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

J.C. Dietrich, J.J. Westerink **University of Notre Dame**

C. Dawson **University of Texas at Austin**

M. Zijlema, L. Holthuijsen, G. Stelling **Delft University of Technology**

R.A. Luettich **University of North Carolina**

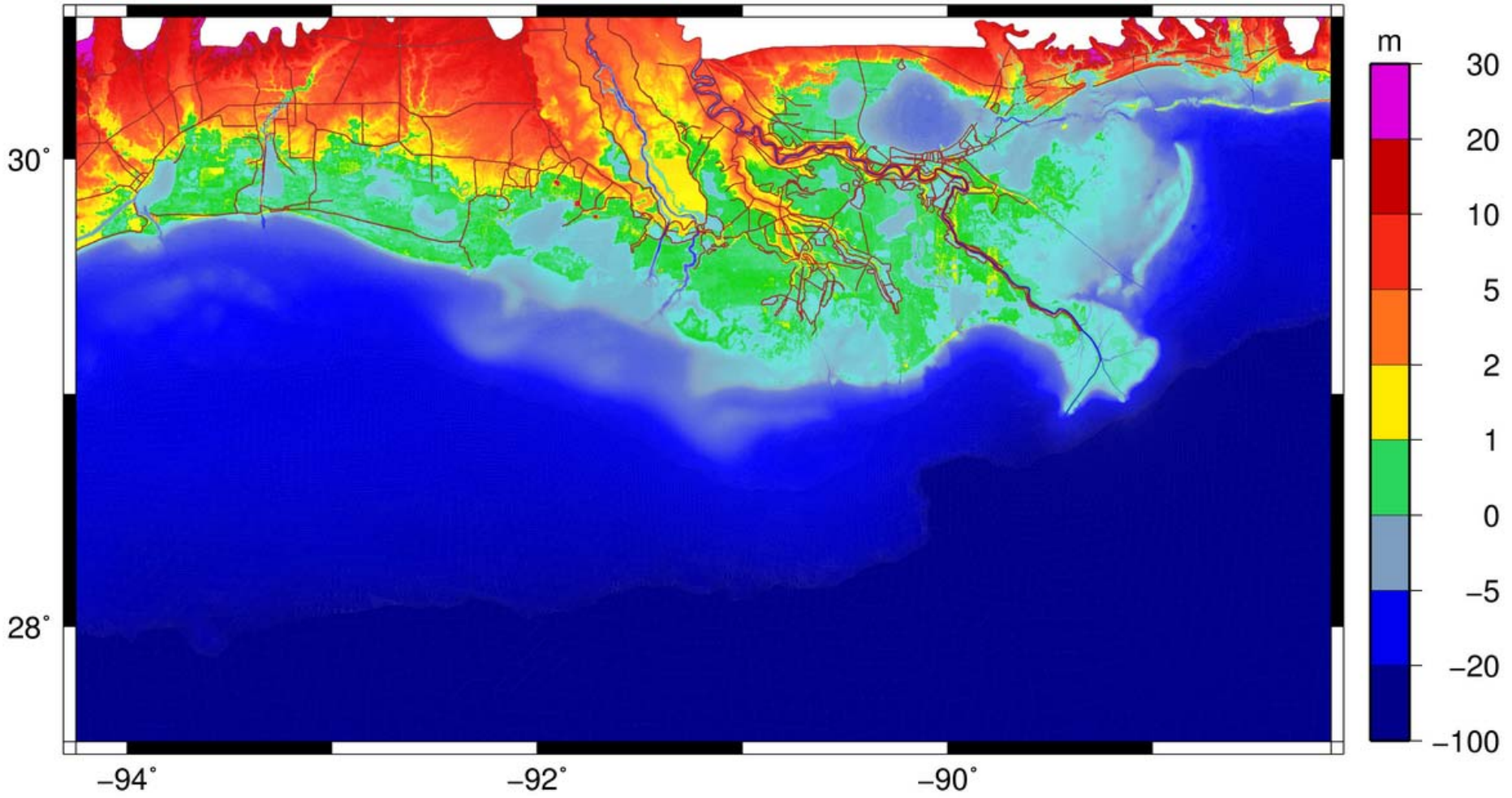
ADCIRC

ADvanced CIRCulation (ADCIRC):

- Developed by Westerink, Luettich, Dawson 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 GWCE for water levels
- Solves the vertically-integrated momentum equations for currents

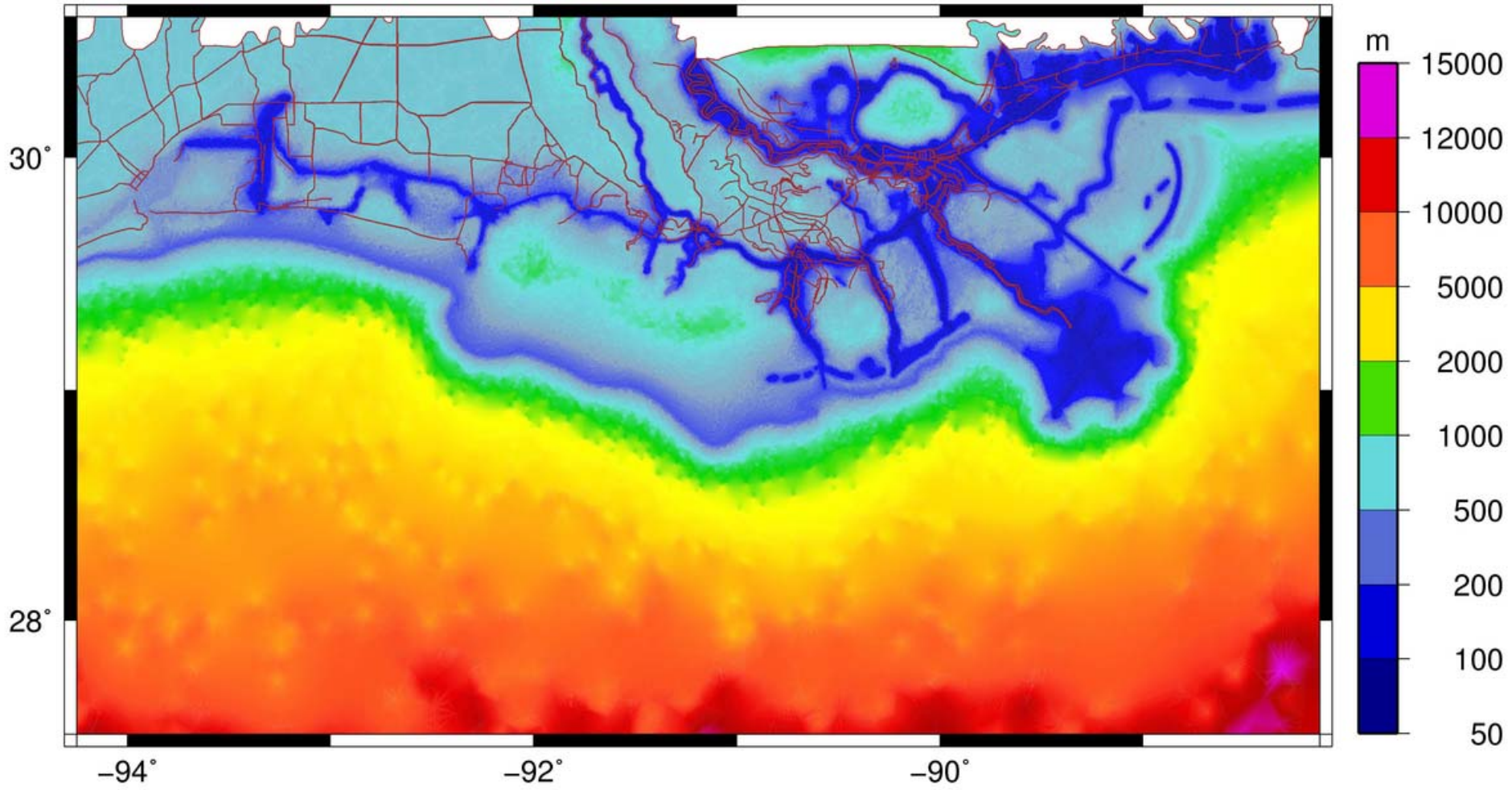
ADCIRC

Example: Louisiana Storm Surge Modeling



ADCIRC

Example: Louisiana Storm Surge Modeling



'Loose' Coupling

'Loose' Coupling:

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

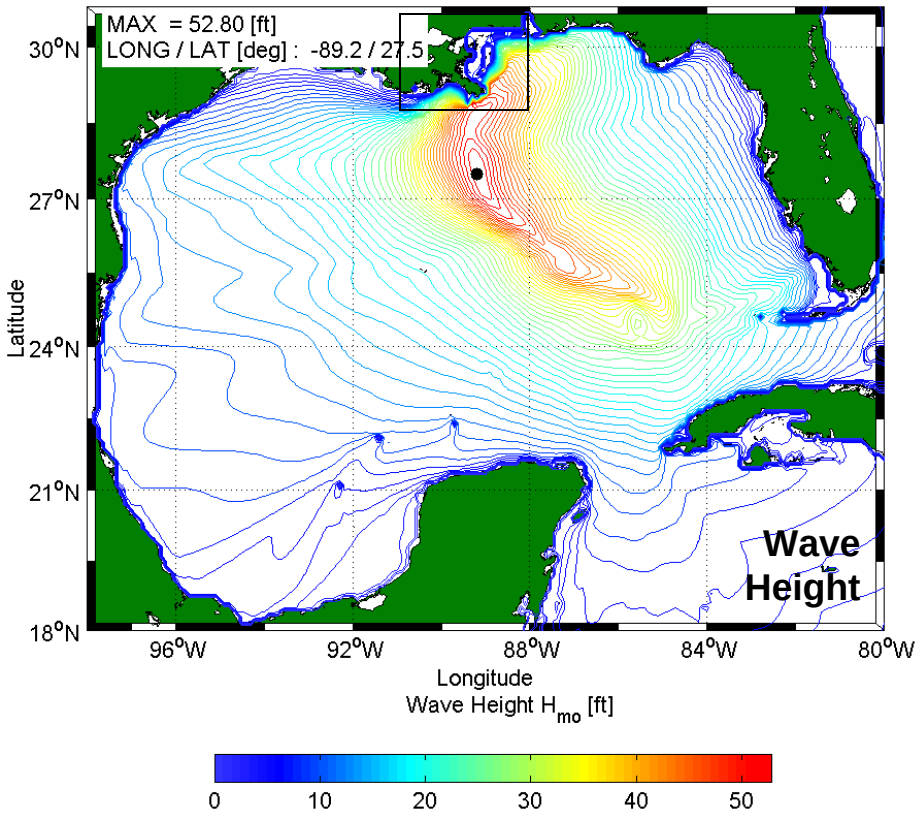
ADCIRC Coupled to Wave Models:

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

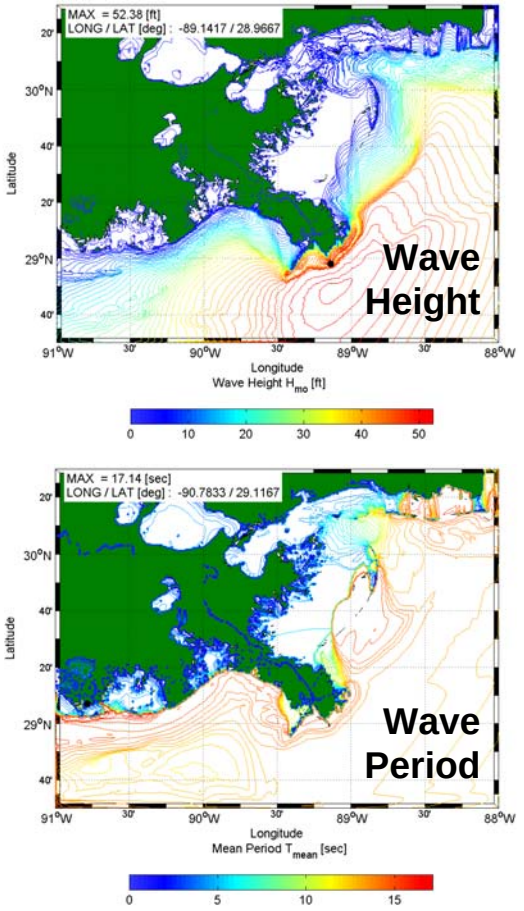
'Loose' Coupling

Example: Louisiana Storm Surge Modeling

Basin-Scale WAM Model



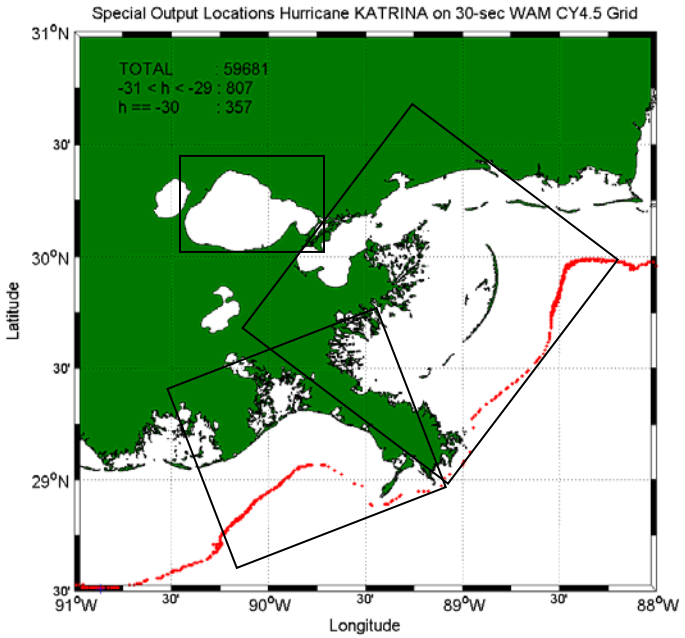
Region-Scale WAM Model

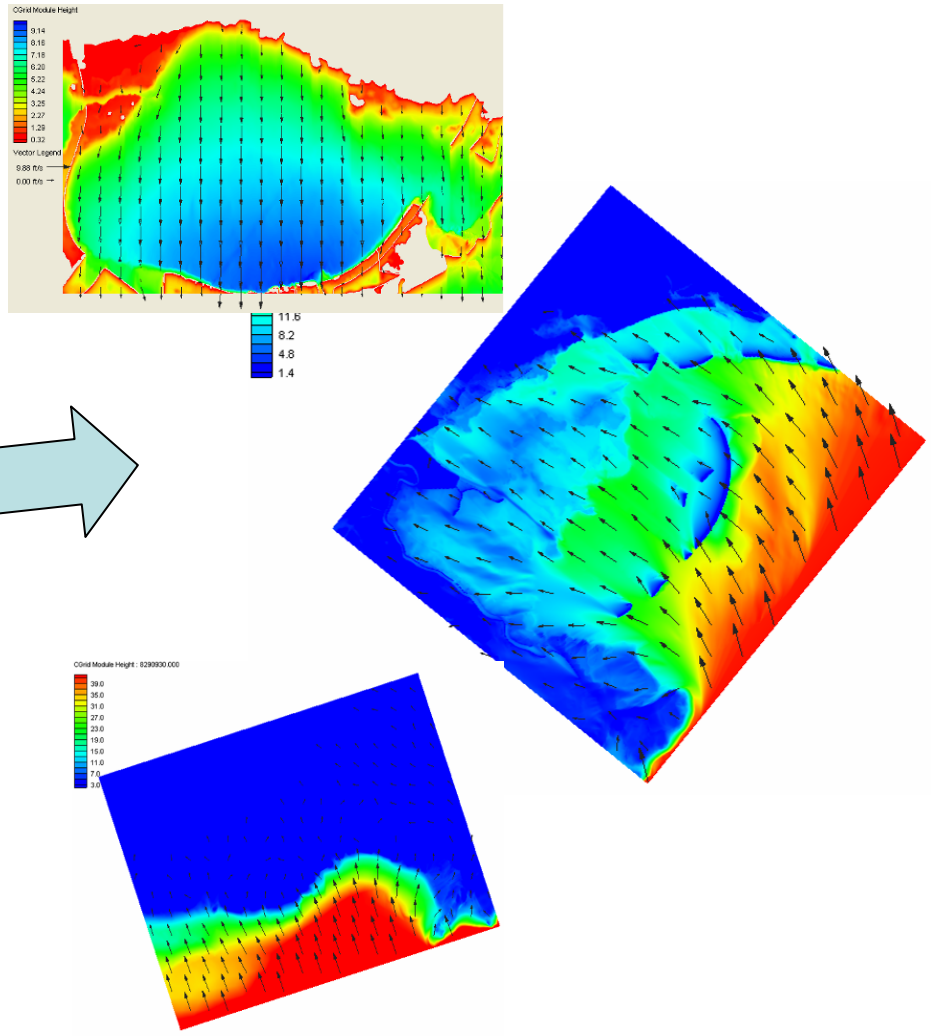


‘Loose’ Coupling

Example: Louisiana Storm Surge Modeling

Nearshore STWAVE Model

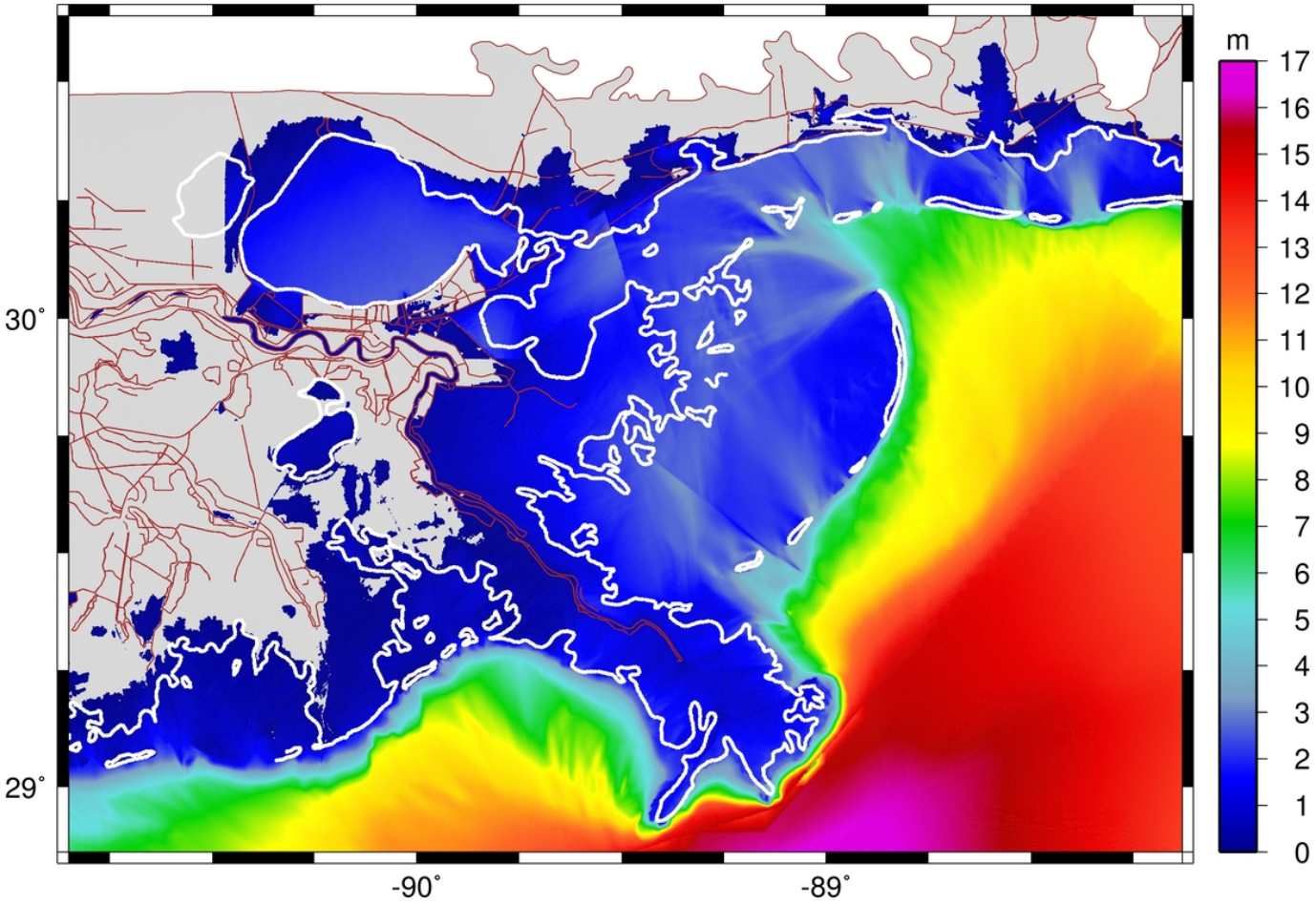




‘Loose’ Coupling

It Works!

