Application of an unstructured grid RANS model to the coastal ocean

Applied Modeling & Simulation Seminar Series

NASA Ames Research Center

June 16, 2015



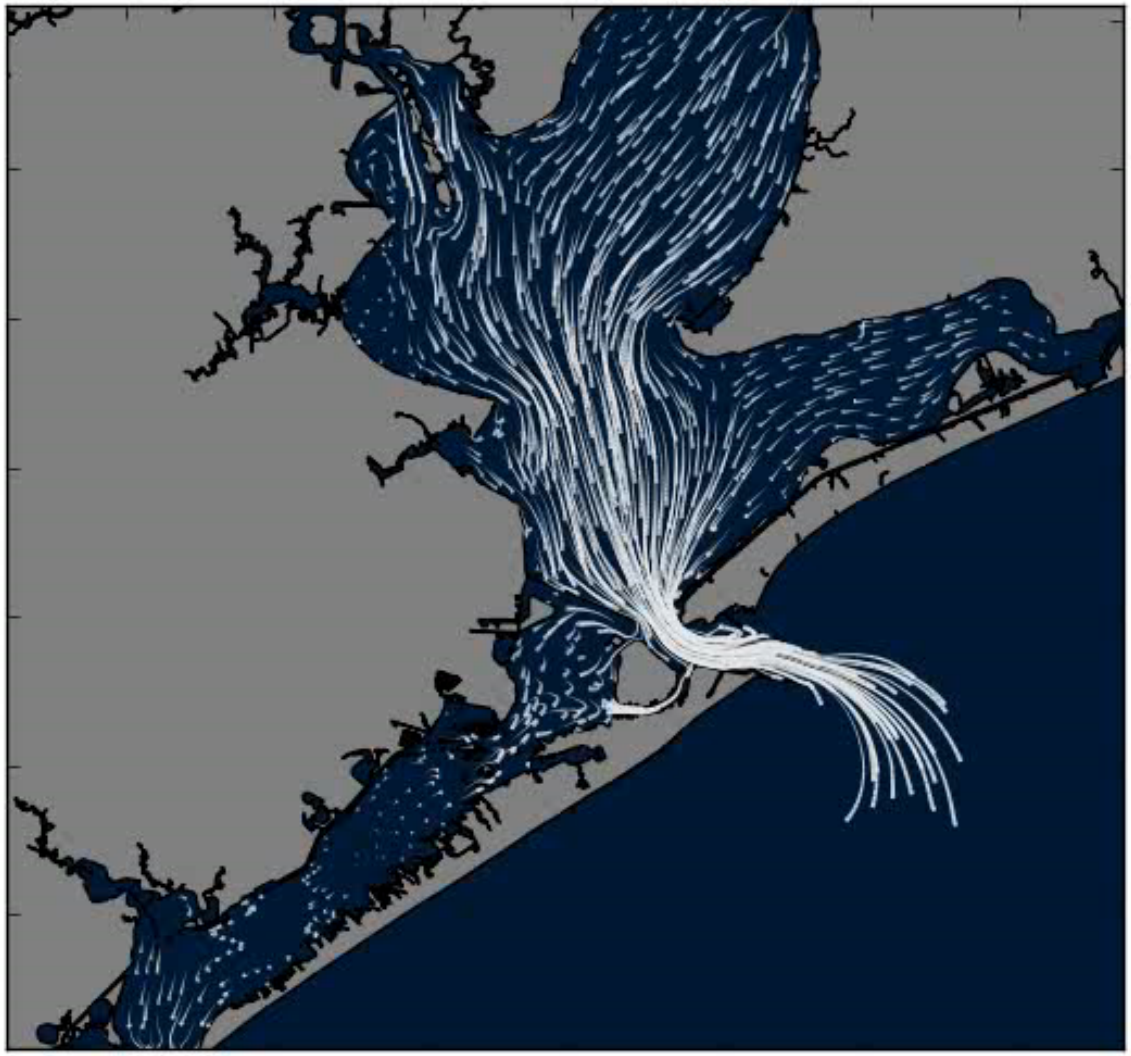
Matt Rayson

Bob and Norma Street Environmental Fluid Mechanics Laboratory
Department of Civil and Environmental Engineering
Stanford University

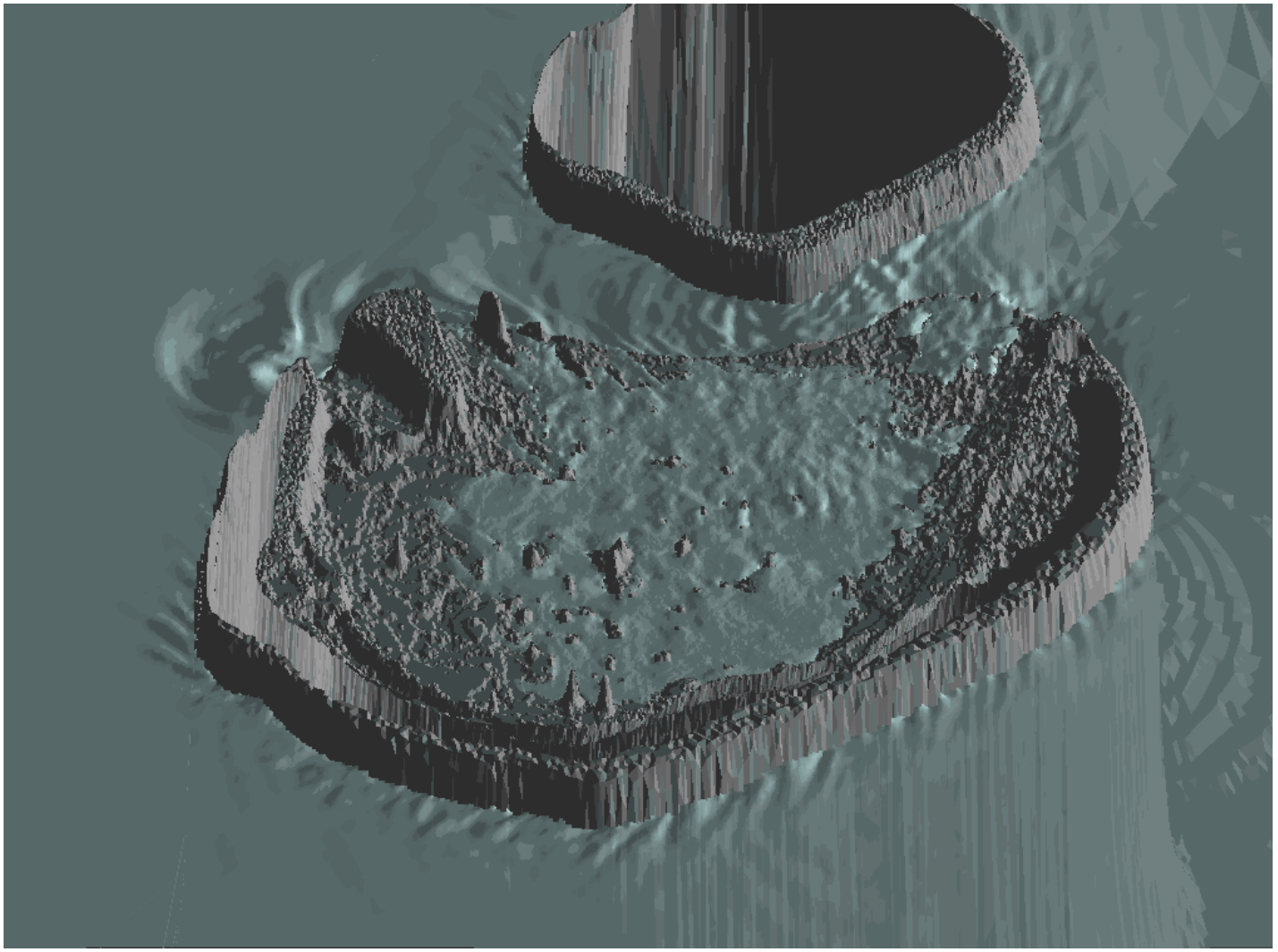
Outline

- Intro to coastal ocean modeling
- Estuarine circulation application
- Internal waves on the continental slope

Estuarine Circulation



Internal wave dynamics



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RANS equations for the coastal ocean

$$\frac{\partial u}{\partial t} + \nabla \cdot (\mathbf{u}u) - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \nabla_H \cdot (\nu_H \nabla u) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + \nabla \cdot (\mathbf{u}v) + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \nabla_H \cdot (\nu_H \nabla v) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial v}{\partial z}\right)$$

$$\frac{\partial w}{\partial t} + \nabla \cdot (\mathbf{u}w) + \frac{g}{\rho_0}(\rho_0 + \rho) = -\frac{1}{\rho_0}\frac{\partial p}{\partial z} + \nabla_H \cdot (\nu_H \nabla w) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial w}{\partial z}\right)$$

Momentum

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Continuity

$$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u}T) = \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right) + \frac{1}{\rho c_p}\frac{\partial Q_{sw}}{\partial z}$$

$$\frac{\partial s}{\partial t} + \nabla \cdot (\mathbf{u}s) = \frac{\partial}{\partial z}\left(K_S \frac{\partial s}{\partial z}\right)$$

Tracer transport

$$\rho = \rho(s,\ T,\ p)$$

Equation of State

Numerical Model Overview

- SUNTANS

  Stanford **U**nstructured **N**onhydrostatic **T**errain-following **A**daptive **N**avier-Stokes **S**imulator

- Solves 3D Reynolds-averaged Navier-Stokes equations
- Hydrostatic or nonhydrostatic

$$\frac{\partial w}{\partial t} + \nabla \cdot (\mathbf{u}w) + \frac{g}{\rho_0}(\rho_0 + \rho) = -\frac{1}{\rho_0}\frac{\partial p}{\partial z} + \nabla_H \cdot (\nu_H \nabla w) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial w}{\partial z}\right)$$

- Unstructured horizontal mesh
- Finite-volume discretization
- Fixed z-level vertical coordinate

Reference:

Fringer *et al*., 2006, *Ocean Modelling*

Code overview

- Written in C
- Parellized with MPI
- ParMETIS used for grid partitioning
- All solvers (CG, tri-diag) internal – no libraries
- NetCDF binary format for model IO

Source code:

github.com/ofringer/suntans

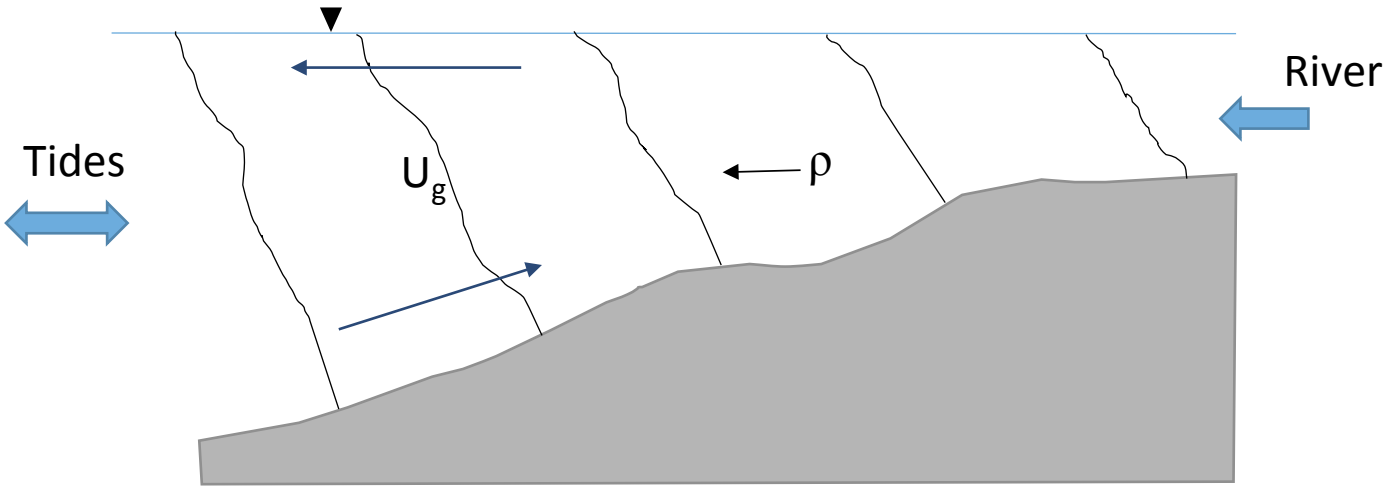
Main Challenges

- Obtaining high-quality observations
- Adequately resolving geometry (shoreline and topography)
- Specifying time and space varying surface and lateral boundary condition data
- Sub-grid scale parameterizations

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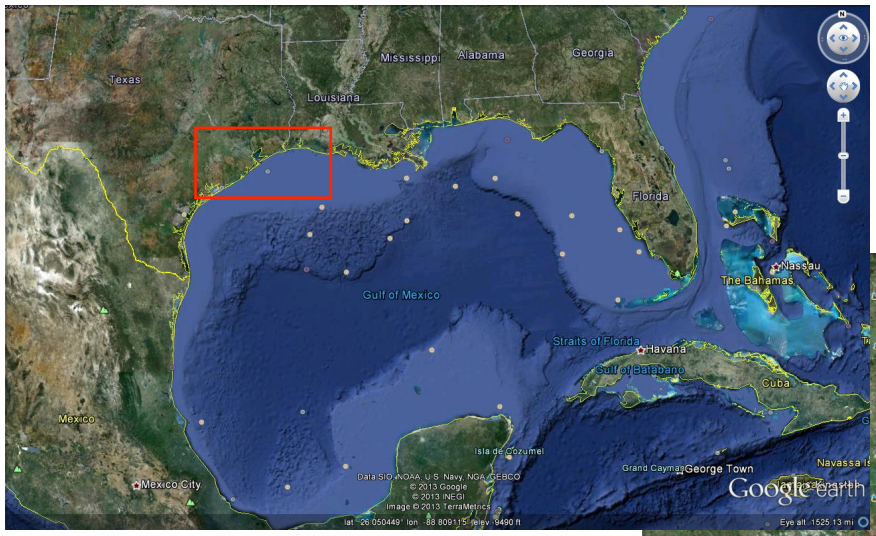
Estuarine Circulation

