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

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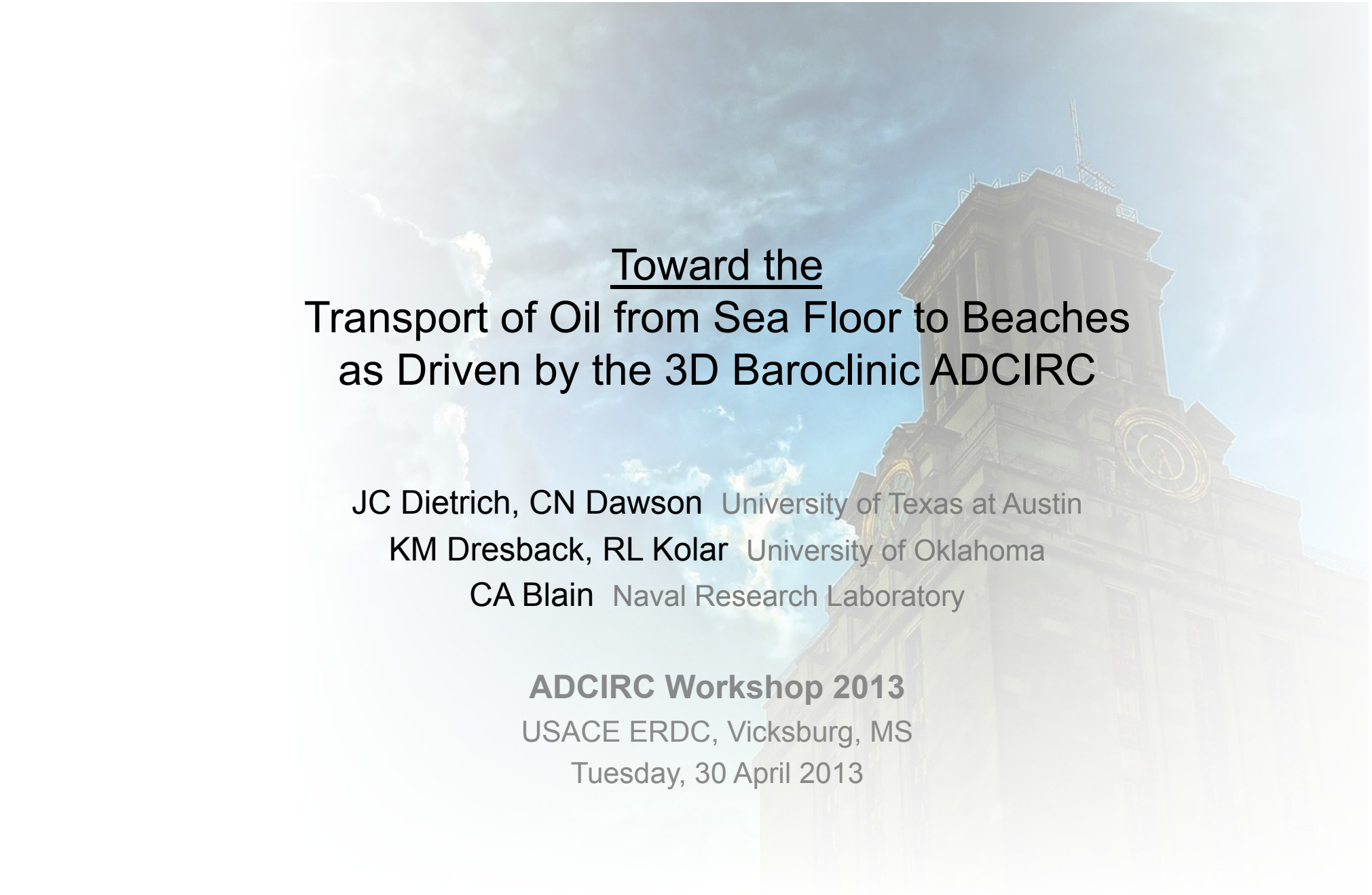
KM Dresback, RL Kolar University of Oklahoma
CA Blain Naval Research Laboratory

**ADCIRC Workshop 2013**
USACE ERDC, Vicksburg, MS
Tuesday, 30 April 2013



# Toward the
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# Motivation : Deepwater Horizon (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?

# 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

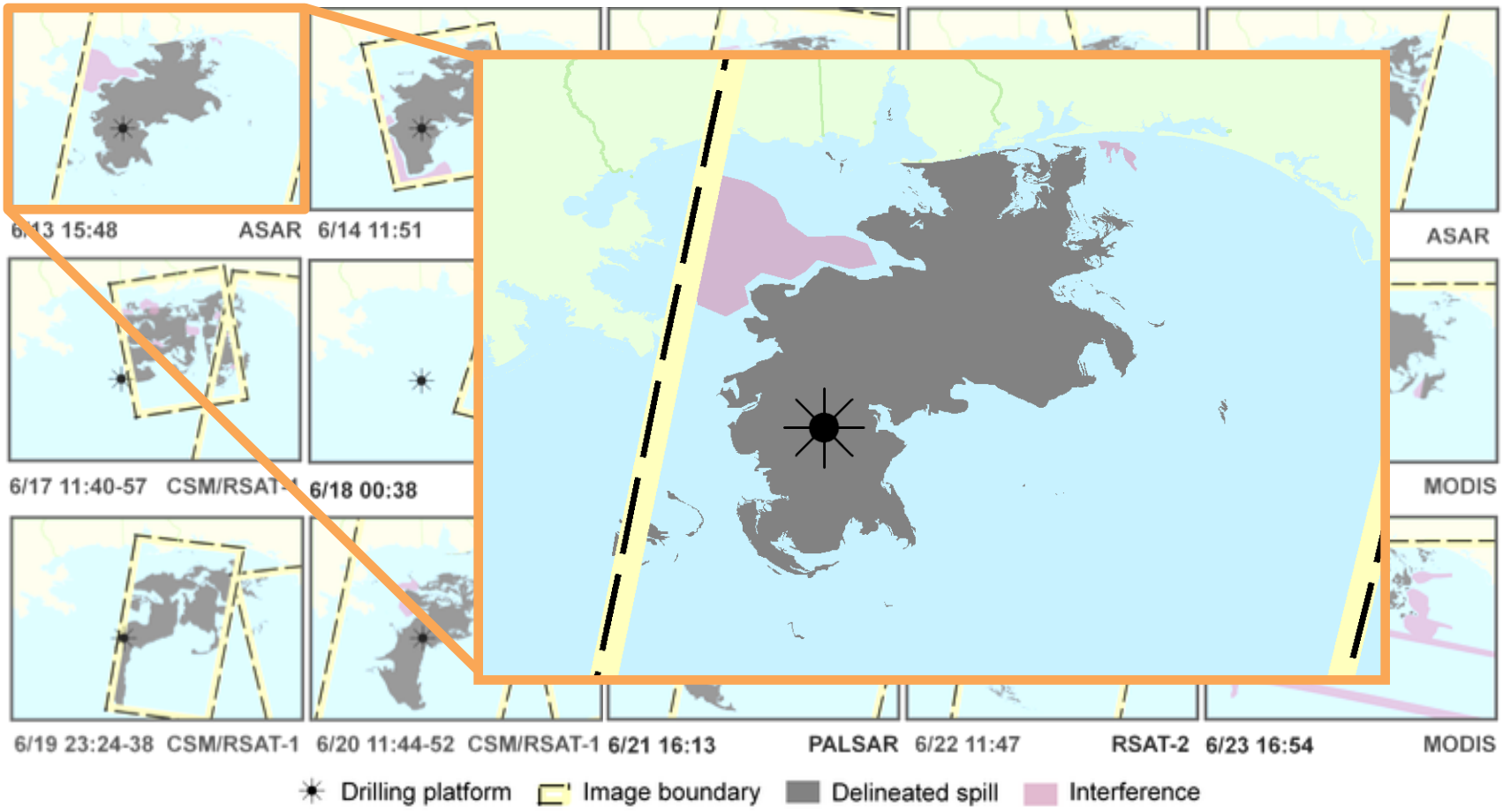
# Surface Oil Transport : 13-23 June 2010

