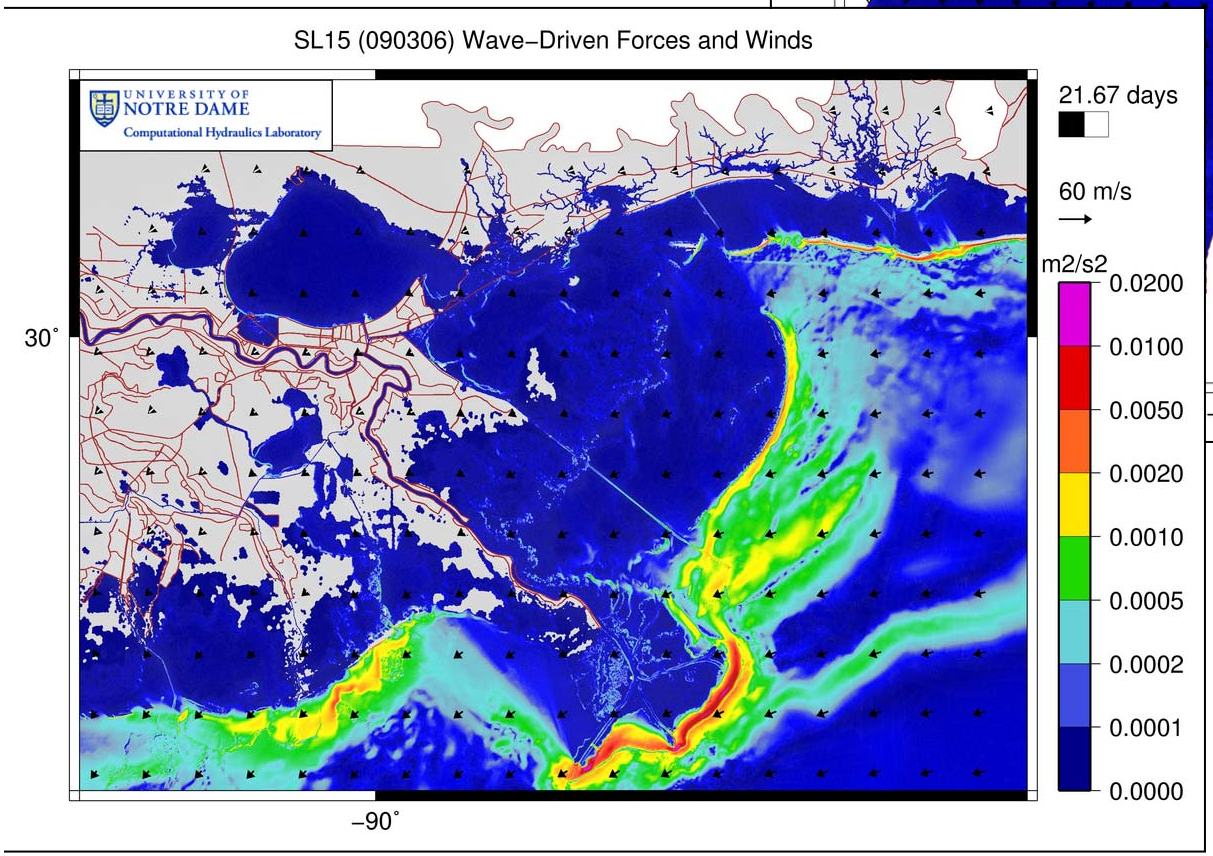


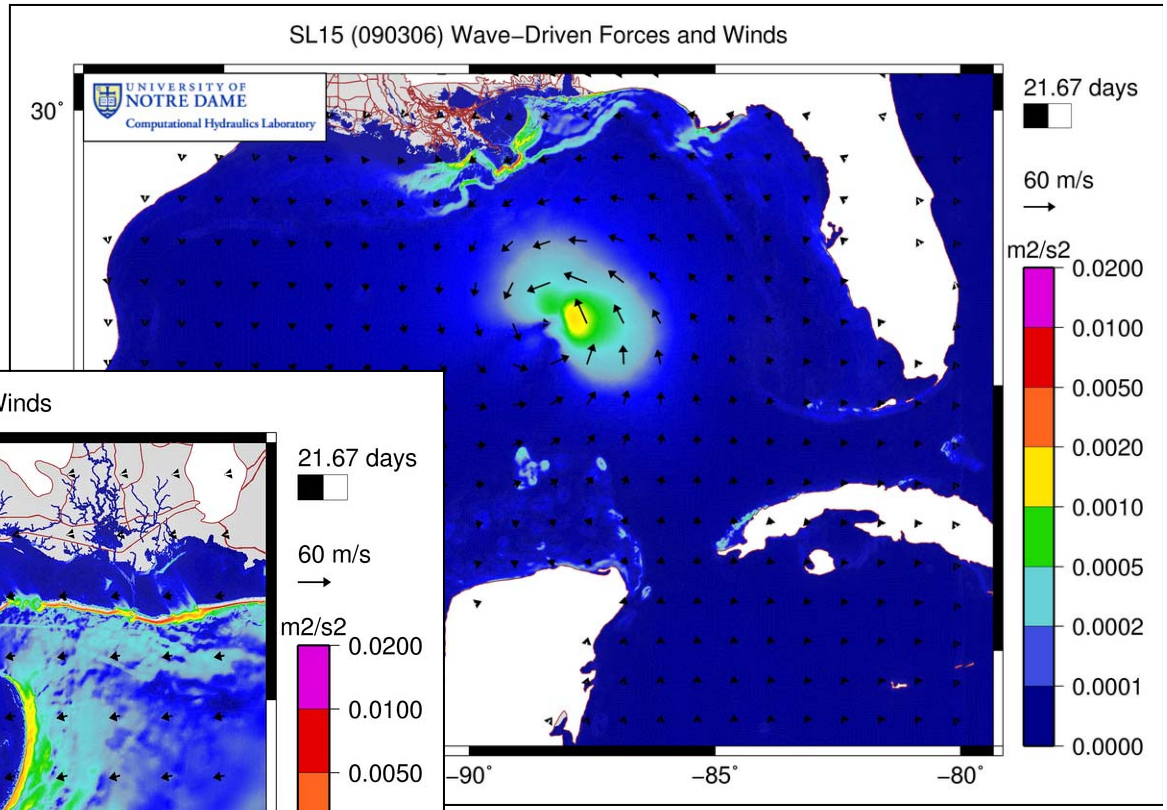


Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/1600Z

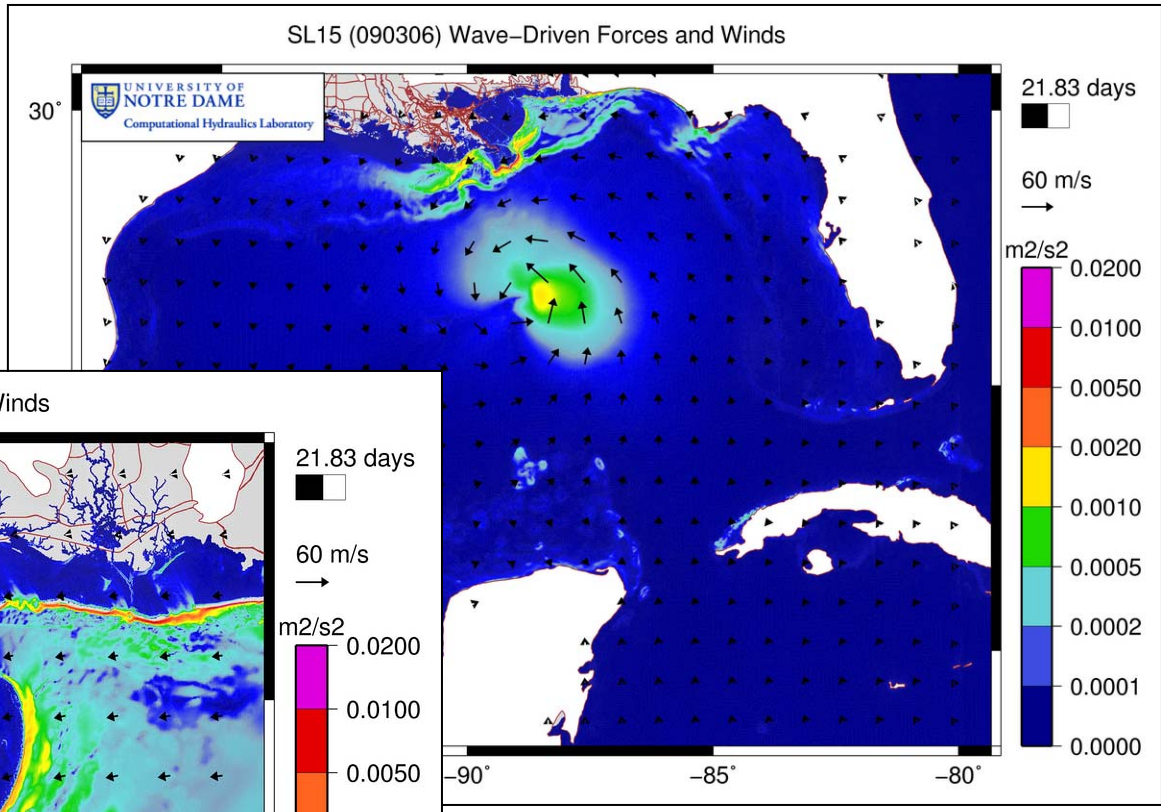


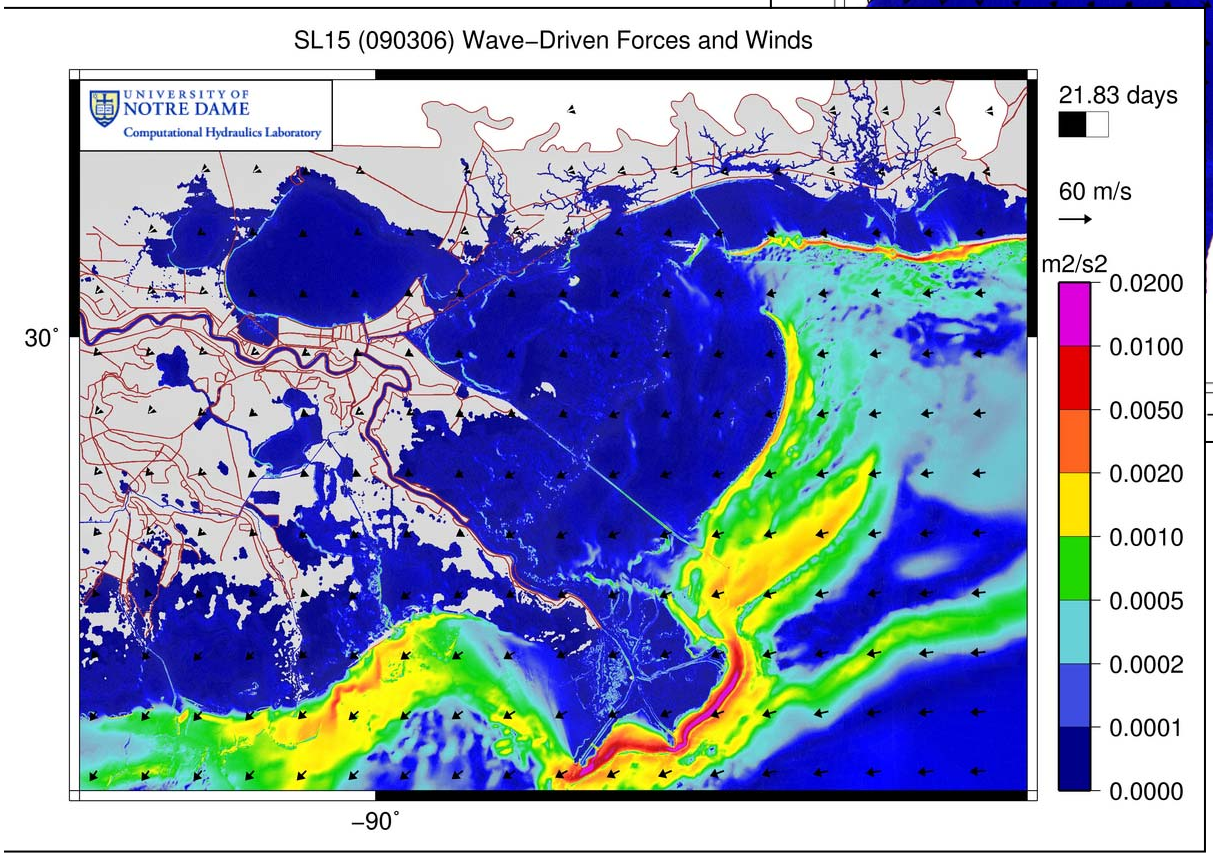


Hurricane Katrina

Wave-Driven Forces

- 2005/08/28/2000Z

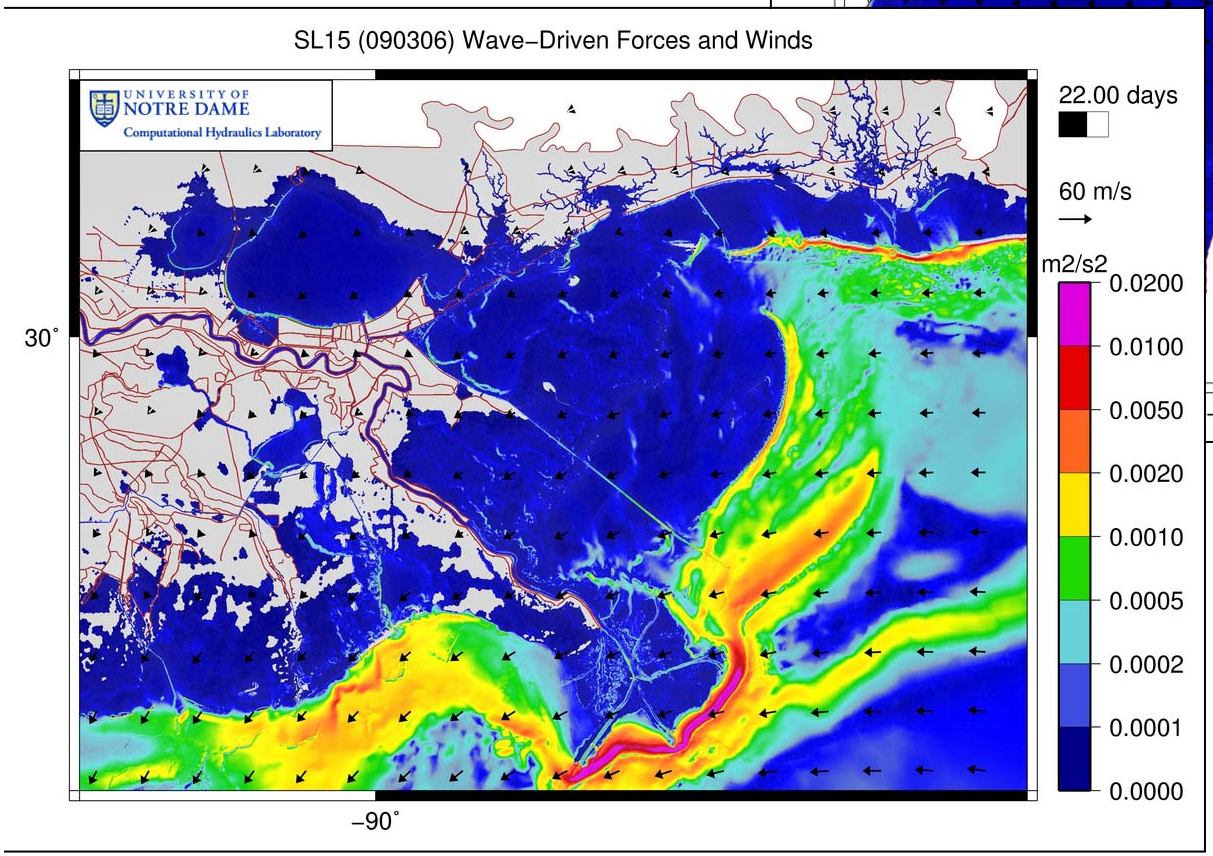


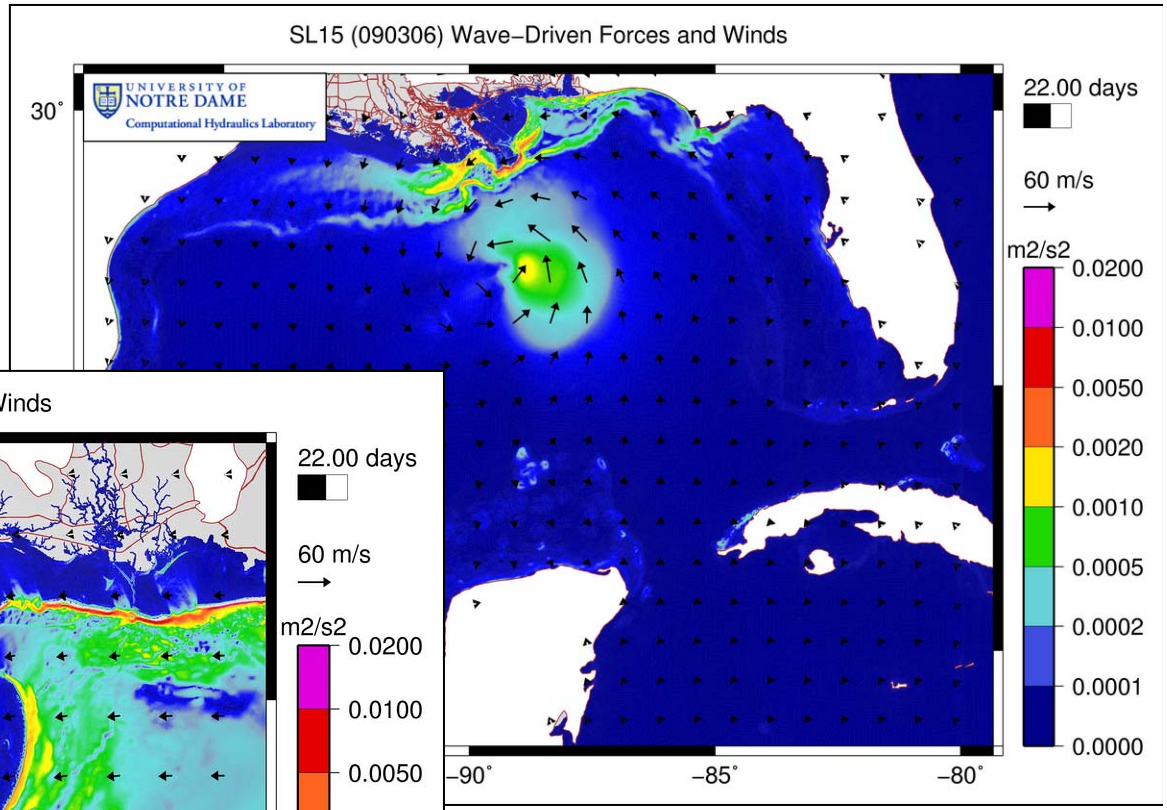


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/0000Z

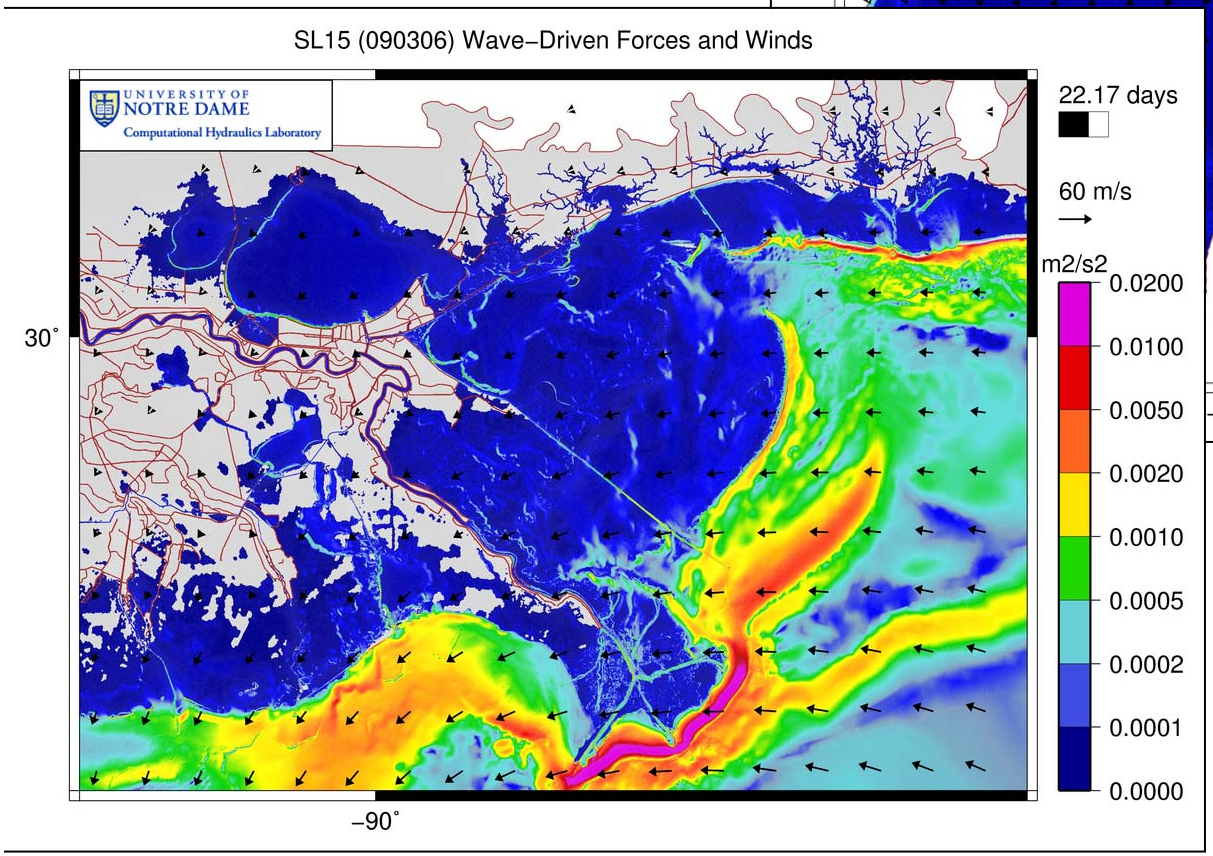


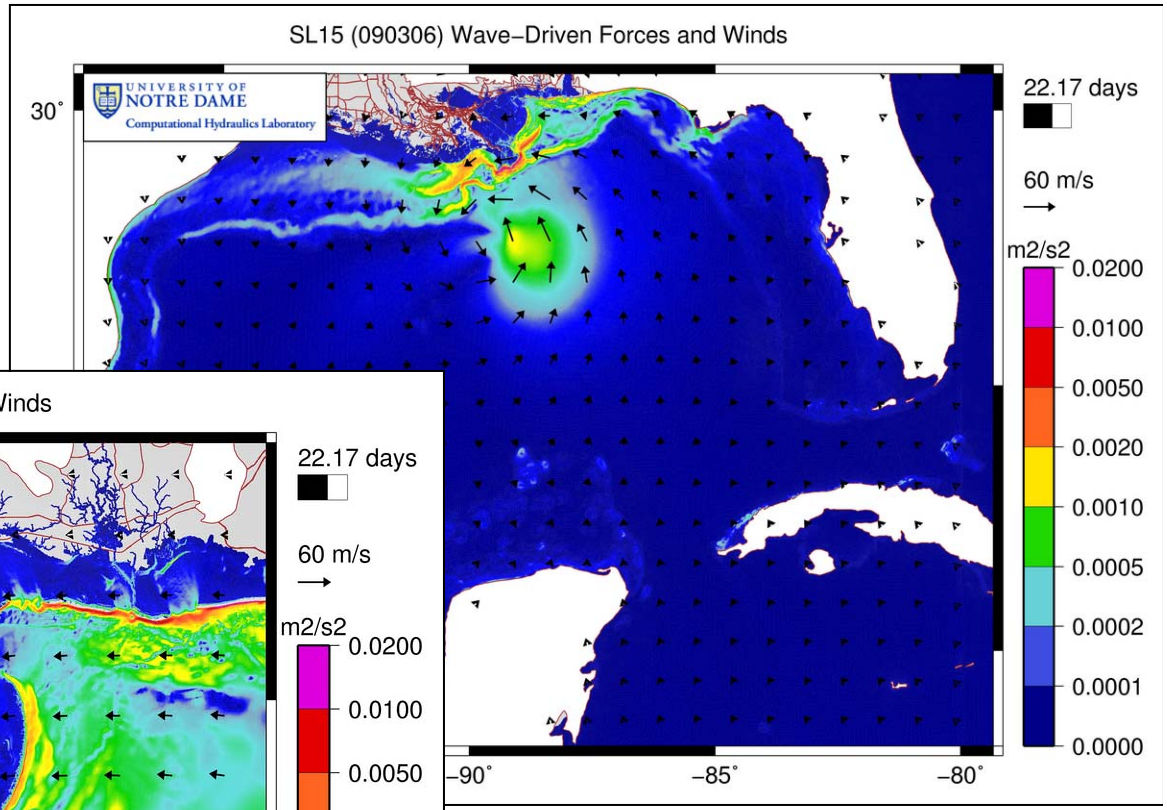