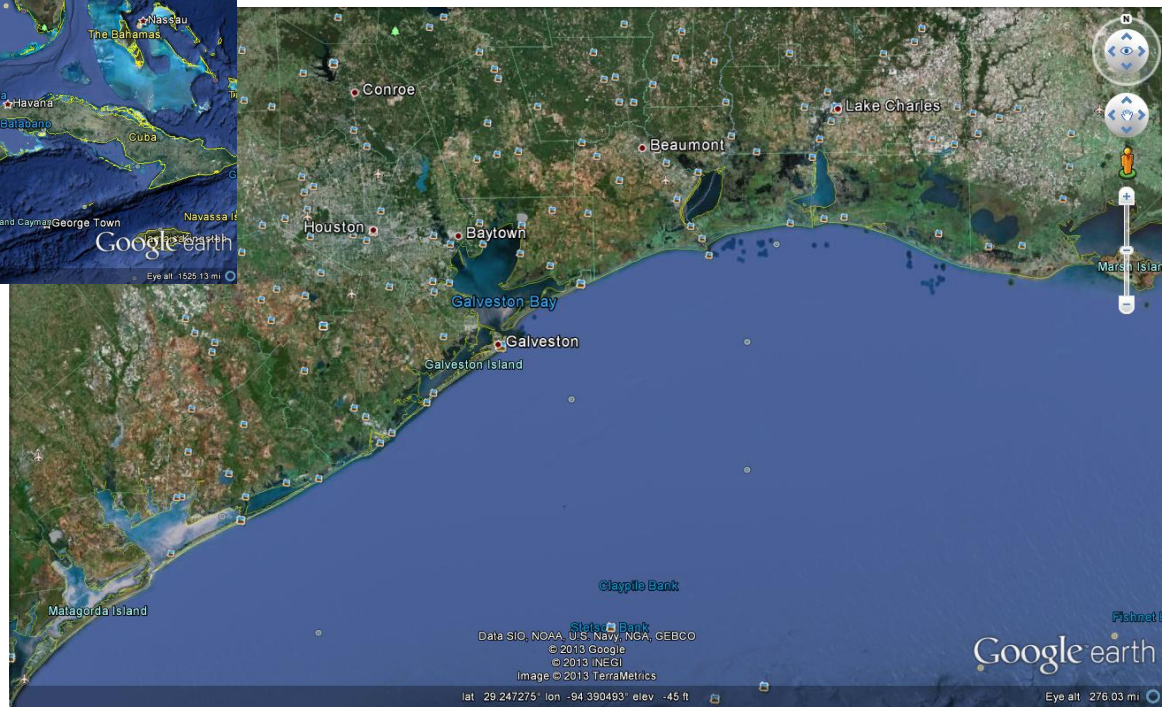


$$U\downarrow g \sim g\beta\partial S/\partial x\, H\uparrow 3\ /\nu\downarrow t \equiv gravitational\ effects/mixing\ effects$$

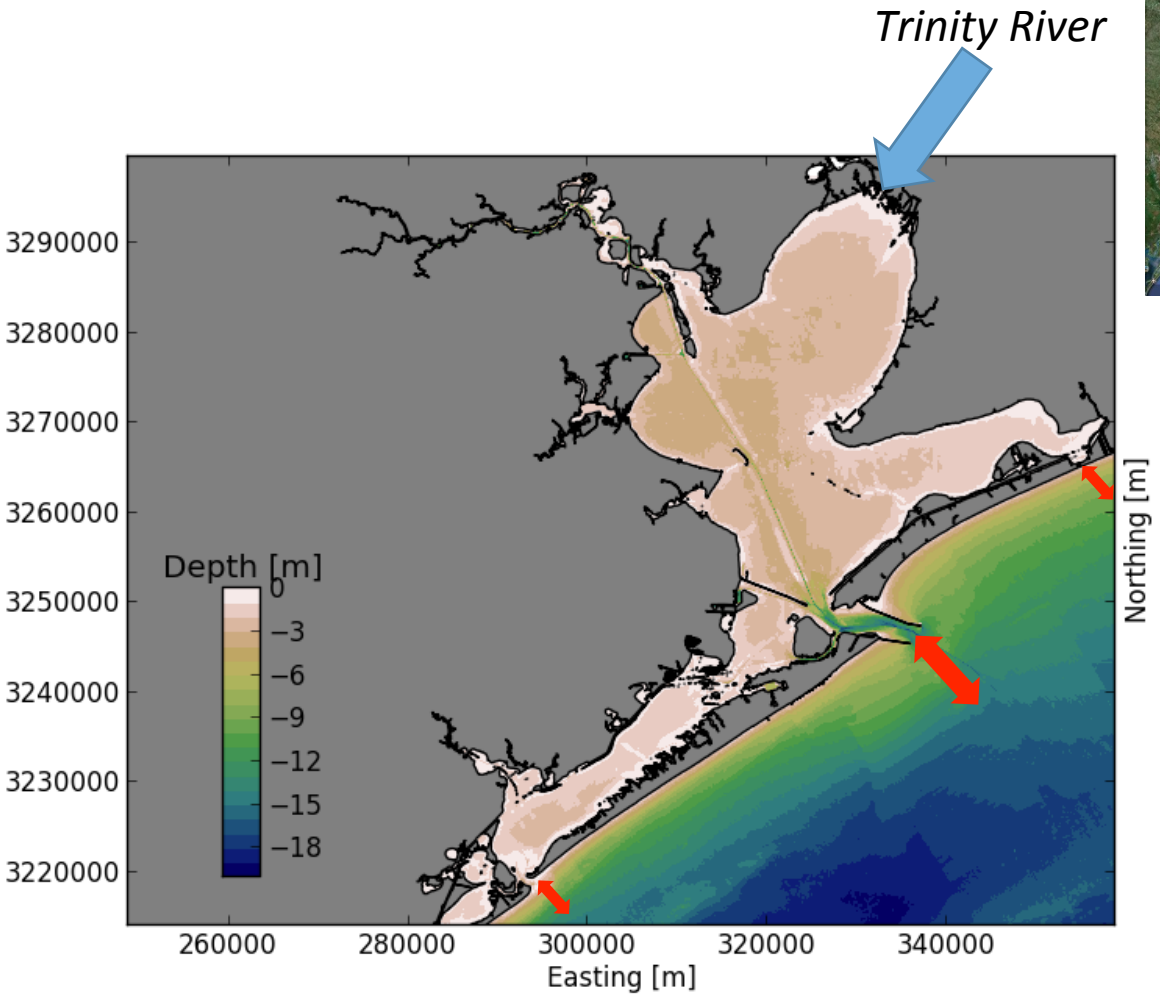
(Monismith et al., 2002)

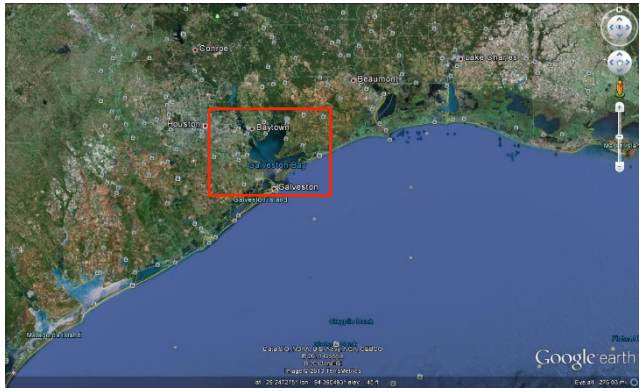
Gulf Estuaries





Galveston Bay





Wide and shallow,

with a shipping channel

Narrow passages into Gulf

Trinity River main freshwater source

Motivation



- Transport and fate question
  - *Where will an oil spill go?*
- Ecological questions
  - *How does salt concentration and/or water temperature vary with river flow?*
  - *What is the residence time of different parts of the bay?*

Circulation Driving Forces

Mechanical forcing:

- Water level variations (tides, weather systems)
- Wind stress

Buoyancy forcing:

- River discharge
- Surface heating and cooling
- Evaporation and precipitation
- Coastal buoyancy currents (Mississippi River plume)

Numerical model requirements

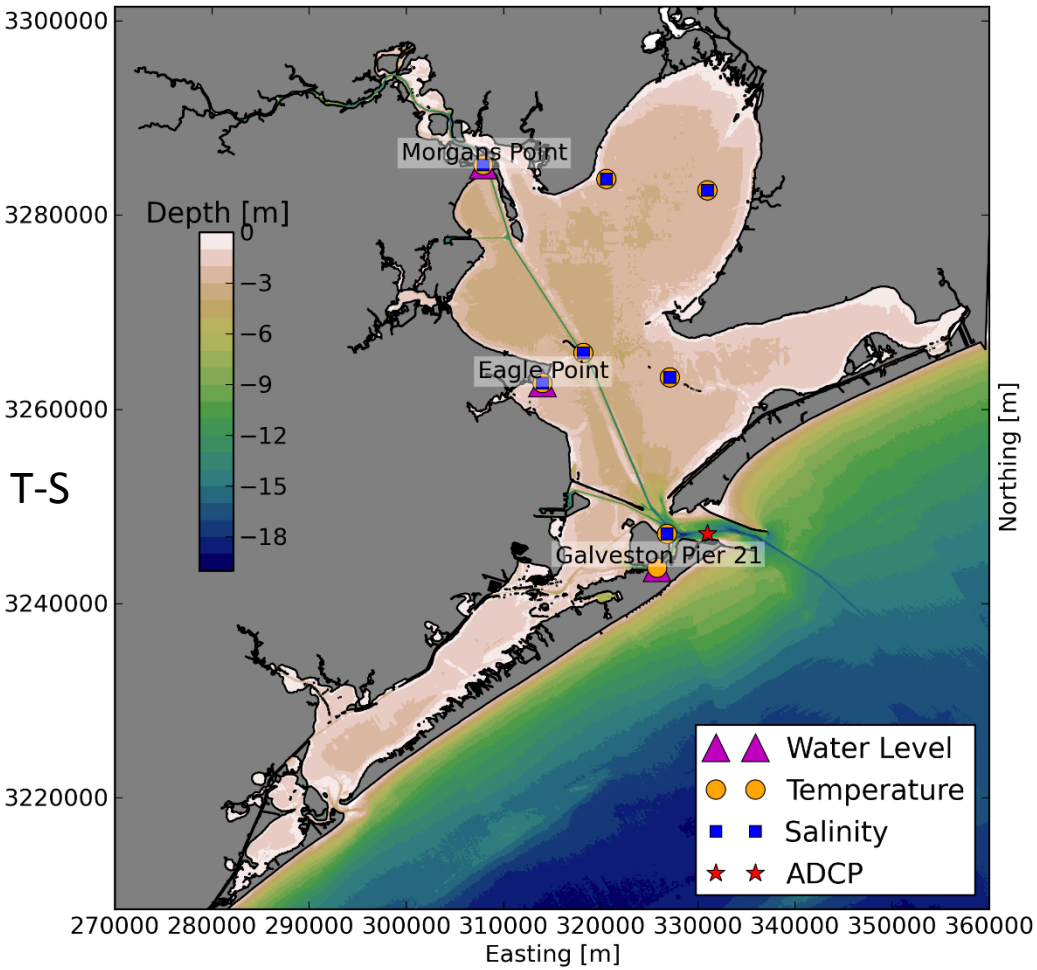
To develop a suitable hydrodynamic for Galveston Bay model we need to:

- Obtain suitable observations for validation
- Resolve complex geometry with grid
- Include all surface forcing processes (wind, heat fluxes)
- Include all lateral open boundary data (temp, salinity, tides and water level, rivers)