Initialize particle locations from observations in satellite imagery

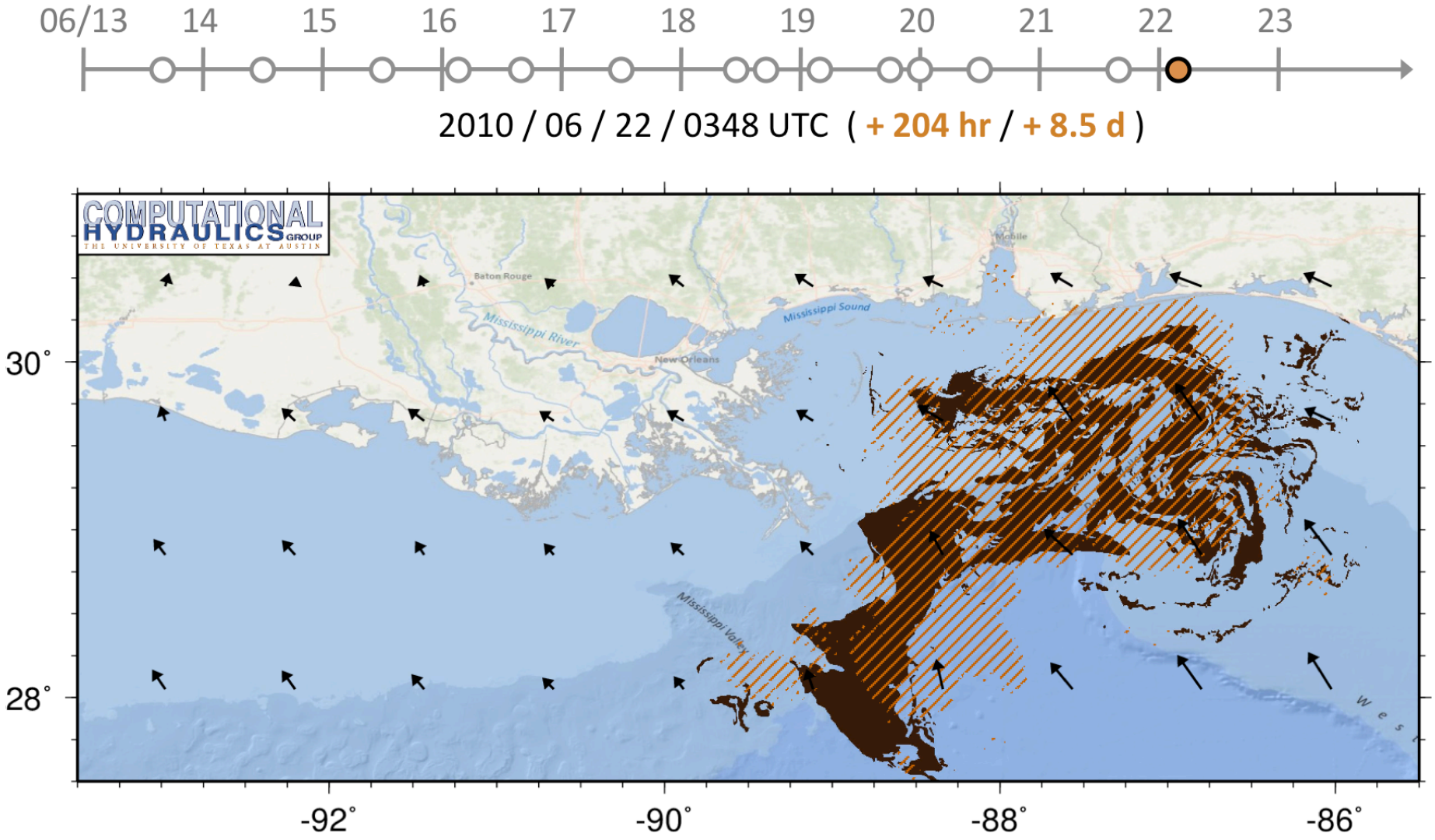
- Digitize daily analysis of slick extents into millions of particles

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

- Uncertainties due to satellite coverage, interference



# Surface Oil Transport : 13-23 June 2010




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

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

- Working already with HYCOM modelers in our GoMRI-funded consortium
- 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 their 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

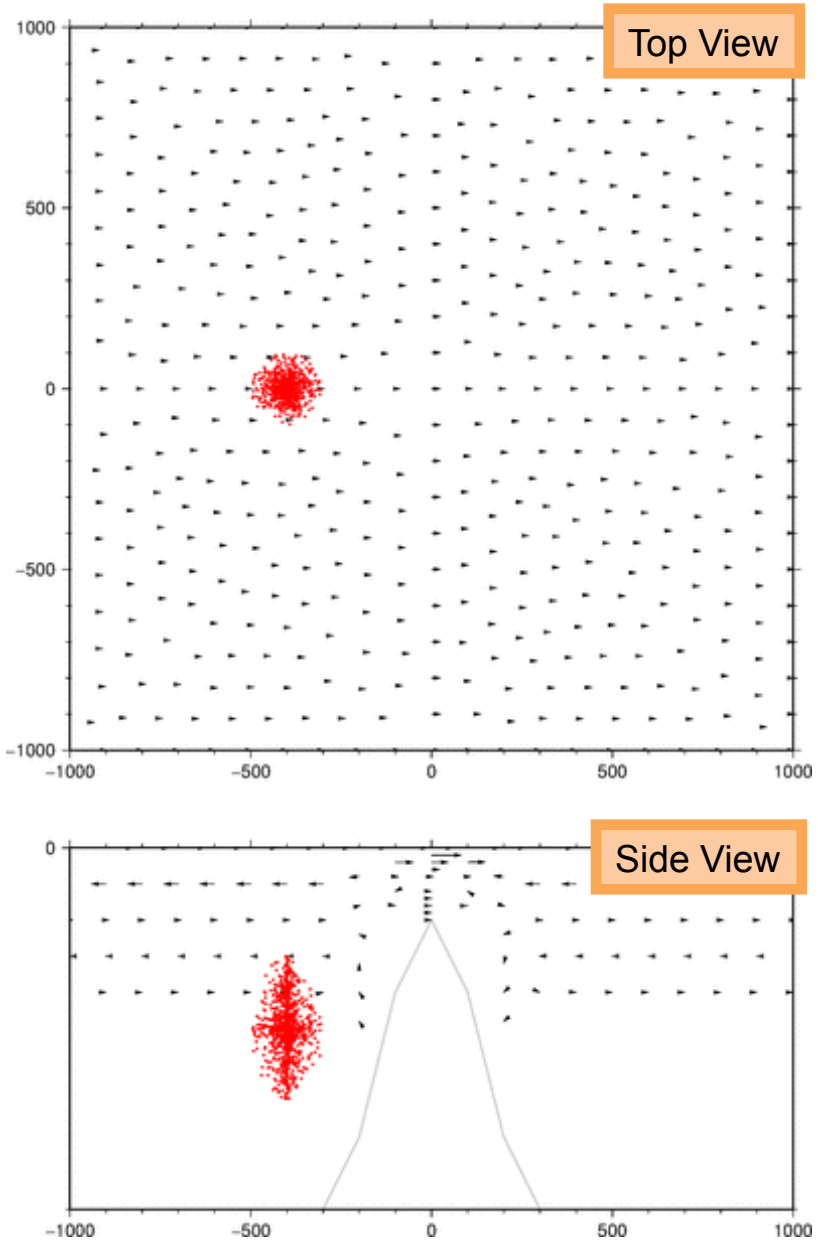
**Submerged Ridge Test Case:**

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:

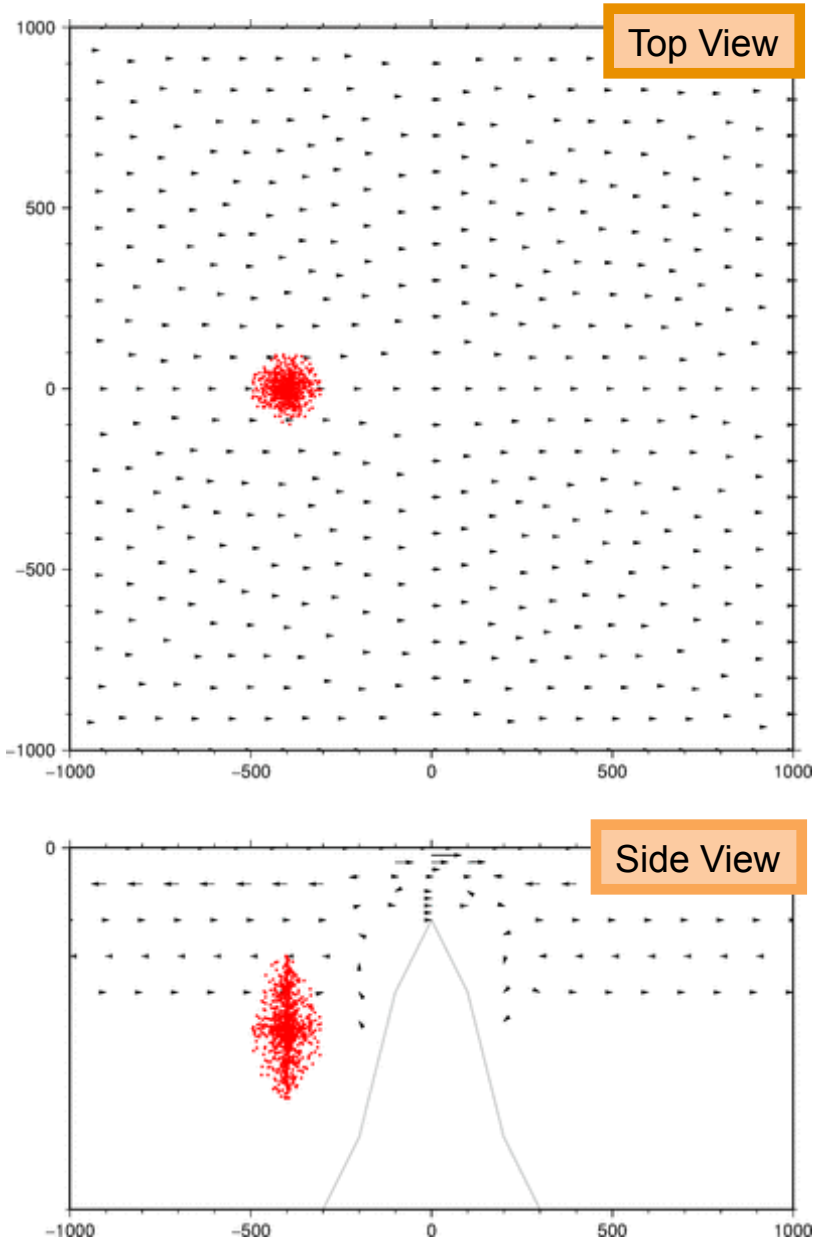
- Spherical droplets (small)
- Ellipsoidal droplets (intermediate)
- Spherical-cap droplets (large)

