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

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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

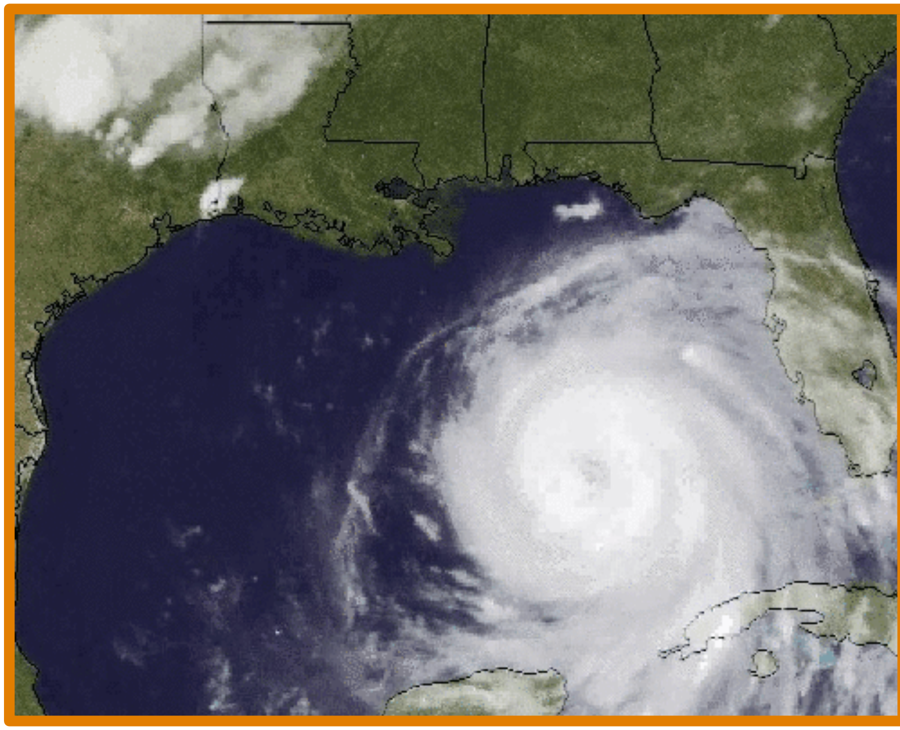
- Department of Civil Engineering and Geological Sciences
  - Graduate Research Assistant: 08/2005 to 10/2010
    - PhD: 12 October 2010

University of Oklahoma

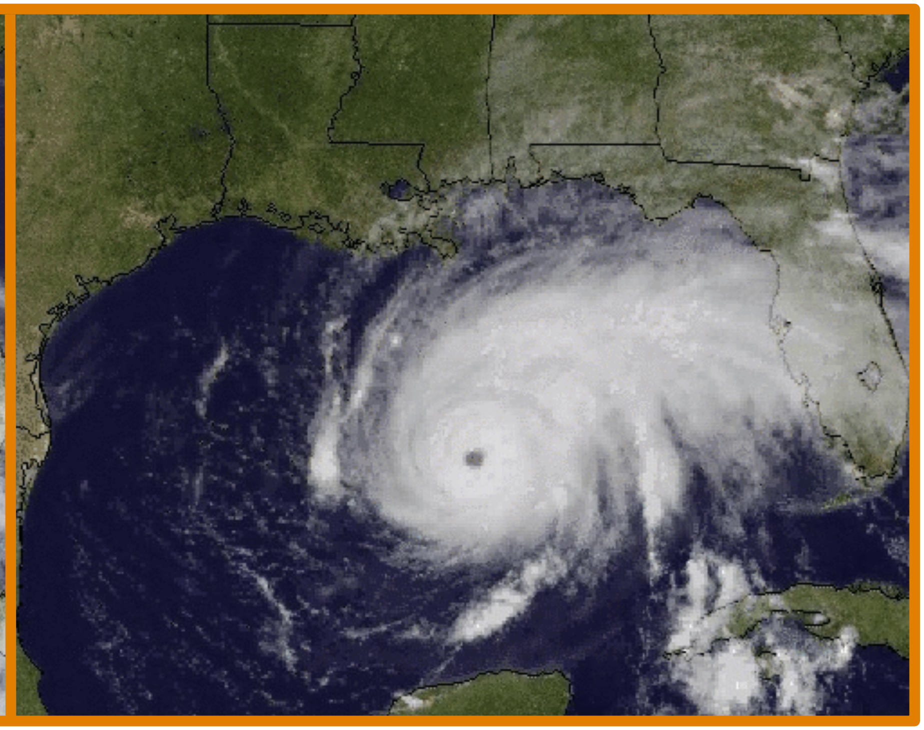
- School of Civil Engineering and Environmental Science
  - Graduate Research Assistant: 06/2004 to 07/2005
    - MS: 23 June 2005
  - Undergraduate Research Assistant: 06/1999 to 05/2004
    - BS & BA: May 2004

Hurricane Season 2005

Katrina : 08/28 – 08/29



Rita : 09/22 – 09/24

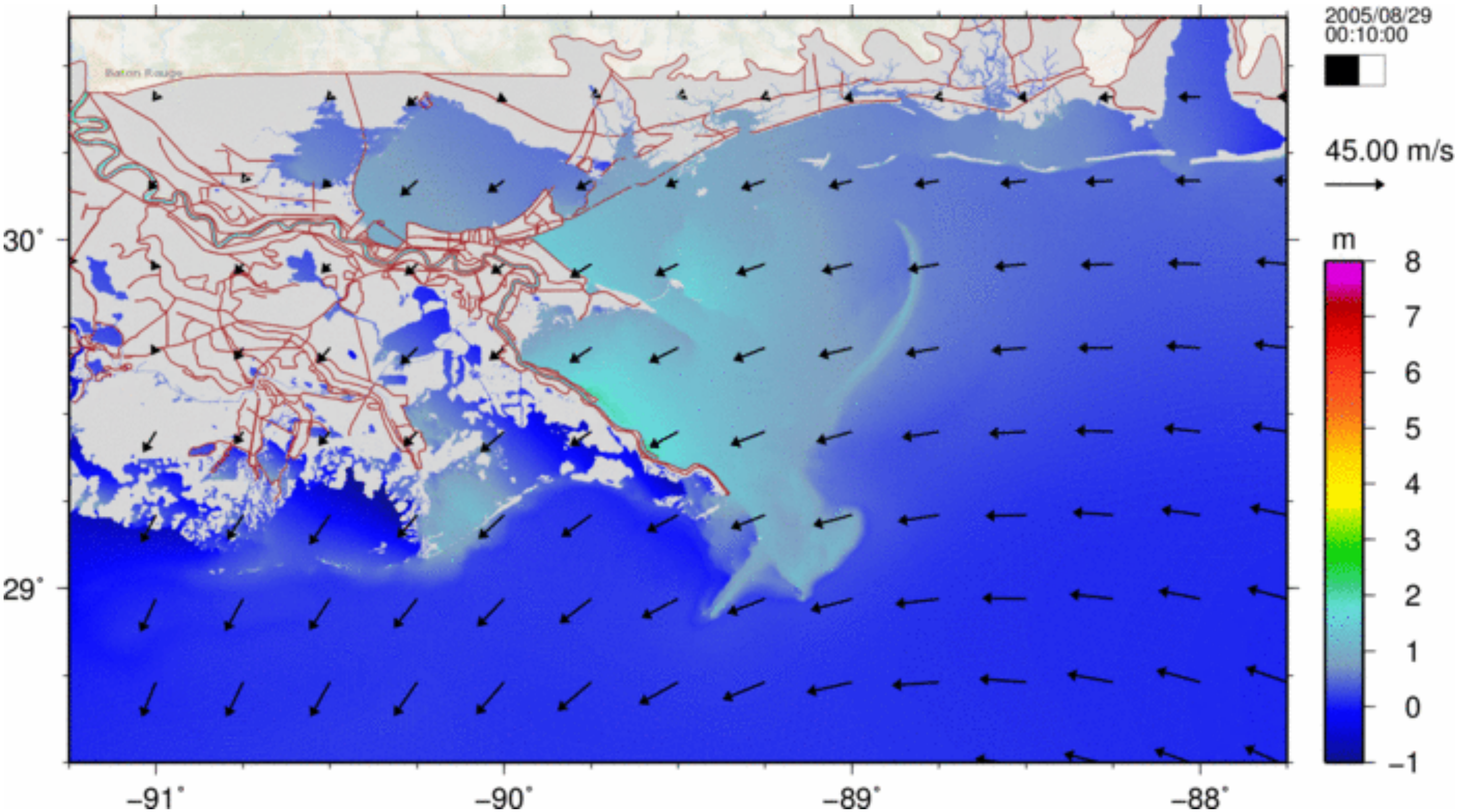


Images: http://cimss.ssec.wisc.edu/

Katrina : Flooding of New Orleans

Images: http://www.nasa.gov/vision/earth/lookingatearth ...

Katrina : Storm Surge : Day of Landfall

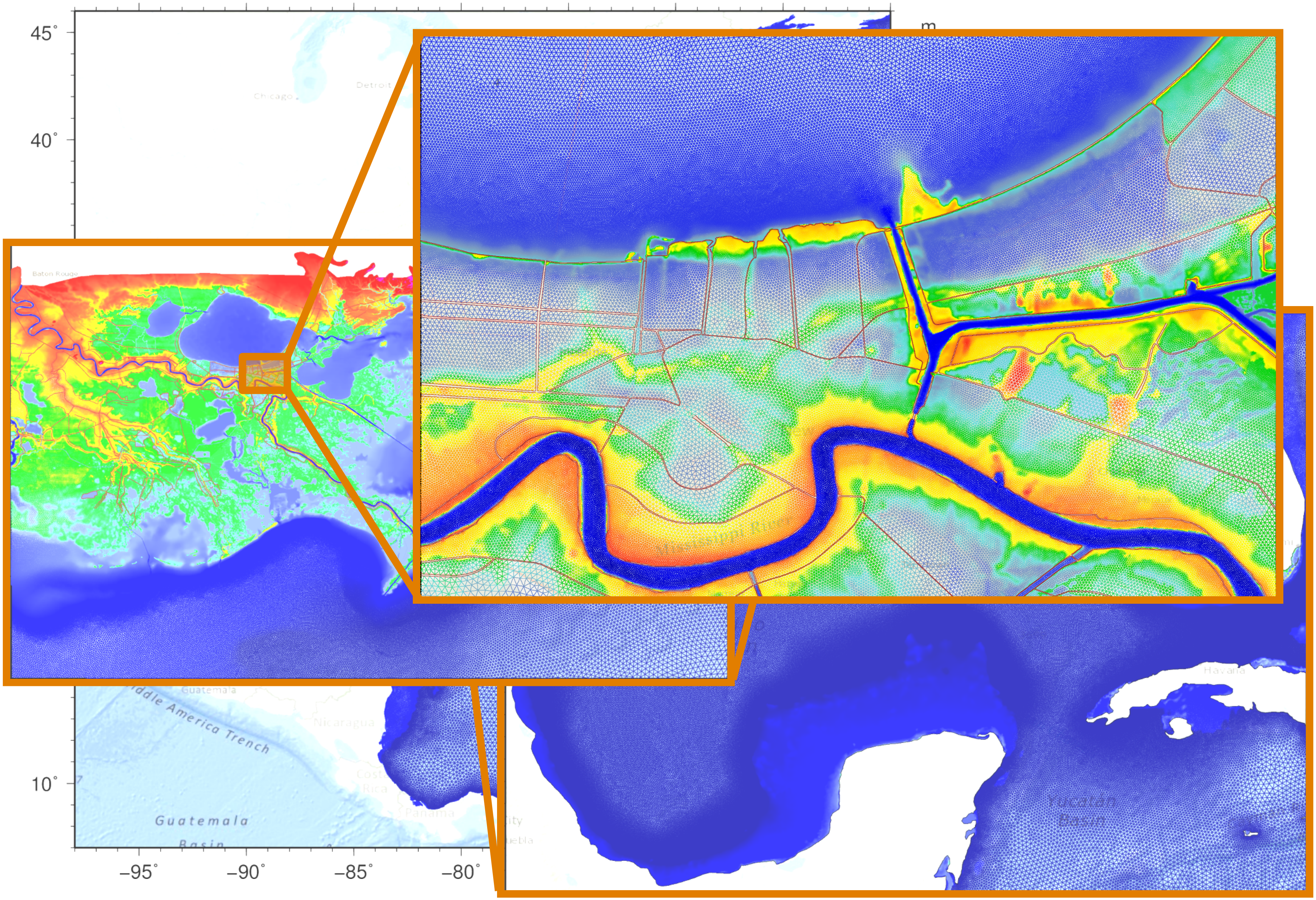


S Bunya, JC Dietrich, *et al.* (2010). A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave and Storm Surge Model for Southern Louisiana and Mississippi: Part I – Model Development and Validation. *Monthly Weather Review*, 138(2), 345-377.