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/0400Z

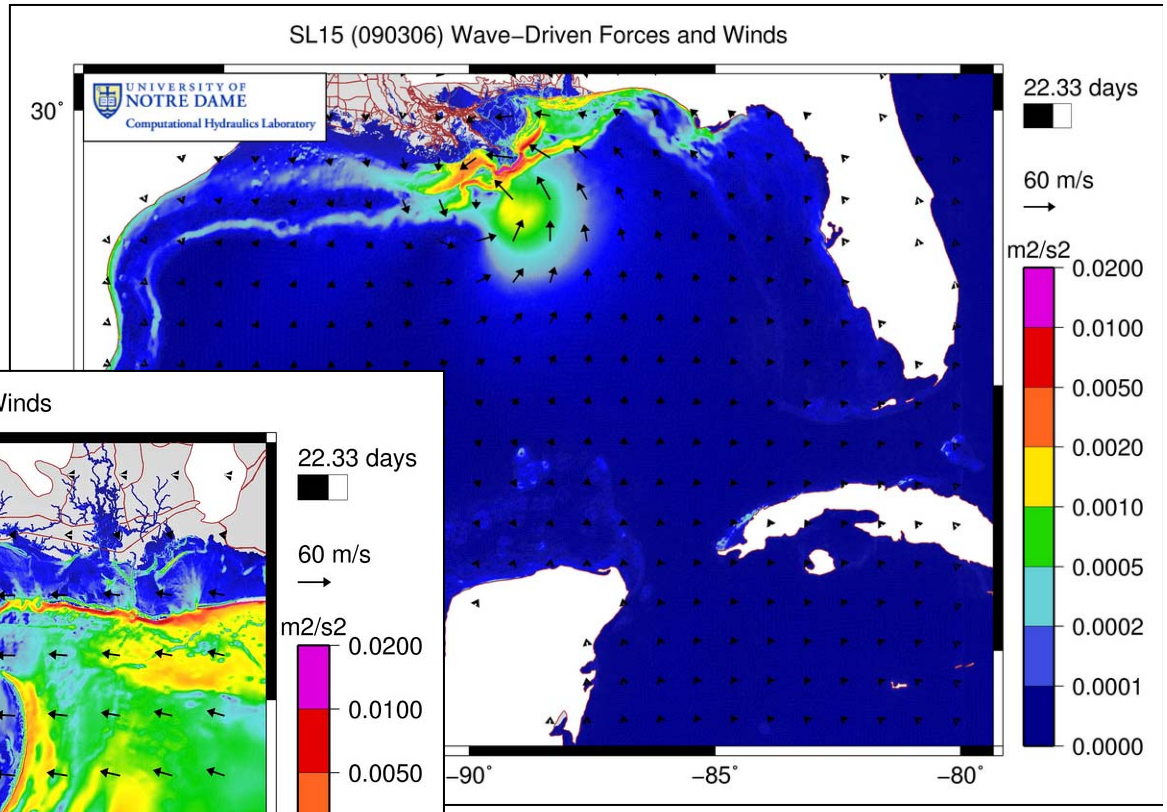


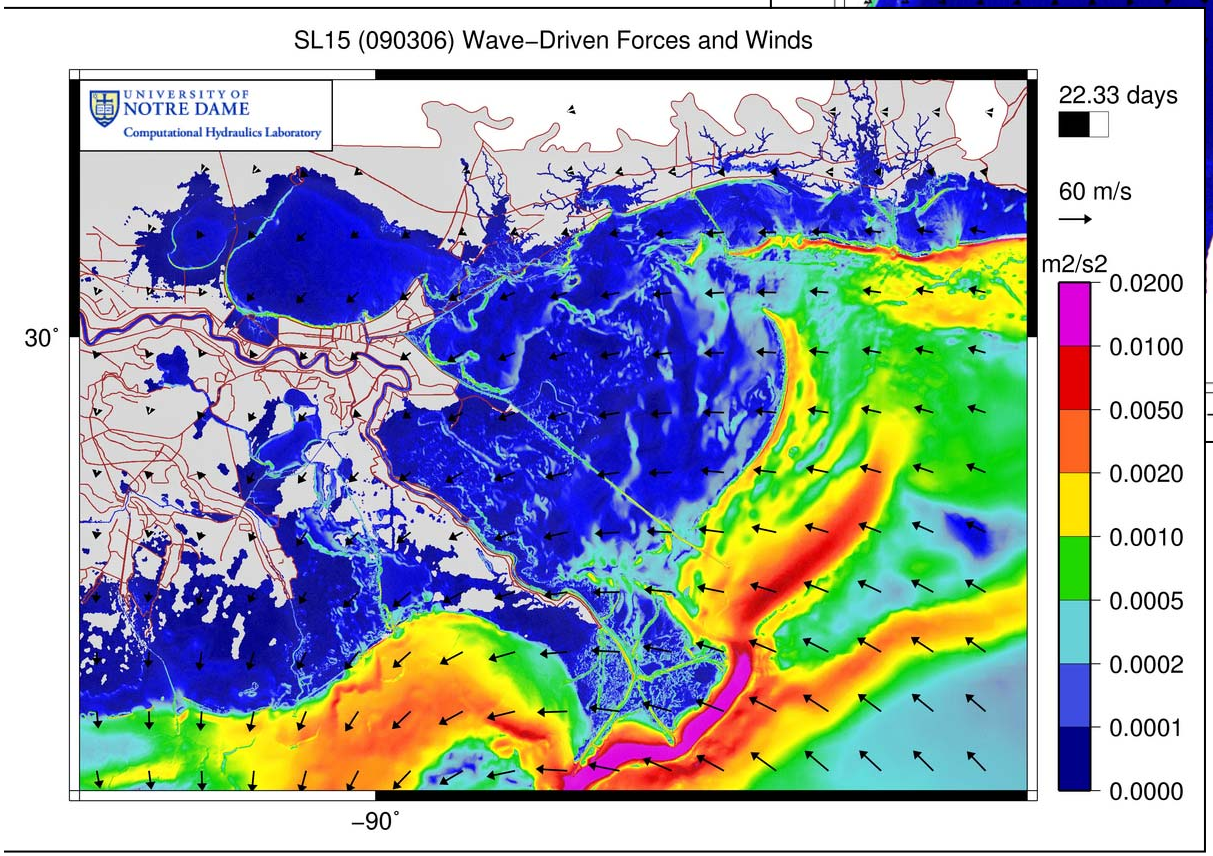


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/0800Z

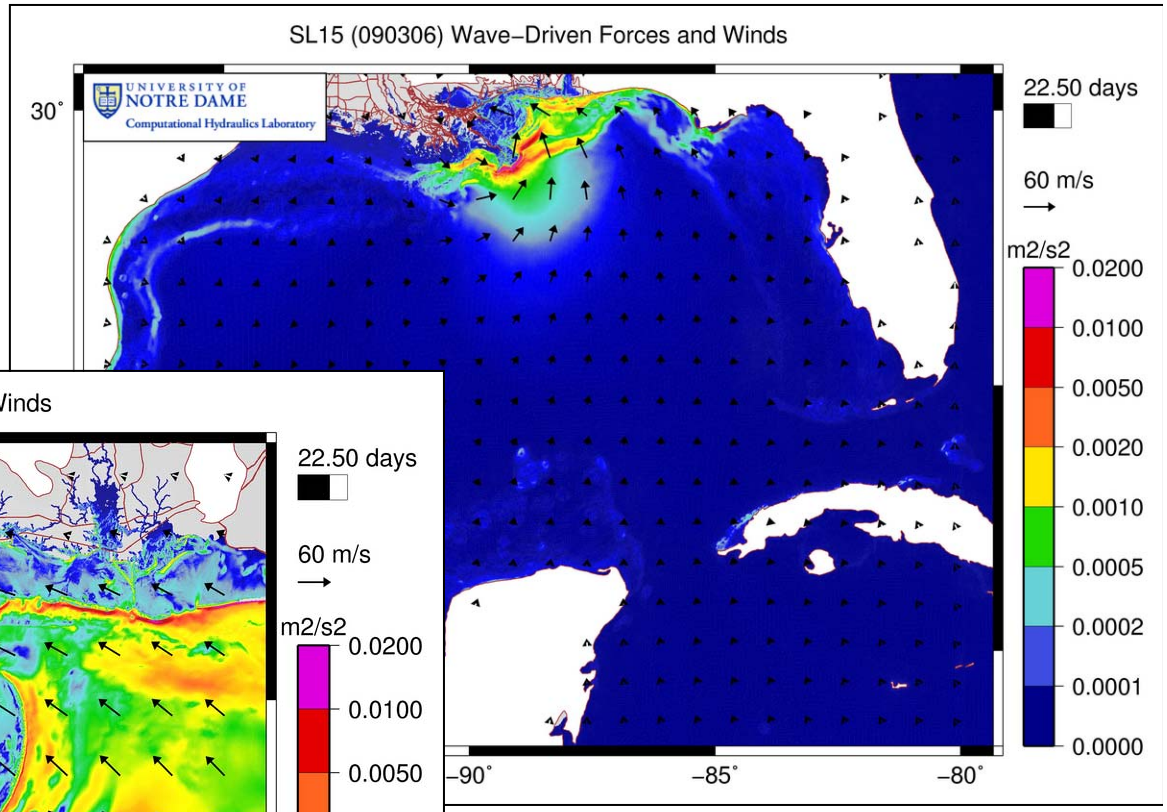


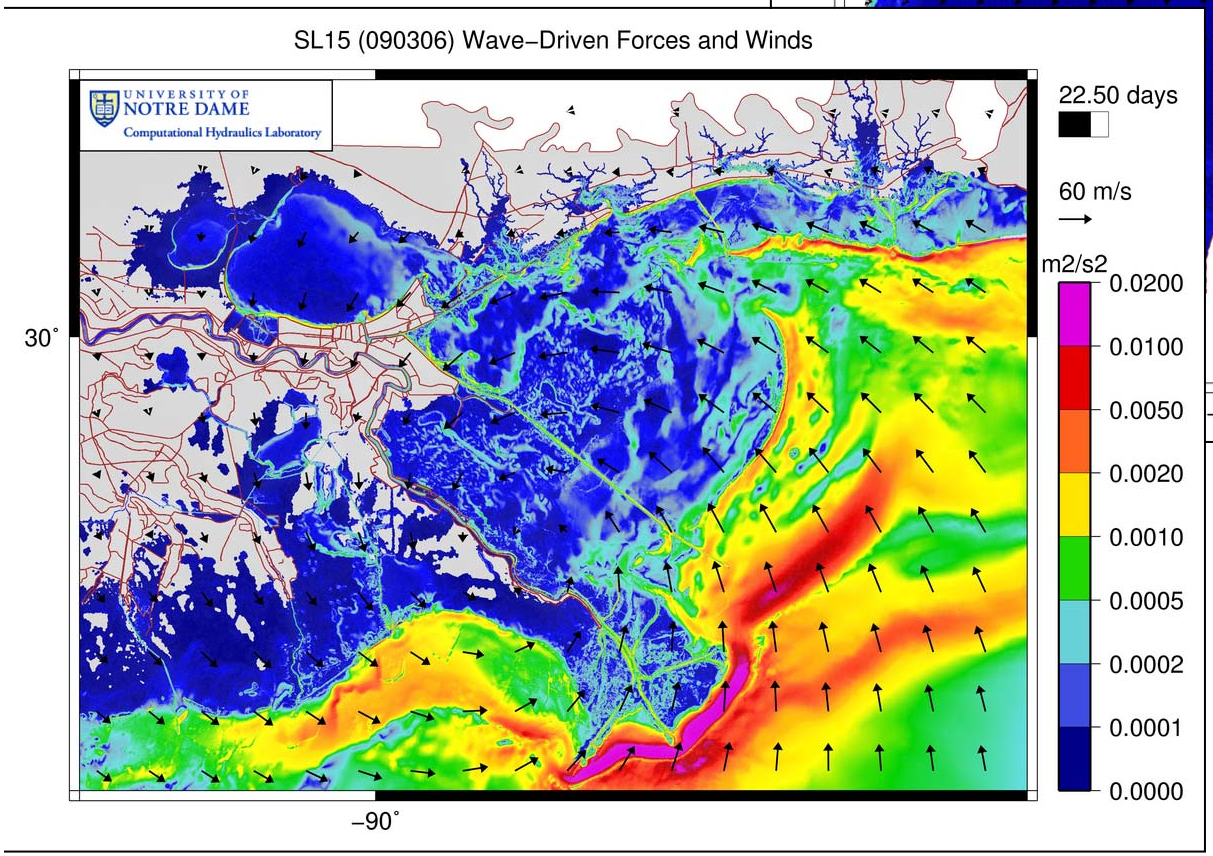


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/1200Z

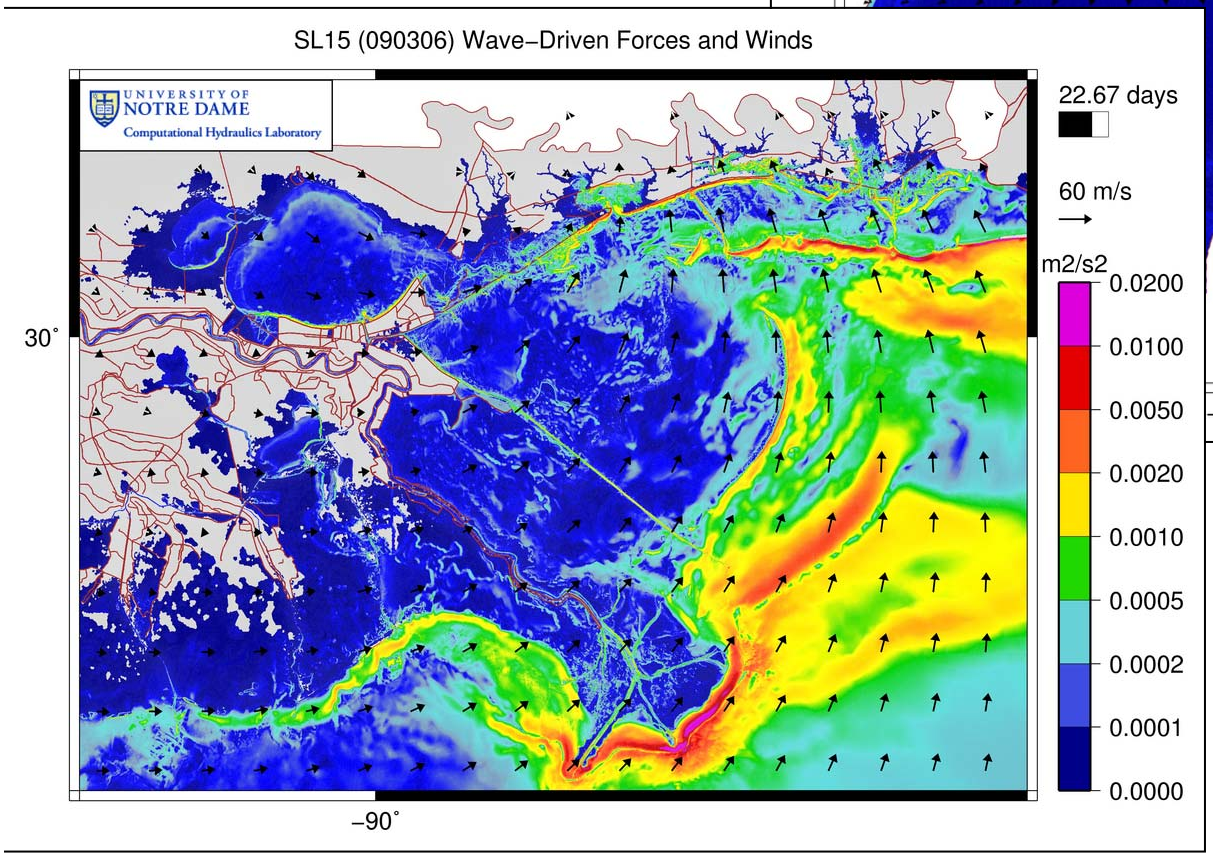


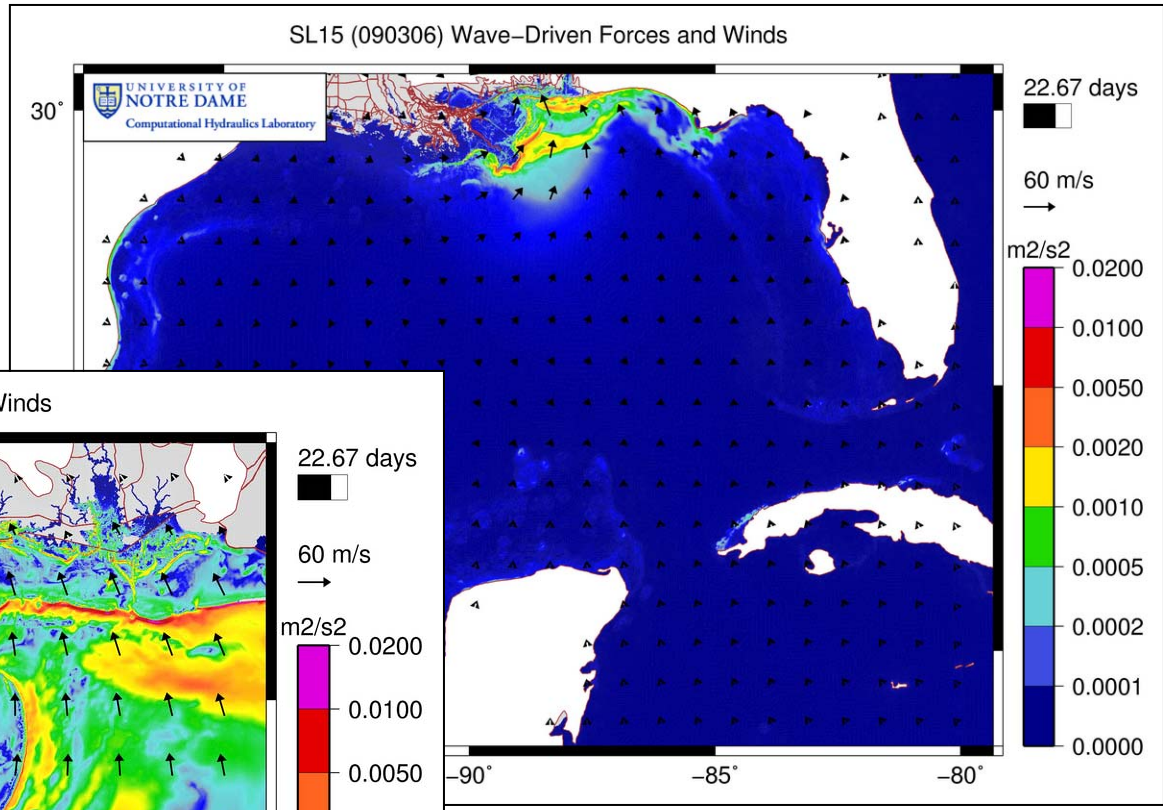


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/1600Z

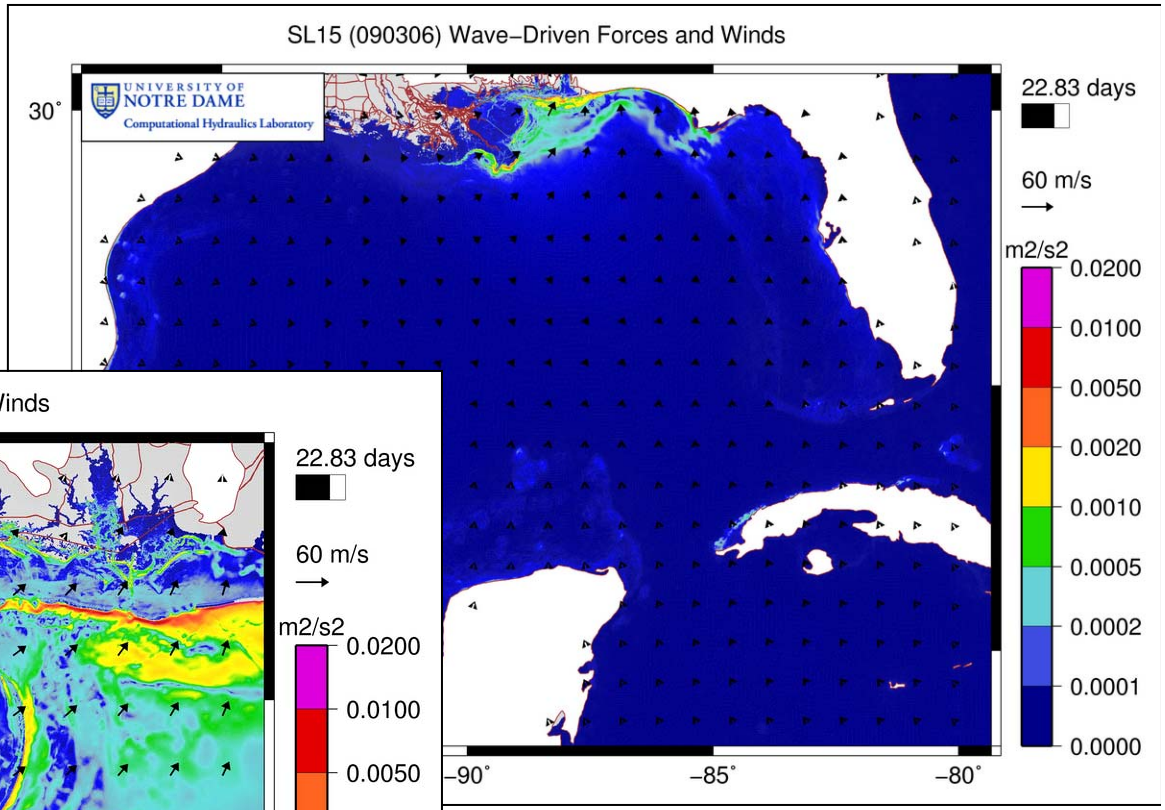