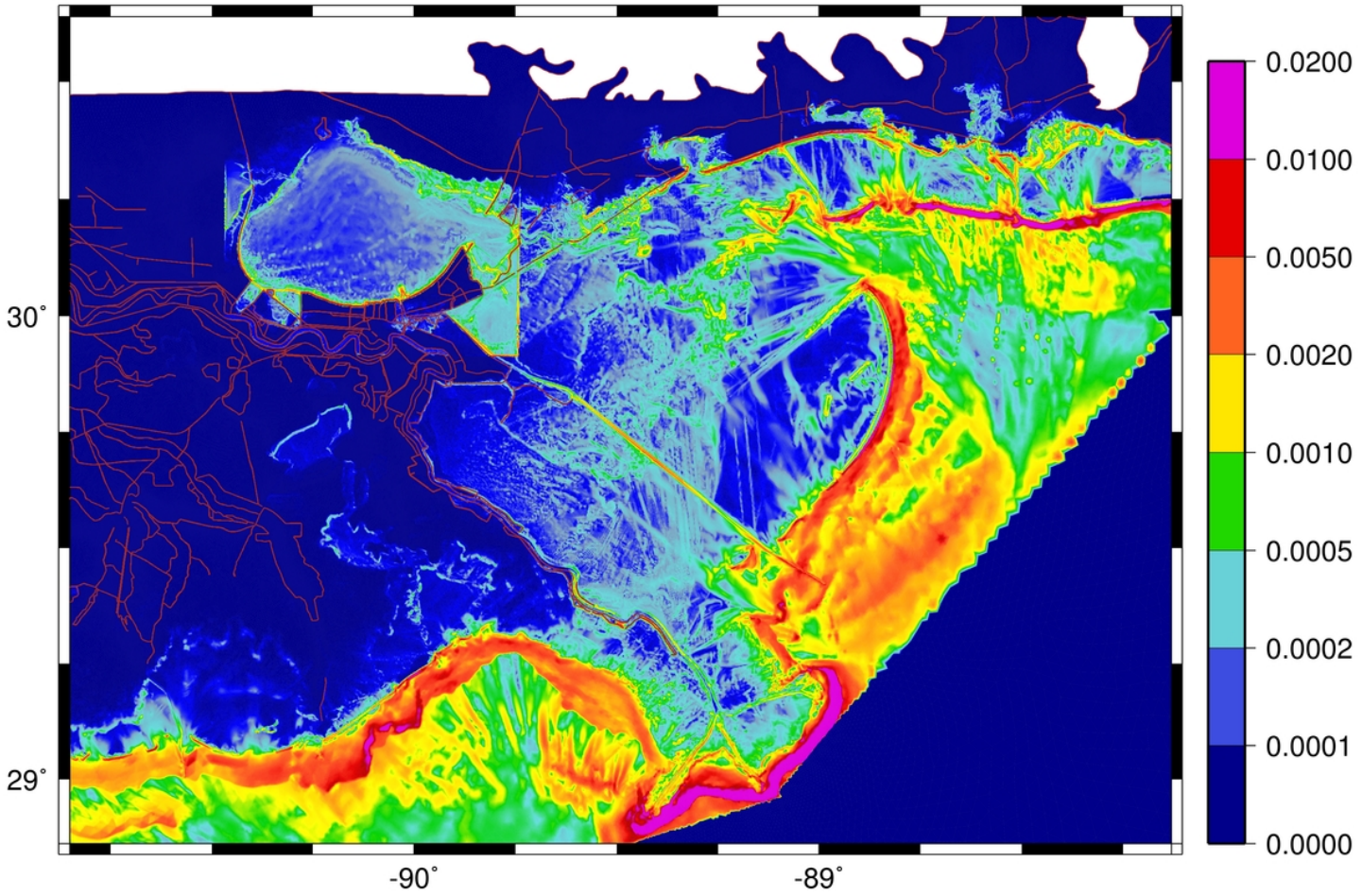
- Maximum significant wave heights in Hurricane Katrina



‘Loose’ Coupling

It Works!

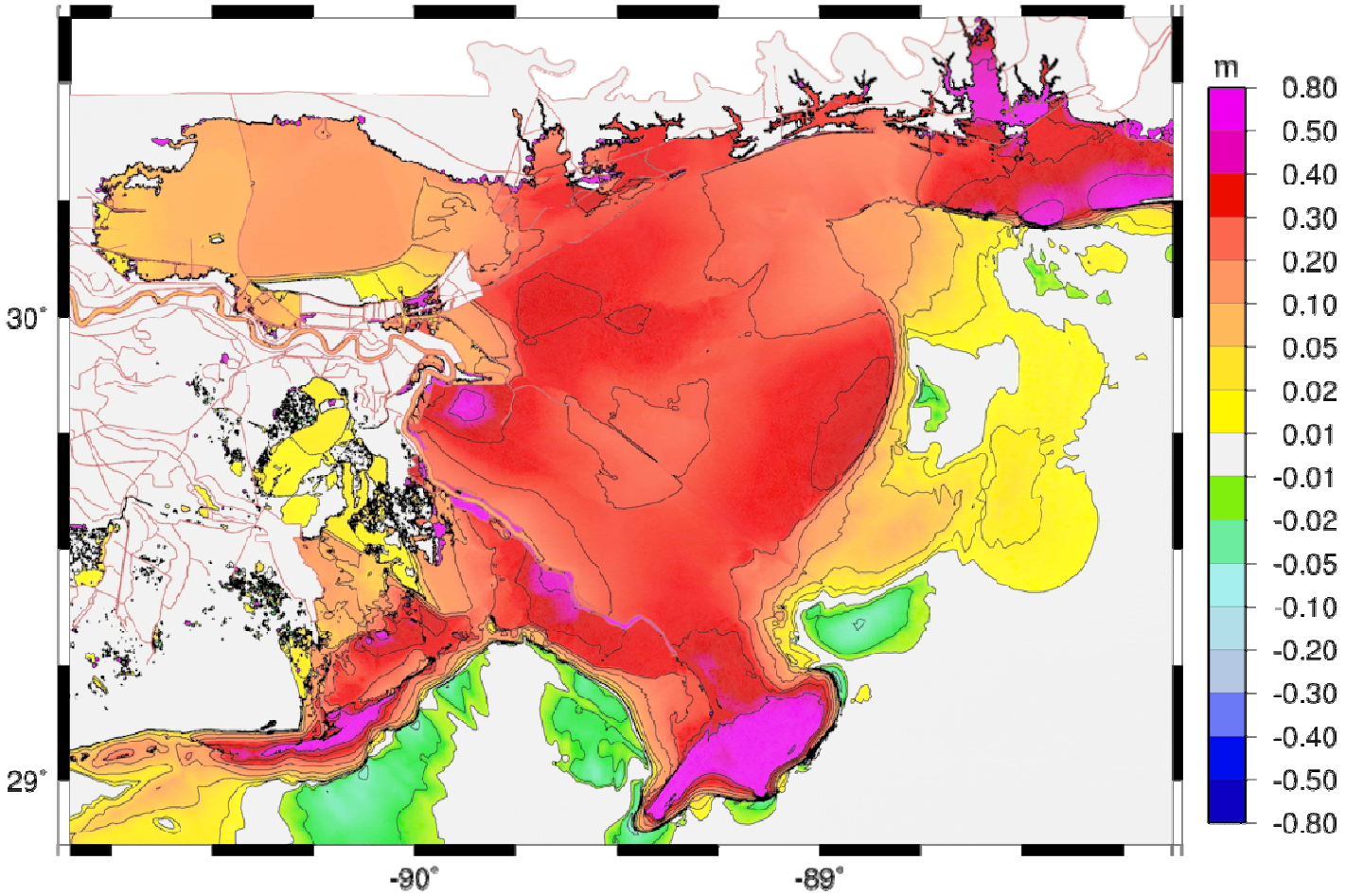
- Maximum wave-driven forces in Hurricane Katrina



‘Loose’ Coupling

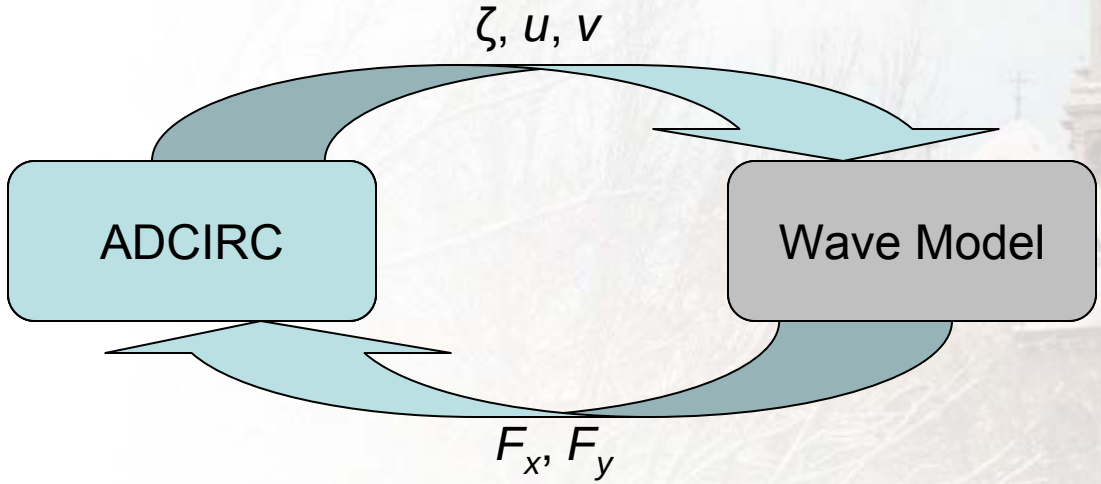
It Works!