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

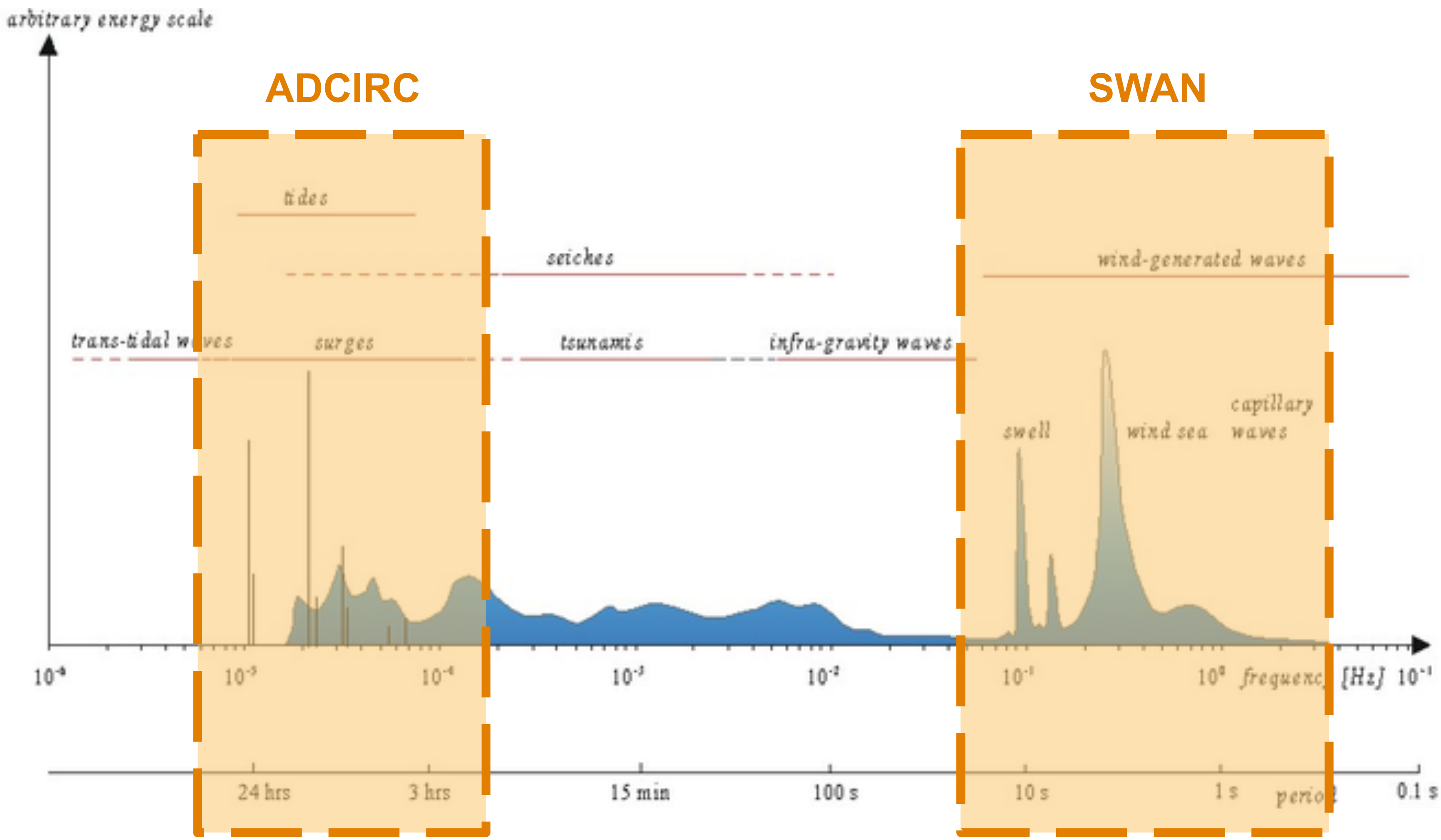


Image: [Holthuijsen (2007)]

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

Image: Holthuijsen (2007)

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):

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

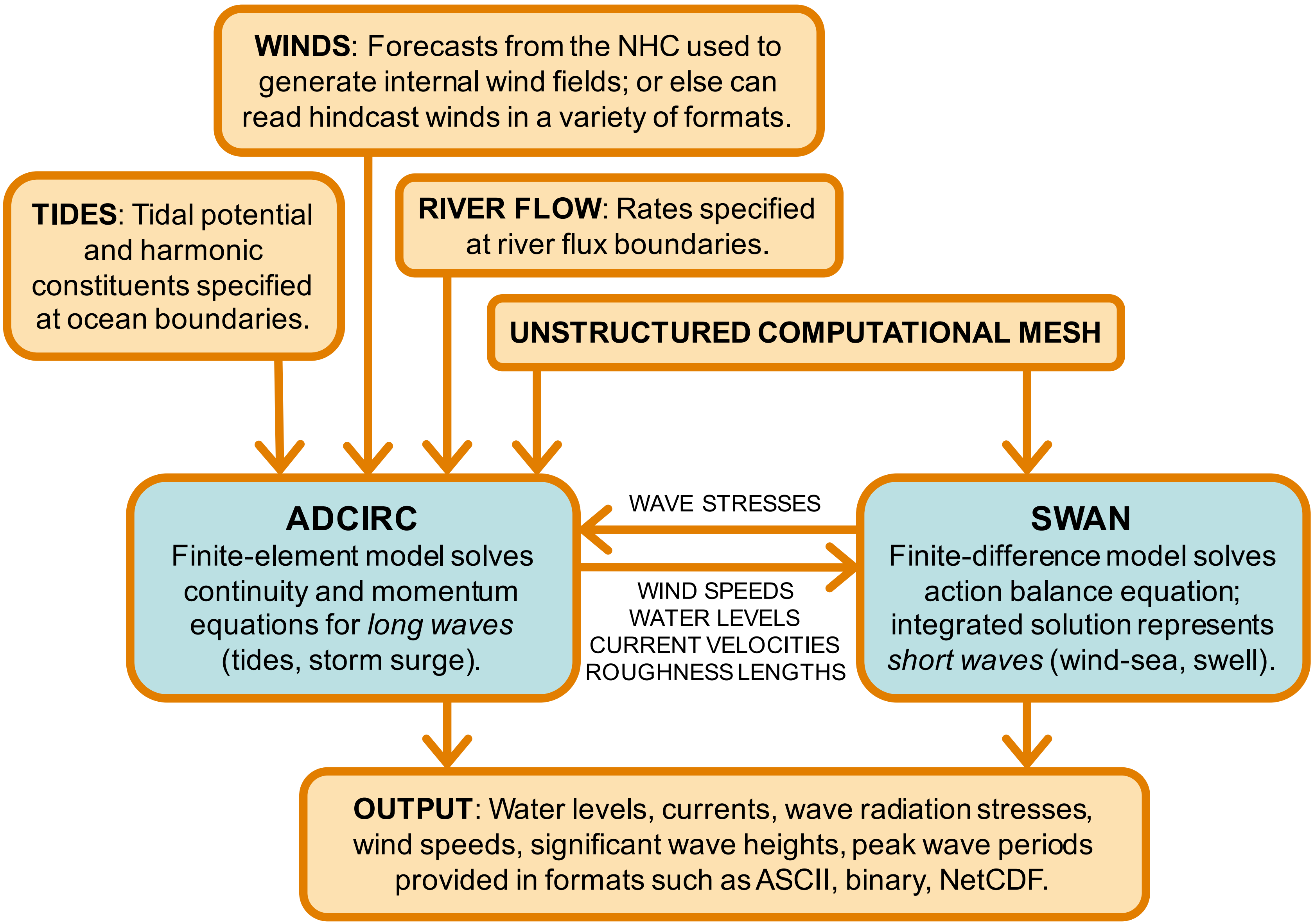
$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \frac{\partial}{\partial y}\left[\zeta + \frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

