Development and Application of High-Resolution Models for Ocean Waves and Circulation

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Via Dept. of Civil and Environmental Engineering
Virginia Tech
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Education and Background

University of Texas at Austin

- Institute for Computational Engineering and Sciences
  - Research Associate: 09/2012 to present
  - Postdoctoral Researcher: 11/2010 to 08/2012

University of Notre Dame

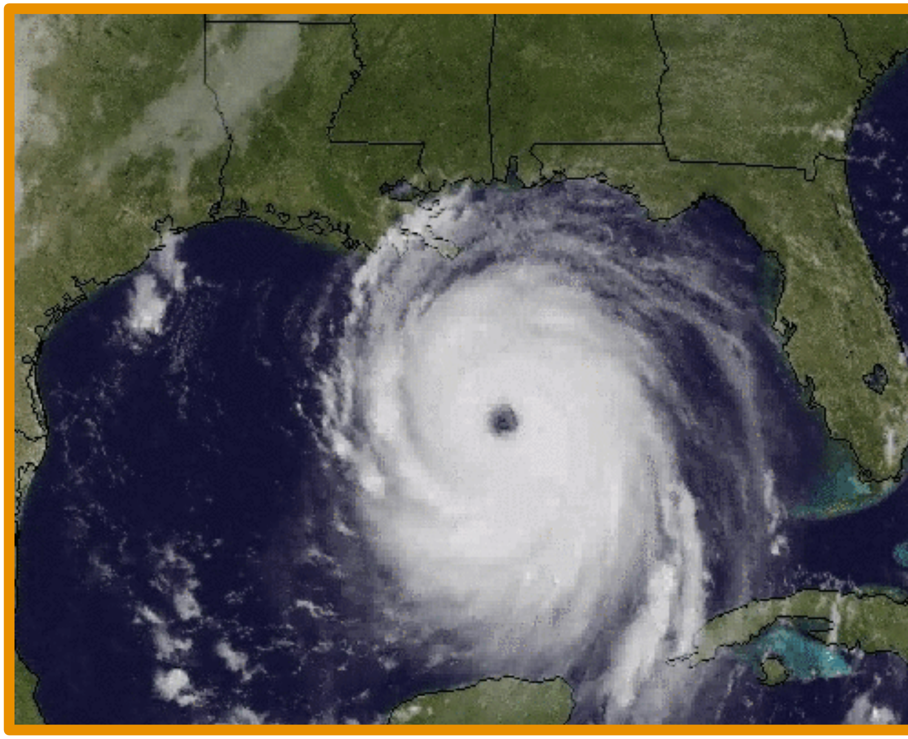
- Department of Civil Engineering and Geological Sciences
  - Graduate Research Assistant: 08/2005 to 10/2010
    - PhD: 12 October 2010

University of Oklahoma

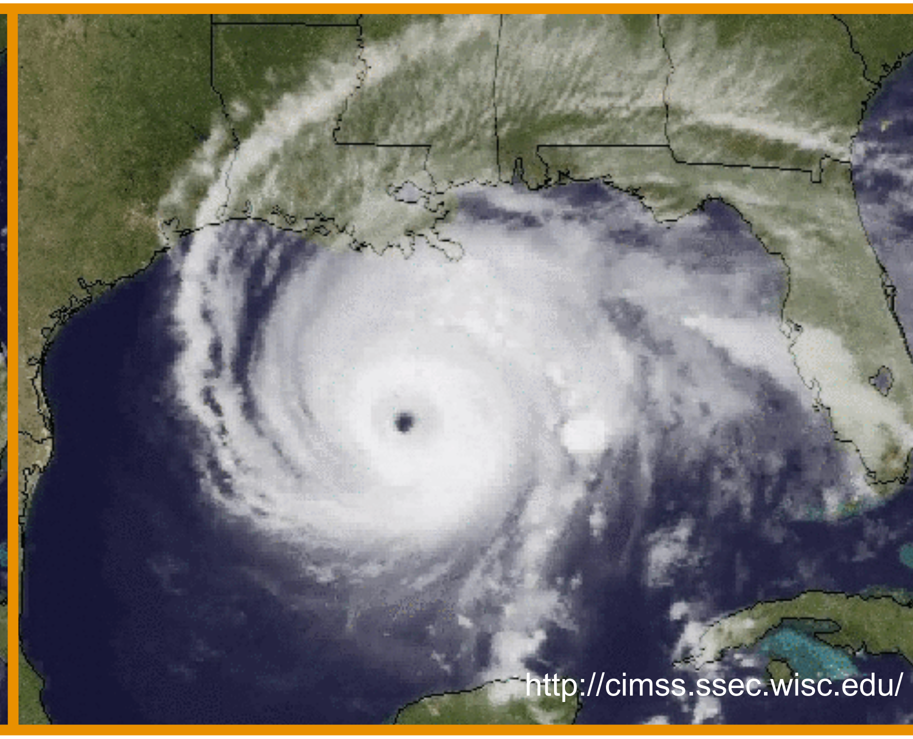
- School of Civil Engineering and Environmental Science
  - Graduate Research Assistant: 06/2004 to 07/2005
    - MS: 23 June 2005
  - Undergraduate Research Assistant: 06/1999 to 05/2004
    - BS & BA: May 2004