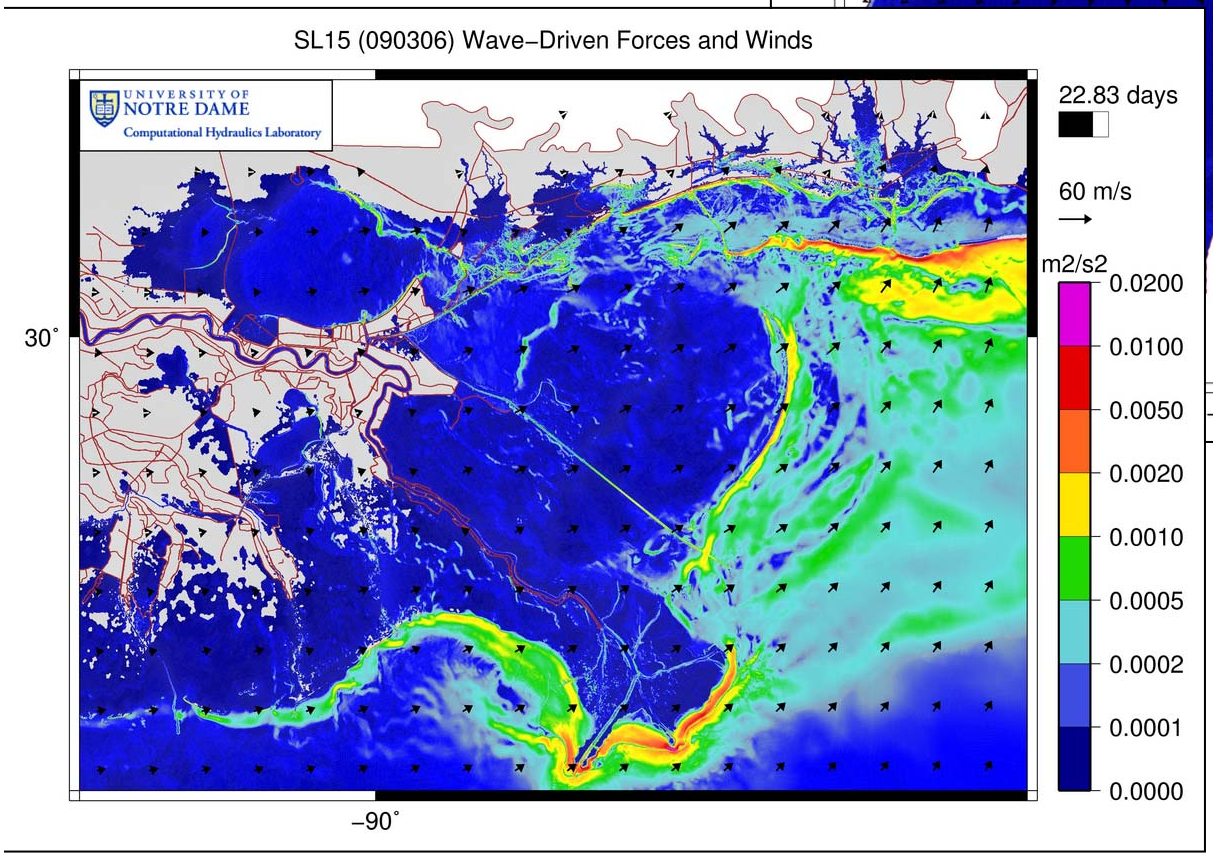


Hurricane Katrina

Wave-Driven Forces

- 2005/08/29/2000Z

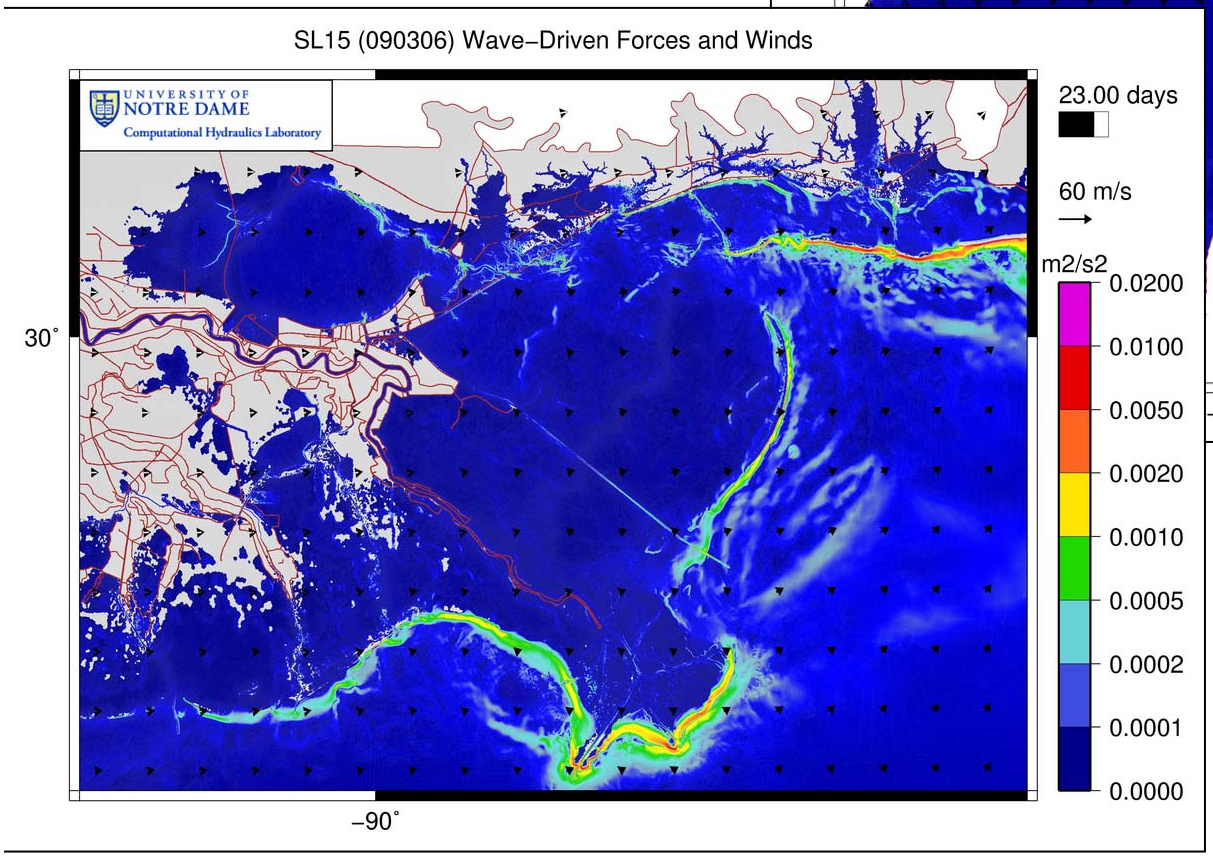


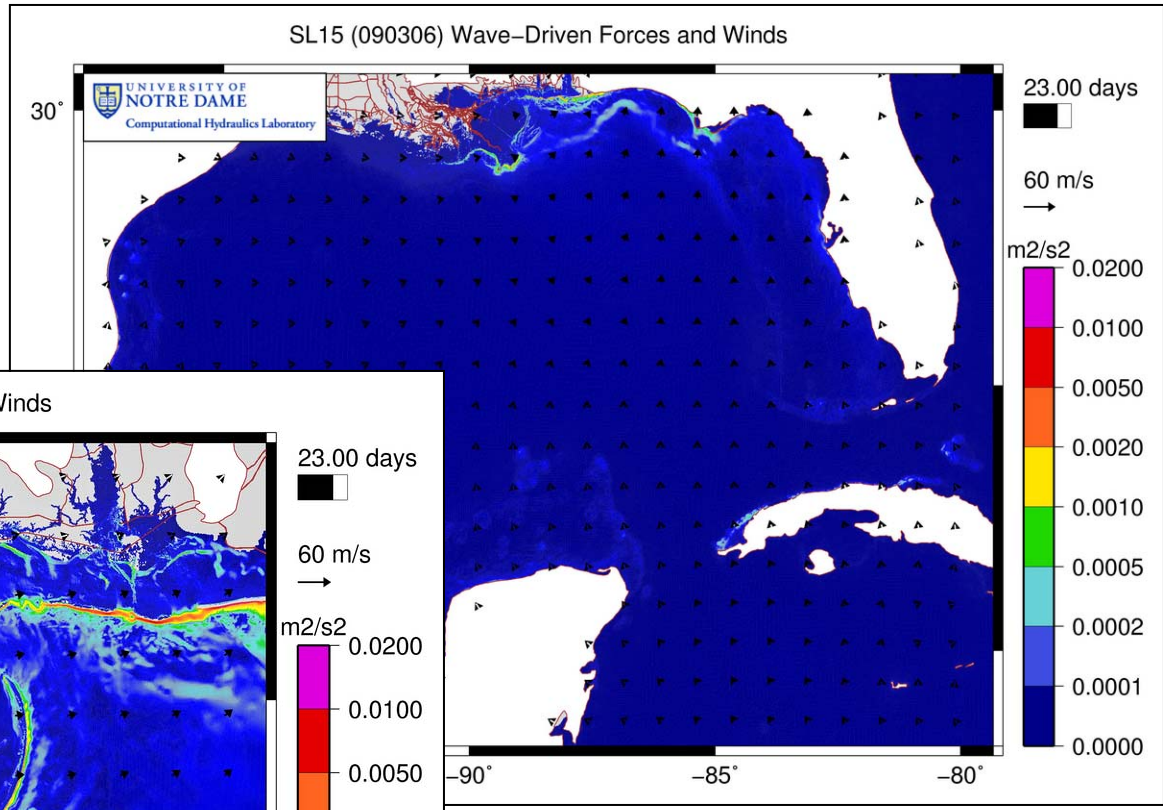


Hurricane Katrina

Wave-Driven Forces

- 2005/08/30/0000Z





Hurricane Katrina

Preliminary Results

- Synoptic histories in Gulf of Mexico and in SE Louisiana:
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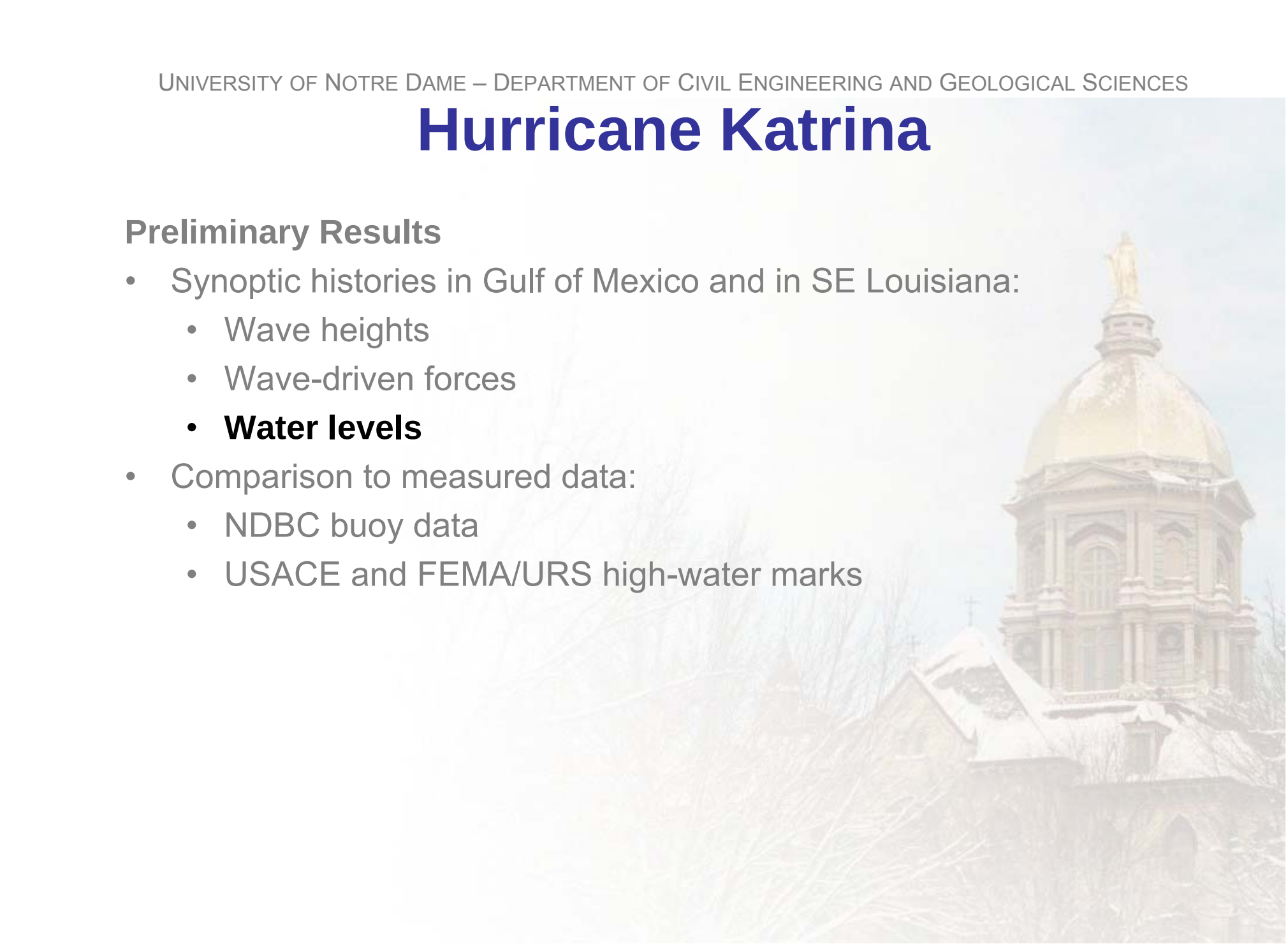
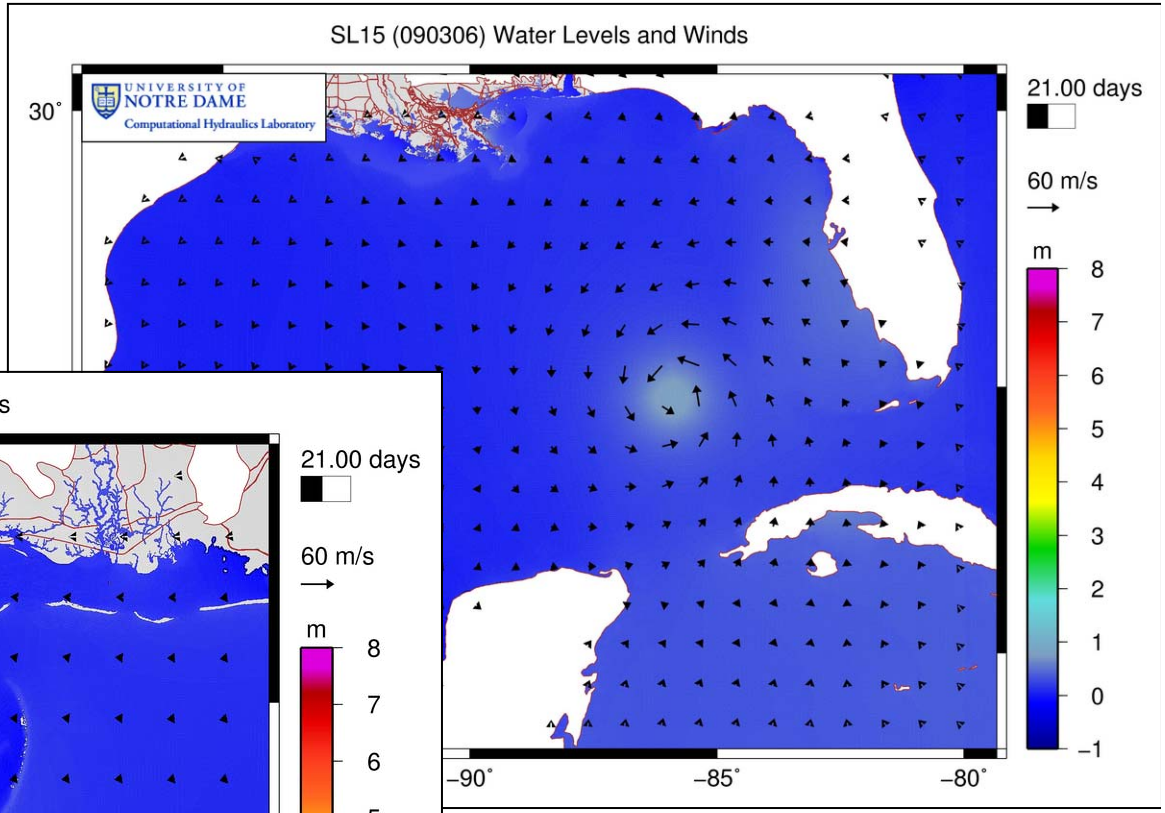
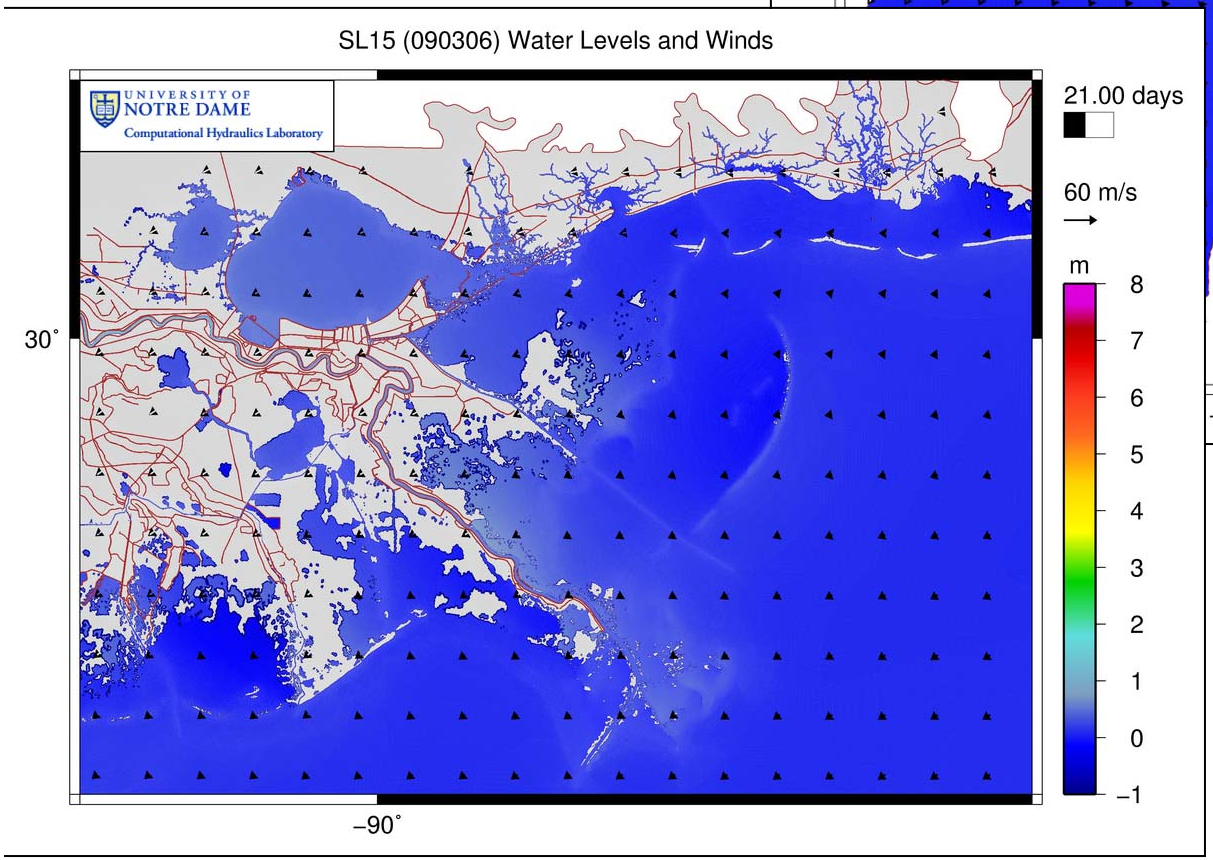


