Toward the Transport of Oil from Sea Floor to Beaches as Driven by the 3D Baroclinic ADCIRC

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CARTHE All-Hands Meeting
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Outline

Initial response was built into the ADCIRC Surge Guidance System (ASGS)

- Used operational, 2D, barotropic version of ADCIRC
- Considered surface transport of oil as 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
    $\vec{c} = 12$ are scaling coefficients

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

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

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

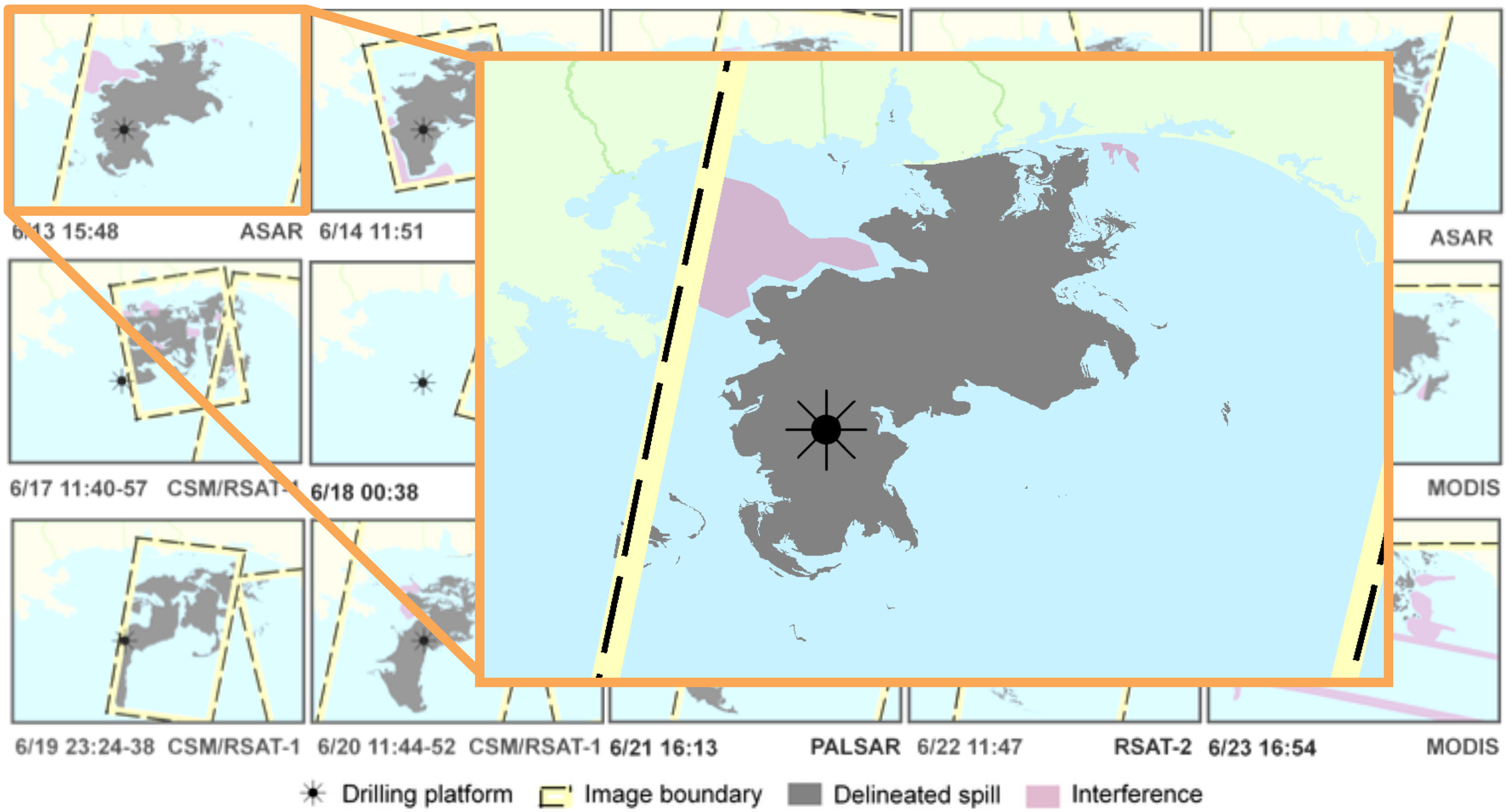
Surface Oil Transport : 13-23 June 2010

Initialize particle locations from observations in satellite imagery

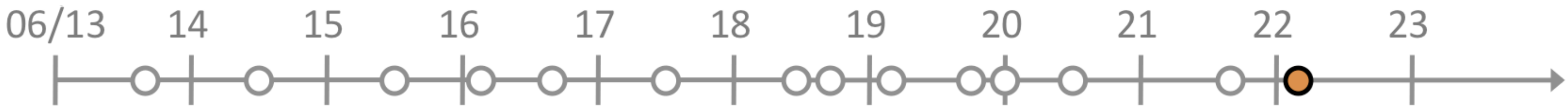
- Digitize daily analysis of slick extents into millions of particles

Examples of available imagery from suite of sensors during mid-June

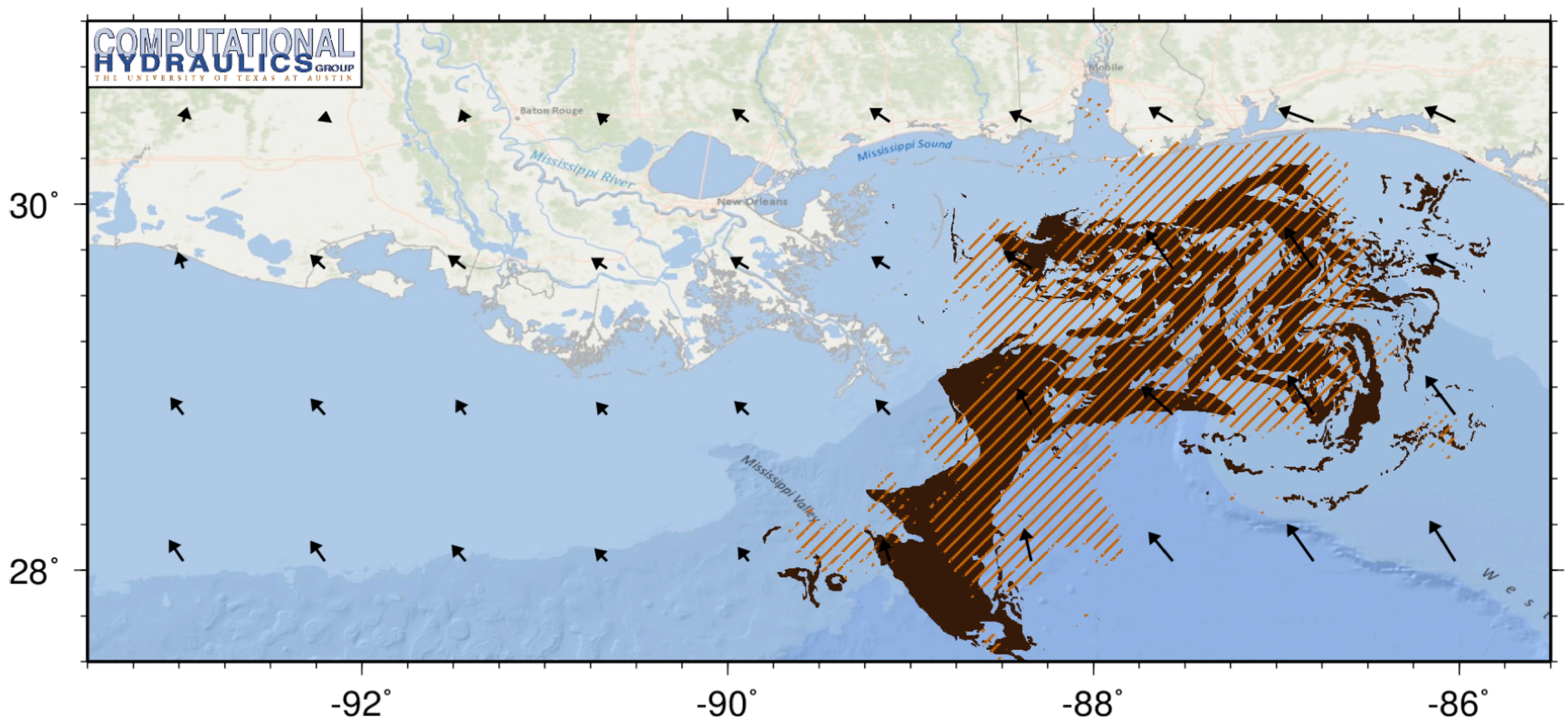
- Uncertainties due to satellite coverage, interference



Surface Oil Transport : 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.

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Can we transport the oil particles from the sea floor to the beaches?

