Surface Trajectories of Oil Transport along the Northern Coastline of the Gulf of Mexico

JC Dietrich, CN Dawson

Institute for Computational Engineering and Sciences

University of Texas at Austin

Computational Methods in Water Resources

University of Illinois at Urbana-Champaign

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Who Are We?

JC Dietrich, CJ Trahan, CN Dawson

Institute for Computational Engineering and Sciences,

University of Texas at Austin

MT Howard, G Wells

Center for Space Research,

University of Texas at Austin

JG Fleming

Seahorse Coastal Consulting,
Morehead City, North Carolina

RJ Weaver, RA Luettich Jr

Institute of Marine Sciences,

Univ. of North Carolina at Chapel Hill

S Tanaka, JJ Westerink

Dept. of Civil Engineering and Geological Sciences,

University of Notre Dame

L Yu, A Lu

Department of Computer Science,

Univ. of North Carolina at Charlotte

K Vega, A Kubach

Texas Advanced Computing Center,
University of Texas at Austin

KM Dresback, RL Kolar

School of Civil Engineering and Environmental Science,

University of Oklahoma

C Kaiser

Dept. of Oceanography and Coastal Sciences, Louisiana State University

RR Twilley

Vice President for Research,

University of Louisiana at Lafayette

Nearshore 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



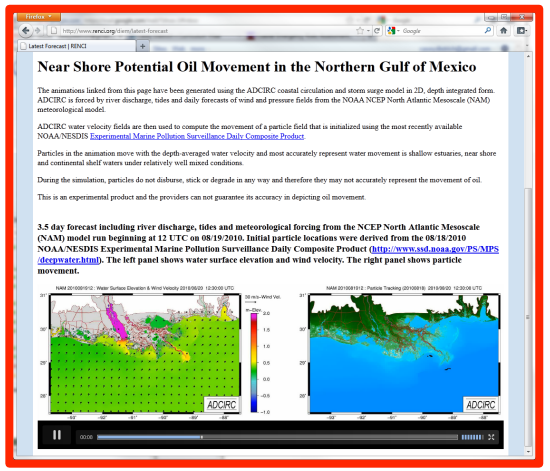
Nearshore Oil Transport : Deepwater Horizon Oil Spill (2010)

Satellite imagery shows current location of the slick

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

Forecasts need to be accurate and fast

- Share computed circulation with NOAA
- Share oil transport with emergency managers in real time (http://adcirc.org/oilspill)







SWAN+ADCIRC : Governing Equations

ADvanced CIRCulation (ADCIRC):

- Solves the Generalized Wave Continuity Equation (GWCE):

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

where:

$$\tilde{J}_x = -Q_x \frac{\partial U}{\partial x} - Q_y \frac{\partial U}{\partial y} + fQ_y - \frac{g}{2}\frac{\partial \zeta^2}{\partial x} - gH \frac{\partial}{\partial x}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0} + \left(M_x - D_x\right) + U\frac{\partial \zeta}{\partial t} + \tau_0 Q_x - gH\frac{\partial \zeta}{\partial x}$$

$$\tilde{J}_y = -Q_x \frac{\partial V}{\partial x} - Q_y \frac{\partial V}{\partial y} - fQ_x - \frac{g}{2}\frac{\partial \zeta^2}{\partial y} - gH \frac{\partial}{\partial y}\left[\frac{p_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0} + \left(M_y - D_y\right) + V\frac{\partial \zeta}{\partial t} + \tau_0 Q_y - gH\frac{\partial \zeta}{\partial y}$$

- Solves the vertically-integrated momentum equations:

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

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

SWAN+ADCIRC : Governing Equations

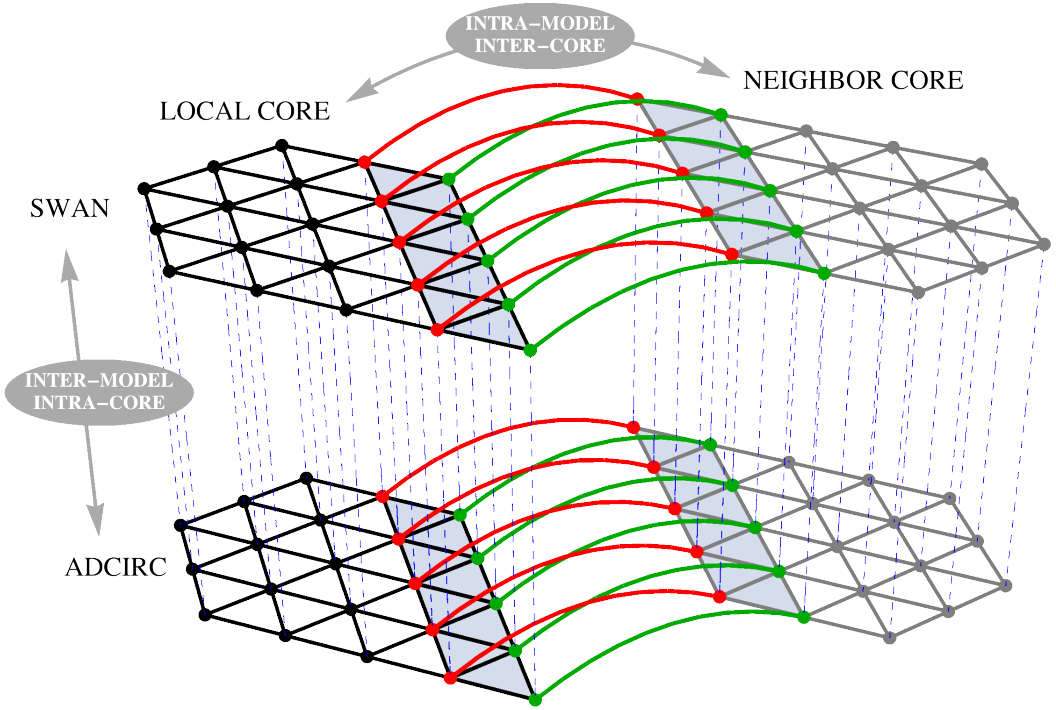
Simulating WAves Nearshore (SWAN):

- Solves the action balance equation:

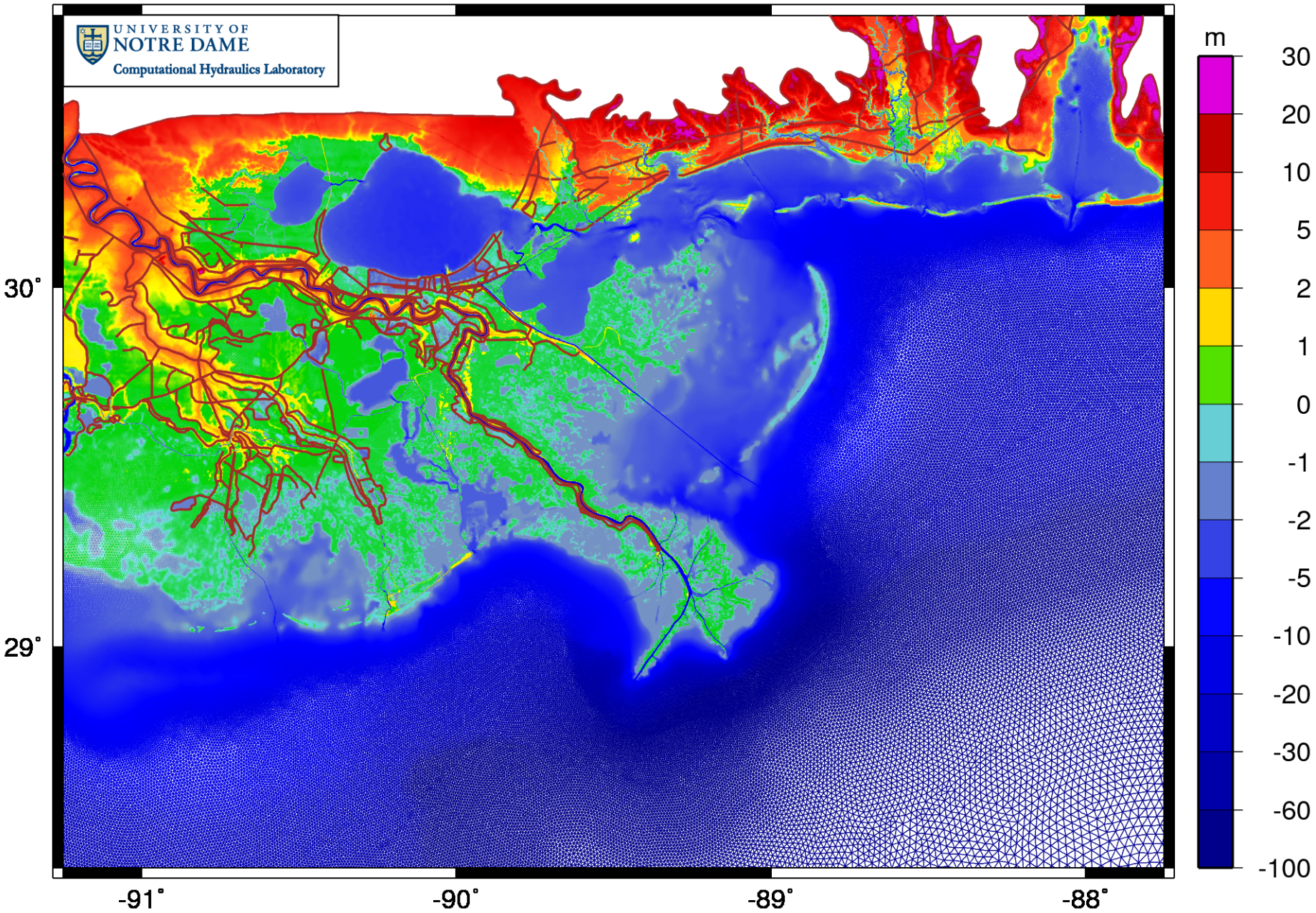
$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \cdot \left[\left(\vec{c}_g + \vec{U} \right) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = \frac{S_{tot}}{\sigma}$$

'Tight' Coupling:

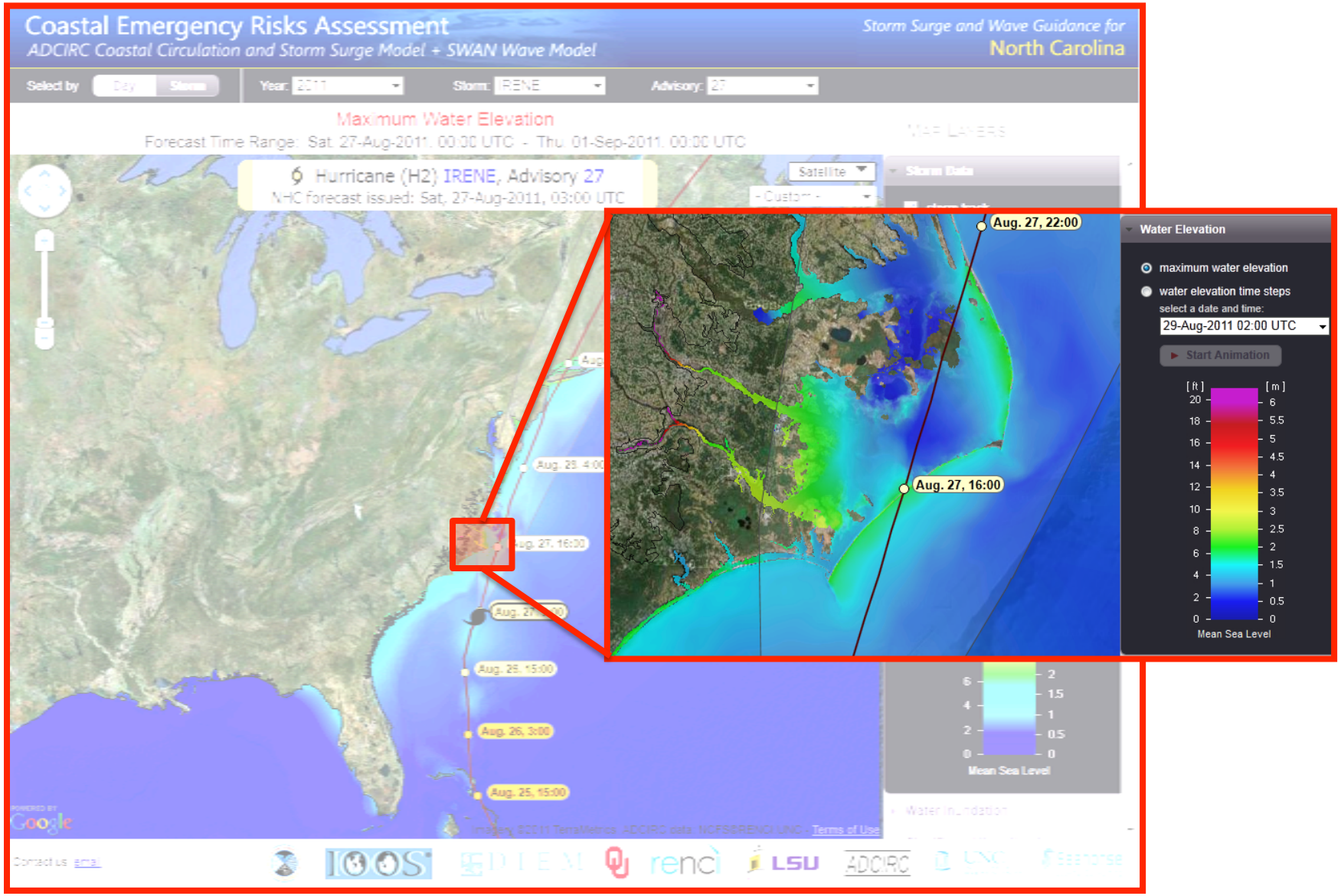
- Communication is optimized for high-performance computing:



SWAN+ADCIRC : High-Resolution Unstructured Meshes

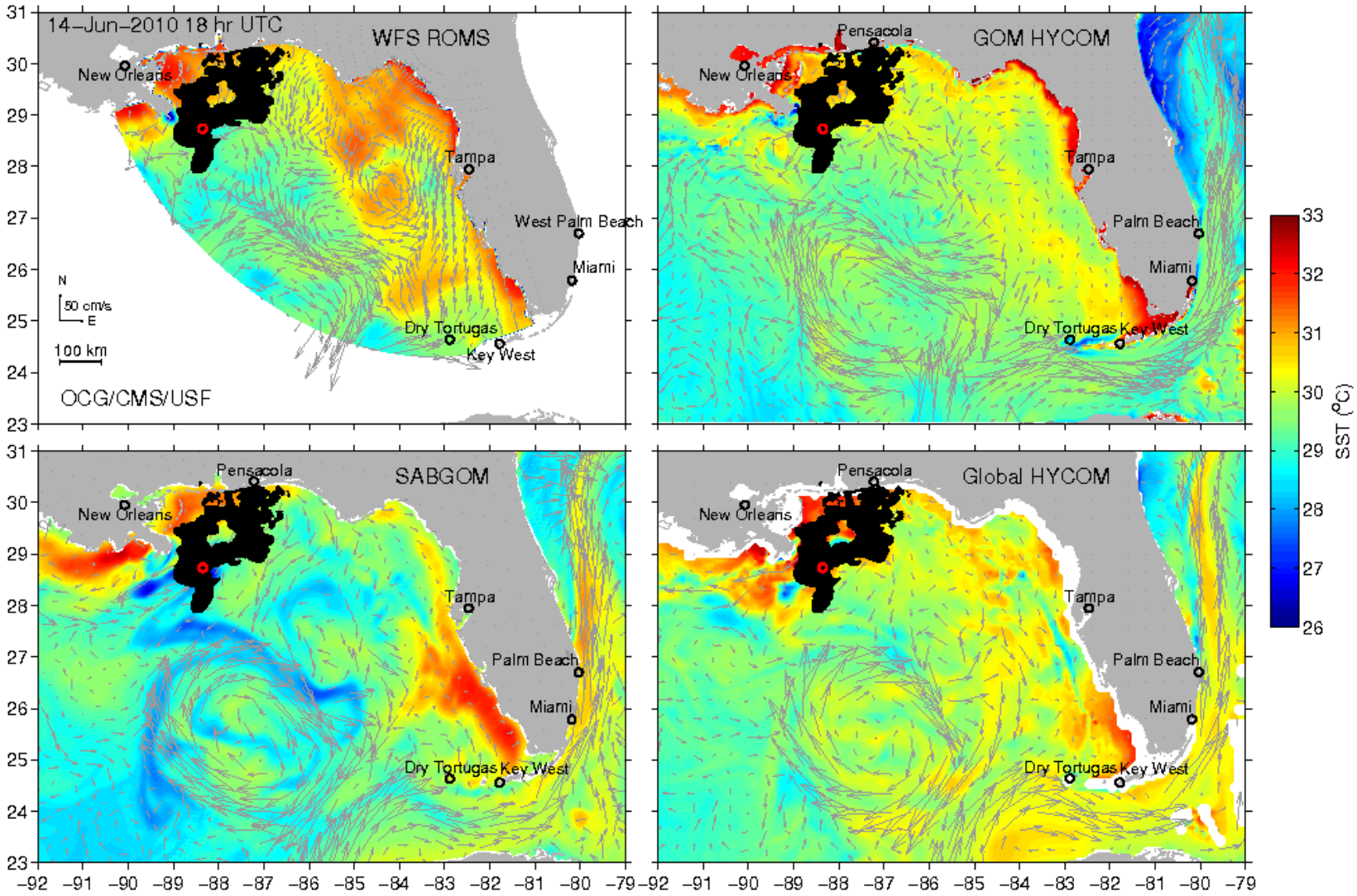


SWAN+ADCIRC : Operational Forecasting of Hurricane Irene (2011)



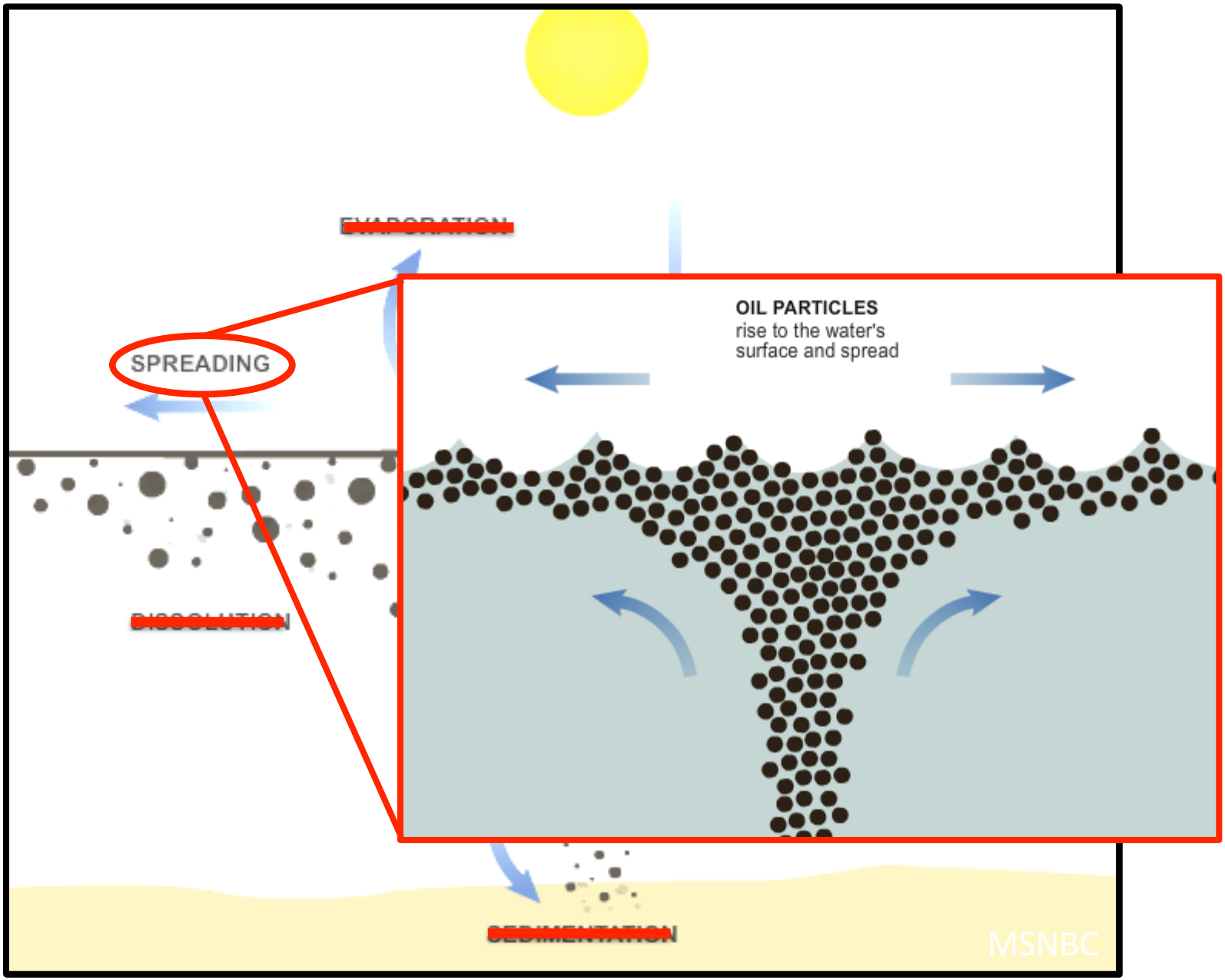
Coastal Emergency Risks Assessment - North Carolina:
http://nc-cera.renci.org/

Nearshore Oil Transport : Challenges

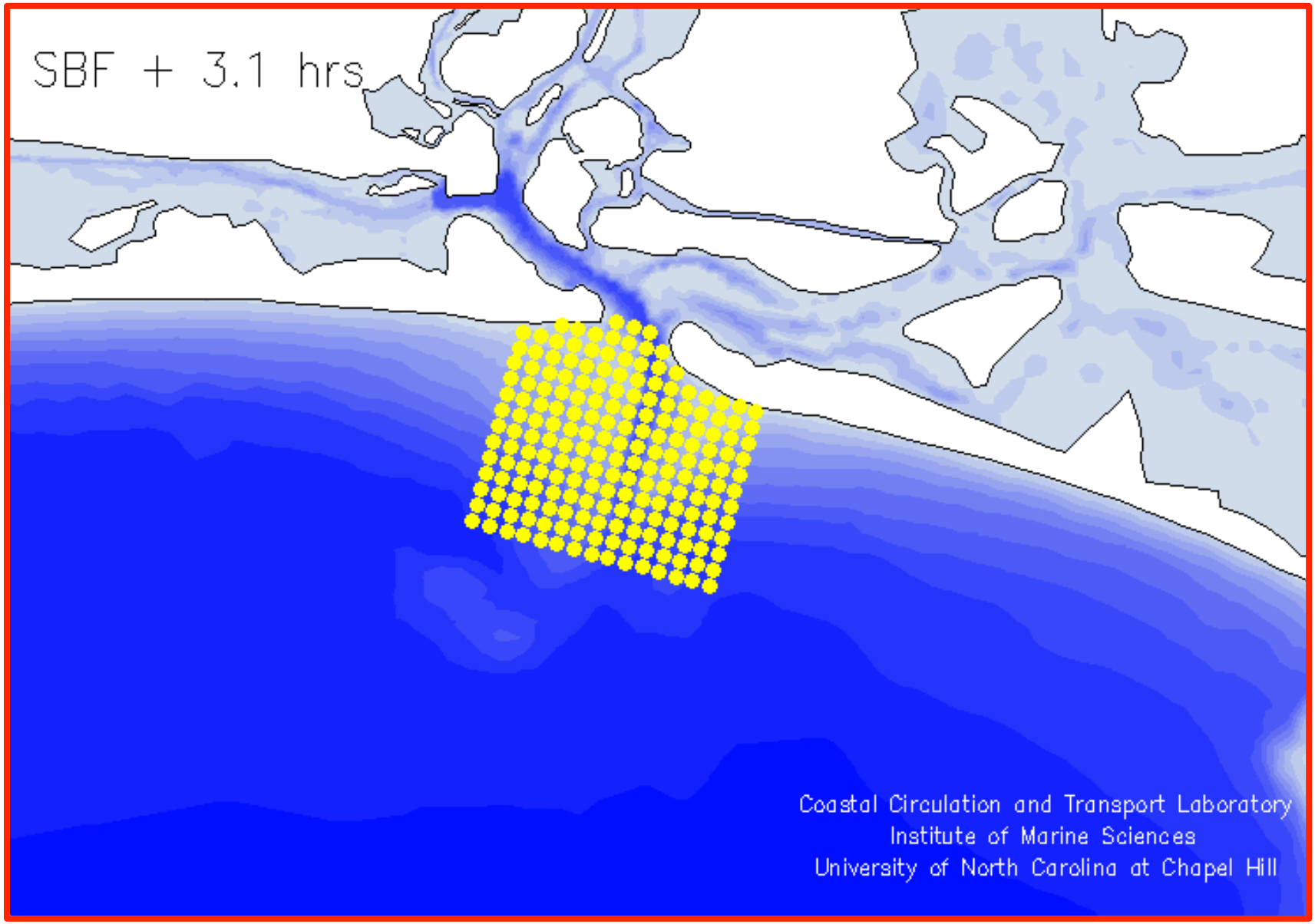


Ensemble forecasts via the Ocean Circulation Group at the University of South Florida:
http://ocgweb.marine.usf.edu/~liu/oil.html

Nearshore Oil Transport : Challenges



Nearshore Oil Transport : Lagrangian Particles



Nearshore 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;

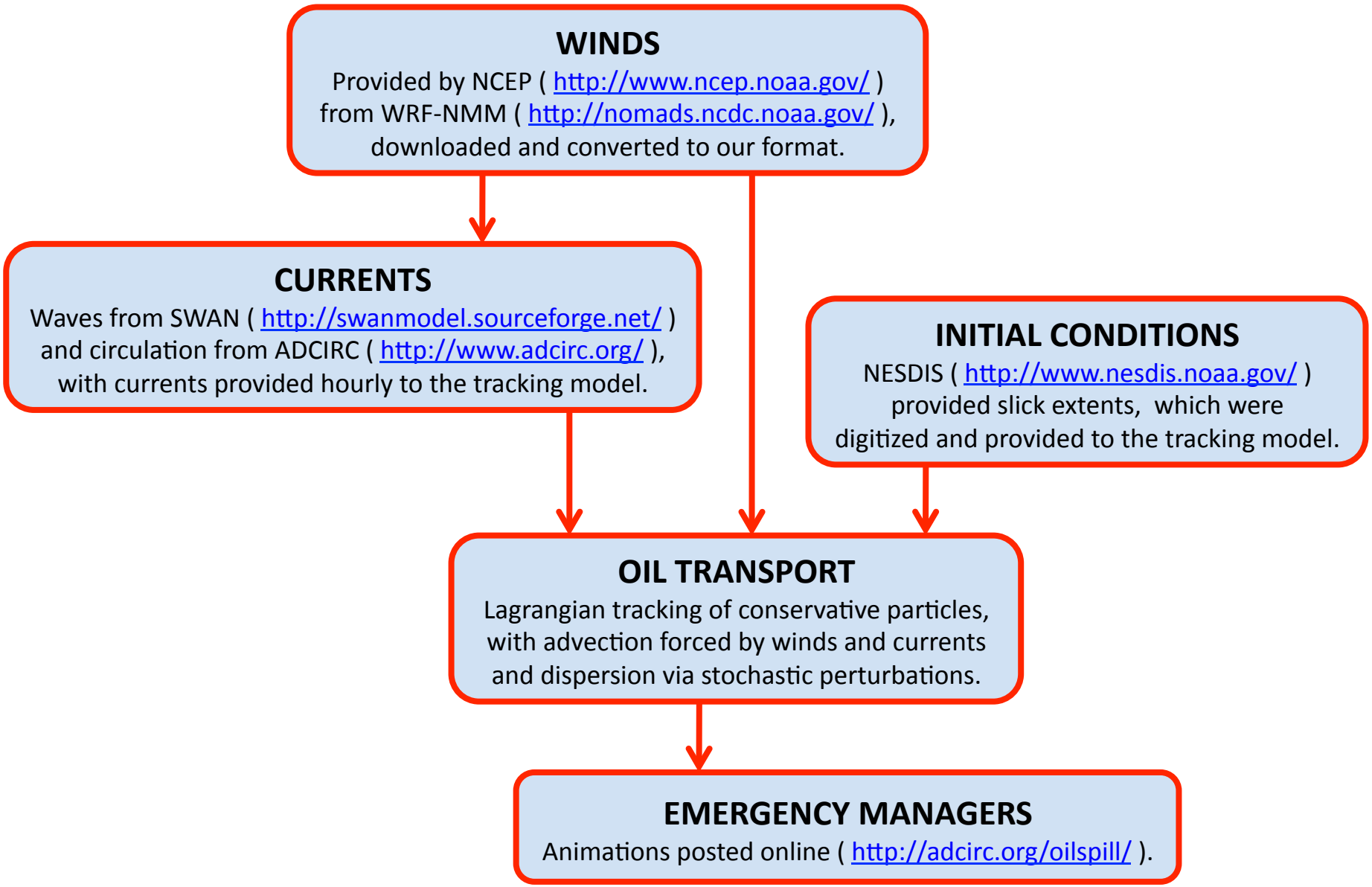
- and where the velocities are a linear combination of currents and winds:

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

- 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.