Hurricane Katrina

Water Levels

- 2005/08/28/0000Z

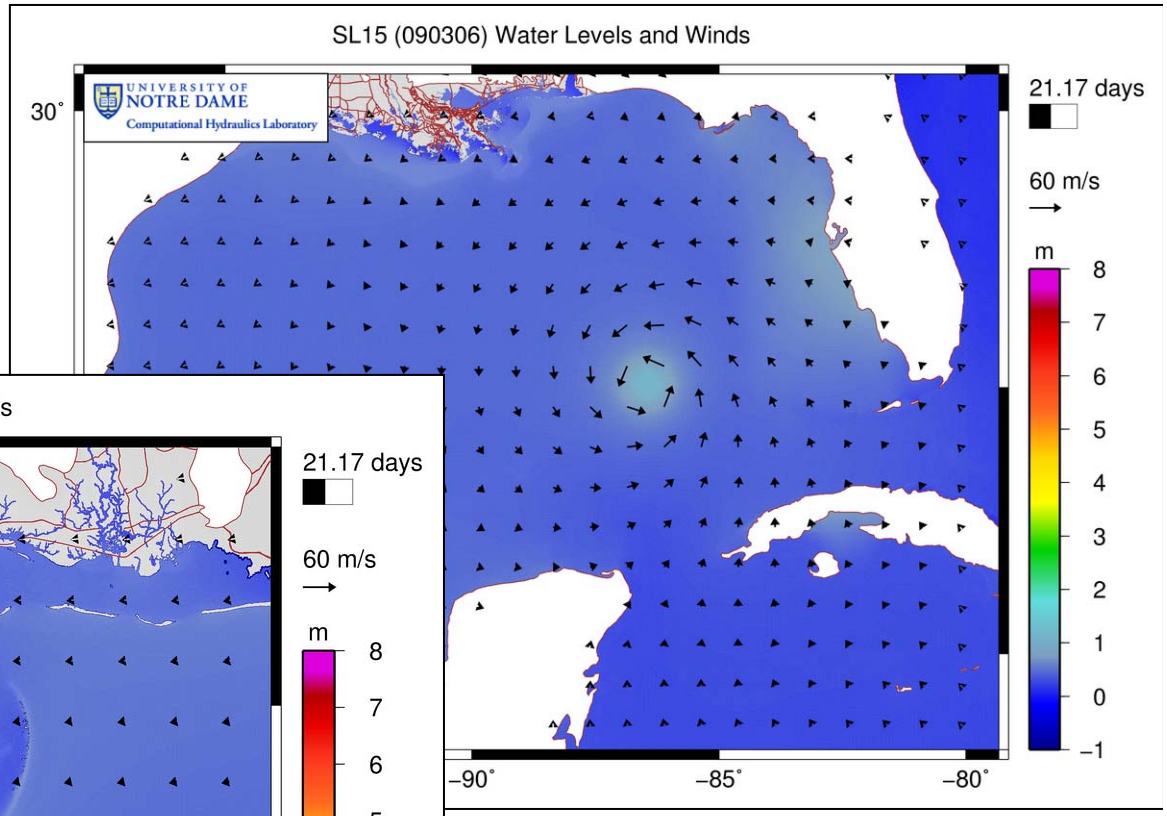


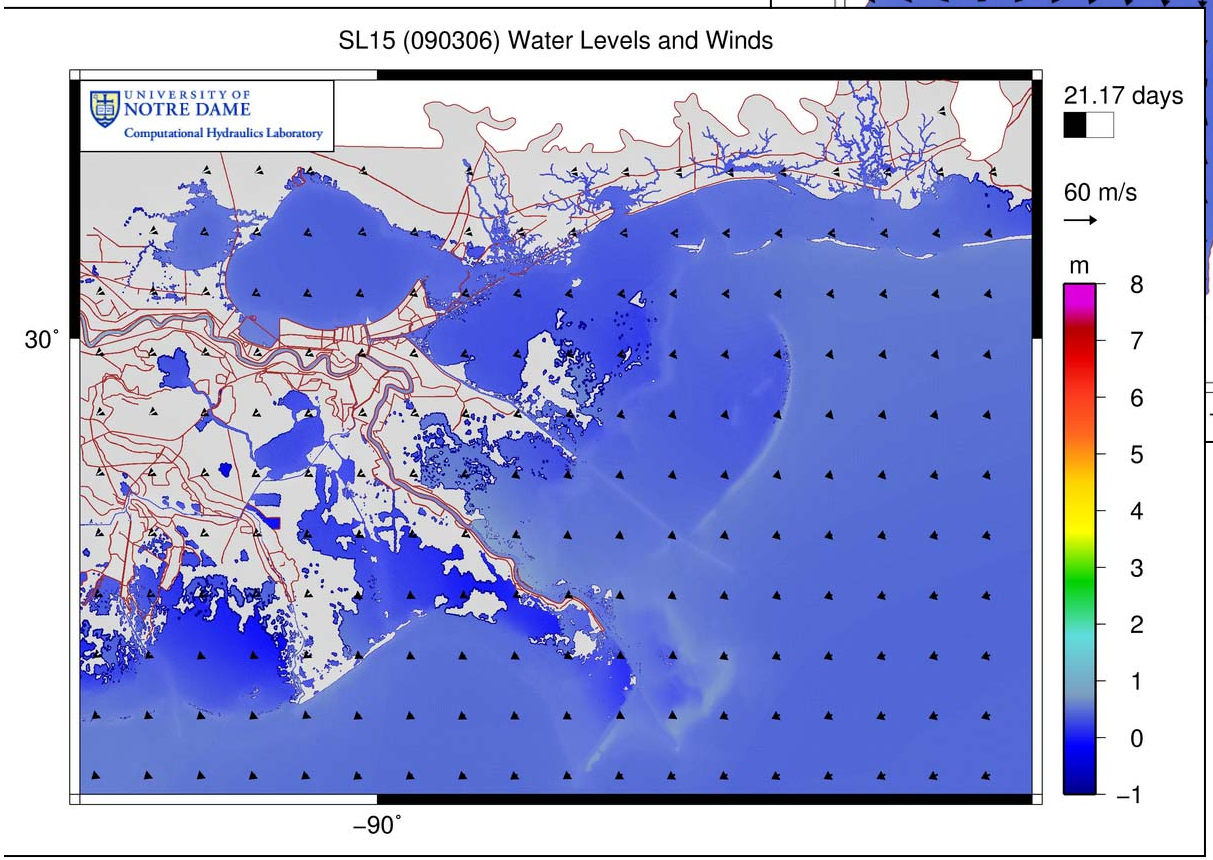


Hurricane Katrina

Water Levels

- 2005/08/28/0400Z

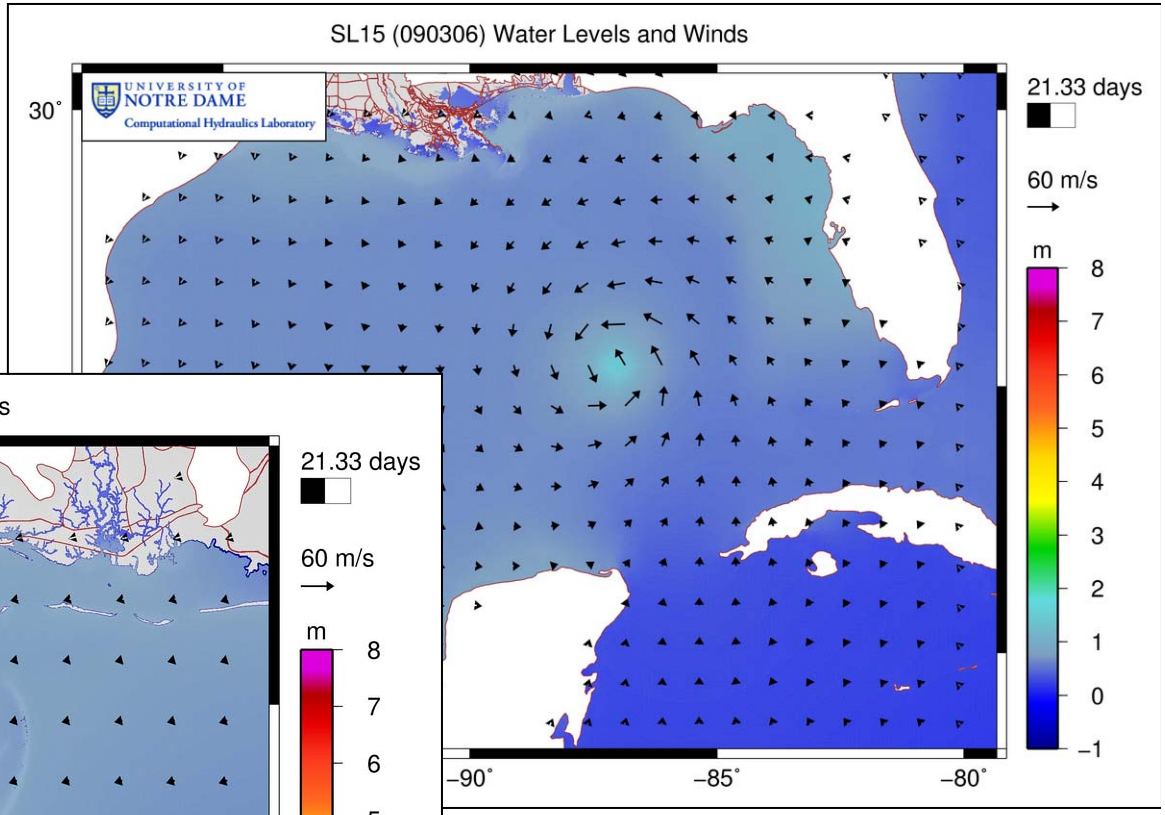


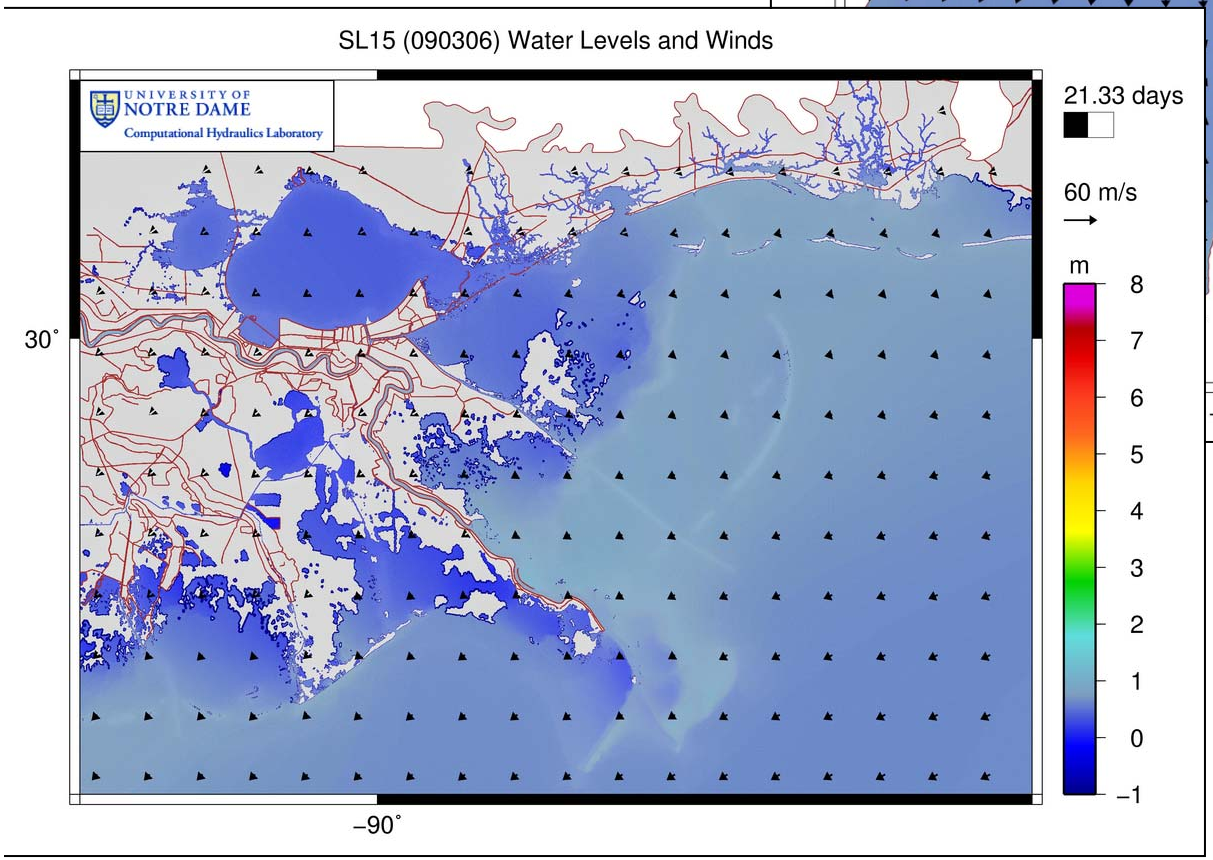


Hurricane Katrina

Water Levels

- 2005/08/28/0800Z

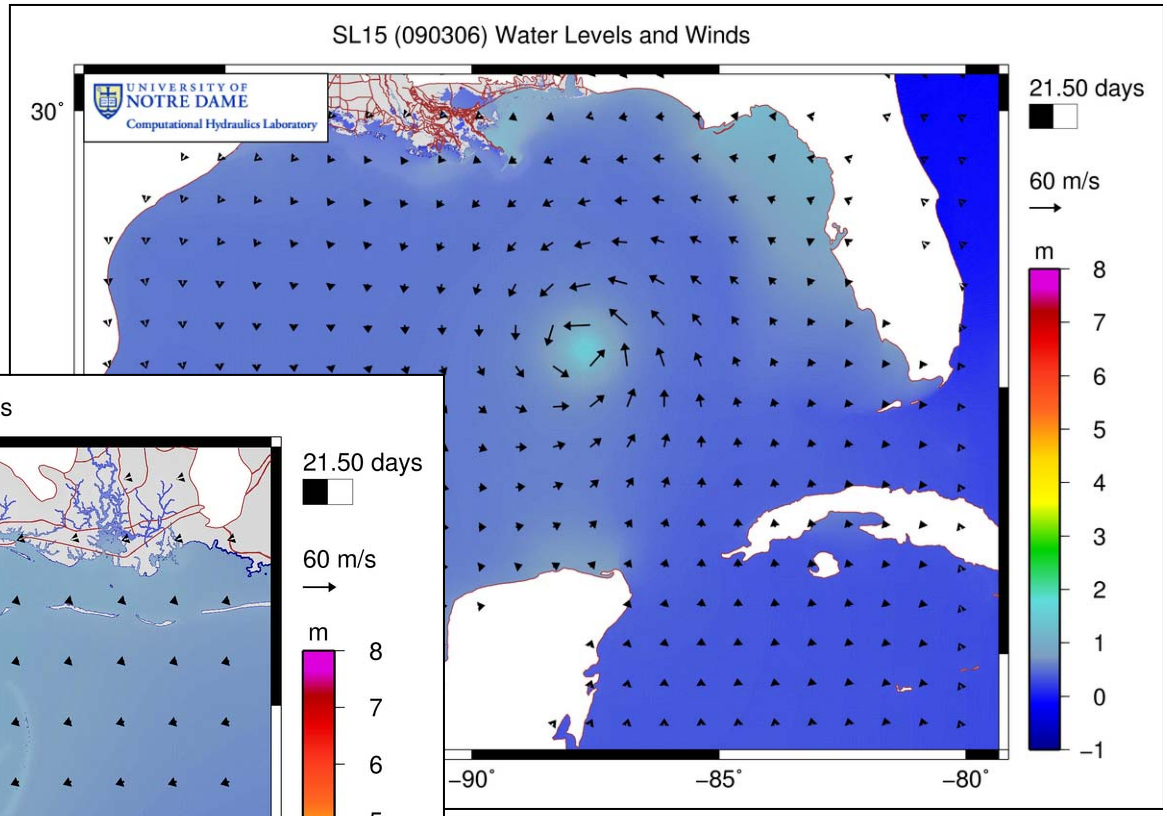


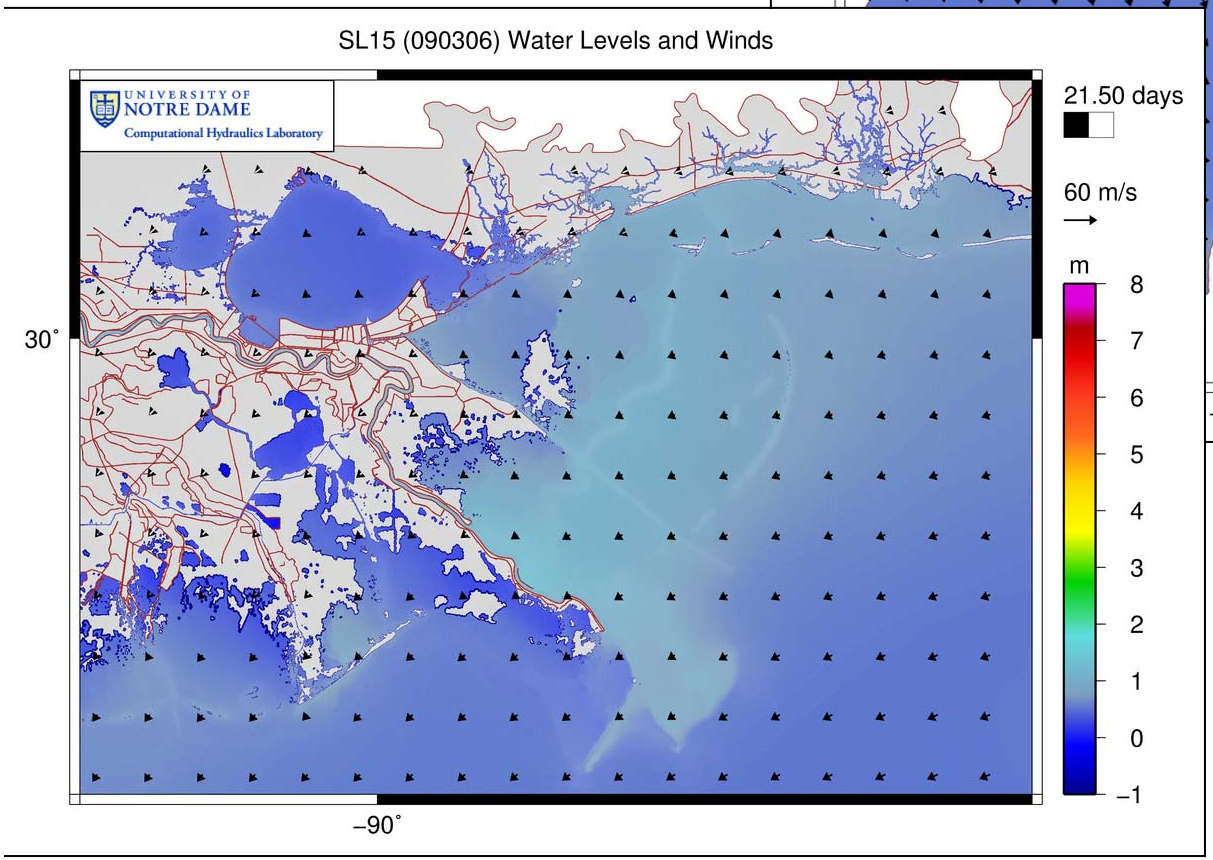


Hurricane Katrina

Water Levels

- 2005/08/28/1200Z