- For currents, need to consider 3D flow due to density gradients
- For oil transport, need source term, buoyancy effects, dispersion, sink terms

First attempt with the **HYbrid Coordinate Ocean Model (HYCOM)**

- Connect with existing expertise in CARTHE
- NRL operates a high-resolution forecast system for the Gulf
  - Horizontal resolution of 1/25° (about 3.5km) with 20 vertical surfaces
  - Data assimilation using Navy Coupled Ocean Data Assimilation (NCODA)
    - Satellite altimeter observations
    - Satellite and in situ sea surface temperatures
    - In situ vertical temperature and salinity profiles
  - Model results are available for download from hycom.org
    - Hourly output containing temperature, salinity, 3D currents, etc.
    - Output at standard Levitus depths (so fixed vertical layers in output)
- Use HYCOM model results as forcing to our oil transport

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

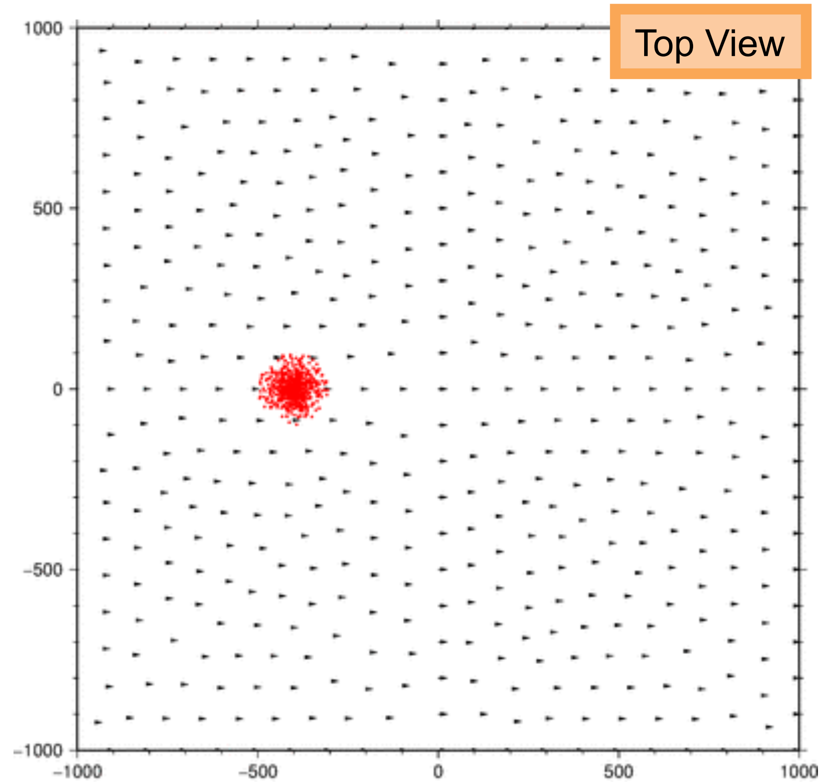
Submerged Ridge Test Case:

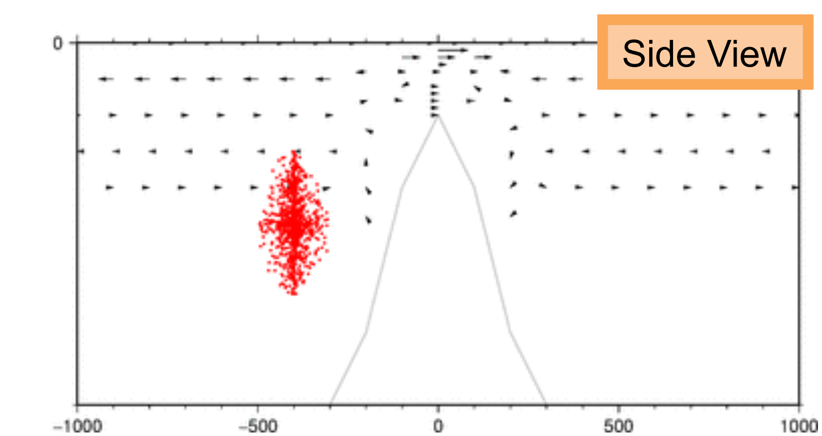
Simple test case to show particle movement

- 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:

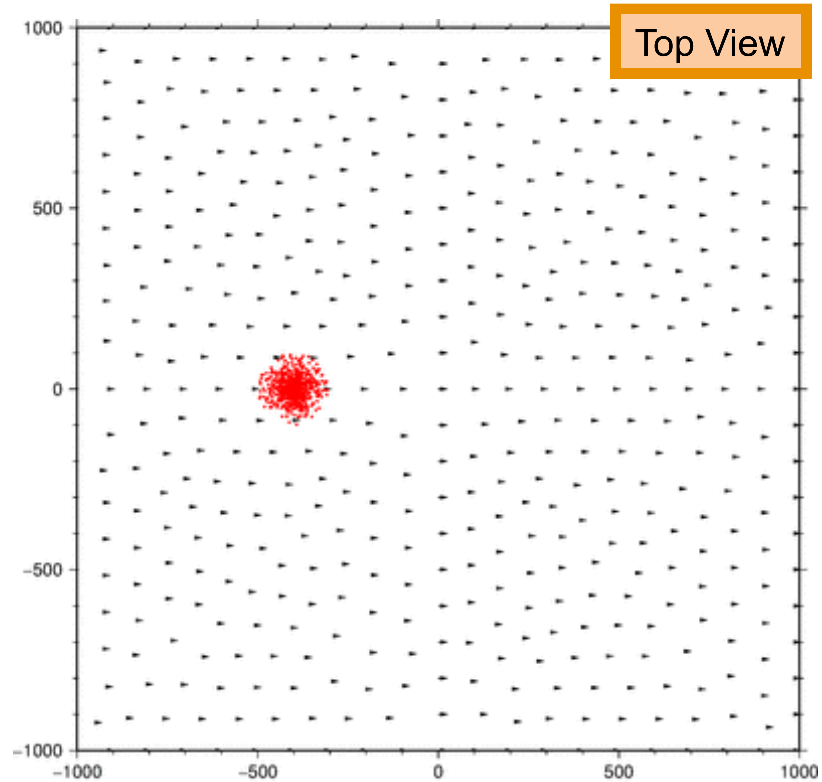
- Spherical droplets (small)
- Ellipsoidal droplets (intermediate)
- Spherical-cap droplets (large)

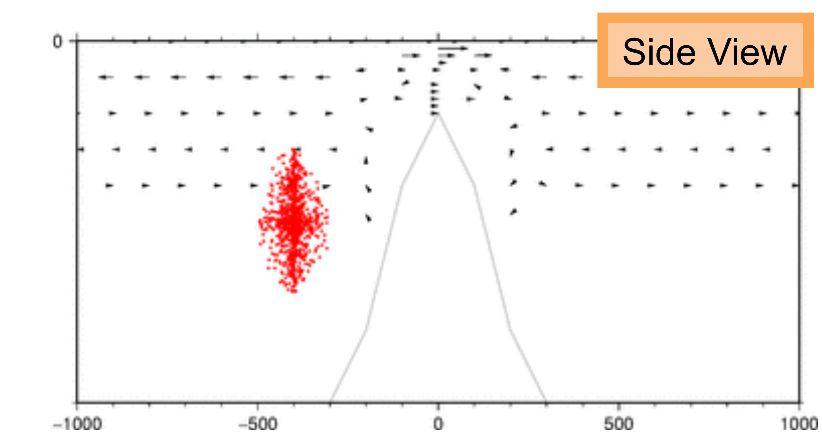
Oil droplets will always fall in spherical class:

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

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:

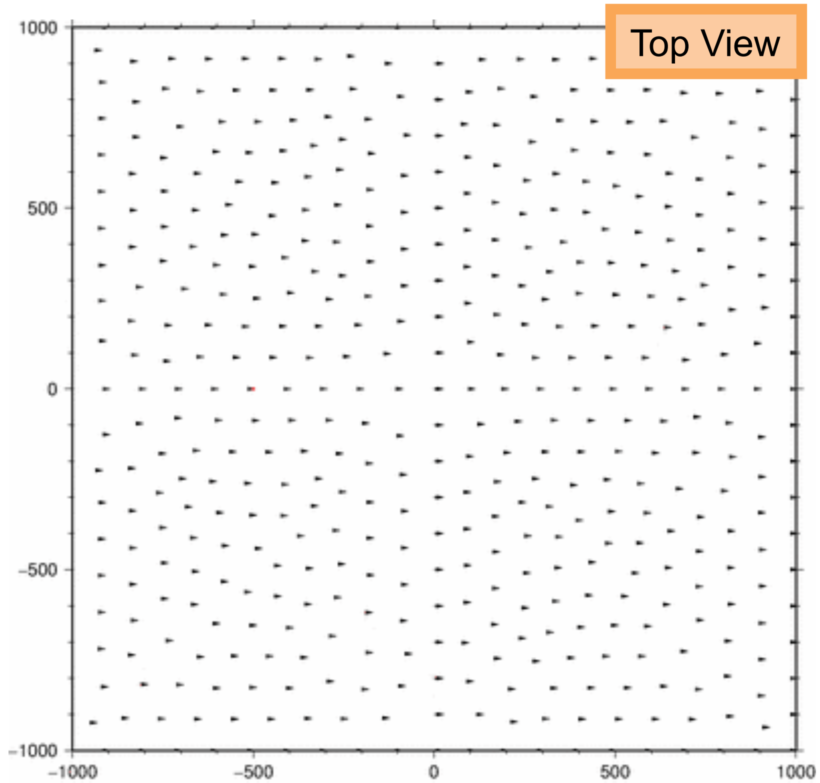
Instead of initializing the particles in a cloud, they are introduced at a source located at (0, -500, -100)m