Hurricane Season 2005

Katrina : 08/28 – 08/29

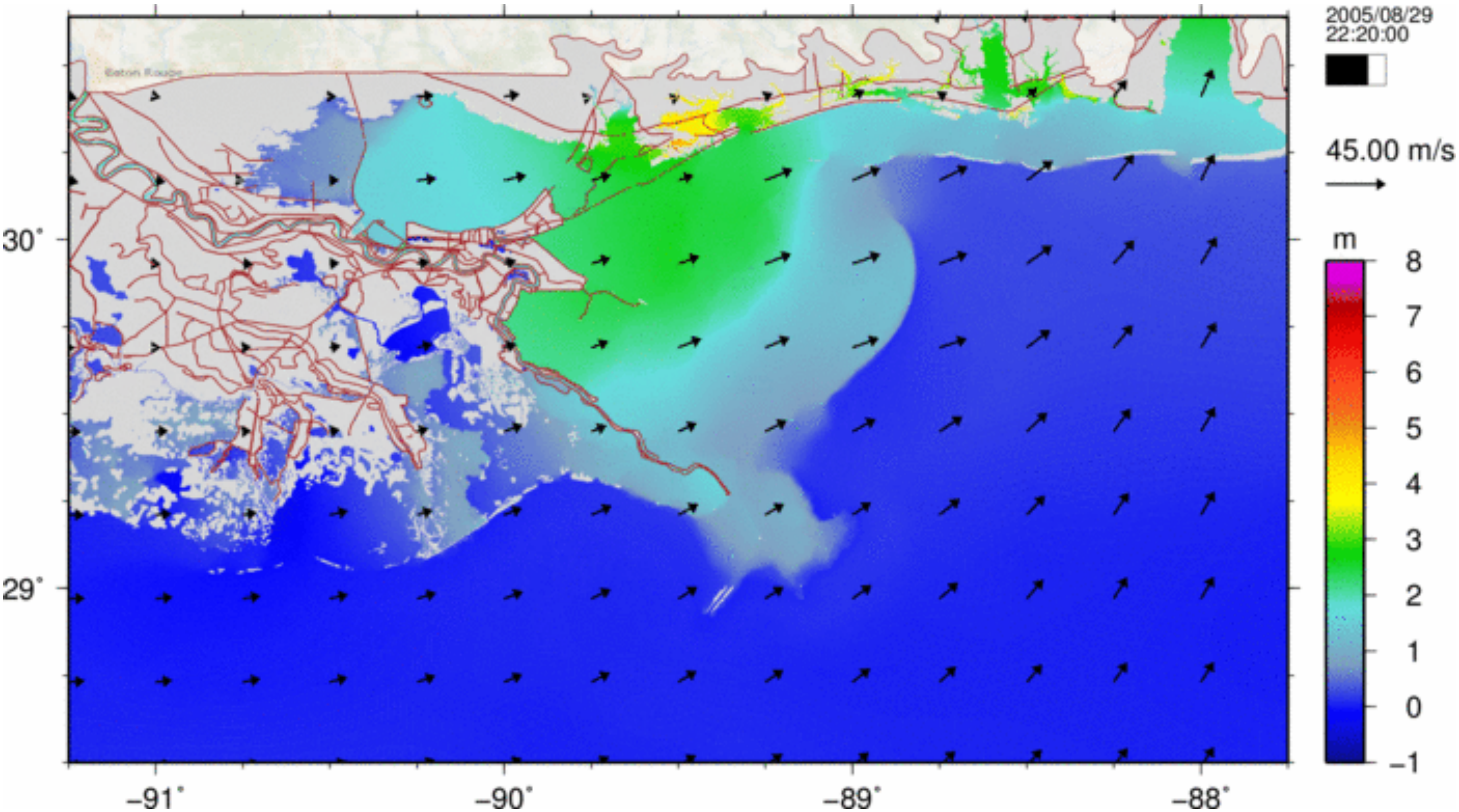


Rita : 09/22 – 09/24



Katrina : Flooding of New Orleans

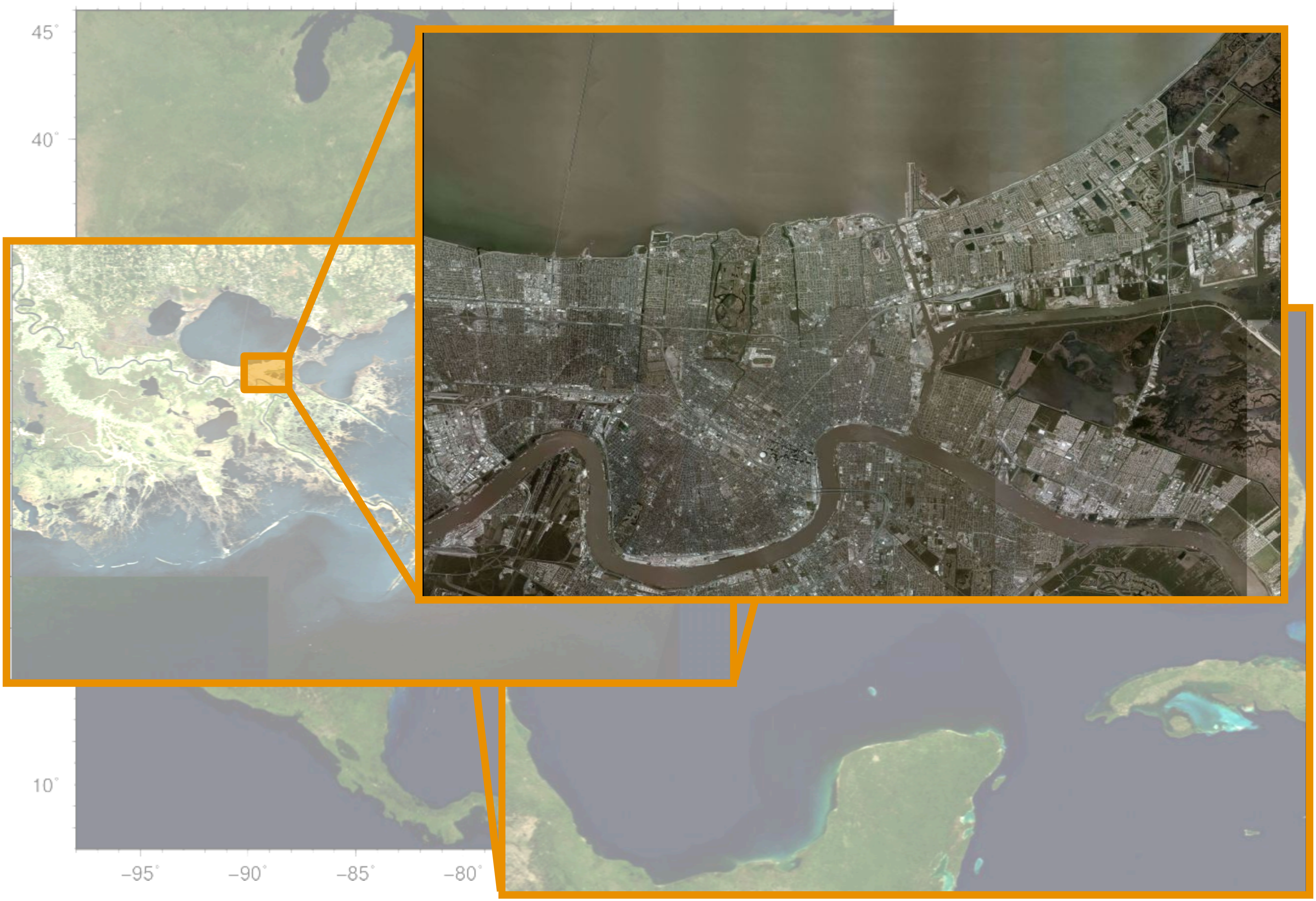
Katrina : Storm Surge : Day of Landfall



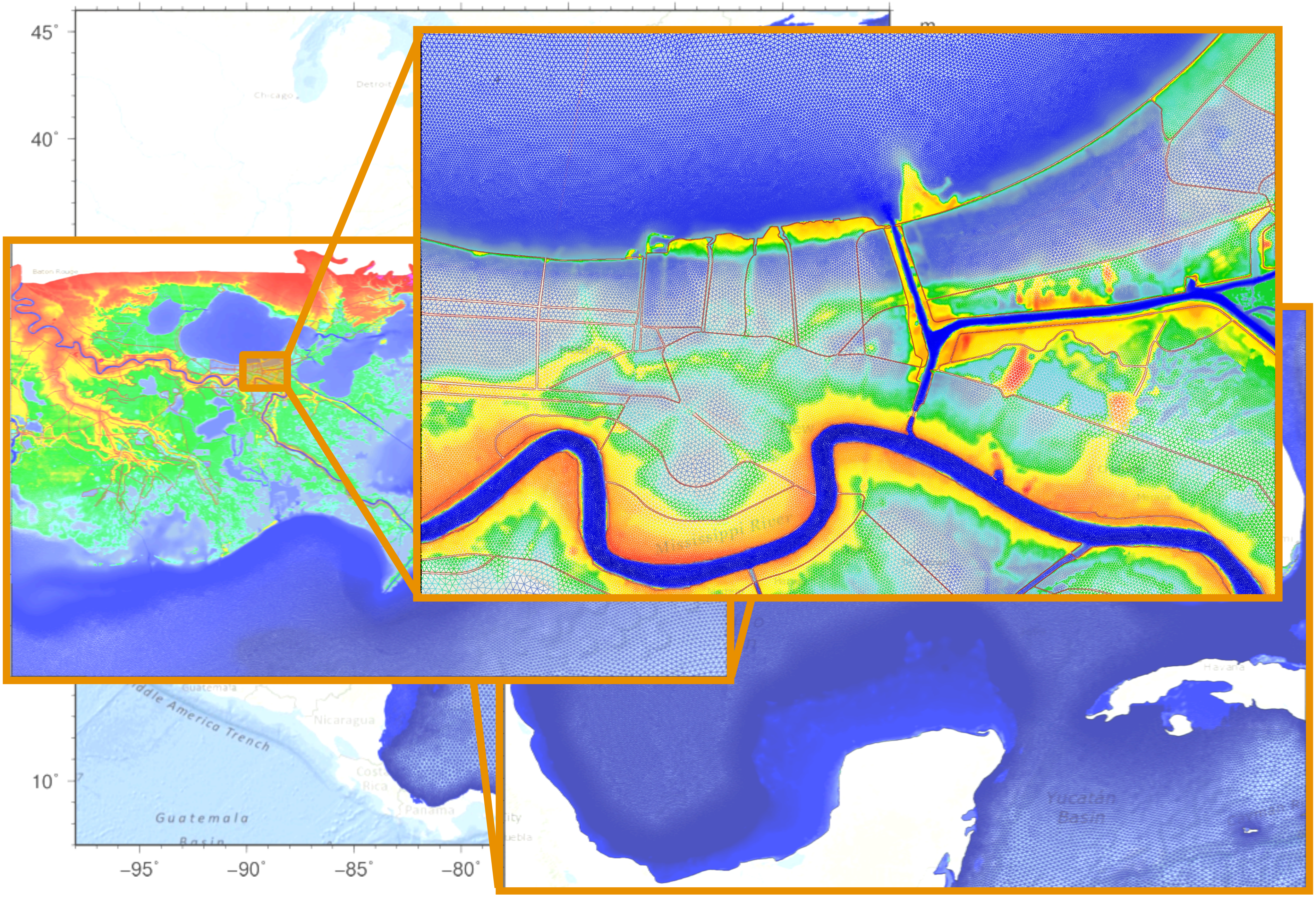
S Bunya, JC Dietrich, *et al.* (2010). A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave and Storm Surge Model for Southern Louisiana and Mississippi: Part I – Model Development and Validation. *Monthly Weather Review*, 138(2), 345-377.

JC 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(2), 378-404.

Spatial Scales : Domain



Spatial Scales : Unstructured Mesh



Models : Long and Short Waves

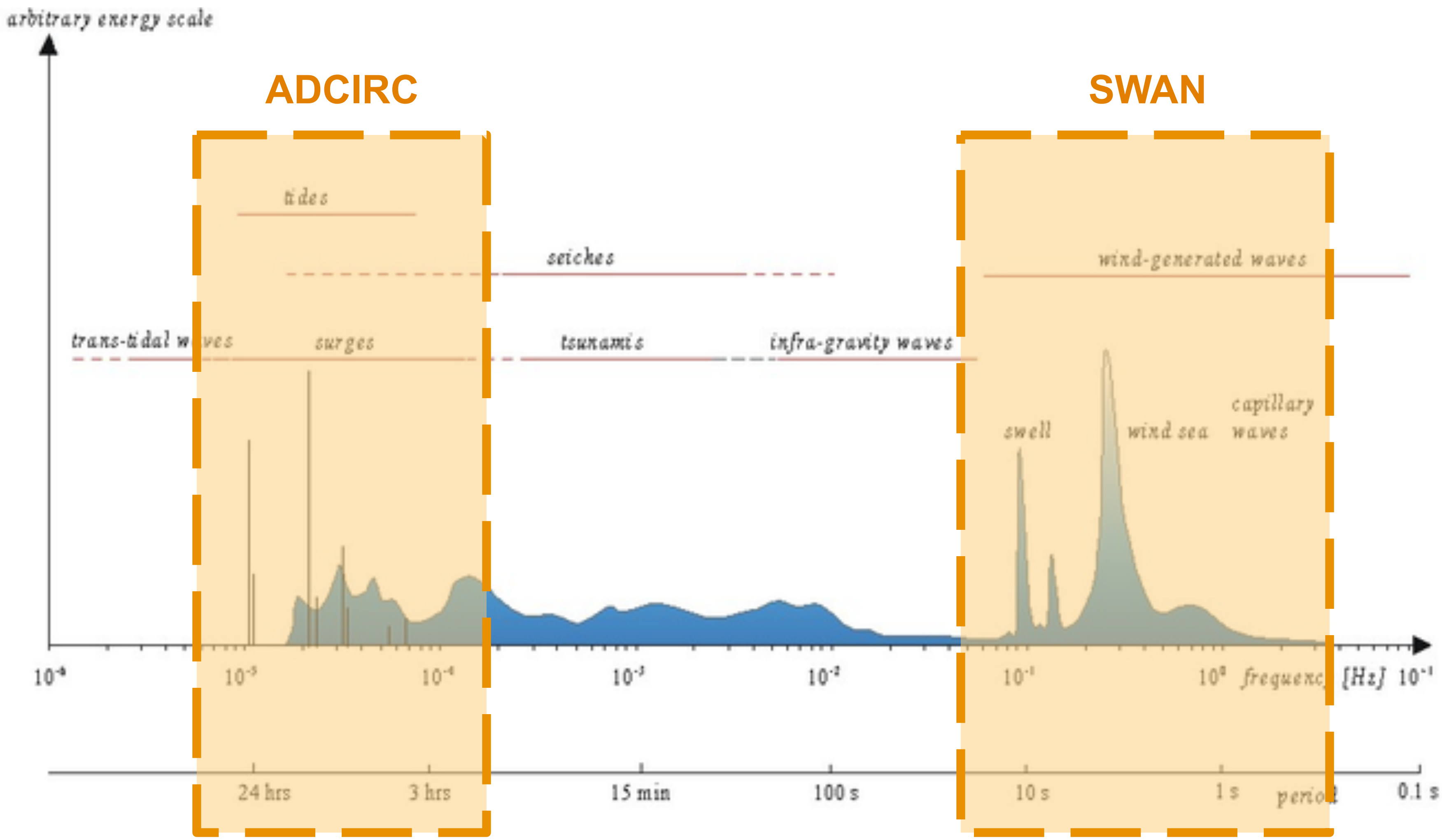


Image: Holthuijsen (2007)

Models : Simulating WAves Nearshore (SWAN)

Does not resolve the phase of each individual wave

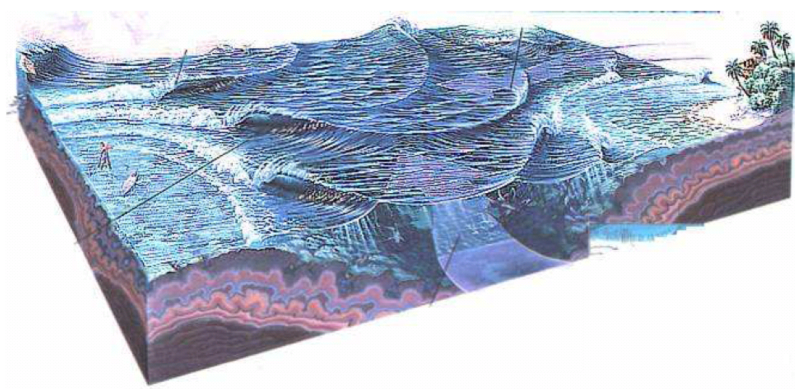
- Conserved quantity is the wave action density $N(t, x, y, \theta, \sigma)$
- Can be integrated to compute statistical wave properties

Solves the action balance equation:

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

Separate solution methods in geographic (x, y) and spectral (θ, σ) spaces:

- Gauss-Seidel sweeping in geographic space
- Iterative solution of matrix system in spectral space



Models : ADvanced CIRCulation (ADCIRC)

Solves the generalized wave continuity equation (GWCE) for water levels ζ:

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

with iterative solution by Jacobi Conjugate Gradient (JCG) method

Solves the vertically-integrated momentum equations for currents (U,V):

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

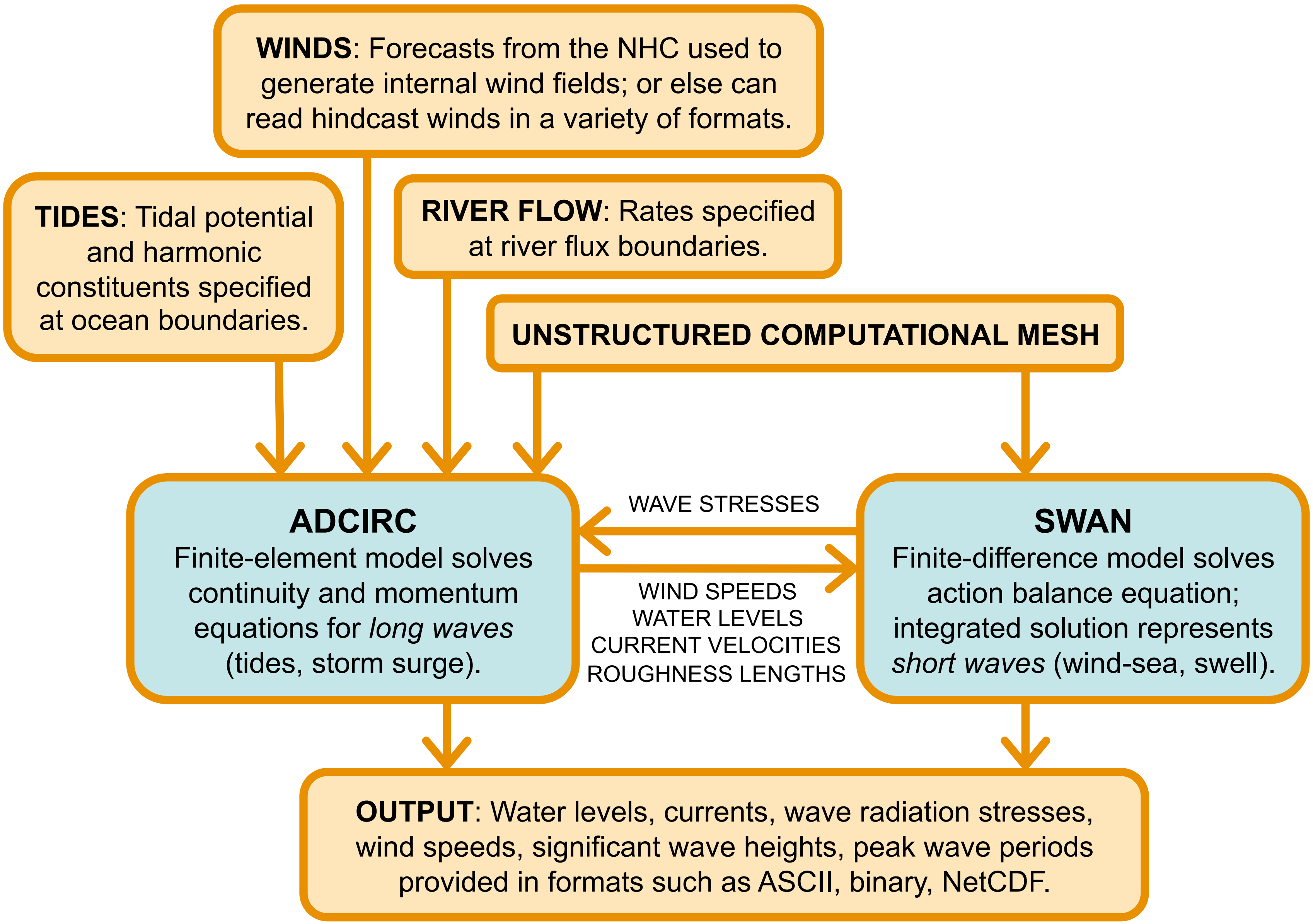
$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \frac{\partial}{\partial y}\left[\zeta + \frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

with explicit solution after updating wet/dry information

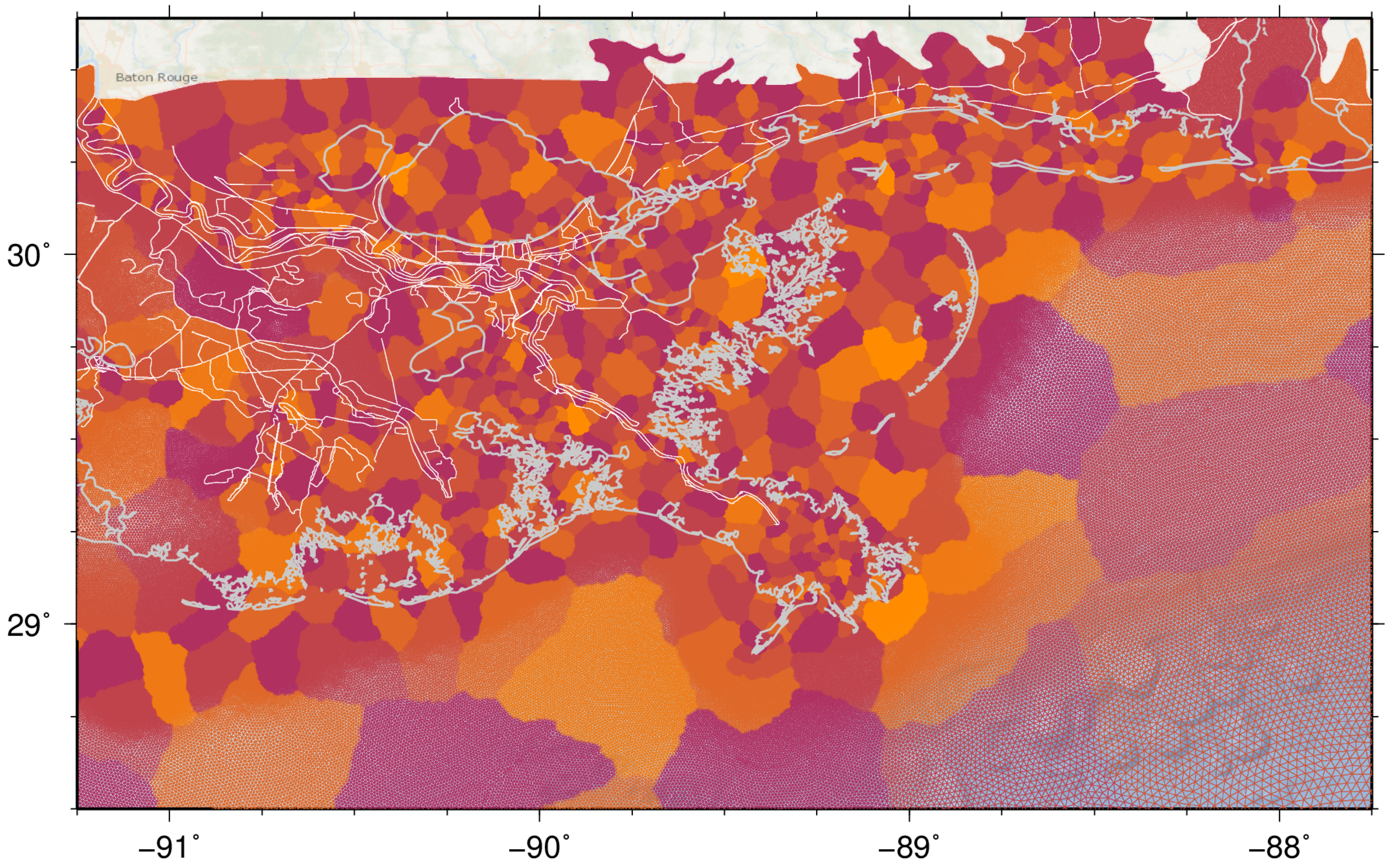
ADCIRC and SWAN interact

- Water levels and currents affect wave transport
- Wave radiation stresses create set-up and alongshore currents

