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Recent evolution and challenges for oceanic dynamical cores across all scales

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► **To cite this version:**

Florian Lemarié. Recent evolution and challenges for oceanic dynamical cores across all scales. Ocean Modeling for Predictions Workshop, Jun 2020, Toulouse, France. hal-03153619

HAL Id: hal-03153619

<https://inria.hal.science/hal-03153619>

Submitted on 19 May 2021

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LABORATOIRE
JEAN KUNTZMANN
MATHÉMATIQUES APPLIQUÉES • INFORMATIQUE

Ocean Modeling for Predictions Workshop

How to improve models for increased prediction skills

Recent evolution and challenges for oceanic dynamical cores across all scales

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Context: oceanic dynamical cores

Acronym	Primary application	Horiz. grid	Method	Vert. coord.	NH option
Croco	coastal	structured	FD/FV	QE	Yes
FESOM	global	unstructured	FV	QE	
GETM	coastal	structured	FD/FV	ALE	Yes
Hycom	global	structured	FD	Lagr. remap	
ICON-O	global	unstructured	FE	QE	
MITgcm	global	structured	FD/FV	QE	Yes
MOM6	global	structured	FD/FV	Lagr. remap	
MPAS-O	global	unstructured	FV	QE/ALE	
NEMO	global	structured	FD/FV	QE/ALE	
Roms-Rutgers	coastal	structured	FD/FV	QE	
SCHISM	coastal	unstructured	FE	QE	
Suntans	coastal	unstructured	FE	Lagr. remap	Yes
Symphonie	coastal	structured	FD	QE	Yes
Thetis	coastal	unstructured	FE	QE	

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

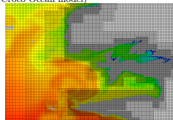
+ ROMS-Ucla, POM, Mars3d, FVCOM, Delft3d, Mike 3, COCO

Some Challenges and prospects

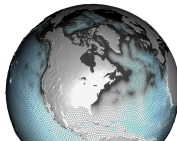
- Inclusion of **non-hydrostatic effects**
- **Multi-resolution strategies** (+ local adaptation of model equations)
- ALE/Lagrangian remap **vertical coordinates**
- **(Time/energy/cost)-to-solution** (Green IT)
(Time-integration strategies; effective resolution)
- Control of **non-negativity** and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

Multi-resolution strategies

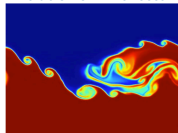
Block structured mesh refinement
(Croco Ocean model)



Variable resolution unstructured meshes
(Courtesy of D. Engwirda)



Inclusion of NH effects

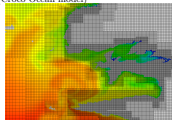


Some Challenges and prospects

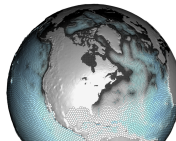
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Multi-resolution strategies

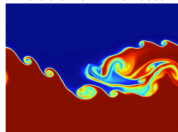
Block structured mesh refinement
(Croco Ocean model)



Variable resolution unstructured meshes
(Courtesy of D. Engwirda)



Inclusion of NH effects



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

1

(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)

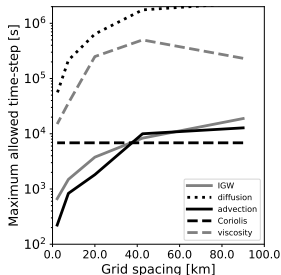
- Methods with local stencils (e.g. Eulerian-based time integration approaches) will be favored [\[Mengaldo et al., 2019\]](#)

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)

Scheme	LFRA	LFAM3	AB3	RK3	DST
Efficiency	0.47	0.44	0.397	0.54	1

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



[Lemarié et al. (2015)]

- ▶ 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.