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

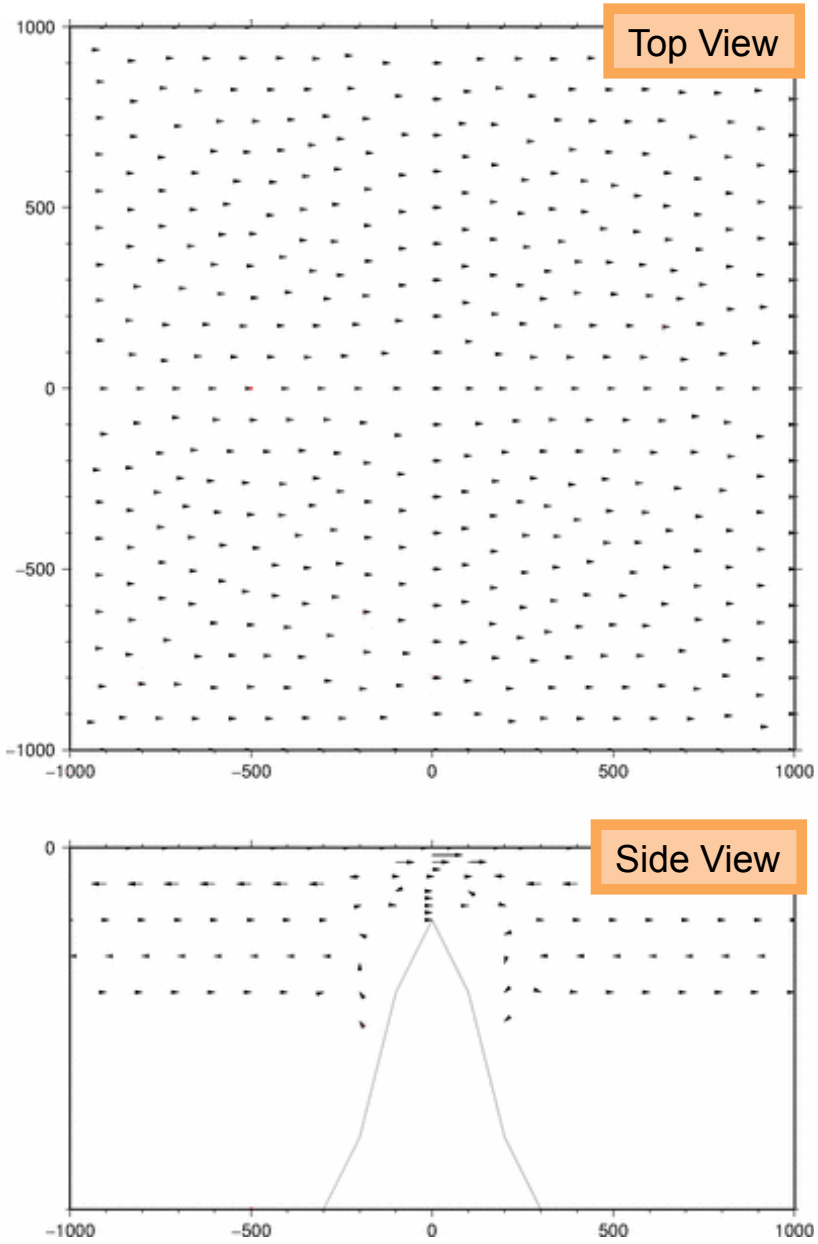
**Submerged Ridge Test Case:**

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)

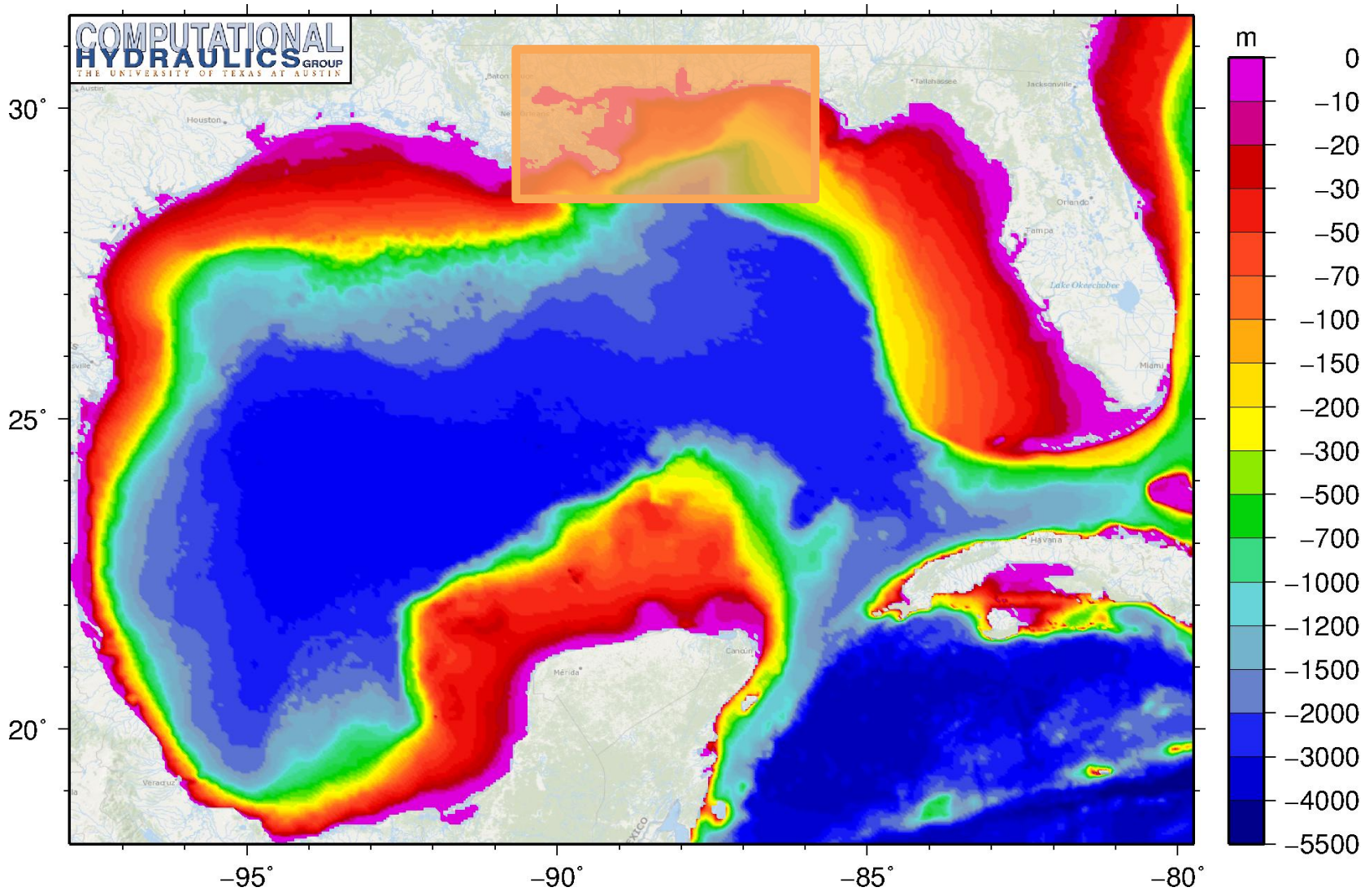
Oil - Density of 858 kg/m$^3$
- **Droplet size of 50µm**
- Interfacial tension of 0.023 N/m