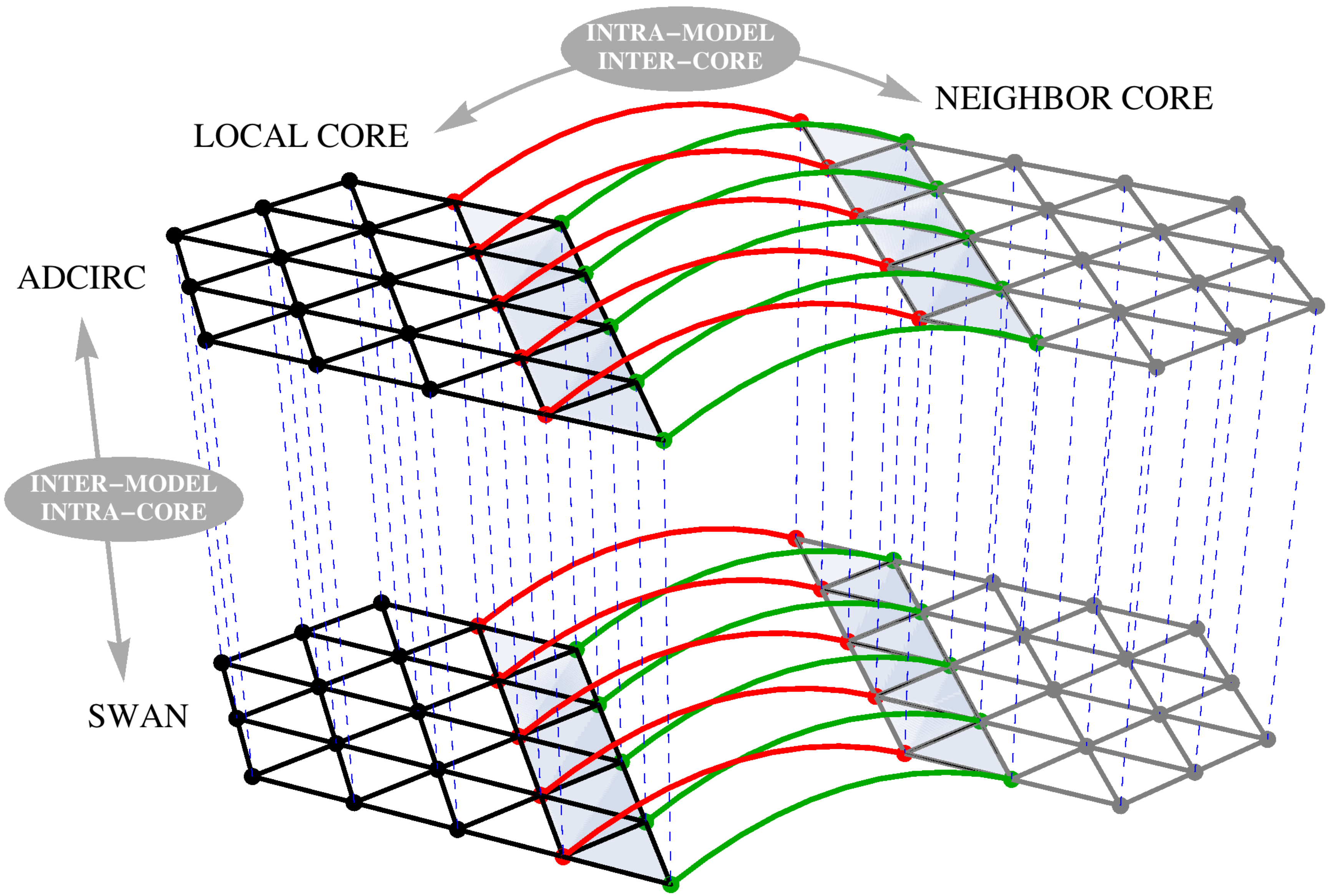
‘Tight’ Coupling : SWAN+ADCIRC



‘Tight’ Coupling : Domain Decomposition

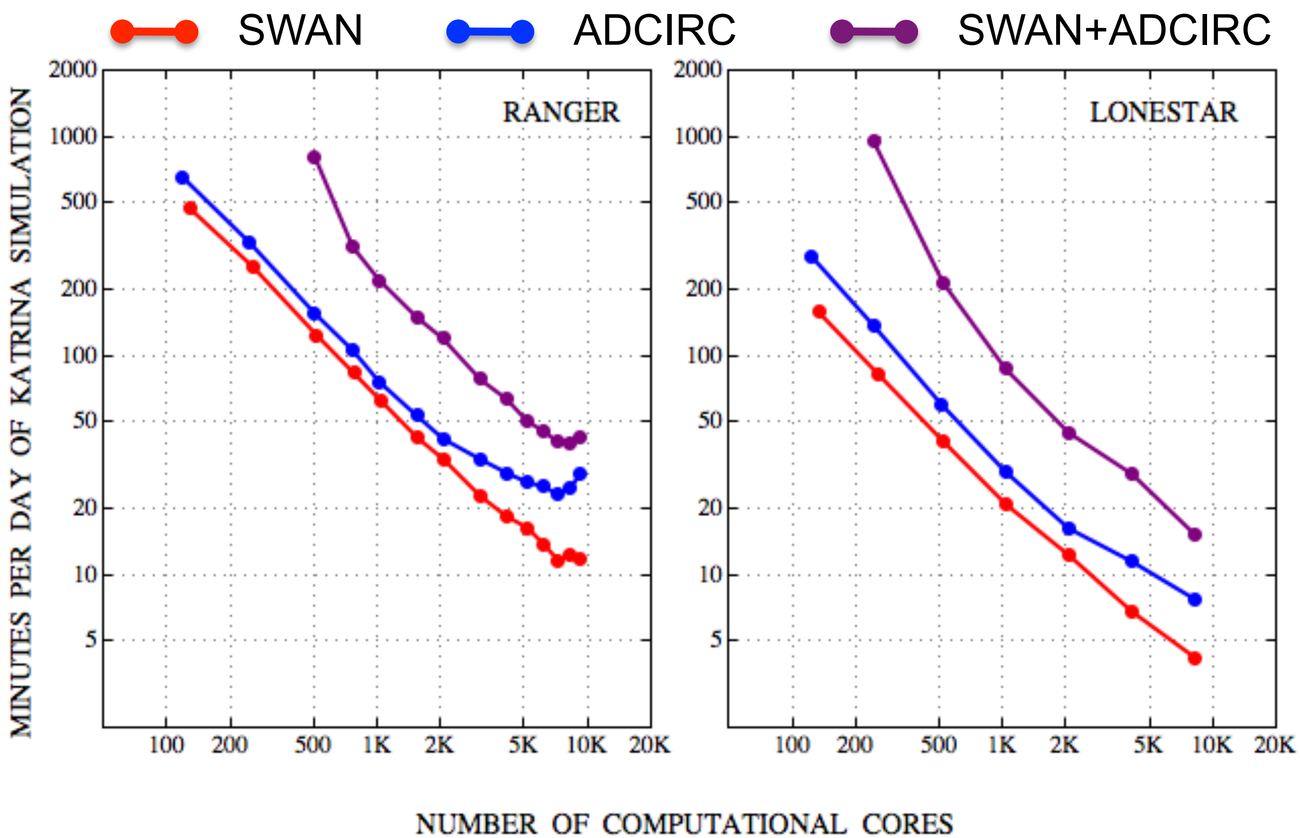


‘Tight’ Coupling : Parallel Communication



JC Dietrich, *et al*. (2011). Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations. *Coastal Engineering*, 58, 45-65, DOI:10.1016/j.coastaleng.2010.08.001.