- Effect of waves on water levels in Hurricane Katrina



Disadvantages of 'Loose' Coupling

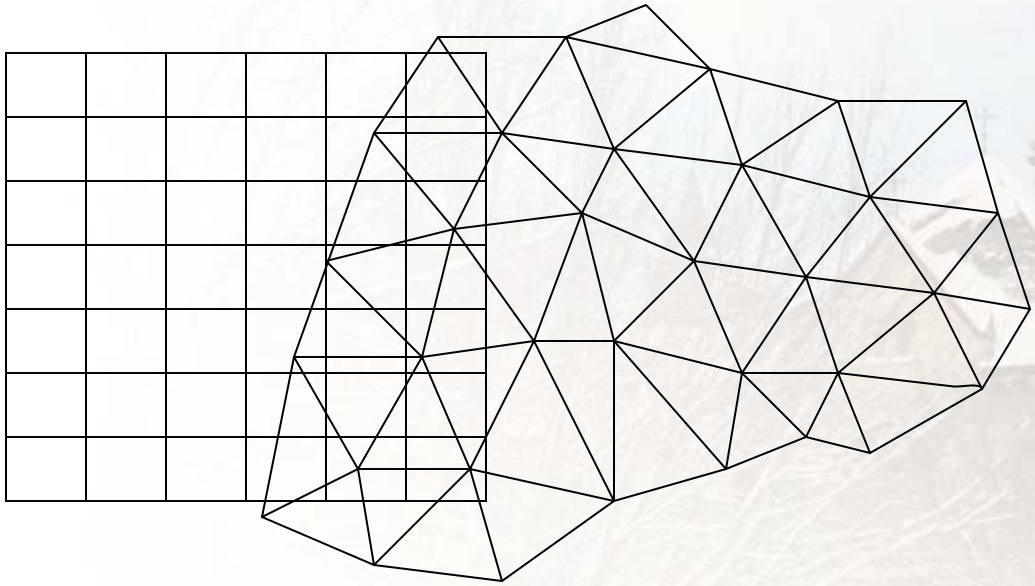
1. **Iteration:**
   - Models coupled through input files
     - Water levels and currents passed to wave model
     - Wave-driven forces passed to shallow-water model
   - Process can be automated, but is still inefficient



Disadvantages of 'Loose' Coupling

2. Interpolation:

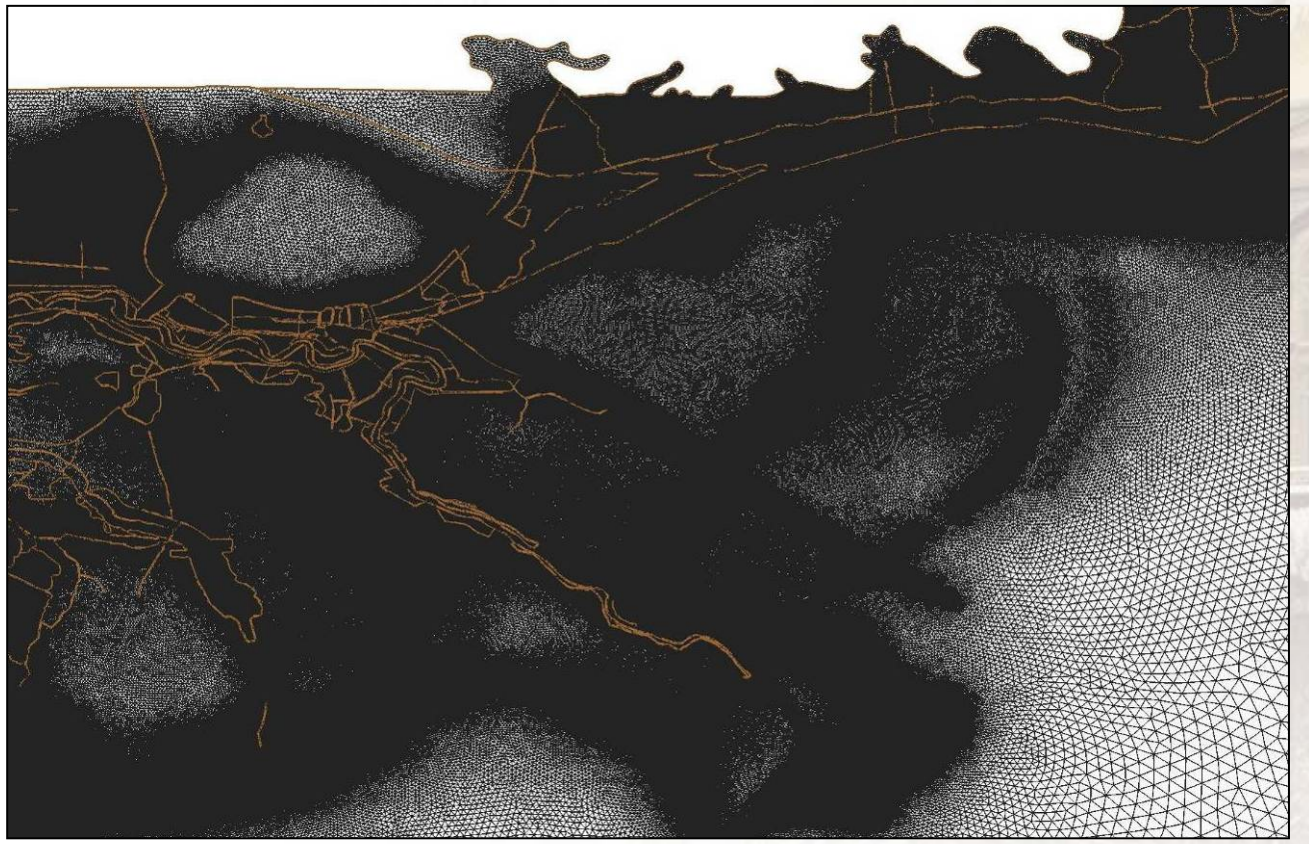
- Wave and circulation models run on different grids
  - Wave models on structured meshes
  - ADCIRC on unstructured, finite element mesh
- Results must be interpolated onto each mesh



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 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

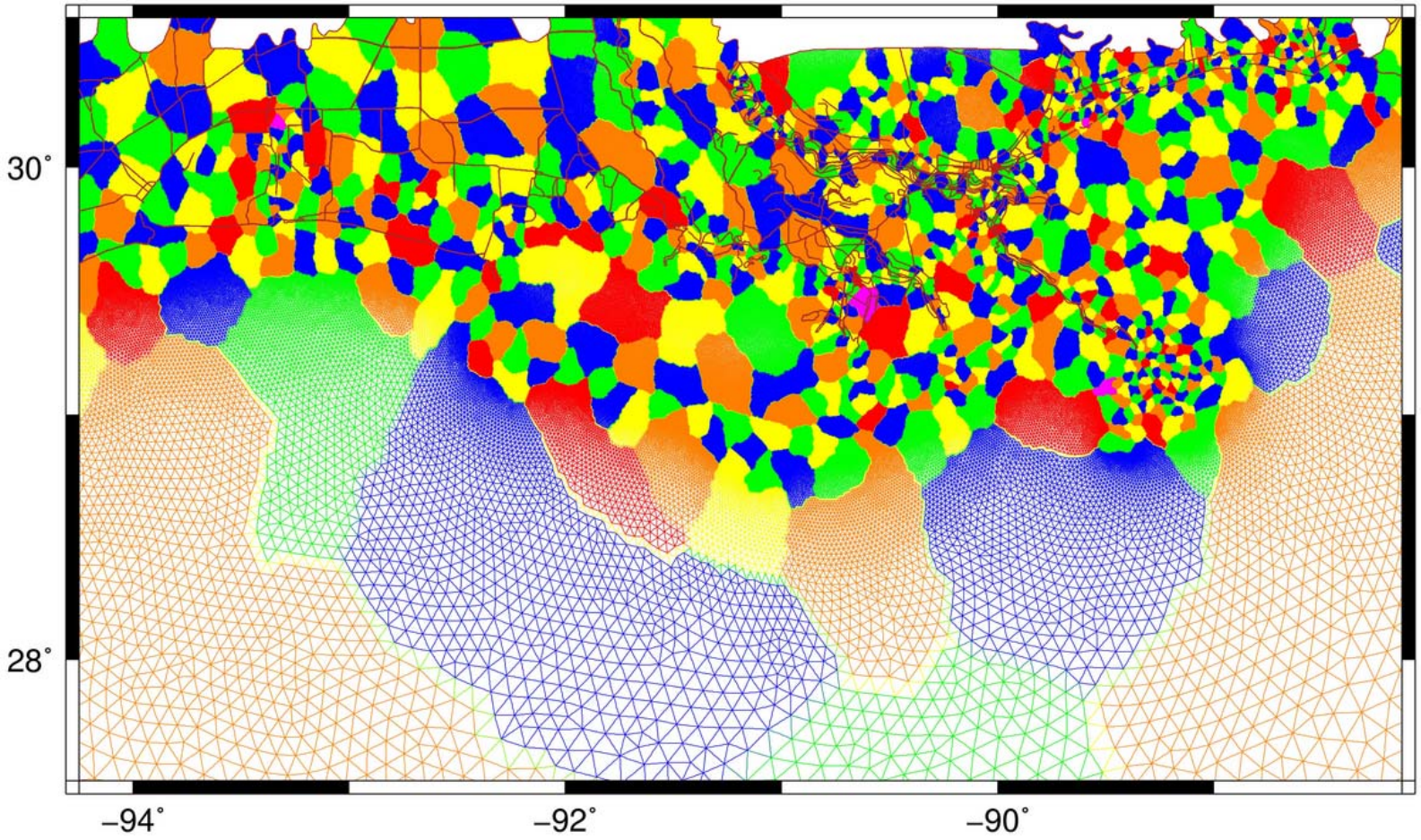
Progress:

- 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 1014 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:

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

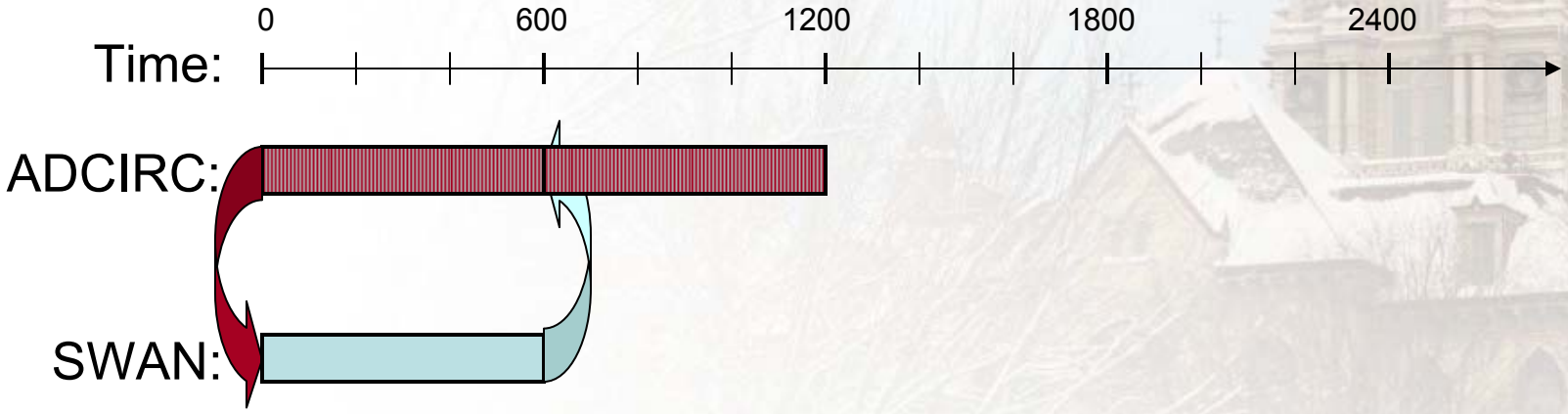
$$S_{xy} = \rho g \int\int (n \sin\theta \cos\theta \sigma N) d\sigma d\theta$$

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

UnSWAN+ADCIRC

Schematic of Coupling:

- ADCIRC is run for 600 seconds (Δt = 1 sec)
- Water levels (ζ) and currents (*u,v*) are passed to Swan
- UnSWAN 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

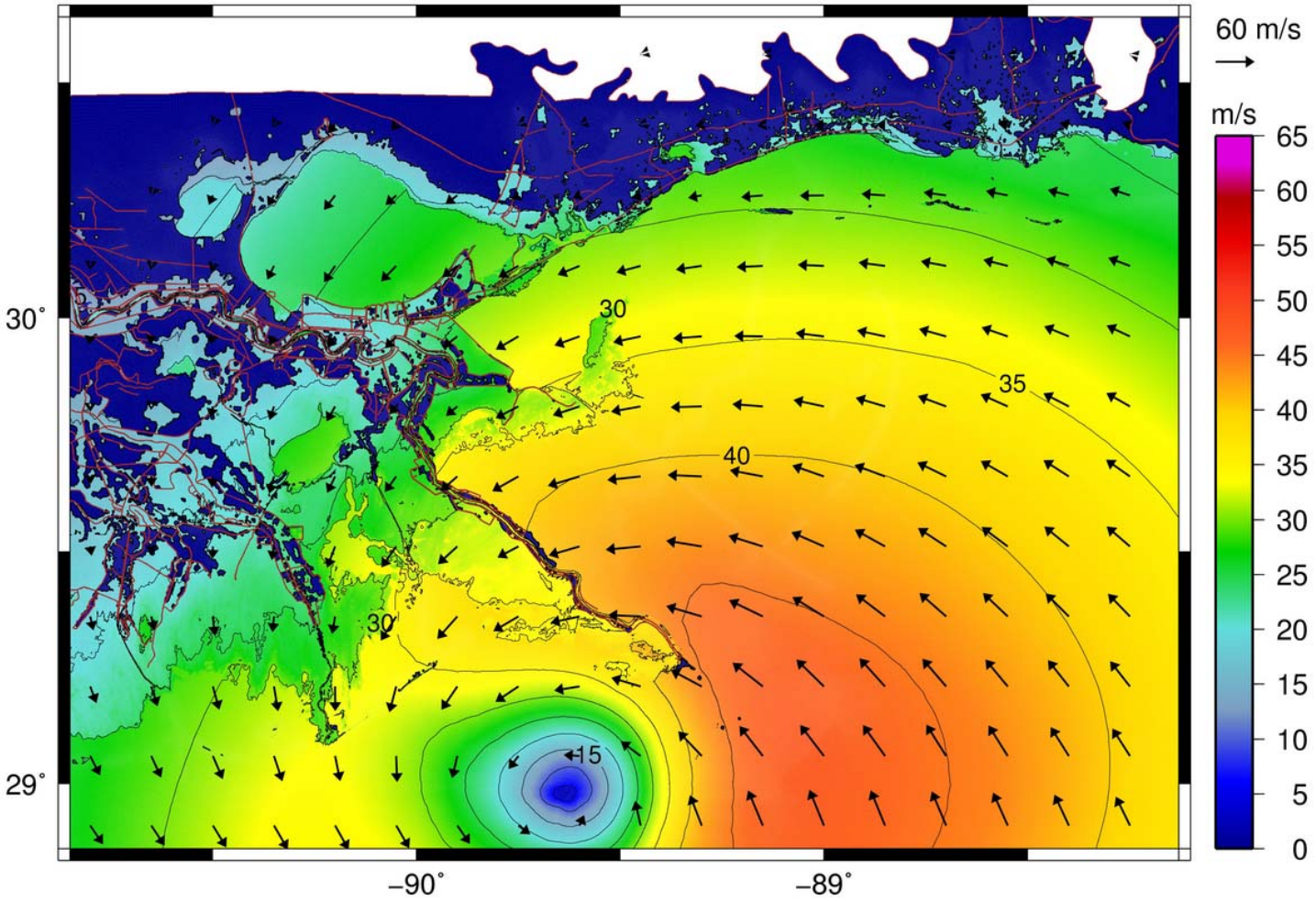


- UnSWAN and ADCIRC are always extrapolating in time

Hurricane Katrina

Katrina at 2005/08/29/1000Z

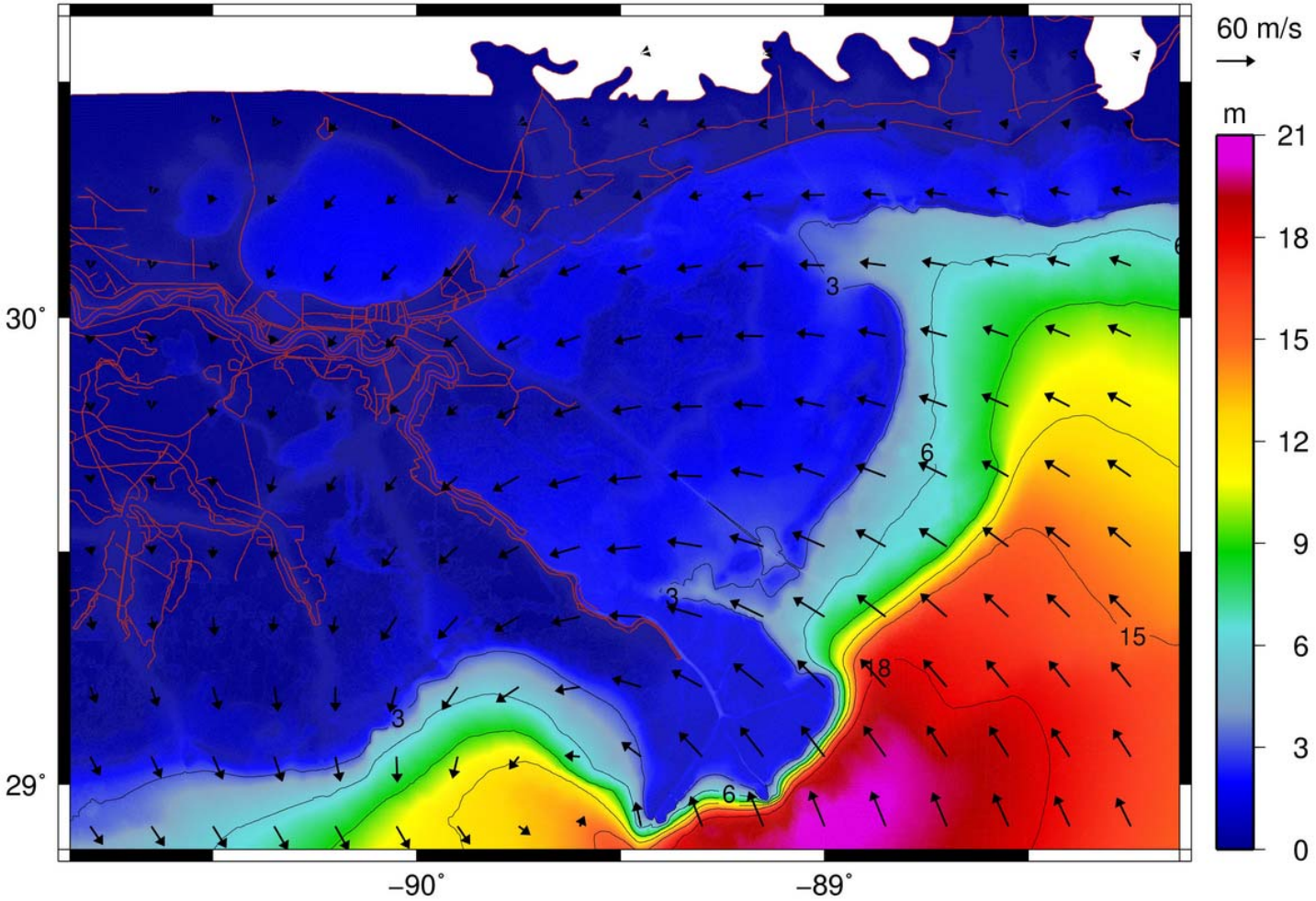
- Wind speed contours (m/s) and vectors (m/s)