with explicit solution after updating wet/dry information

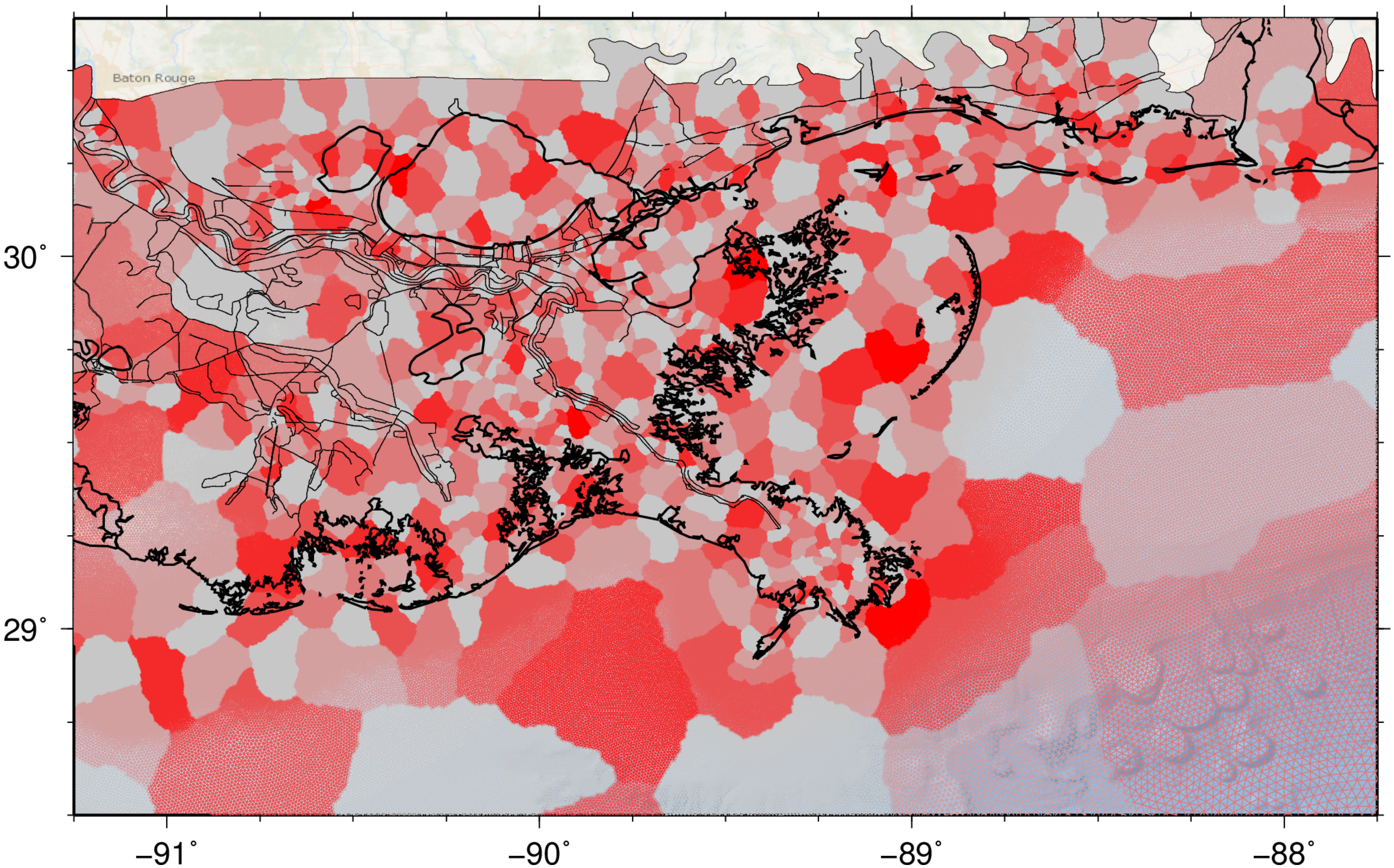
ADCIRC and SWAN interact

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

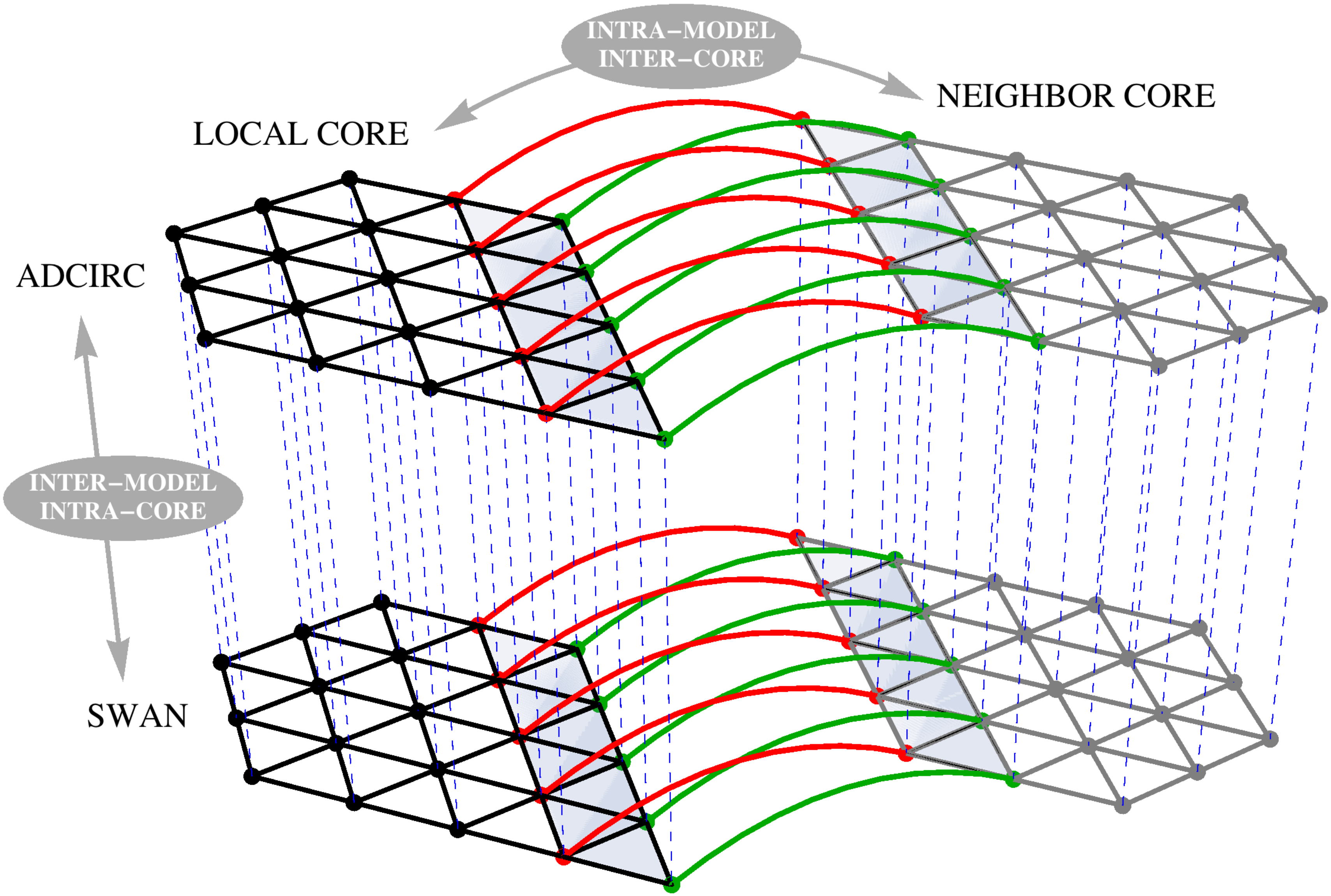
‘Tight’ Coupling : SWAN+ADCIRC



‘Tight’ Coupling : Domain Decomposition

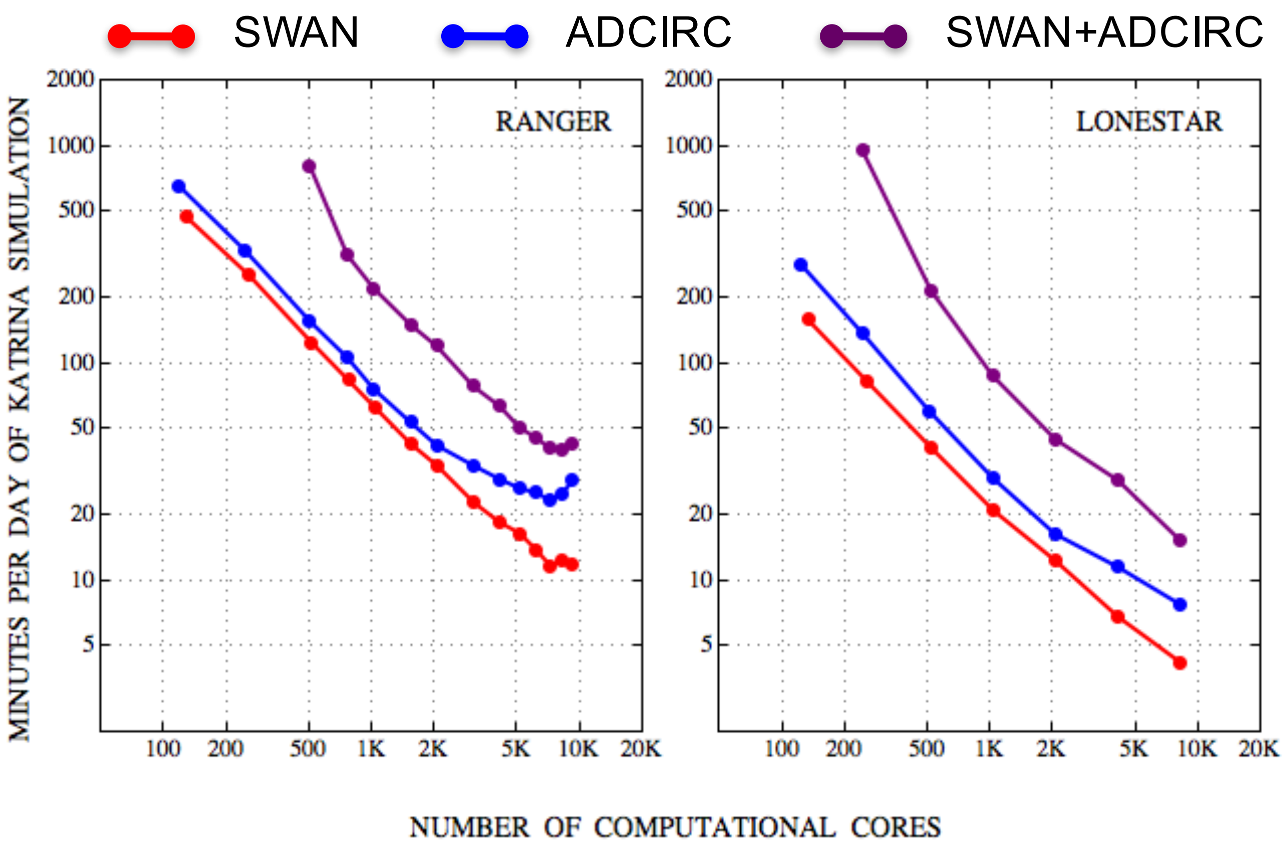


‘Tight’ Coupling : Parallel Communication



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.

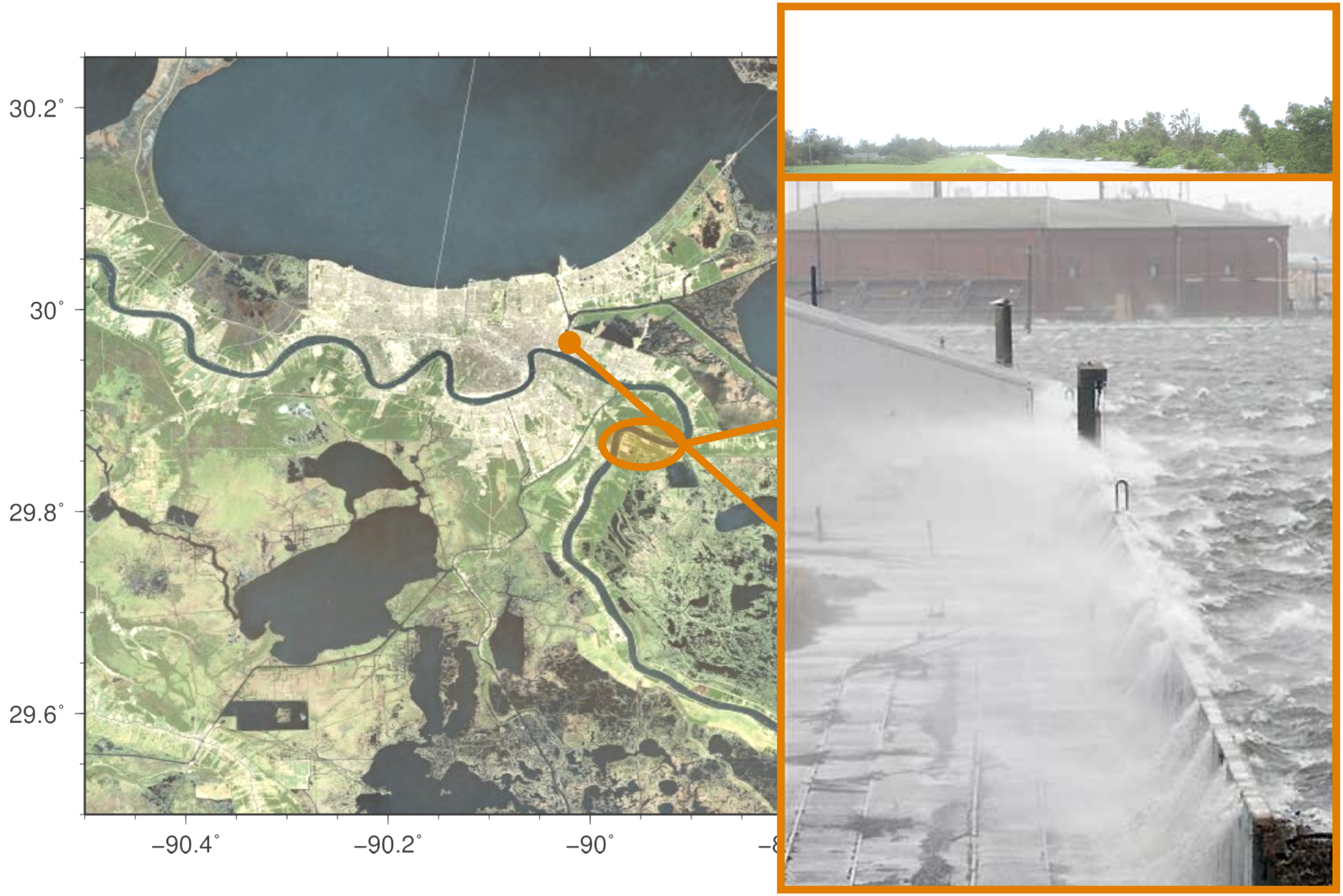
‘Tight’ Coupling : Parallel Scaling



	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)

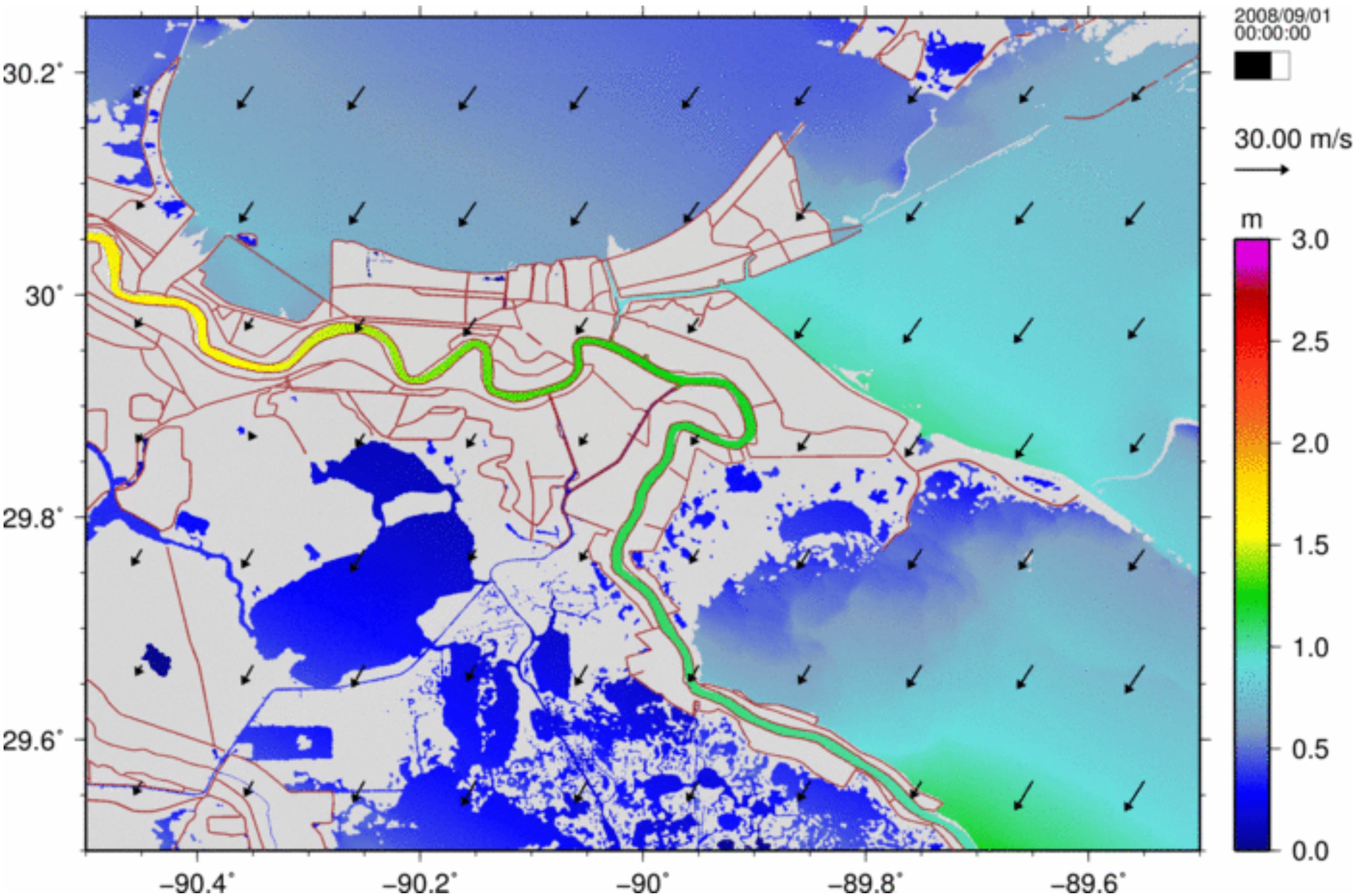
JC Dietrich, *et al.* (2012). Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge. *Journal of Scientific Computing*, 52(2), 468-497, DOI:10.1007/s10915-011-9555-6.