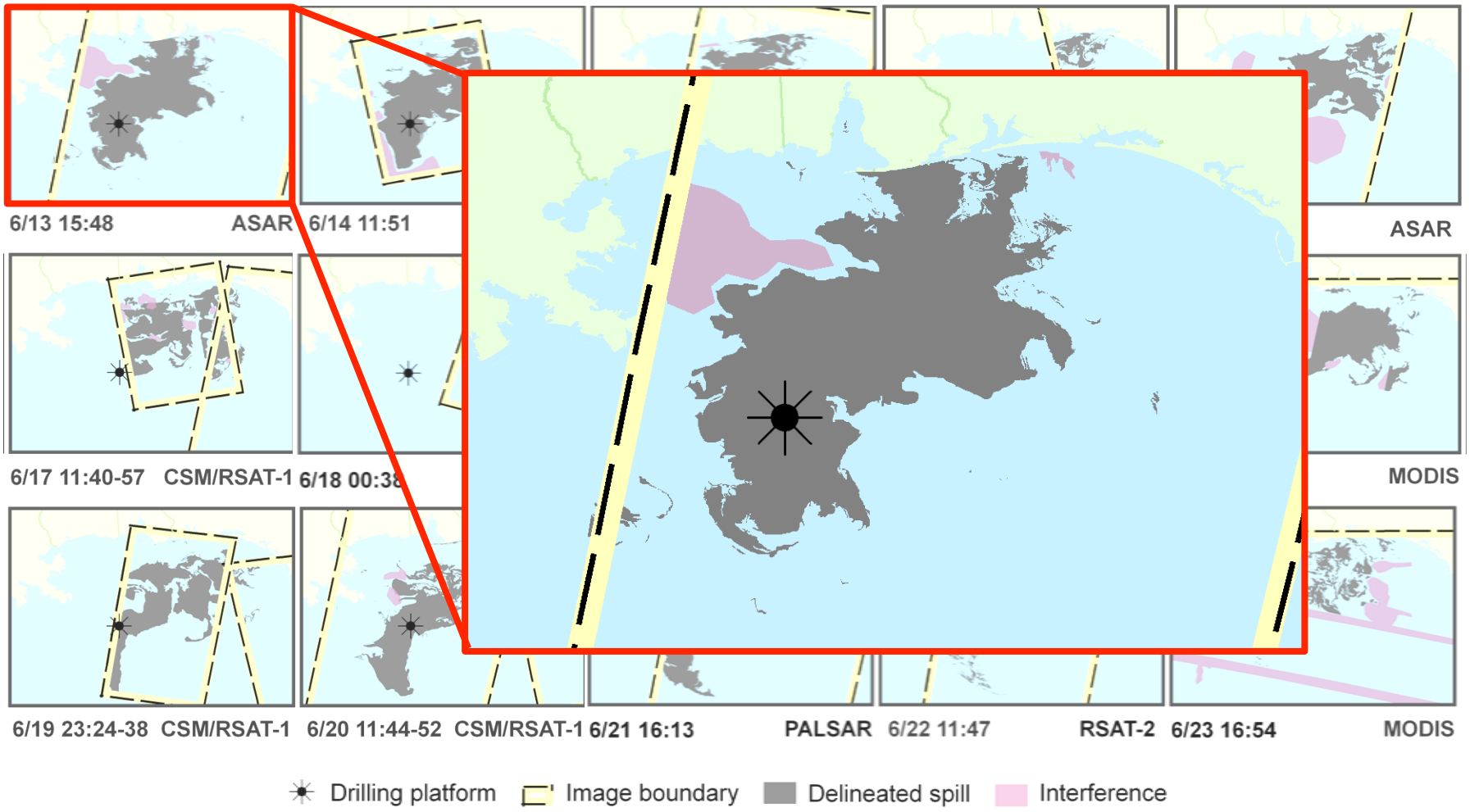
Nearshore Oil Transport : Flow Chart



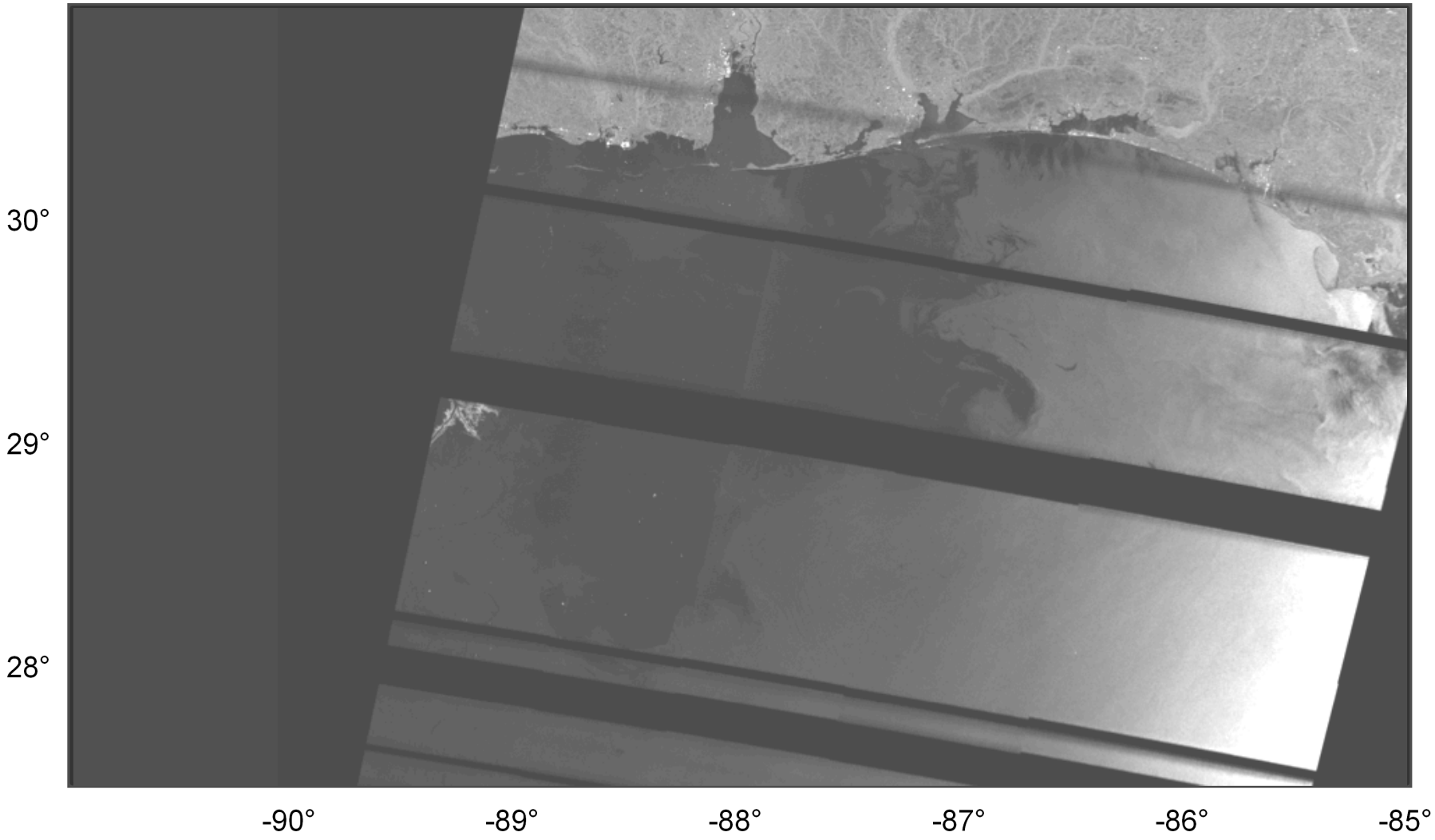
Validation : Mid-June

Examples of available imagery during 13-23 June 2010:

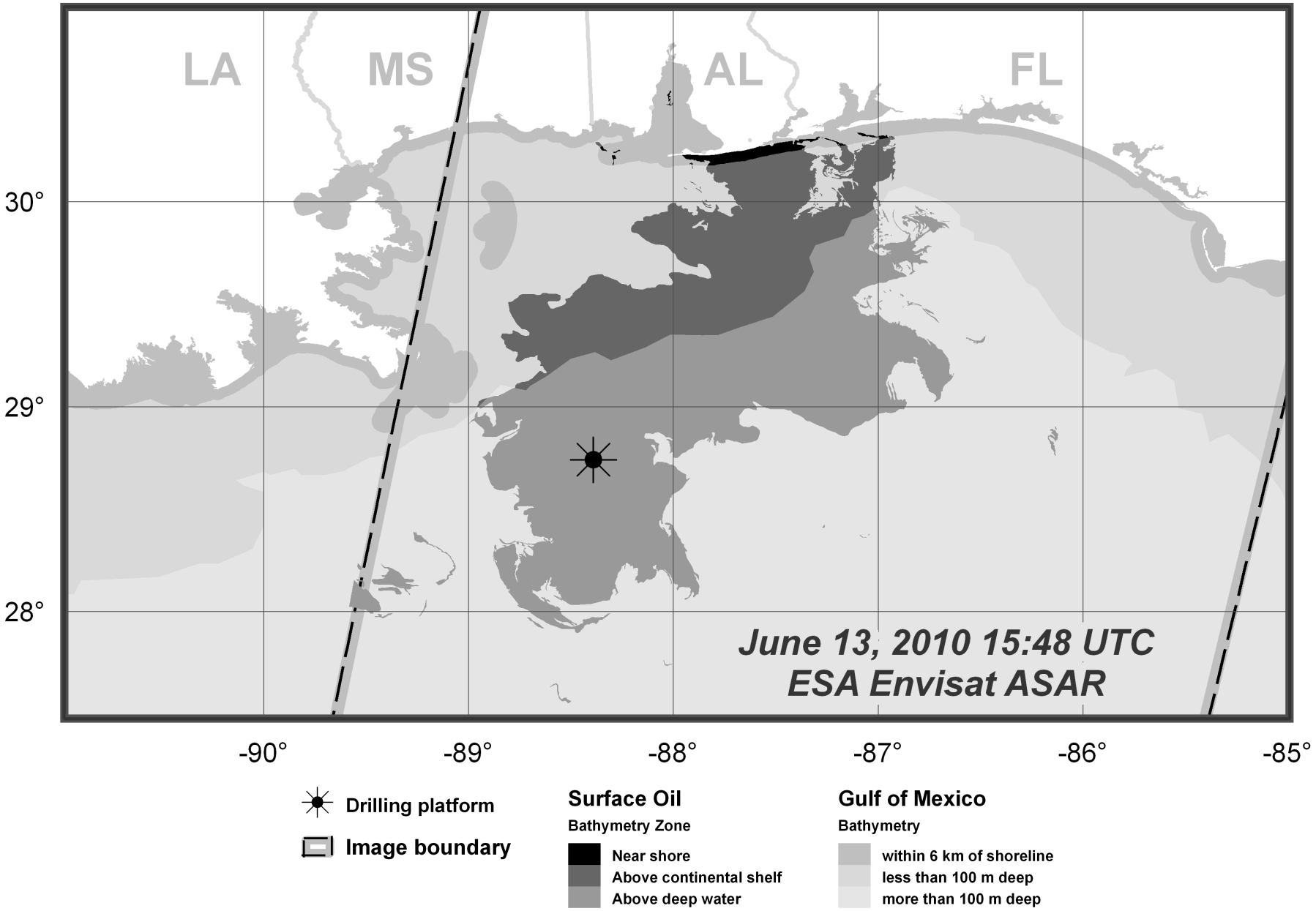
- NESDIS consolidated observations from a suite of satellite sensors