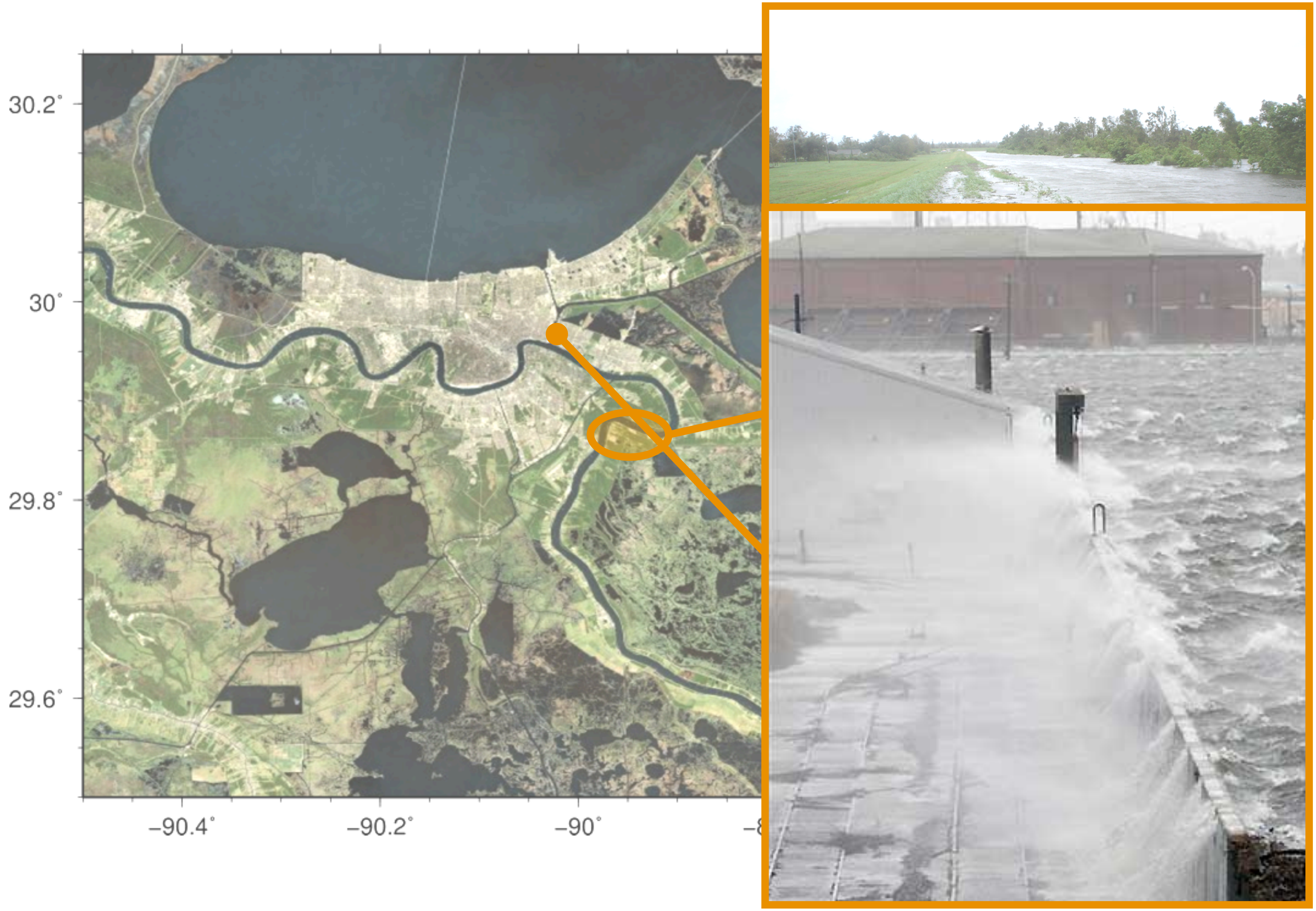
‘Tight’ Coupling : Parallel Scaling



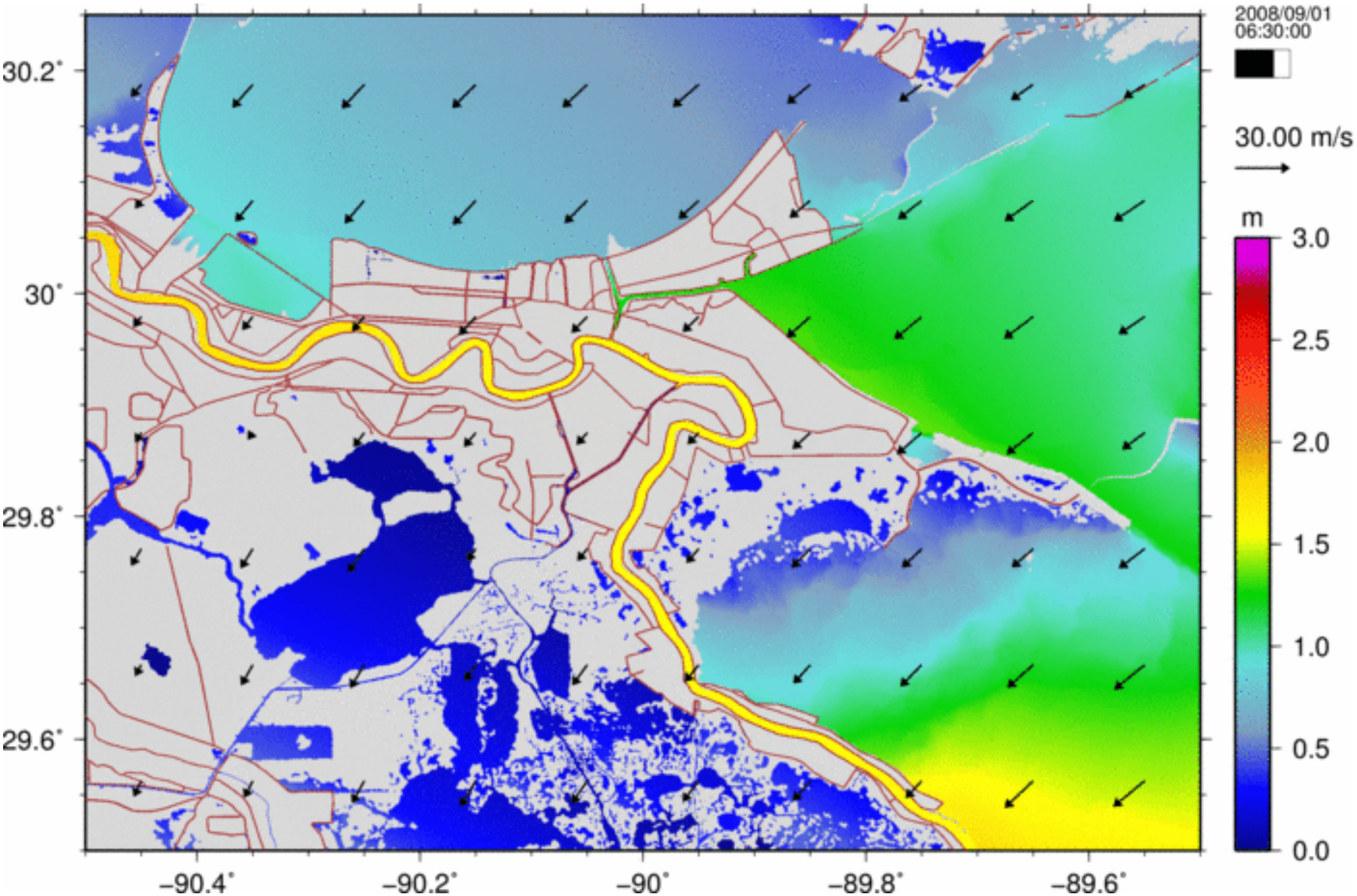
	TACC Ranger	TACC Lonestar
Node	Sun Blade x6420	Dell PowerEdge M610
CPU	4 Quad-core AMD Opteron 8356	2 Six-core Xeon 5680
Frequency	2.3 GHz	3.33 GHz
Architecture	AMD K10 (Barcelona)	Intel Nehalem (Westmere-EP)

JC Dietrich, *et al.* (2012). Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge. *Journal of Scientific Computing*, 52(2), 468-497, DOI:10.1007/s10915-011-9555-6.

Gustav : Storm Surge : Near-Flooding of New Orleans

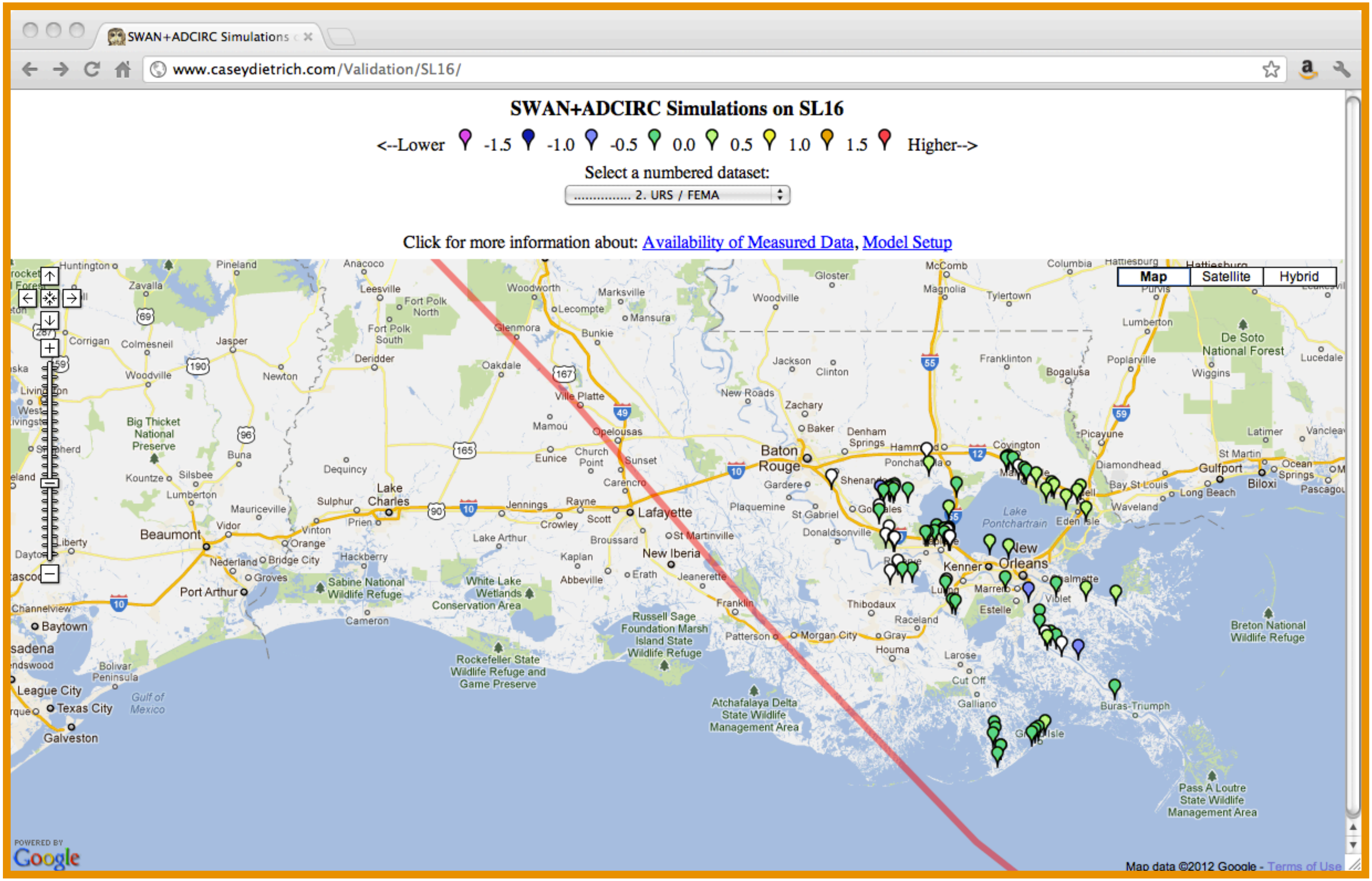


Gustav : Storm Surge : Day of Landfall

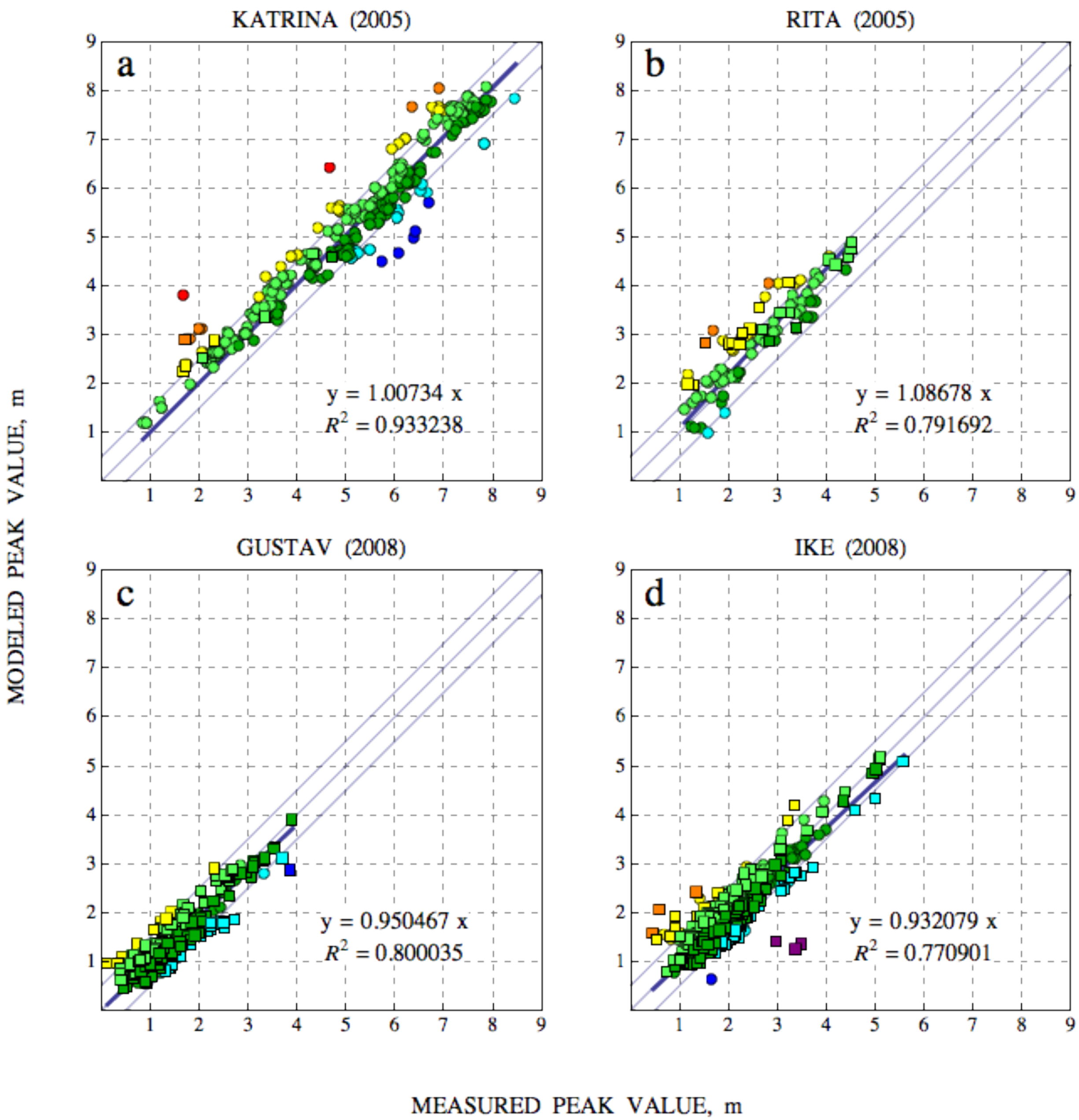


JC Dietrich, *et al*. (2011). Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Validation and Synoptic Analysis in Southern Louisiana. *Monthly Weather Review*, 139(8), 2488-2522, DOI:10.1175/2011MWR3611.1.

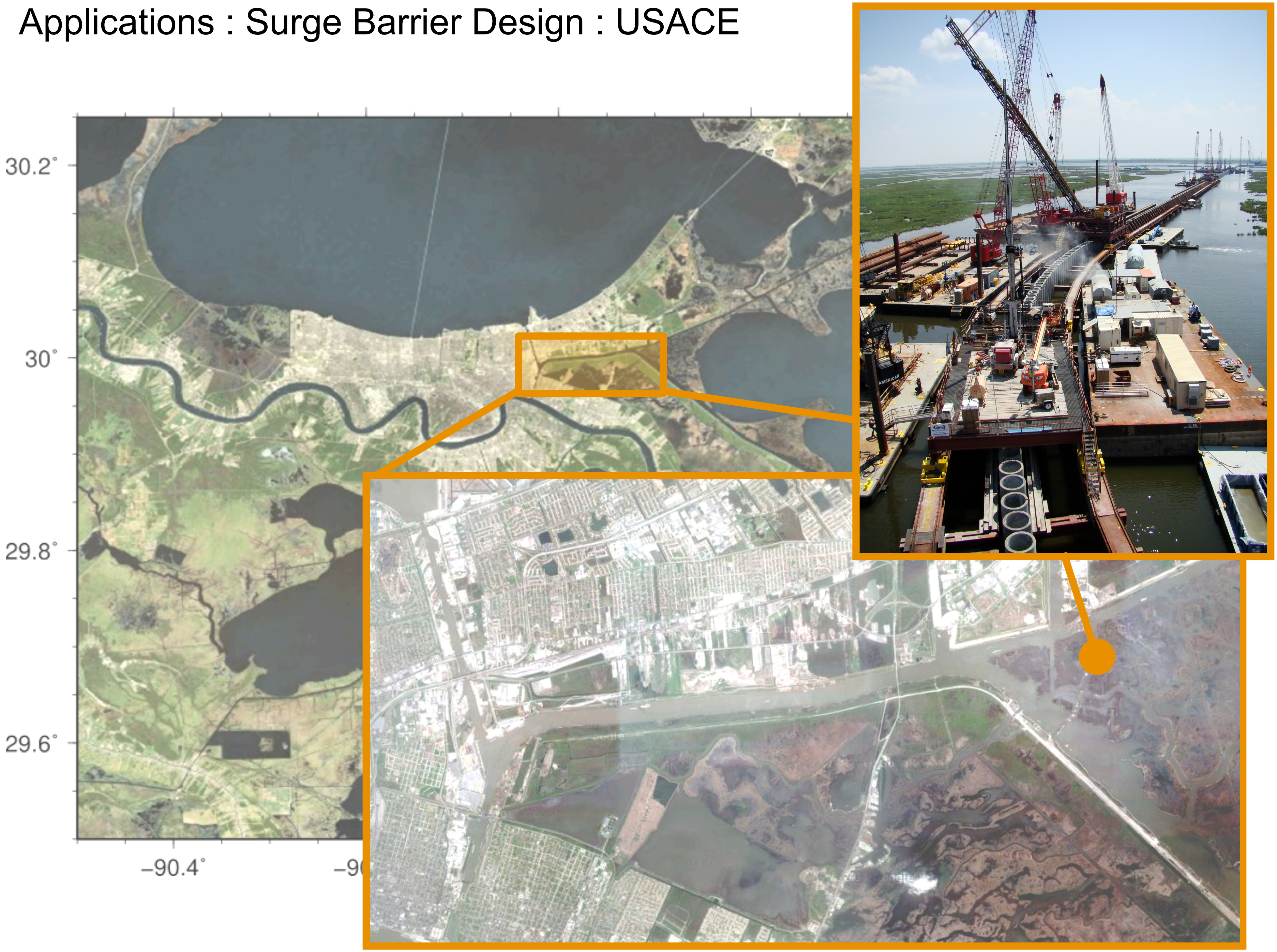
Gustav : Validation : Web-Based Mapping of Results