Hurricane Katrina

Katrina at 2005/08/29/1000Z

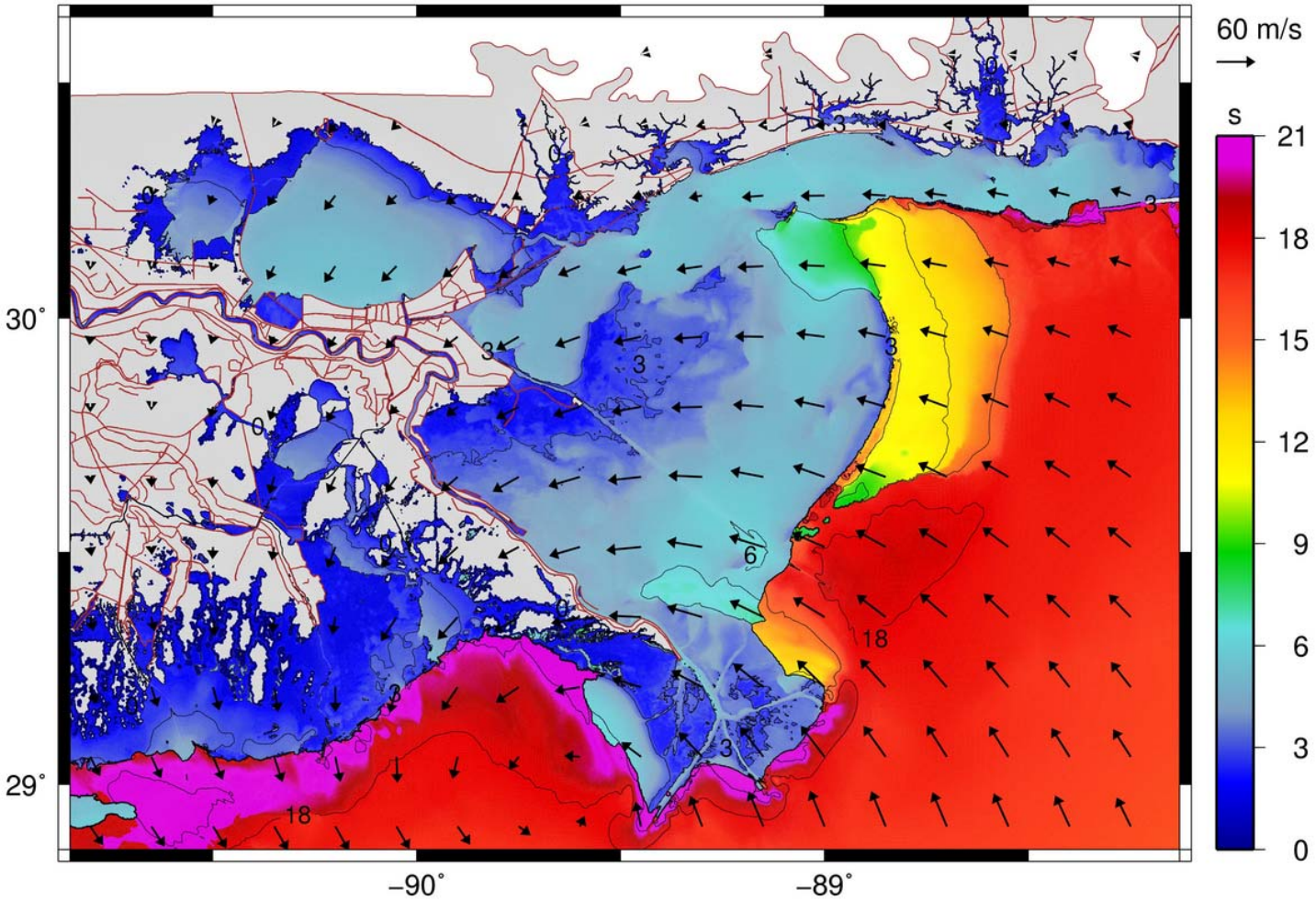
- Significant wave height contours (m) and wind vectors (m/s)



Hurricane Katrina

Katrina at 2005/08/29/1000Z

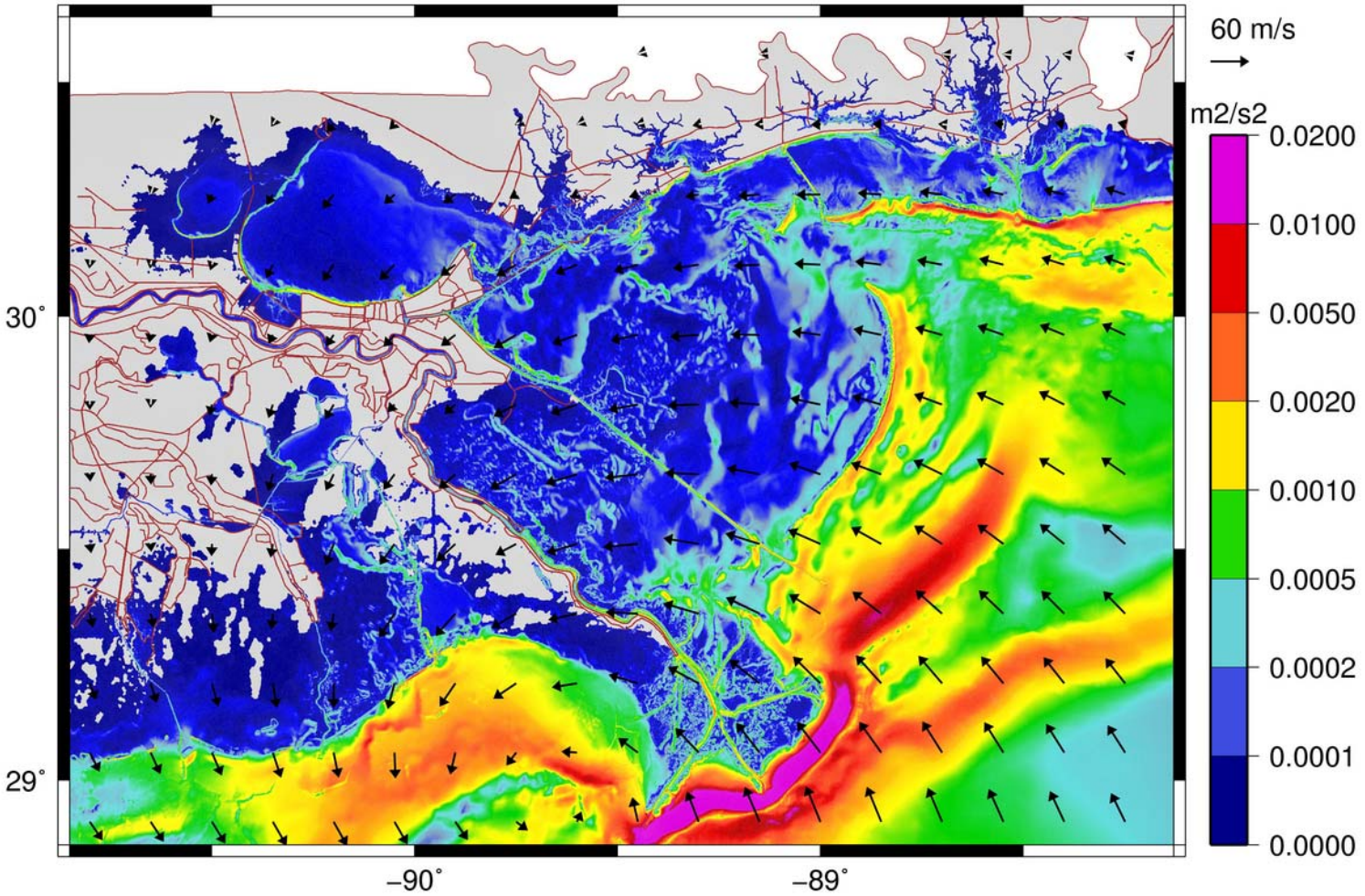
- Peak wave period contours (s) and wind vectors (m/s)