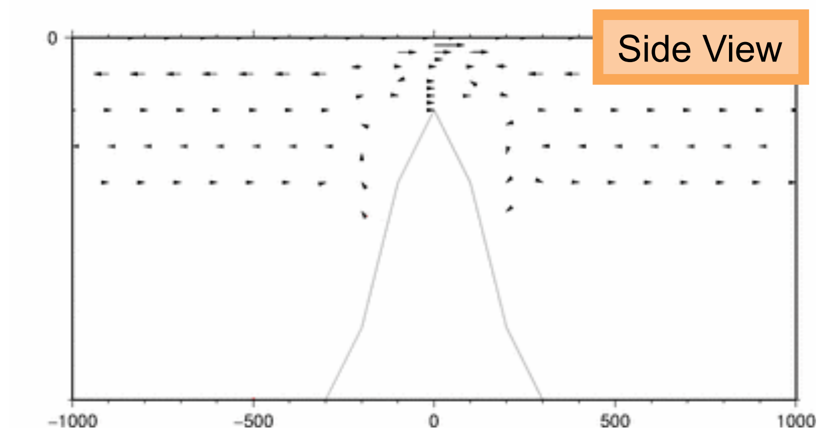
Assumptions:

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

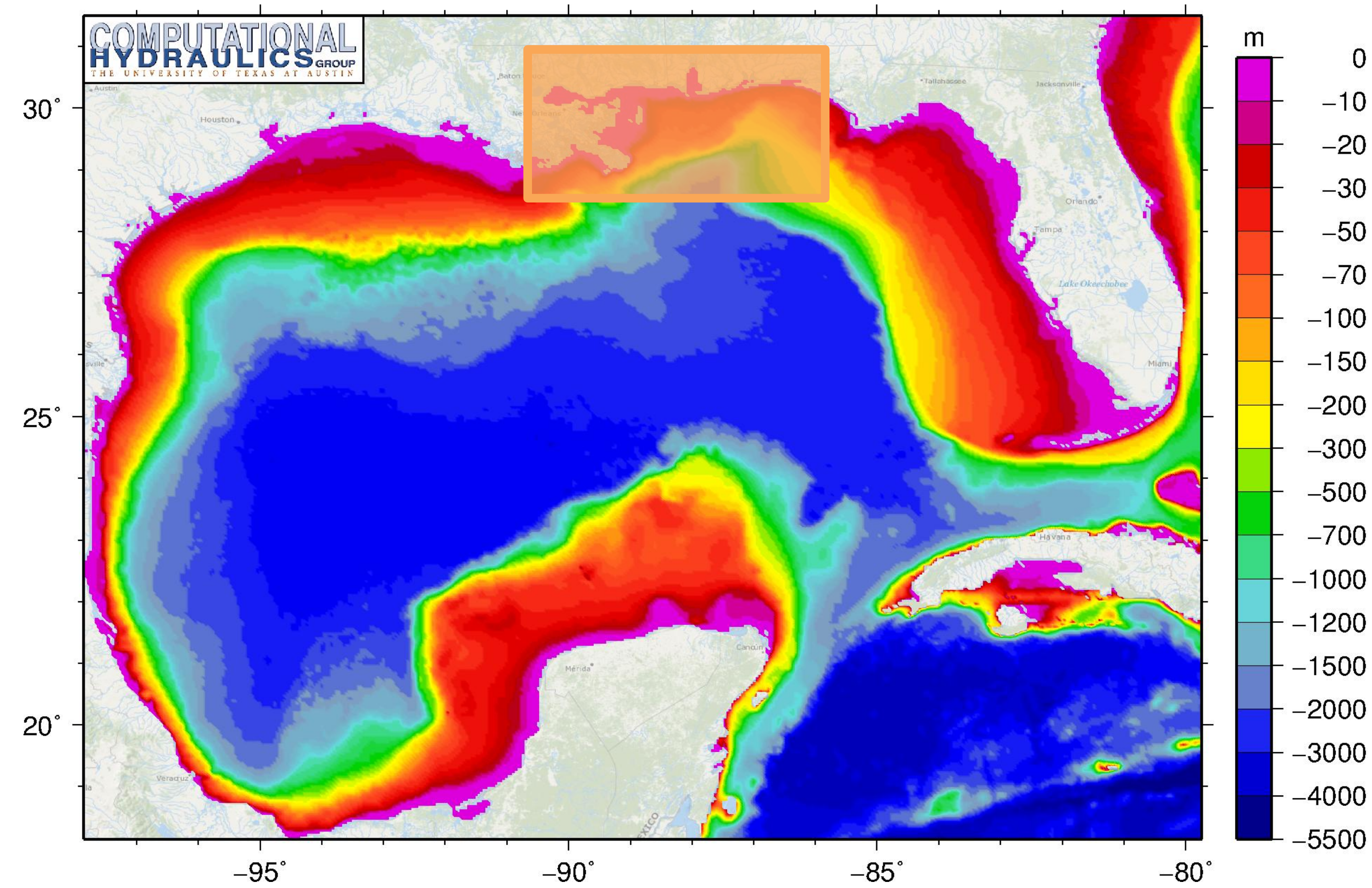




HYCOM+NCODA Gulf of Mexico 1/25° Analysis : Bathymetry

High-resolution HYCOM simulation with 20 vertical surfaces of varying depths

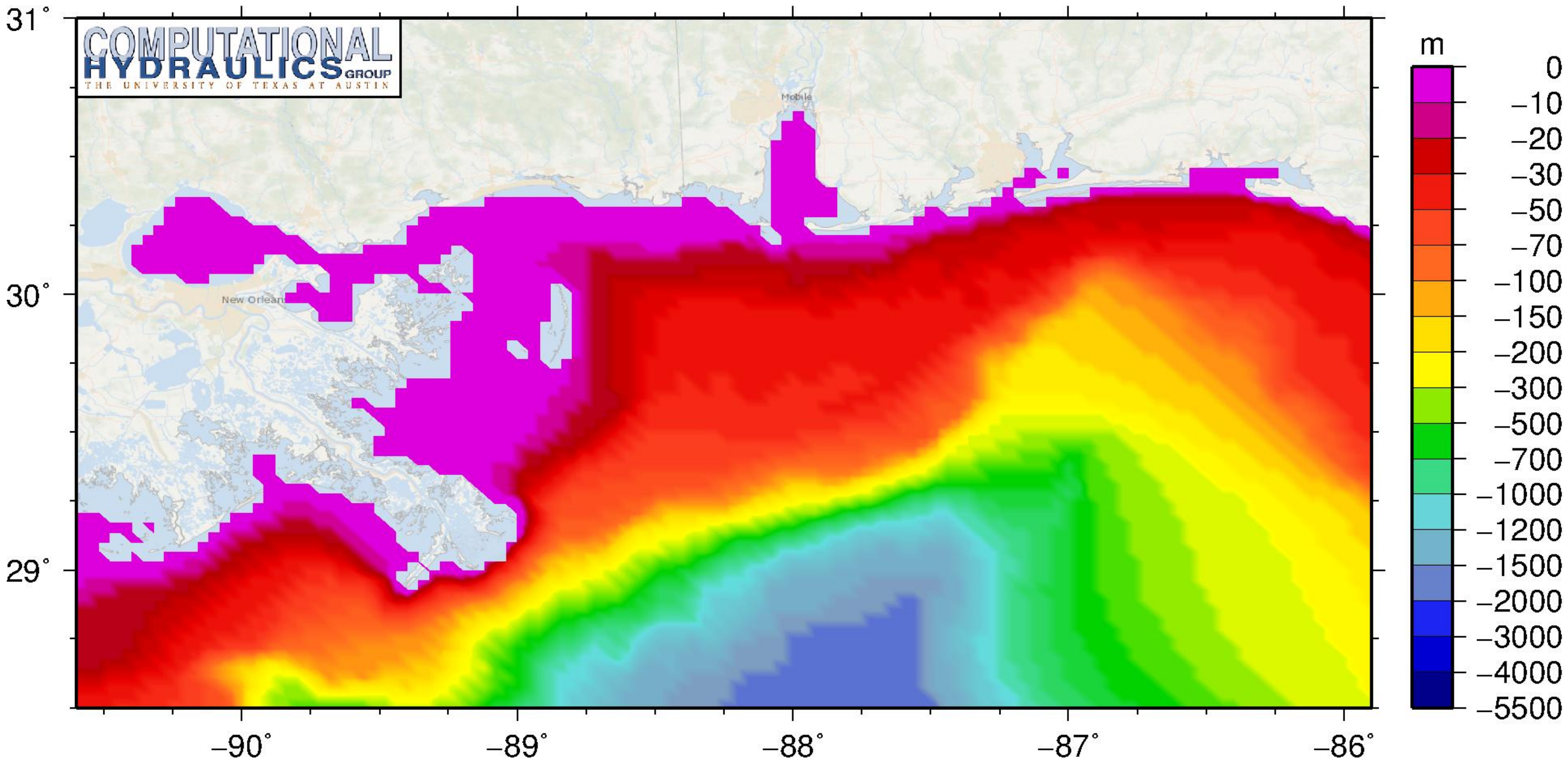
- However, model output is archived at 40 constant depths