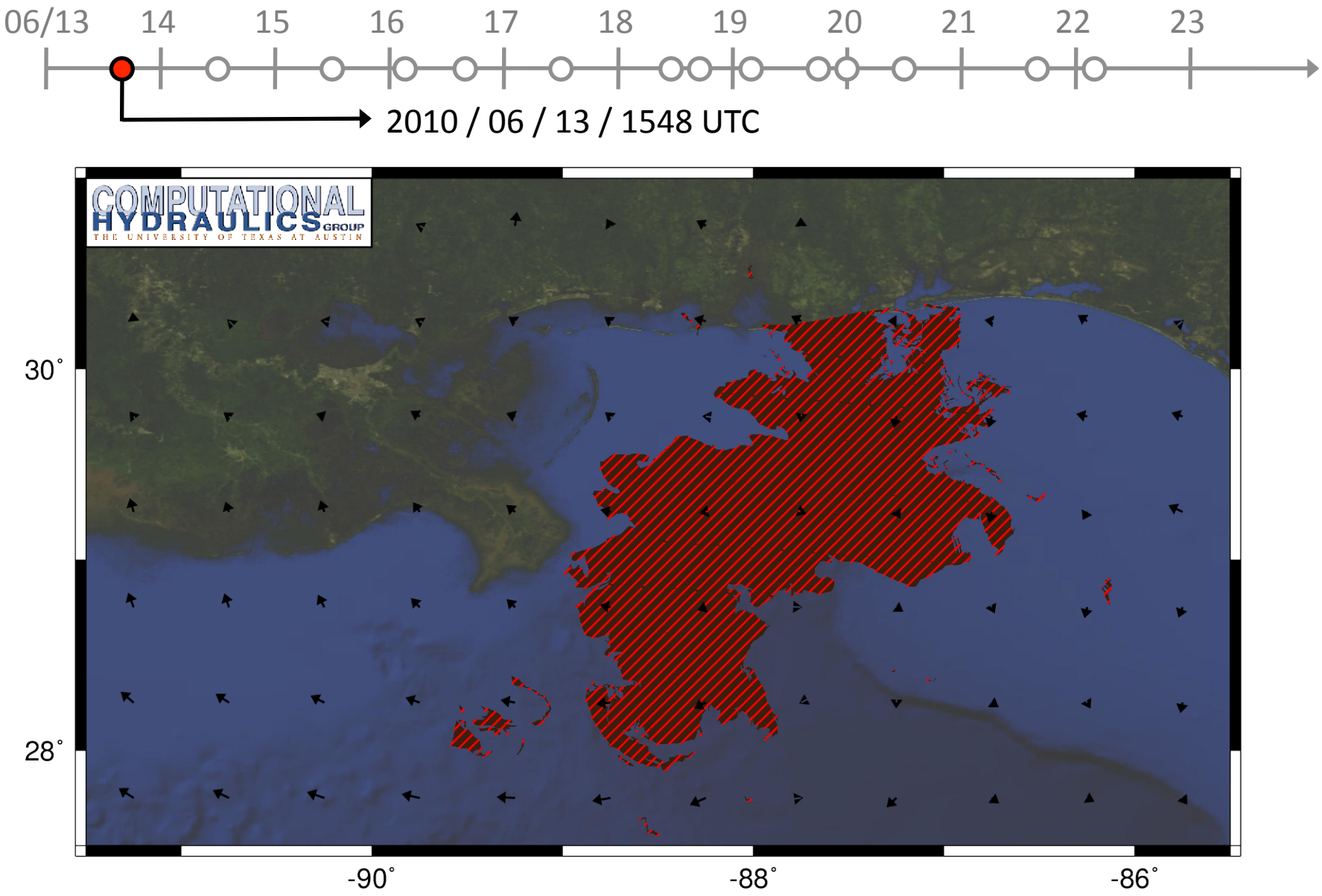


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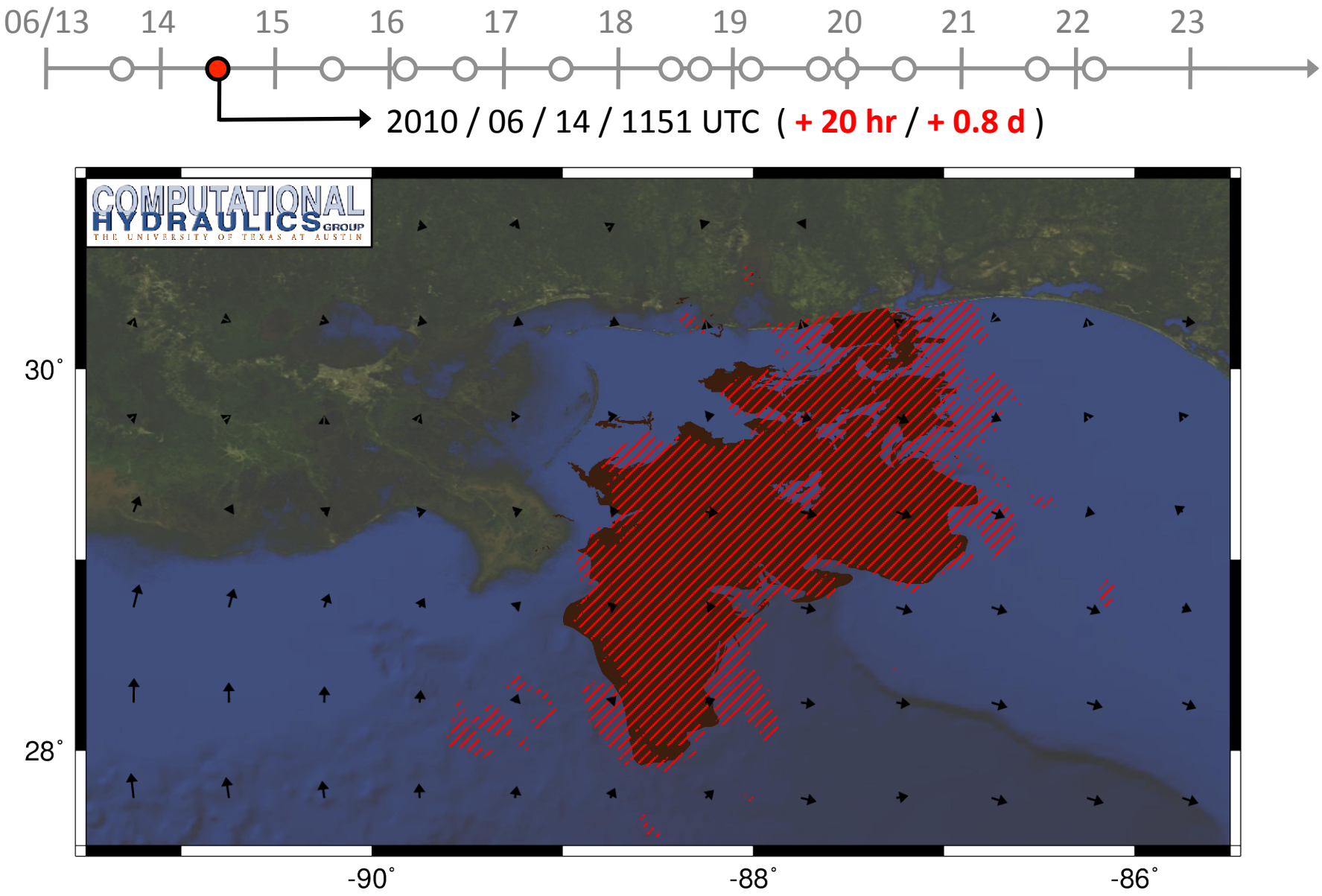


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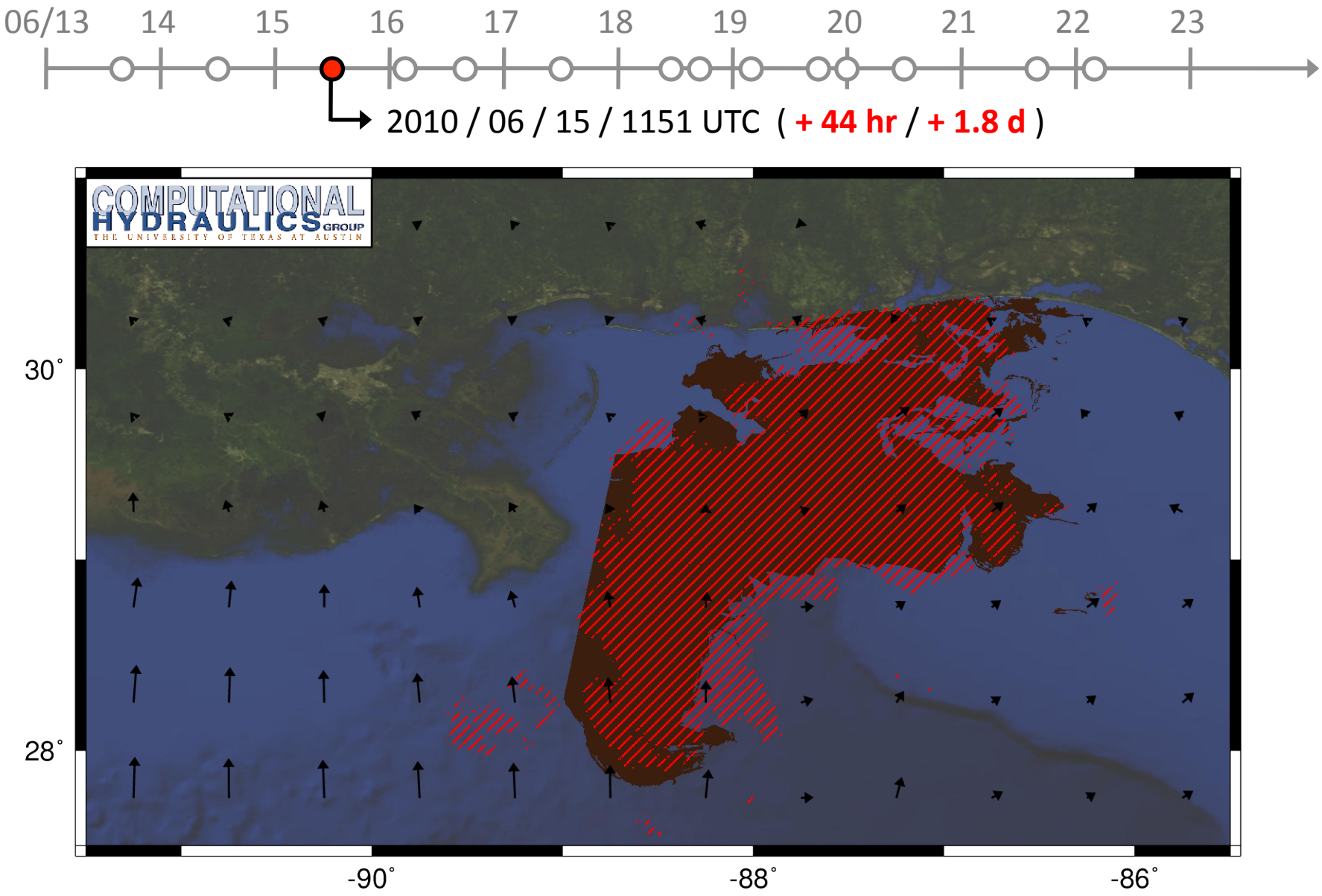




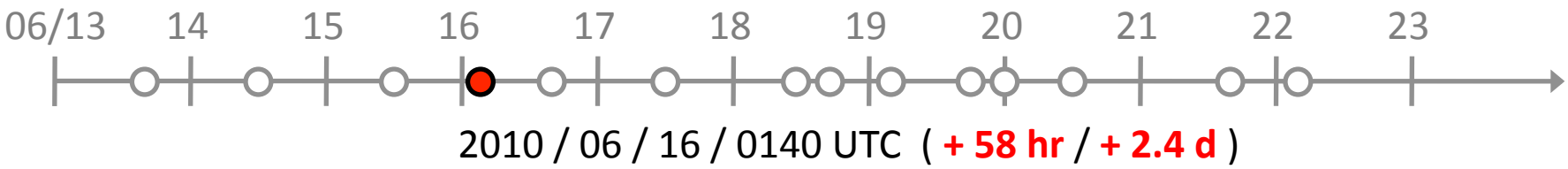
Satellite Observations **Predicted Particle Locations**



