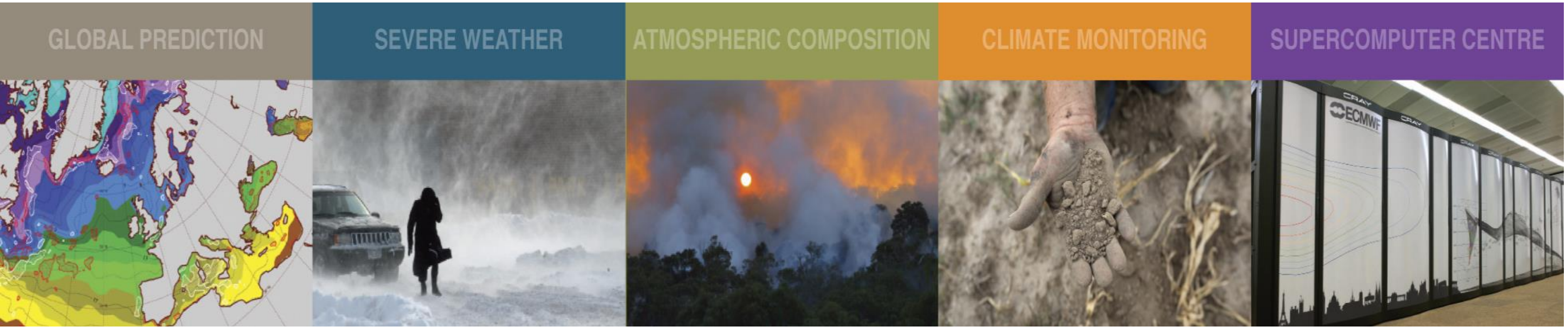
COMMODORE benchmarks

Laurent Debreu, Nils Wedi, Sibylle Techene, Jaques Sainte-Marie, Julie Deshayes, Florian Lemarie, Sergei Danilov, Alistair Adcroft, Joseph Zhang …



Test cases, COMMODORE group: main objectives

1. Test cases for a more systematic validation of new releases of state-of-the-art ocean models

2. Evaluation of innovative model developments on a well-established / documented suite of test cases

    1. Numerical methods
    2. Reduced precision computations
    3. HPC in general

3. One objective is also to open the door to a more interdisciplinary research (applied mathematicians, computer scientists, atmosphere/ocean feedback …)

COMMODORE workshop

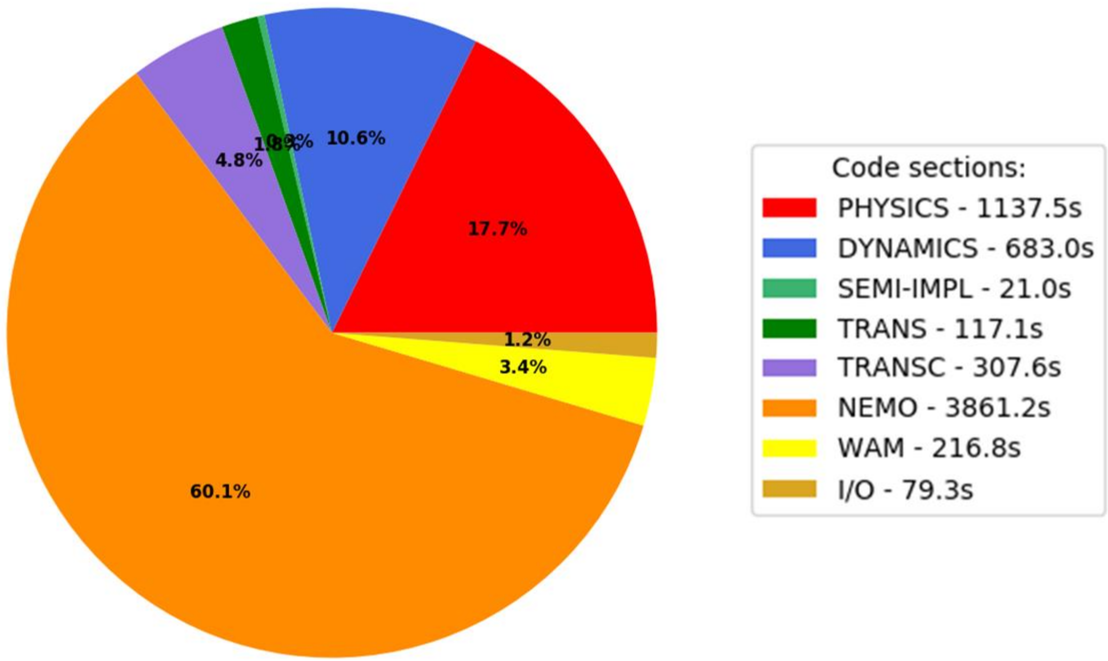
Community for the numerical modeling of the global, regional and coastal ocean

