COMPAS – A coastal version of MPAS-O

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Unstructured models provide superior resolution transition

Region XII, Patagonia, Chile
Types of models

- **Finite difference - structured**
  - Structured grids
  - Finite difference solution to partial derivatives
    - Taylor series expansions to approximate derivatives

- **Finite element - unstructured**
  - Unstructured grids
  - Expand fields in basis functions defined on elements and analytically manipulate
    - Continuous or discrete elements

- **Finite volume - unstructured**
  - Unstructured grids
  - Integrate over control volumes to derive discretized equations
Unstructured models have issues

- **Speed:** ‘Codes designed to work on unstructured meshes are as a rule slower than their regular mesh counterparts per degree of freedom’ – Danilov (2013),
- **Generation of spurious modes,**
  - Danilov (2010) for triangular meshes: C-grid
  - Stabilization against pressure modes: A-grids
- **Geostrophy – no stationary geostrophic modes,**
- **Resolving mesoscale baroclinic instability,**
- **Conservation,**
  - Discrete FE only conserves momentum & kinetic energy globally (Peron (2000) Journal of Computational Physics 159, 58–89),

Unstructured approaches

• Models use a variety of placement of variables:

  - Velocity or scalar
  - Normal velocity

• No consensus – all have particular problems.
Unstructured modelling packages

- **Finite Volume (FV)**
  - MPAS (Hex C-grid)
  - FVCOM ($P_0 - P_1$)
  - MIKE FM (cell-cell)
  - SUNTANS (Tri C-grid)
  - ICON (Tri C-grid)

- **Finite element (FE)**
  - ICOM / Fluidity: Continuous ($P_1^{DG} - P_2$)
  - FESOM: Continuous ($P_1 - P_1$)
  - SLIM ($P_1^{nc} - P_1$)
  - SELFIE
  - ADCIRC: Continuous ($P_1 - P_1$)
  - TELEMAC

- **Finite volume / element**
  - SCHISM
  - ELCIRC
Criteria for selecting a model to use in EMS

• **Essential:**
  - Not finite element
    - continuous FE suboptimal for oceanography - unwanted features in hydrostatic case,
    - discrete are too computationally expensive.
  - Speed comparable to current structures models
  - Not implicit (limits OBC implementation / distributed processing)
  - Minimal stabilization procedures
  - Ease of mesh generation

• **Desirable**
  - Mode split
  - Hydrostatic, Bousenesq
  - C-grid
  - Grid agnostic
Choose to use the MPAS framework

- Used for climate prediction modelling,
- Contains ocean, atmosphere and sea-ice modules,
- ALE vertical coordinate,
- Uses Delaunay dual grid; Voronoi (grid agnostic),
- MPAS-O*: Ocean model component,
  - Conserves volume, mass, momentum and vorticity,
  - Supports a stationary geostrophic mode,
  - Generates mesoscale baroclinic instabilities,
  - No stabilization,
  - Uses a C-grid placement of variables,
  - Uses the vector invariant momentum advection approach.

Include the MPAS-O dynamic core in EMS

Algorithm changes for C grid

- **Vertical algorithms remain unchanged:**
  - Turbulence closure
  - Vertical mixing
  - Implicit vertical momentum advection in vertical mixing
  - Baroclinic pressure
  - Barotropic pressure
- **Need new algorithms for:**
  - Momentum advection
  - Coriolis
  - Horizontal mixing

**COMPAS:**
Coastal Ocean Model Prediction Across Scales
Grid generation

- Use JIGSAW developed by Darren Engwirda ([https://github.com/dengwirda/jigsaw](https://github.com/dengwirda/jigsaw))
- Designed to create MPAS compatible meshes
  - Orthogonal Centroidal Voronoi Tessellation (CVT) meshes
- Active collaboration with MPAS team (and now with CSIRO)
Use weighting function to define resolution

- Determines what resolution is placed where in the grid,
- May be a function of:
  - Bathymetry,
  - Distance from coast,
  - Turbulent kinetic energy
  - Tidal amplitude,
  - Salinity,
  - Arbitrary.

- E.g. for bathymetry, specify (max / min) resolution for (min / max) depth, and map depths with linear, exponential, cosine etc. function.
Example mesh: SE Tasmania

10072 cell centres
Mean horizontal edge length = 673.40 m
Mean horizontal distance between centres = 385.17 m
Minimum horizontal distance between centres = 116.94 m
Maximum horizontal distance between centres = 5039.33 m
Mean cell area = 0.62 km²
Example mesh: Hi-resolution automated meshes

- Weighting function is Gaussian centered on a defined location,
- Creates circular mesh with maximum resolution at centre, minimum resolution at edges,
- Minimizes OBC specification error by using 1:1 boundary ratios.

Mesh over EAC region, with coastal masking.
Maximum resolution ~800 m
Minimum resolution ~11 km
Mean resolution ~1.8 km
Example mesh: Australian shelf

- National tidal model is developed,
- Weighting function is a combination of tide and bathymetry (e.g. shallow areas with high amplitude get high resolution).