Hurricane Katrina

Katrina at 2005/08/29/1000Z

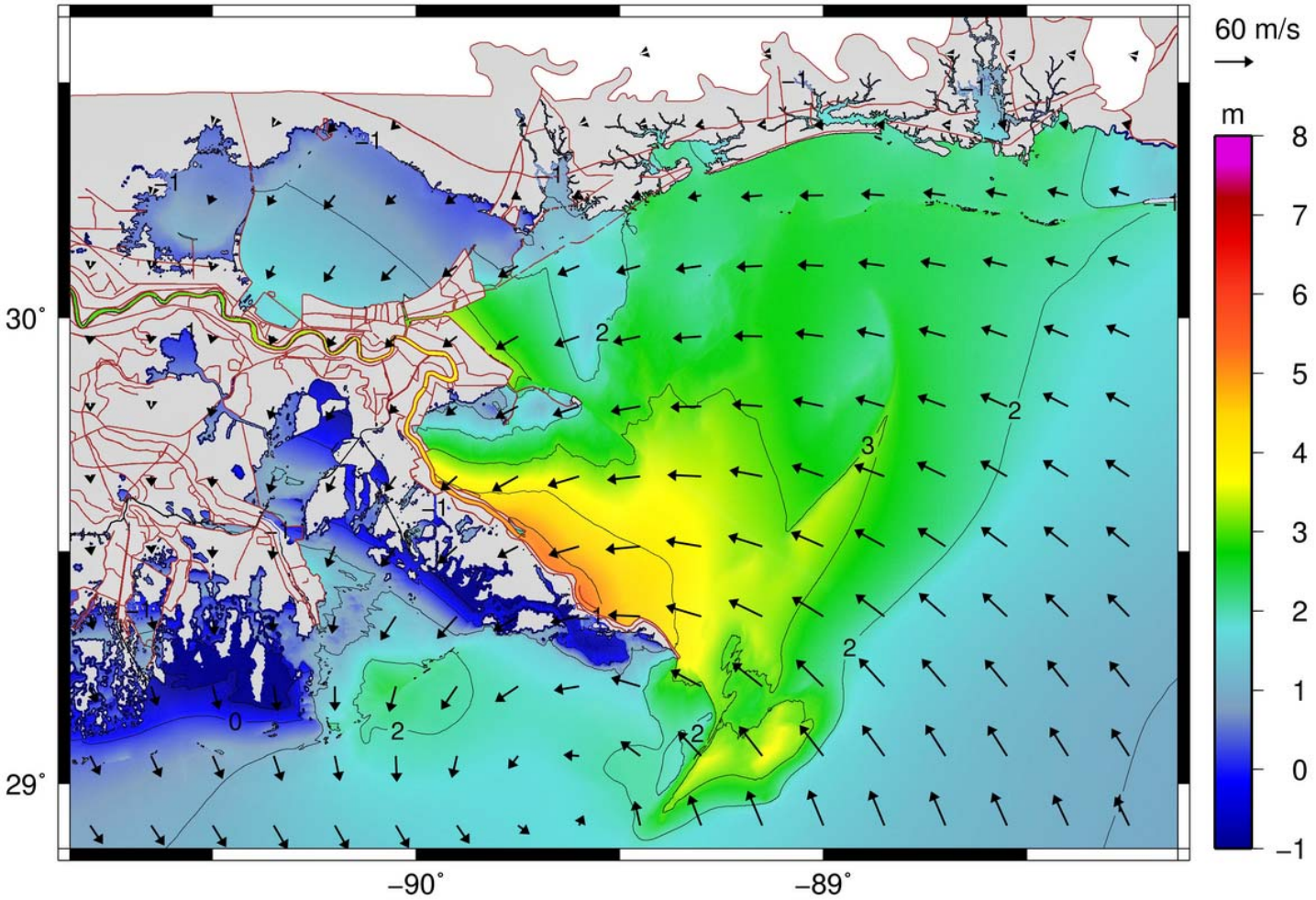
- Wave-driven force contours (m^2/s^2) and wind vectors (m/s)



Hurricane Katrina

Katrina at 2005/08/29/1000Z

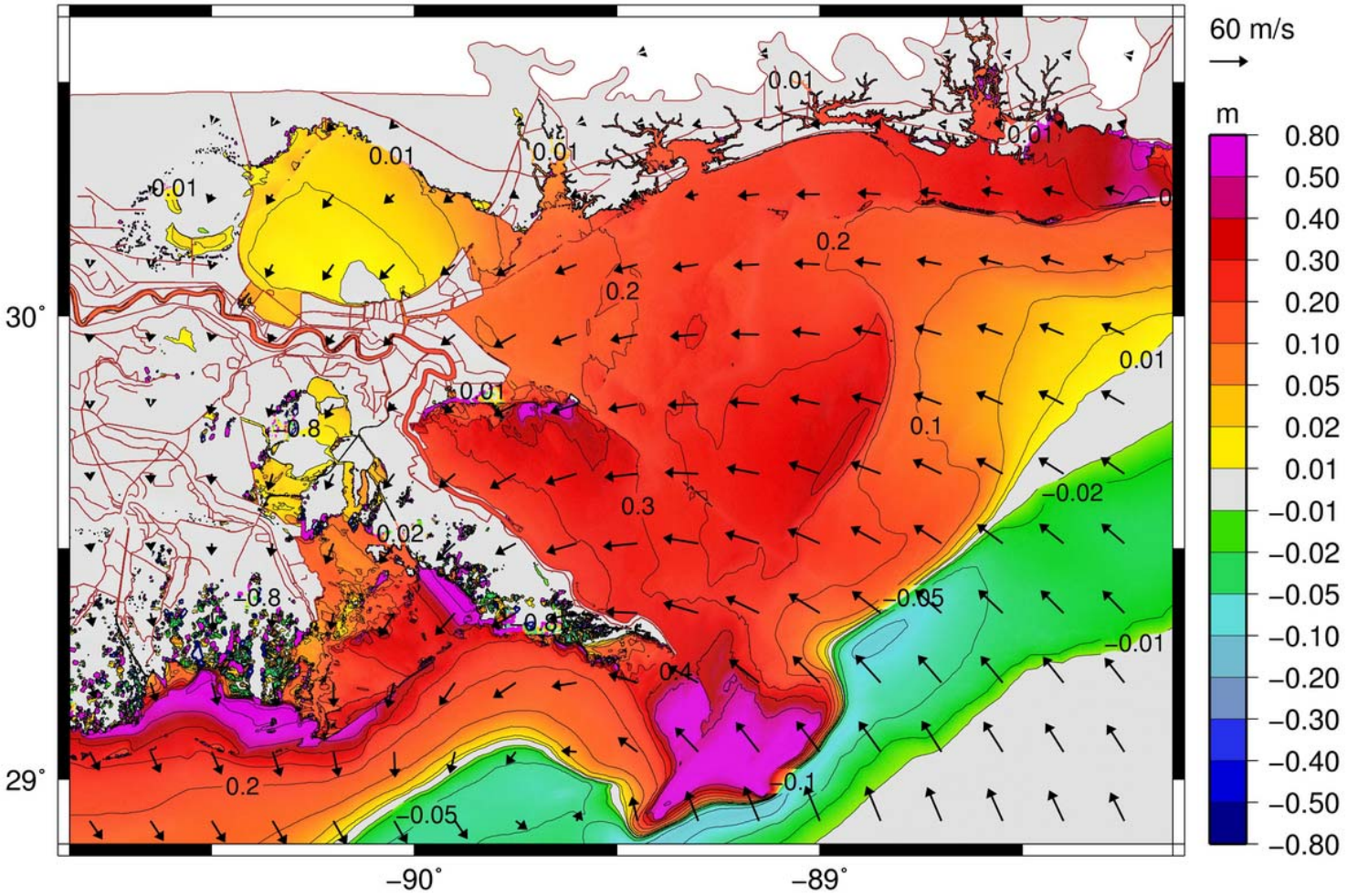
- Water level contours (m) and wind vectors (m/s)