Atmosphere Experience

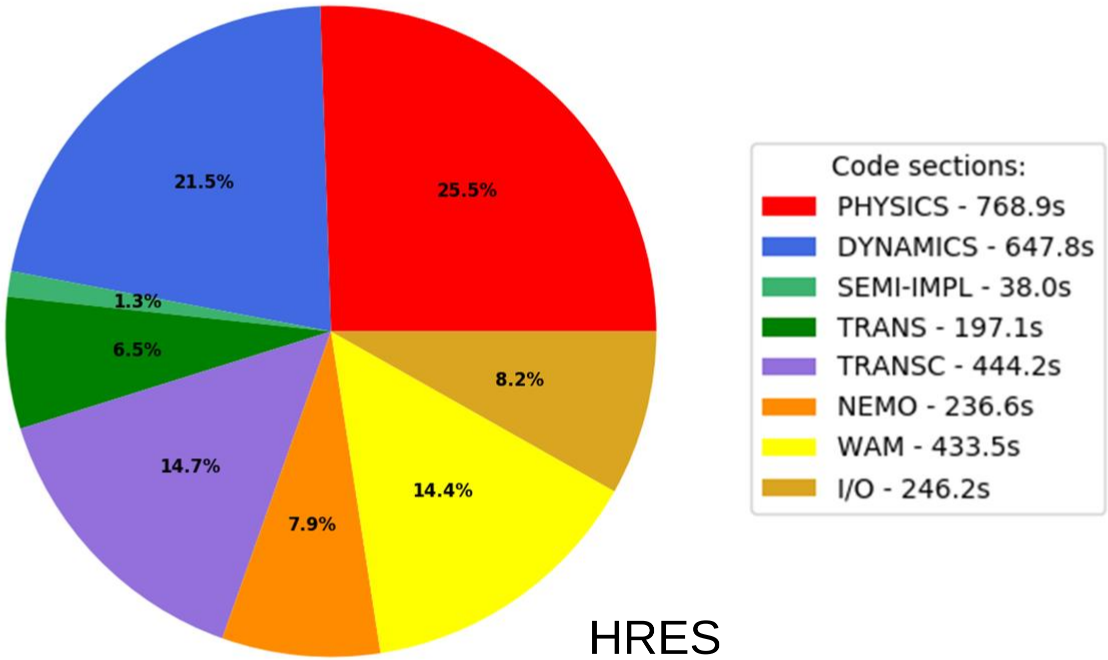
- The Dynamical Core Model Intercomparison Project (DCMIP-2016) and Summer School: Future-Generation Non-Hydrostatic Weather and Climate Models
  - DCMIP-2012 and DCMIP-2016 have been endorsed by the WMO Working Group on Numerical Experimentation (WGNE).

DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models, (P Ullrich, C. Jablonowski et al, 2019; https://www.geosci-model-dev.net/10/4477/2017/)