Number of 2D wet cells = 212686
Number of 3D wet cells = 2322647
52 vertical layers
Mean horizontal edge length = 4162.61 m
Mean distance between centres = 2394.27 m
Min. distance between centres = 445.25 m
Max. distance between centres = 54501.19 m
Mean cell area = 23.23 km²
Seamless resolution transition
Precisely prescribe areas of high resolution
Flinders Island ~4 km
Model results for EAC, Dec 2014

Sea level and 2D depth averaged currents (left) and surface temperature and 3D surface currents (right) for EAC region. Model is 10 km resolution.
Comparison to hex meshes, EAC, Dec 2014

Surface temperature and currents. Resolution ~5km.
Southern Tasmania

Sea level at Hobart

QUAD / Hex
2D wet cells = 54404 / 34992
3D wet cells = 1014963 / 414185
Mean horizontal edge length = 252.90 / 198.67 m
Mean horizontal distance between centres = 252.75 / 114.28 m
Minimum horizontal distance between centres = 101.10 / 40.73 m
Maximum horizontal distance between centres = 992.22 / 3384.05 m
Resolution transition effects

Resolution (m) Sea level & surface currents
Conclusion

• **COMPAS** is a viable unstructured model.
• **Examples documented on:**
  • Quad and hex models functional in simple test pools, closed basin (wind forced), test estuary (wind, tidal, river forced).
  • Quad and hex models functional in regular ROAM-like domain (EAC) with full forcing.
  • Quad model functional in irregular domain (SE Tas) with full forcing.
• **EMS grid generation coupled to JIGSAW inline.**
• **Beta version available on GitHub:**
  [https://github.com/csiro-coasts/EMS](https://github.com/csiro-coasts/EMS)
Thank you

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Open Boundaries

- An OBC cell may be associated with multiple edges having different normal vector directions,
- The direction normal to the boundary is difficult to define,
  - Radiation conditions may contain error
- Full OBC suite is available,
- Flux adjusted Dirichlet condition (Herzfeld & Andrewartha, 2012) is well suited to finite volume,
  - Flux adjustment is equally spread over cell edges.
• Use the MPAS algorithm - high order solution (3rd or 4th order via Skamarock and Gassmann, 2011).

• 3rd and 4th order schemes require second derivative at an edge.

• Uses a quadratic least squares polynomial to approximate second derivative required for high order schemes. \( T = c_0 + c_x x + c_y y + c_{xx} x^2 + c_{xy} xy + c_{yy} y^2 \)

• Use singular value decomposition to pre-compute weighting matrix, then require vector operation to retrieve the second derivative value.

• Use FCT for monotonic solution.
Least squares polynomial: \( T = c_0 + c_x x + c_y y + c_{xx} x^2 + c_{xy} xy + c_{yy} y^2 \)

\[ F_{i-1/2} = 0.5(T_{i+1} - T_{i-1}) - q_{i-1/2} (T_i - T_{i-1}) - \frac{1}{6} - \frac{1}{6} q_{i-1/2}^2 \text{CURV} \]

\[ q_{i-1/2} = u_i \Delta t / h \]

\[ \text{CURV} = T_i - 2T_{i-1} + T_{i-2} \quad \text{for} \quad q_{i-1/2} > 0 \]

\[ \text{CURV} = T_{i+1} - 2T_i + T_{i-1} \quad \text{for} \quad q_{i-1/2} < 0 \]
• **Delaunay triangulation**: no vertex falls in the interior of the circumcircle (circle that passes through all three vertices) of any triangle in the triangulation

• Can be generated using existing software, e.g.
  ‘Triangle’; [https://www.cs.cmu.edu/~quake/triangle.html](https://www.cs.cmu.edu/~quake/triangle.html)
  ‘Jigsaw’; [https://sites.google.com/site/dengwirda/jigsaw](https://sites.google.com/site/dengwirda/jigsaw)
Dual – Voronoi diagram

- The dual of a Delaunay triangulation is a Voronoi diagram.
- Voronoi diagram: all points within a Voronoi cell have a minimum distance to its generating point.
Centroidal Voronoi Tessellation (CVT)

- Centroidal Voronoi Tessellation (CVT): generating points coincide with the cell’s centre of mass.
  - Generated iteratively using Lloyd’s algorithm or k-means clustering.

- MPAS framework uses CVTs and the dual Delaunay triangulation.
- The centroids of the mesh must be orthogonal to the edges.
- MPAS will operate on any centroidal orthogonal polygon.
MPAS Placement of variables

- **MPAS** uses a C-grid representation for placement of variables;
  - Sea level / tracers at the polygon centres,
  - Normal velocity on the polygon edges,
  - Vorticity on the vertices.
• Developed a generic unstructured system that supports all mappings required to run an unstructured algorithm
• (SHOC already uses an unstructured coordinate system)
Visualisation: UGRID

- CF compliant netCDF standard developed (CF-1.6 UGRID-1.0) ([https://github.com/ugrid-conventions/ugrid-conventions](https://github.com/ugrid-conventions/ugrid-conventions))
- We use 3D layered mesh topology
- UGRID compatible netCDF can be visualized by Godiva 3
- Can use ParaView with UGRID reader plugin
- Developing in-house tools using python / bokeh (web based)