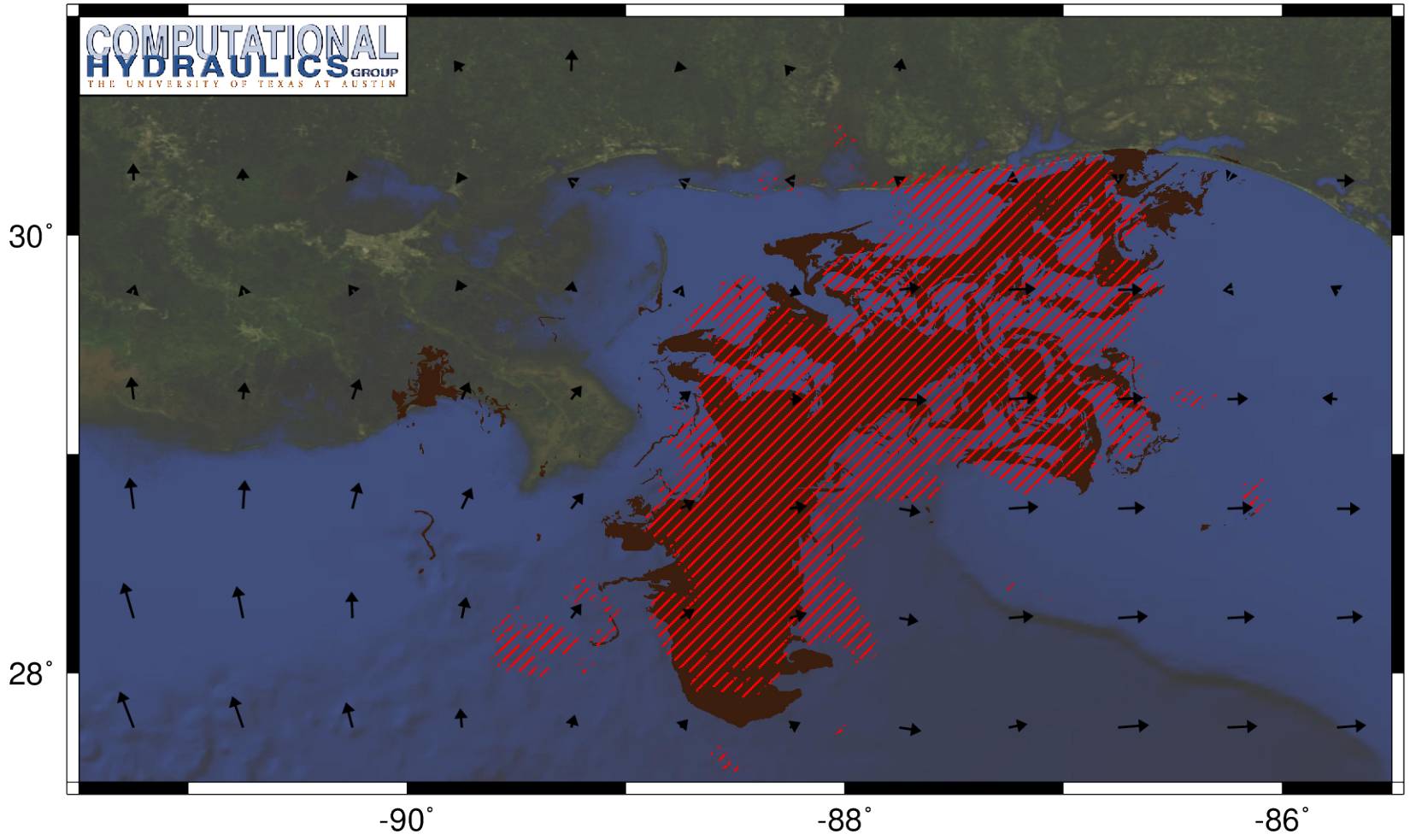
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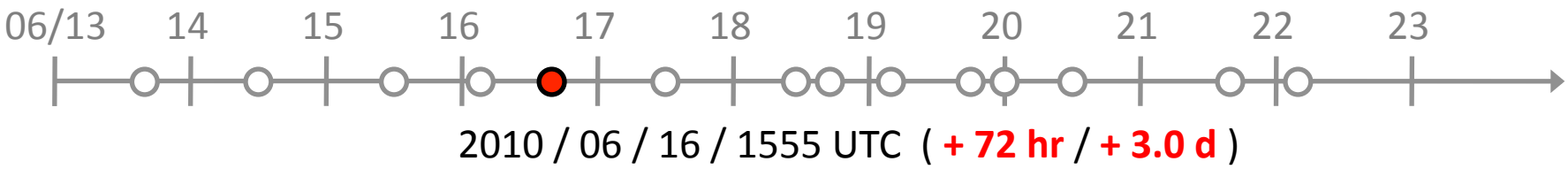
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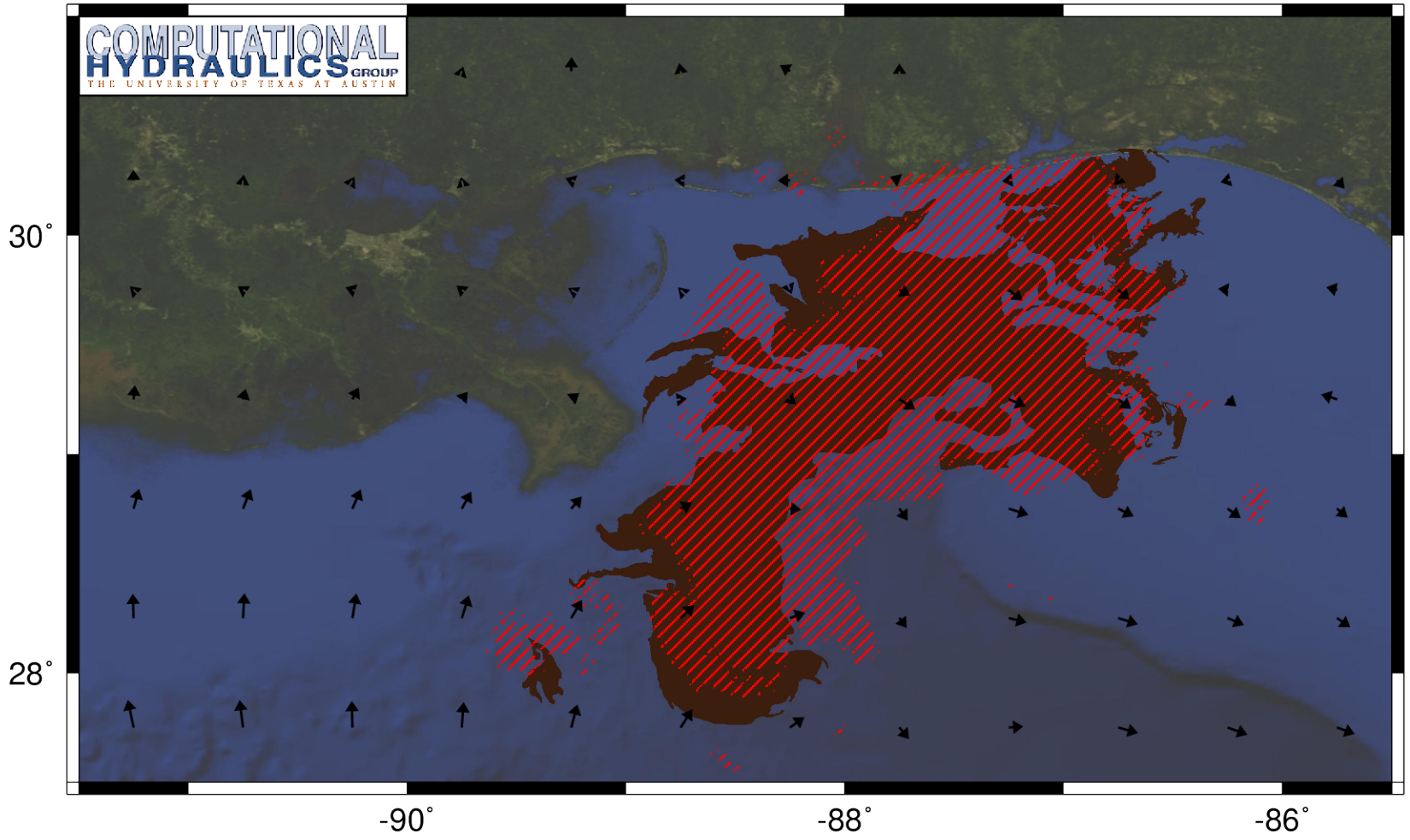
2010 / 06 / 16 / 0140 UTC (**+ 58 hr** / **+ 2.4 d**)



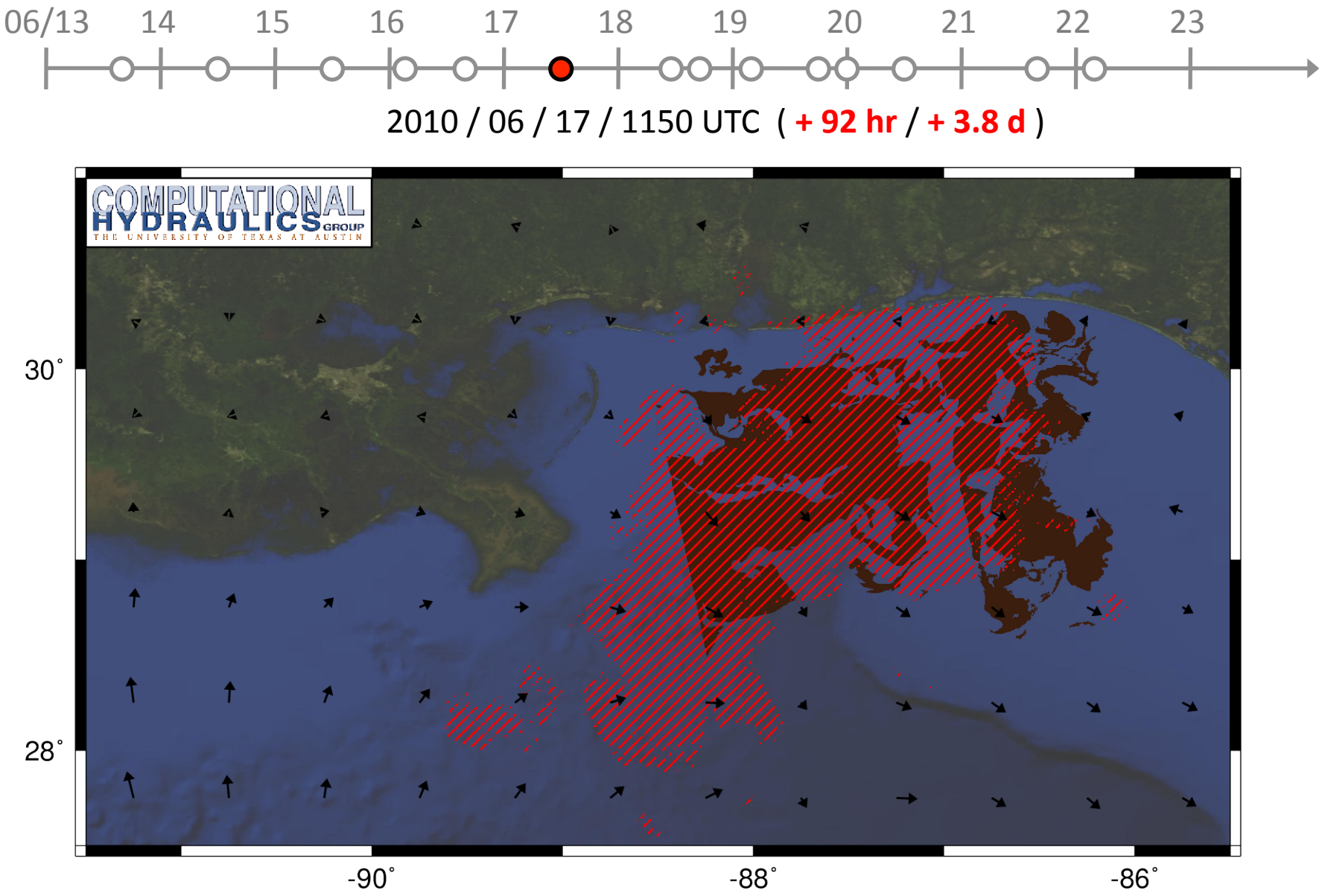
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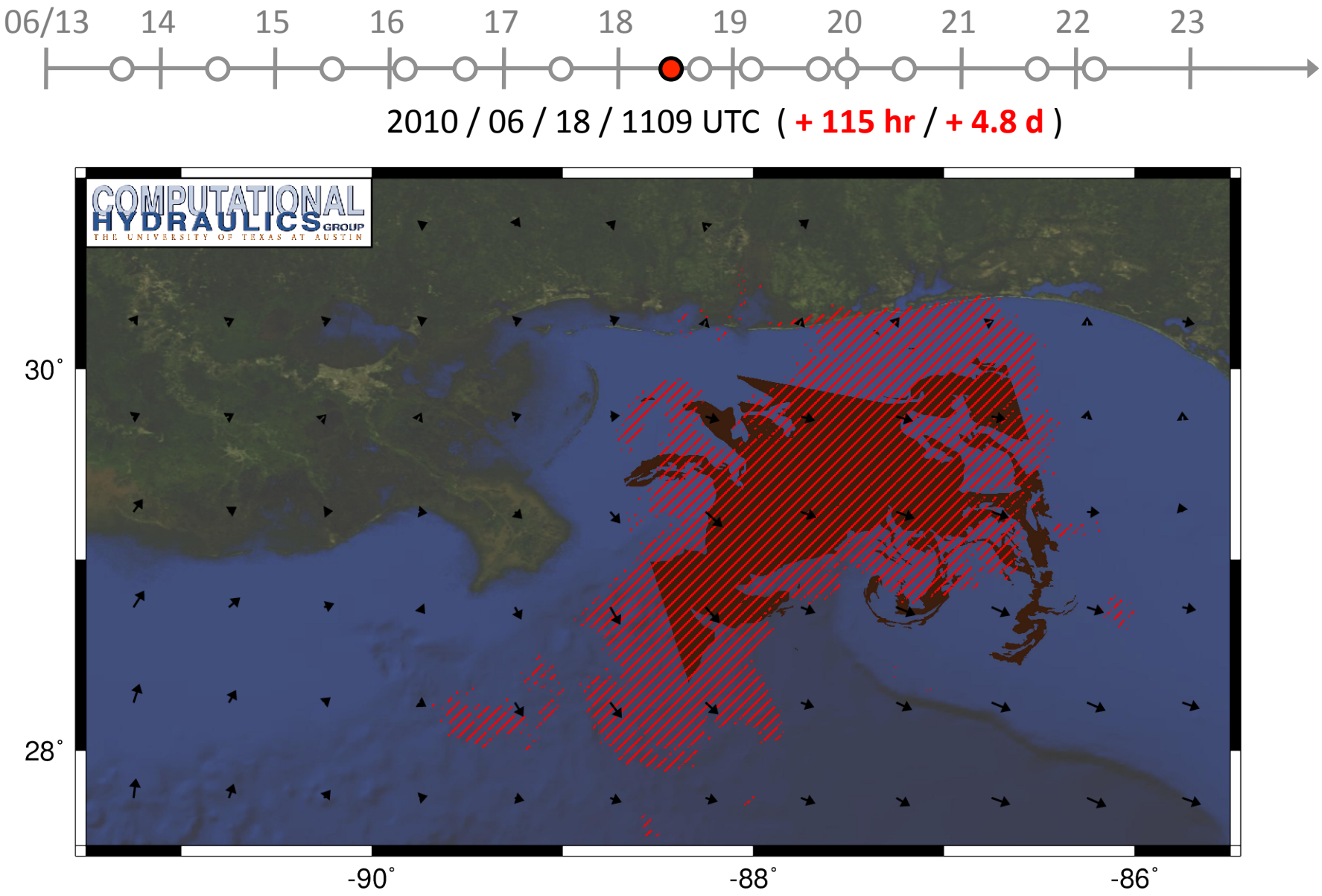
2010 / 06 / 16 / 1555 UTC (**+ 72 hr** / **+ 3.0 d**)