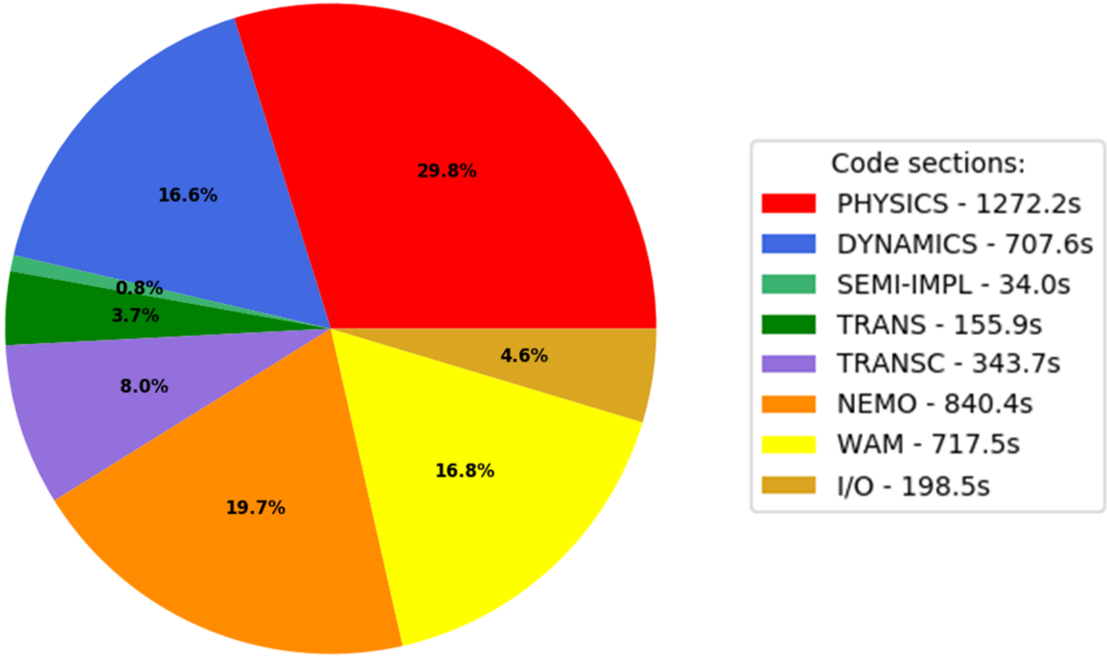
Coupled ocean cost at ECMWF



Extended-range

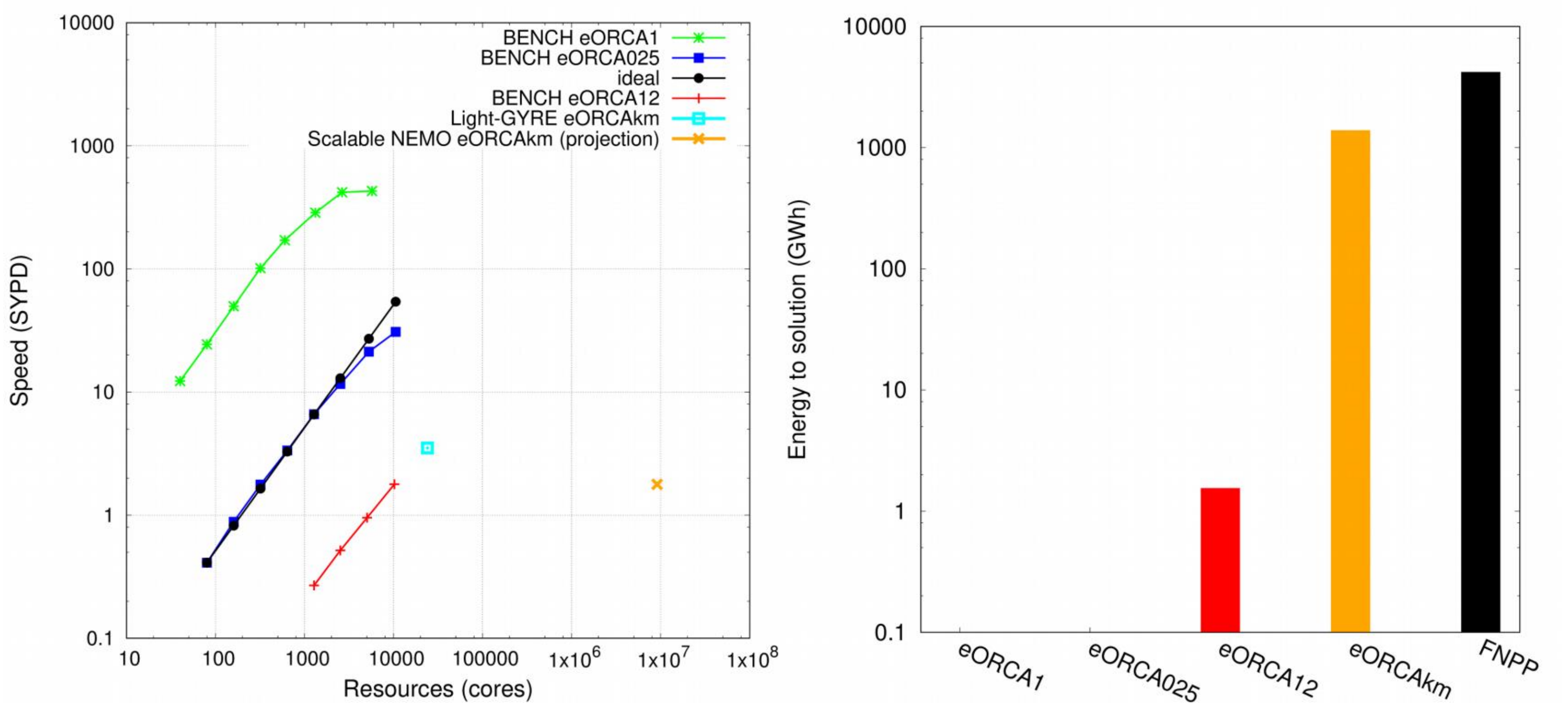


HRES



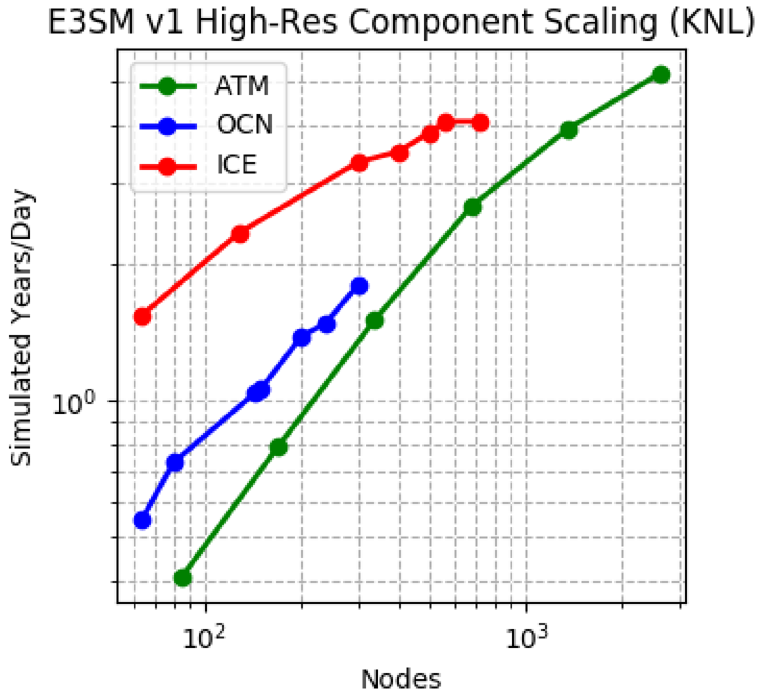
ENS

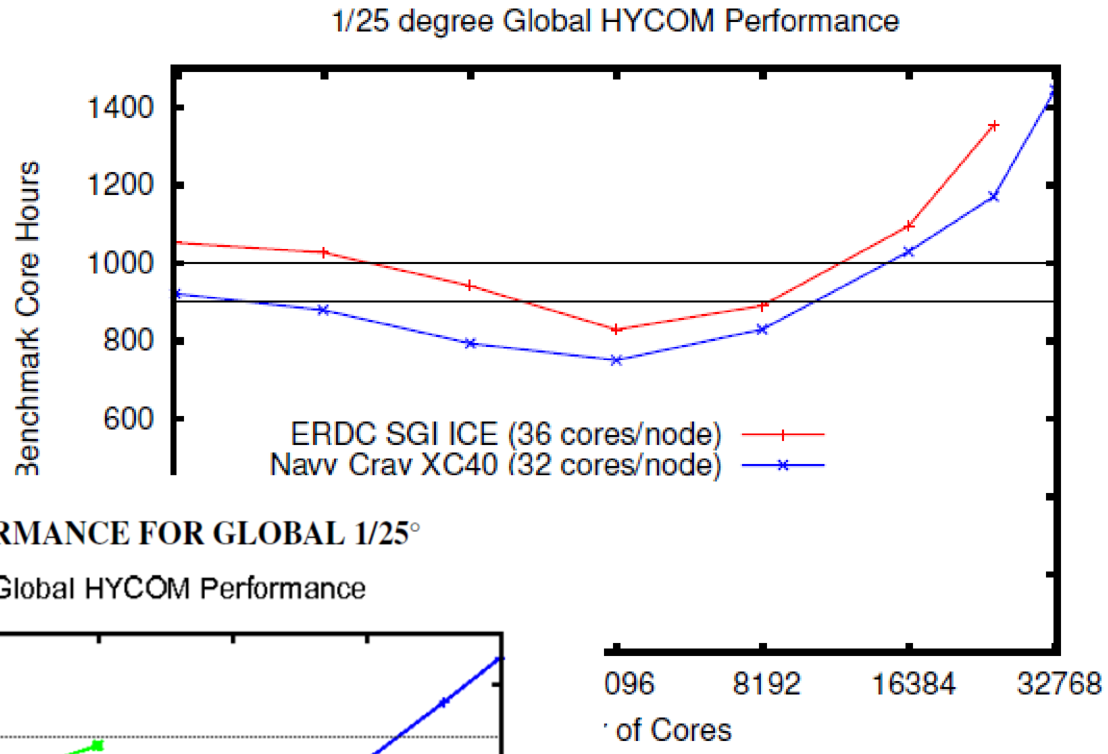
NEMO performance tests

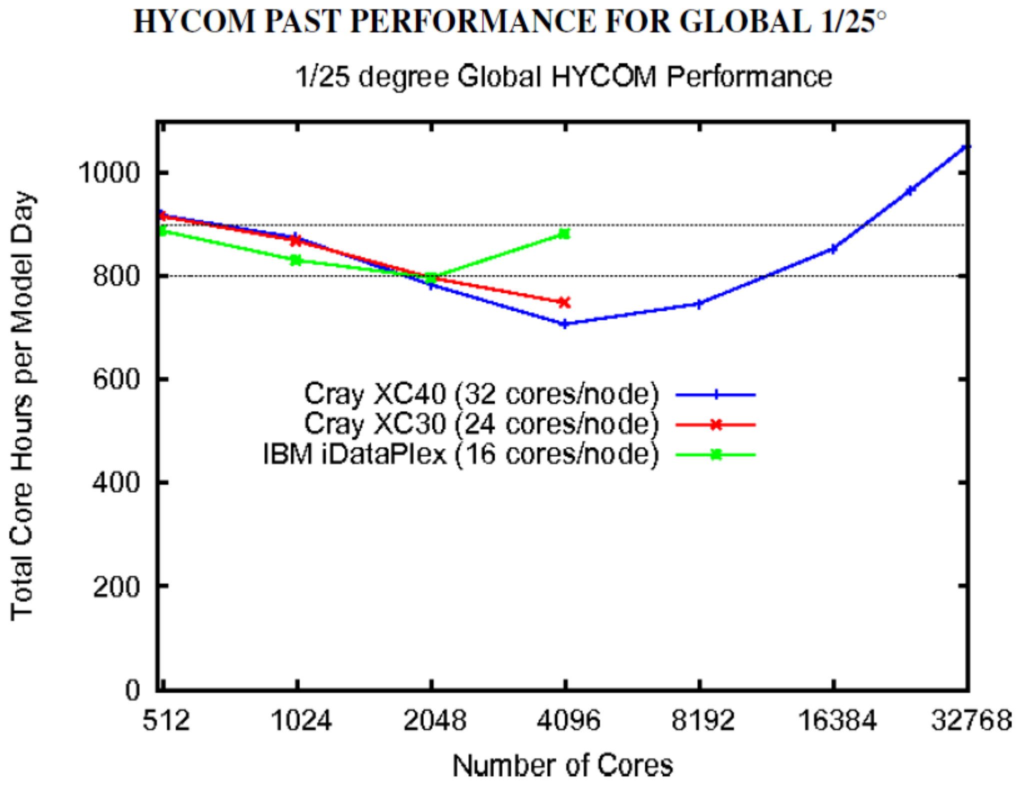


Scalability (left) and energy consumption (right) of several NEMO 3.6 model configurations, measured on `beaufix2` Météo-France supercomputer, Intel Broadwell processors. BENCH and GYRE configurations (I) have 75 vertical levels, (ii) exclude realistic bathymetry (no effect on performance), sea-ice, bio-geo-chemistry and output but (iii) include TOP tracers, appropriate physics at each resolution and polar grid folding (BENCH only). Horizontal resolution varies from 1 degree (eORCA1) to 1 km (eORCAkm). Scalable NEMO eORCAkm performances are extrapolated from measurements of a simplified GYRE km scale configuration, assuming a perfect scalability until a 10 million MPI subdomain decomposition. Right figure compares the total production of one reactor of a power plant (FNPP) similar to Fessenheim, France and the energy consumption of a 1,000 year long simulation led with the four NEMO configurations (eORCAkm: projection) at maximum scalability, approximated as suggested in Balaji et al. 2017, assuming `beaufix2` consumption E = 2.15e12 J/month and total capacity A = 5.2e7 CH/month