Gustav : Validation : High-Water Marks



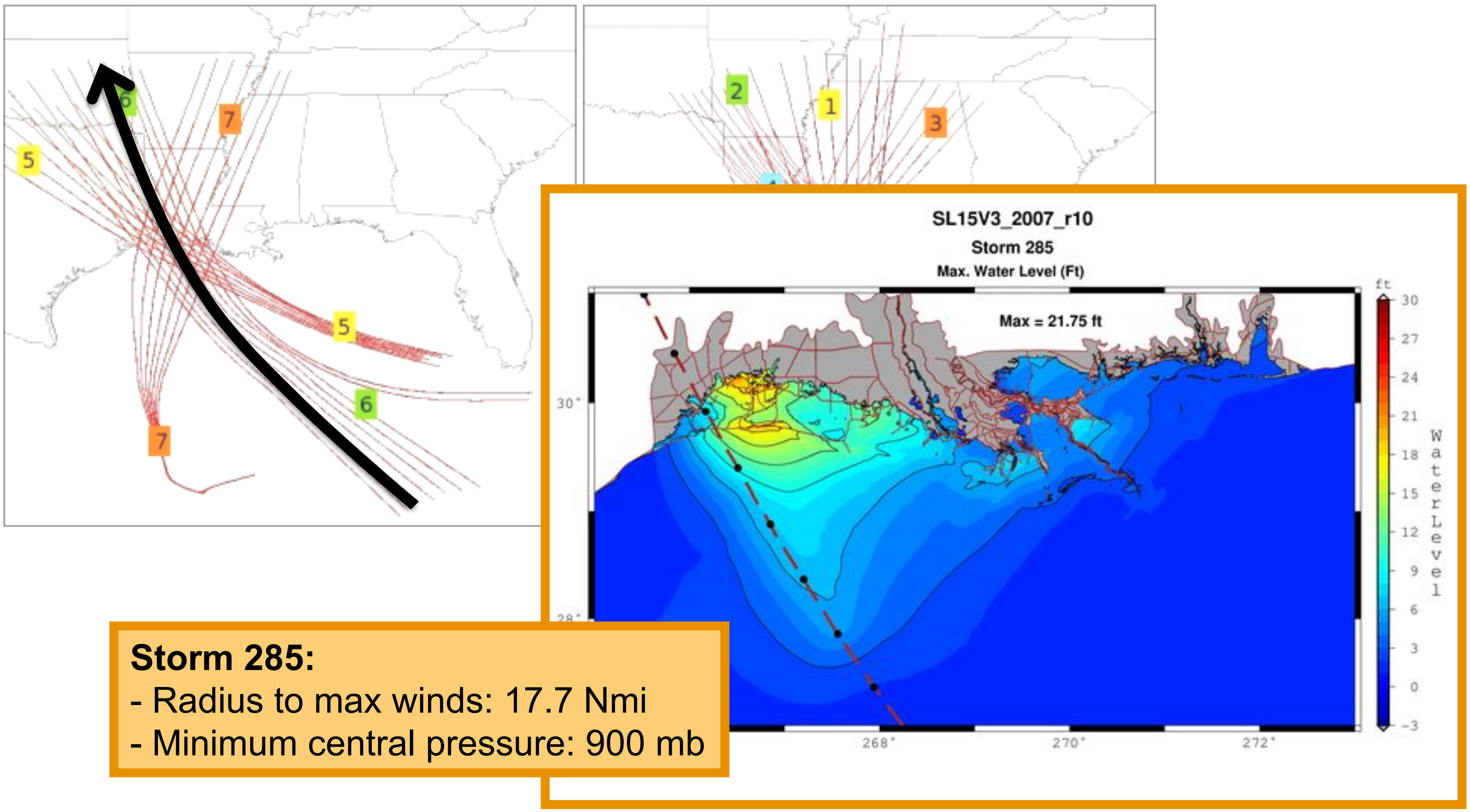
Applications : Surge Barrier Design : USACE



Applications : Flood Insurance Rate Maps : FEMA

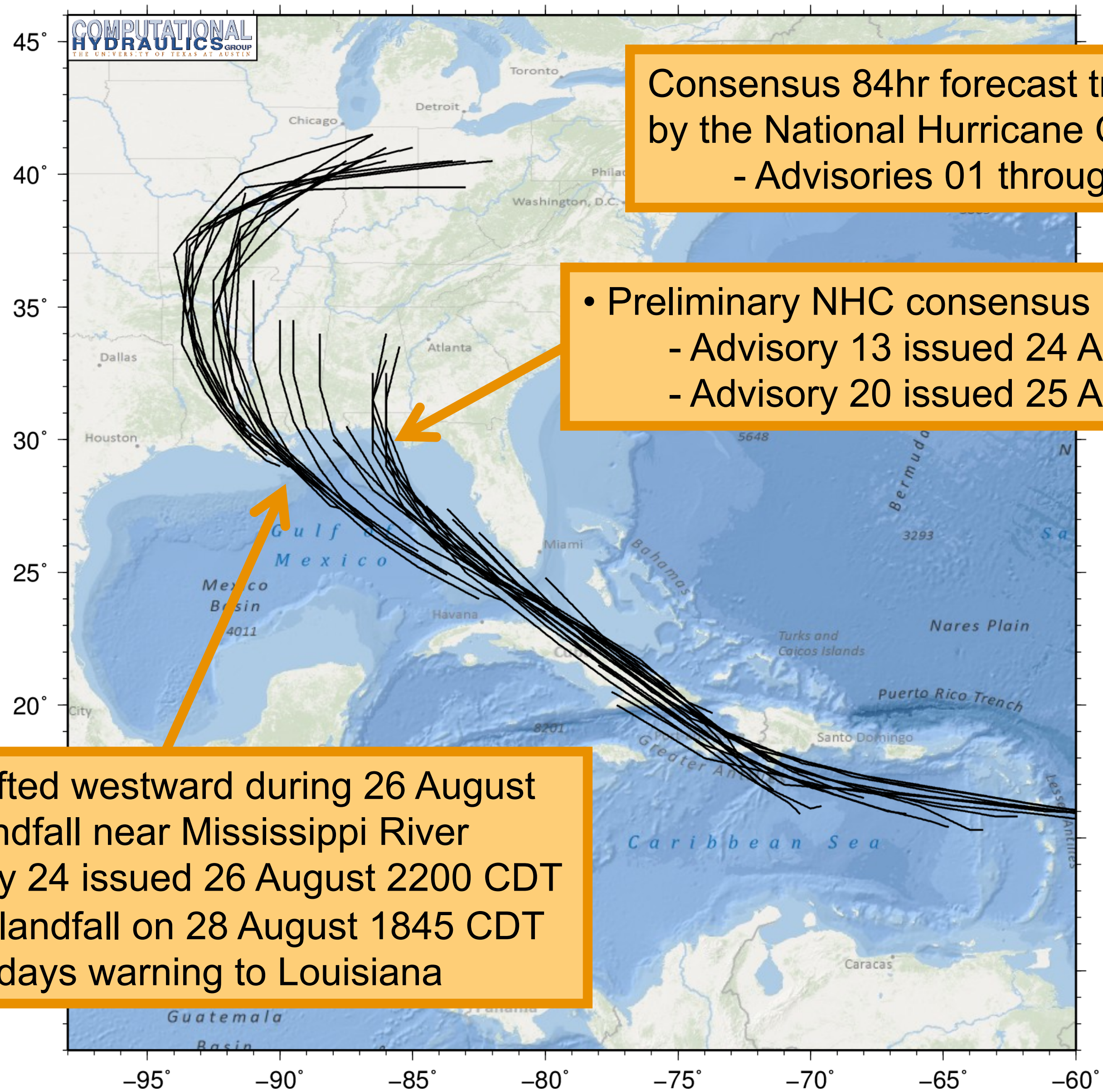
Joint Probability Method with Optimal Sampling (JPM-OS):

- Hypothetical storms with varying characteristics
- Combine results to develop 100-yr flood maps



Storm 285:
- Radius to max winds: 17.7 Nmi
- Minimum central pressure: 900 mb

Applications : Forecasting of Isaac (2012) : Track Uncertainty

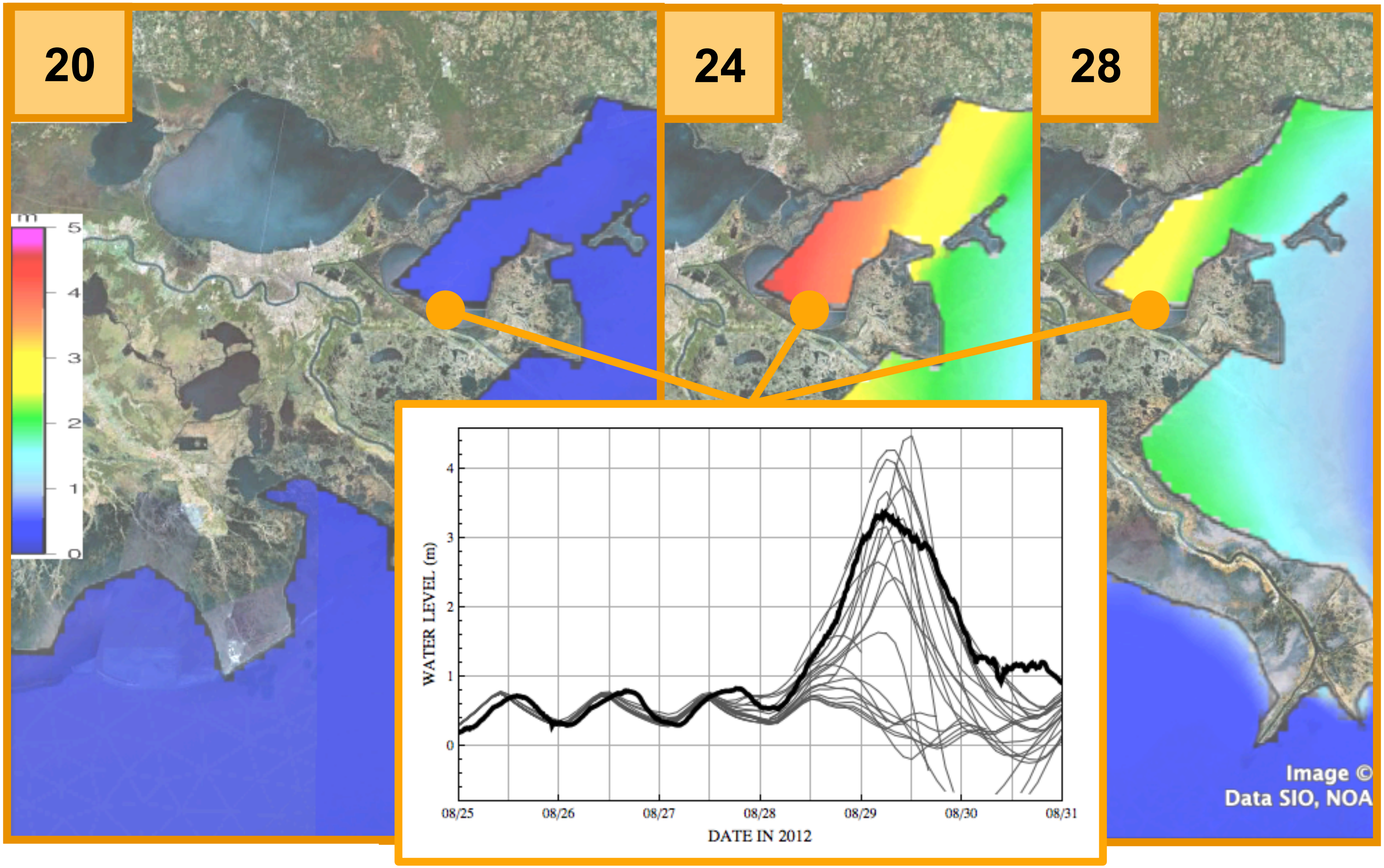


Consensus 84hr forecast tracks issued by the National Hurricane Center (NHC)
- Advisories 01 through 38

- Preliminary NHC consensus landfall in Florida
  - Advisory 13 issued 24 August 0400 CDT
  - Advisory 20 issued 25 August 2200 CDT

- Forecast shifted westward during 26 August
- Projected landfall near Mississippi River
  - Advisory 24 issued 26 August 2200 CDT
  - Official landfall on 28 August 1845 CDT
- Less than 2 days warning to Louisiana

Applications : Forecasting of Isaac (2012) : Storm Surge



JC Dietrich, *et al*. (2013). Real-Time Forecasting and Visualization of Hurricane Waves and Storm Surge using SWAN+ADCIRC and FigureGen. *Computational Challenges in the Geosciences,* CN Dawson and M Gerritsen, eds., Institute for Mathematics and Its Applications, v156, Springer, in press.

