Recent evolution and challenges for oceanic dynamical cores across all scales
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Recent evolution and challenges for oceanic dynamical cores across all scales

F. Lemarié

Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, LJK, Grenoble, France
Context: oceanic dynamical cores

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Primary application</th>
<th>Horiz. grid</th>
<th>Method</th>
<th>Vert. coord.</th>
<th>NH option</th>
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<tbody>
<tr>
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<td>QE</td>
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</table>

QE: quasi-Eulerian; ALE: Arbitrary Lagrangian Eulerian; FE: Finite Element; FV: Finite Volume

+ ROMS-Ucla, POM, Mars3d, FVCOM, Delft3d, Mike 3, COCO
Some Challenges and prospects

- Inclusion of **non-hydrostatic effects**
- **Multi-resolution strategies** (+ local adaptation of model equations)
- ALE/Lagrangian remap **vertical coordinates**
- **(Time/energy/cost)-to-solution** (Green IT) (Time-integration strategies; effective resolution)
- Control of **non-negativity** and dry states
- **Energy consistency** and resolved/unresolved scales coupling
- Control of **spurious modes** and **spectral gaps** (FE methods)
- Reduce subjectivity and improve reproducibility
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Outline

1. (Time/energy/cost)-to-solution

2. Inclusion of non-hydrostatic effects

3. Multi-resolution strategies (+ local adaptation of model equations)

4. Ongoing initiatives
(Time/energy/cost)-to-solution
(Time/energy/cost)-to-solution

Main drivers:

- Time-integration strategy (stability)
  → Eulerian vs (Semi)-Lagrangian time integration

- Effective resolution (accuracy)
  → Dissipative and dispersive properties of numerical schemes

- Software environment (efficiency)
  → Local vs global communications
  → Memory/IO access pattern

Hardware evolution: many-core architectures and co-processors (GPUs)
  → Methods with local stencils (e.g. Eulerian-based time integration approaches) will be favored [Mengaldo et al., 2019]
Stability of time-integration

- Limiting process at high resolution: advection (especially vertical adv.)
  - Semi-Lagrangian approach not competitive in the oceanic context (e.g. [Subich et al., 2020])
  - Efficiency of Eulerian-based time integration for advection (with 3rd-order spatial discretization)

<table>
<thead>
<tr>
<th>Scheme</th>
<th>LFRA</th>
<th>LFAM3</th>
<th>AB3</th>
<th>RK3</th>
<th>DST</th>
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<td>Efficiency</td>
<td>0.47</td>
<td>0.44</td>
<td>0.397</td>
<td>0.54</td>
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</table>

efficiency = (Max time-step) / (number of rhs computation)

- Active research within the H2020 IMMERSE project to define the most efficient time-integration procedure (RK3 is the frontrunner so far)
- An unconditionally vertical advection scheme in NEMO allowed to increase the time-step of ORCA025 from $\Delta t = 1200$ s to $\Delta t = 1800$ s for a marginal increase of the computational cost per time-step.

[Lemarié et al. (2015)]
## Computational aspects

### Sequential performance (Intel Vtune profiler)

<table>
<thead>
<tr>
<th></th>
<th>NEMO (3.6)</th>
<th>CROCO (ROMS)</th>
<th>Mars3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory size</td>
<td>2Gb</td>
<td>800Mb</td>
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<tr>
<td>Number of instructions</td>
<td>5.5 bil.</td>
<td>3.3 bil.</td>
<td><strong>13.9 bil.</strong></td>
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<tr>
<td>Vectorization (%)</td>
<td>40</td>
<td>78</td>
<td>45</td>
</tr>
<tr>
<td>Cache bound(^1) (%)</td>
<td>14</td>
<td>14</td>
<td><strong>71</strong></td>
</tr>
<tr>
<td>FP Arith./Mem. Rd Instr.(^2)</td>
<td>0.56</td>
<td><strong>1.43</strong></td>
<td>0.62</td>
</tr>
<tr>
<td>Execution time (s)</td>
<td><strong>609</strong></td>
<td><strong>160</strong></td>
<td><strong>686</strong></td>
</tr>
</tbody>
</table>

\(^1\) percentage of execution time spent in cache memory accesses  
\(^2\) floating point arithmetic instructions per Memory Read or Write

Baroclinic jet testcase  
[Soufflet et al., 2016]
Inclusion of non-hydrostatic effects
Example (strait of Gibraltar)

\[ r = \frac{\text{NH pressure}}{\text{Hydro pressure}} = \frac{\varepsilon^2 U_0^2 \text{Ro}}{\max (U_0^2, H_0^2 N_0^2)} \]

Fig. 1. Illustration of small-scale processes in the Strait of Gibraltar induced by tidal interaction with stratification and bathymetry. (a) Linear/Small amplitude internal wave. (b) Hydraulic Jump. (c) Kelvin-Helmholtz instabilities. (d) Large-amplitude internal waves or internal solitary waves (ISW).