Gustav : Storm Surge : Near-Flooding of New Orleans



Images: Nancy Powell, USACE

Gustav : Storm Surge : Day of Landfall

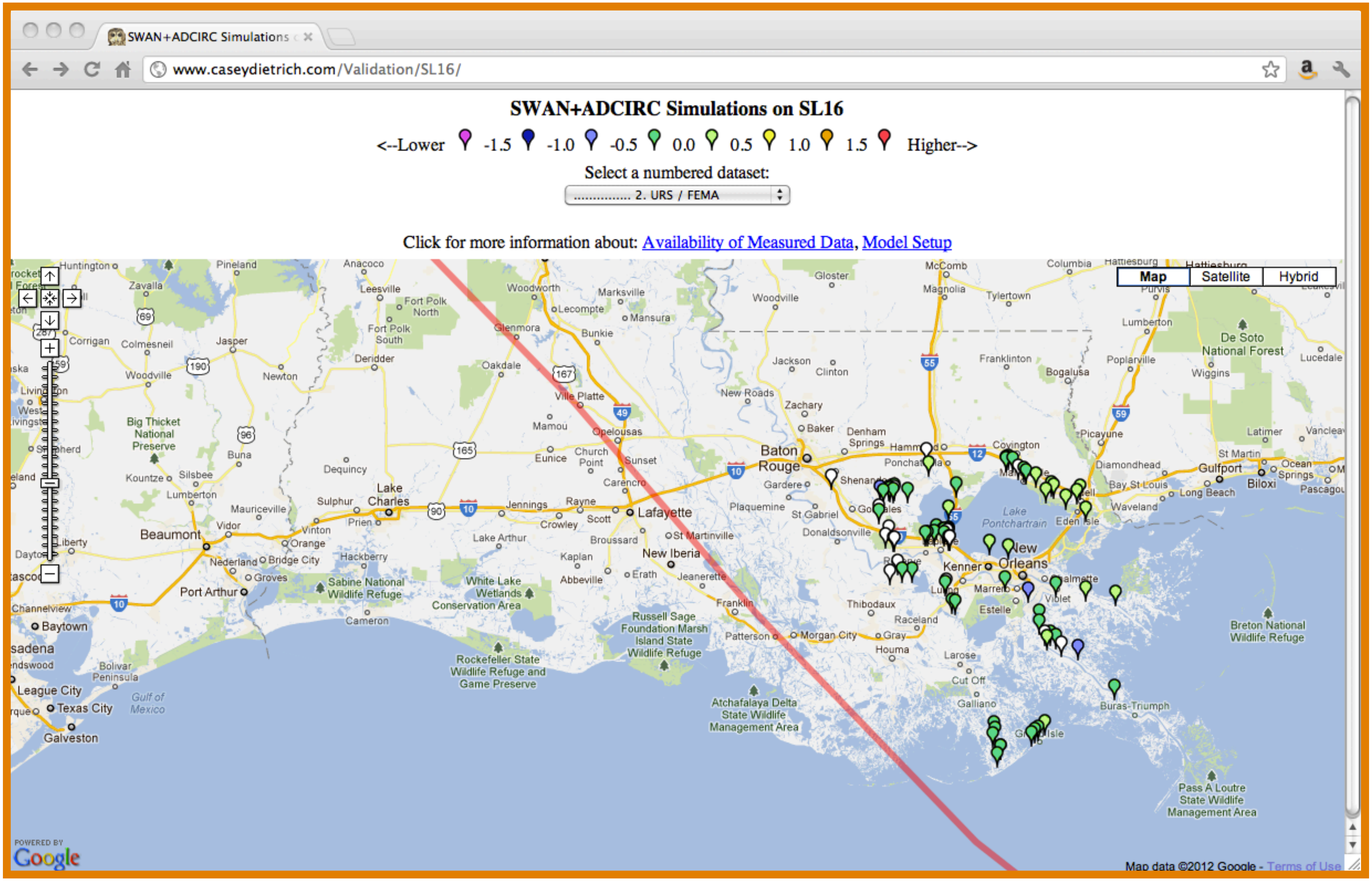


JC Dietrich, *et al*. (2011). Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Validation and Synoptic Analysis in Southern Louisiana. *Monthly Weather Review*, 139(8), 2488-2522, DOI:10.1175/2011MWR3611.1.

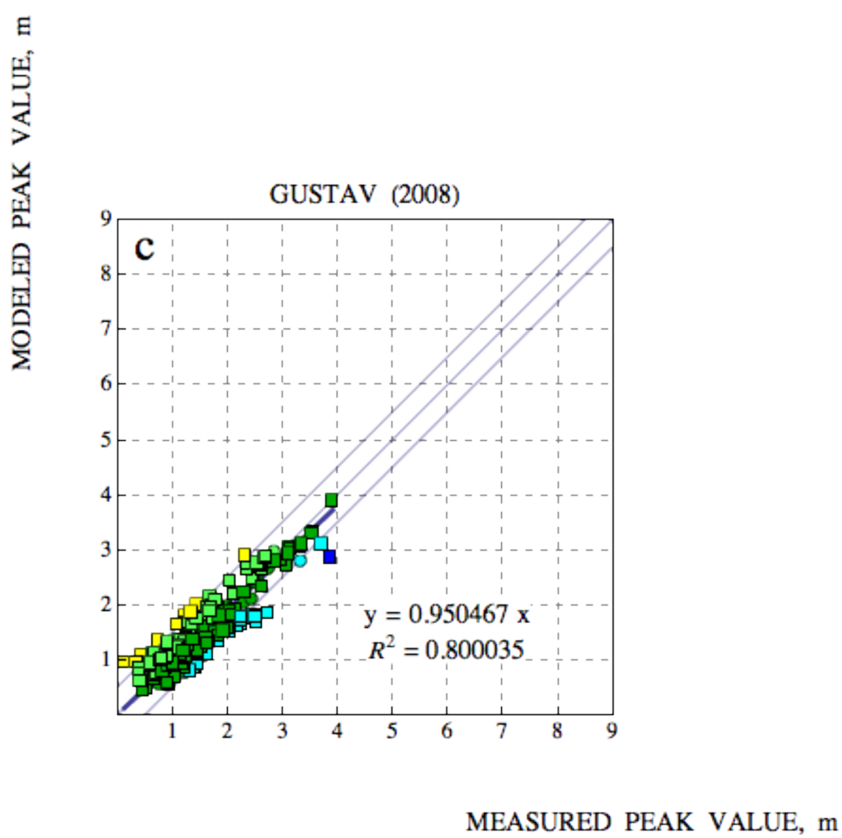
Gustav : Validation : Increased Availability of Measurement Data

	Katrina (2005)		Gustav (2008)	
High-Water Marks	**Total:**	**399**	**Total:**	**82**
	URS/FEMA	193	URS/FEMA	82
	USACE	206		
Time Series	**Water Levels:**	**9**	**Water Levels:**	**443**
			CSI	5
			Andrew Kennedy	16
	NOAA	3	NOAA	26
			USACE-CHL	6
			USACE	54
			USGS (Deployable)	61
	USGS (Permanent)	6	USGS (Permanent)	48
			CRMS	243
	Wave Parameters:	**17**	**Wave Parameters:**	**39**
	NDBC	14	NDBC	12
	CSI	3	CSI	5
			Andrew Kennedy	16
			USACE-CHL	6

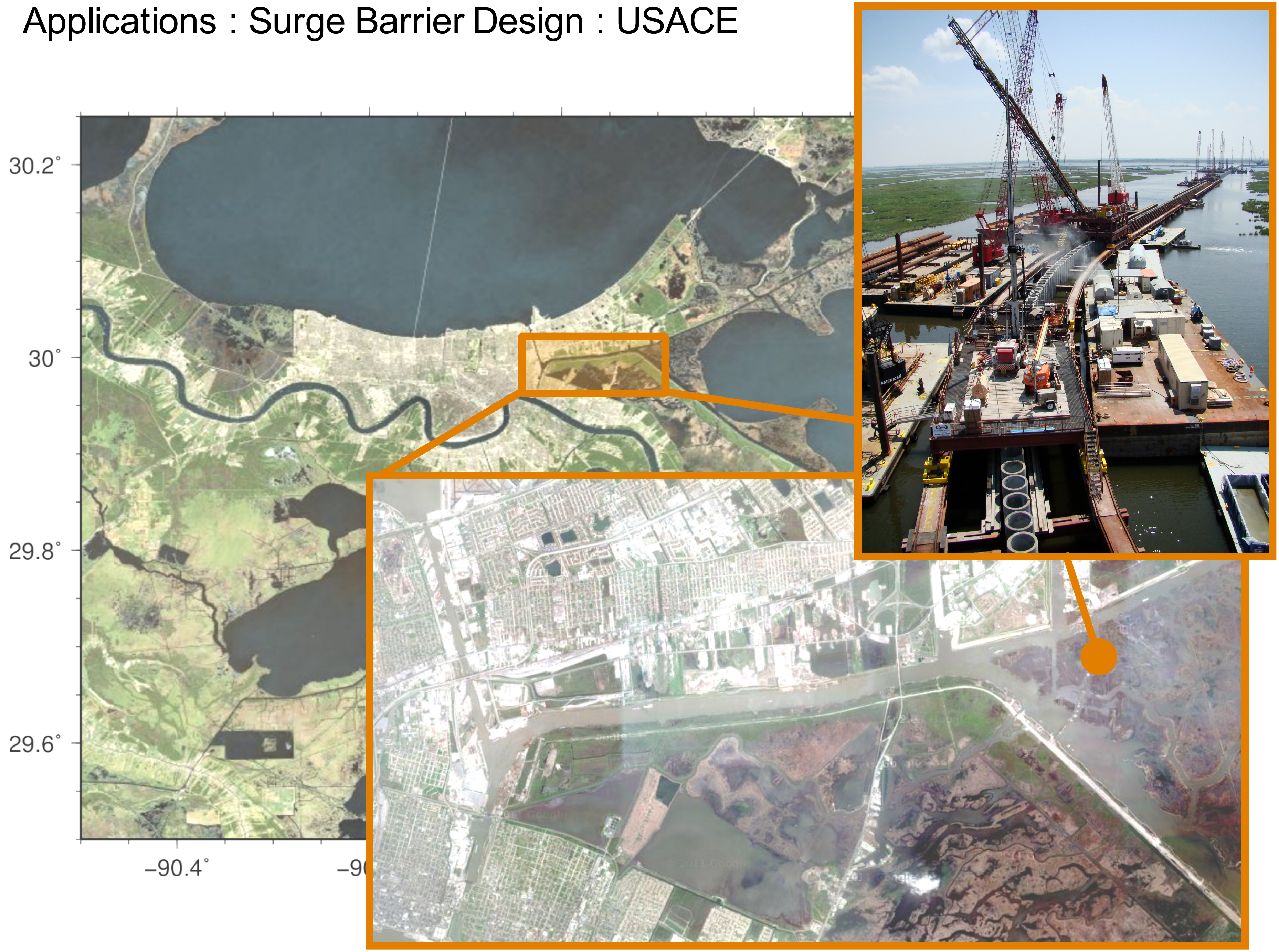
Gustav : Validation : Web-Based Mapping of Results



Gustav : Validation : High-Water Marks



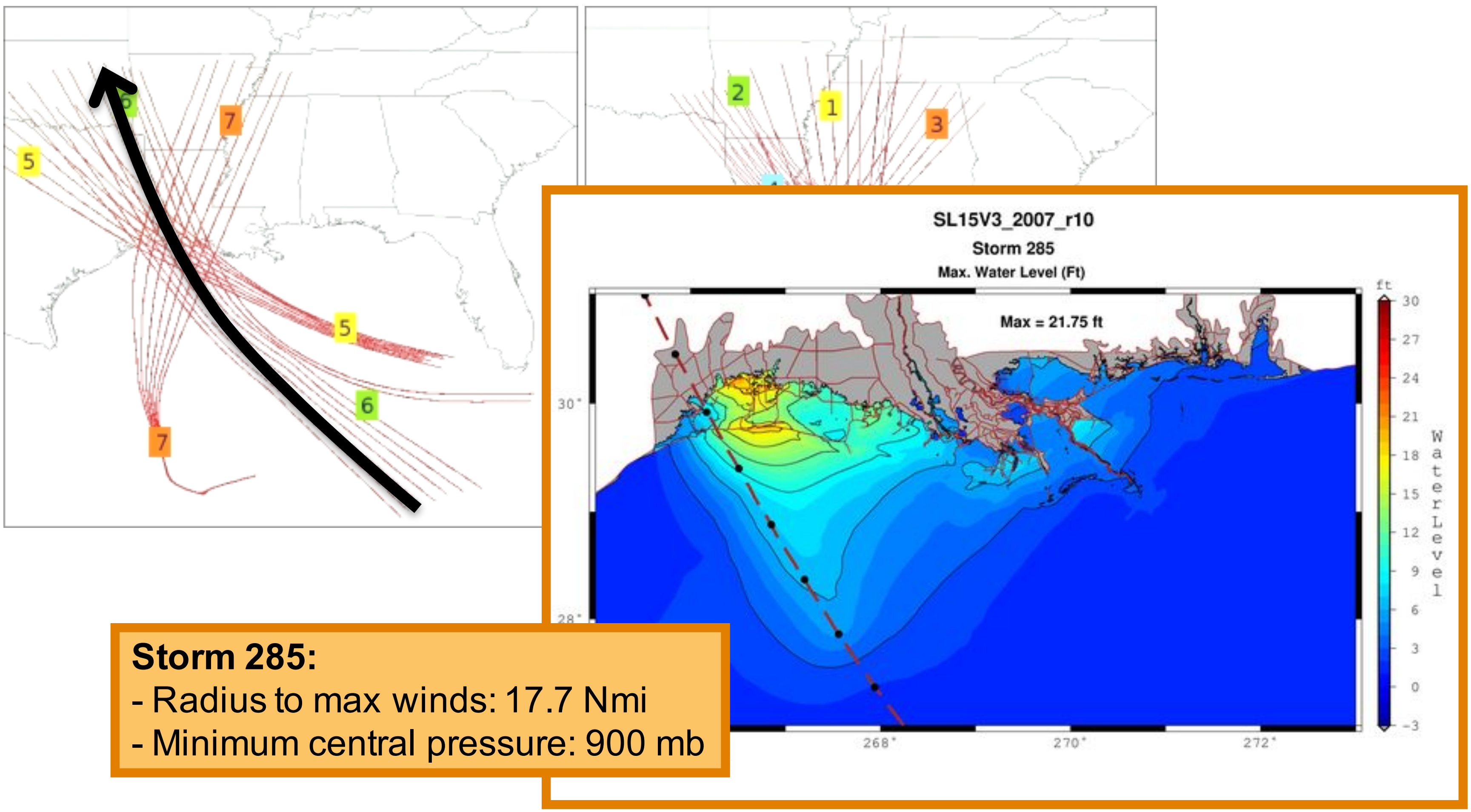
Applications : Surge Barrier Design : USACE