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

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

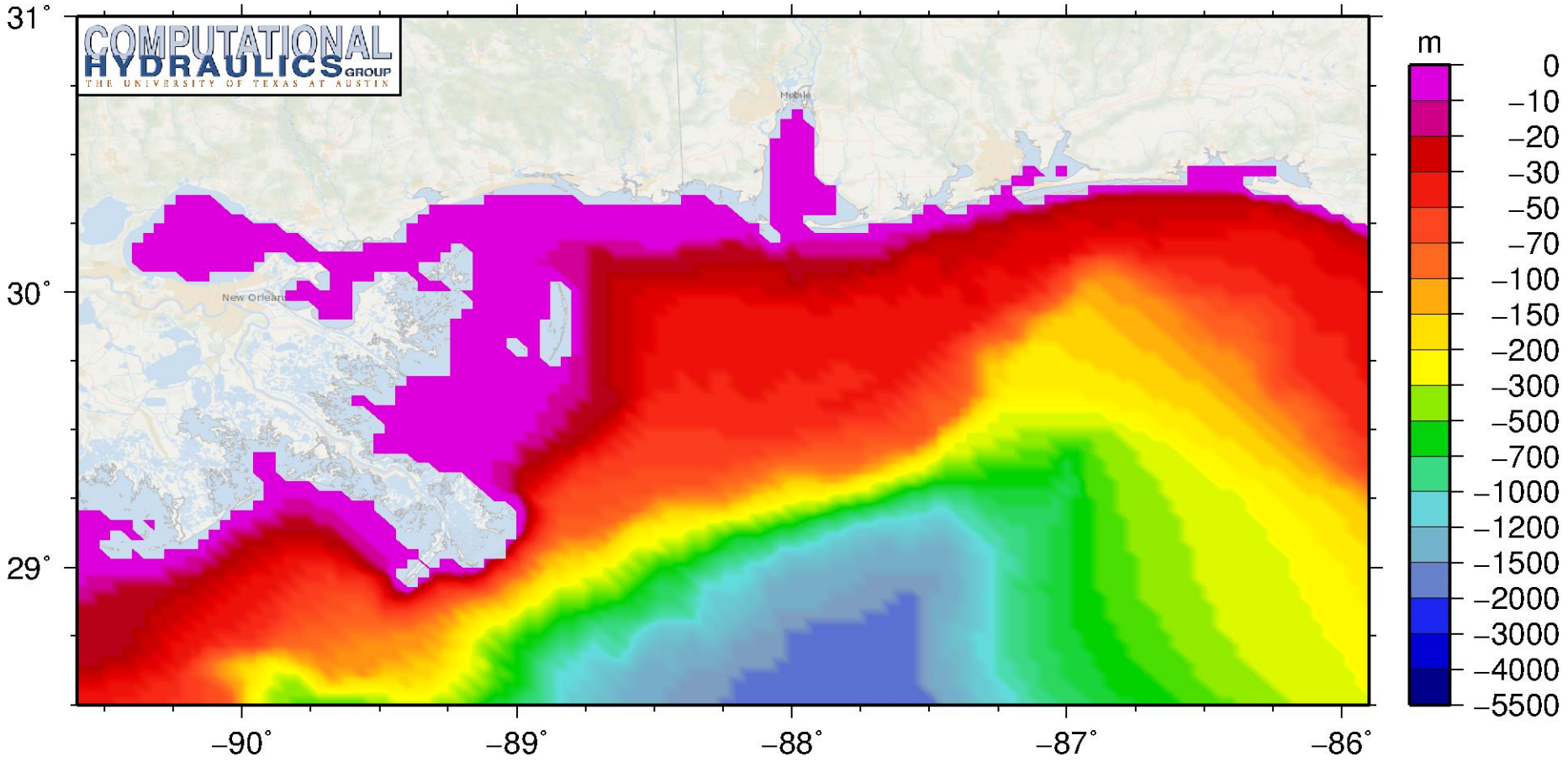
- However, model output is archived at 40 constant depths



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

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

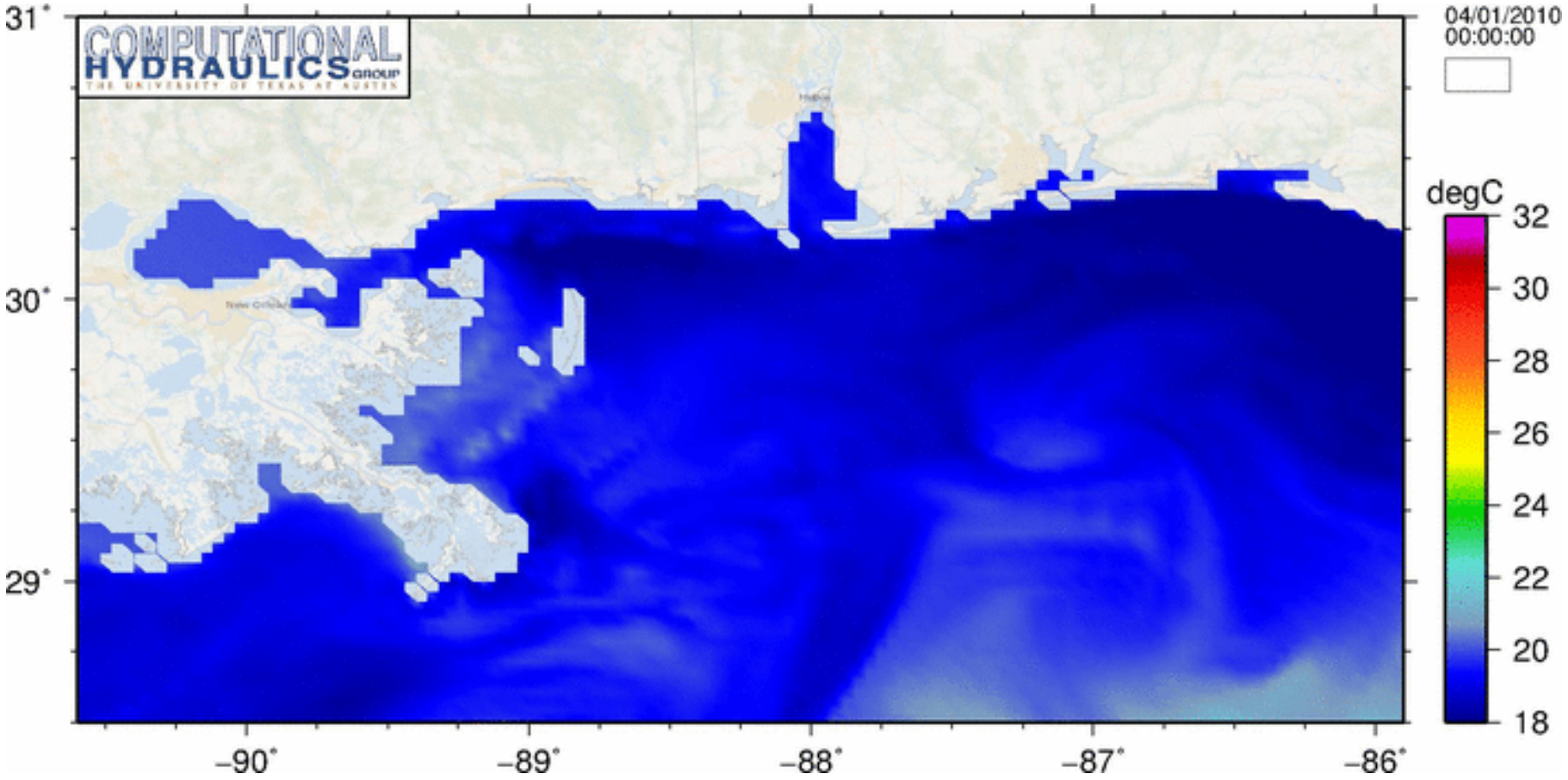
- Coarse on the continental shelf and into the nearshore
- Approximately 208K horizontal vertices



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

Examples from April-May 2010 - Temperatures (°C) at sea surface

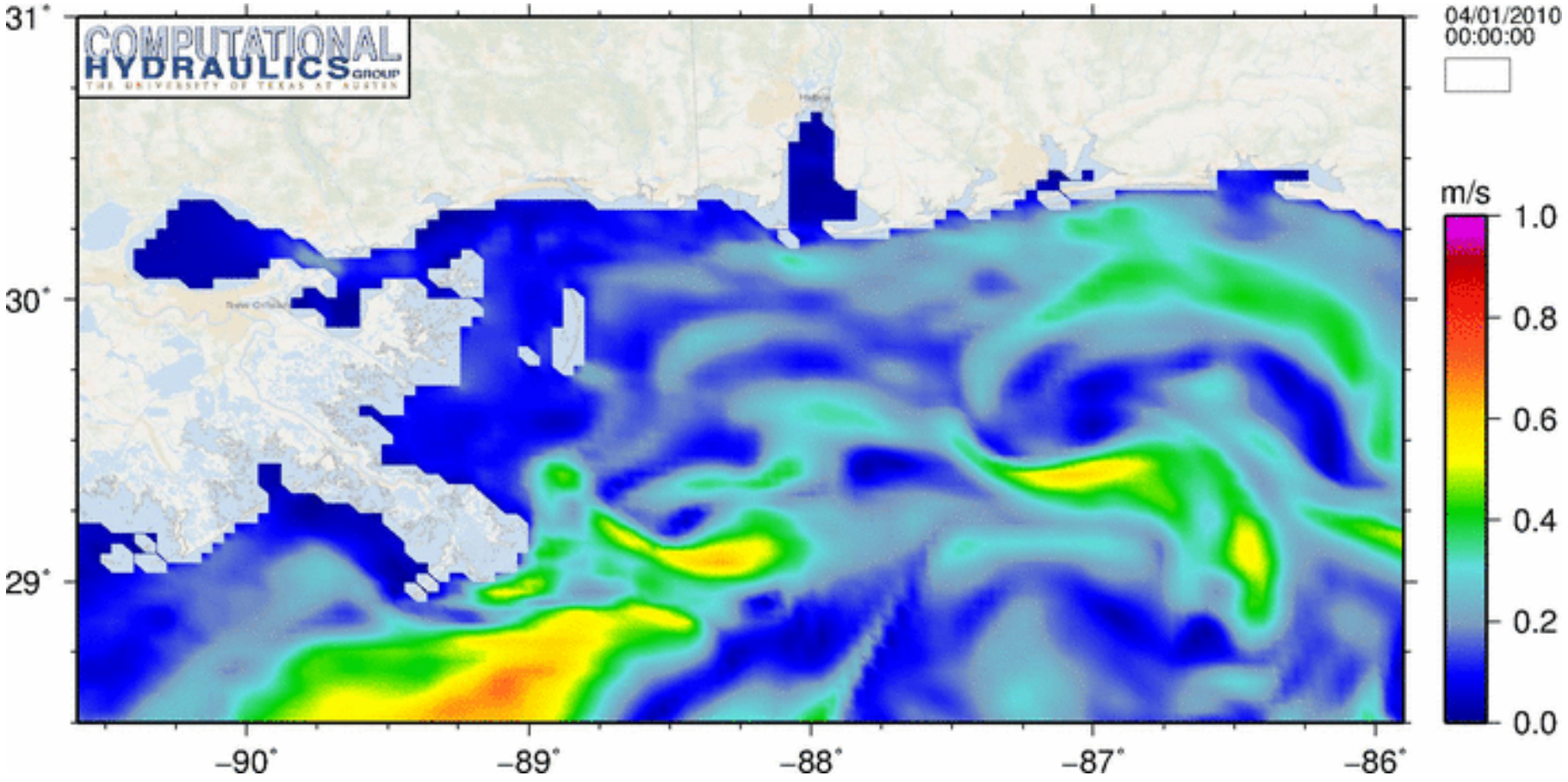
- Adjusted with data assimilated from satellite and *in situ* measurements
- Daily variability, but also general warming into summer