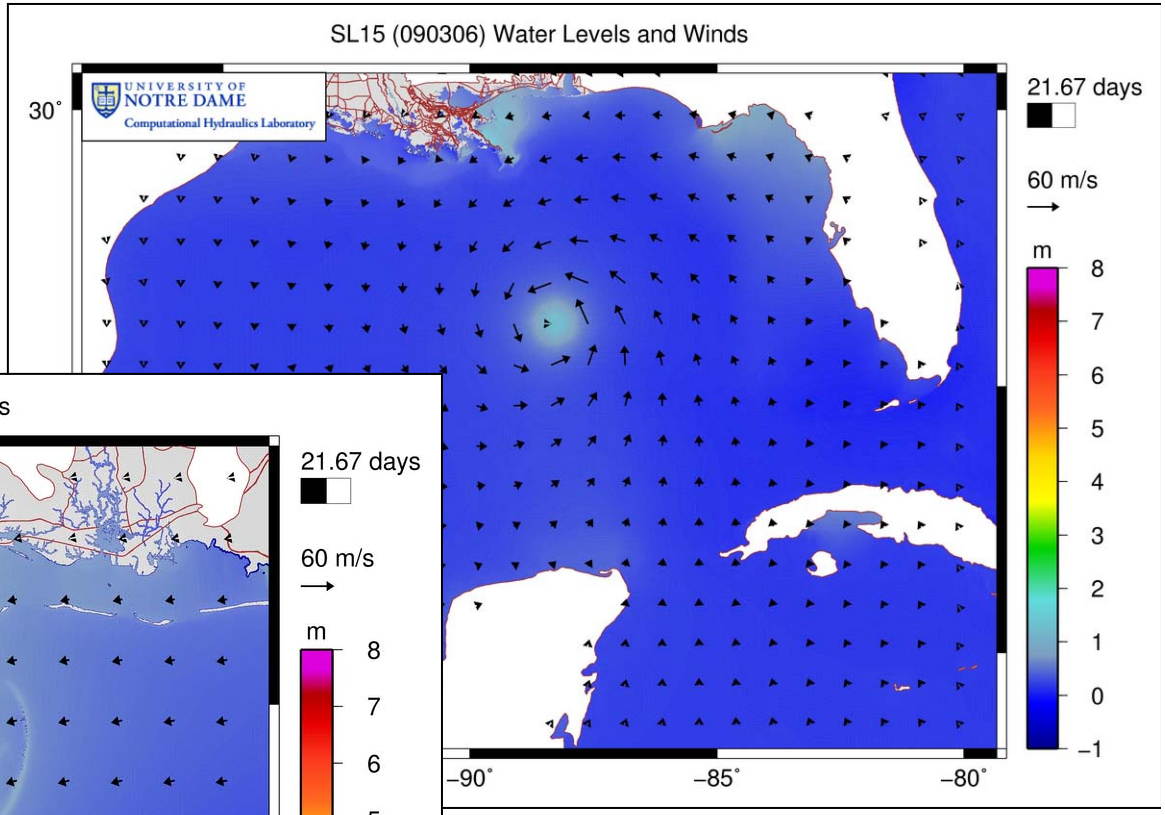


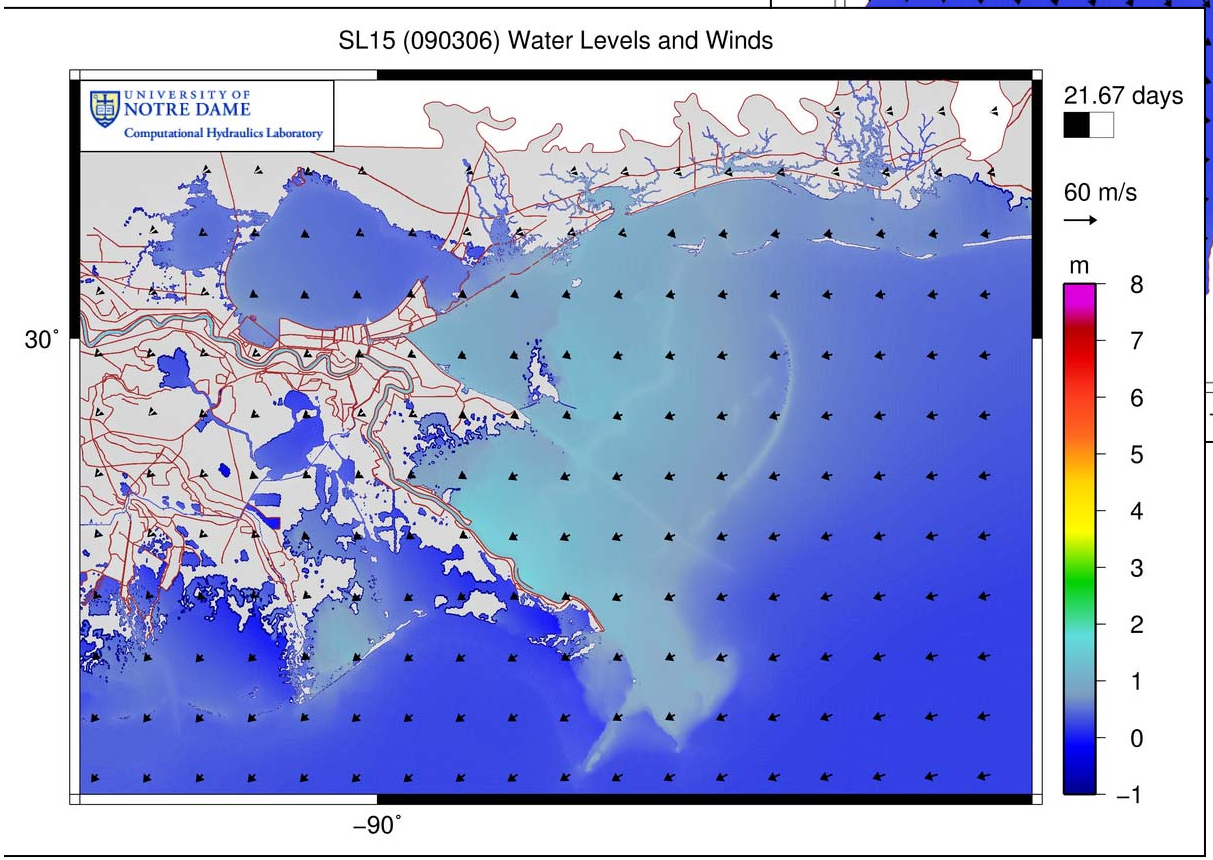


Hurricane Katrina

Water Levels

- 2005/08/28/1600Z

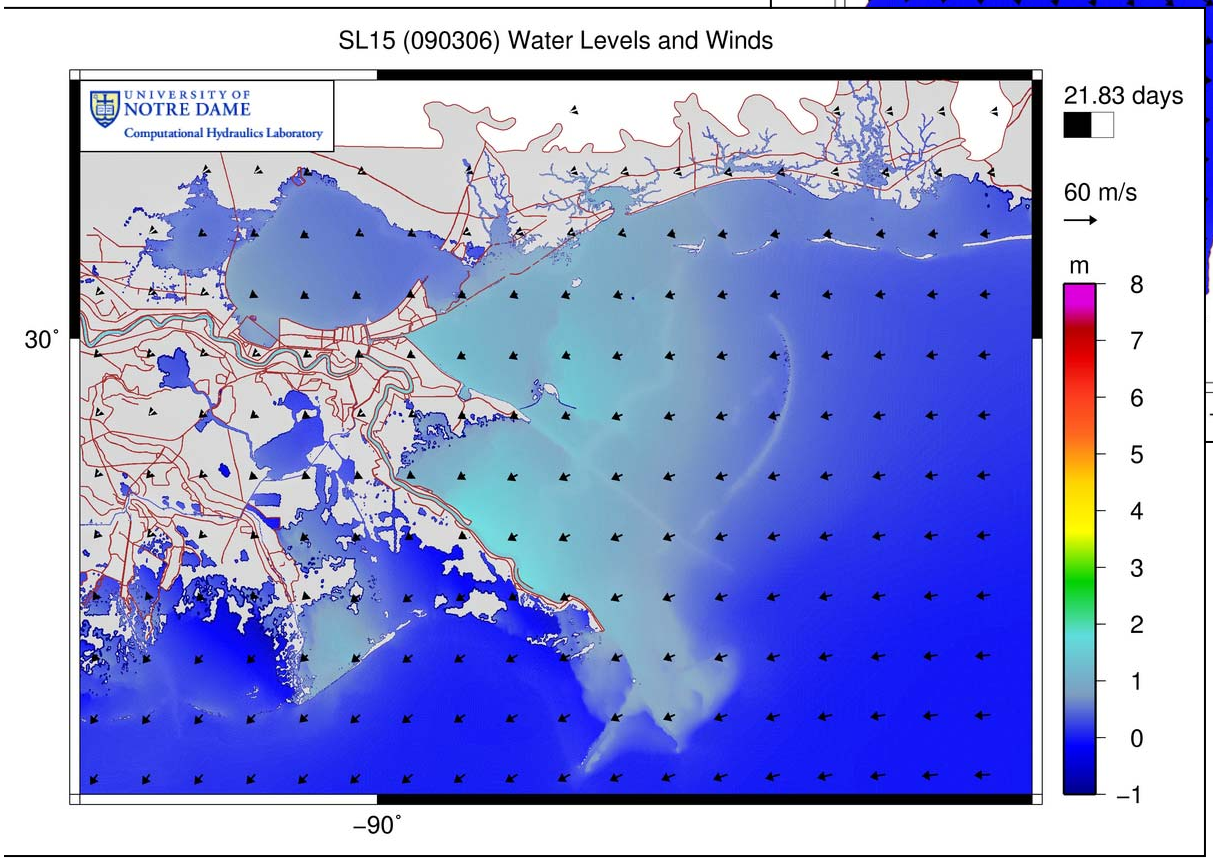


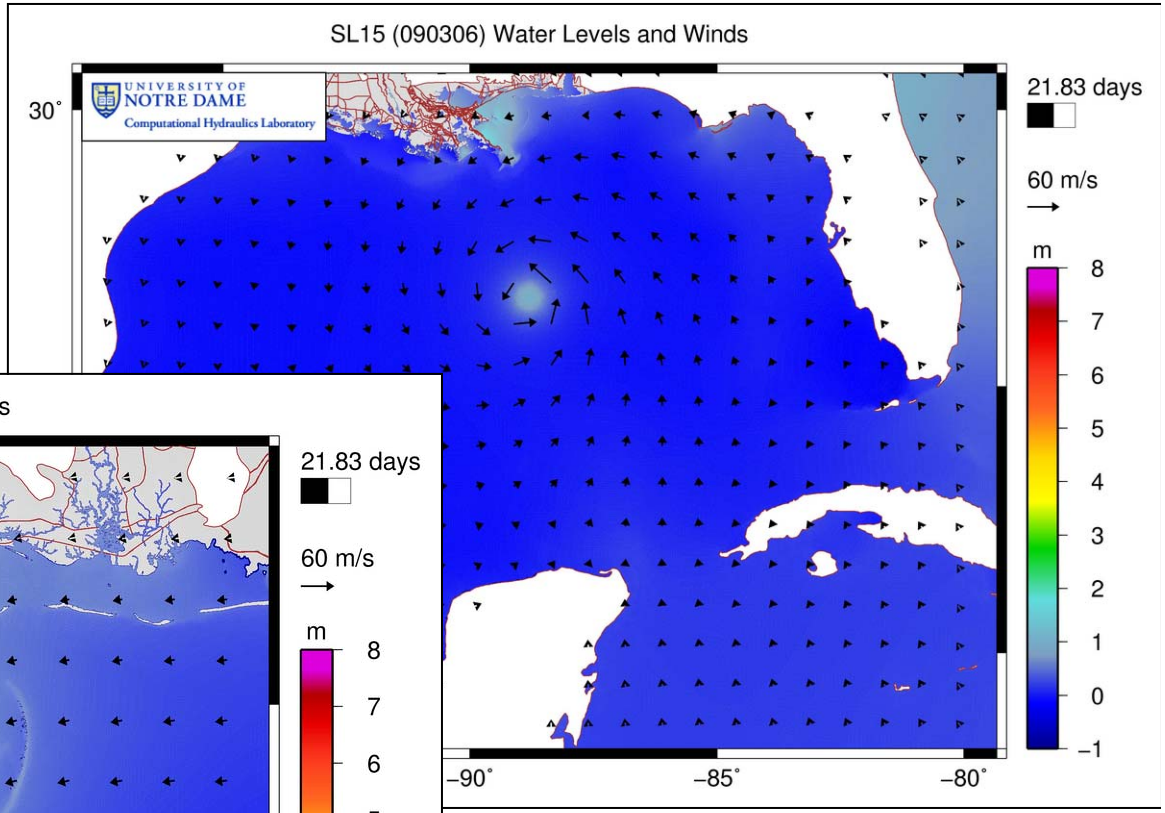


Hurricane Katrina

Water Levels

- 2005/08/28/2000Z

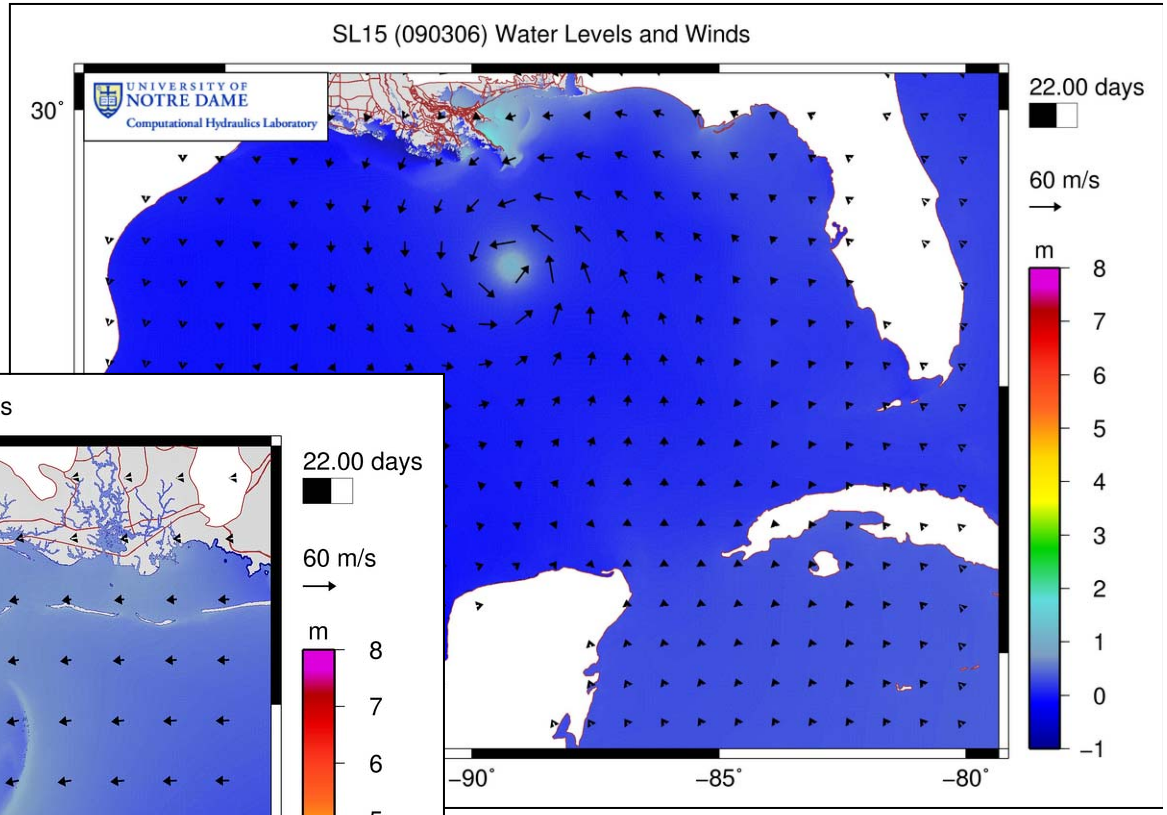


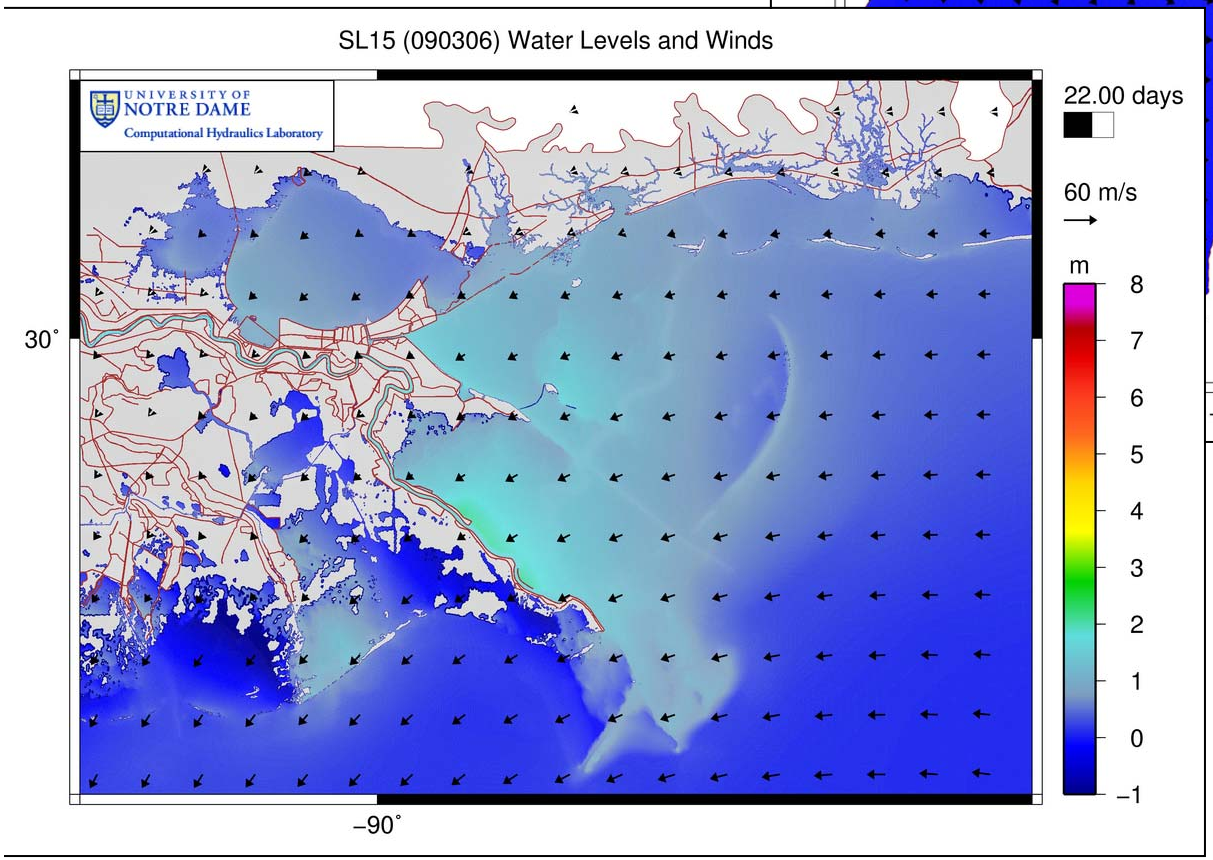


Hurricane Katrina

Water Levels

- 2005/08/29/0000Z

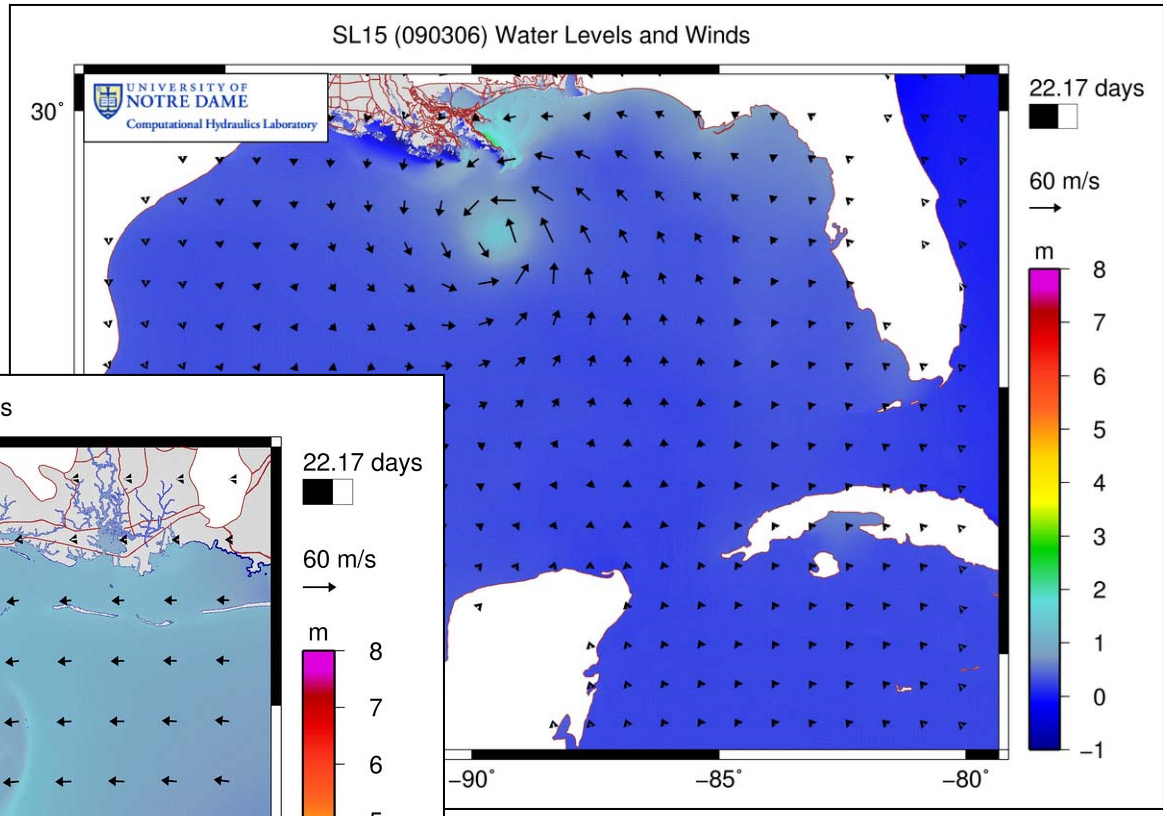