HYCOM+NCODA Gulf of Mexico 1/25° Analysis : Bathymetry

Horizontal resolution of 1/25° (about 3.5km) is constant throughout the domain

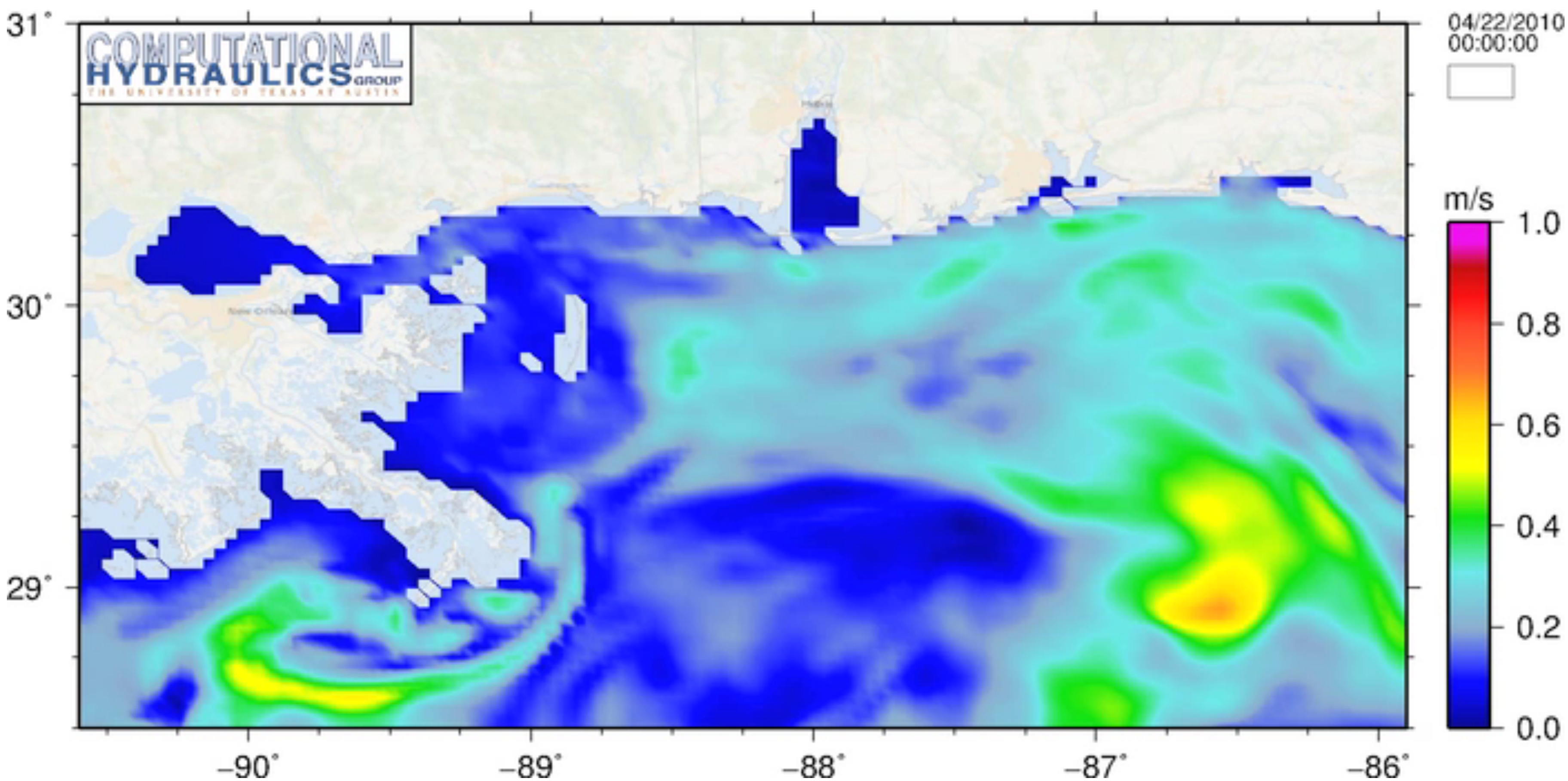
- Coarse on the continental shelf and into the nearshore
- Approximately 208K horizontal vertices



HYCOM+NCODA Gulf of Mexico 1/25° Analysis : Surface Currents

Examples from April-May 2010 - Current velocity magnitudes (m/s) at sea surface

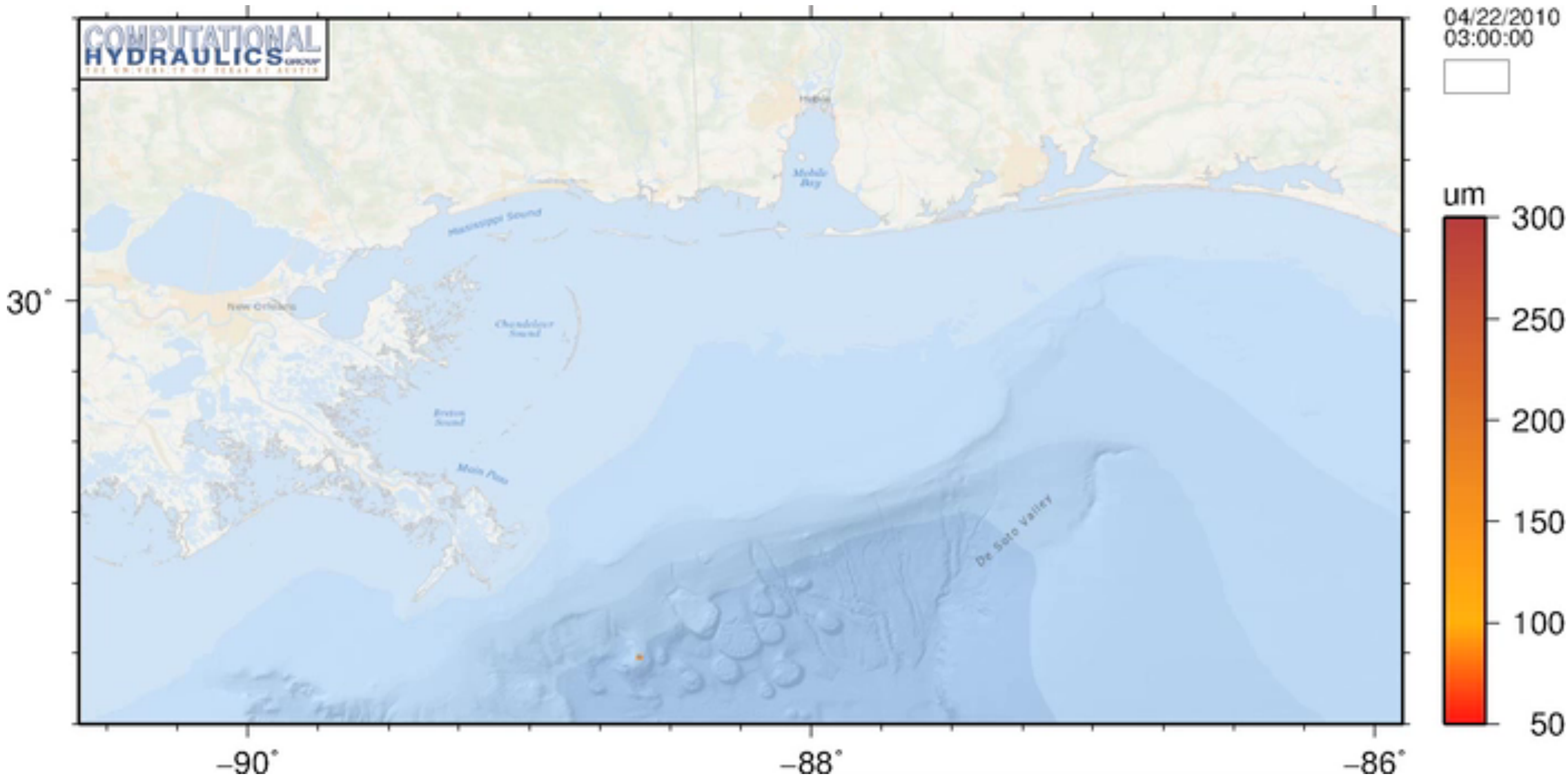
- Variability with strong peaks near Mississippi River delta
- Currents are relatively weaker on continental shelf