Surface Oil Transport : Deepwater Horizon Oil Spill (2010)

Deepwater Horizon was a 9-year-old, mobile offshore drilling unit

Located 66km from the Louisiana coastline, in 1500m of water

Platform was engulfed on 20 April by an explosion of methane gas; structure burned for more than 24hr before sinking on 22 April

Explosion killed 11 workers and injured 17

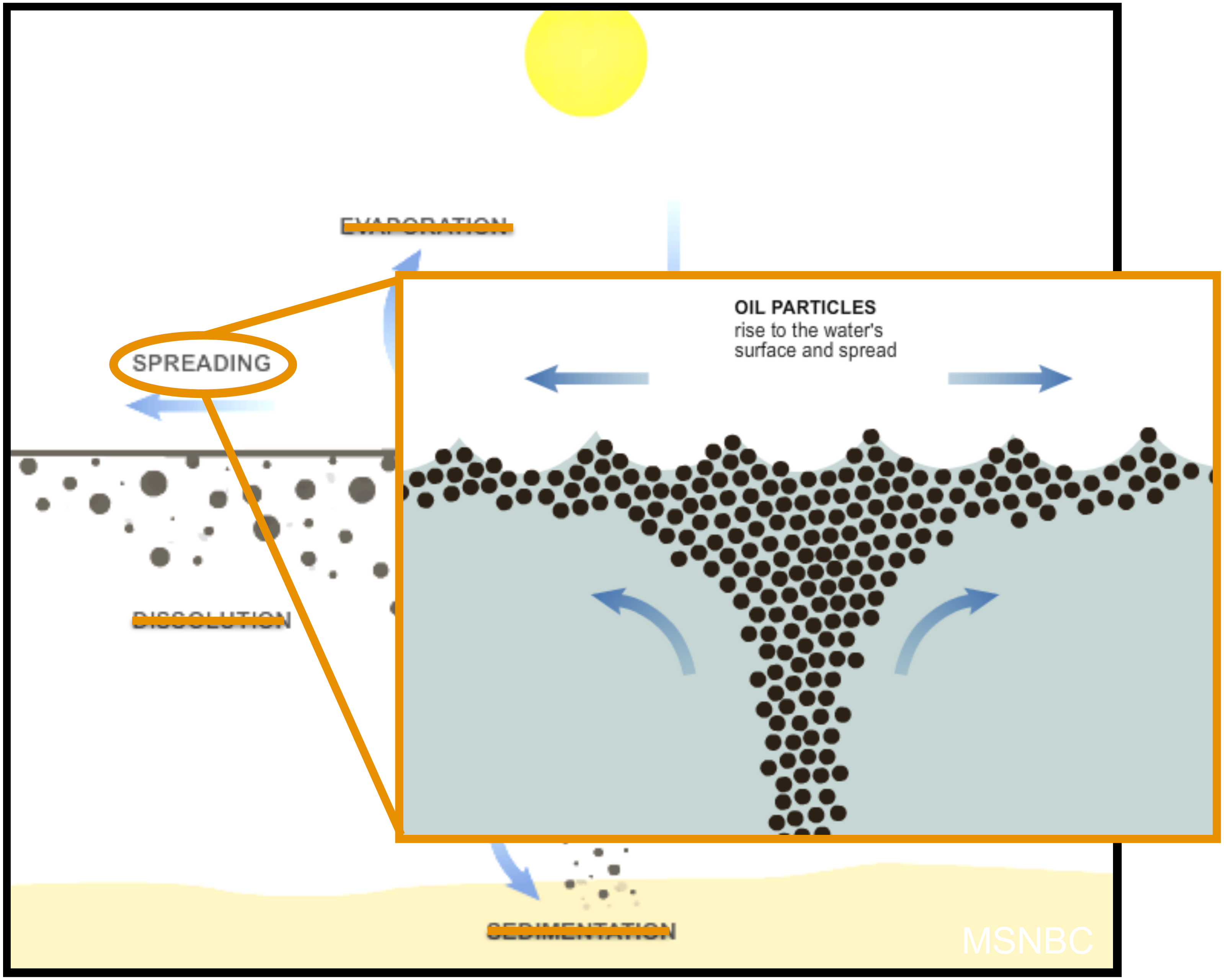
Oil spill flow rates:

- Estimated to have begun at a rate of 9900 $m^3\ d^{-1}$
- Diminished over time to a final rate of 8400 $m^3\ d^{-1}$ on 15 July 2010

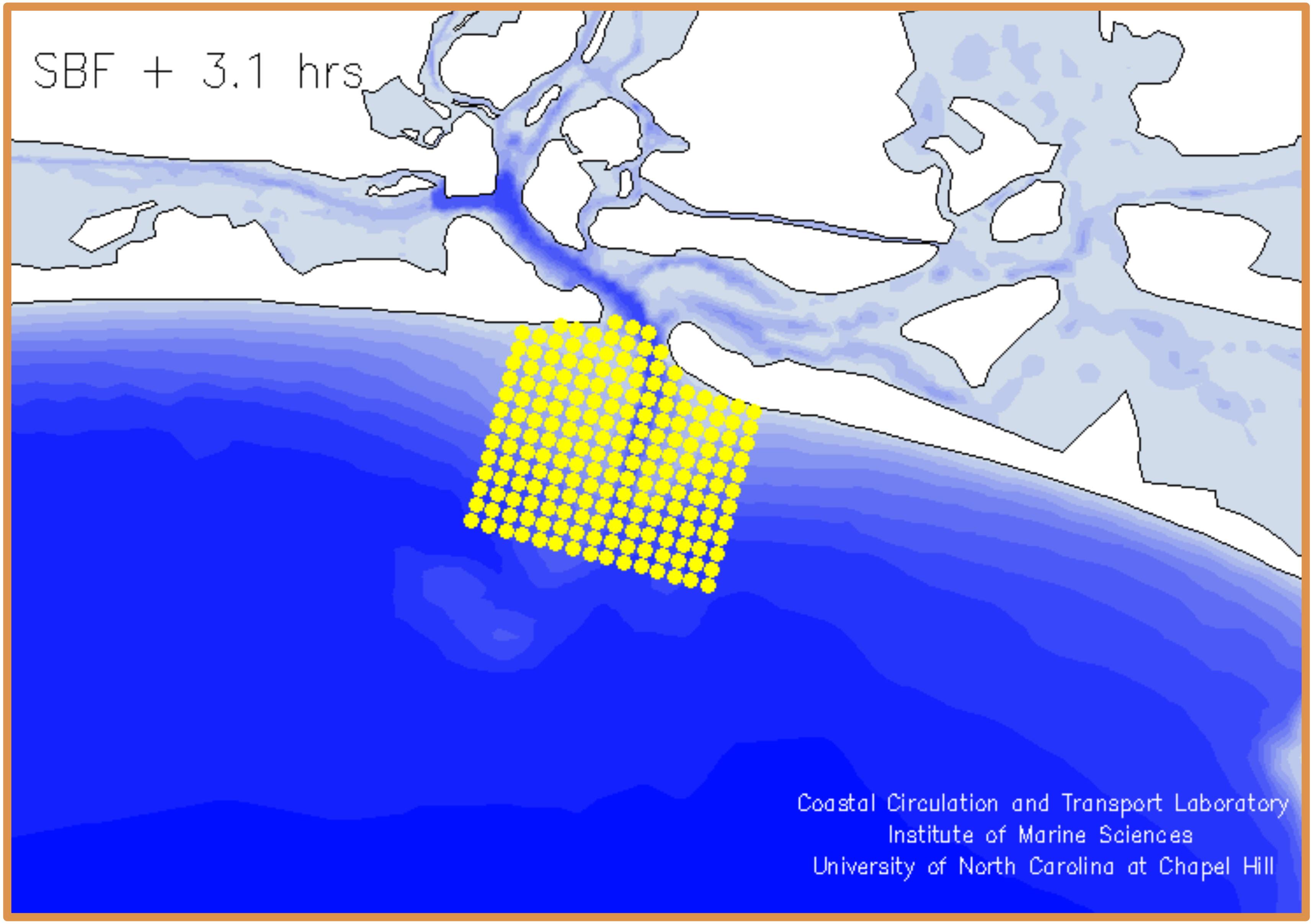
Emergency responders relied on satellite and aerial imagery

- Where will the oil move?
- What if a hurricane approaches?

Surface Oil Transport : Challenges



Surface Oil Transport : Lagrangian Particles



Surface Oil Transport : Lagrangian Particles

Particle positions are tracked through the unstructured mesh:

$$\vec{x}_p(t+\Delta t) = \vec{x}_p(t) + \vec{u}(\vec{x}_p, t)\Delta t + \vec{D}$$

- where the dispersion uses a stochastic perturbation (Proctor *et al.*, 1994):

$$\vec{D} = (2R-1)\sqrt{\vec{c}\vec{E}_v \Delta t}$$

- with: $0 < R < 1$ is a random number,
  $\vec{E}_v = 10$ m²/s are turbulent coefficients, and
  $\vec{c} = 12$ are scaling coefficients;

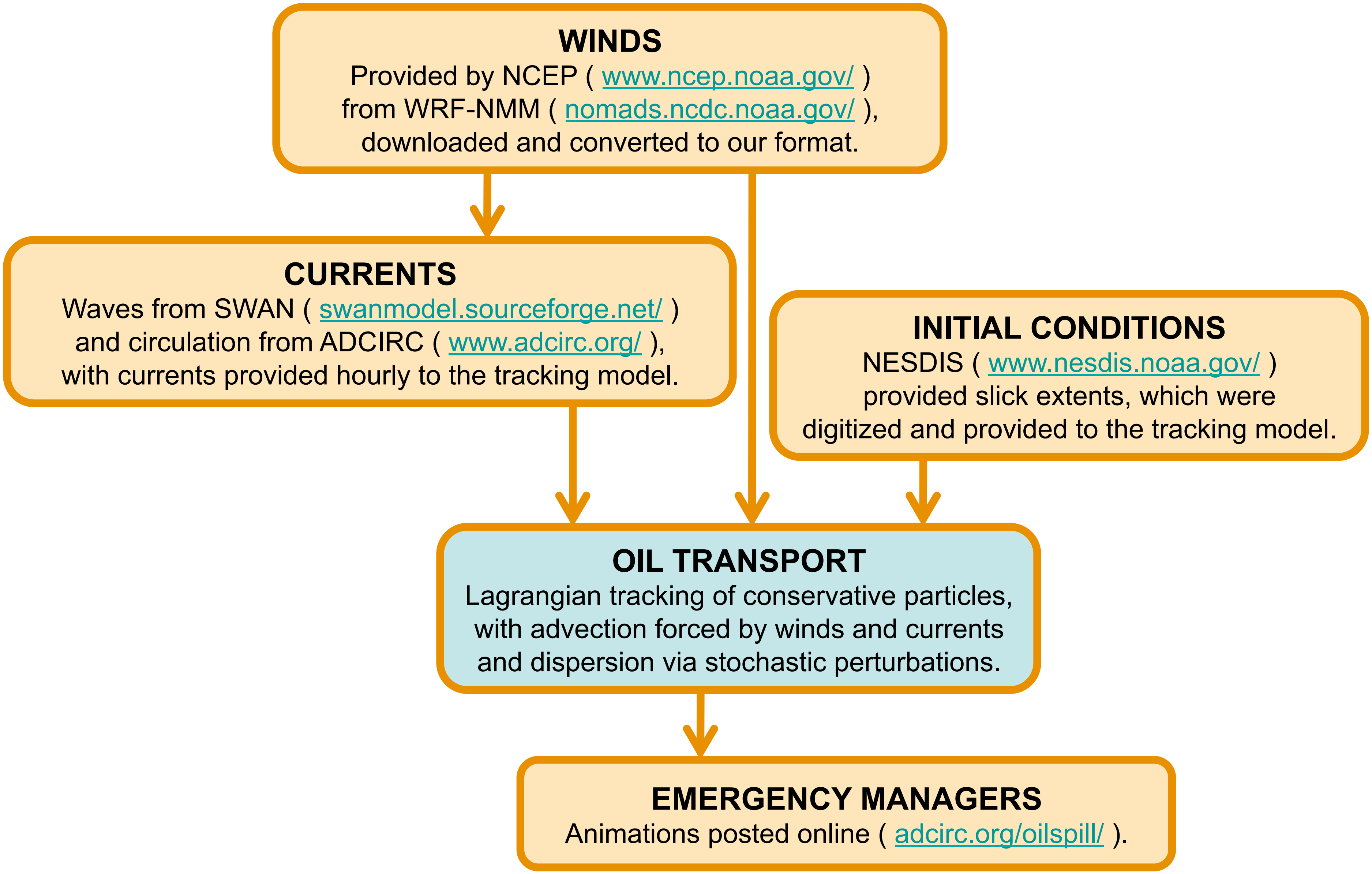
- and where the velocities are a linear combination of currents and winds:

$$\vec{u}(\vec{x}_p, t) = F_c \vec{u}_c(\vec{x}_p, t) + F_w \vec{u}_w(\vec{x}_p, t)$$

- with: $F_c = 1$ and $F_w = 0$.

Using hybrid OpenMP/MPI, 11M particles can be tracked on a 10M-element mesh in about **5.5 min/day** using 256 cores on TACC Ranger.