[Hilt et al., 2020]
Solution methods

• **Incompressible pressure projection/correction approach** (MITGcM, Suntans, Croco-NH, FVCOM, etc.)
  → Global 3D elliptic Poisson equation
  → Overhead of about 150% vs hydrostatic is generally reported
  → Overhead depends on solver, tolerance, geometry, etc

• **Pseudo-compressible approach** [Auclair et al., 2018; Hilt et al., 2020] (Croco, SNH)
  → Local problem with explicit treatment of acoustic mode (good scaling)

• **Artificial compressibility method** [Lee et al., 2006; Marsaleix et al., 2019]
  → Global 3D parabolic problem and inaccurate continuity equation (Symphonie)

• **Diagnostic approach for NH pressure** [Klingbeil & Burchard, 2013]
  → Not robust enough for practical use (GETM)
3

Multi-resolution strategies (+ local adaptation of model equations)
Multi-resolution strategy (static refinement)

- **Strategy#1**: multiresolution simulations using **block structured mesh refinement** [Debreu & Blayo, 2008; Debreu et al., 2012]

- **Strategy#2**: variable resolution unstructured mesh [Sein et al., 2016, 2017; Hoch et al., 2020]

---

**Figure 3.** Resolution maps for various unstructured model configurations, showing (clockwise, from top-left): (a) the FESOM HR mesh, with resolution adapted to a measure of SSH variability; (b) the FESOM XR mesh, with resolution scaled to estimates of one-half of the Rossby radius, (c) the MPAS-O high-resolution RS-18-to-6km eddy-permitting mesh, and (d) the MPAS-O low-resolution EC-60-to-30km eddy-parameterisation mesh.

4 levels of refinement from 350 m to 2.8 km (Croco)

- **Level 1**: 100% (1 grid)
- **Level 2**: 43% (8 grids)
- **Level 3**: 18% (20 grids)
- **Level 4**: 7% (46 grids)
Multi-resolution strategy (static refinement)

- **Strategy#1**: multiresolution simulations using **block structured mesh refinement** [Debreu & Blayo, 2008; Debreu et al., 2012] → ongoing CMEMS project to generalize this approach to NEMO

- **Strategy#2**: variable resolution unstructured mesh [Sein et al., 2016,2017] in FESOM, [Hoch et al., 2020] in MPAS-O

Possible alternatives:

- An unstructured grid model like FESOM offers the flexibility to be structured in the middle of the basin (with quadrangles) and unstructured at the coast (with triangles).

- **Offline nesting** (comes with a lot of subtleties and tuning in OBC treatment + possibly large phase difference between the coarse- and nested-grid solutions).
**Strategy#1**: block structured mesh refinement

- Time-step locally adapted to spatial resolution
- Parameter values and numerical schemes adapted for each level of refinement
- Built upon mature numerical methods and computational library (e.g. Agrif)
- Conservation properties and consistent phase between the coarse- and nested-grid solutions at the nested-grid boundary (unlike in offline nesting)
  - Coarse and fine resolution grids need to share common edges
  - Time-stepping rather complex for coupling at the barotropic time-step level
  - Data processing for a large number of grids

**Strategy#2**: variable resolution unstructured meshes

- Smooth transition of mesh resolution to minimize numerical artefacts
- Flexibility in the mesh definition to adjust to very complex geometries
  - Time-step for explicit methods set by the finer resolution
  - Scale-aware parameterizations
- Mesh generation
- Data processing (loss of information when not using the native grid)
Multi-resolution with local adaptation of model equations

• **Strategy#1**: use block structured mesh refinement with high-resolution NH nests into a coarse resolution primitive equations model.

→ *PhD of E. Duval funded by French navy (Croco)*

• **Strategy#2**: use variable resolution unstructured meshes with automatic selection of NH zones [Voltzinger & Androsov, 2016]

→ *detection of zones where NH solution is needed*

\[
\rho = \frac{\text{NH pressure}}{\text{Hydro pressure}} = \frac{\varepsilon^2 U_0^2 \text{Ro}}{\max (U_0^2, H_0^2 N_0^2)}
\]
4

Ongoing initiatives
French context: the CROCO initiative

**Phase 1:** COMODO project (2012-2016, PI: L. Debreu, Inria)

- Most modeling groups had common objectives for coastal applications (e.g. NH option, flexible horiz. and vert. grids, coupling with waves, etc)
  - Minimize the duplication of efforts
  - Promote interoperability across numerical models (e.g. Oasis, XIOS)

**Phase 2:** CROCO Research group (supported by Ifremer, SHOM, Cnrs, Ird, Inria)

- **Roms-Agrif** numerical kernel
- **Online nesting capability via Agrif library**
- **Non-hydrostatic Non-Boussinesq from S-NH**
- **Sediment module from Mars3d**
- **OAW coupling interface (shared w. Nemo)**
- **ALE-type vertical coordinate (ongoing + shared w. Nemo)**

Complementary to NEMO in term of target applications
International context: the COMODORE initiative

Motivation: "bring together a community of “model oriented” researchers to foster regular exchanges and share expertise on outstanding issues and perspectives, irrespective of target applications (regional, coastal, or global)" [Lemarié et al., 2019]

Actions:

• Collective paper "Challenges and prospects for dynamical cores of oceanic models across all scales" In preparation for JAMES

• Special issue on oceanic dynamical cores and their evaluation to come in JAMES

• Test strategy and benchmark suite
  - define evaluation methods to compare the behavior and performances of different models
  - existing test cases are scattered in the literature and not always fully documented and reproducible
  - motivate communication between modeling groups and open room for prospective approaches from applied mathematicians

Models represented: Croco, FESOM, GETM, Hycom, ICON, MITGcM, MOM6, MPAS, NEMO, ROMS, SCHISM, Suntans, Symphonie, Thetis.
Recent references