Applications : Flood Insurance Rate Maps : FEMA

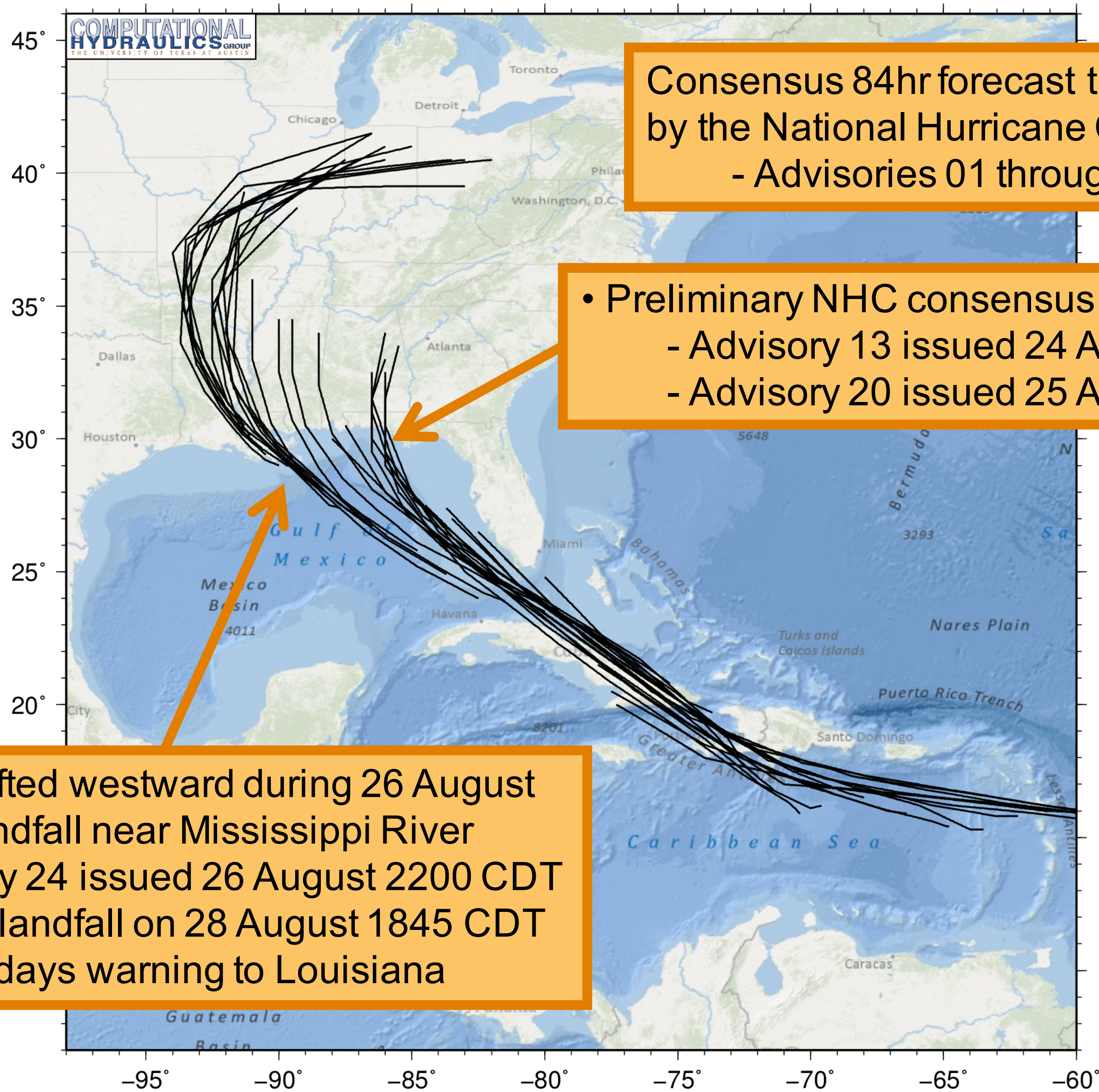
Joint Probability Method with Optimal Sampling (JPM-OS):

- 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

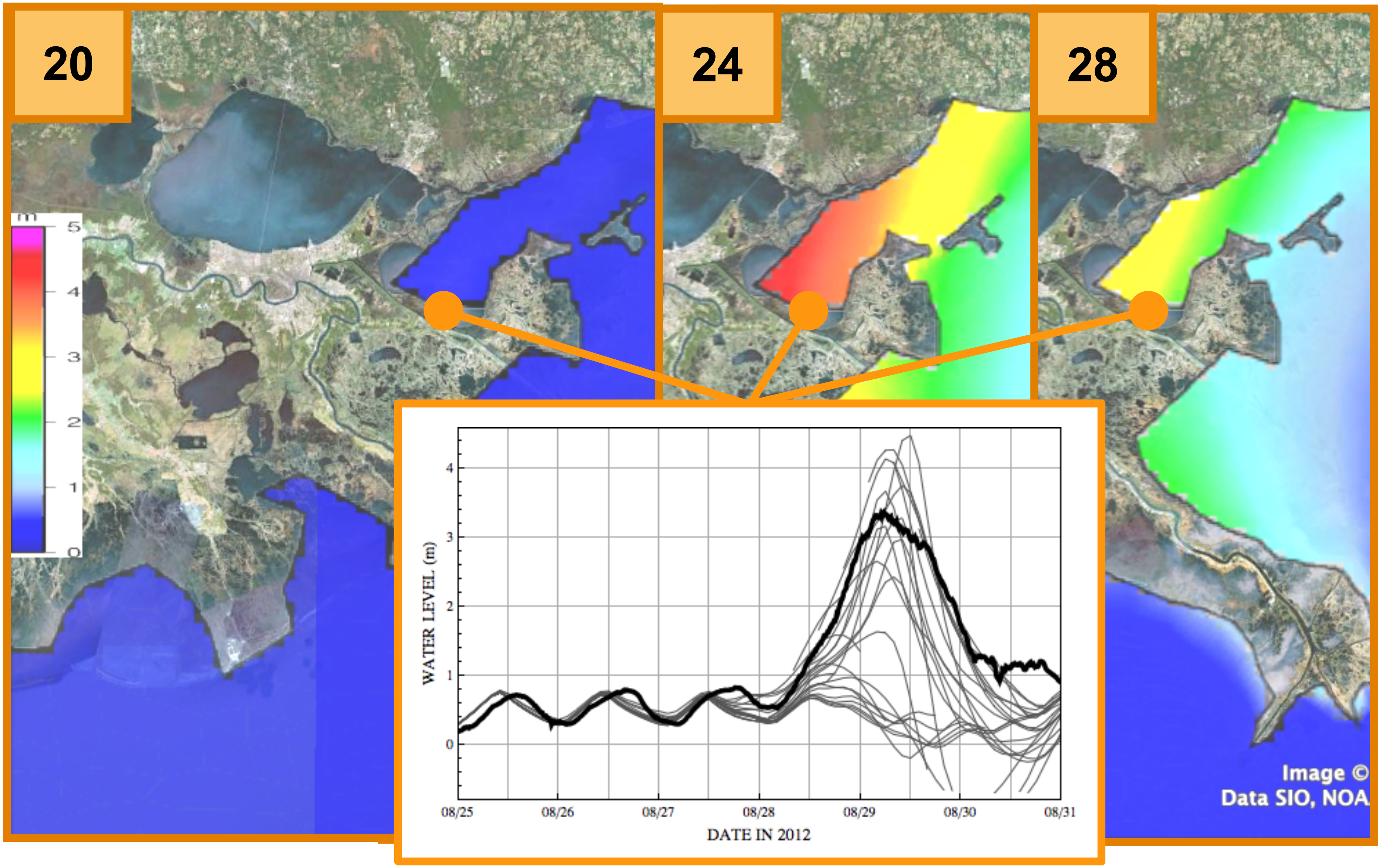


Consensus 84hr forecast tracks issued by the National Hurricane Center (NHC)
- Advisories 01 through 38

- 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

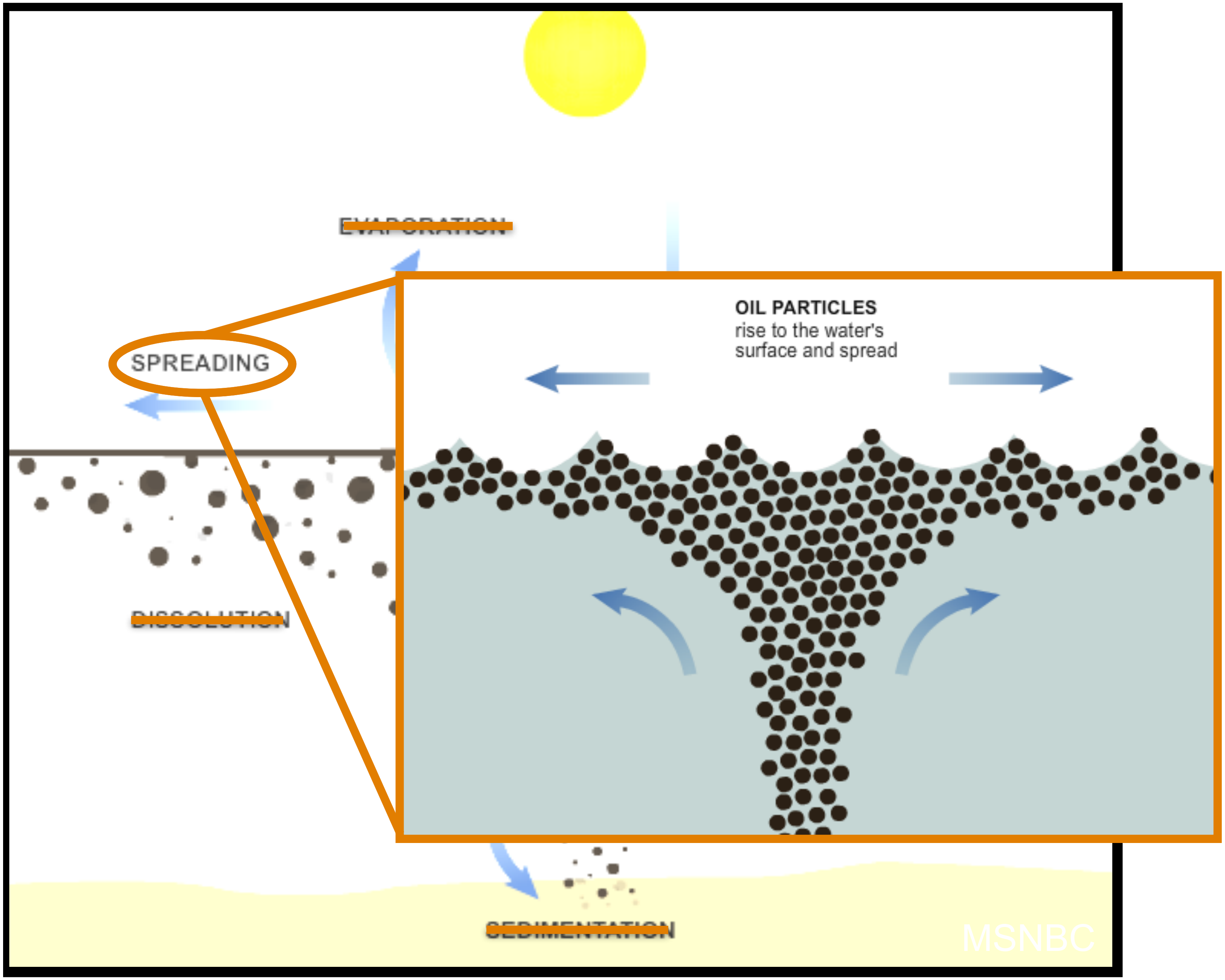
Oil spill flow rates:

- 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

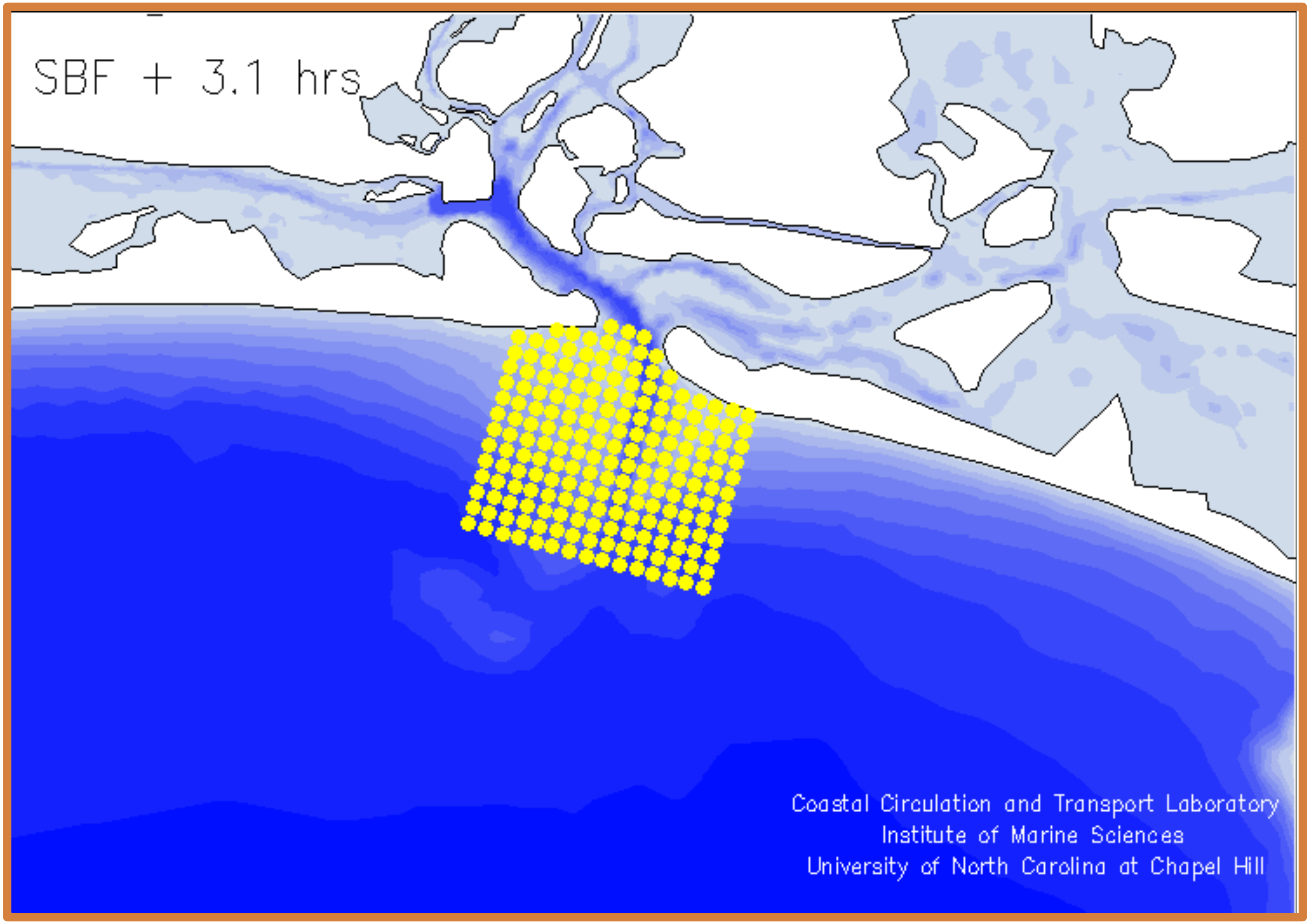
Emergency responders relied on satellite and aerial imagery

- 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:

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

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

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

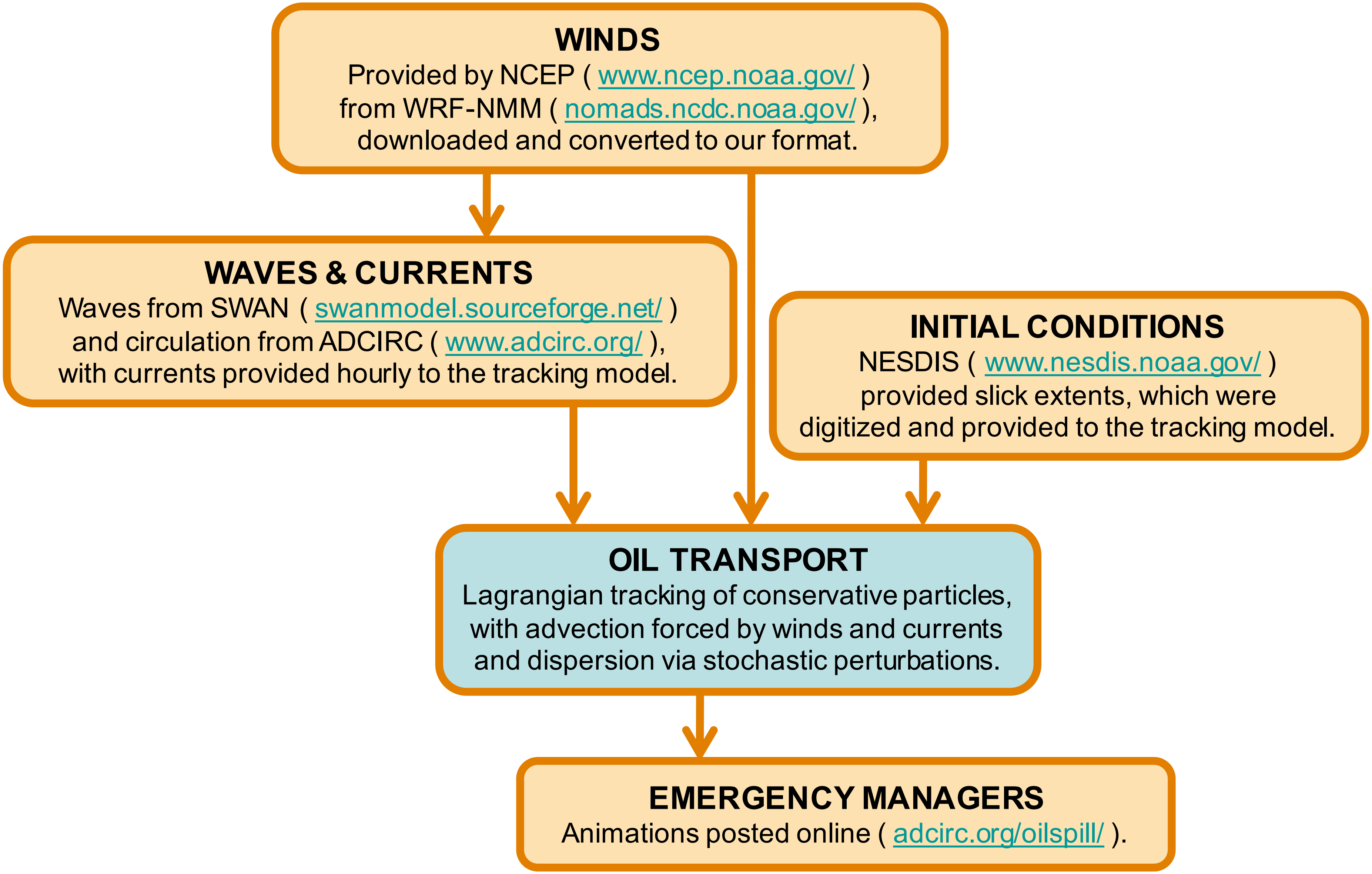
- with: $0 < R < 1$ is a random number,
  $\vec{E}_v = 10$ m²/s are turbulent coefficients, and
  $\vec{c} = 12$ are scaling coefficients;
- and where the velocities are a linear combination of currents and winds:

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

- 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.

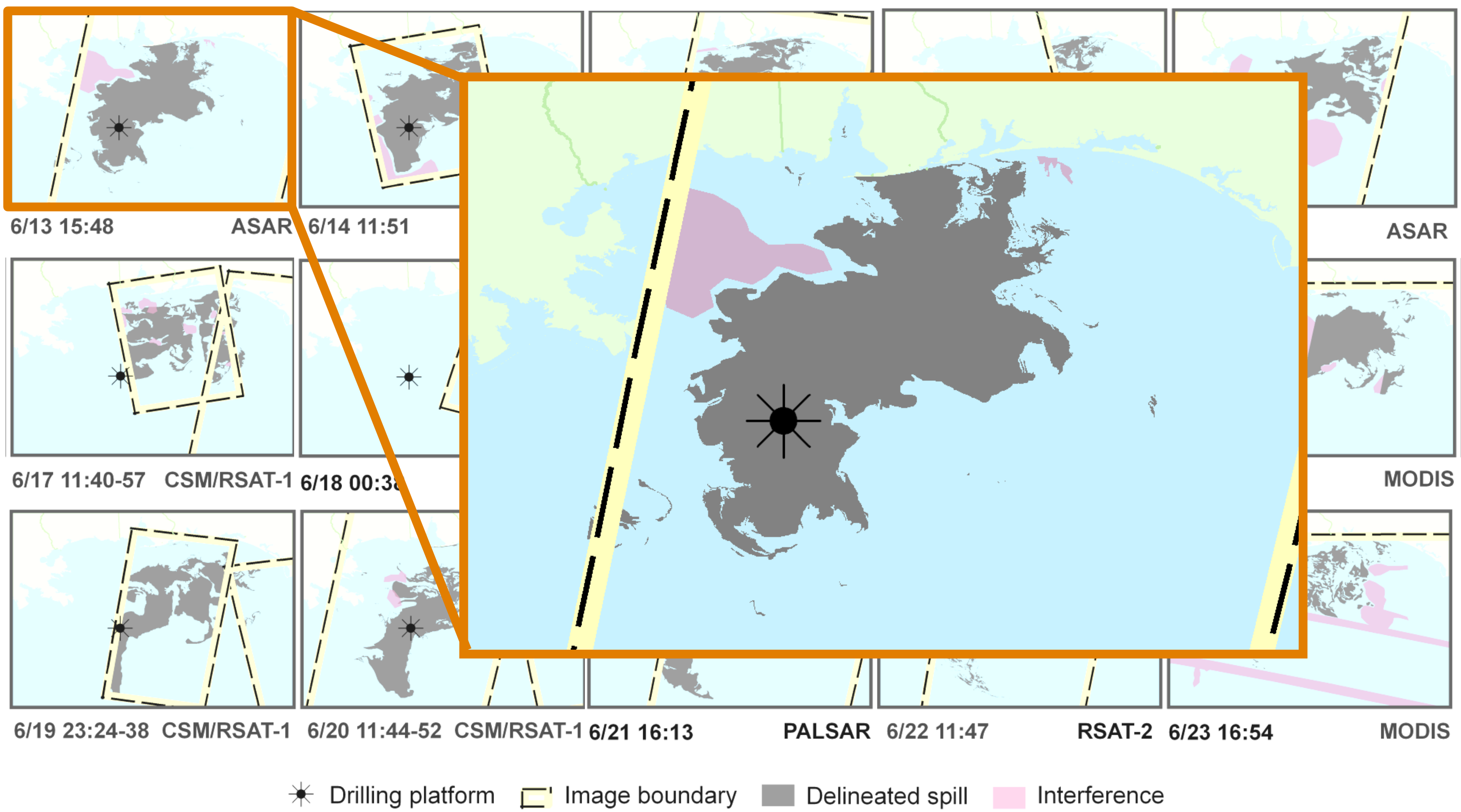
Surface Oil Transport : Flow Chart



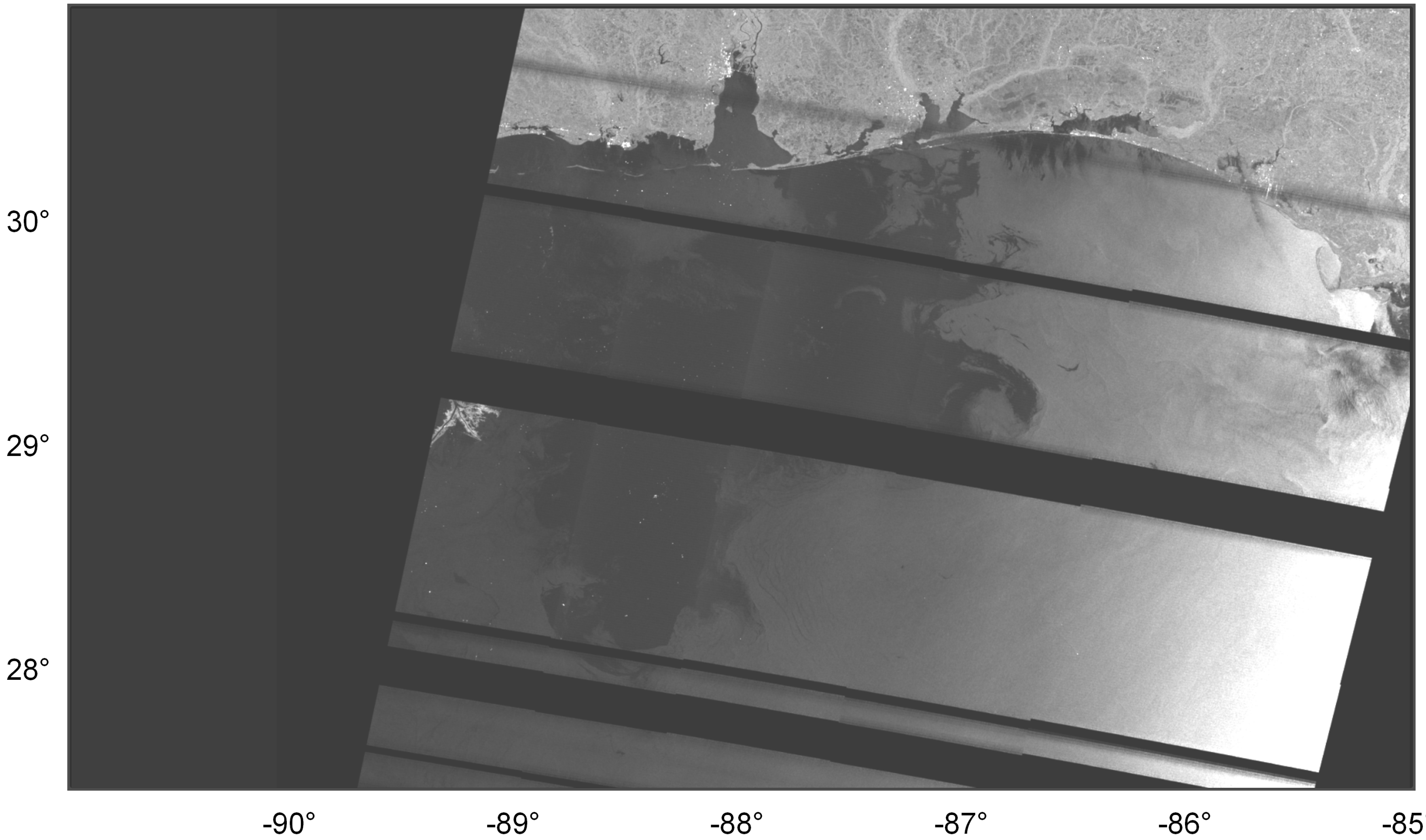
Surface Oil Transport : Validation : 13-23 June 2010