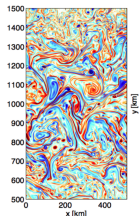
Computational aspects

Sequential performance (Intel Vtune profiler)

	NEMO (3.6)	CROCO (ROMS)	Mars3D
Memory size	2Gb	800Mb	1,4Gb
Number of instructions	5.5 bil.	3.3 bil.	13.9 bil.
Vectorization (%)	40	78	45
Cache bound ¹ (%)	14	14	71
FP Arith./Mem. Rd Instr. ²	0.56	1.43	0.62
Execution time (s)	609	160	686

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]

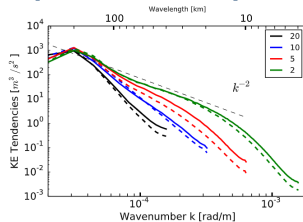


Fig. 12. Near surface KE spectra (m^3/s^2) for ROMS (solid lines) and NEMO (dashed lines) at 20 km, 10 km, 5 km and 2 km resolution.

2

Inclusion of non-hydrostatic effects

Example (strait of Gibraltar)

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

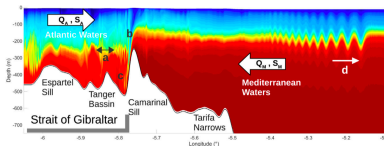
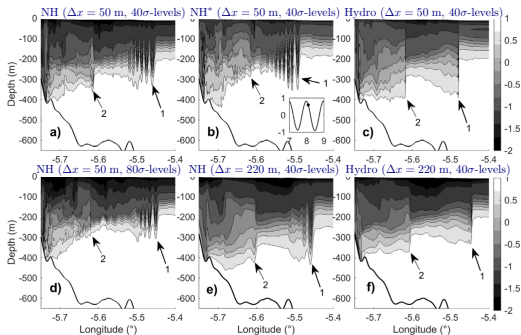
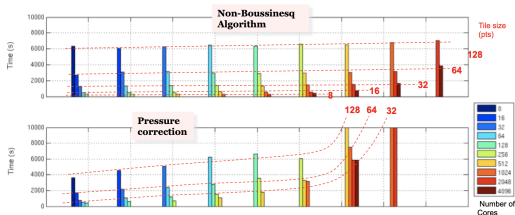


Fig. 1. Illustration of small-scale processes in the Strait of Gibraltar induced by tidal interaction with stratification and bathymetry. (a) Linear/Small amplitude internal wave. (b) Hydraulic jump. (c) Kelvin-Helmholtz instabilities. (d) Large-amplitude internal waves or internal solitary waves (ISW).



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]

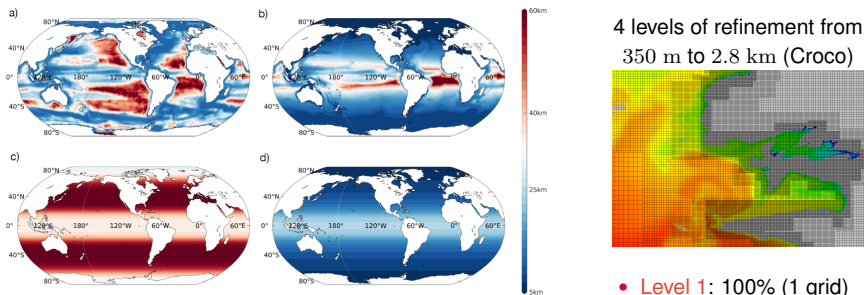


Figure 3. Resolution maps for various unstructured model configurations, showing (clockwise, from top-left): (a) the FESOM HR mesh, with resolution adapted to a measure of SSH variability, (b) the FESOM XR mesh, with resolution scaled to estimates of one-half of the Rossby radius, (c) the MPAS-O high-resolution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

- **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*

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

4

Ongoing initiatives

French context: the CROCO initiative

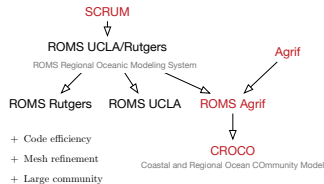
Phase 1: COMODO project (2012-2016, PI: L. Debreu, Inria)

- 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.

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