HYCOM+NCODA Gulf of Mexico 1/25° Analysis : Oil Transport

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

- Diameters assigned randomly in the range of **50μm** to **300μm**
- General movement is correct, but limited transport into the nearshore



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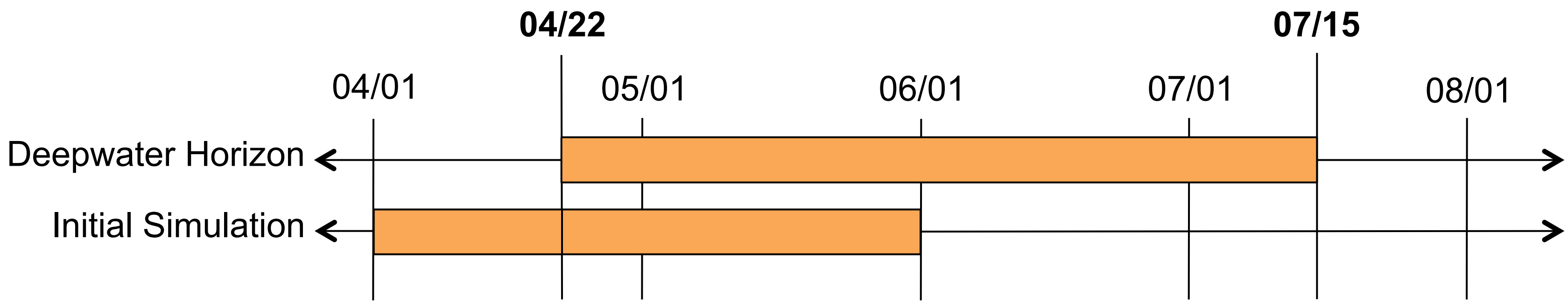
Now extending to the **3D version of ADCIRC**

- **What is the benefit of additional resolution in the nearshore?**
- Try with baroclinic version of ADCIRC, coupled to HYCOM
  - Use HYCOM results to force ADCIRC simulation on a high-resolution mesh with coverage of the Louisiana-Mississippi continental shelf
- Track oil particles with velocities from both models
  - As particles move into onto the shelf, switch to ADCIRC velocities
  - Do particles move closer toward coastline?

Deepwater Horizon : ADCIRC Simulation



Deepwater Horizon Event:

04/22 - Drilling platform sinks to the seafloor, oil spill begins

07/15 - Oil spill is capped

Initial Simulation:

04/01 - Cold-start of 21-day spin-up

04/22 - Hot-start of 40-day simulation

- Particles added every hour at spill location, tracked with 3D velocity field

06/01 - End of simulation

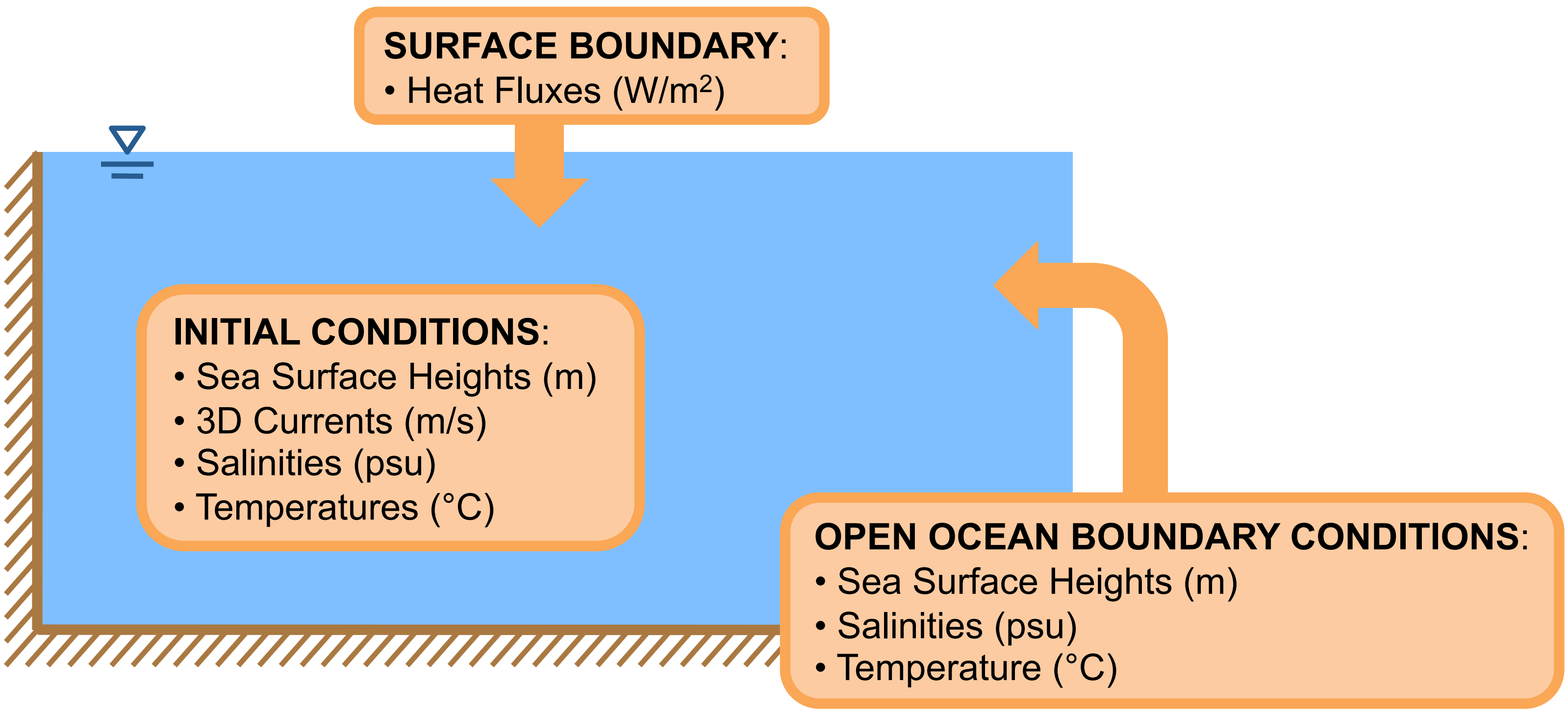
Deepwater Horizon : ADCIRC Simulation : Coupling to HYCOM

For transport of temperature and/or salinity, solve the transport equation:

$$\frac{\partial c}{\partial t} + \vec{v}_{3D} \cdot \nabla c = \frac{\partial}{\partial x}\left(N_H \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(N_H \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(N_V \frac{\partial c}{\partial z}\right)$$

Interpolate information from the high-resolution HYCOM results

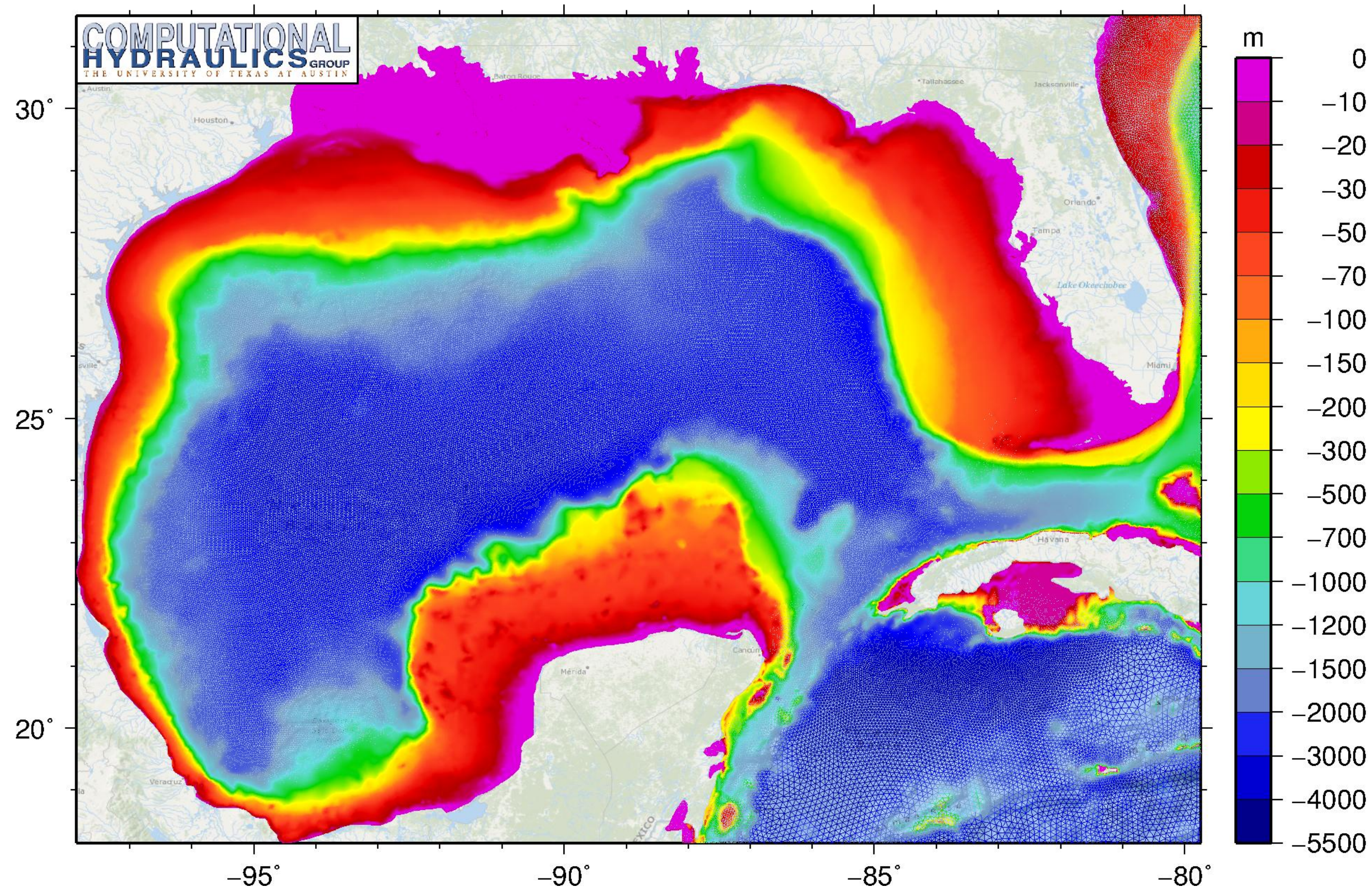
- Need initial and boundary conditions, in addition to winds, tides, waves, etc.