# 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

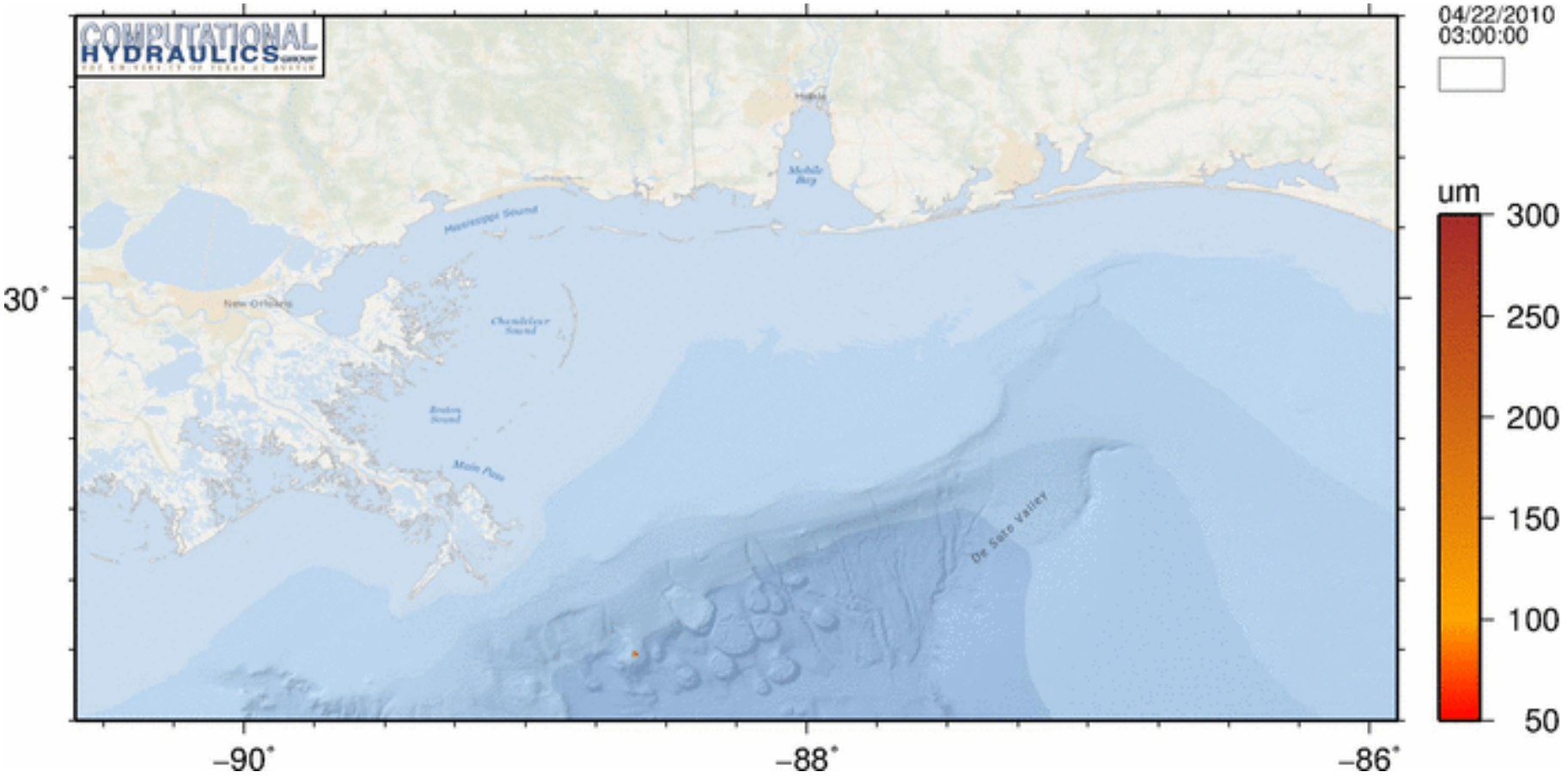


# HYCOM+NCODA Gulf of Mexico 1/25° Analysis : Oil Transport

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**



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- NRL operates a high-resolution forecast system for the Gulf
- Use their model results as forcing to our oil transport

Current attempts with the **3D version of ADCIRC**

- **What is the benefit of additional resolution in the nearshore?**
- Try with barotropic, then baroclinic versions of ADCIRC
  - 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
  - Do particles move closer toward coastline?

# Deepwater Horizon : Meteorological Forcing

**NAM (WRF-NMM):**

NOAA provides high-resolution meteorological forecasts over North America

- Posted every 6hr with durations of 84hr
- Available via HTTP, FTP, THREDDS, etc.

Historical winds are also archived as “Analysis Only”

- Contain the existing wind conditions from the start of each forecast

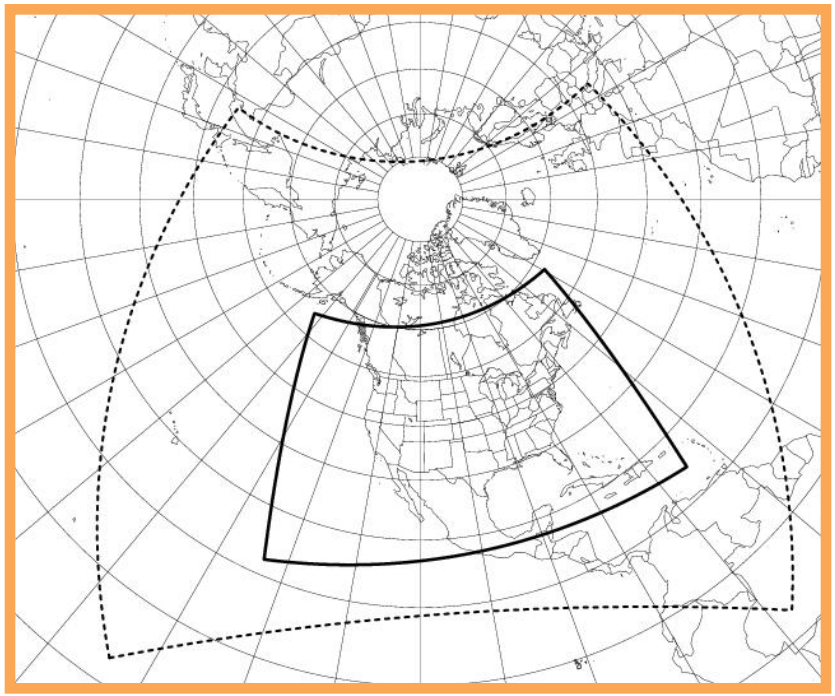
**Wind Field for Oil Spill Event:**

ASGS routines can process NAM data

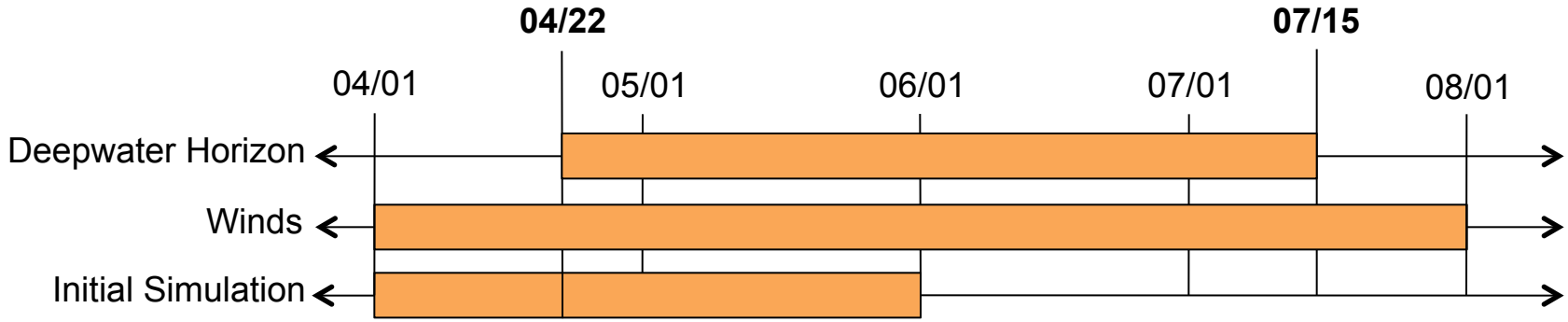
- Rotate and extract wind fields for any region and resolution

Use existing resolution of 0.1° (about 12km)

- Much **finer than previous winds** from oil spill work ( 0.25° / 30km )
- Coverage only of Gulf of Mexico



# 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 for tides, winds, etc.

04/22 - Hot-start of 40-day simulation with tides, winds, etc.