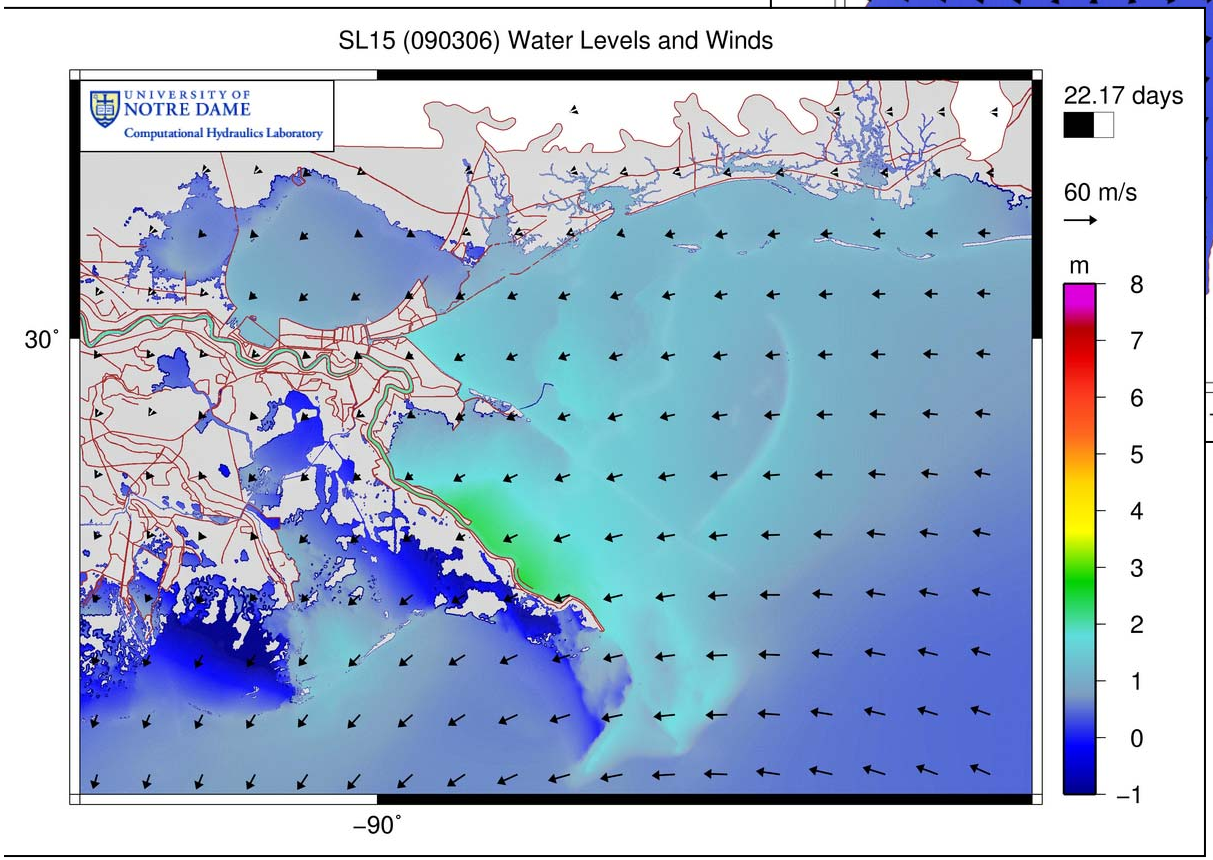


Hurricane Katrina

Water Levels

- 2005/08/29/0400Z

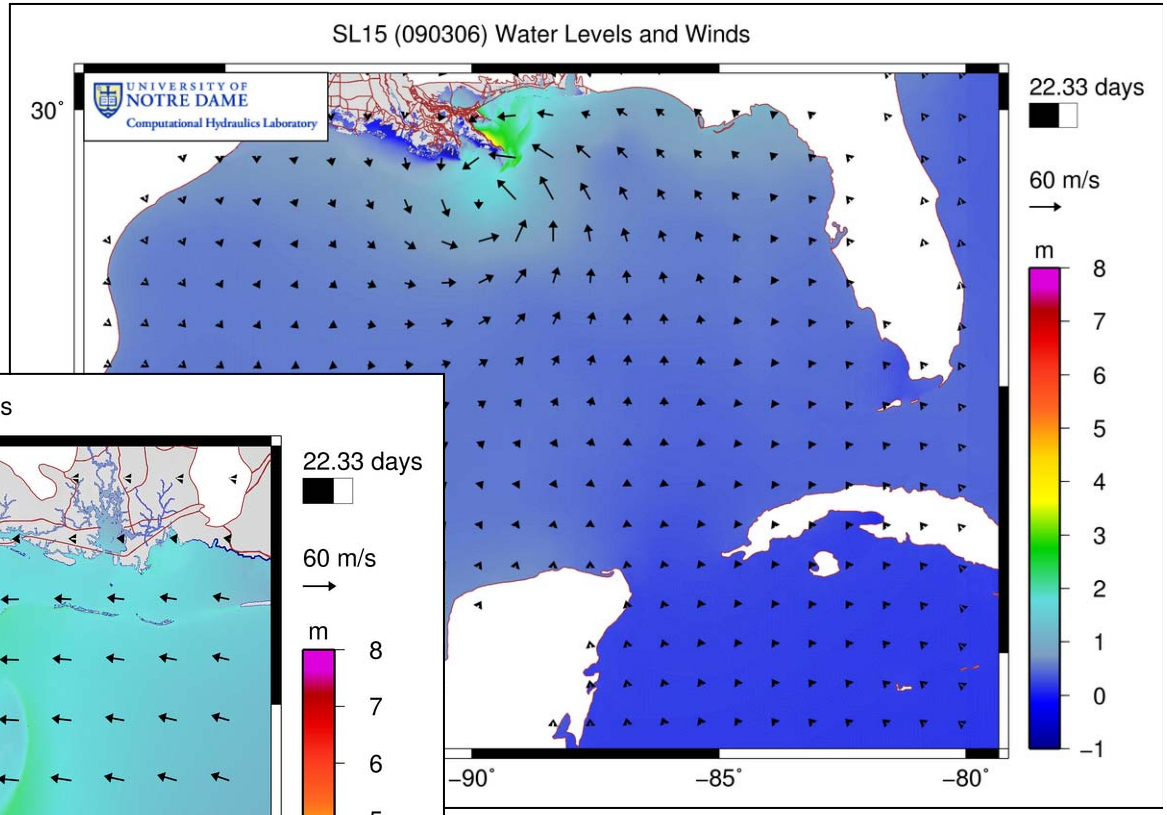


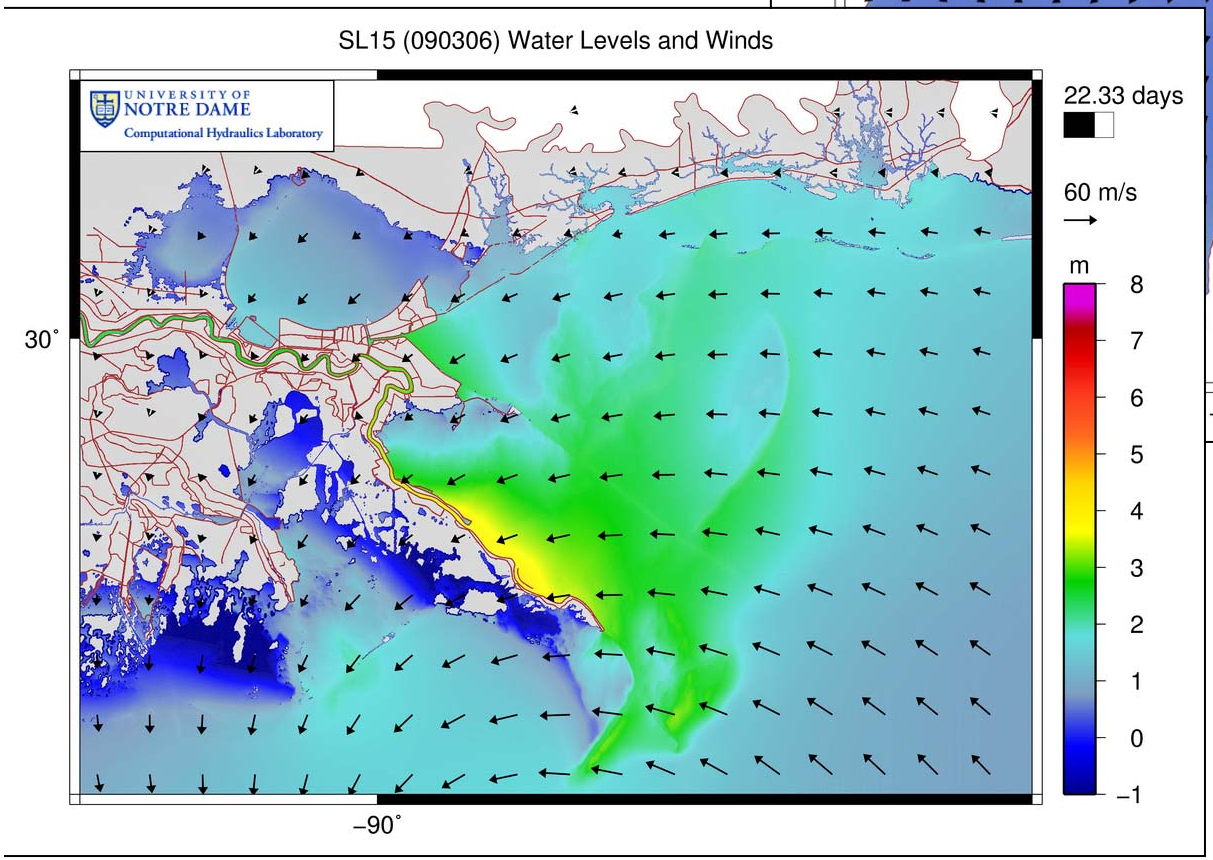


Hurricane Katrina

Water Levels

- 2005/08/29/0800Z

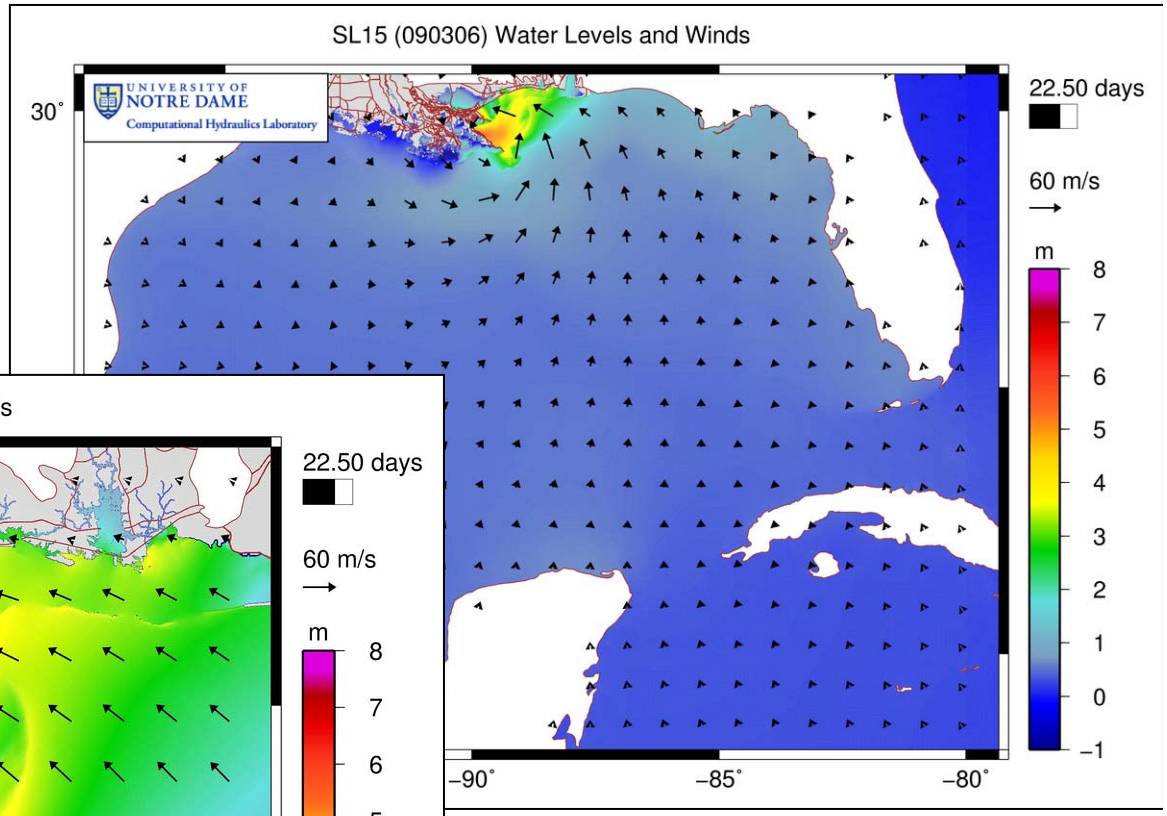


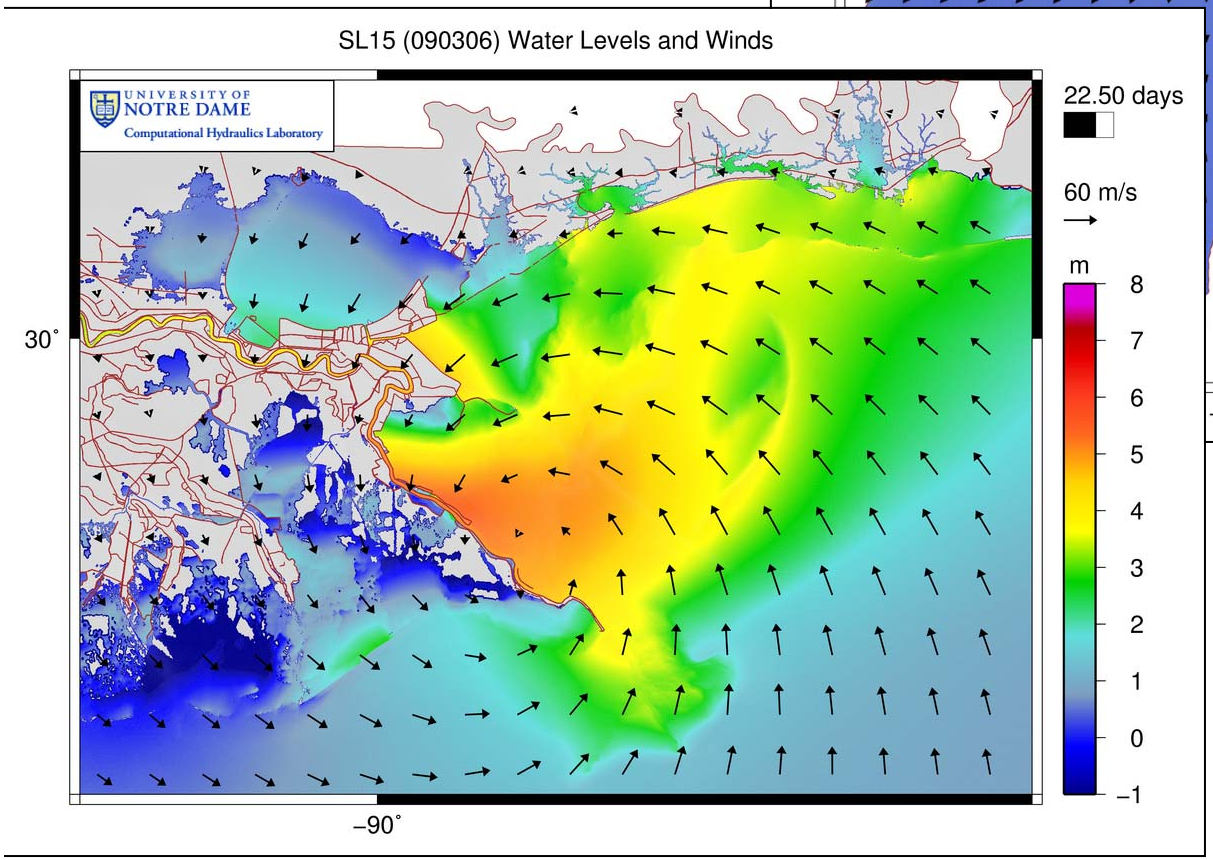


Hurricane Katrina

Water Levels

- 2005/08/29/1200Z

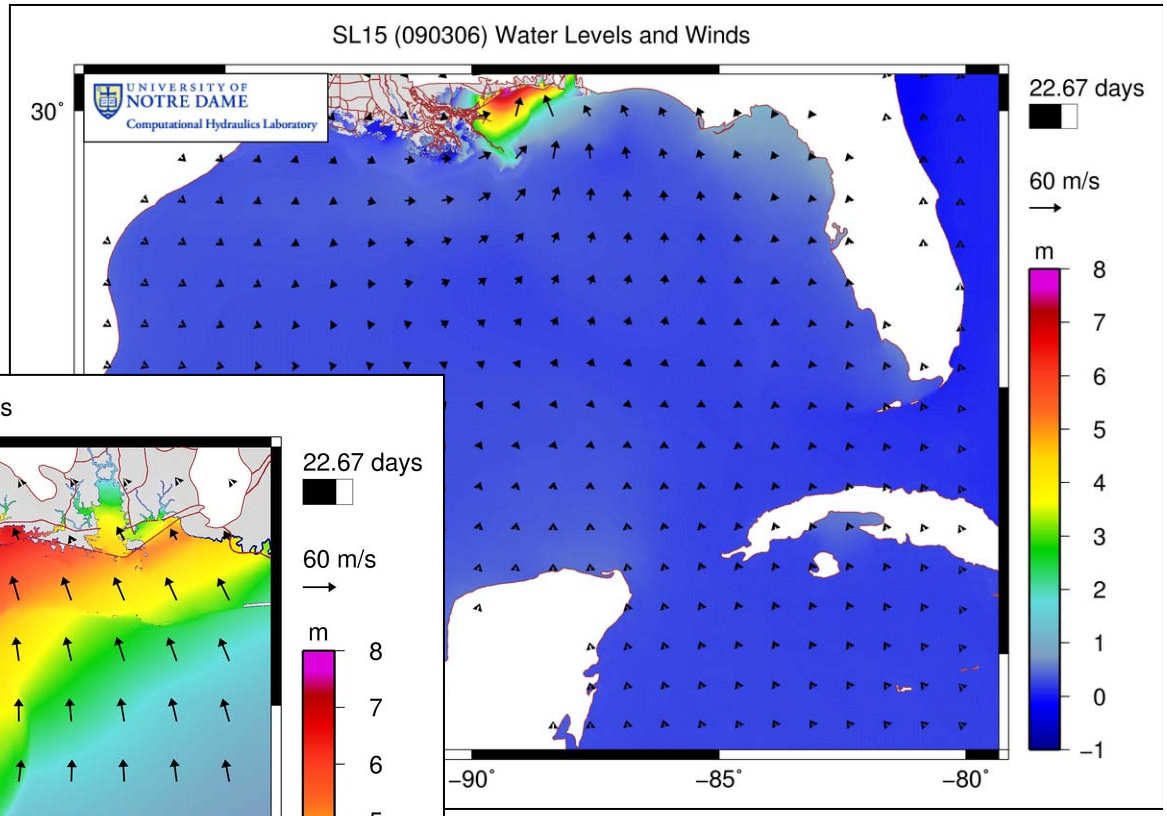


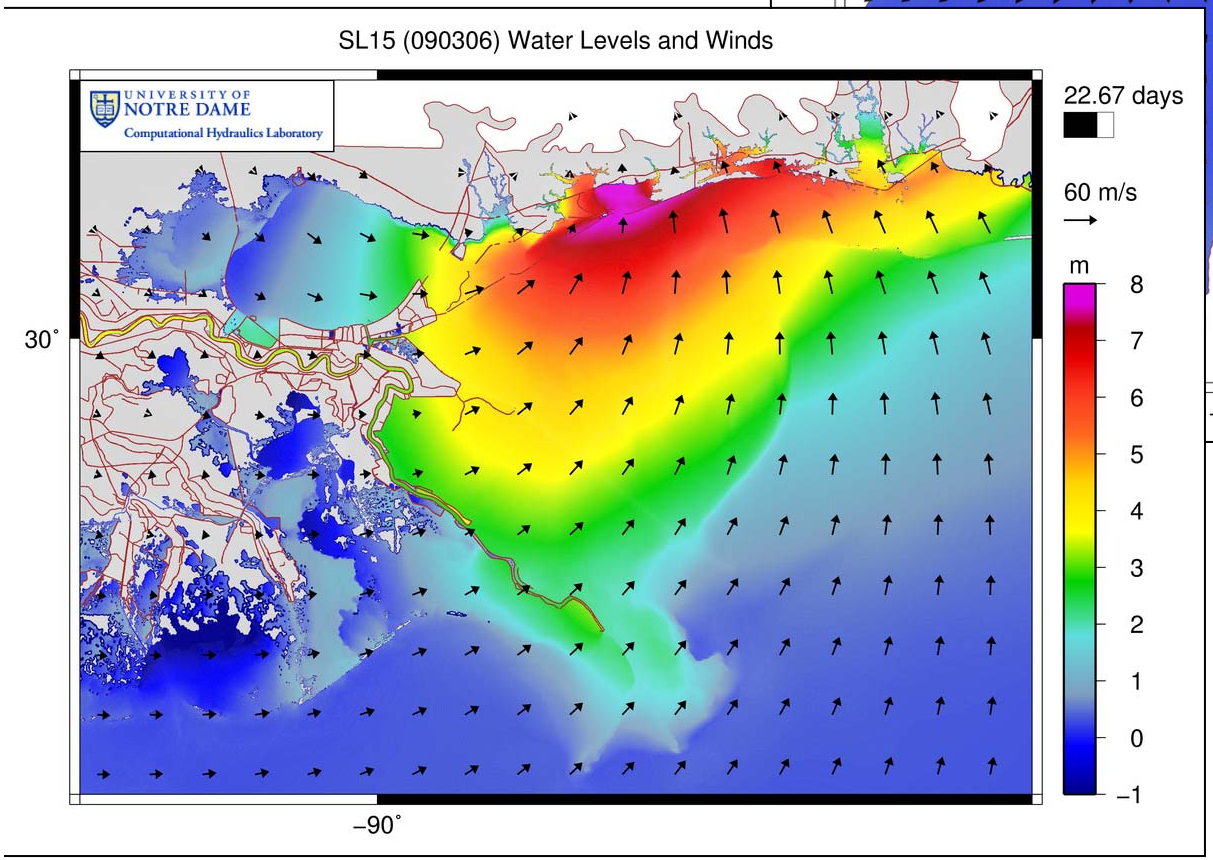


Hurricane Katrina

Water Levels