ADCIRC SL16v31 : Bathymetry

ADCIRC community has developed high-resolution meshes for this region

- SL16v31 mesh was validated for tides, riverine flows, waves and storm surge



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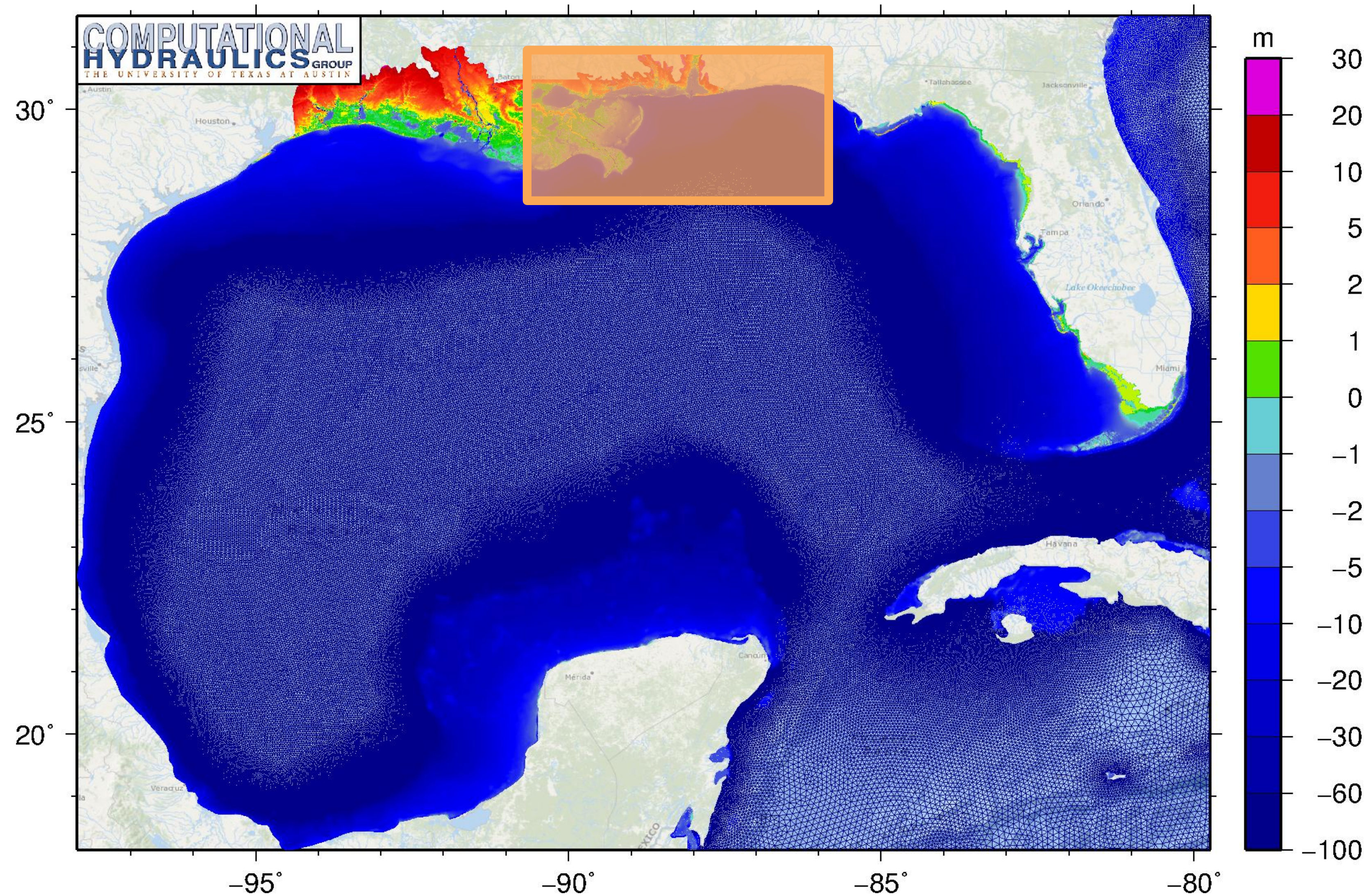
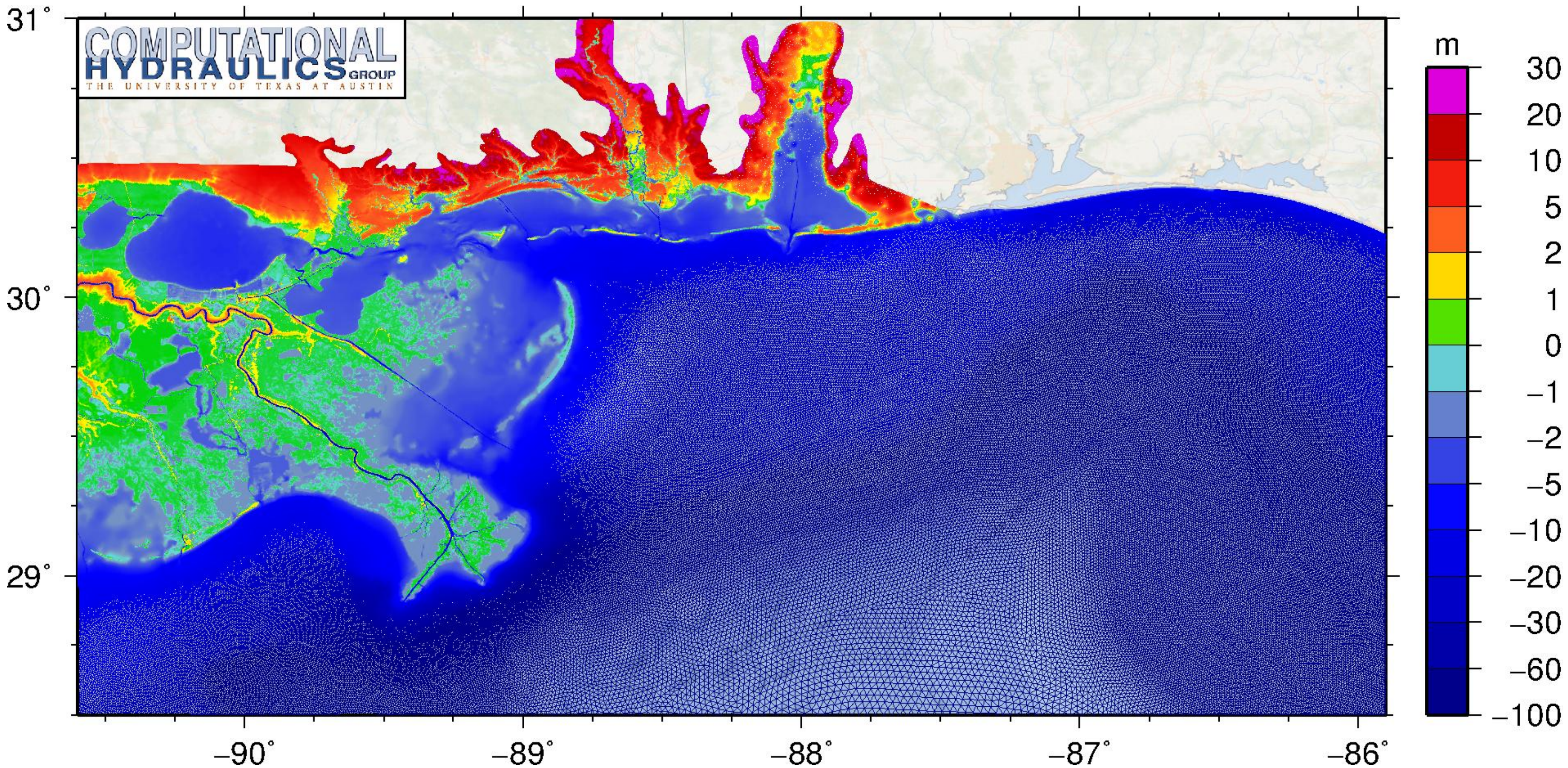