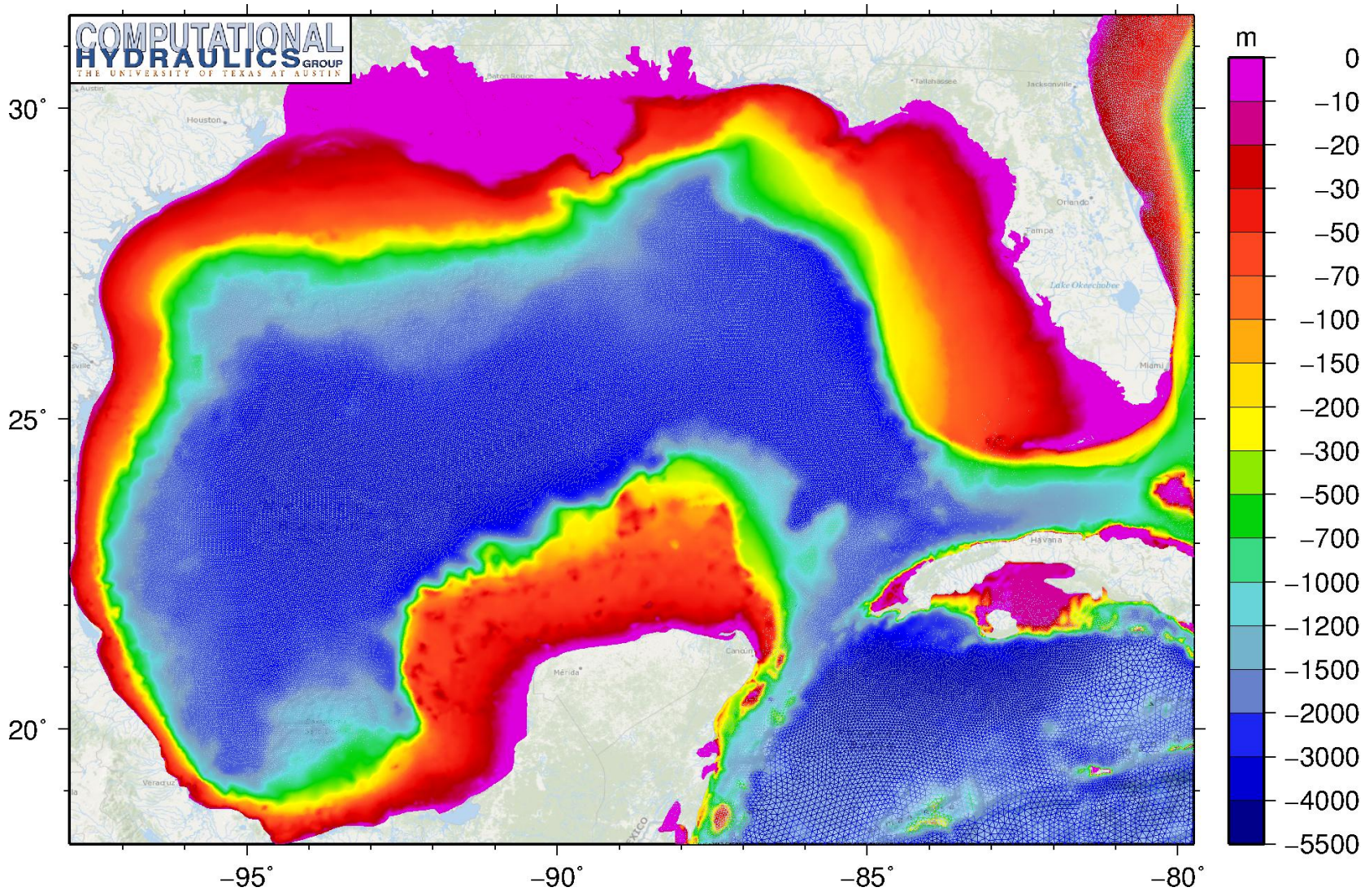
- Particles added every hour at spill location, tracked with 3D velocity field

06/01 - End of simulation

# ADCIRC SL16v31 : Bathymetry

ADCIRC community has developed high-resolution meshes for this region

- SL16v31 mesh has been validated for tides, riverine flows, waves and surge



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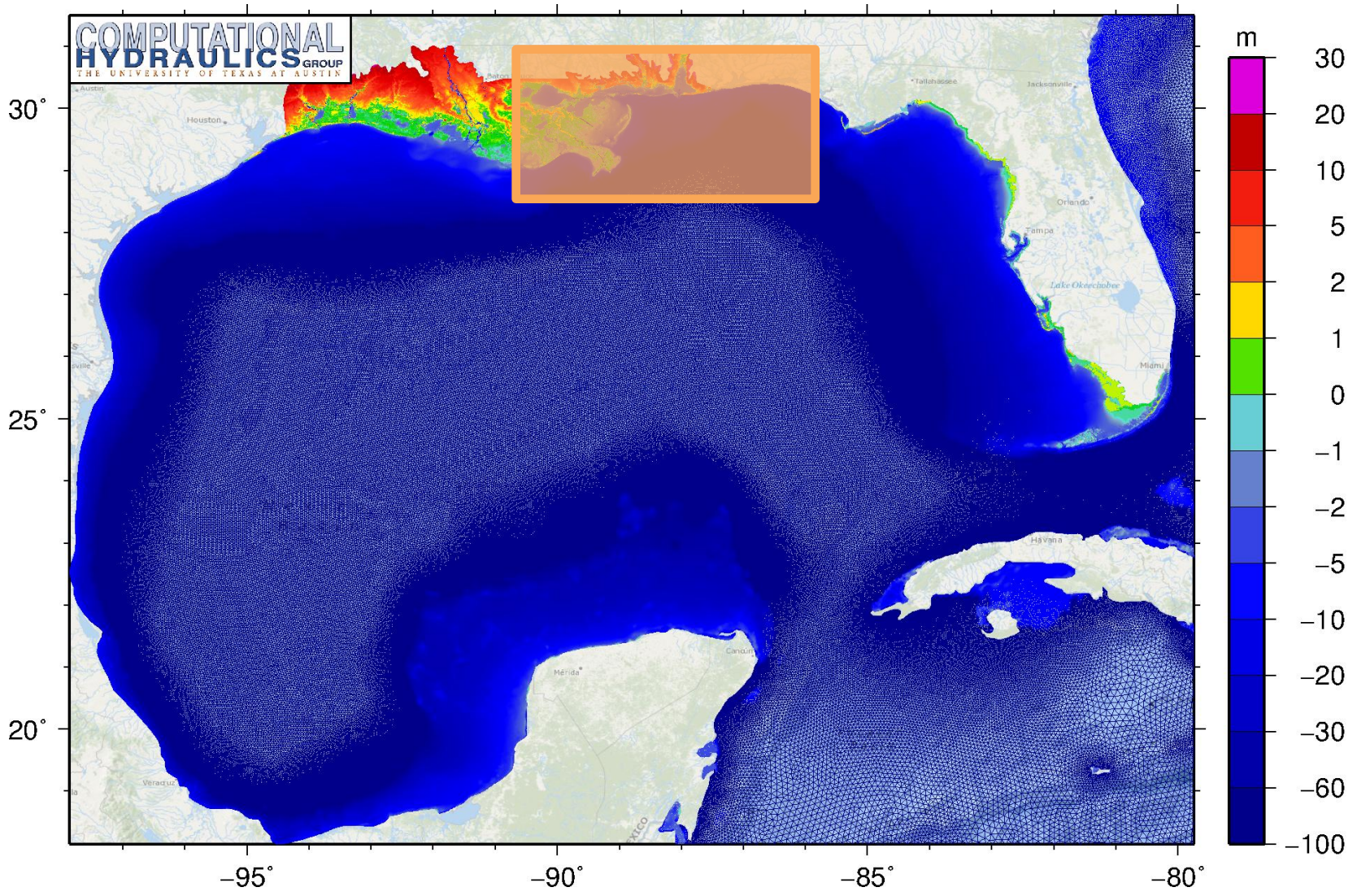
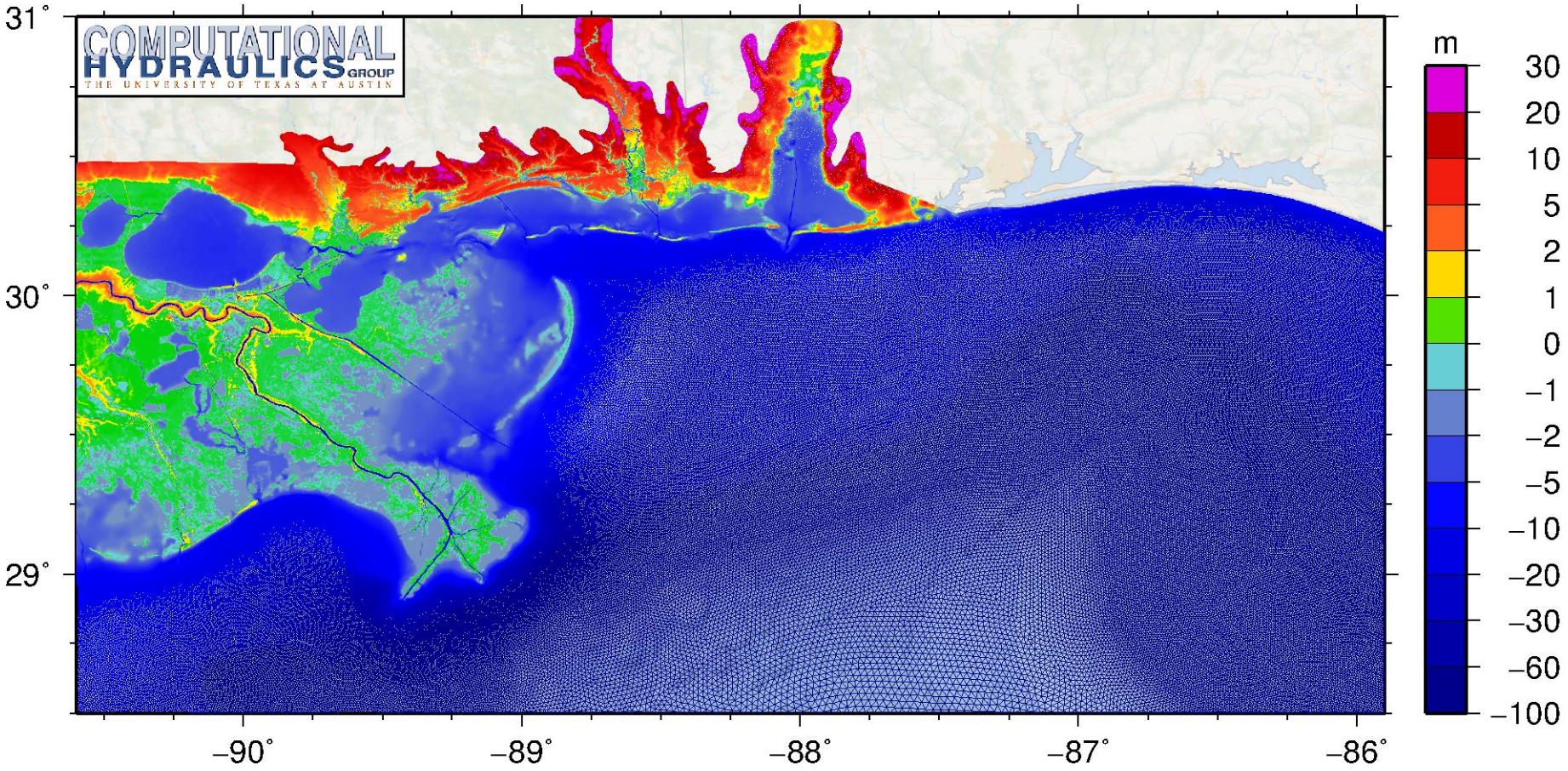