Hurricane Katrina

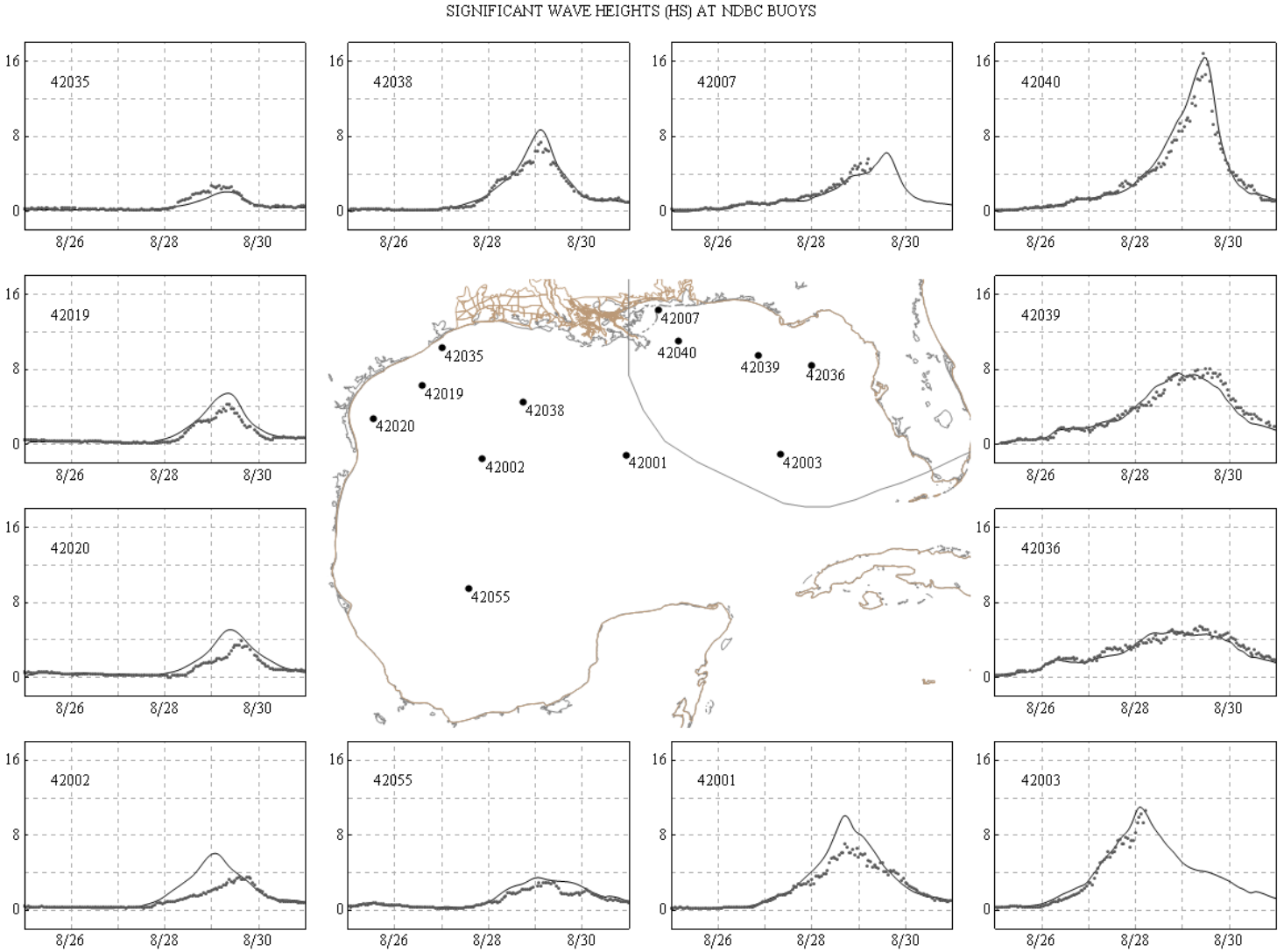
Katrina at 2005/08/29/1000Z

- Wave set-up contours (m) and wind vectors (m/s)



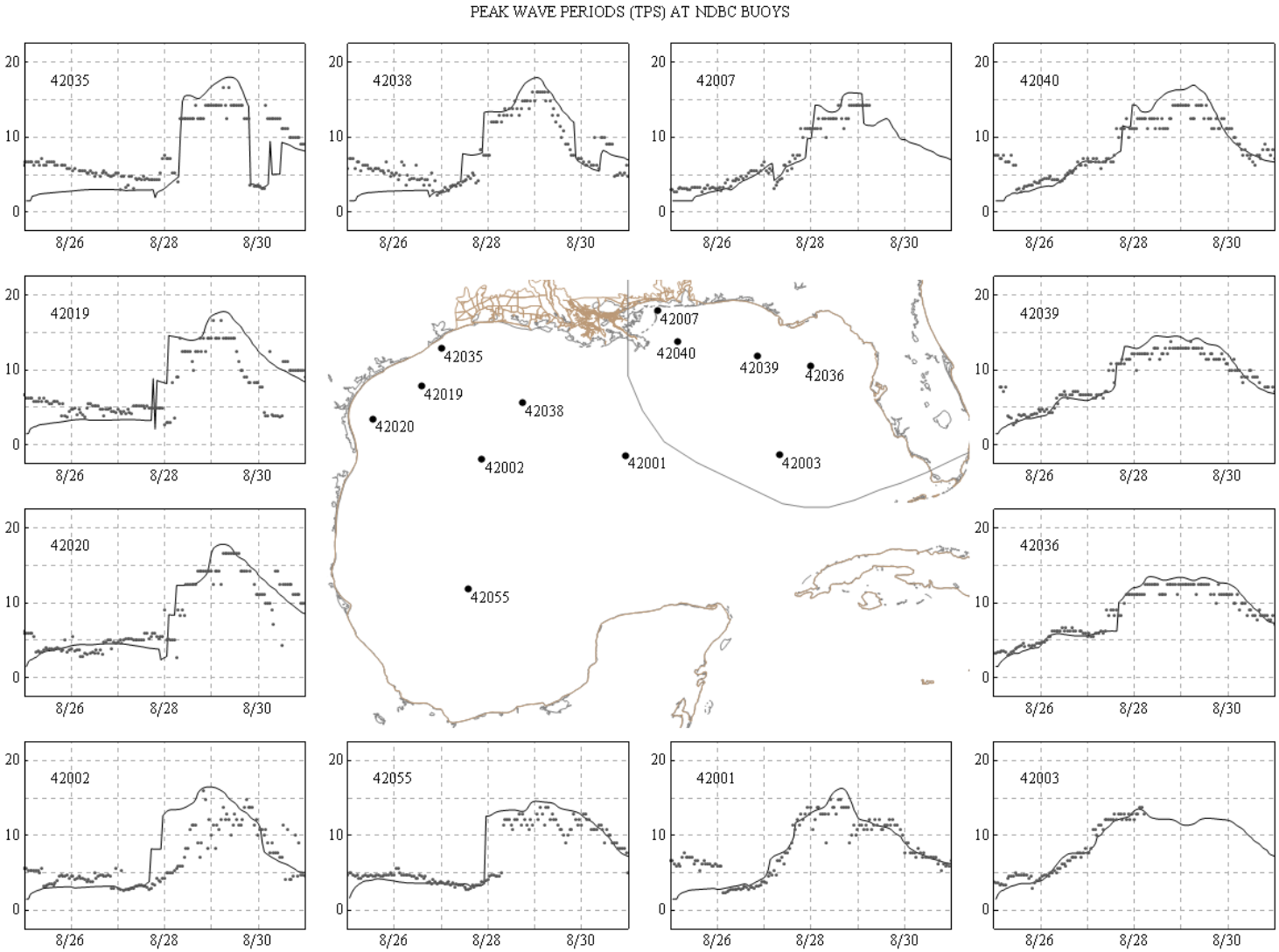
Hurricane Katrina

Validation of SWAN in deep water



Hurricane Katrina

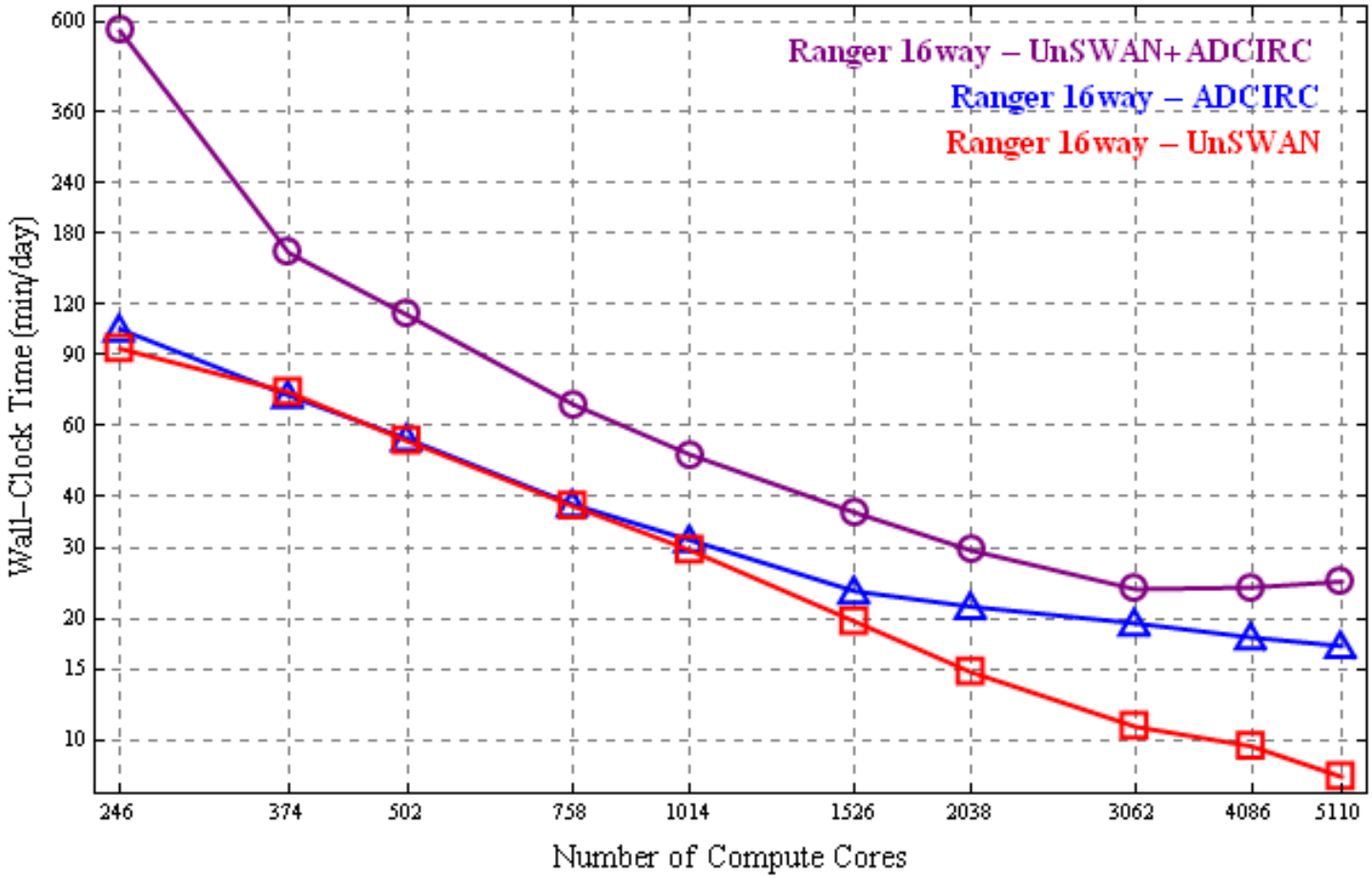
Validation of SWAN in deep water



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
- 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

Future Work

- Next generation of meshes
- Next generation of storms