An Unstructured Grid, Finite-Volume Coastal Ocean Model (FVCOM), Validations and Applications

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Outline

1. Brief description of FVCOM

2. Validation experiments

3. Applications:
   a) estuaries (Satilla River, Georgia)
   b) regional (Gulf of Maine)
   c) basin (Arctic Ocean)

4. Summary
Critical Issues in Coastal Ocean Modeling

- Irregular geometry
- Mass Conservation?
- Steep topography
- Intertidal wetlands
Basic Classes of Ocean Model Grids:

• Structured – cartesian (rectangular), orthogonal curvilinear, spherical (examples: POM, ECOM-si, ROMS)

• Unstructured – triangular, trapezoidal (*geometric flexibility*) (examples: ADCIRC (FE), SELFE FE), Finite-Volume Coastal Ocean Model (FVCOM)
FVCOM: Unstructured-grid, Finite-Volume Coastal Ocean Model

• All variables are computed in the integral form of the equations, which provides a better representation of the conservative laws of mass, momentum and heat in the coastal region with complex geometry.

• The numerical computational domain consists of non-overlapping unstructured cells.

• Combines the best from the finite-element method for the geometric flexibility and finite difference method for the simplest discrete computation.

• Both current and tracer remain the second-order accuracy.
For Example: The Continuity Equation:

\[ \int \int \frac{\partial \zeta}{\partial t} \, dx \, dy = -\int \int I \frac{\partial (\bar{u}D)}{\partial x} + \frac{\partial (\bar{v}D)}{\partial y} \, j \, dx \, dy = -\oint_{s} \bar{v}_{n} D \, ds \]
Spherical Coordinate FVCOM

\[ F: \text{ Scalar variables such as } \zeta, T, S, K_m, K_h, \text{ and vertical velocity } \omega. \]

- The node of triangles where scalar variable or vertical velocity is calculated.

\( \otimes: \text{ The centroid of a triangle where the horizontal velocity is calculated.} \)

**Example:** Continuity equation

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{r \cos \varphi} \left( \frac{\partial \bar{u} D}{\partial \lambda} + \frac{\partial \bar{v} \cos \varphi D}{\partial \varphi} \right) = 0
\]

\[
\int_{\Omega} \int \frac{\partial \zeta}{\partial t} r^2 \cos \varphi d\lambda d\varphi + \int_{\Omega} \frac{1}{r \cos \varphi} \left( \frac{\partial \bar{u} D}{\partial \lambda} + \frac{\partial \bar{v} \cos \varphi D}{\partial \varphi} \right) r^2 \cos \varphi d\lambda d\varphi = 0
\]

\[
\frac{\partial \zeta}{\partial t} = -\frac{r}{\Omega} \left[ \oint (D \bar{u}) d\varphi - \oint (D \bar{v} \cos \varphi) d\lambda \right]
\]

The gradient of the water temperature (or salinity) is determined by the Green’s function through the integration over the larger volume (with boundaries linked to nodes).
Treatment of North Pole

- Node calculated using the polar stereographic projection coordinate.
- Centroid calculated using the polar stereographic projection coordinate.
- Node calculated directly in the spherical coordinate system.
- Centroid calculated directly in the spherical coordinate system.

Conversion formulae between \((u_p, v_p)\) and \((u_s, v_s)\):

\[
\begin{pmatrix}
  u_p \\
  v_p
\end{pmatrix} =
\begin{pmatrix}
  -\sin \lambda & -\cos \lambda \\
  \cos \lambda & -\sin \lambda
\end{pmatrix}
\begin{pmatrix}
  u_s \\
  v_s
\end{pmatrix}
\]

\[
\begin{align*}
  u_p &= h_x \frac{dx}{dt} \quad & h_x &= \frac{1 + \sin \phi}{2} \\
  v_p &= h_y \frac{dy}{dt} \quad & h_y &= \frac{1 + \sin \phi}{2}
\end{align*}
\]
1. Non-hydrostatic version of FVCOM in development
2. Generalized terrain-following coordinate
ViSiT

Software developed by Lawrence Livermore National Laboratory
http://www.llnl.gov/visit/

- Open source
- Parallel visualization
- Interactive simulation support
- Multiple platform support (LINUX, UNIX, PC, MAC)

FVCOM Plug-in for VISIT 1.5.3:
Developed by David Stuebe in cooperation with the LLNLVISIT team
- FVCOM NETCDF files
- Visualization and animation of 3D vector and scalar fields
- Database linking to NETCDF formatted particle tracking output

Example of density isosurfaces from a high resolution FVCOM GOM model
Hydrostatic FVCOM Validation Experiments

1. Advection scheme
2. Wind-induced oscillation \((POM, ECOM-si)\)
3. Wind-induced waves over sloping bottom topography \((POM, ECOM-si)\);
4. Tidal Resonances in a semi-enclosed channel and a sector \((POM, ECOM-si)\);
5. Freshwater discharge plume \((POM, ECOM-si)\)
6. Bottom boundary layer over a step bottom slope \((POM; ECOM-si)\)
7. Equatorial Rossby soliton \((ROMS)\)
8. Wind-induced lateral boundary \((ROMS)\)
9. Super-critical current \((ROMS)\)


Non-Hydrostatic FVCOM Validation Experiments

1. Shoaling internal waves on inclined plane
2. Lock exchange

FVCOM website: http://fvcom.smast.umassd.edu
Tidal Resonance in a Semi-closed Channel