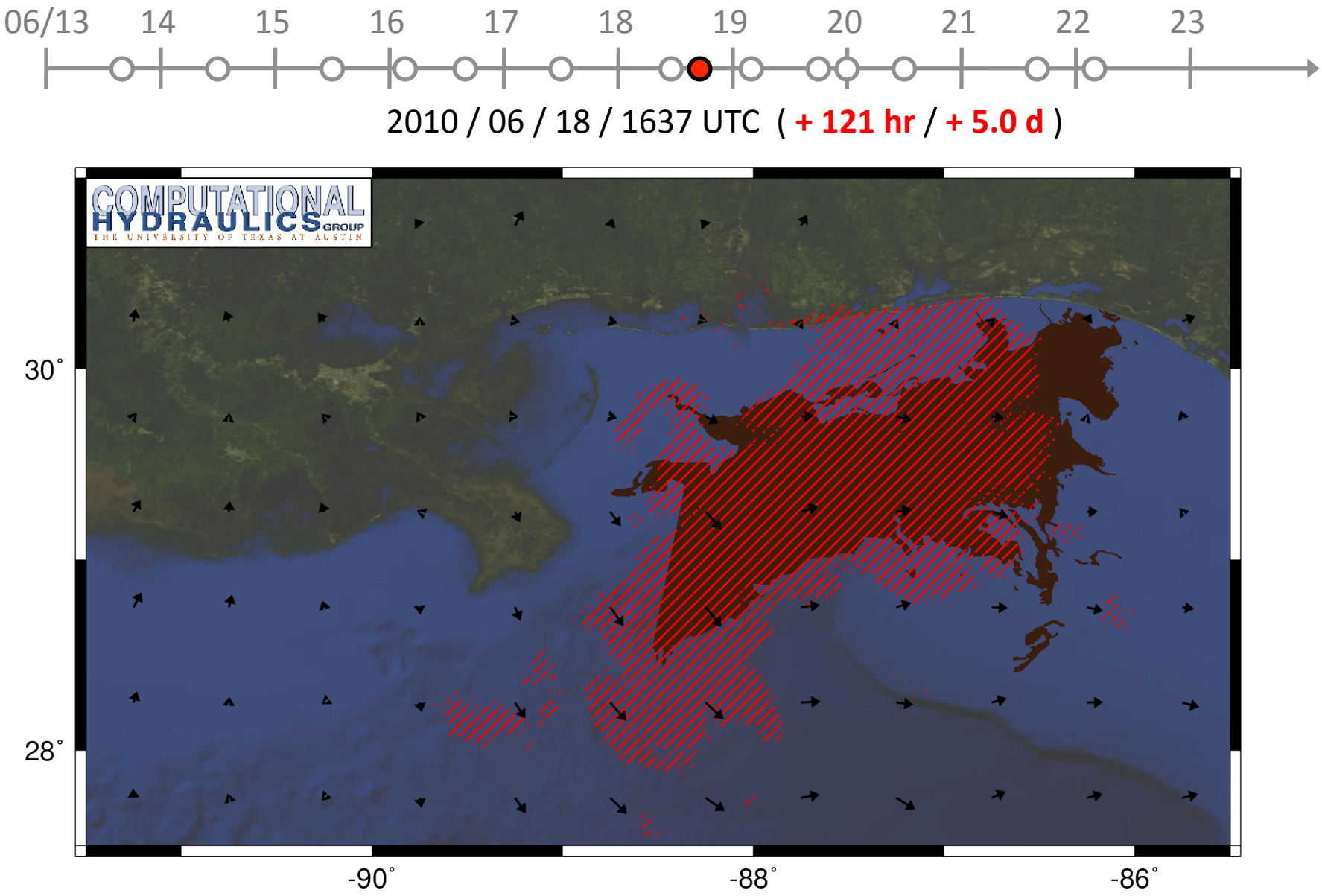
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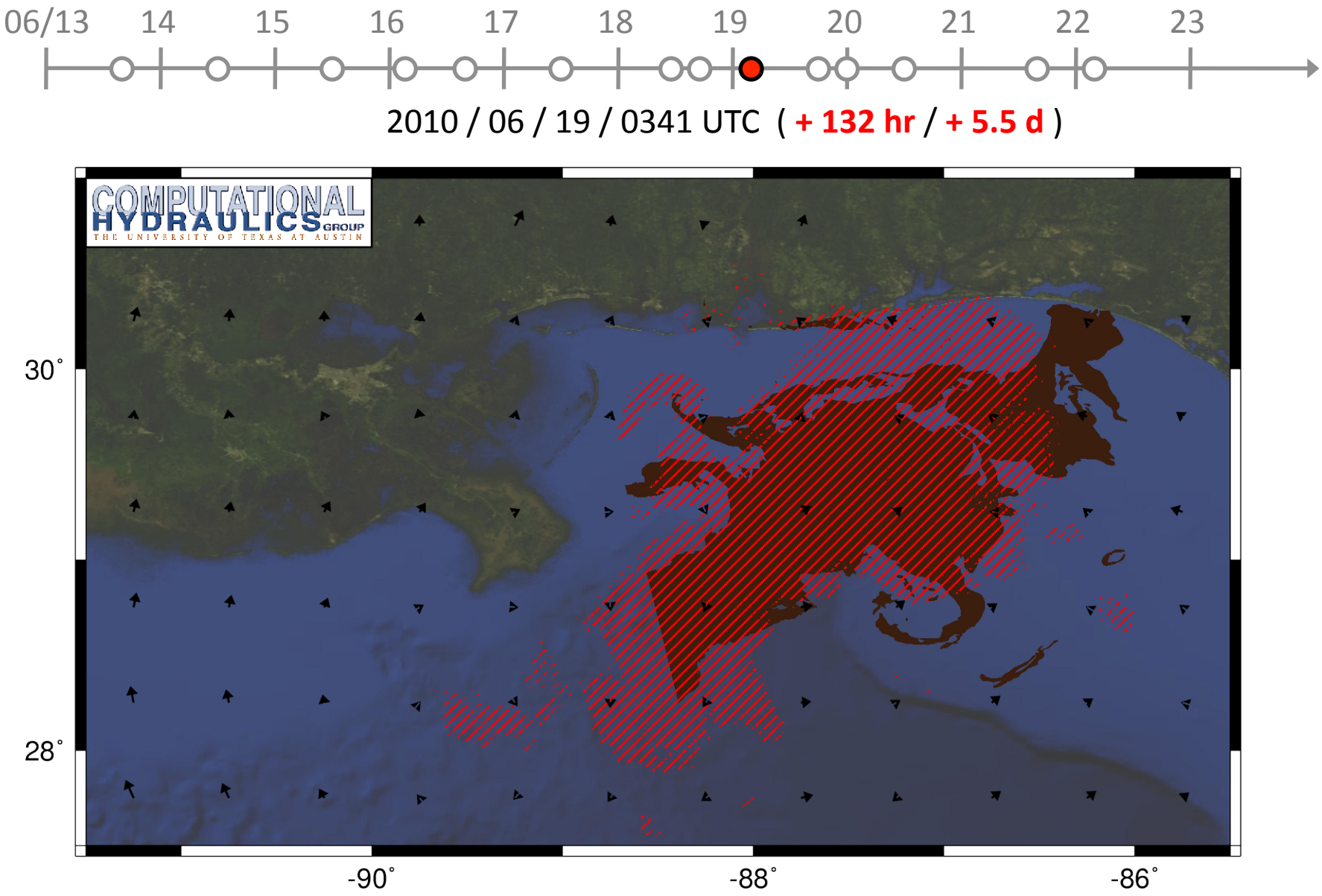
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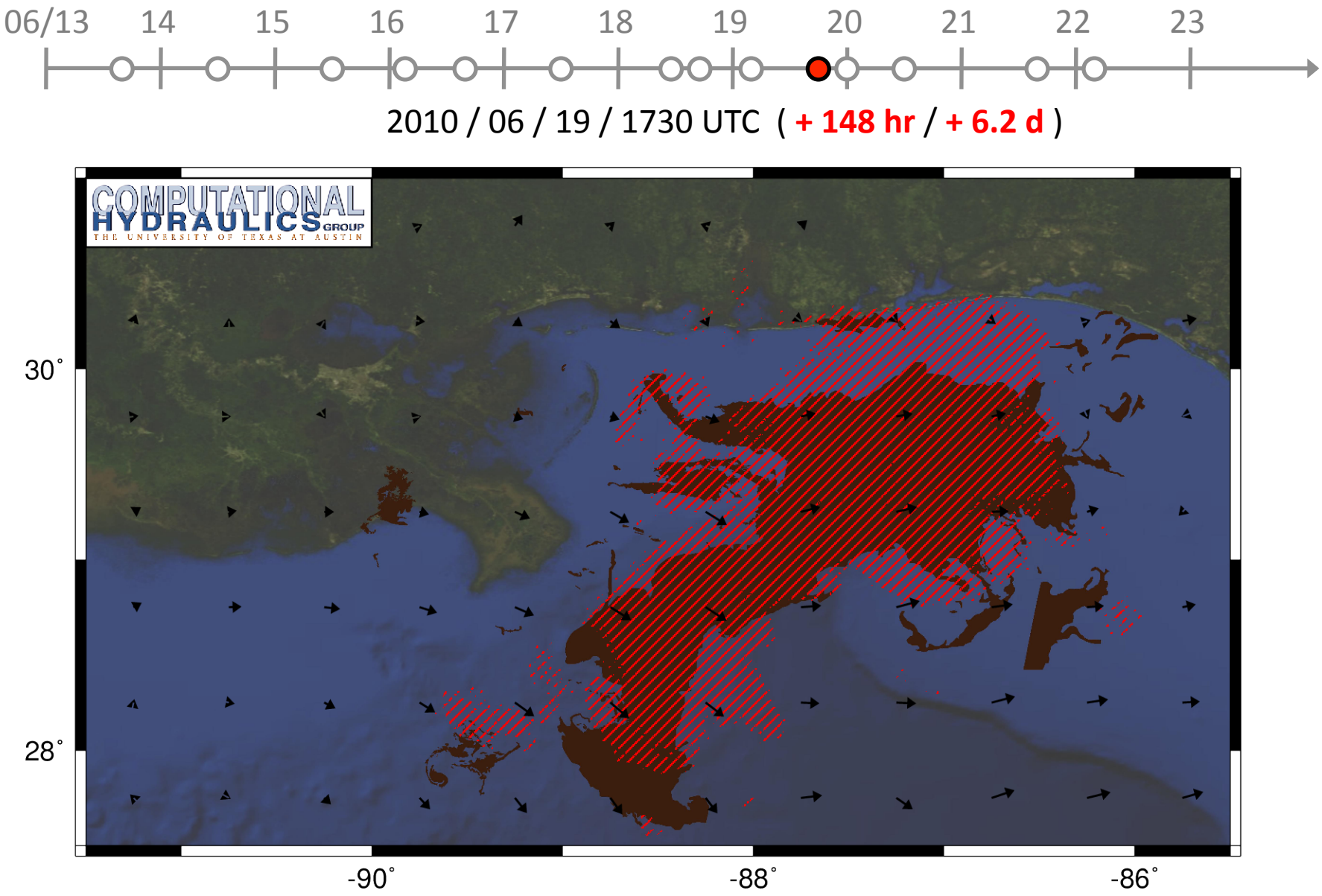
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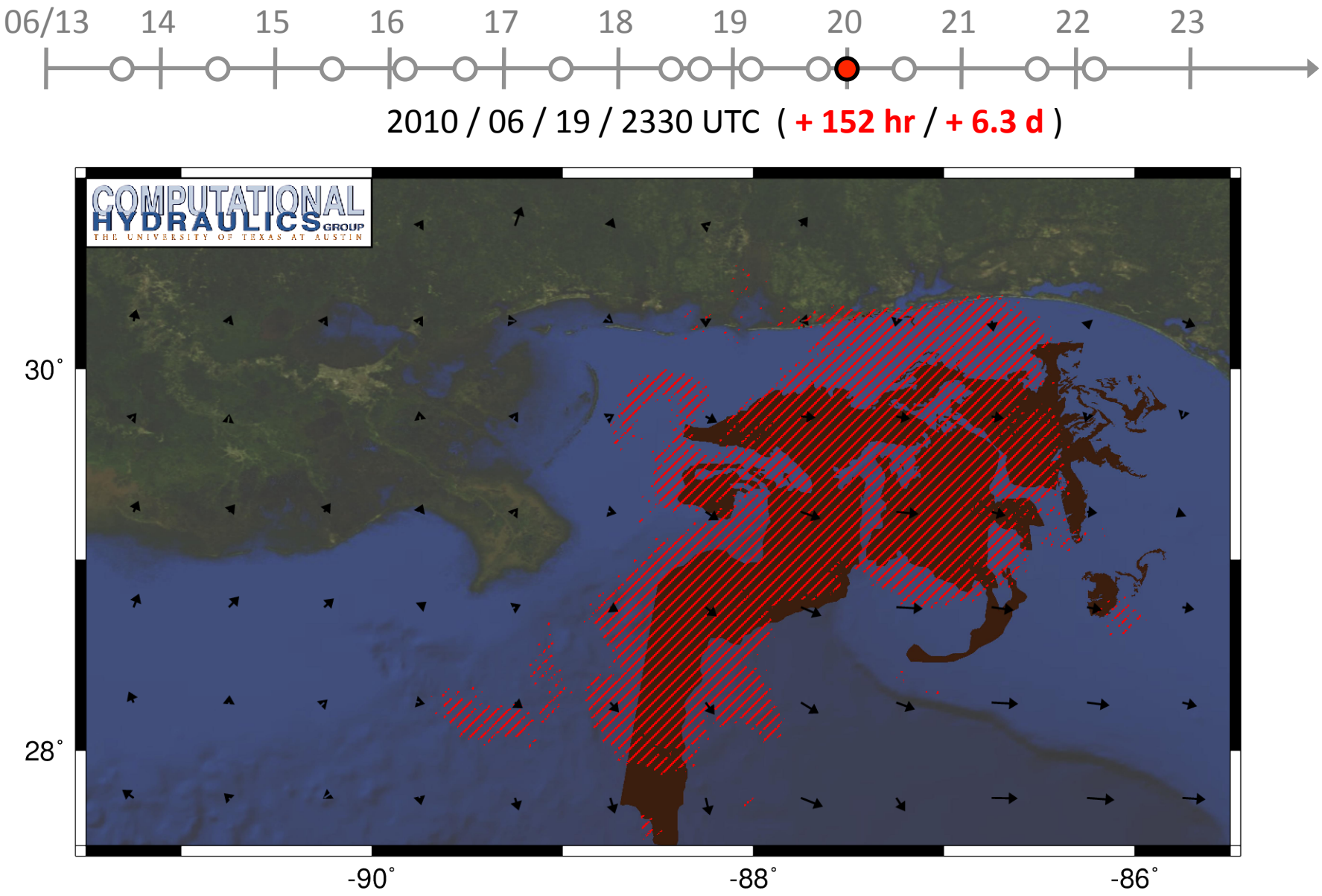