- 2005/08/29/1600Z

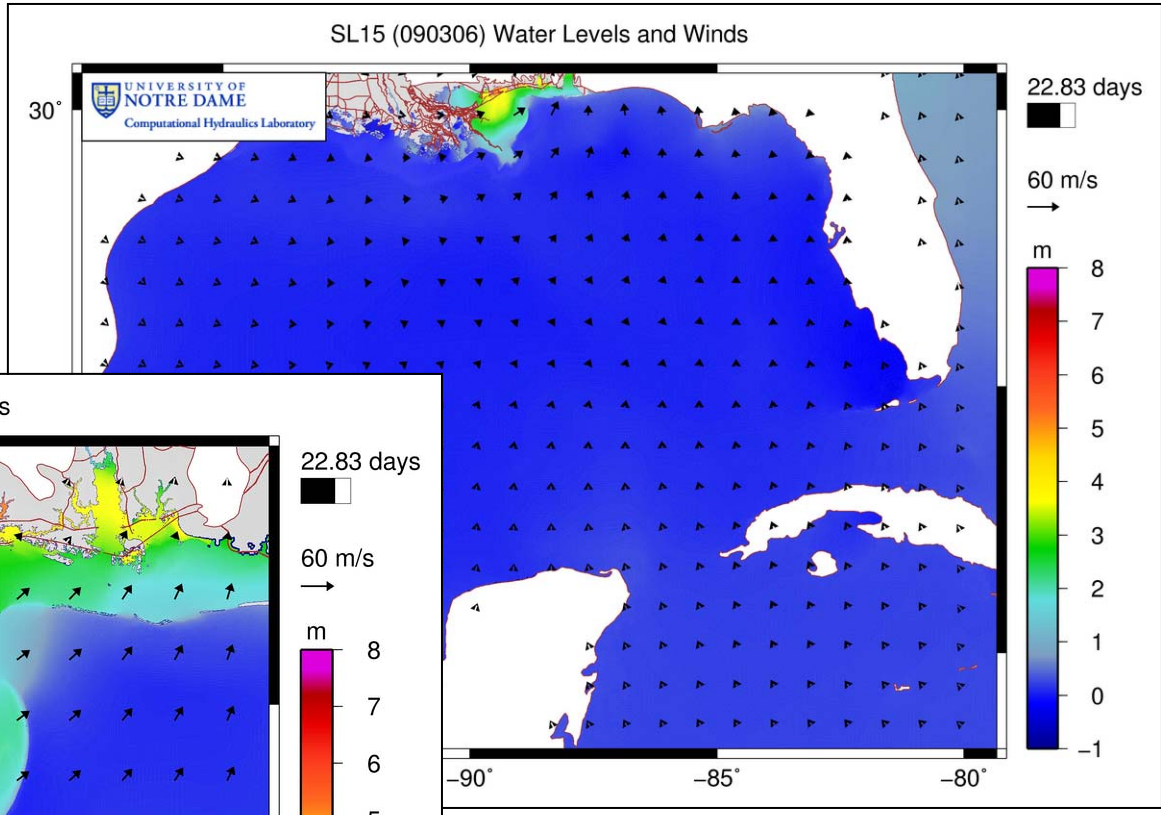


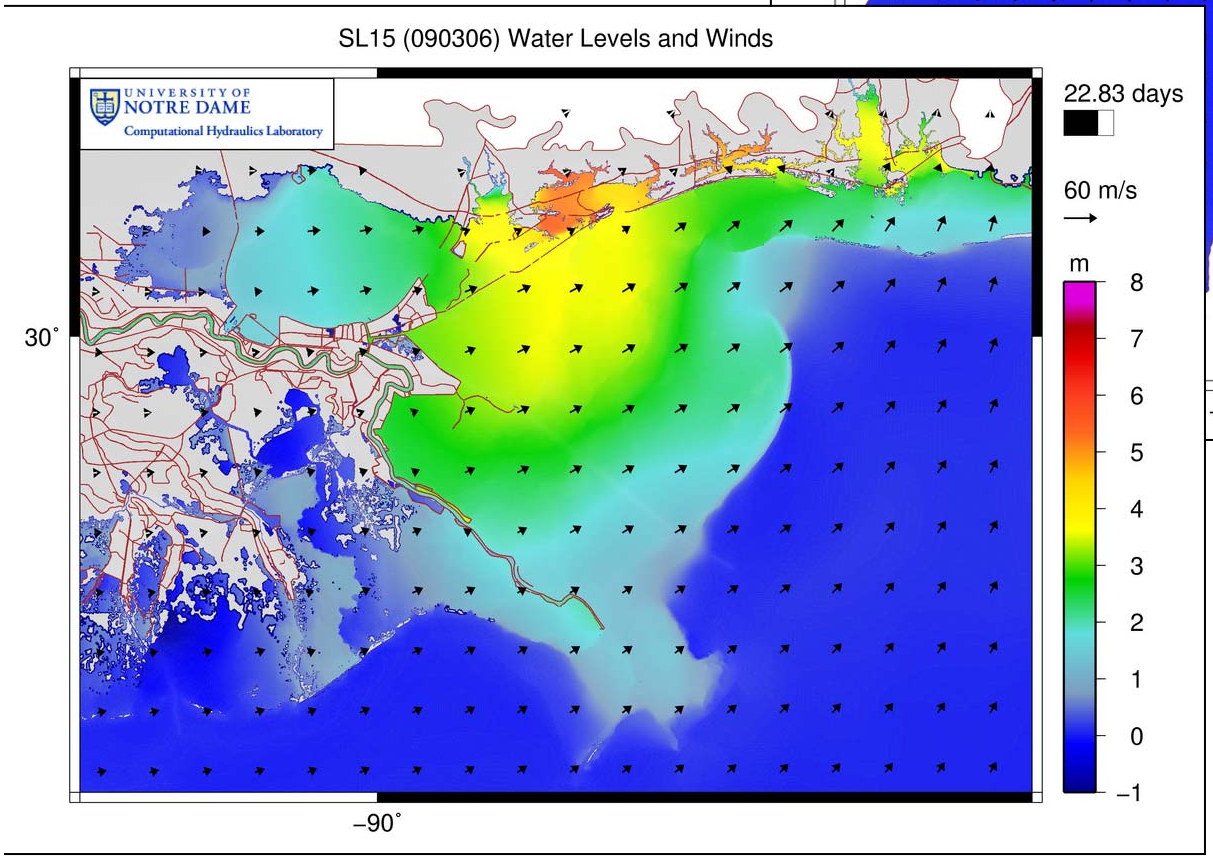


Hurricane Katrina

Water Levels

- 2005/08/29/2000Z

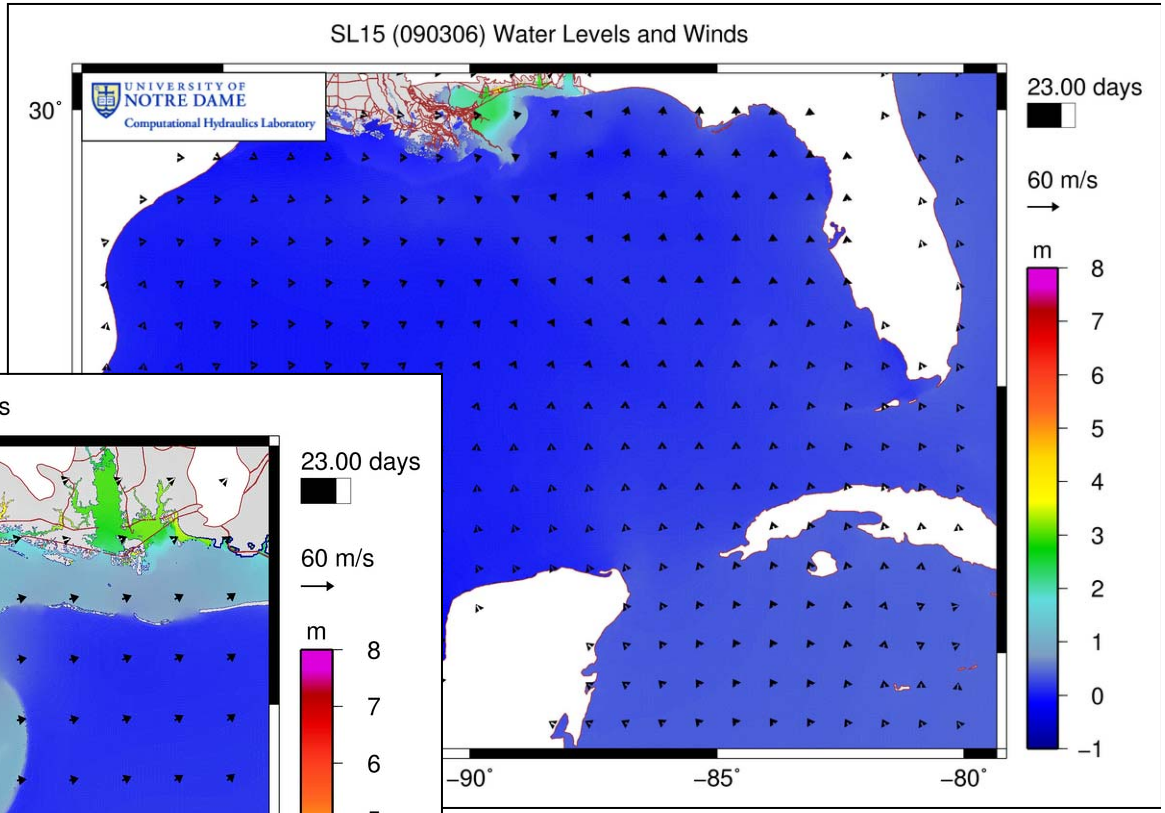


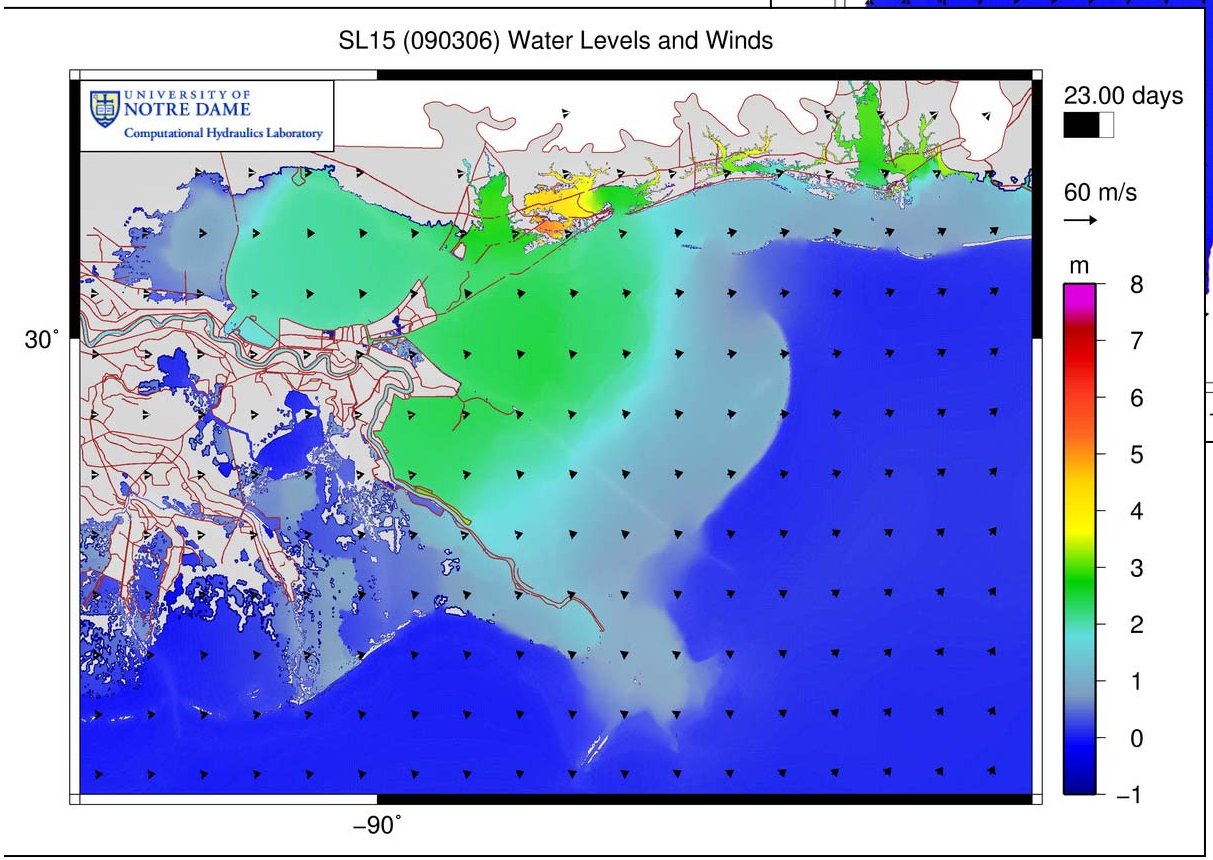


Hurricane Katrina

Water Levels

- 2005/08/30/0000Z





Hurricane Katrina

Preliminary Results

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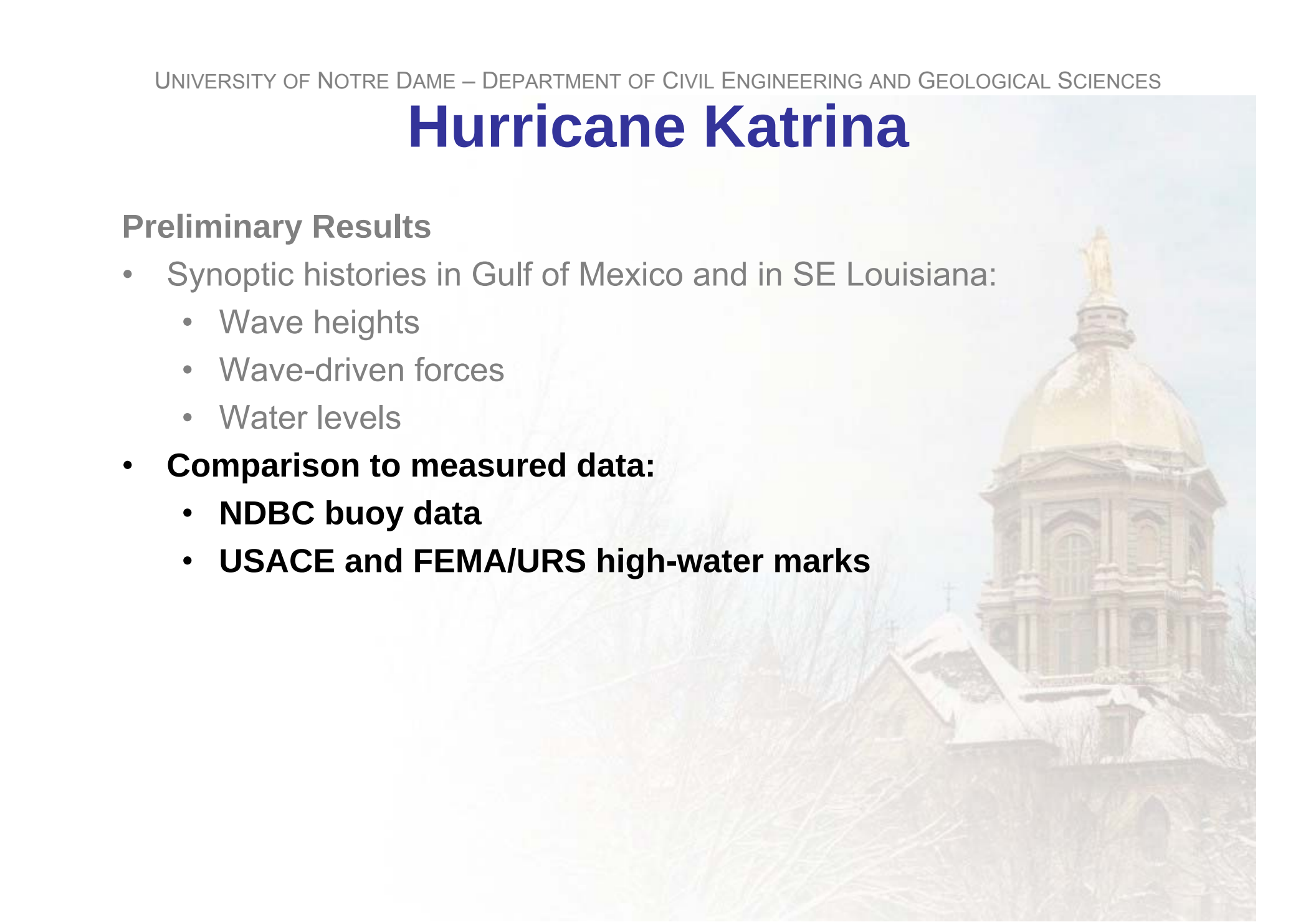
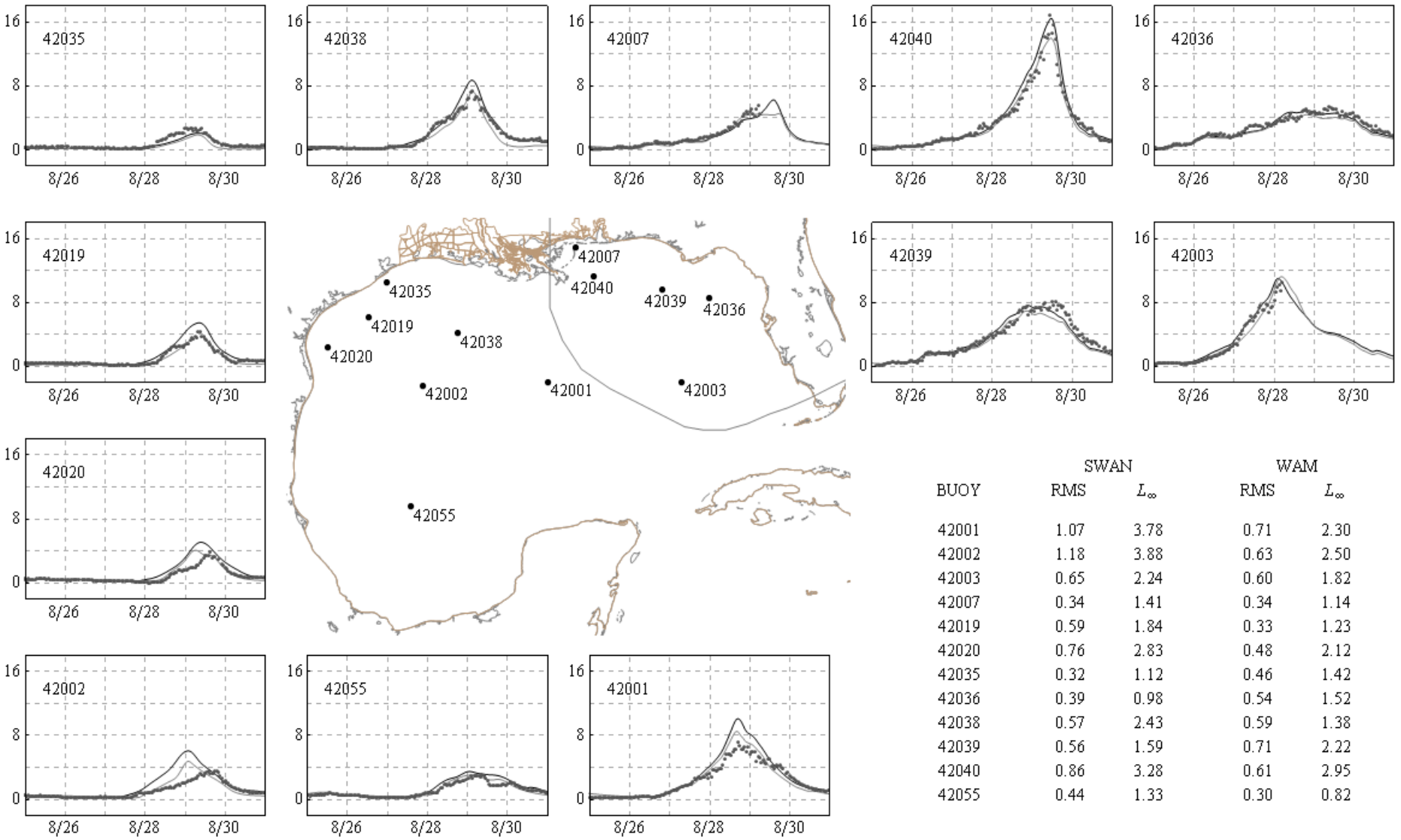