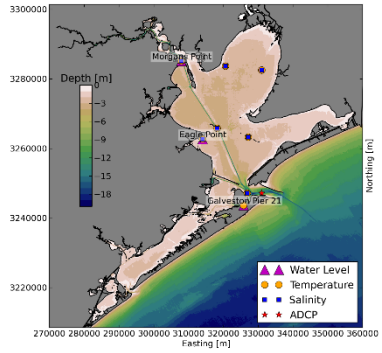
Observations

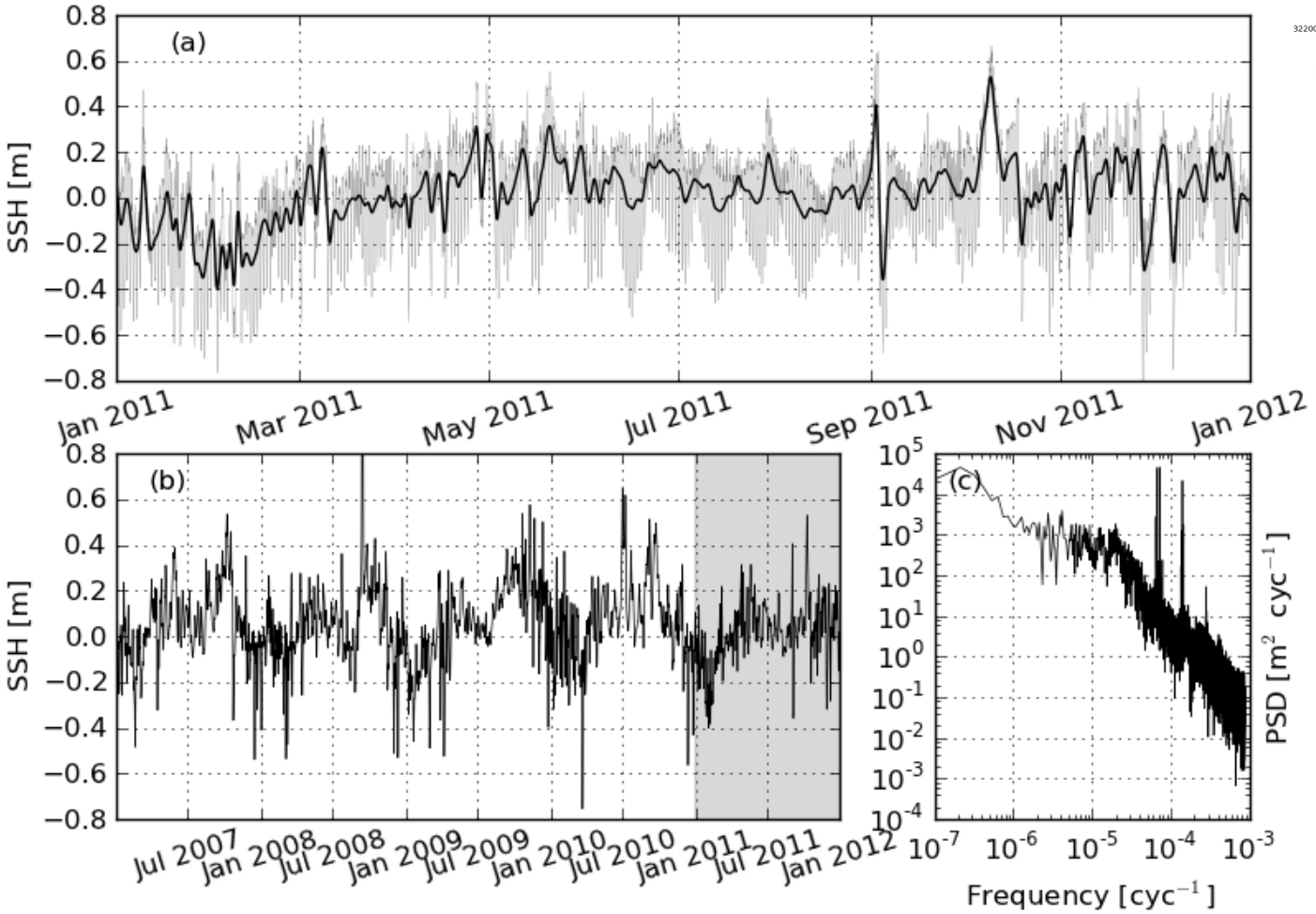
Long-term monitoring (1990 -> Present):

- NOAA-IOOS: water level, T
- NOAA PORTS: currents
- Texas Water Development Board: T-S

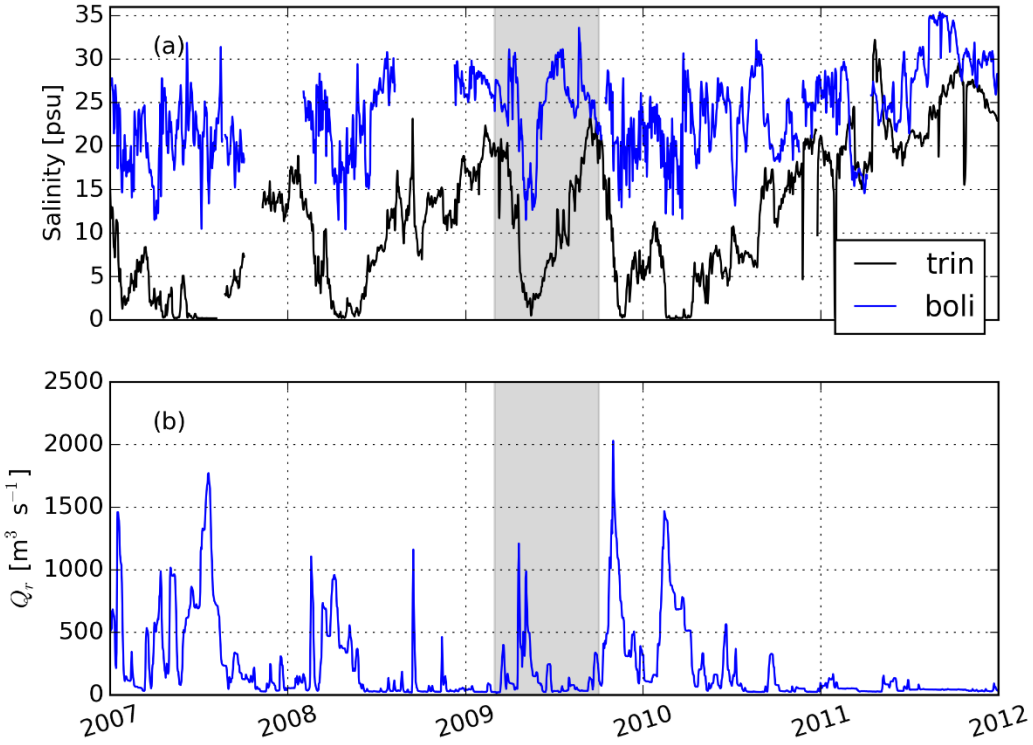


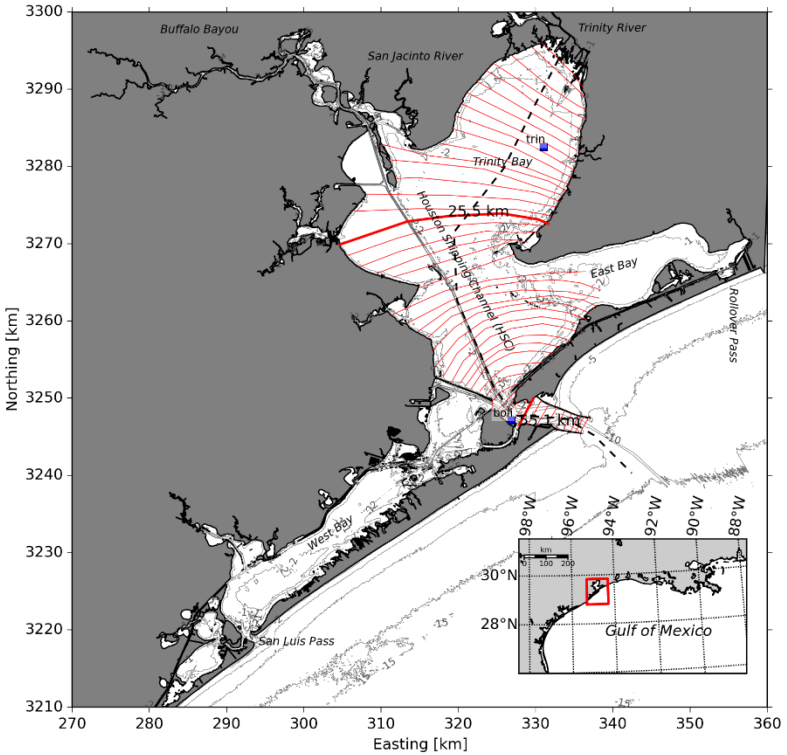
Water level variability





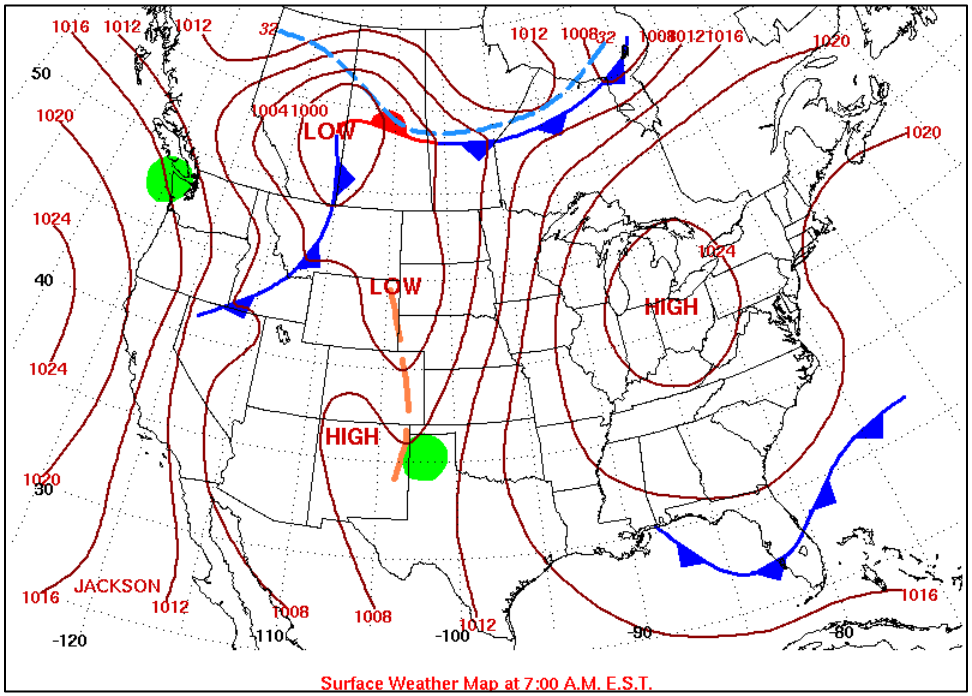
Salinity variability





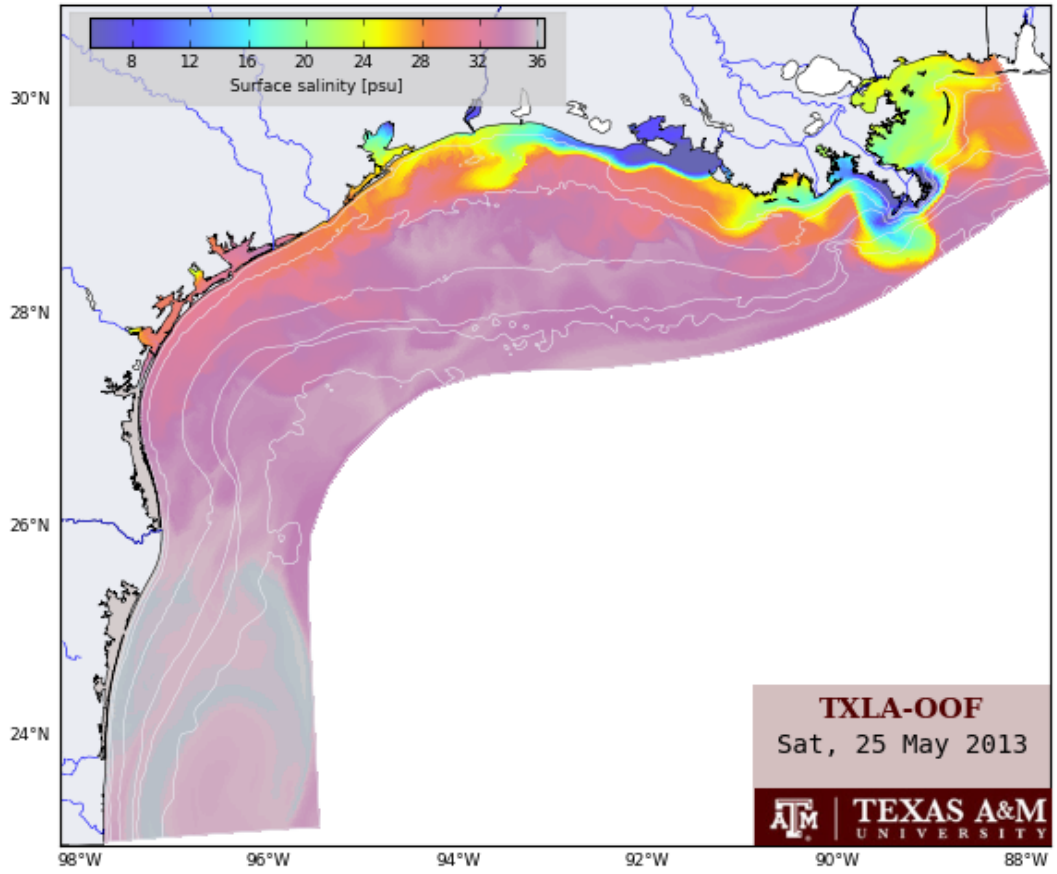
Meteorological Forcing

- Prevailing S-SE Winds
- NW'ly low pressure systems (winter)
- Summer seabreeze
- Hurricanes



→ *Drive water level variability and surface currents directly*

Shelf Circulation

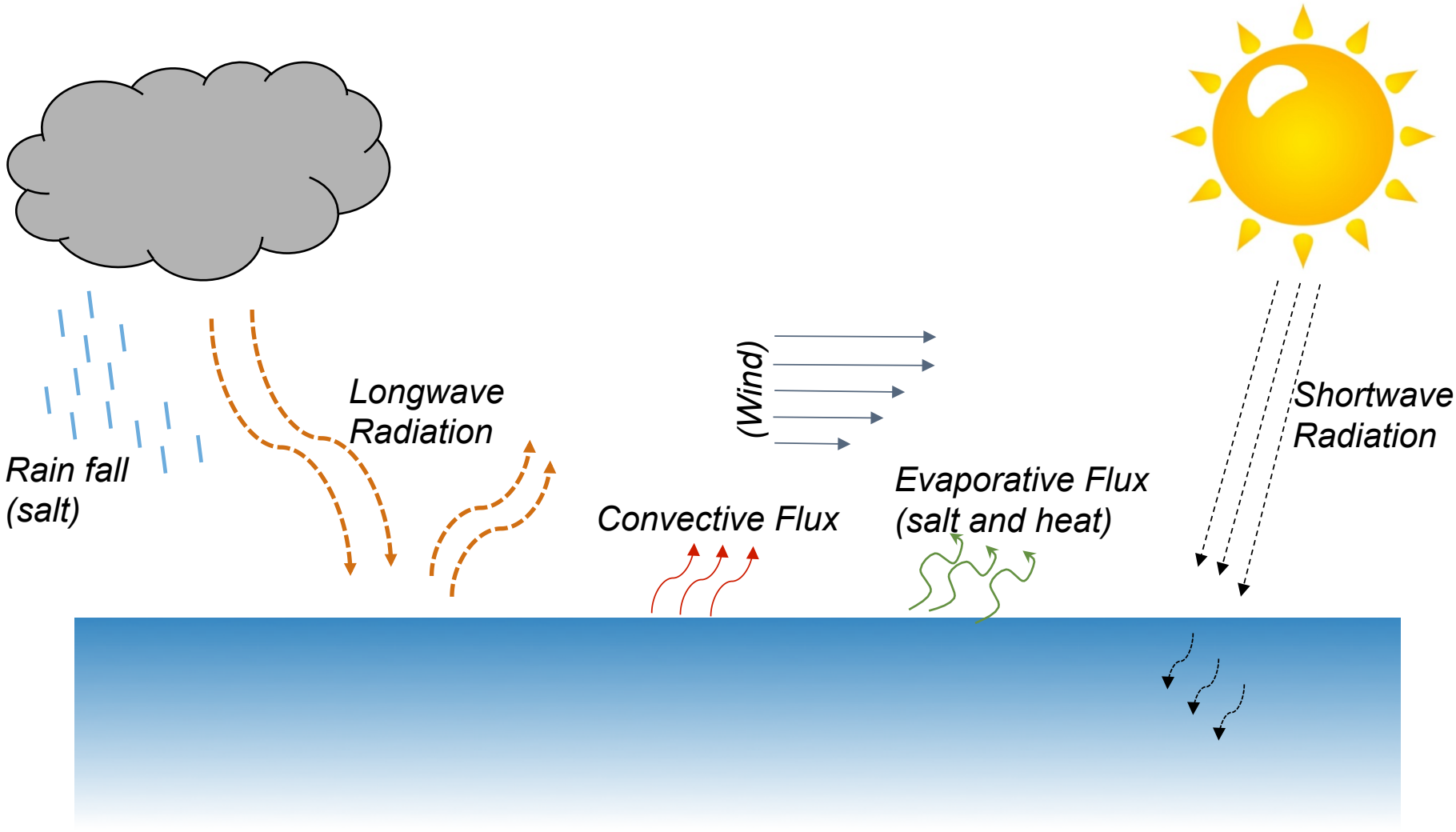


Modifies:

- Coastal water level
- Temperature and salinity

http://pong.tamu.edu/~mma/oof/main/forecast.php

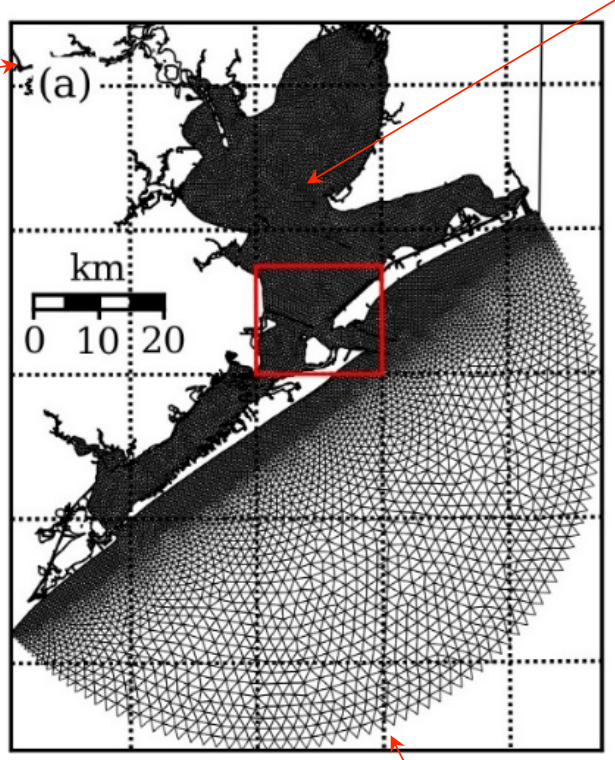
Surface buoyancy fluxes



3D SUNTANS Model of Galveston Bay

Model Inputs:

USGS gauged river flows



NCEP NARR model for atmospheric forcing (wind and heat surface boundaries)

- Realistic tides (OSU TPXO model)
- ROMS coastal boundaries (Hetland Group @ Texas A&M)

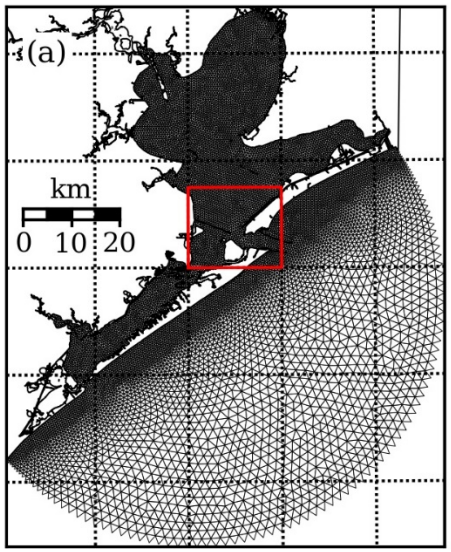
SUNTANS Grids

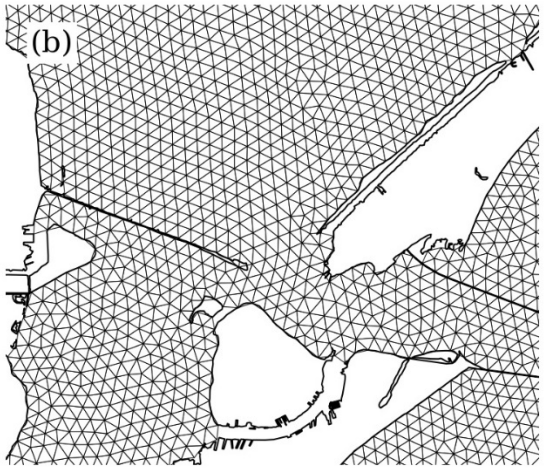
1. Coarse Triangular (b)
   N = 21,484
   dx = 400 m
2. Fine triangular (c)
   N = 59,818
   dx = 100 m
3. Mixed quad-tri (d)
   N = 57,305
   dx = 100 m

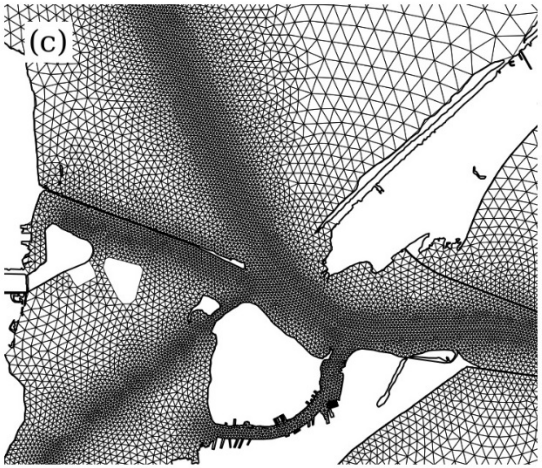
20 vertical layers
dz = 0.5 m
~10^5 total 3d cells

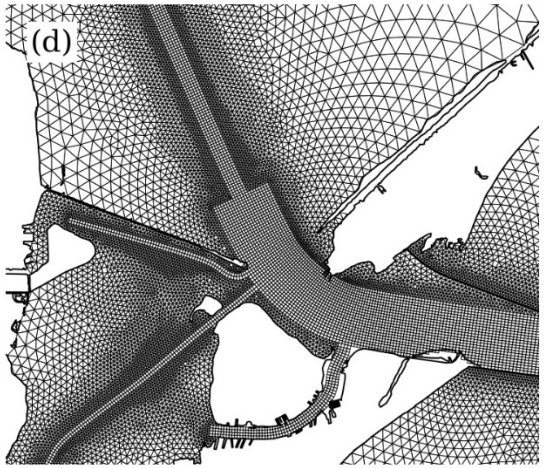
Run time:

20x real-time with 64 CPUs



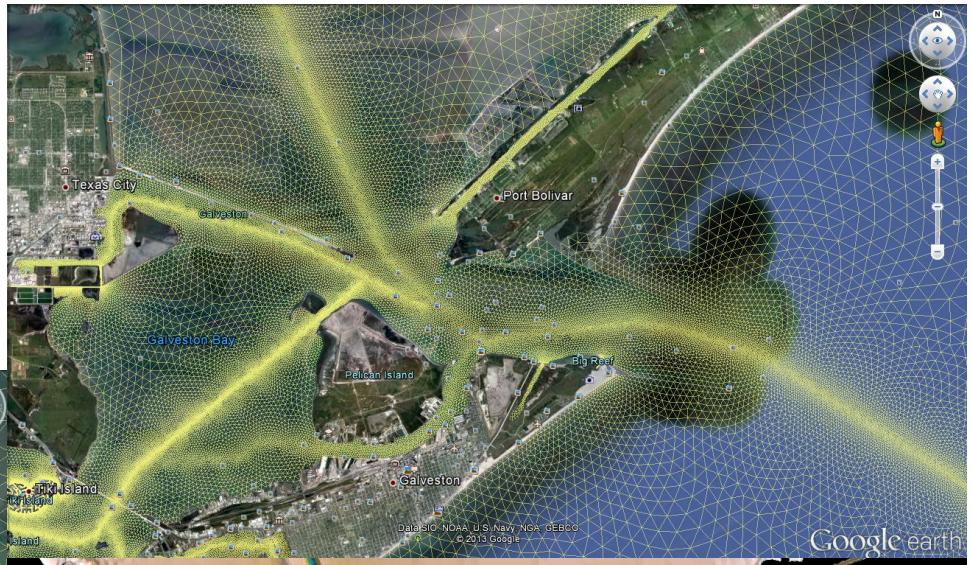


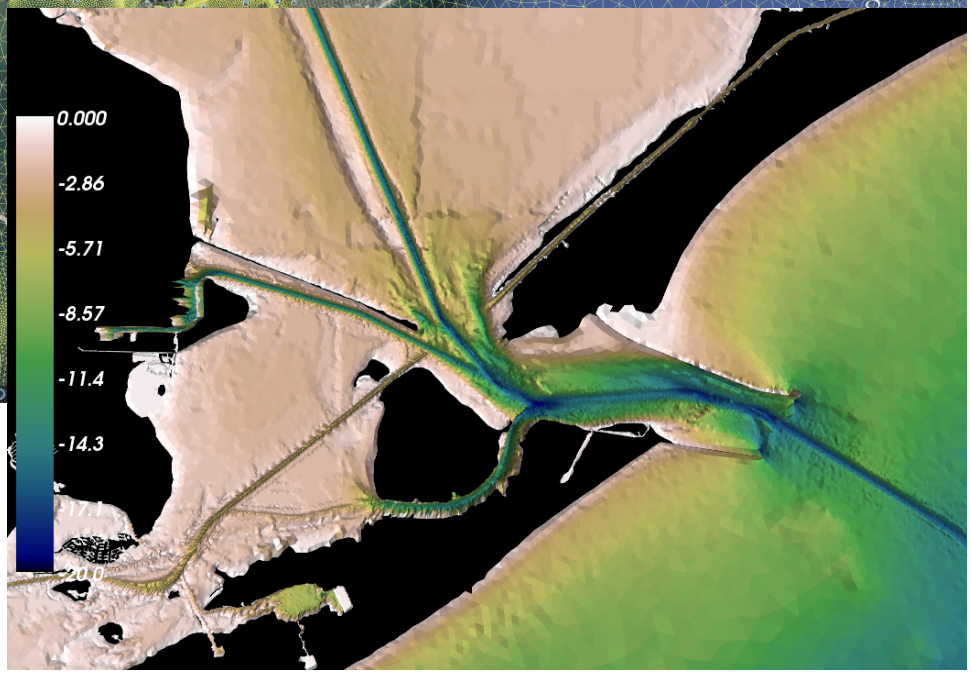




Unstructured grid



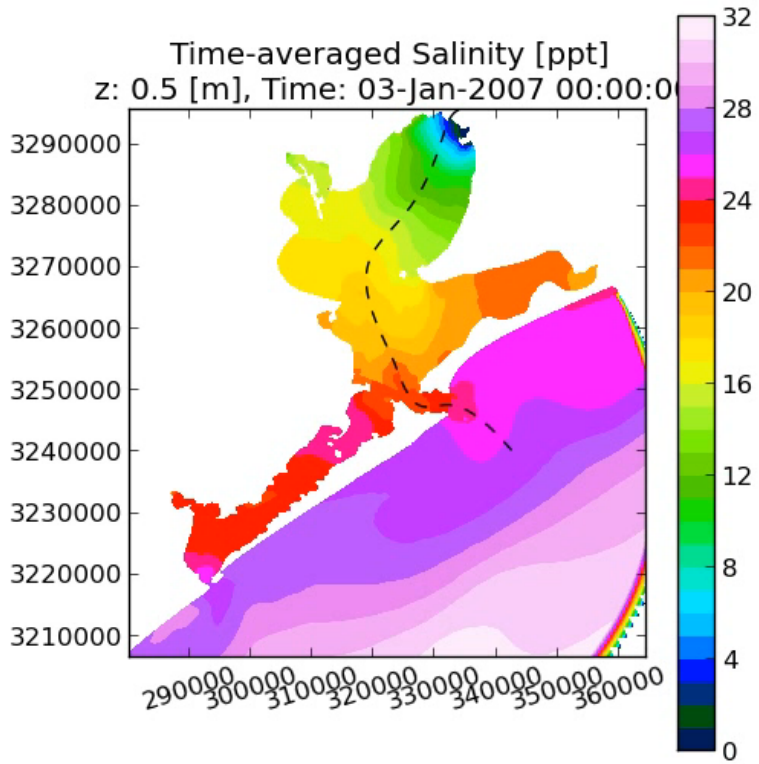


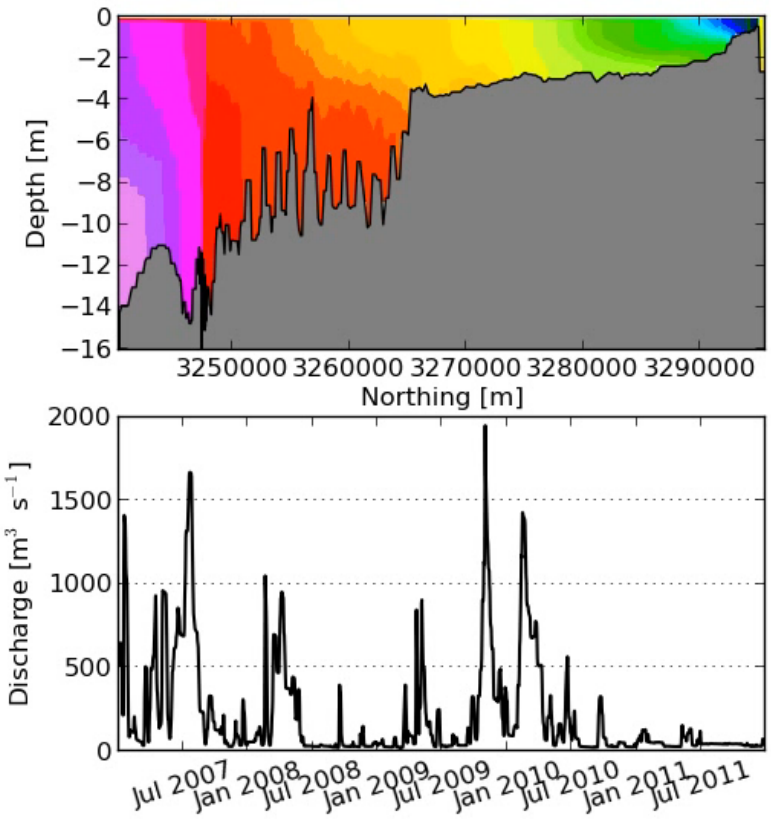


Salinity response to river forcing

Ocean

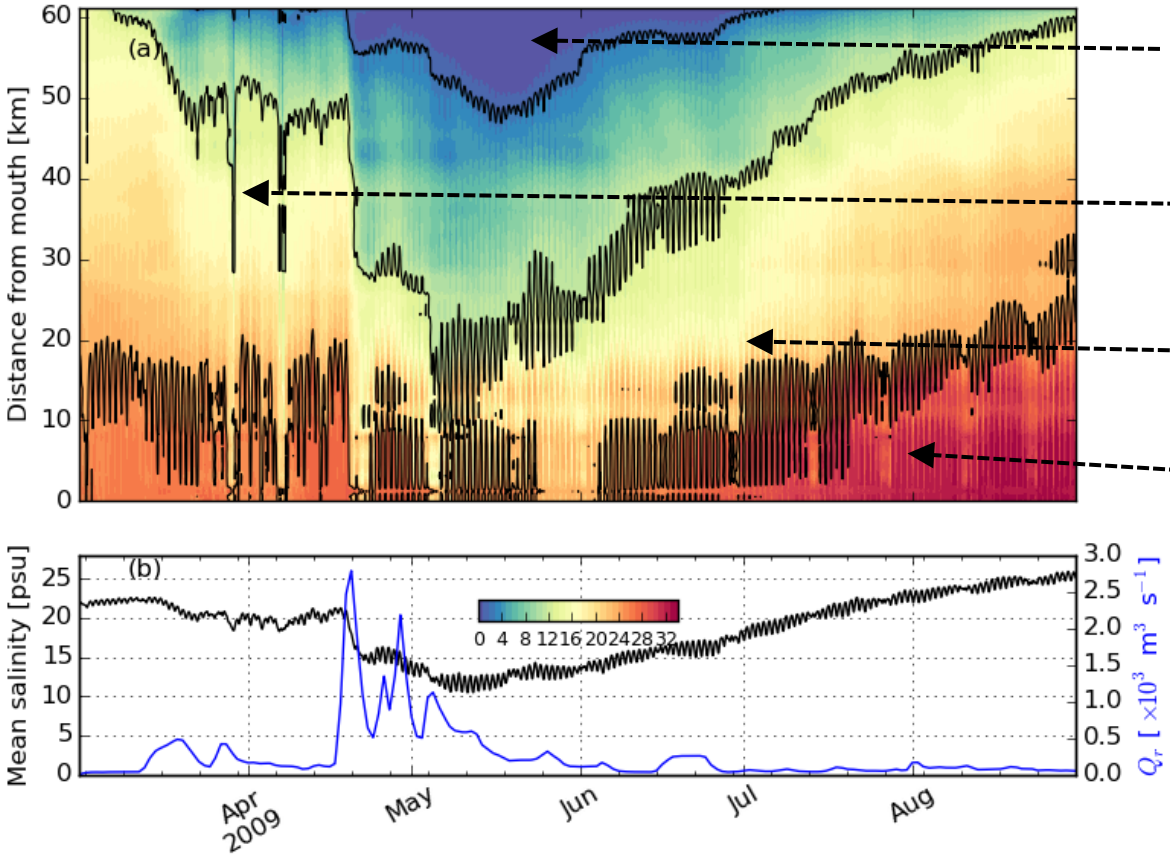
River





Salinity response to forcing

Cross-sectional average salinity: $\overline{s}^{yz}(x,\ t) = \frac{1}{A}\int_{-b/2}^{b/2}\int_{-d}^{\eta} s(x,\ y,\ z,\ t)\ dz\ dy$



River discharge (*note lag*)

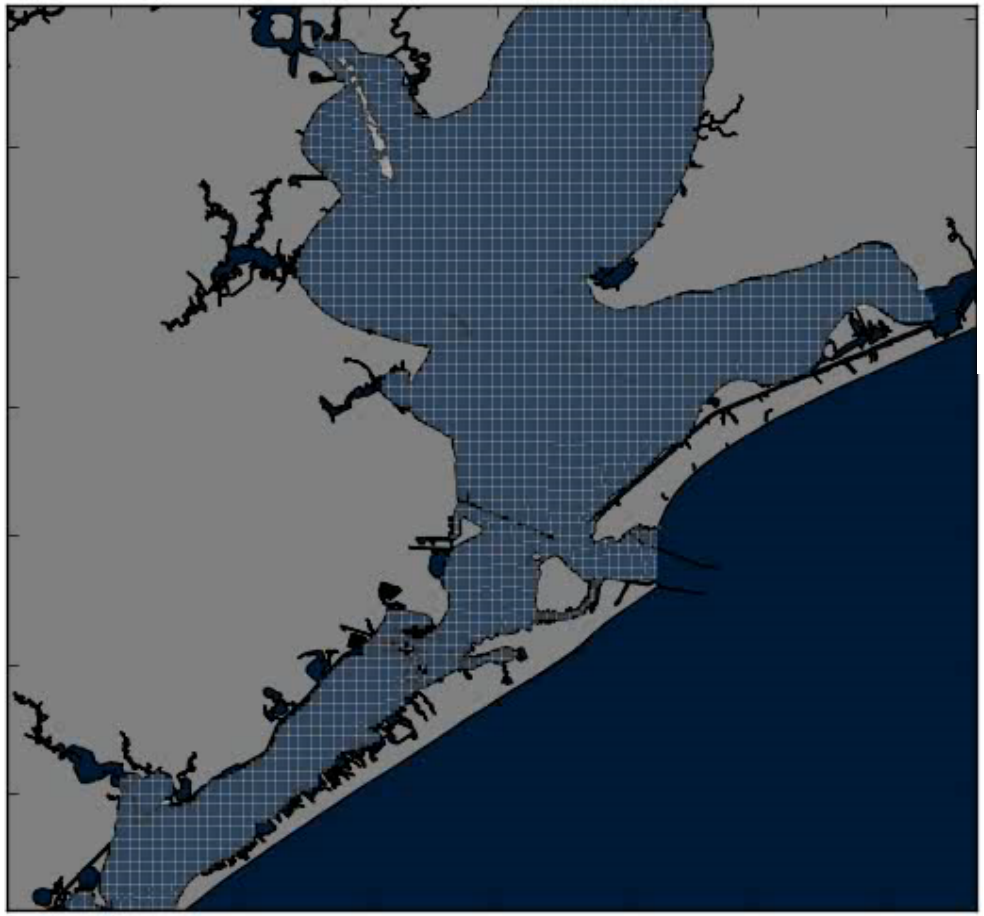
Storms (*wind stress an water level*)