# ADCIRC SL16v31 : Bathymetry

Better representation of continental shelf and nearshore

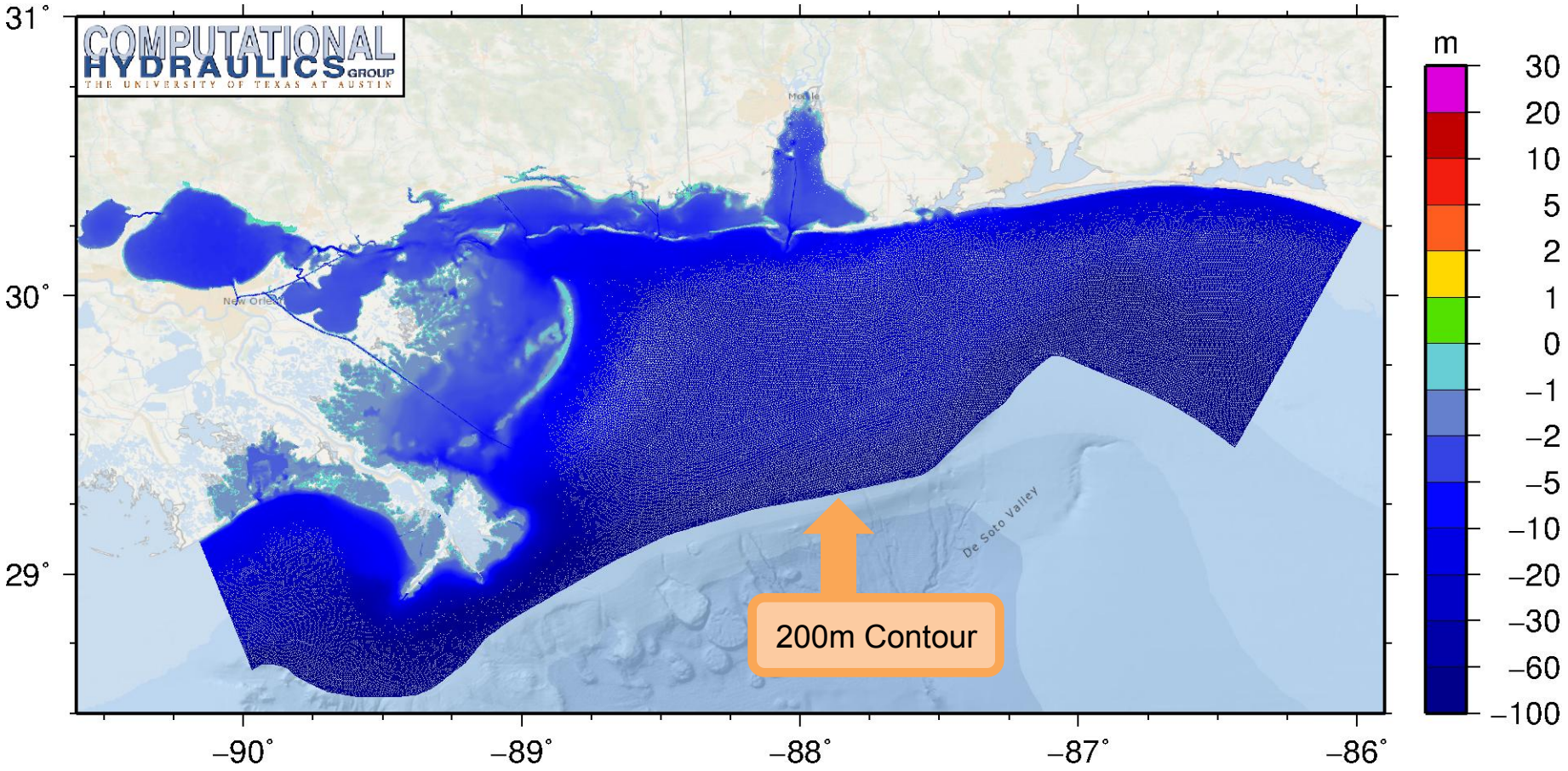
- Mesh spacings less than 1km on shelf, less than 200m in floodplains
- Element sizes range downward to minimum of 20m in channels, etc.



# ADCIRC SL16v31 LA-MS : Bathymetry

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

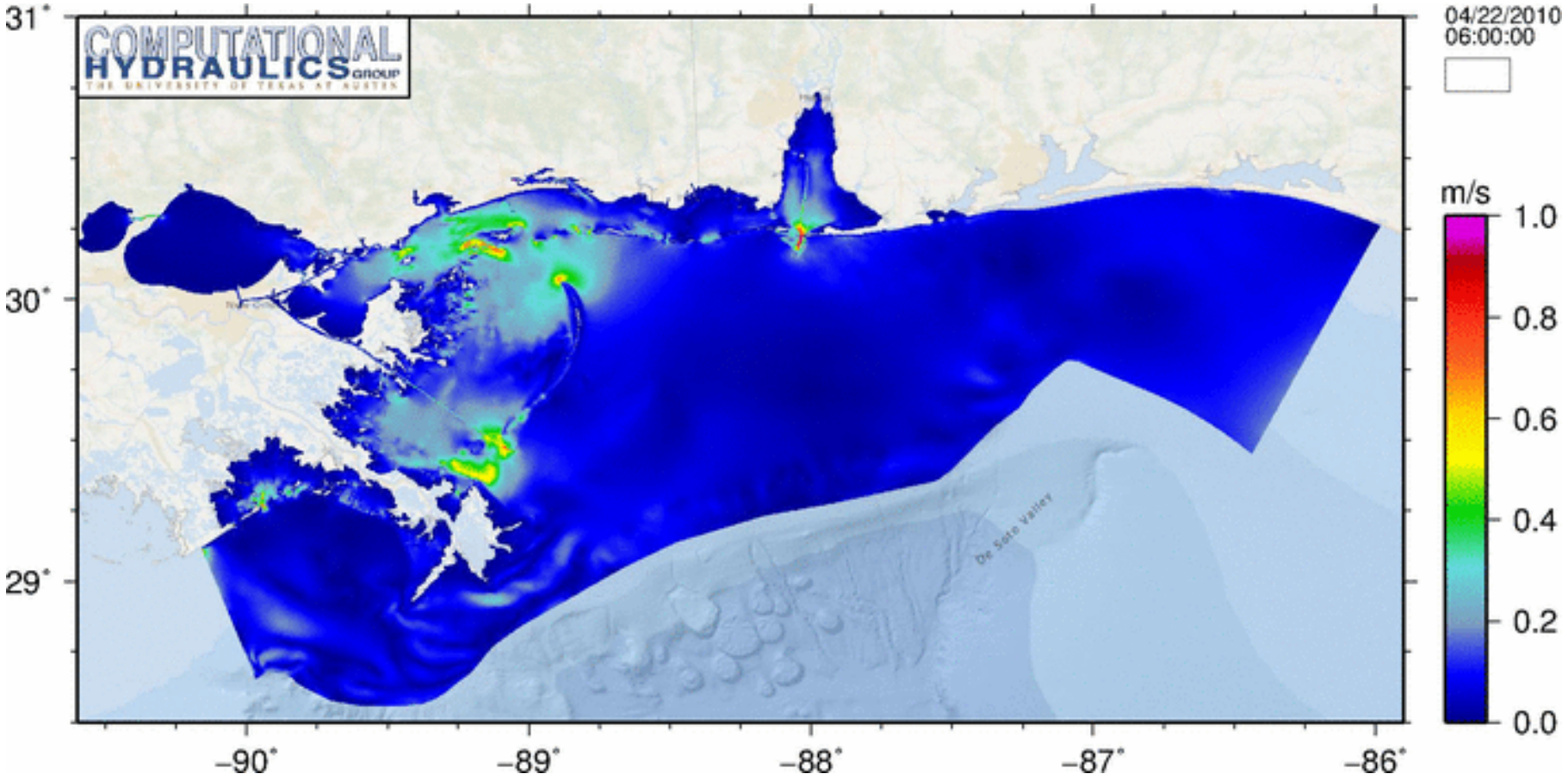
- No overland coverage of floodplains, limited inland water bodies
- Extend to depths of about 200m, total of 1.1M vertices