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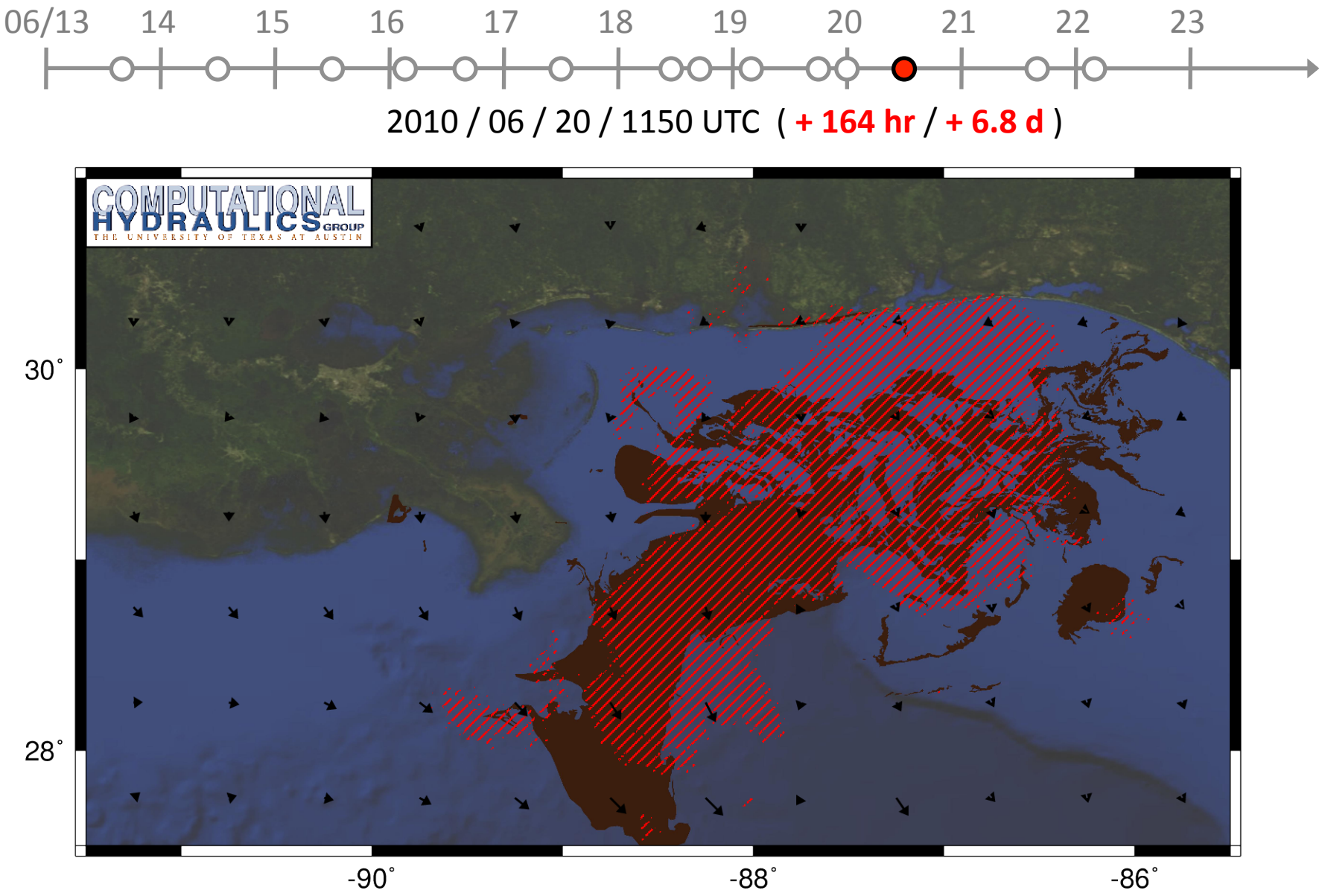
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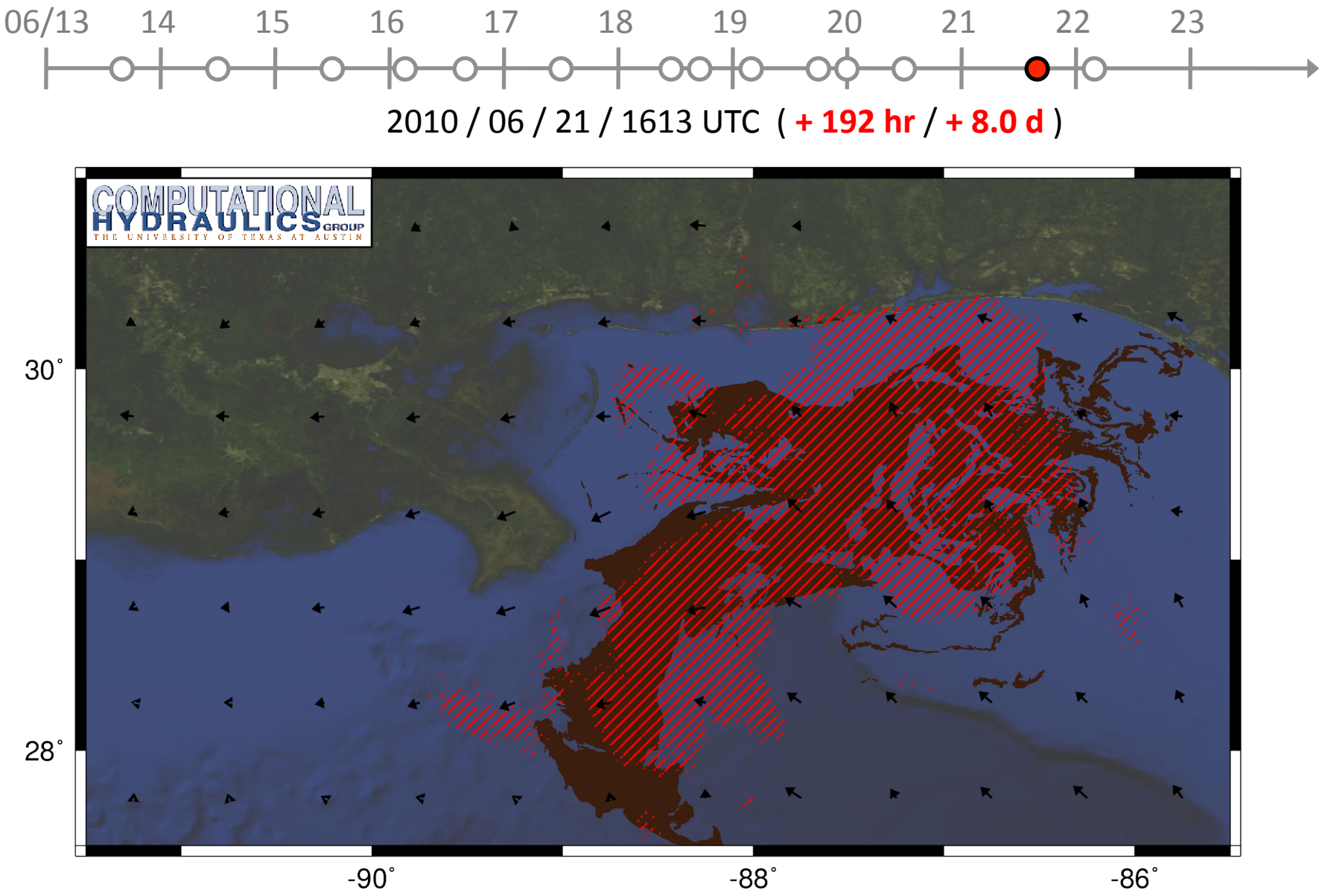
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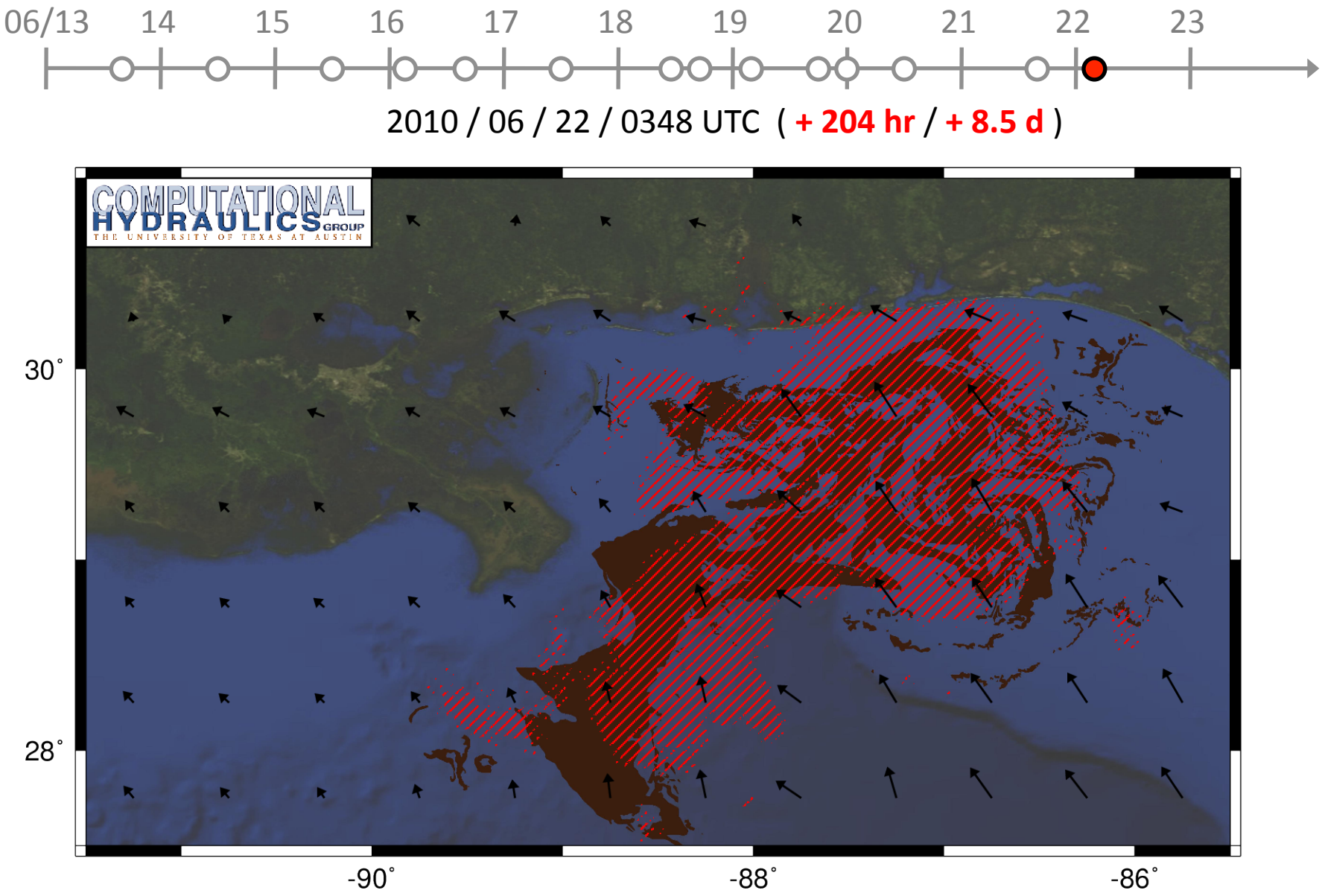
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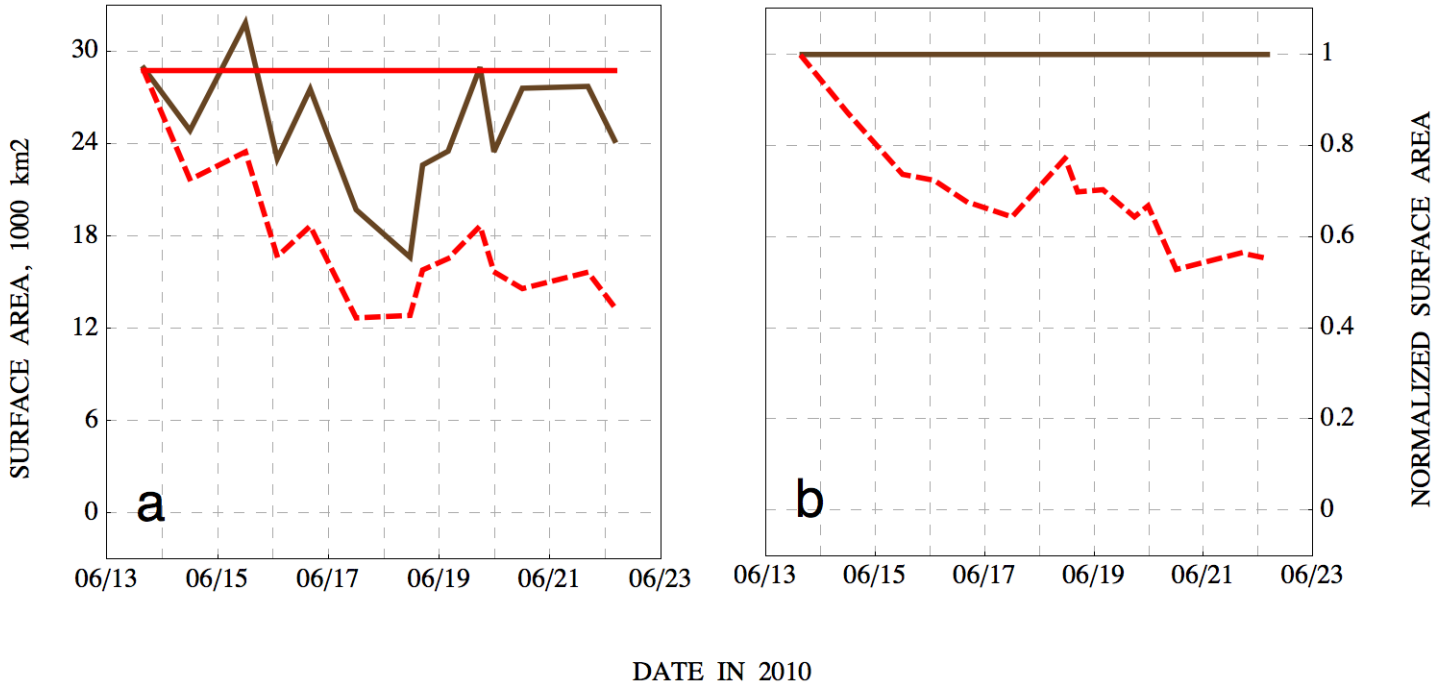