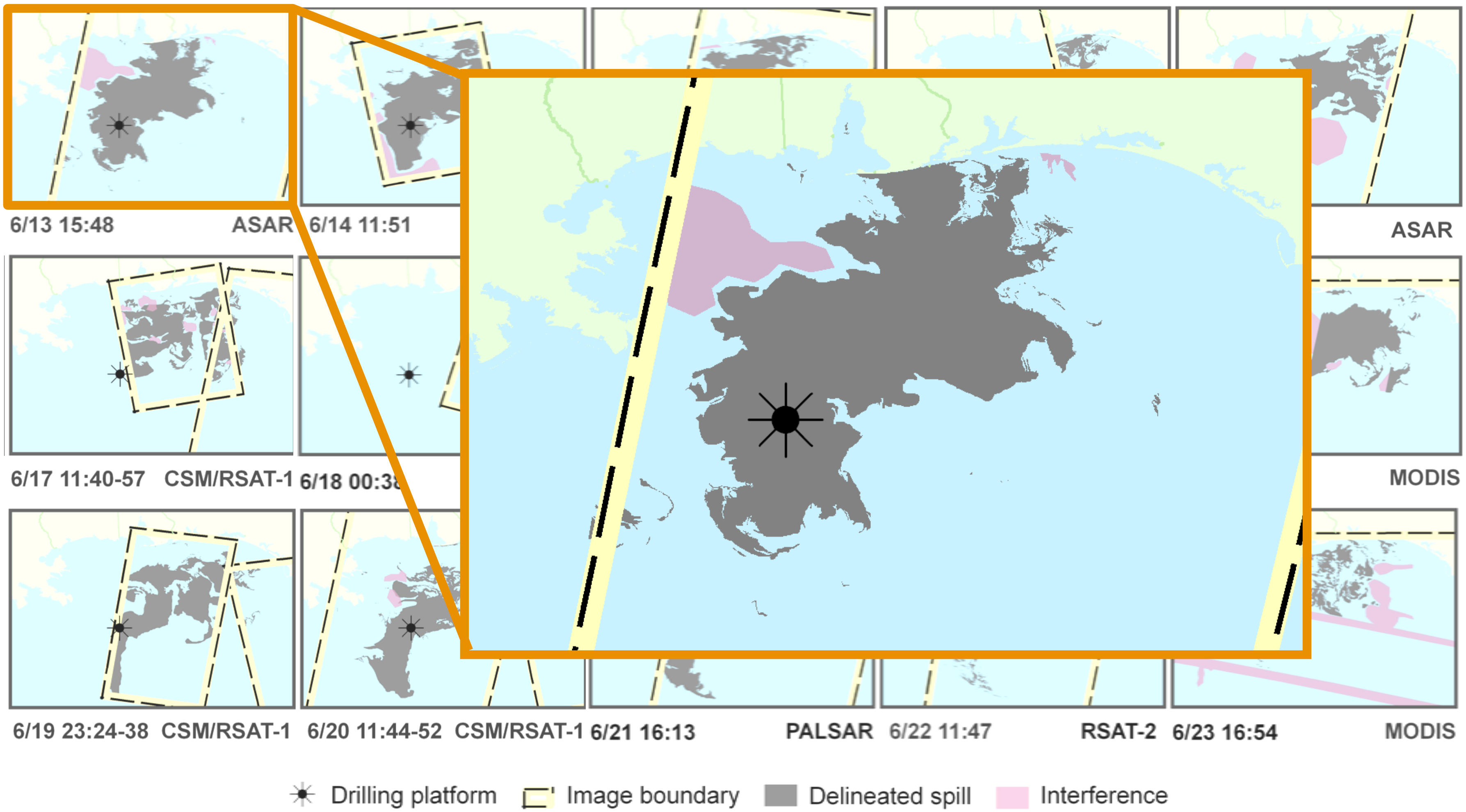
Surface Oil Transport : Flow Chart



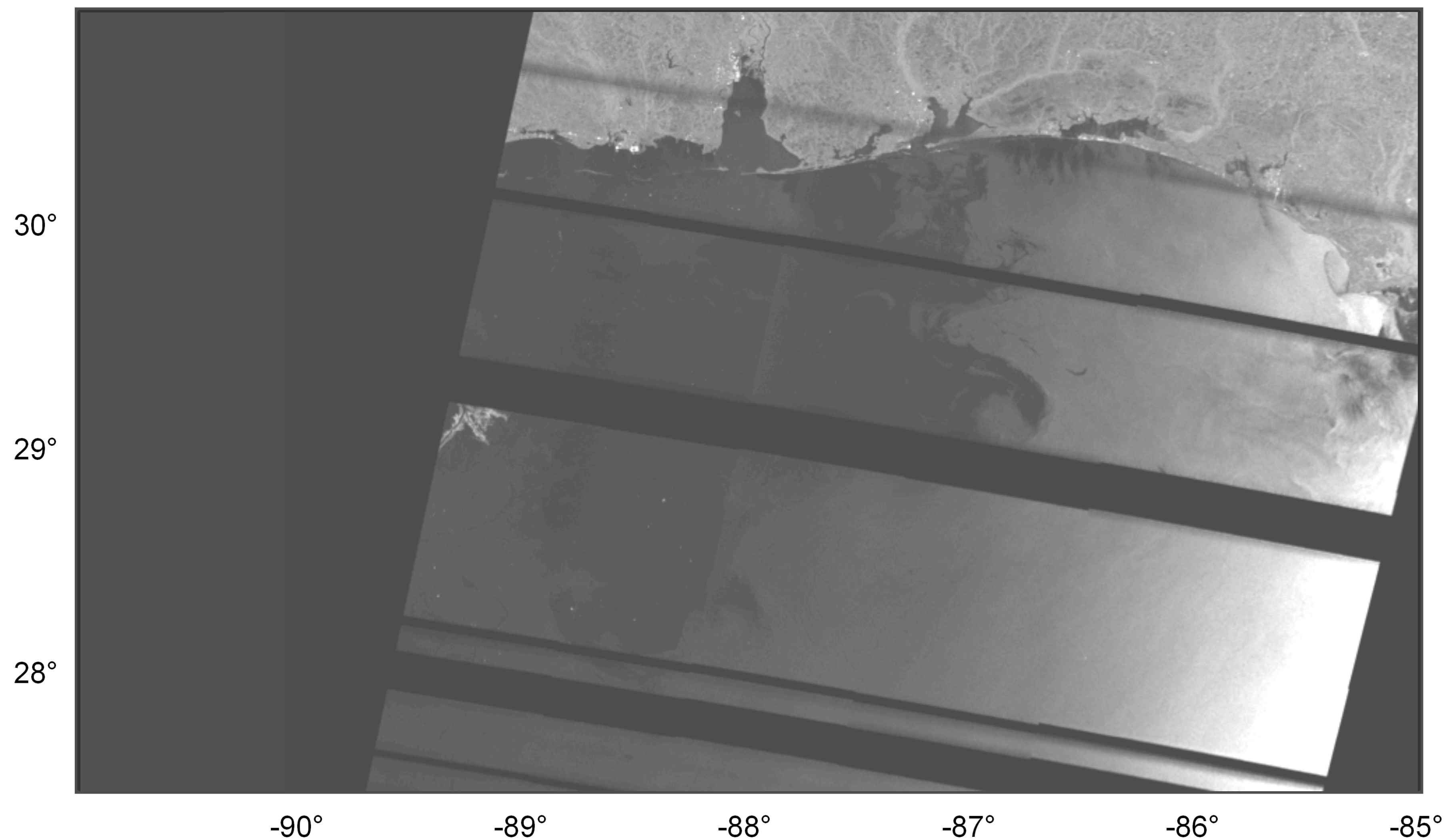
Surface Oil Transport : Validation : 13-23 June 2010

Examples of available imagery:

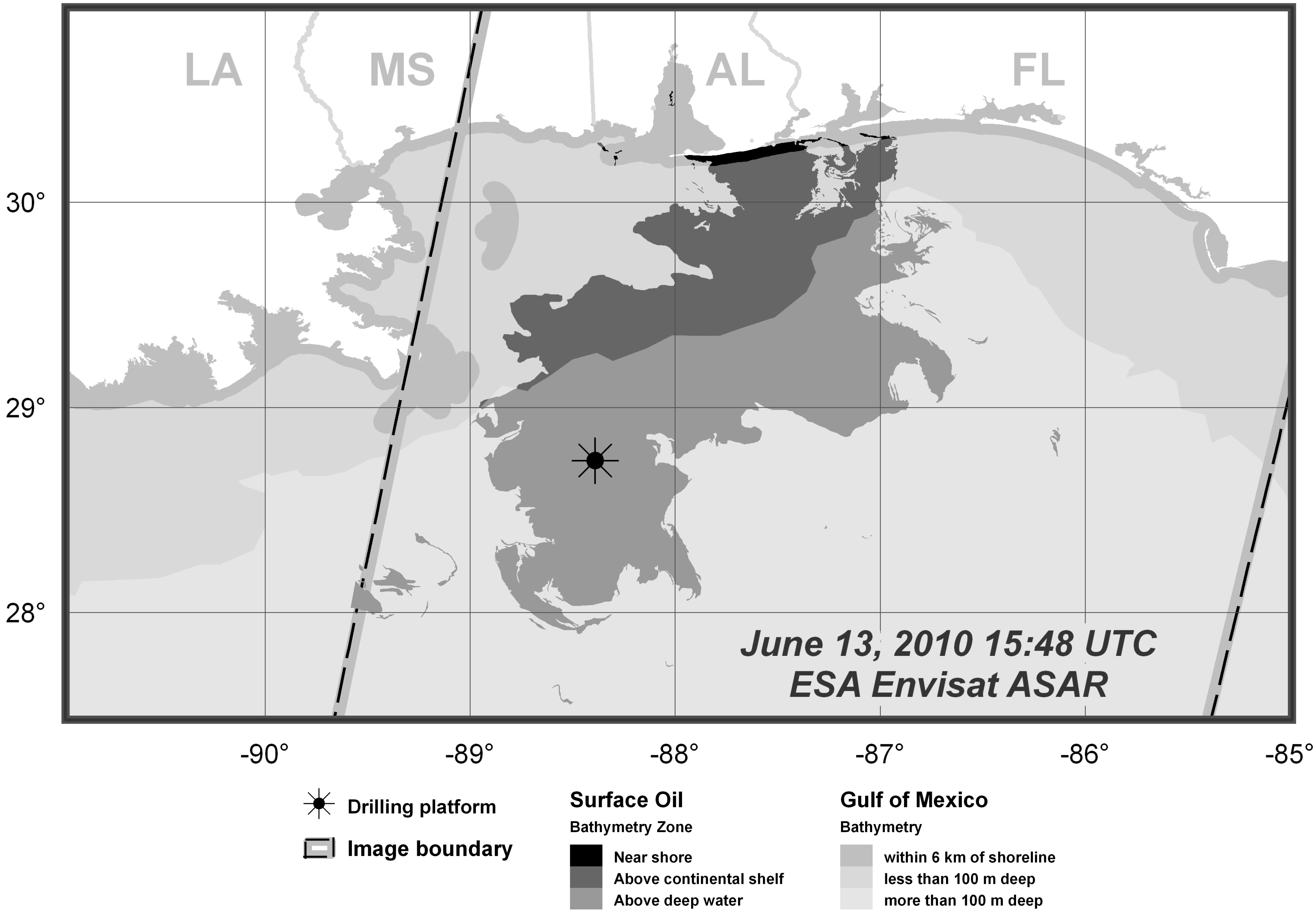
- NESDIS consolidated observations from a suite of satellite sensors



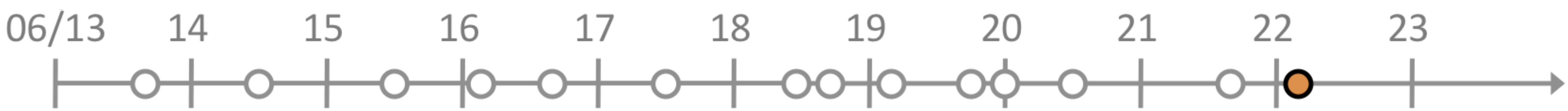
Surface Oil Transport : Validation : 13-23 June 2010



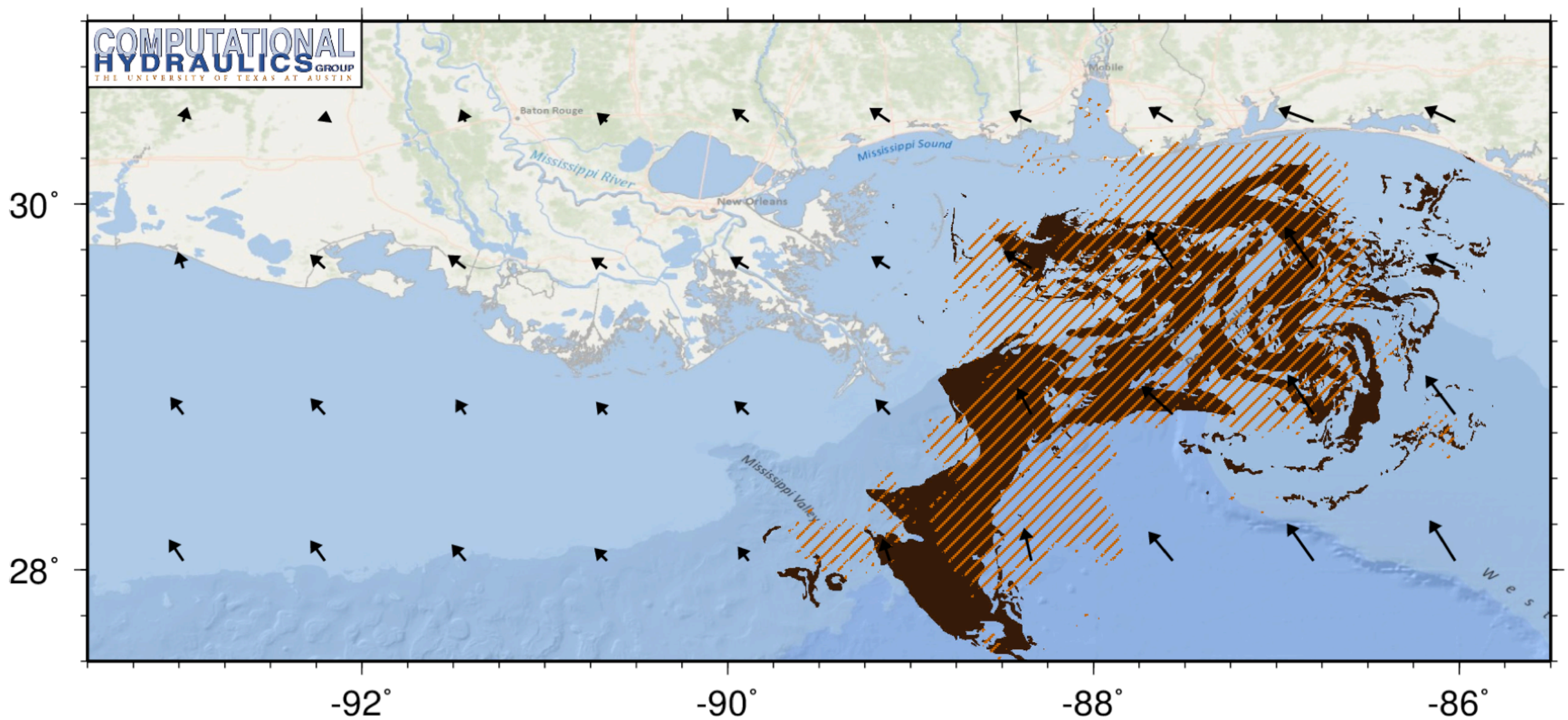
Surface Oil Transport : Validation : 13-23 June 2010



Surface Oil Transport : Validation : 13-23 June 2010



2010 / 06 / 22 / 0348 UTC (+ 204 hr / + 8.5 d)



Satellite Observations **Predicted Particle Locations**

JC Dietrich, *et al*. (2012). Surface Trajectories of Oil Transport along the Northern Coastline of the Gulf of Mexico. *Continental Shelf Research*, 41(1), 17-47, DOI:10.1016/j.csr.2012.03.015.