# ADCIRC SL16v31 LA-MS : Barotropic : Surface Currents

Initial attempt with barotropic version, **without coupling to HYCOM**

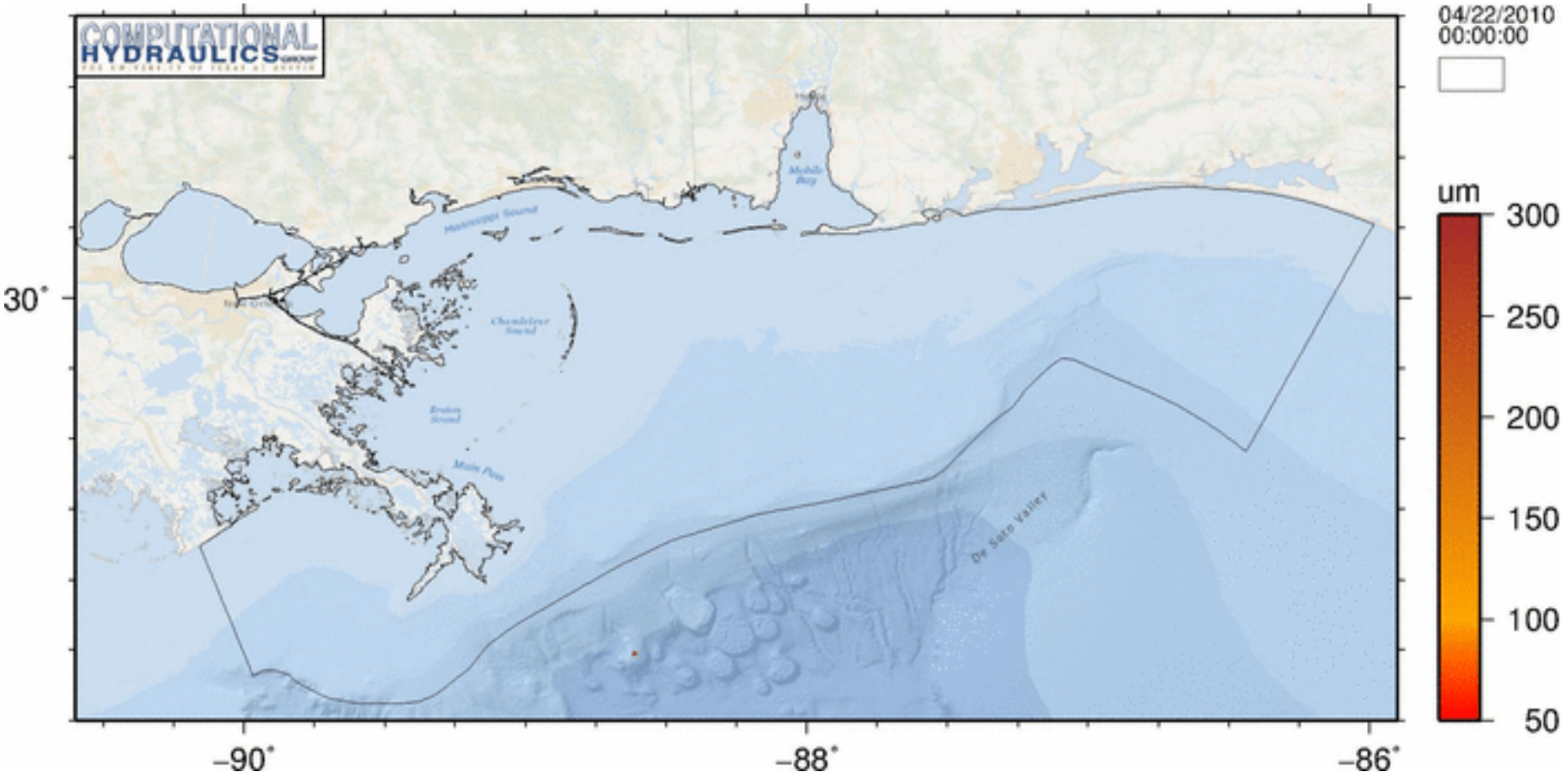
- Need to smooth the tidal forcing at the open ocean boundary
- Peak currents are focused more to channels and near barrier islands



# ADCIRC SL16v31 LA-MS : Barotropic : Oil Transport

Initial attempt with barotropic version, **without coupling to HYCOM**

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



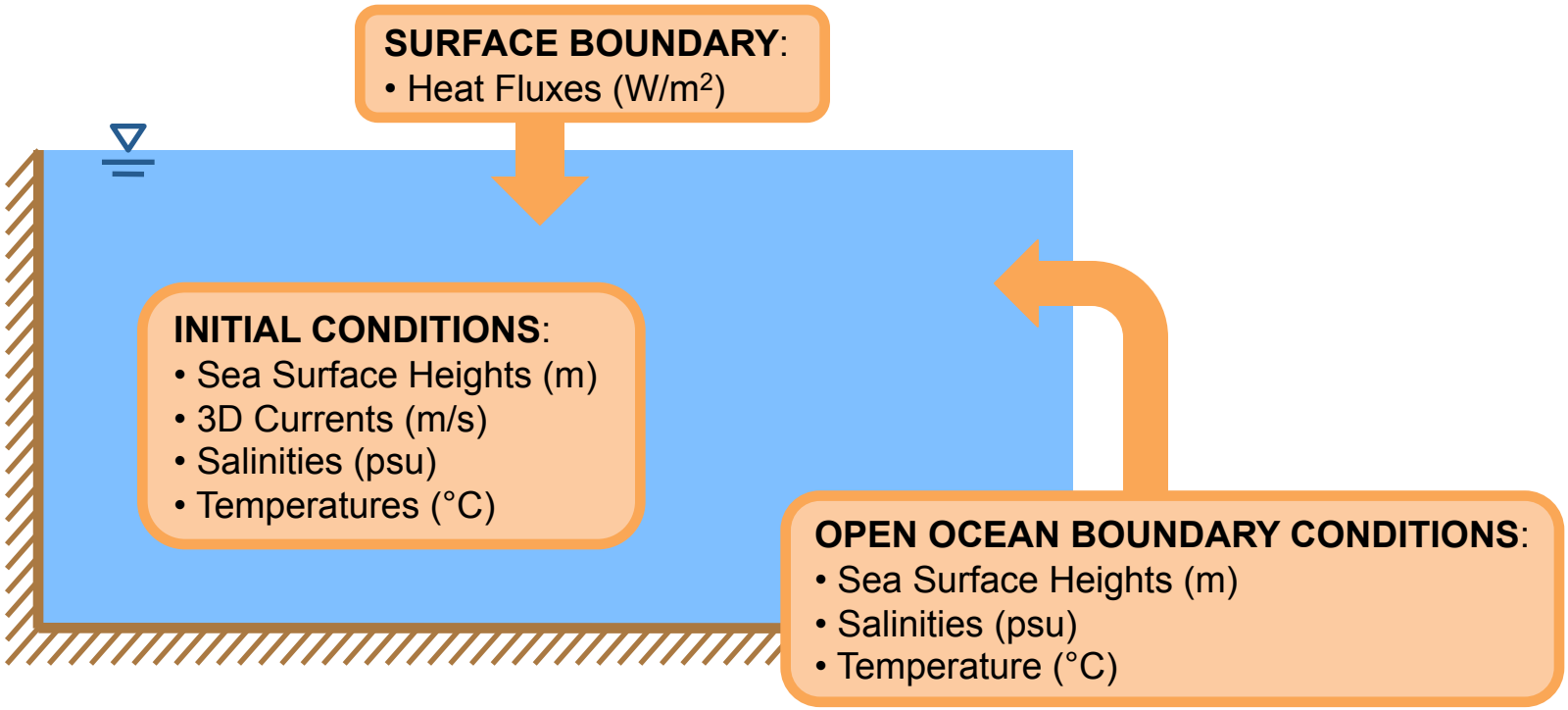
# ADCIRC SL16v31 LA-MS : Baroclinic : Initial and Boundary Conditions

For transport of temperature and/or salinity, solve the non-conservative form of 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.



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- Track oil particles with velocities from both models

Future work …

- Push through the 3D baroclinic simulation on the high-res shelf mesh
- Update tracking code to force particles with both velocity fields
- Add dispersion, sink terms (evaporation, biodegradation, etc.)