Consider a 2-D linear, non-rotated initial problem such as

\[
\begin{align*}
\frac{\partial V_r}{\partial t} + g \frac{\partial \eta}{\partial r} &= 0 \\
\frac{\partial V_\theta}{\partial t} + g \frac{\partial \eta}{r \partial \theta} &= 0 \\
\frac{\partial \eta}{\partial t} + \frac{\partial r V_r H_0}{r \partial r} + \frac{\partial V_\theta H_0}{r \partial \theta} &= 0
\end{align*}
\]

The solution:

\[\eta_0(r, \theta) = [c_1 J_{\gamma_m} \left(r \frac{\omega}{\sqrt{gH_0}}\right) + c_2 Y_{\gamma_m} \left(r \frac{\omega}{\sqrt{gH_0}}\right)] \cdot \cos\left[\frac{m \pi (\theta + \alpha / 2)}{\alpha}\right]\]

where

\[c_1 = A \cdot J_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) / [J_{\gamma_m} \left(L \frac{\omega}{\sqrt{gH_0}}\right) Y_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) - J_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) Y_{\gamma_m} \left(L \frac{\omega}{\sqrt{gH_0}}\right)]\]

\[c_2 = -A \cdot J_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) / [J_{\gamma_m} \left(L \frac{\omega}{\sqrt{gH_0}}\right) Y_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) - J_{\gamma_m}' \left(L_1 \frac{\omega}{\sqrt{gH_0}}\right) Y_{\gamma_m} \left(L \frac{\omega}{\sqrt{gH_0}}\right)]\]

\[\gamma_m = m \pi / \alpha\]
1. Normal condition (non-resonance)

2. Near-resonance condition
Normal Case: rectangular
Near-resonance Case: 2 km, curvilinear

A
FVCOM

C
POM

C
ECOM-si

Amplitude (cm)

Phase (degree)

Distance (km)

Analytical
80 TC
60 TC
40 TC
20 TC
Near-resonance Case: rectangular

[Graph and diagrams with labels and annotations]
Estuarine Application: The Satilla River, Georgia
Regional Application: Gulf of Maine

- GLOBEC NW Atlantic/Georges Bank Program
- Field Program 1995-1999
- FVCOM simulation 1995 to present
- Model Validation Studies (manuscripts)
  - Tides and tidal dynamics
  - Houghton 1999 GB Dye Dispersion Study
  - 1996-97 Coastal Mixing and Optics Study (CMO)
MM5-GoM

**Horizontal Resolution**
- Regional domain = 30 km
- Local domain = 10 km

**Vertical Resolution**
- 31-sigma levels
- Assimilate NDBC and C-MAN surface data

**Input:** NCEP, satellite SST, ISCCP short- and longwave radiation

**Output:** wind stress, heat flux
Gulf of Maine Regional Model

First Generation

Horizontal Resolution:
- 0.5-1.0 km in the coastal region
- 31-sigma levels in the vertical

Second Generation

Horizontal Resolution:
- 0.3-1.0 km in the coastal region
- 31-sigma levels in the vertical
FVCOM Model Validation: Comparison with CMO Observations


Location: New England Shelf, SW of Nantucket
# Moorings: 4 (Central, Alongshore, Inshore, Offshore)
Oceanic Variables: velocity, temp, conductivity, bottom pressure, bottom stress.
Atmospheric Variables: wind stress, heat flux, buoyancy flux.

CMO data: Lentz
Analysis: Cowles and Lentz
Model start: January 1, 1995

BCs: 5 tidal components, T/S data/climatology

Z adjustment for local wind-forced current

GoM river input

MM5 $\tau$ and $Q$

Radiation, damping

Bathymetry (m)
Temperature (Celsius) during CMO Period at Central Site
August 1996 - June 1997

Observed

FVCOM
Wind stress amplitude (obs-grey; MM5-black)

% underestimation by MM5

- Fall: 15%
- Winter: 20%
- Spring: 10%
Subtidal Surface Current During CMO: Observed (red) FVCOM (black) Along Isobath (Above, ~east) and Cross Isobath (Below, ~north)
Time mean velocity at CMO-C
Model depth-averaged mean current at COM-C

CMO-C

$U_{\text{obs}} = 7.7 \text{ cm/s}$

$U_{\text{mod}} = 6.7 \text{ cm/s}$

$U_{\text{TR}} = 1.0 \text{ cm/s}$
256 Processors (Intel 3.4 GHz Pentium 4)
256 Gigabytes RAM, Infiniband High Speed Network  7 Terabytes disk space

Third generation of GOM FVCOM
Horizontal resolution: 10 -500 m in the coastal region

Improvements:
• use WRF for surface forcing
• add Kalman Filter DA
• use combination of data and BIO eastern Scotian Shelf model to improve upstream BC’s
The horizontal resolution (measured by the side length of the triangle):

1-3 km near the coast and in the Canadian Archipelago, inlets, and narrow straits

10-15 km in the basin interior.

41 non-uniform $\sigma$ levels are specified in the vertical, which corresponds to a vertical resolution of 10 m near the surface and bottom and in the main thermoclines in the interior region where the water is deeper than 4000 m.

Bathymetry data; DBDDV (NRL) and IBCAO (NOAA)

The model is driven by the oscillating tidal elevation at the open boundaries. Four major tidal constituents ($M_2$, $S_2$, $K_1$, and $O_1$) are considered here. The amplitudes and phases of these four tidal constituents at open boundaries are specified using inversed global tidal model outputs (TPXO6.2).
Summary

1. Unstructured grid models can provide a good approach for realistic coastal ocean simulation, and to link to basin and global ocean model systems

2. FVCOM uses finite-volume approach – providing local mass, momentum, heat, salt conservation

3. FVCOM is an open community ocean model.

4. Visit website http://fvcom.smast.umassd.edu for more information about FVCOM, test problems, applications, how to be user, new user workshops, etc.