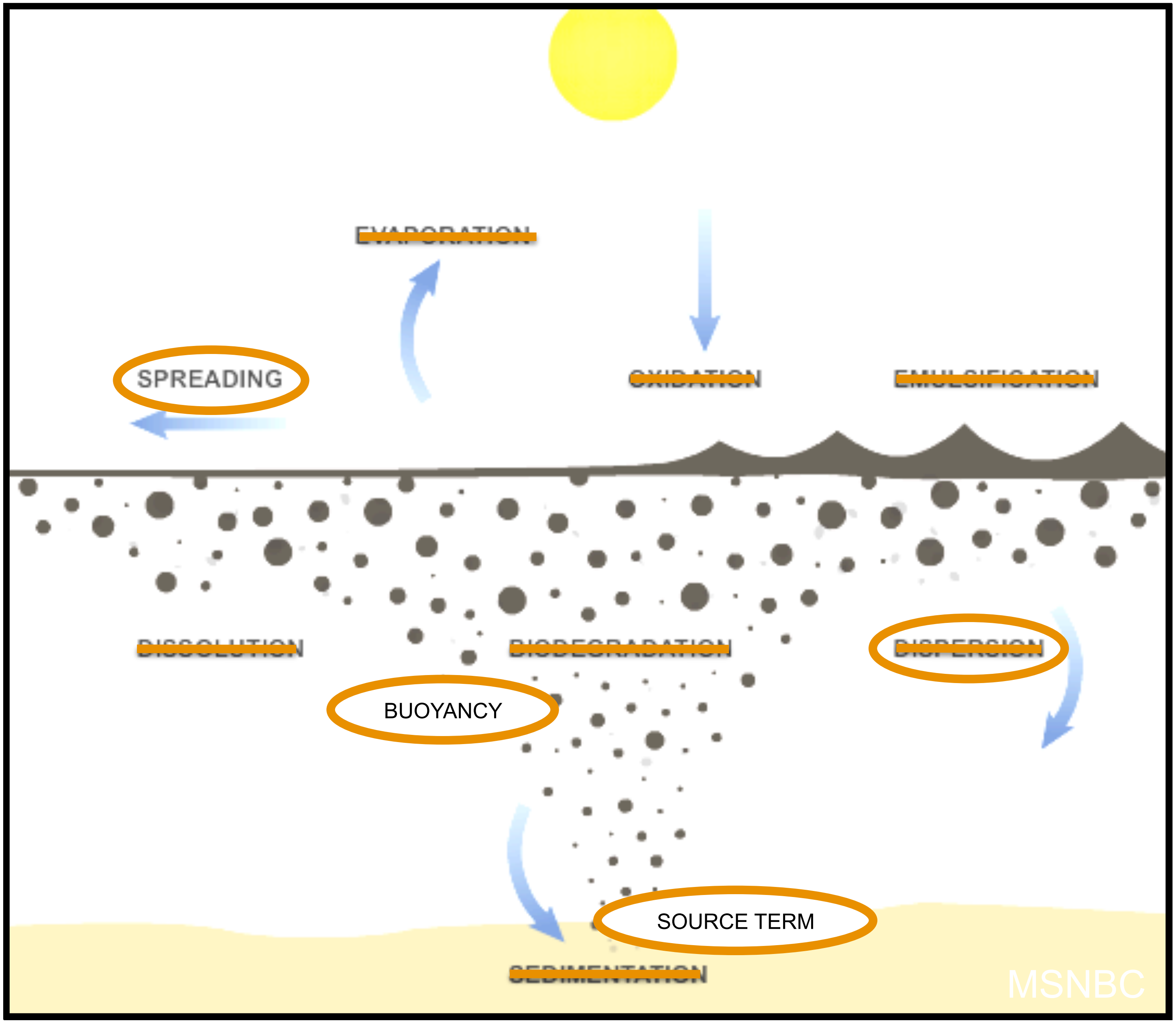
Surface Oil Transport : Sources of Error

Our initial response had many potential sources of error:

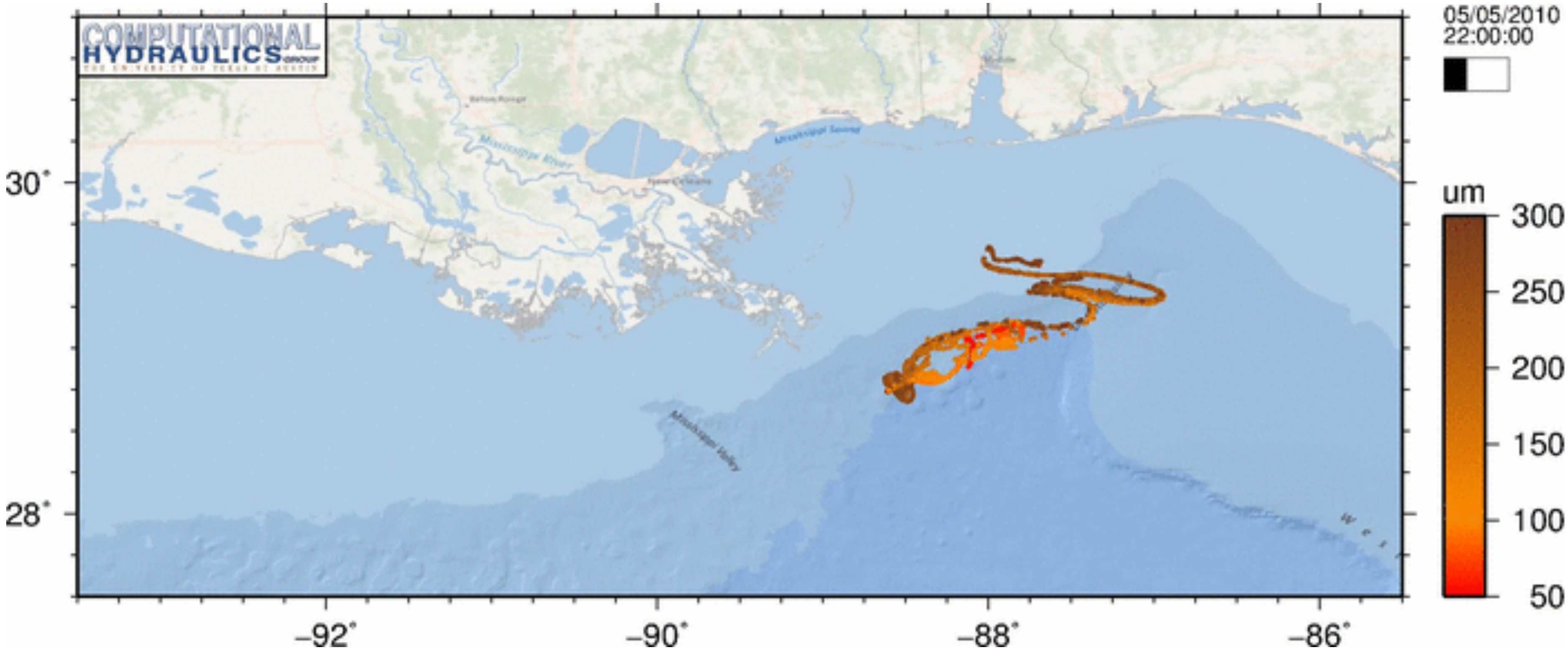
- Winds - Meteorological forcing does not have sufficient resolution in time (6hr) or space (30km) to capture small-scale features
- Currents - Depth-averaged velocities are insufficient in deep water
  - Lacking flow features created by density gradients
- Waves - Not accounting for increased mixing at the sea surface
- Oil Physics - Lacking a source term at the wellhead
  - Lacking sink terms due to evaporation, biodegradation, etc.
- And probably many others …

So let’s try again …

3D Oil Transport : Challenges



3D Oil Transport : Initial Results



Hindcast simulation for initial 40 days of DWH

Particles released at wellhead and transported by buoyancy and 3D velocities

- Diameters assigned randomly in the range of **50μm** to **300μm**
- Need parameterizations for dispersion and sinks (evaporation, biodegradation)

Velocities from HYCOM - need 3D baroclinic flow from ADCIRC

Future Research Questions : Wave Physics

Can we expand the existing wave-current coupling?

- Move beyond the simple transfer of momentum from the wave model
- How does the wave breaking process affect the circulation?
    - Enhanced mixing at the sea surface - Oil transport
    - Enhanced roughness at the sea floor - Sediment transport
- How else can we use our knowledge of the wave environment?
    - Wind momentum transfer linked to surface wave roughness

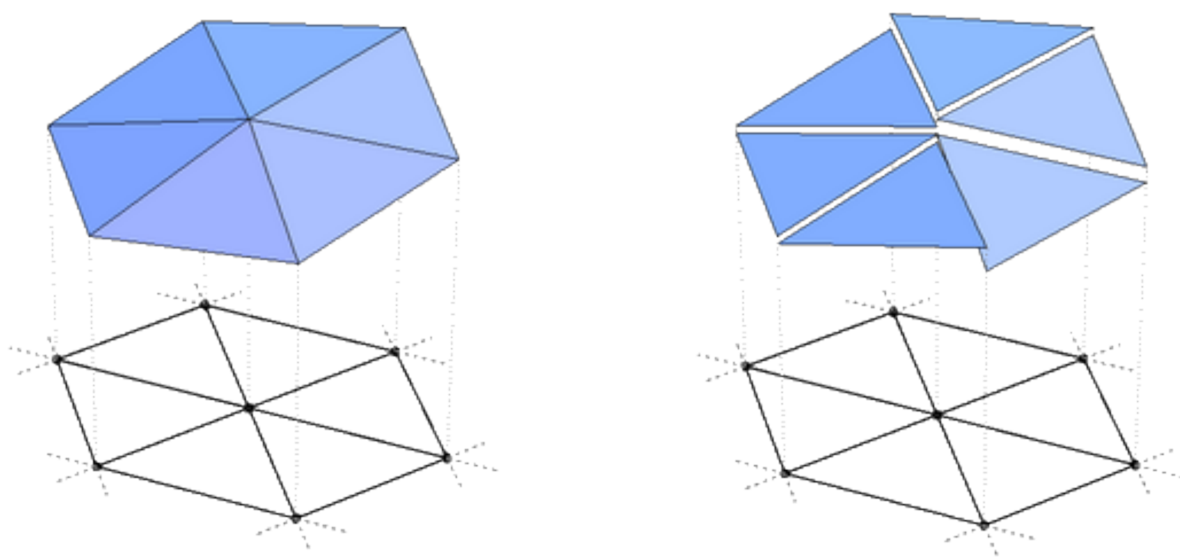
Can we expand the wave models in the nearshore?

- Move beyond the phase-averaged, statistical description of the wave field
- How do we couple with the phase-resolving wave model?
    - Improved understanding of dissipation against coastal structures
    - Improved transport of oil onto beaches

Future Research Questions : Improved Numerics

Can we scale efficiently to 100K cores?

- Enable the application to larger, more interesting problems
- Utilize the Discontinuous Galerkin (DG) method
    - Integrate over each <u>local element</u> instead of the <u>global domain</u>
    - Elements communicate through fluxes
    - Solution can be discontinuous along element edges
- How do we mesh adaptively during a large-scale hurricane simulation?
    - Start with smaller problem, then increase resolution only where necessary



Future Research Questions : Coastal Hazards

Can we connect hazard vulnerability with coastal communities?

- NSF Interdisciplinary Research in Hazards and Disasters (Hazards SEES)
- Adaptive capacity - ability of communities to adjust to change and moderate hazard vulnerability
- Working with urban planners to assess how adaptive capacity has evolved, and how it may be affected by climate change, sea level rise, etc.
- Examine through scenarios in the Galveston Bay region of Texas
    - Hazard exposure - Flooding from storm surge and associated rainfall
    - Physical vulnerability - Large population centers in low-lying areas
    - Social vulnerability - Range of population segments with varying abilities to evacuate or otherwise moderate vulnerability

Conclusions and Future Work

Predictive, high-resolution modeling of ocean waves and circulation:

‘Tight’ Coupling of SWAN+ADCIRC:

- Models use same unstructured mesh
- Information passed dynamically through local cache
- Coupled model is efficient to 1000s of computational cores
- Validation to wealth of measurement data

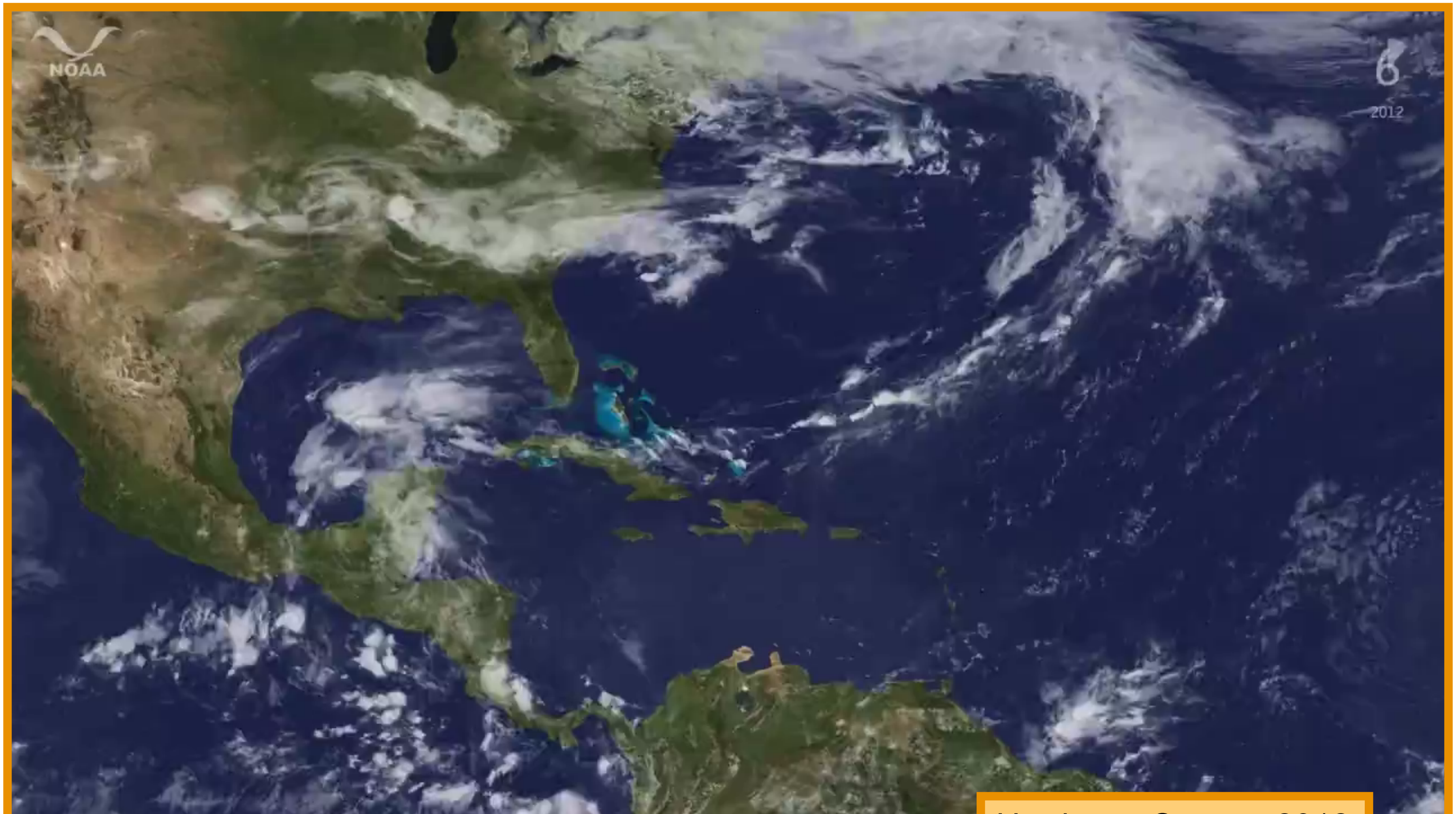
Applications to Nearshore Waves and Circulation:

- Design of surge barrier to protect New Orleans
- Development of floodplain risk maps
- Forecasting of hurricanes, oil spill

Future Research Directions:

- Next-generation coupling of ocean circulation and waves
- Increased efficiency through the Discontinuous Galerkin (DG) method
- Connect hazard vulnerability with coastal communities

Thank You!



Hurricane Season 2012