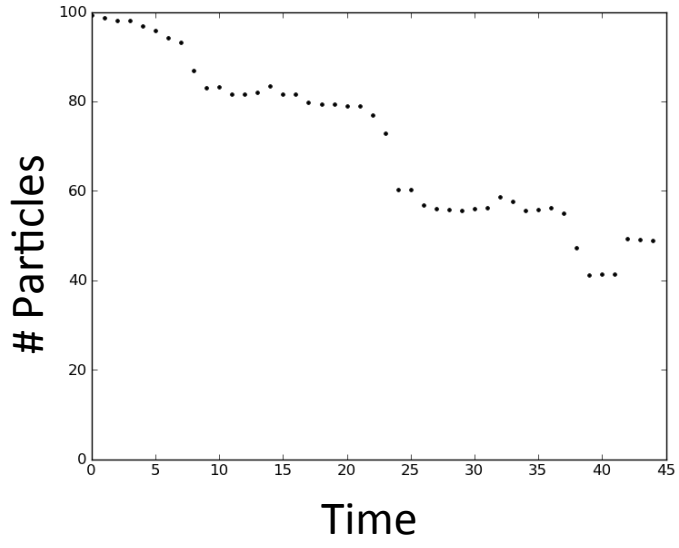
Tides

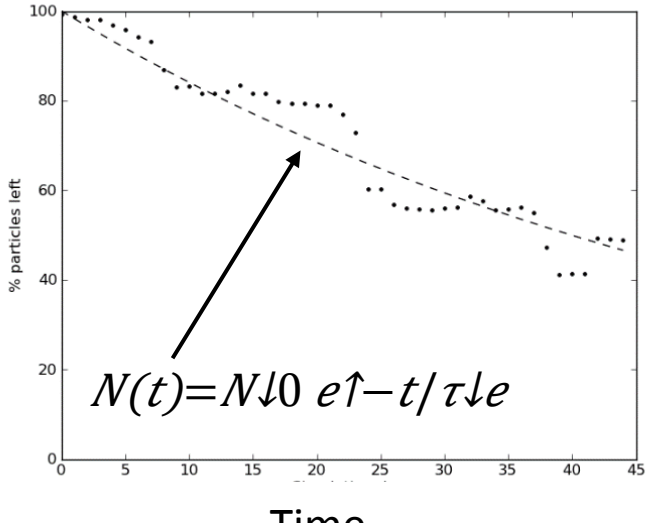
Coastal salinity

→ **Salinity is unsteady due to transient forcing**

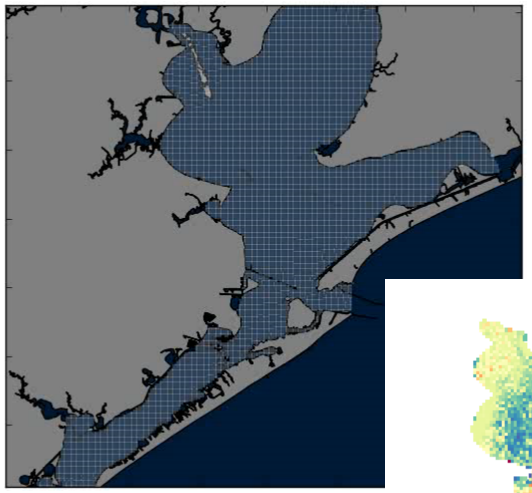
Flushing time

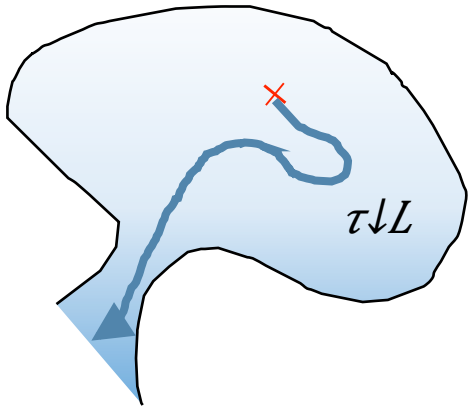


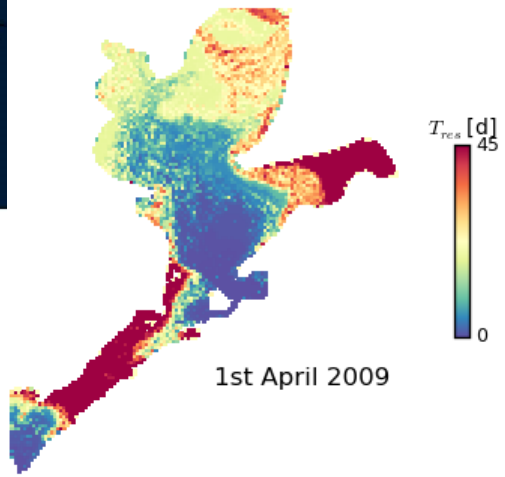


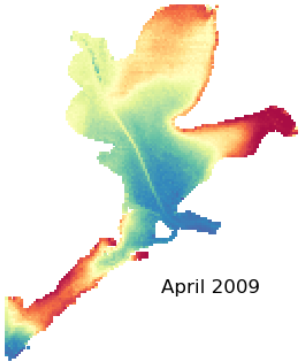


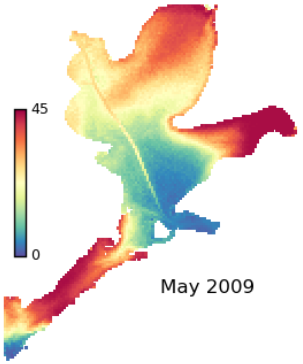
Lagrangian residence time

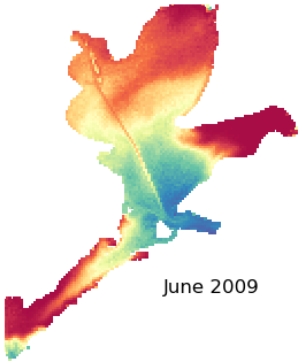












Summary - Estuaries

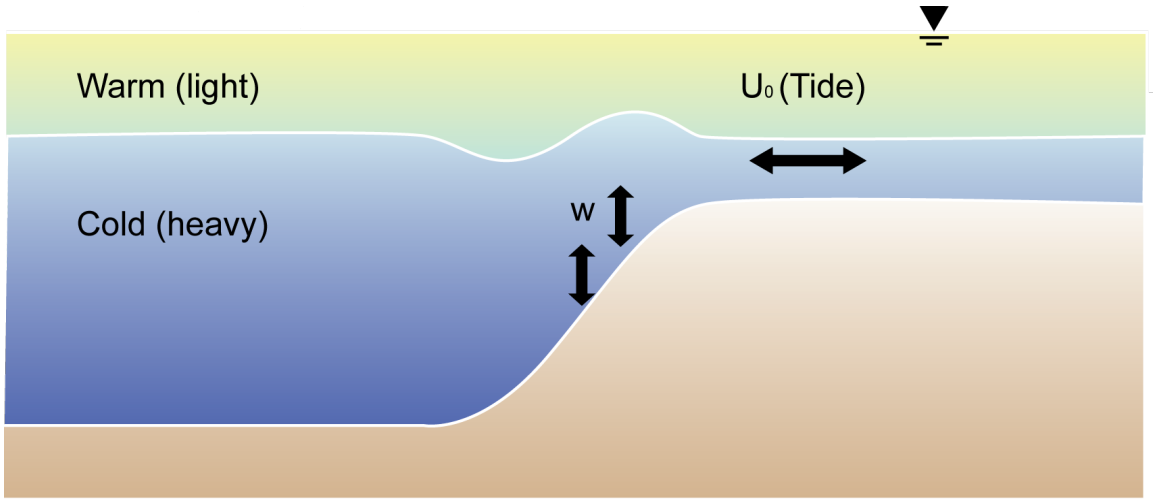
- Flow driven by balance between pressure gradients and vertical mixing
- Challenges with obtaining suitable observations and boundary condition data
- Unsteady time-dependent problem subject to variations in forcing

Outline

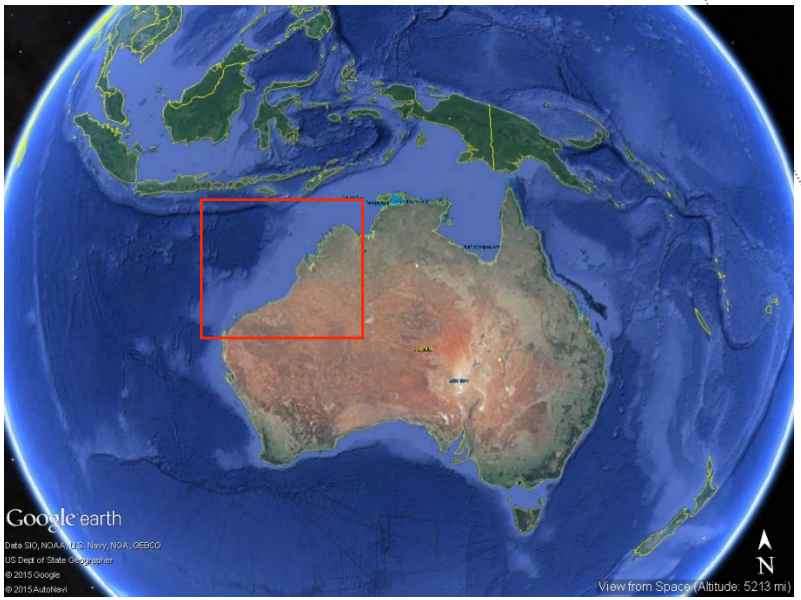
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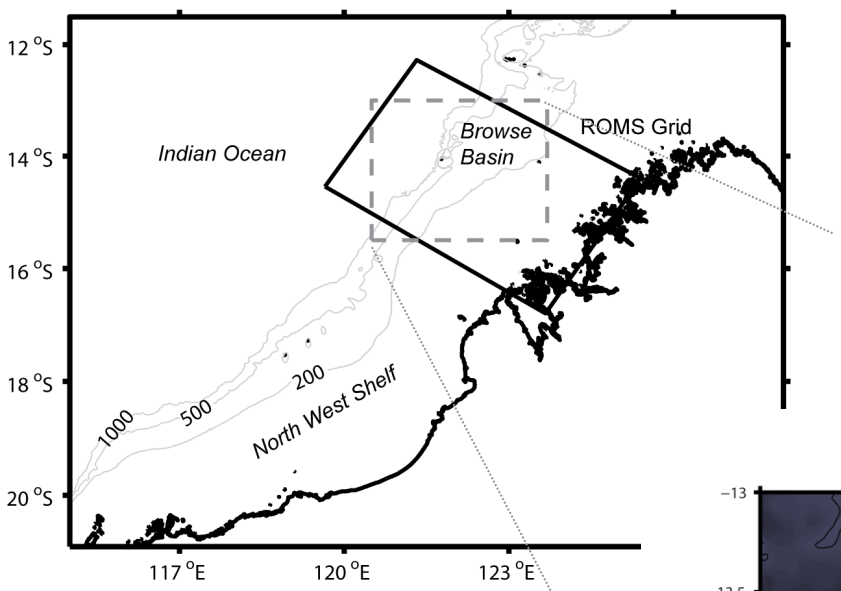
Internal wave background