ADCIRC SL16v31 : Bathymetry

Better representation of continental shelf and nearshore

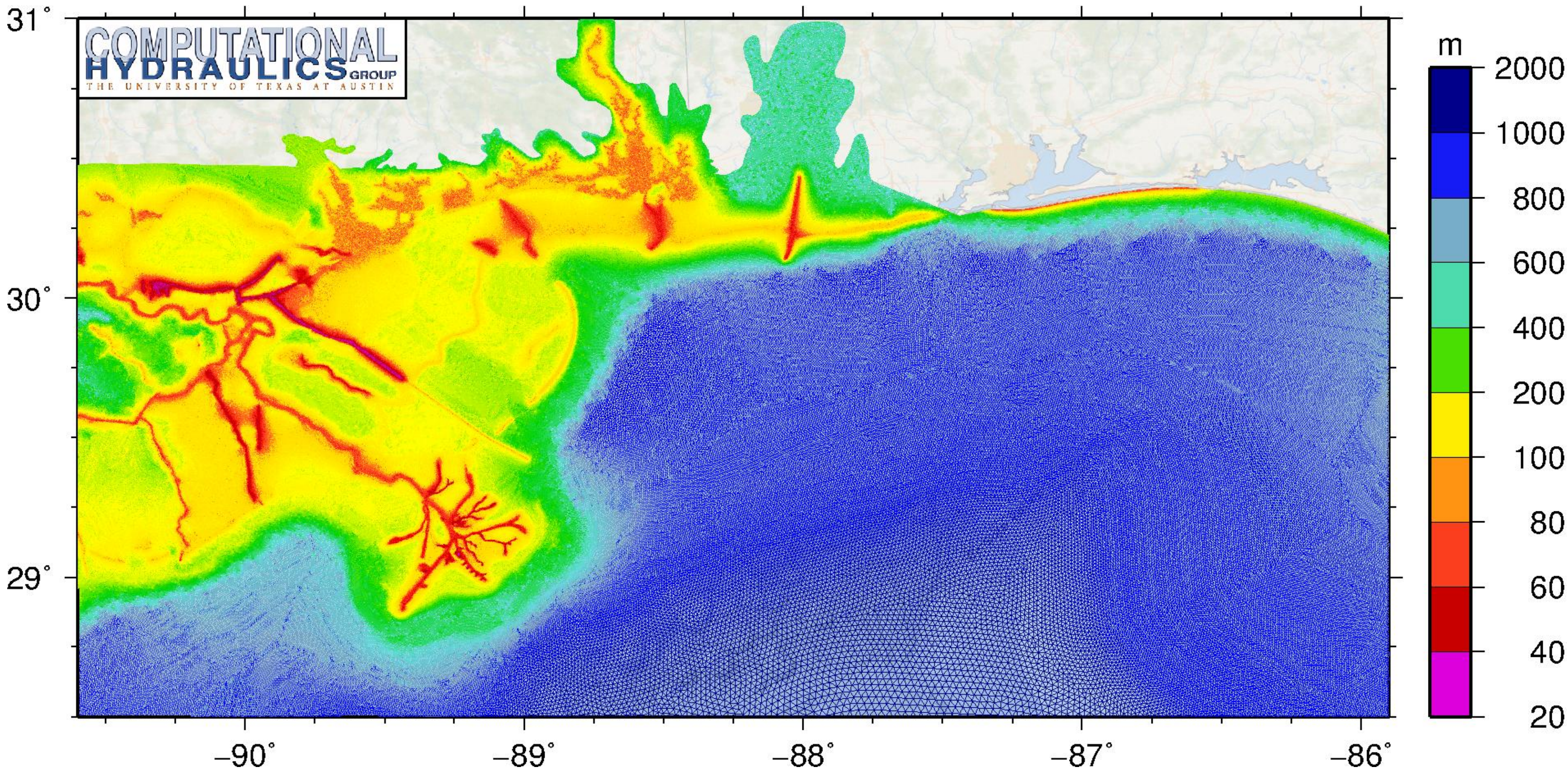
- Includes the barrier islands, coastal marshes/floodplains, natural and man-made channels, levee protection system, etc.



ADCIRC SL16v31 : Element Sizes

Better representation of continental shelf and nearshore

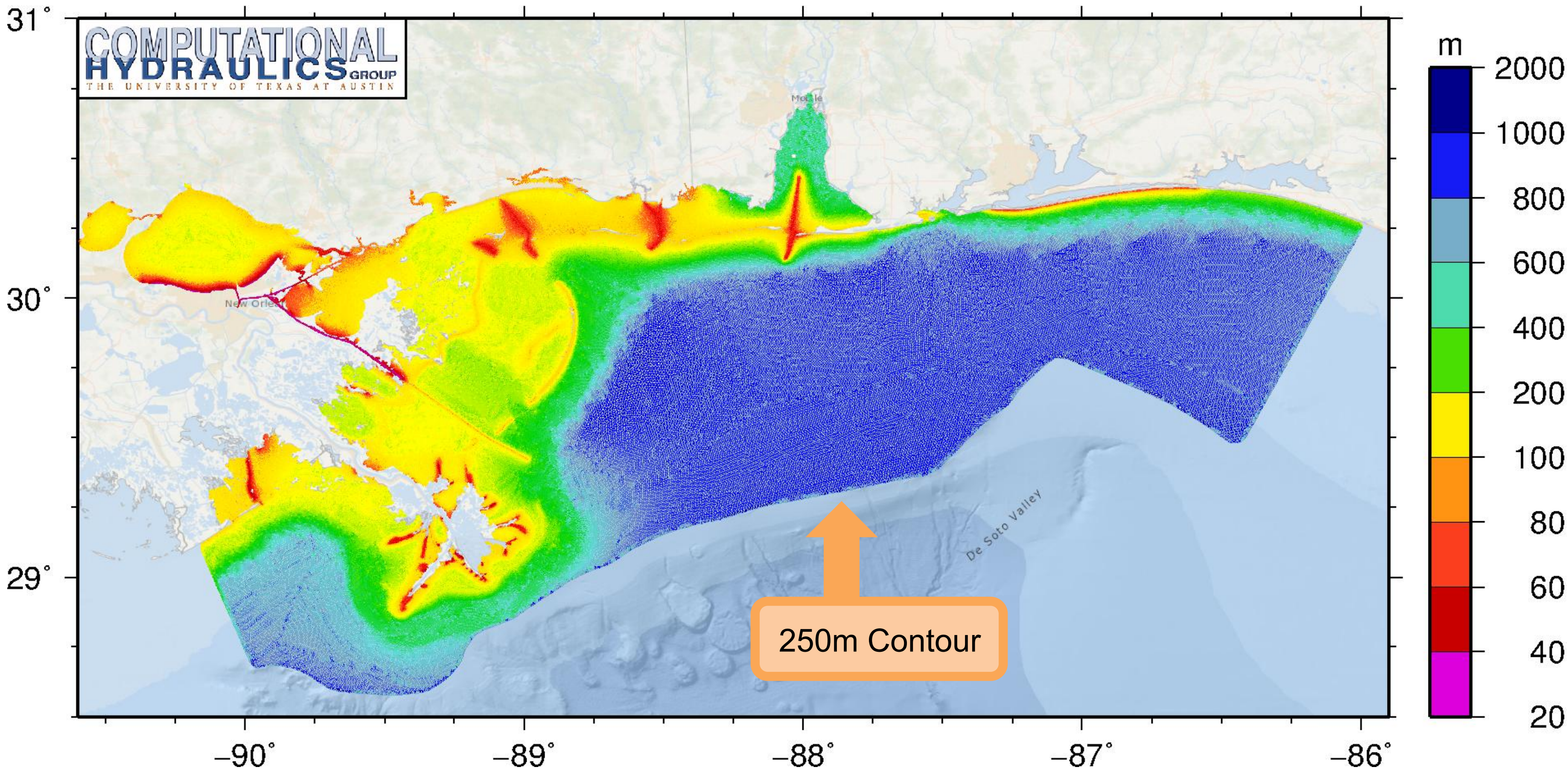
- Mesh spacings less than 1km on shelf, less than 200m in floodplains
- Element sizes range downward to minimum of 20m in channels, etc.