Examples of available imagery:

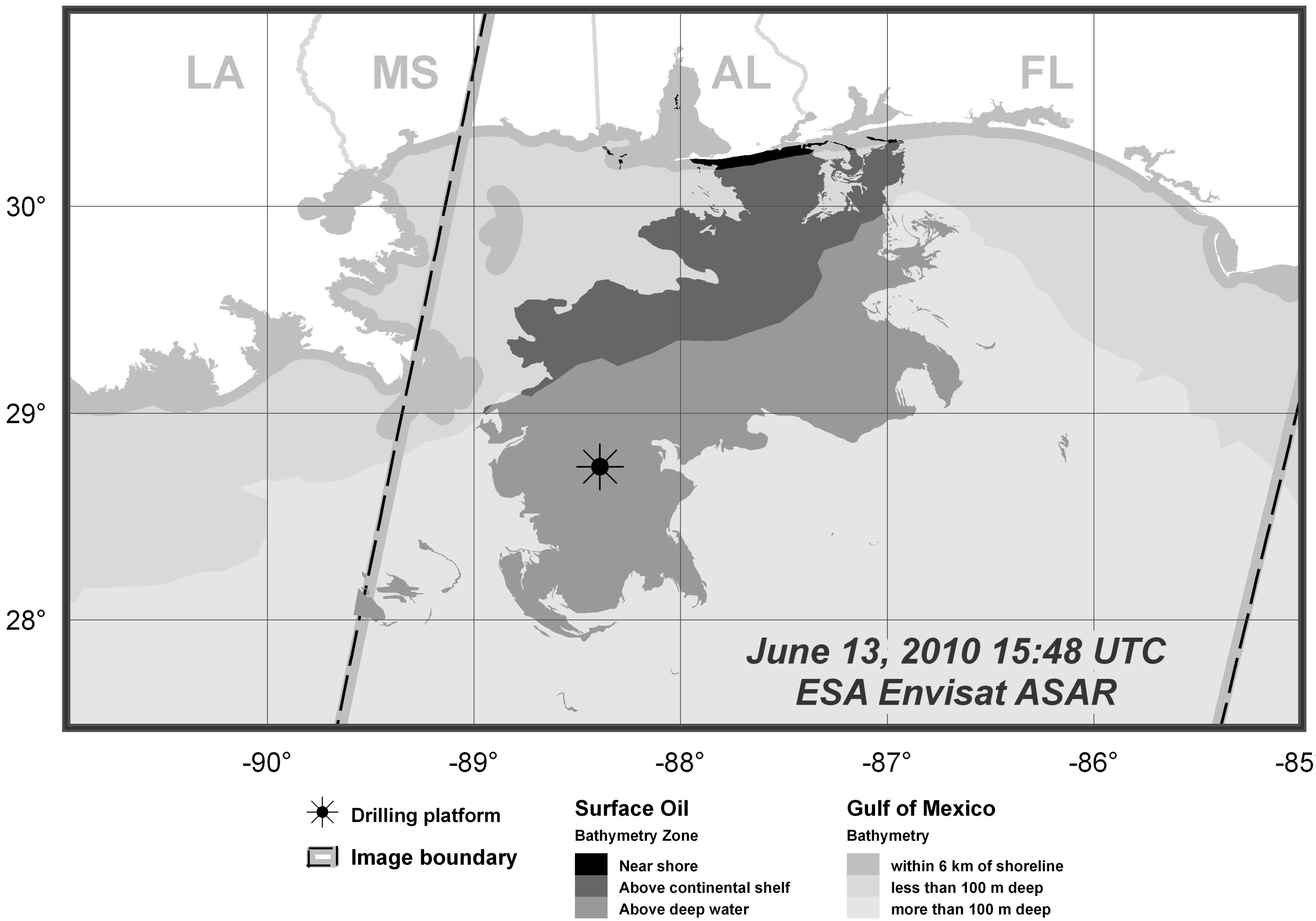
- NESDIS consolidated observations from a suite of satellite sensors



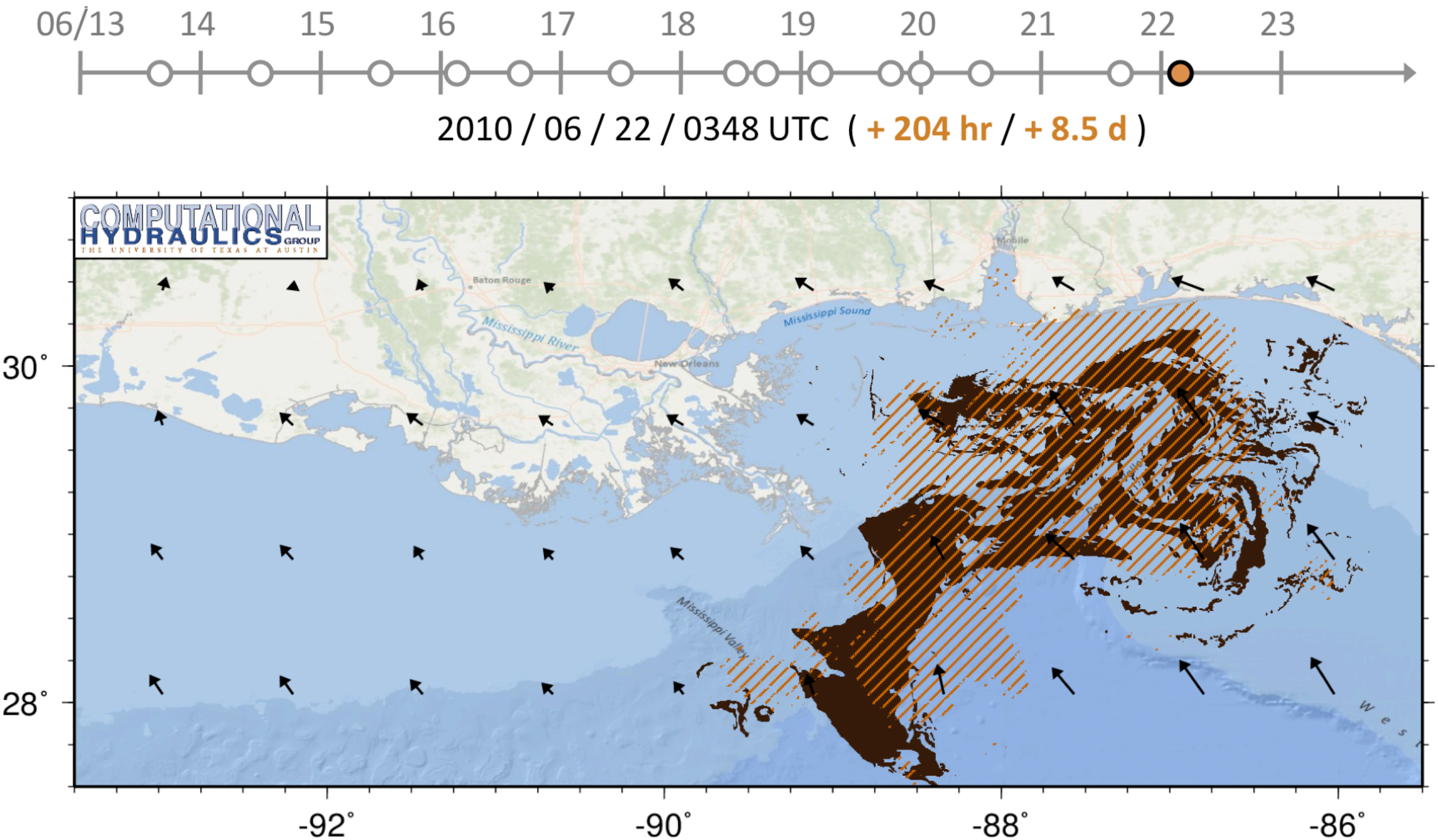
Surface Oil Transport : Validation : 13-23 June 2010



Surface Oil Transport : Validation : 13-23 June 2010



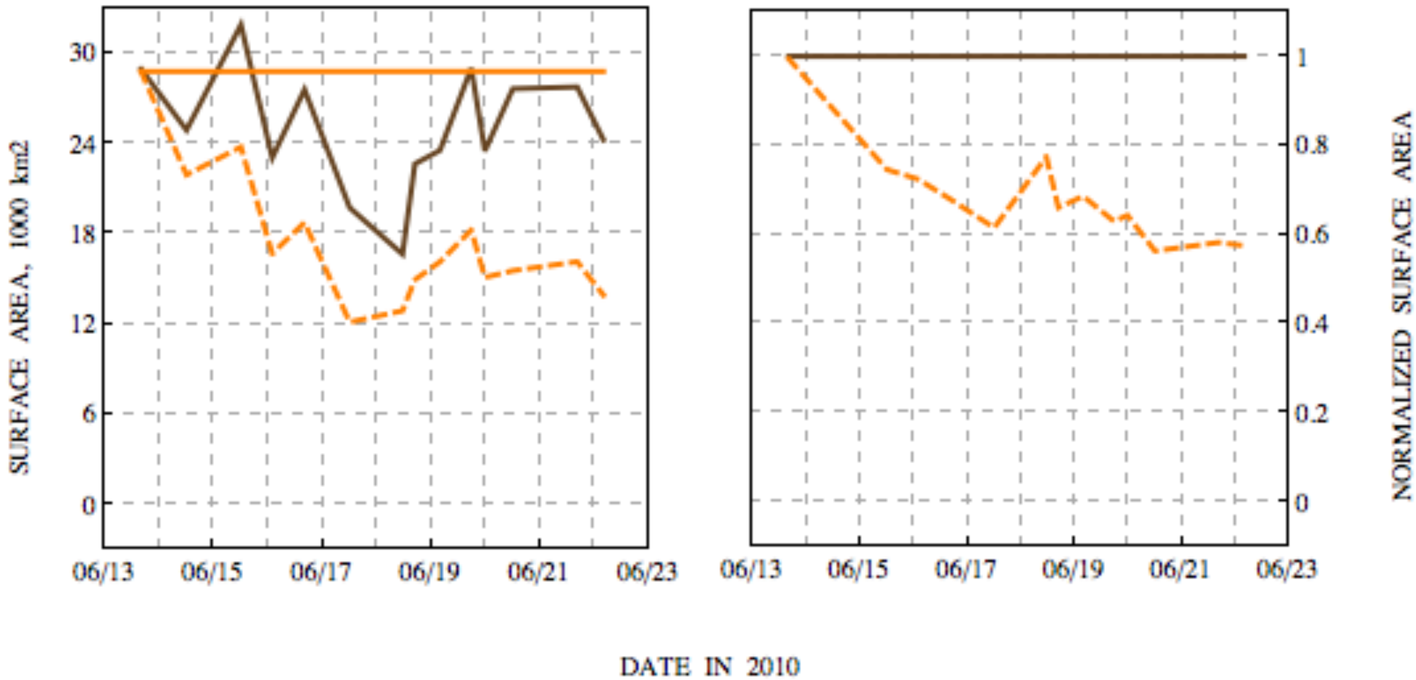
Surface Oil Transport : Validation : 13-23 June 2010



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 : Validation : 13-23 June 2010



Overlap of our predictions to observations:

- **Solid brown** - Total areas of observed oil in satellite imagery
- **Solid orange** - Total areas of predicted locations of Lagrangian particles
- Dashed orange - Overlap between predictions and observations

After one week of simulation, overlap is about 60 percent

- Qualitative and quantitative match to observations

Surface Oil Transport : Sources of Error

Our rapid 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 : Submerged Ridge

Transition to 3D Flow and Transport:

ADCIRC computes 3D flow by adding layers of vertical elements below the mesh

- u,v from horizontal momentum, then w from vertical momentum

Tracking code must account for particle depth

- Interpolate 3D velocities within the vertical element containing particle

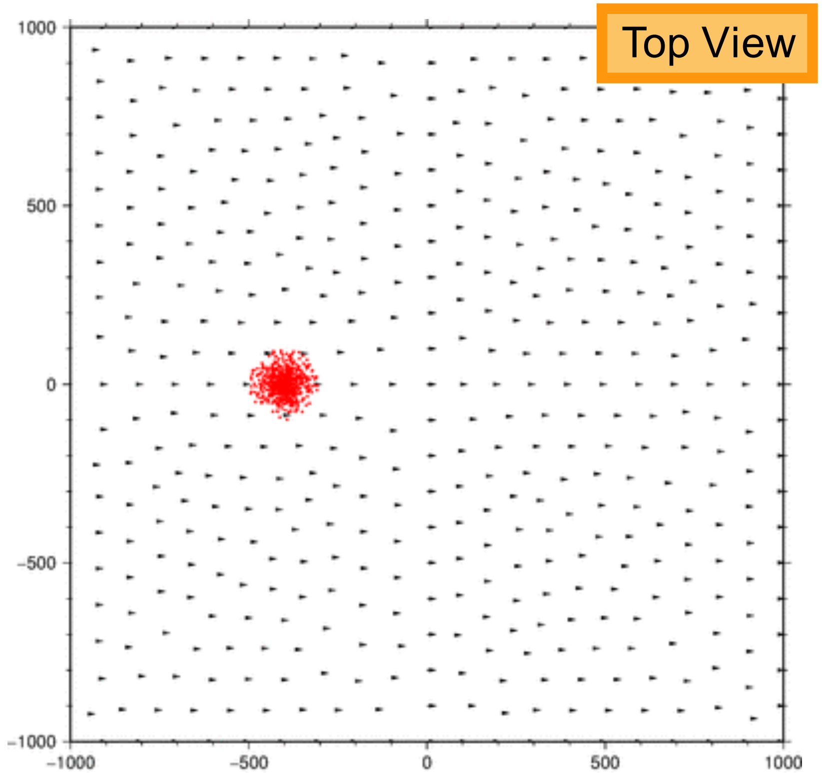
Submerged Ridge Test Case:

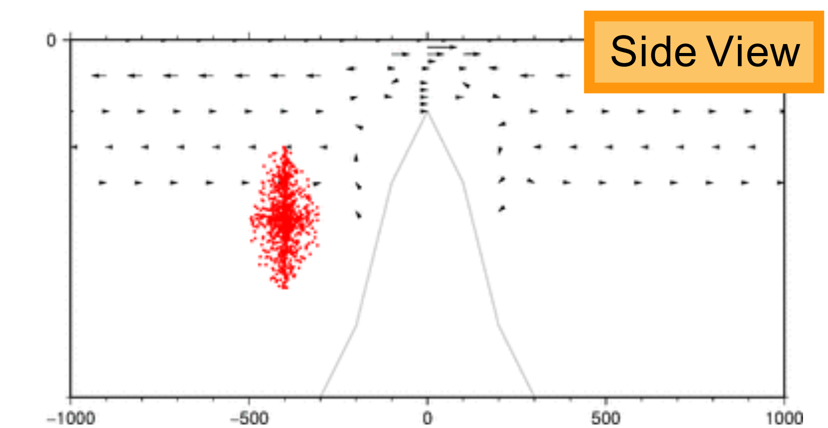
Simple test case to show particle movement

- Domain is 2km x 2km x 100m
- Submerged central ridge with 20m depth

Wind oscillates with magnitude of 10m/s

Initial 'cloud' of 1000 particles (shown in red)





3D Oil Transport : Submerged Ridge : Buoyancy

Floating Oil Droplets:

Zheng and Yapa (2000) divide droplets into shapes/classes based on size:

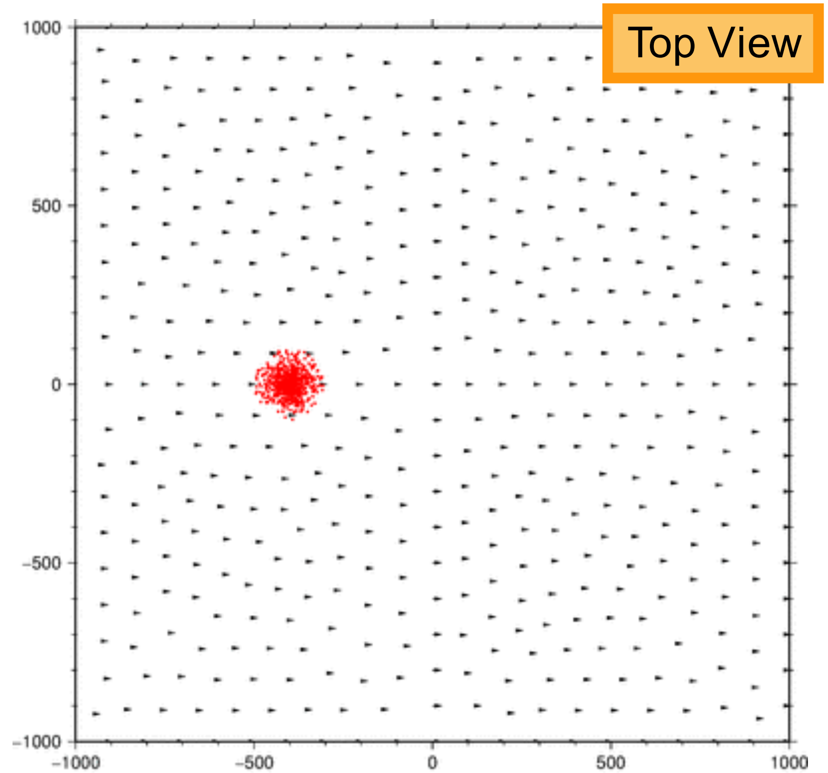
- Spherical droplets (small)
- Ellipsoidal droplets (intermediate)
- Spherical-cap droplets (large)

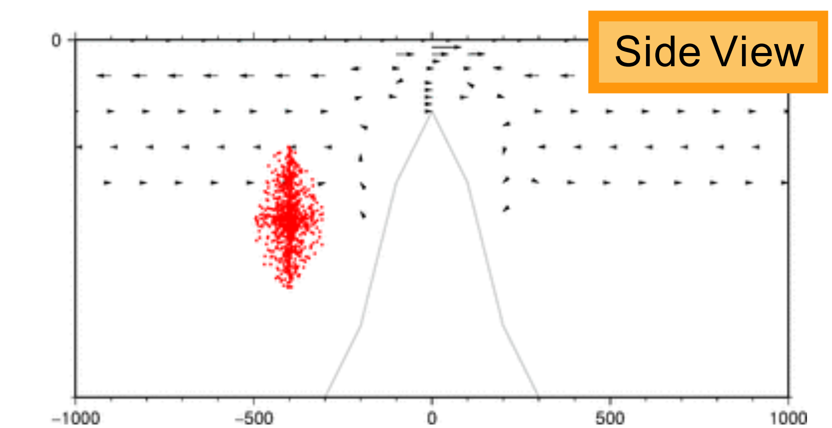
Oil droplets will always fall in spherical class:

$$U_T = \frac{R\mu}{\rho d}$$

Droplet size is most important factor:

Particle Diameter (μm)	Buoyant Velocity (m/hr)
10	0.027
50	0.685
100	2.723
300	20.549





3D Oil Transport : Submerged Ridge : Source Term

Oil Leaks from Seafloor:

At every tracking step, insert particle(s)
at a user-defined location

- Number of particles increases over time

Submerged Ridge Test Case:

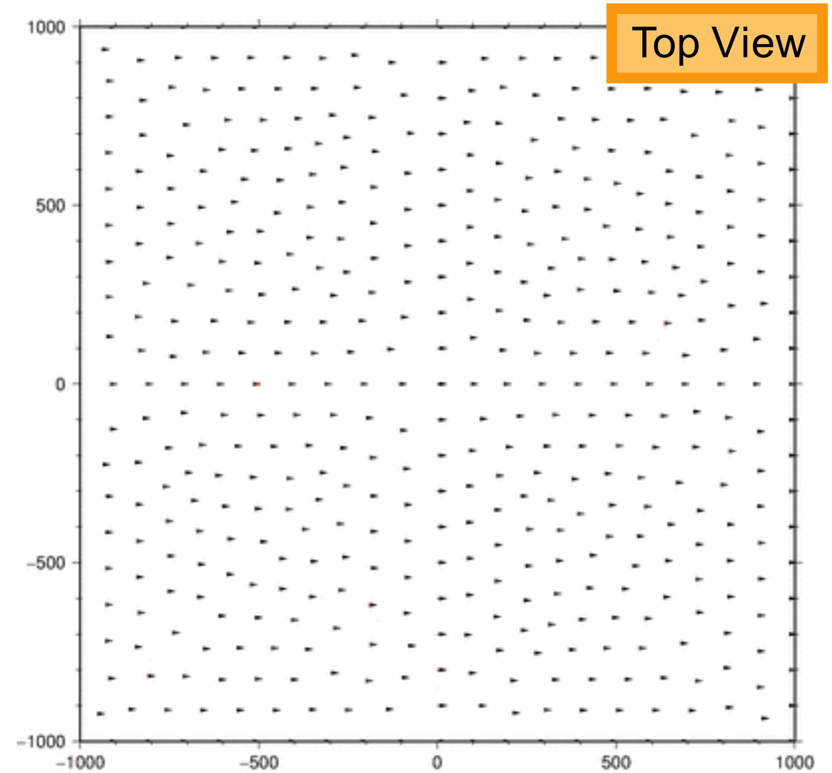
Instead of initializing the particles in a cloud,
they are introduced at a source
located at (0, -500, -100)m

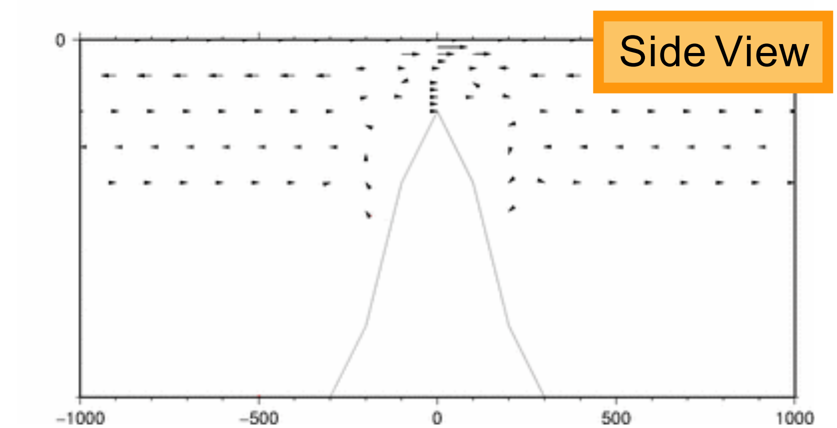
Assumptions:

Water - Density of 998.2071 kg/m^3 (at 20°C)

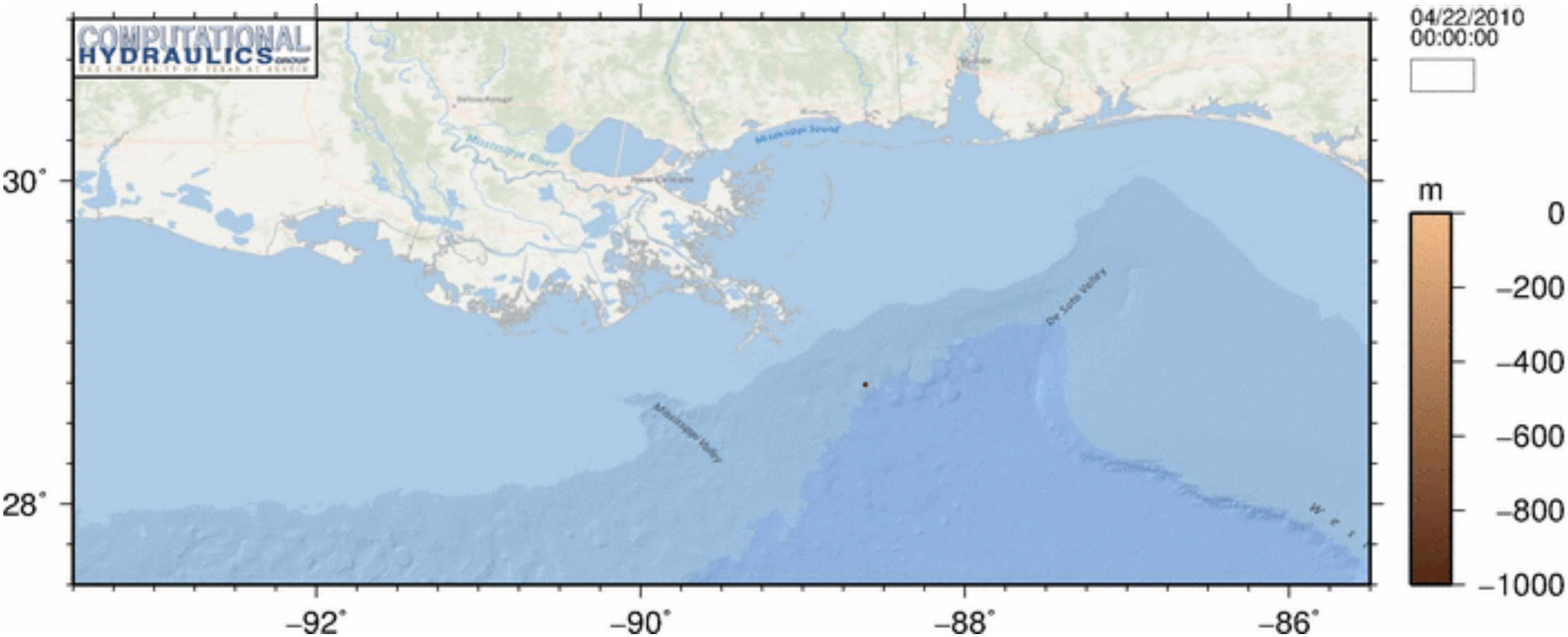
Oil - Density of 858 kg/m^3

- **Droplet size of 50μm**
- Interfacial tension of 0.023 N/m





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

Conclusions and Future Work

'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

Predictive, high-resolution modeling of nearshore ocean waves and circulation for applications in coastal engineering

Thank You!

Hurricane Season 2012