Hurricane Katrina

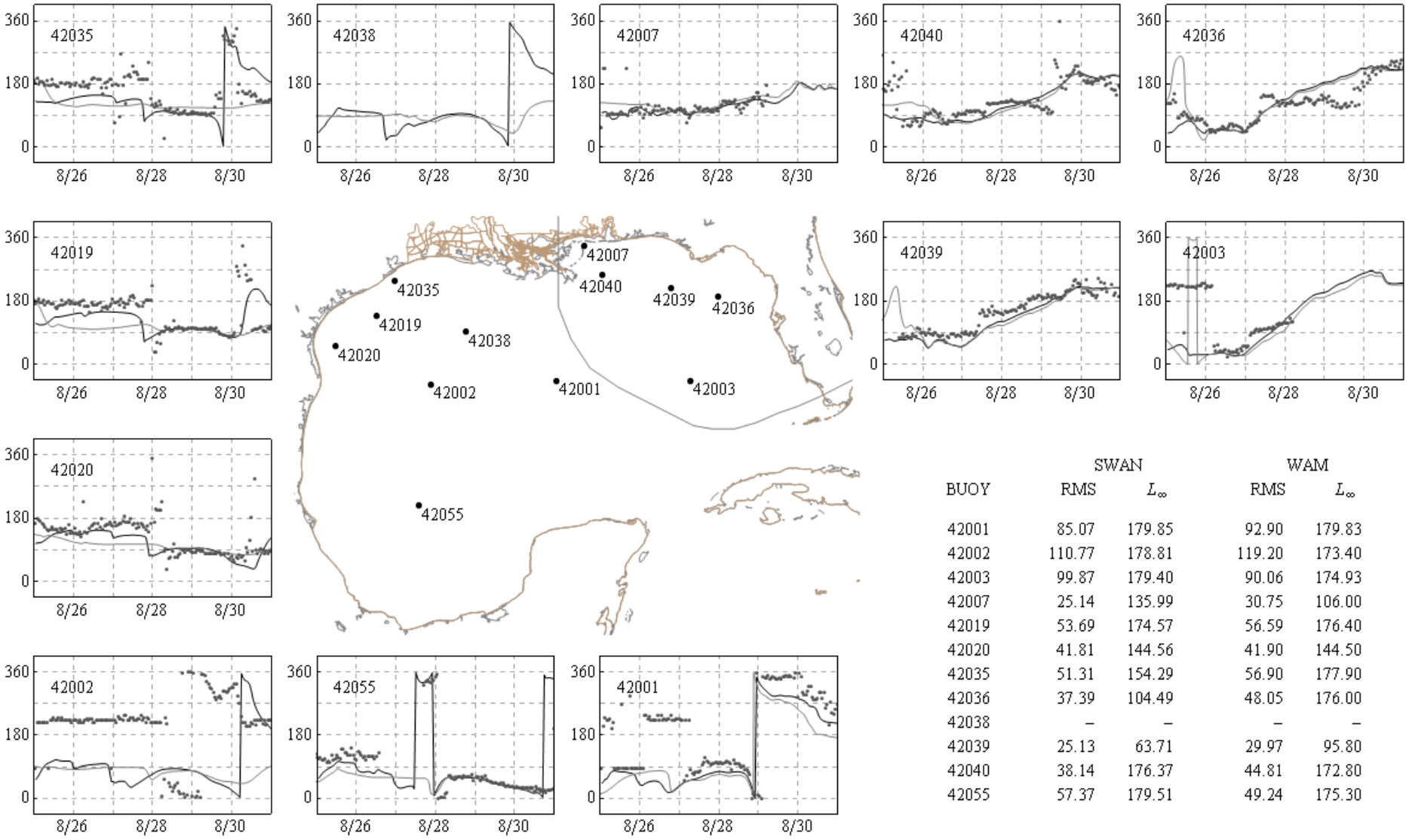
SIGNIFICANT WAVE HEIGHTS (HS) AT NDBC BUOYS



BUOY	SWAN RMS	SWAN L_∞	WAM RMS	WAM 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

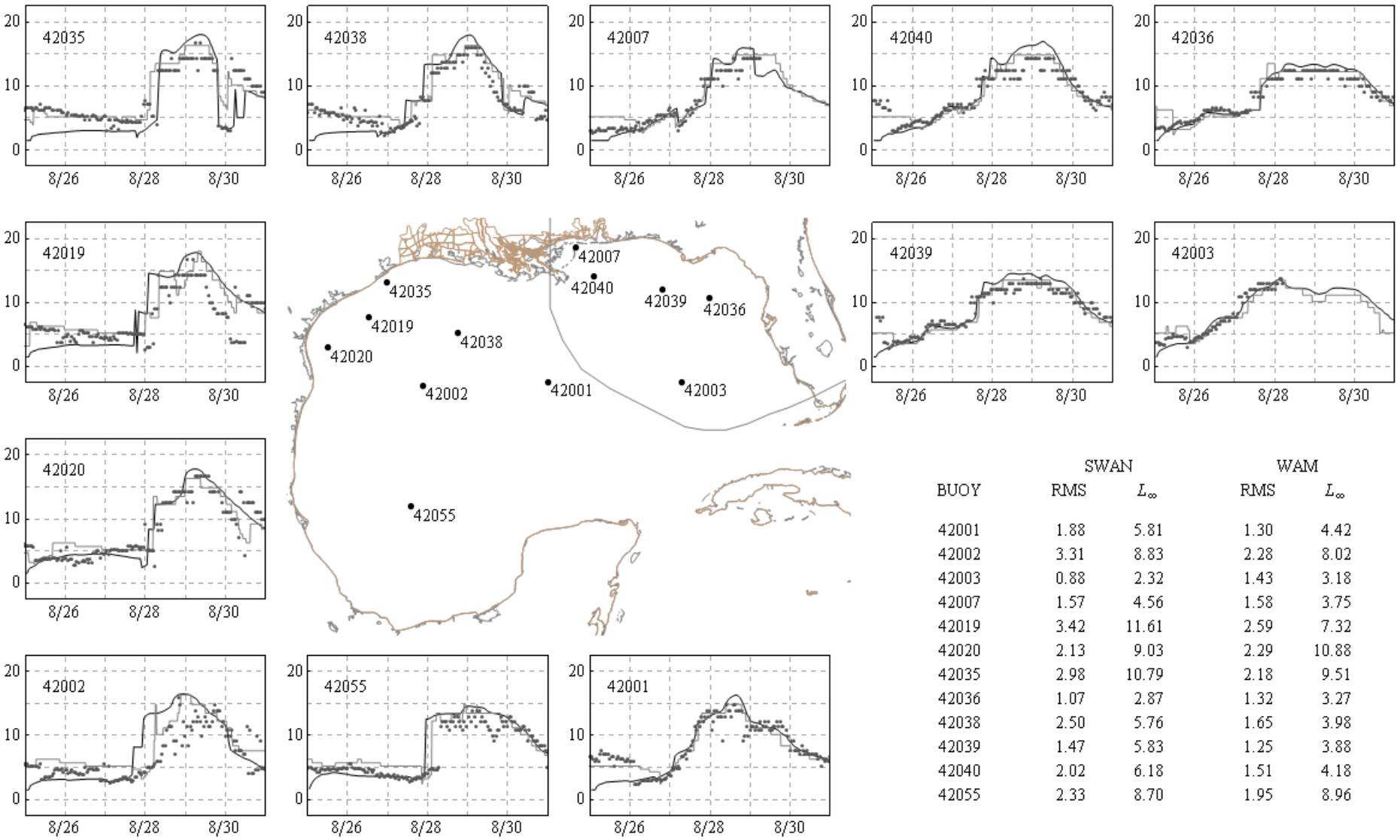
MEAN WAVE DIRECTIONS (DIR) AT NDBC BUOYS



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

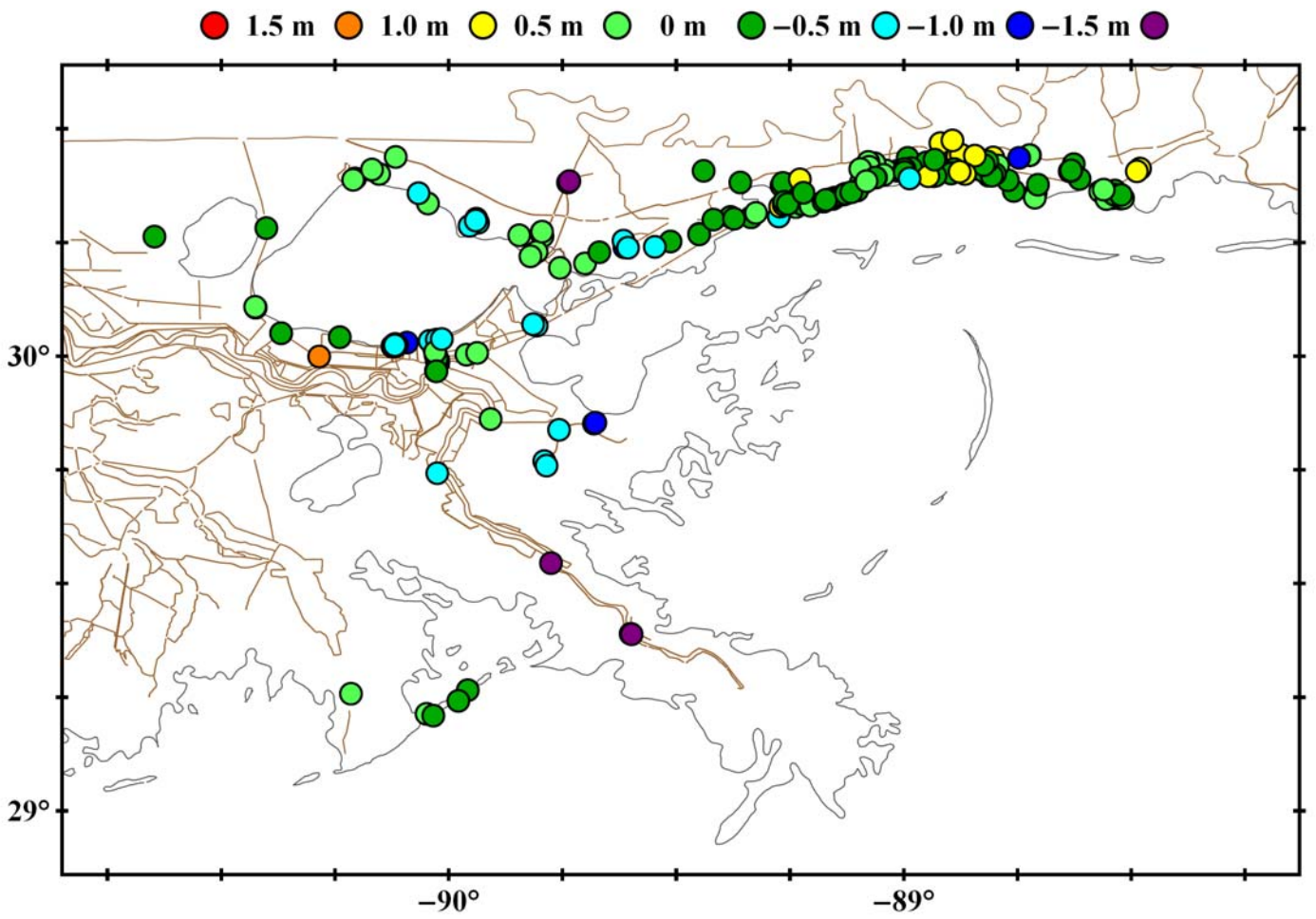
PEAK WAVE PERIODS (TPS) AT NDBC BUOYS



BUOY	SWAN RMS	SWAN L_∞	WAM RMS	WAM 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

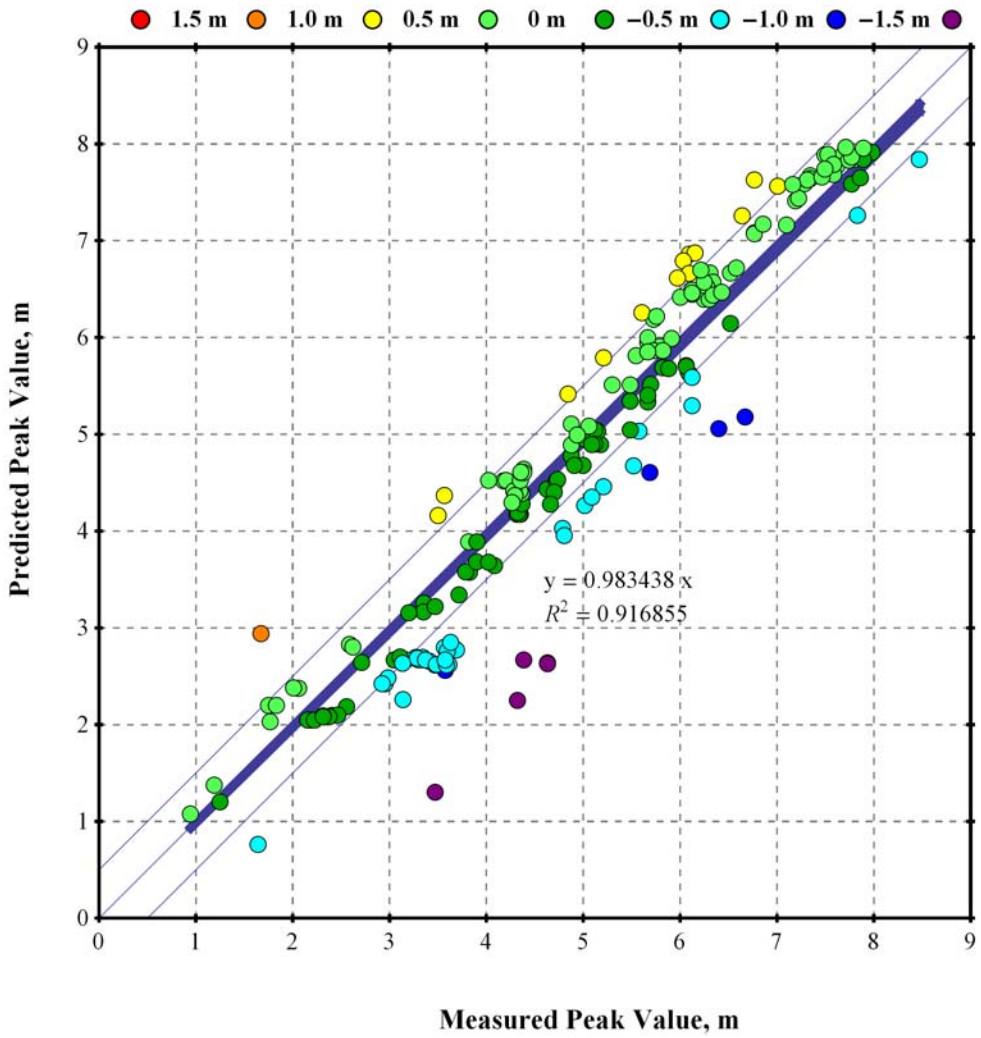
Hurricane Katrina

USACE High-Water Marks



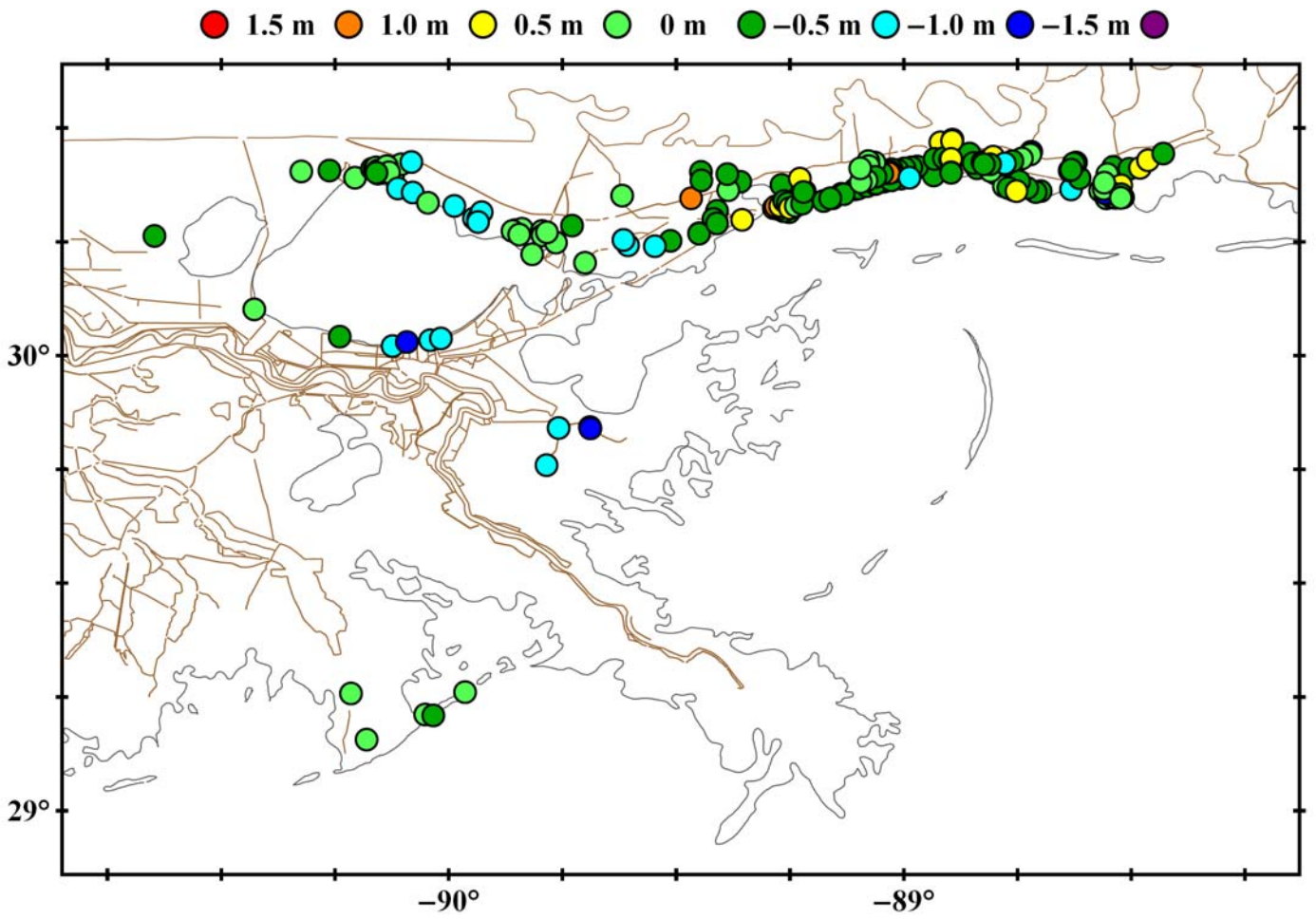
Hurricane Katrina

USACE High-Water Marks



Hurricane Katrina

FEMA/URS High-Water Marks



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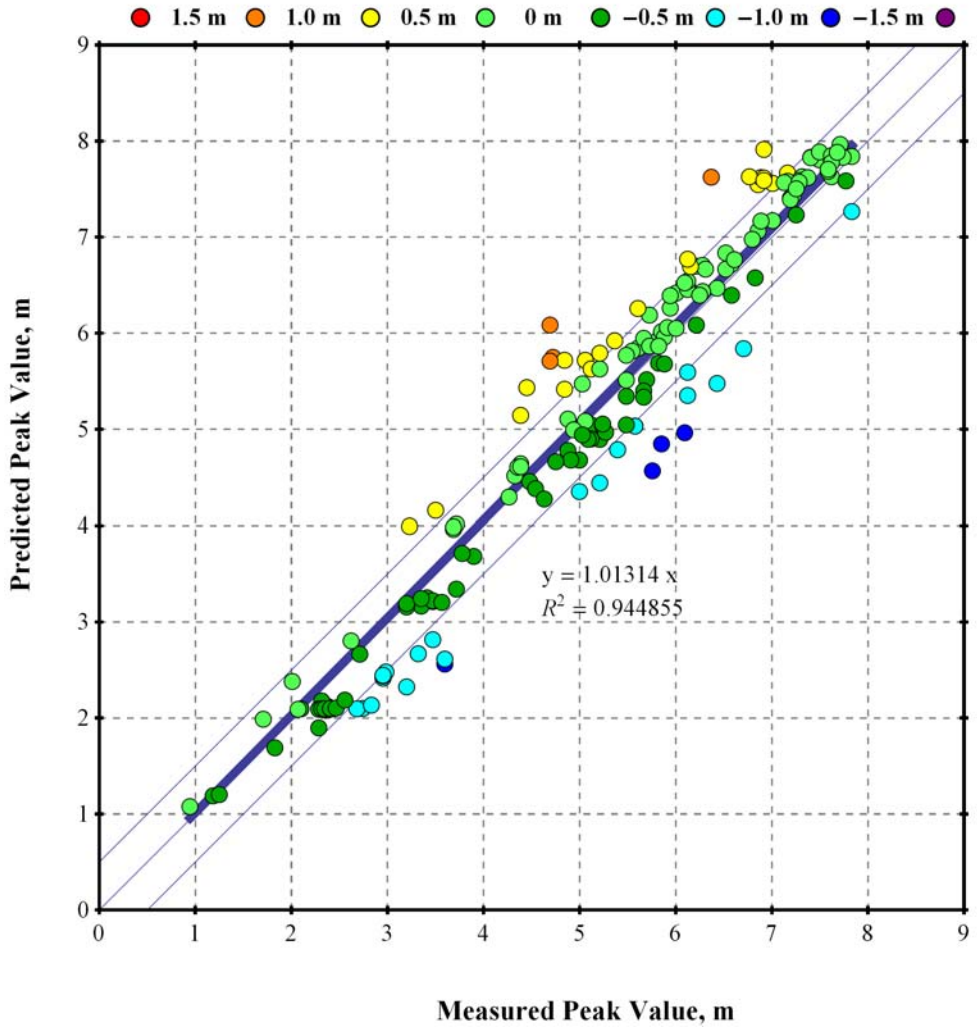

Conclusions

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:

- Run the ADCIRC-SWAN model on the next generation of meshes
- Katrina and Rita (2005)
- Gustav (2008)
- Ike (2008)