Application of an unstructured grid RANS model to the coastal ocean

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Outline

• Intro to coastal ocean modeling

• Estuarine circulation application

• Internal waves on the continental slope
Estuarine Circulation
Internal wave dynamics
Outline

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RANS equations for the coastal ocean

\[
\begin{align*}
\frac{\partial u}{\partial t} + \nabla \cdot (uu) - fv &= -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \nabla_H \cdot (\nu_H \nabla u) + \frac{\partial}{\partial z} \left( \nu_v \frac{\partial u}{\partial z} \right) \\
\frac{\partial v}{\partial t} + \nabla \cdot (uv) + fu &= -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \nabla_H \cdot (\nu_H \nabla v) + \frac{\partial}{\partial z} \left( \nu_v \frac{\partial v}{\partial z} \right) \\
\frac{\partial w}{\partial t} + \nabla \cdot (uw) + \frac{g}{\rho_0} (\rho_0 + \rho) &= -\frac{1}{\rho_0} \frac{\partial p}{\partial z} + \nabla_H \cdot (\nu_H \nabla w) + \frac{\partial}{\partial z} \left( \nu_v \frac{\partial w}{\partial z} \right)
\end{align*}
\]

Momentum

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0
\end{align*}
\]

Continuity

\[
\begin{align*}
\frac{\partial T}{\partial t} + \nabla \cdot (uT) &= \frac{\partial}{\partial z} \left( K_T \frac{\partial T}{\partial z} \right) + \frac{1}{\rho c_p} \frac{\partial Q_{sw}}{\partial z} \\
\frac{\partial s}{\partial l} + \nabla \cdot (u_s) &= \frac{\partial}{\partial z} \left( K_s \frac{\partial s}{\partial z} \right)
\end{align*}
\]

Tracer transport

\[
\rho = \rho(s, T, p)
\]

Equation of State
Numerical Model Overview

- **SUNTANS**
  
  Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator

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

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

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

Reference:

Fringer et al., 2006, Ocean Modelling
Code overview

- Written in C
- Parallelized 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

\[ U_{\downarrow g} \sim g \beta \partial S / \partial x H \Theta / \nu \downarrow t \equiv \text{gravitational effects/mixing effects} \]

(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 questions
  • 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

(a) Salinity [psu] over time with two lines: trin (black) and boli (blue).

(b) Discharge $Q_s$ [m$^3$/s] over time with peaks in 2009, 2010, and 2012.

Map showing the location of Buffalo Bayou, San Jacinto River, Trinity River, and the Gulf of Mexico.
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

- Rain fall (salt)
- Longwave Radiation
- Convective Flux
- Evaporative Flux (salt and heat)
- Shortwave Radiation

(Wind)
3D SUNTANS Model of Galveston Bay

Model Inputs:

- USGS gauged river flows
- Realistic tides (OSU TPXO model)
- ROMS coastal boundaries (Hetland Group @ Texas A&M)
- NCEP NARR model for atmospheric forcing (wind and heat surface boundaries)
SUNTANS Grids

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

20 vertical layers
\[ dz = 0.5 \text{ m} \]
\[ \sim 10^5 \text{ total 3d cells} \]

Run time:

20x real-time with 64 CPUs
Unstructured grid
Salinity response to river forcing

Time-averaged Salinity [ppt]
z: 0.5 [m], Time: 03-Jan-2007 00:00:00

Depth [m]

Northing [m]

Discharge [m³/s]

Ocean

River
Salinity response to forcing

Cross-sectional average salinity:

\[
s_{yz}^{\text{ave}}(x, t) = \frac{1}{A} \int_{-b/2}^{b/2} \int_{-d}^d s(x, y, z, t) \, dz \, dy
\]

- River discharge (note lag)
- Storms (wind stress and water level)
- Tides
- Coastal salinity

→ Salinity is unsteady due to transient forcing
Flush Time

\[ N(t) = N_{\downarrow 0} e^{\uparrow -t/\tau_{\downarrow}} \]
Lagrangian residence time

1st April 2009

April 2009

May 2009

June 2009
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
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Internal wave background

\[ \omega_{\text{bottom}} = \vec{u} \cdot \nabla H \]
Observations
Motivation

- Offshore engineering
- Ecosystem dynamics
- Role of small scale processes in climate models
A multi-scale problem

Surface tides (~1000 km)

Internal waves (~10 km)

Nonlinear internal waves (~100 m)

Turbulence (~1 mm)

Energy cascade
SUNTANS model

- $dx = 100 - 10000 \text{ m}$
- $dz = 5 - 50 \text{ m}$ (150 layers)
- $\sim 10^6$ total 3D cells

Run time:
4x real-time on 64 CPUs
Internal wave signature

Time-averaged Water temperature [degrees C]
z: 130.8 [m], Time: 2015-04-14 07:00:00
...down to smaller length scales
Quantifying internal waves

Mechanical Energy Equation:

\[ \text{Generation} \approx \text{Propagation} - \text{Residual} \]

Energy Loss/ Mixing?
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 \( \Delta x \sim 10 \) 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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Galveston Bay

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