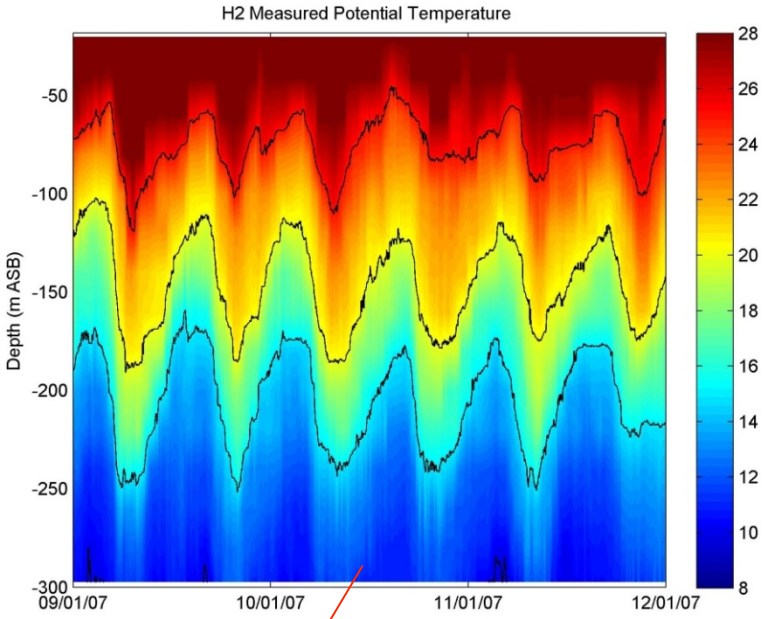
$$w_{bottom} = \vec{u} \cdot \nabla H$$

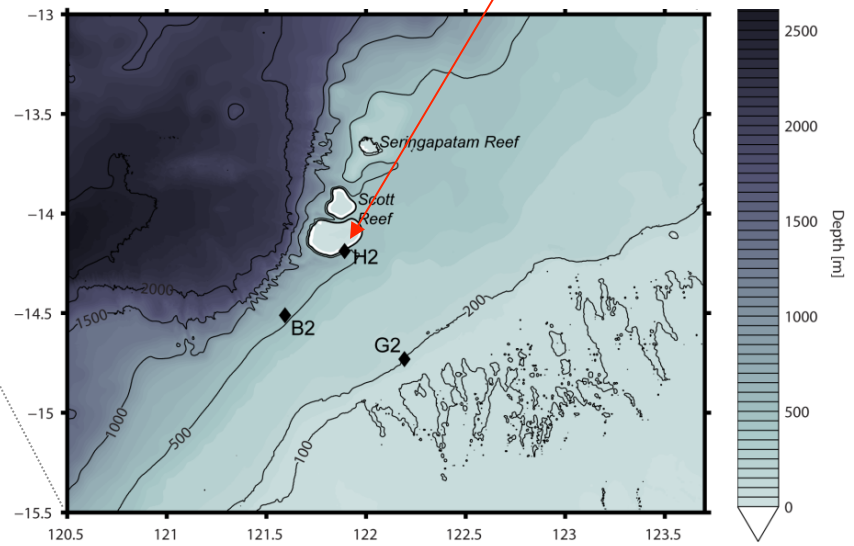


Observations

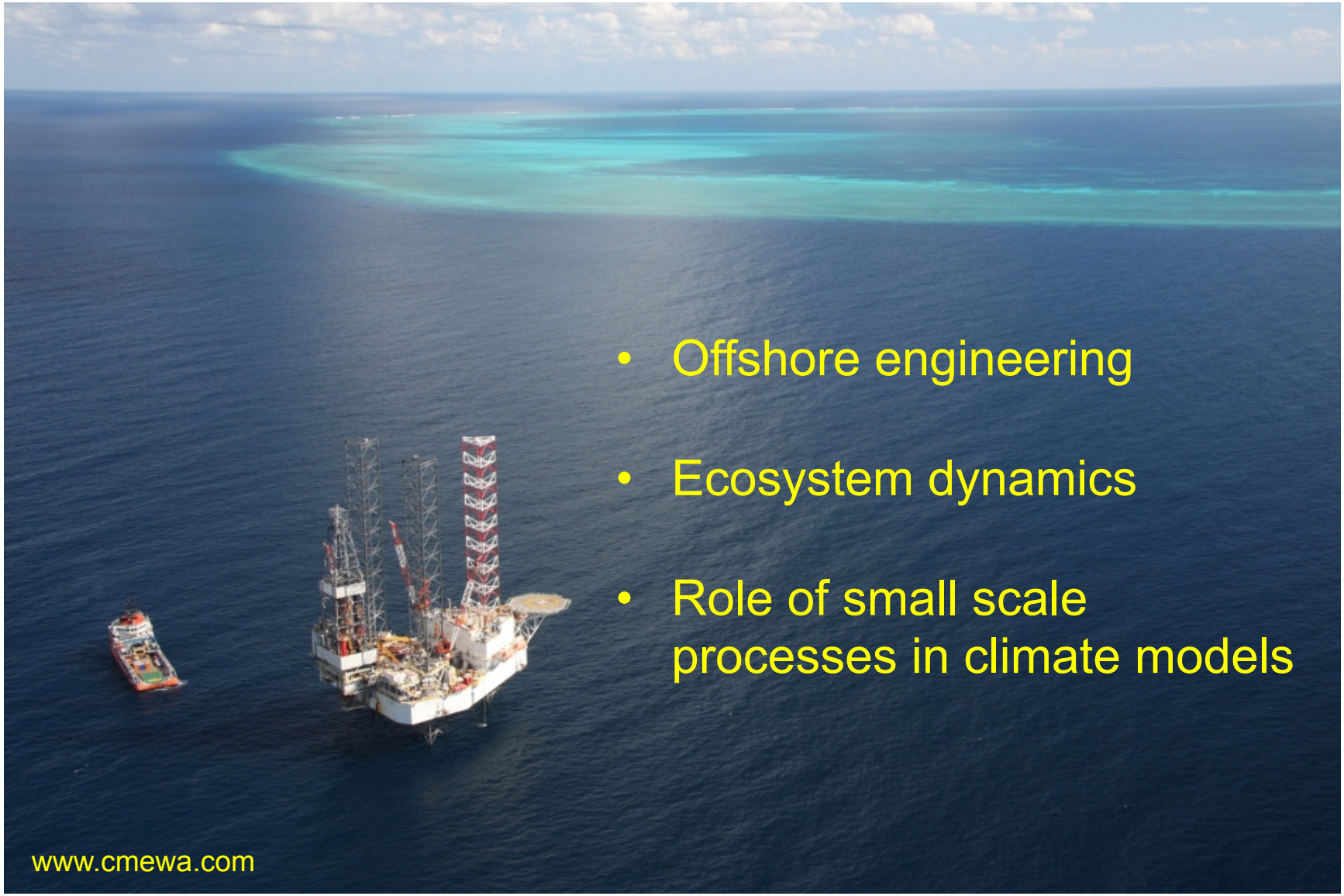




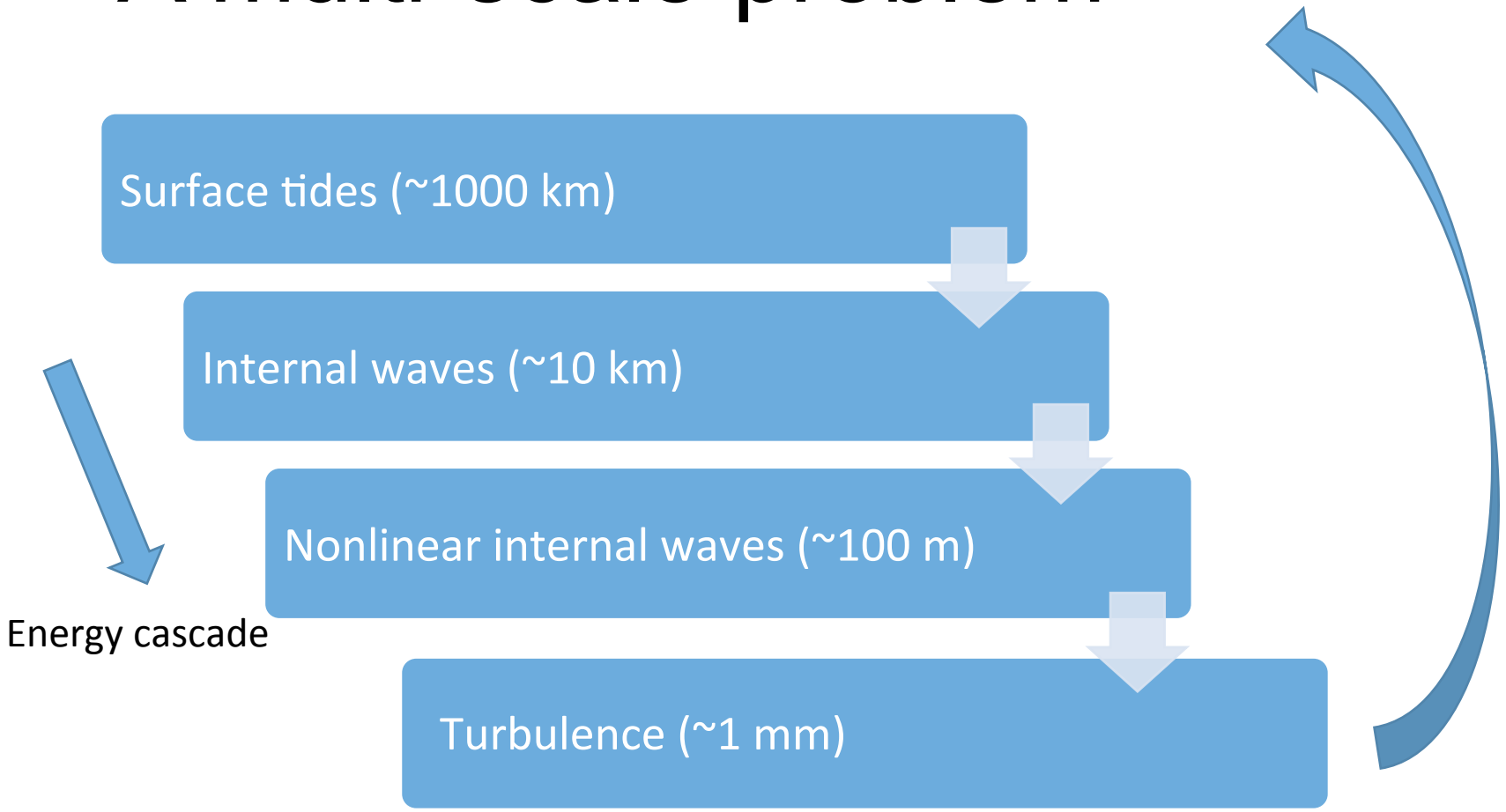




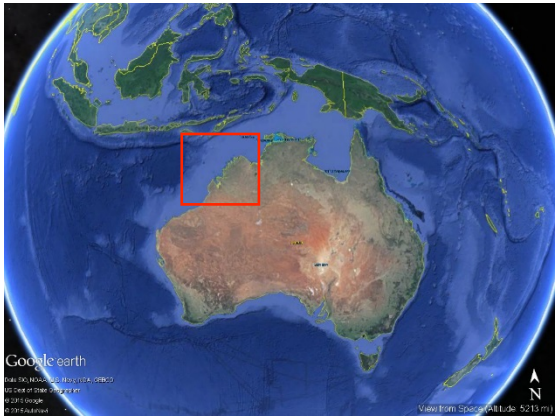
Motivation

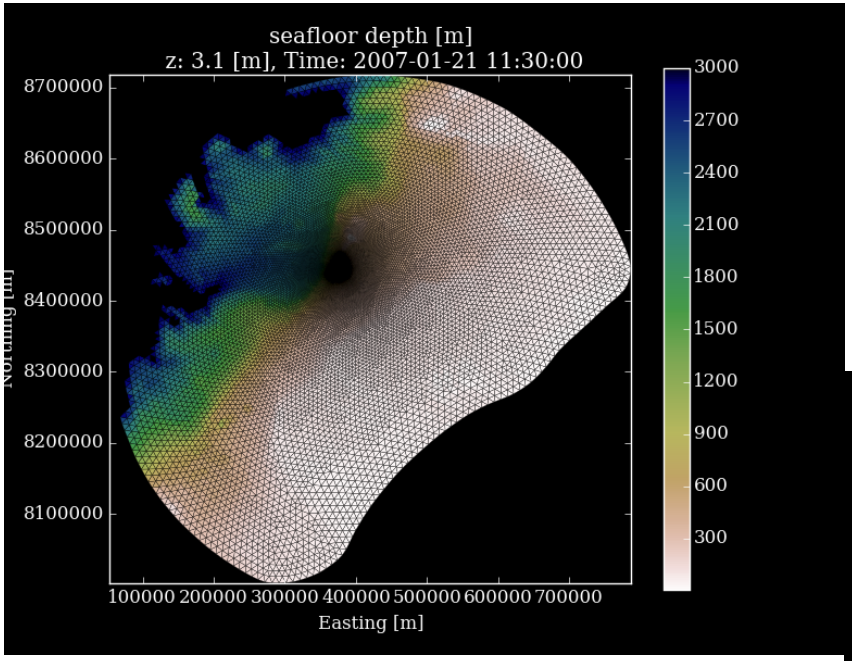

• Offshore engineering
• Ecosystem dynamics
• Role of small scale processes in climate models
www.cmewa.com

A multi-scale problem



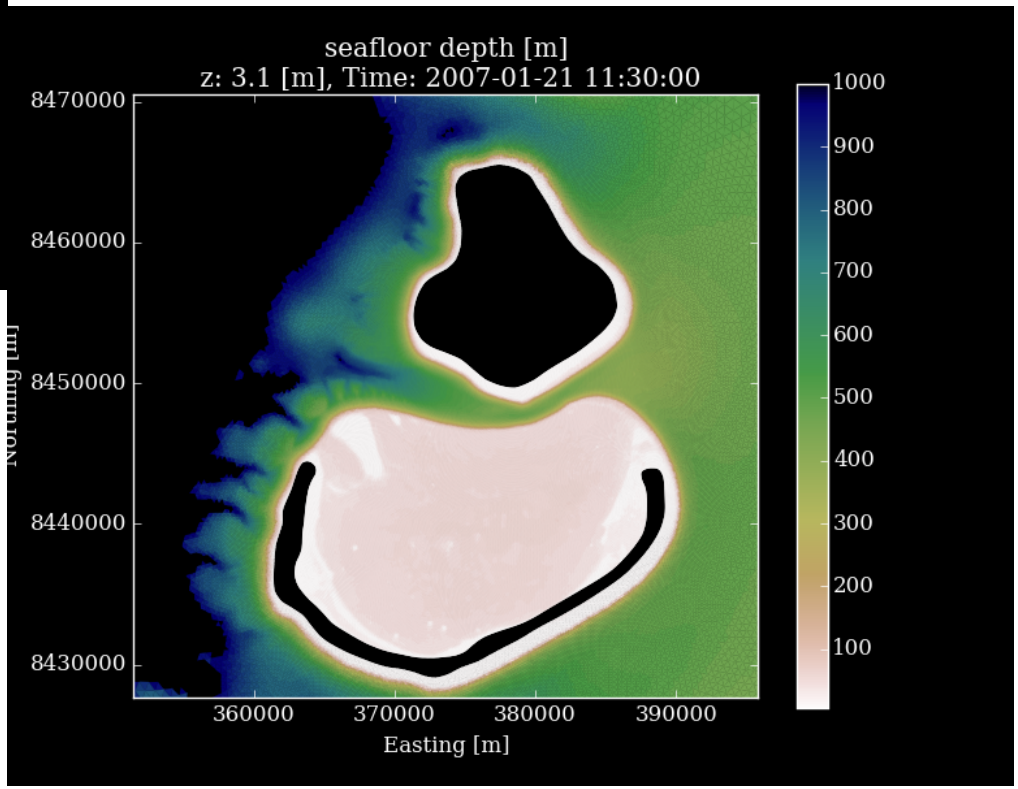
SUNTANS model





≈800 km

≈30 km

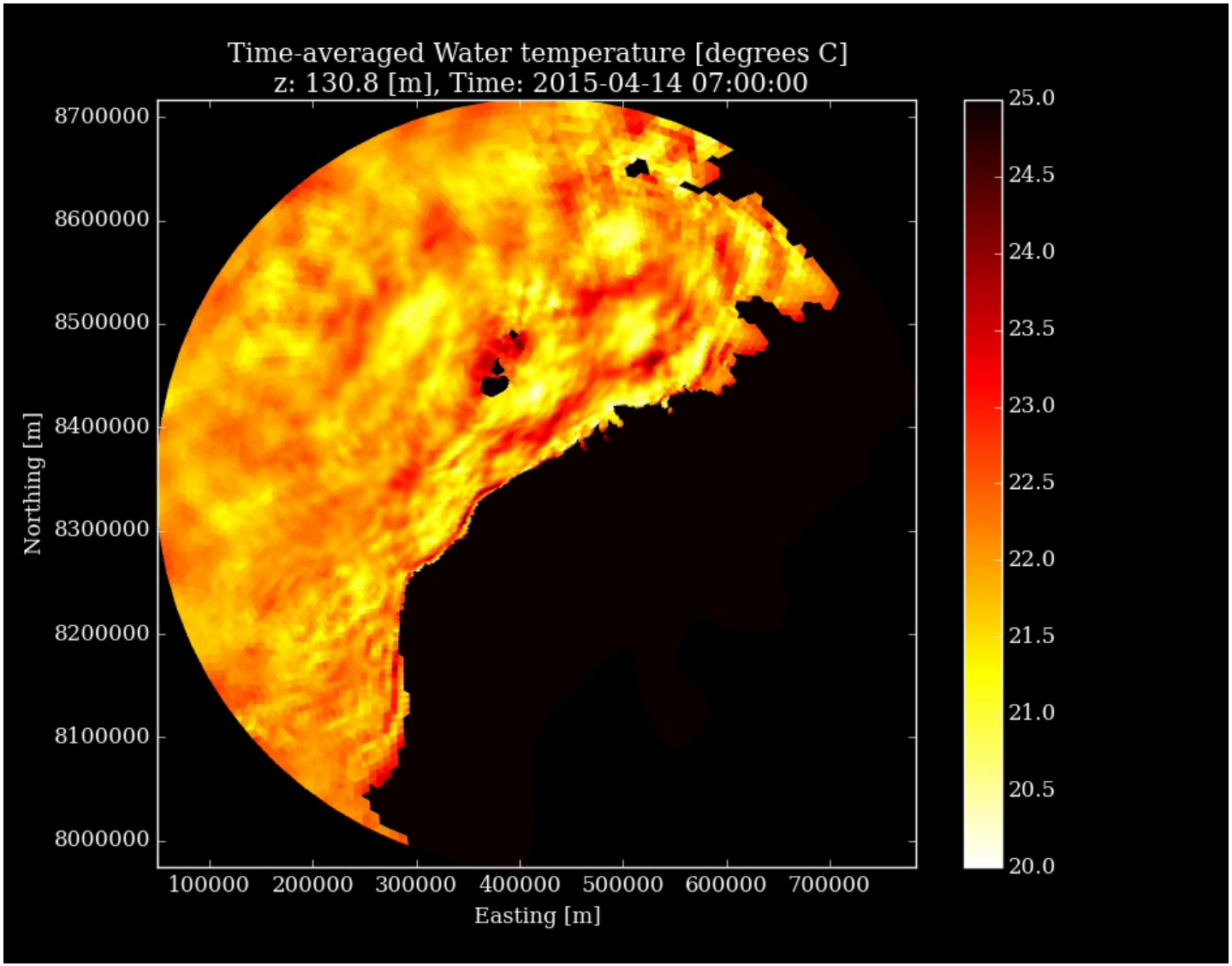


- dx = 100 – 10000 m
- dz = 5 – 50 m (150 layers)
- ~10^6 total 3D cells

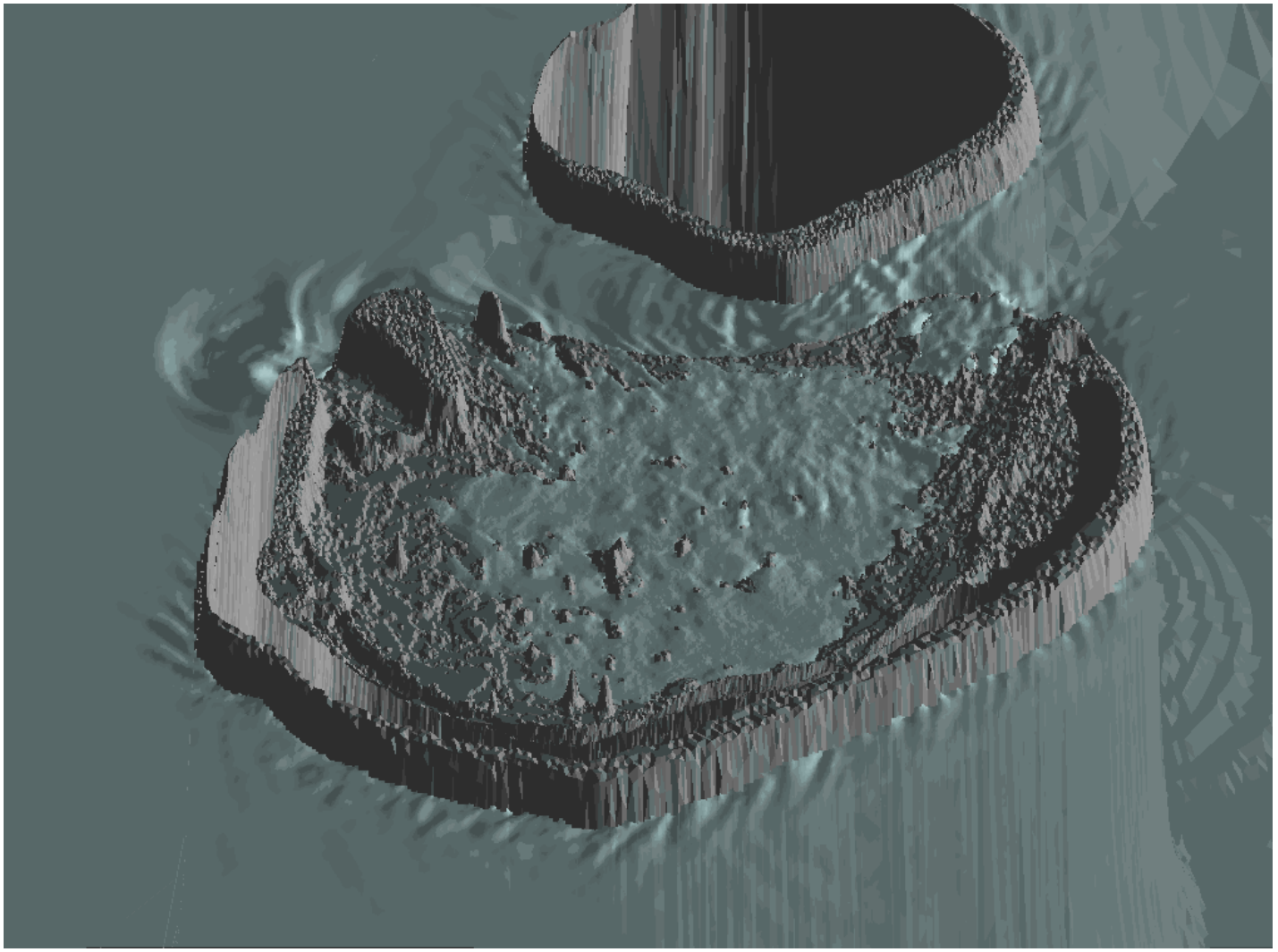
Run time:

4x real-time on 64 CPUs

Internal wave signature



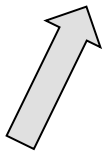
…down to smaller length scales



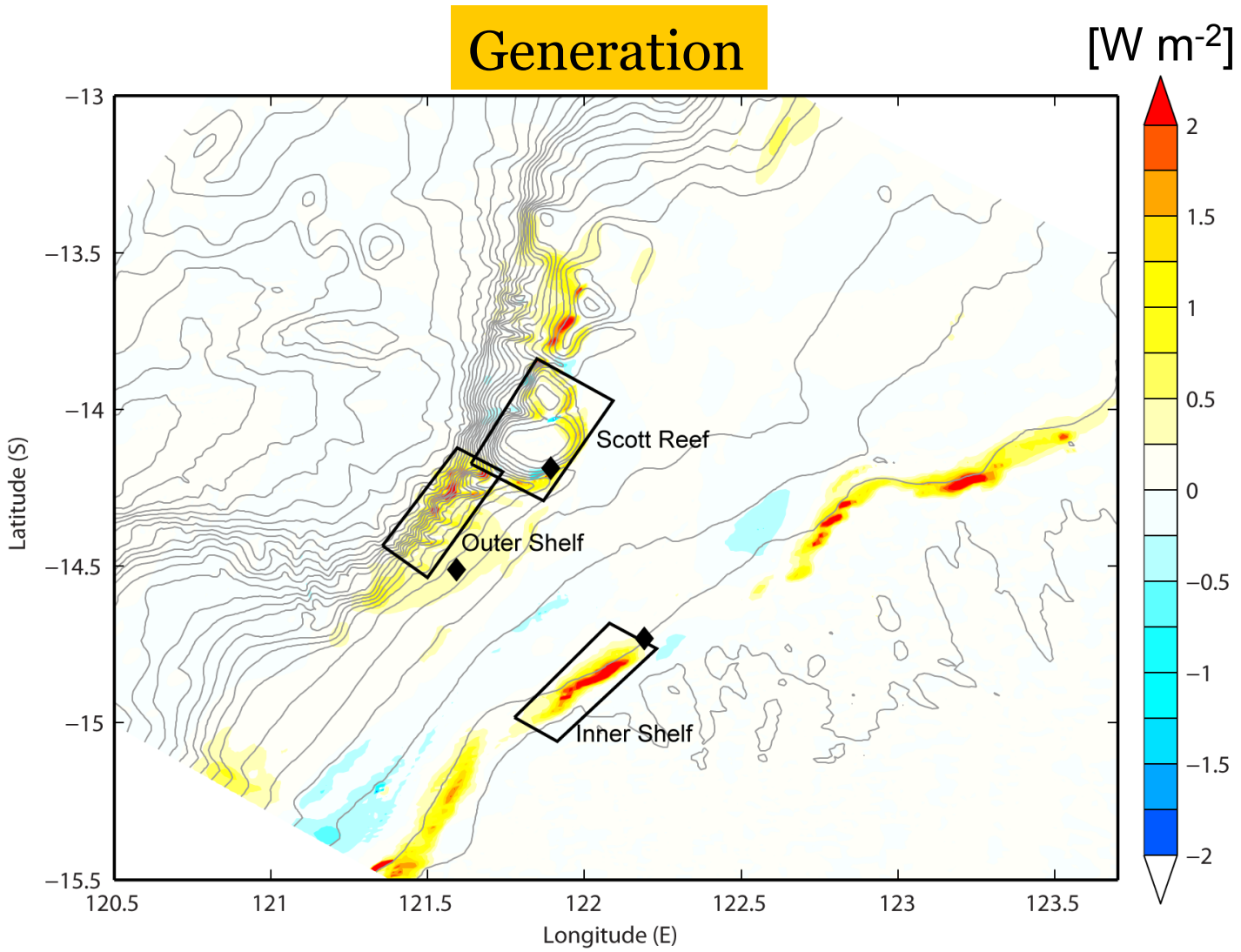
Quantifying internal waves

Mechanical Energy Equation:

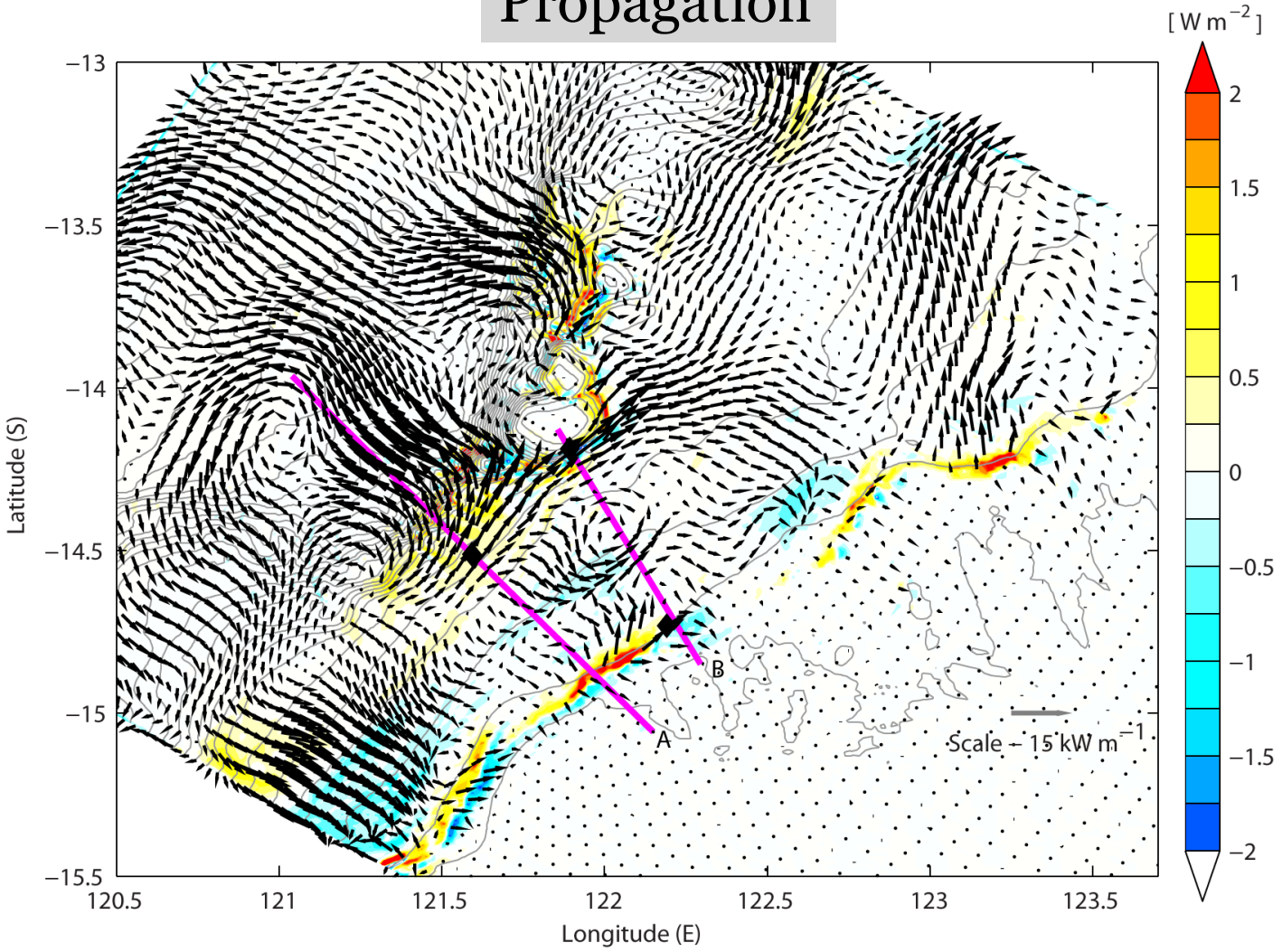
Generation ≈ Propagation - Residual



Energy Loss/ Mixing?


Generation
[W m-2]
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−13
−13.5
−14
−14.5
−15
−15.5
Latitude (S)
120.5
121
121.5
122
122.5
123
123.5
Longitude (E)
Scott Reef
Outer Shelf
Inner Shelf

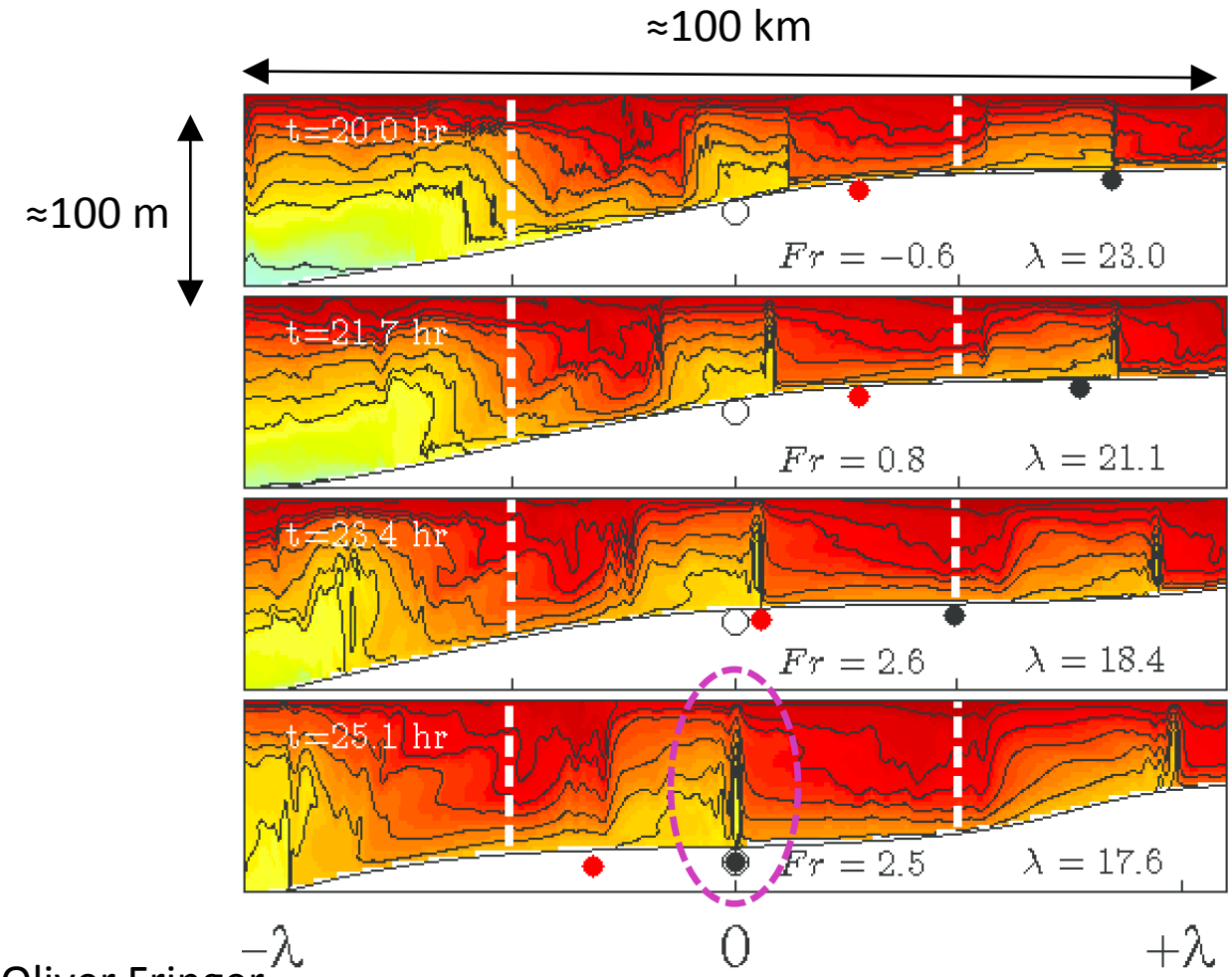
Propagation



Nonlinear internal wave modeling

2D (x-z) SUNTANS

- dx = 50 m
- dz = 10 m
- L = 400 km
- Include nonhydrostatic terms



Courtesy of Bing Wang and Oliver Fringer

Summary – Internal waves

- Multi-scale problem
- Unstructured grid can focus on small topographic feature (10 km) while capturing the large scale dynamics (1000 km)
- Nonlinear waves require dx ~ 10 m and nonhydrostatic terms

Summary

- RANS equations solve coastal flow problems
- Help answer practical engineering and ecological questions
- Uncertainties with boundary conditions is first order issue
- Main research questions on sub-grid scale processes

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