ADCIRC SL16v31 LA-MS : Element Sizes

For testing purposes, cut a smaller mesh with coverage of Louisiana-Mississippi shelf

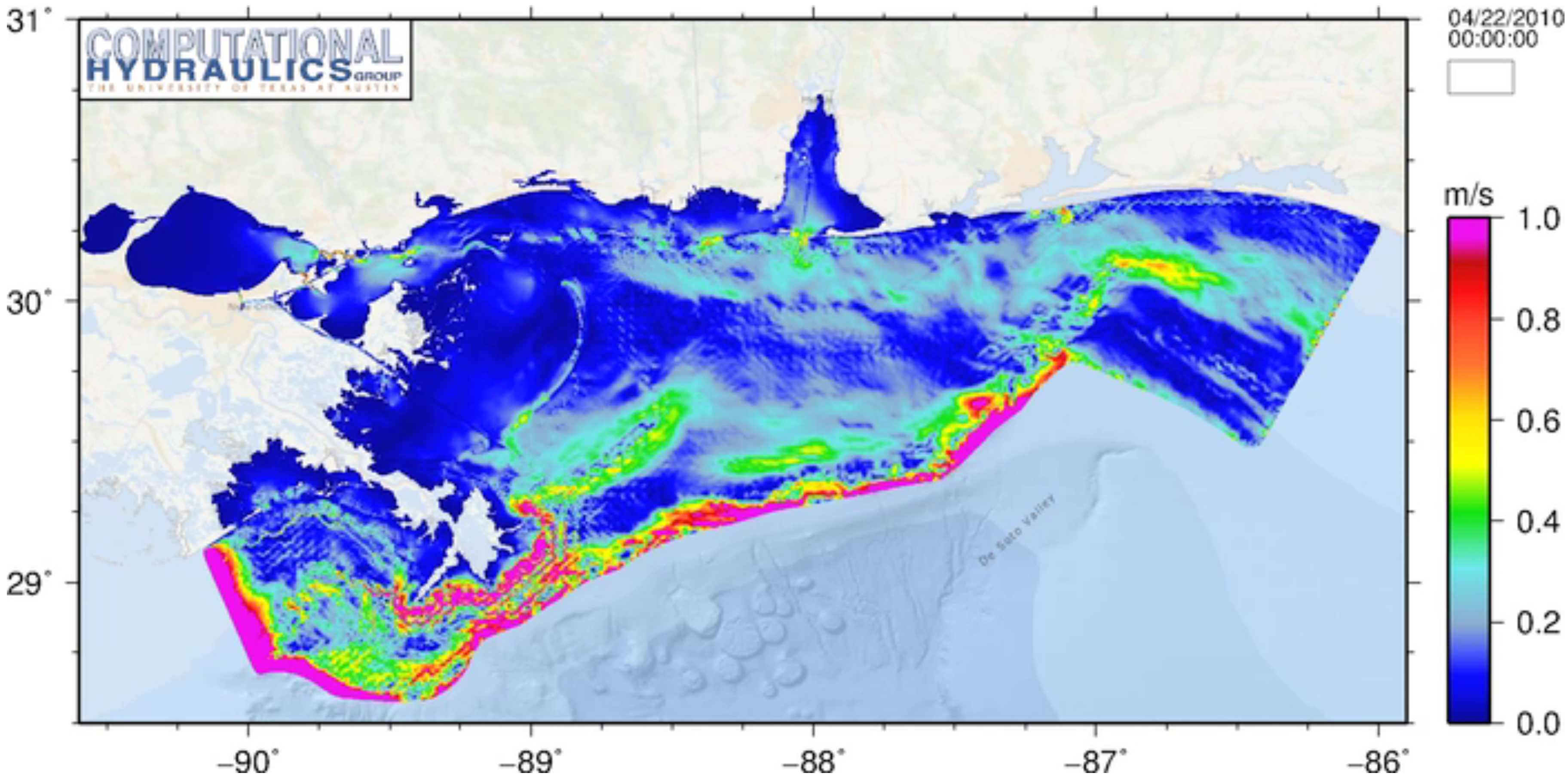
- No overland coverage of floodplains, limited inland water bodies
- Extend to depths of about 250m, total of 1.1M vertices



ADCIRC SL16v31 LA-MS : Surface Currents

Initial attempt with coupling to HYCOM

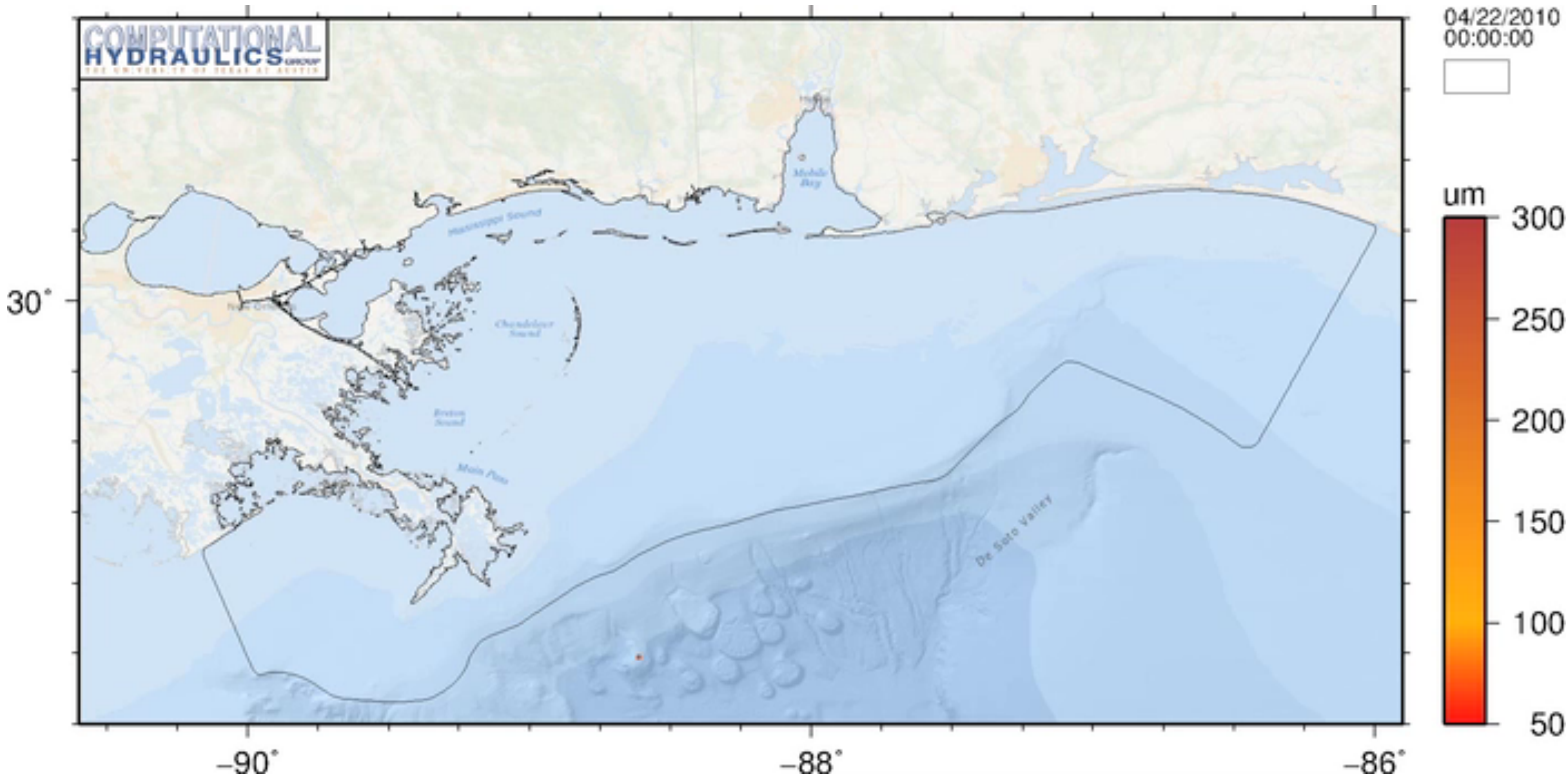
- Forced with tides at open boundary (no winds, waves, etc.)
- Spurious currents are generated along the shelf break, near boundary



ADCIRC SL16v31 LA-MS : Oil Transport

Initial attempt with coupling to HYCOM

- Particles forced with ADCIRC currents only if they move into the domain
- Obvious discontinuity in current fields at domain boundary



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Now extending to the **3D version of ADCIRC**

- **What is the benefit of additional resolution in the nearshore?**
- Track oil particles with velocities from baroclinic ADCIRC, coupled to HYCOM

Moving forward …

- Increase resolution near shelf break, couple to HYCOM velocities at boundary
- Update tracking code to force particles with both velocity fields
- Connect to dispersion parameterization from GLAD?
- Add sink terms for evaporation, biodegradation, etc.