Satellite Observations **Predicted Particle Locations**



Satellite Observations **Predicted Particle Locations**

Validation : Mid-June : Computed Overlap



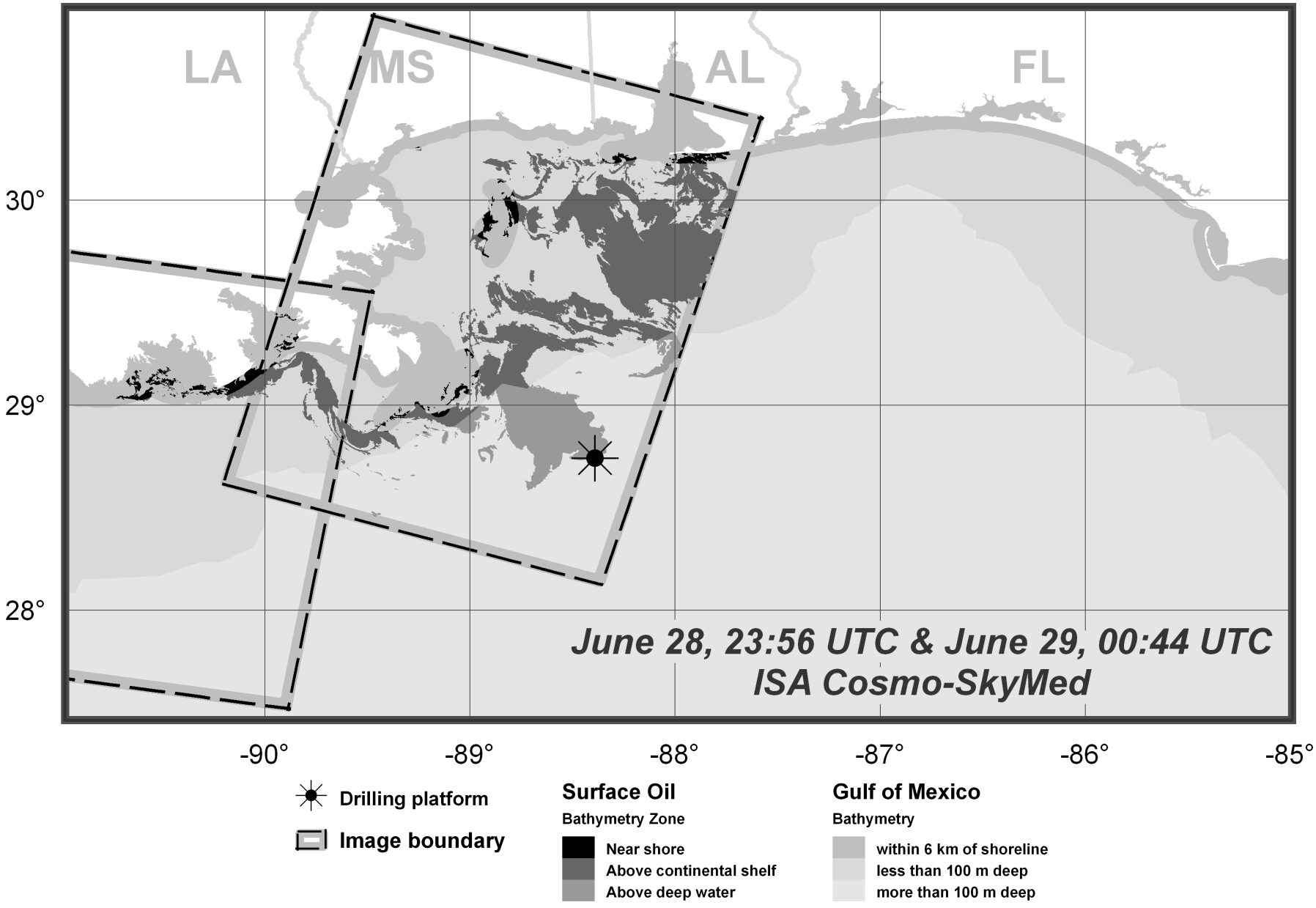
Overlap of our predictions to observations:

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

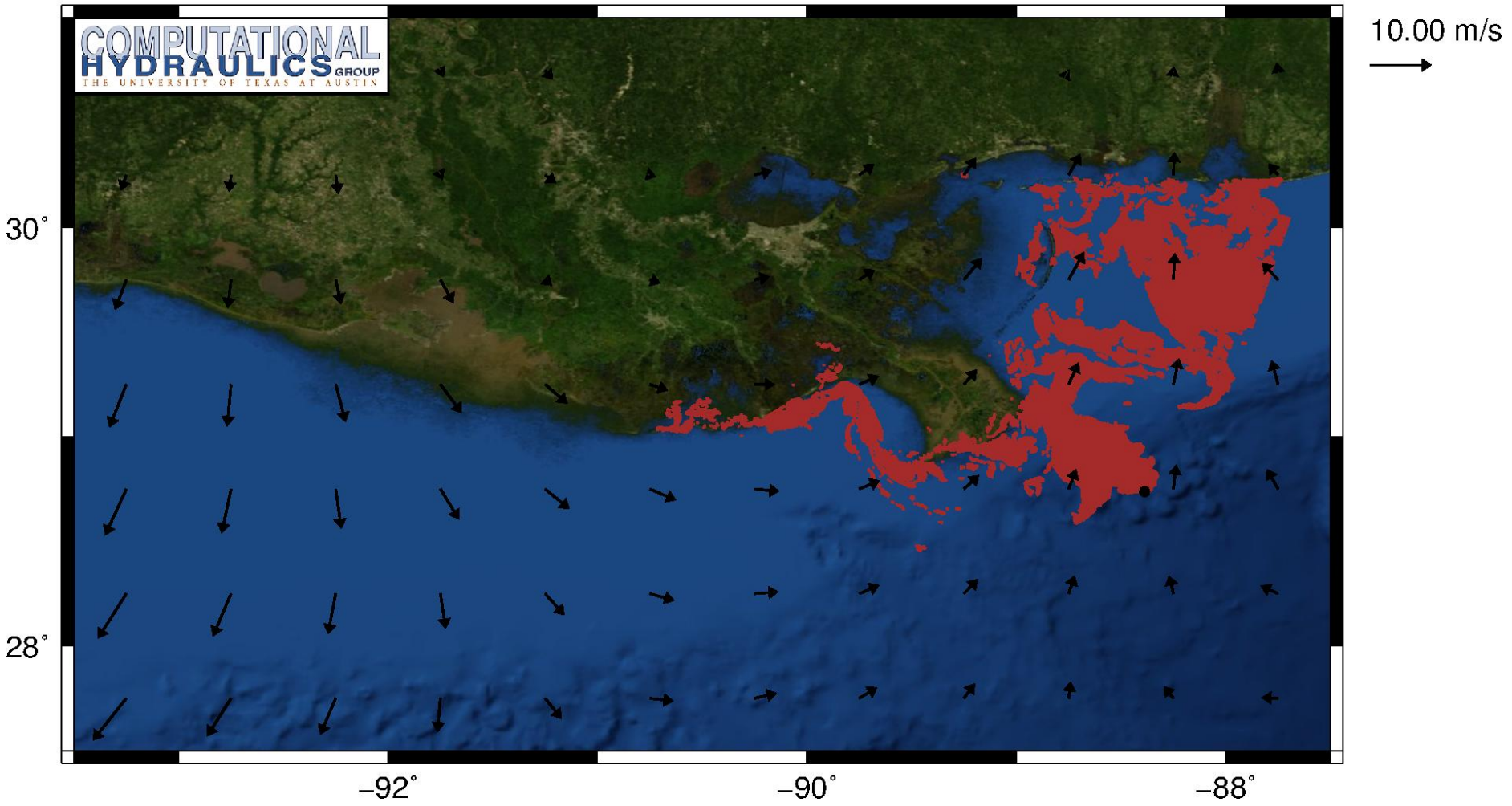
After one week of simulation, overlap is about 60 percent

- Good qualitative and quantitative match to observations

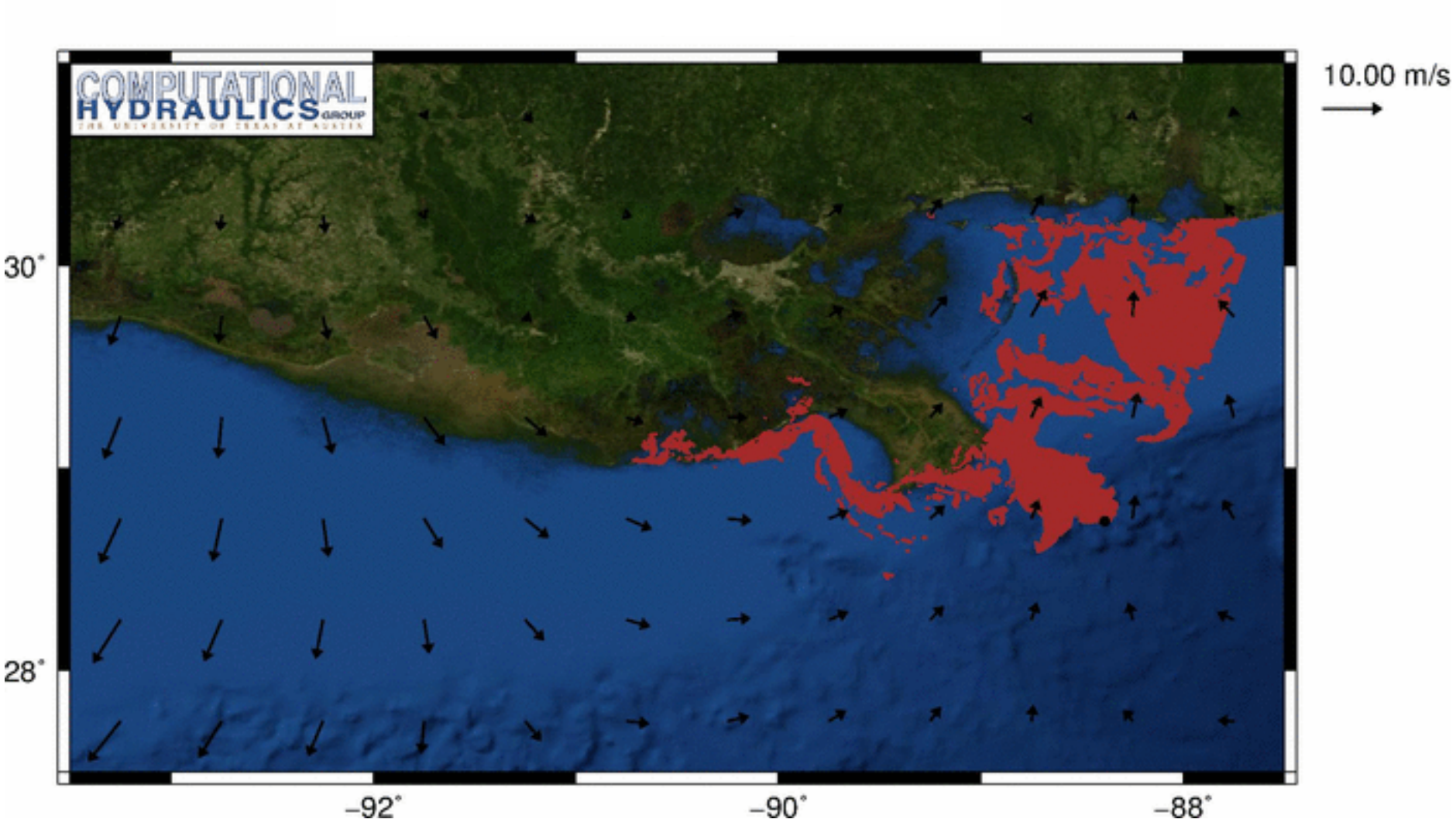
Hypothetical Oil Transport : Hurricane Ike (2008)



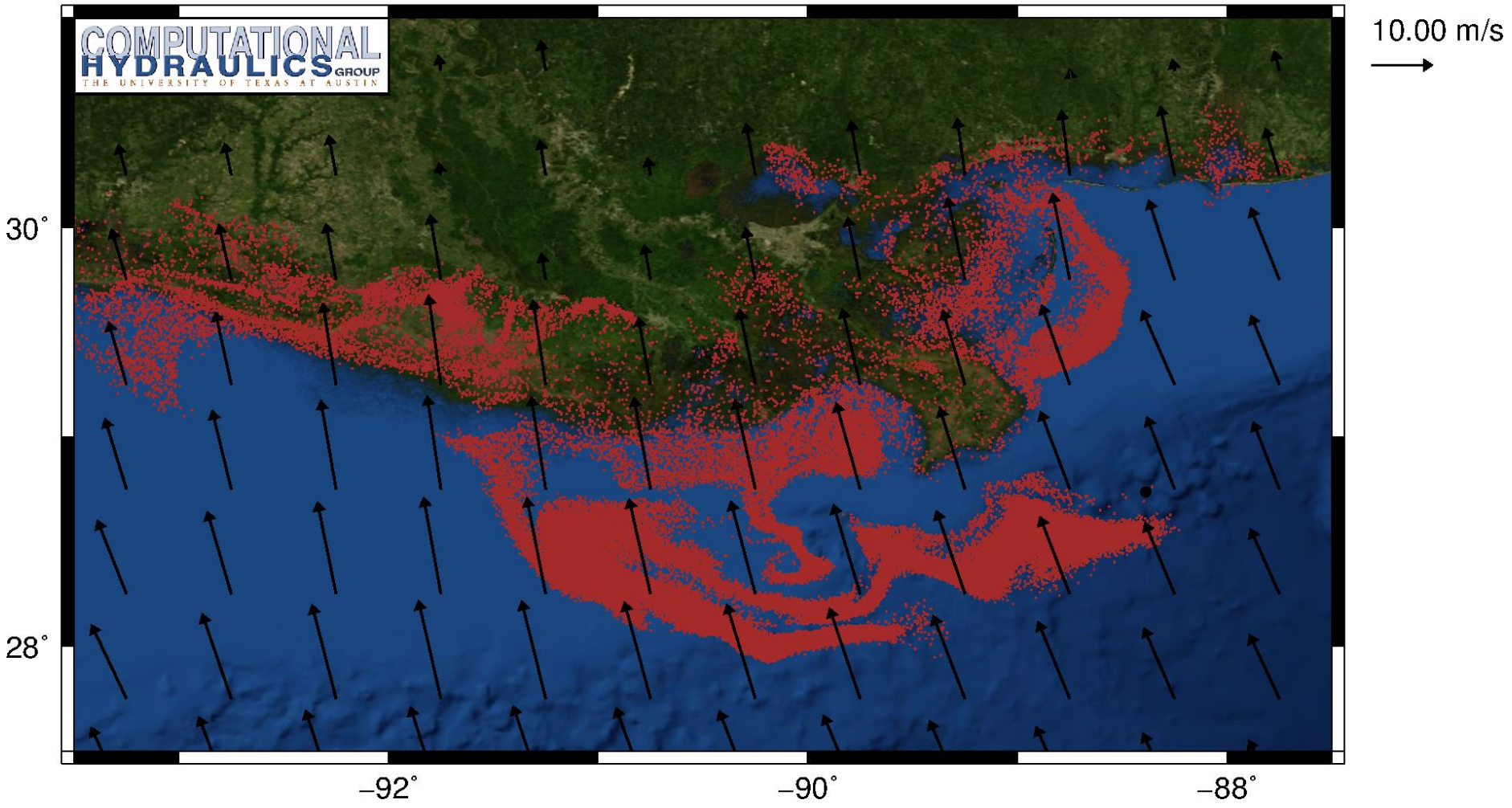
Hypothetical Oil Transport : Hurricane Ike (2008)



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Hypothetical Oil Transport : Hurricane Ike (2008)



Conclusions

Automated system runs successfully in real-time

Good match to overall movement of oil spill

- Some small-scale features are modeled successfully

Validation is highly sensitive to quality of overhead imagery

Oil would have been influenced heavily by a hurricane in the region

- Movement into marshes of southern Louisiana
- Movement along the coastline toward Texas