Other ocean models scalability





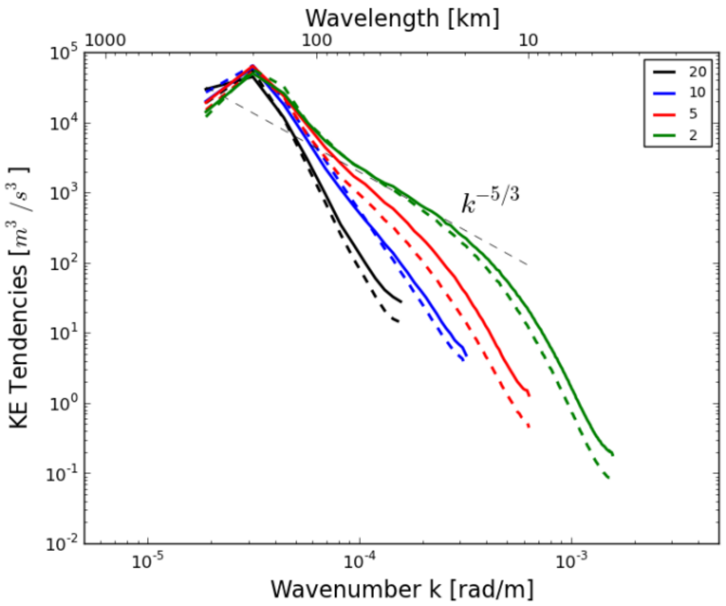


GPUs and reduced precision ?

Testing (reduced-precision) sensitivity of ocean models on pathological ocean modelling issues

- Behaviour at different time-scales
- Vertical mixing (more levels, change to isopycnal coordinates, more accurate advection)
- Barotropic mode (2D) coupling to the deep ocean (scalability bottleneck beyond ~6000 cores ?)
- Sea-ice model rheology
- Physics coupling and lateral ocean boundaries
- Complex ocean bathymetry interactions
- Coupling interface to the atmosphere and other ESM components (ABL, wave model)
  - E.g. mixing effects and wave excitation in the presence of (hurricane-like) atmospheric forcing

How to define a test case ?



From Soufflet et al, 2016: 20 years average spectra at 10m depth for ROMS (plain line) and NEMO (dashed) at different resolutions

1. Physical description of what we are looking at
2. A given set of equations
    1. Several test cases should be able to run with simplified equations system
3. A configuration
4. A reference solution (analytical solution when available)
5. A set of diagnostics including sensitivity studies (Model resolution, viscosity …)

Test cases

- Some difficulties
  - Model developers tends to tune their code according to a given test case
    - -> not representative of the general setup
    - Solution : the model parameters / choices should be detailed in the results
  - Representativeness of test cases for real simulations of ocean or coupled systems

- Different kind of test cases :
  - “Sanity” test cases
  - A suite of test cases to validate of model
  - Test cases that address a specific challenge:
    - Example : An idealized test case with a complex geometry

Considerations / Open questions

- Reference solutions:
  - Developments of analytic solutions for complex equations systems
  - Lab experiments
- Easy reduction of complexity for existing 3D ocean models
- Extending the test cases for the dynamical cores to
  - Physics-Dynamics coupling
  - Ocean-Atmosphere coupling
  - Tests that can be performed with both atmosphere and ocean dynamical cores
- In addition to idealized test cases, a small number of realistic configurations
  - COMMODORE encompasses a large variety of ocean models (global, regional, coastal)
  - Field based / observations constraint test cases

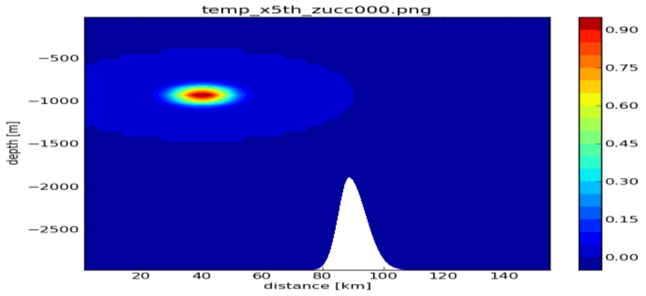
Momentum Continuity

THE FRENCH COMMODO Project

Trajectory of Barotropic vortex

Baroclinic vortex

Transport of passive



Instable Jet

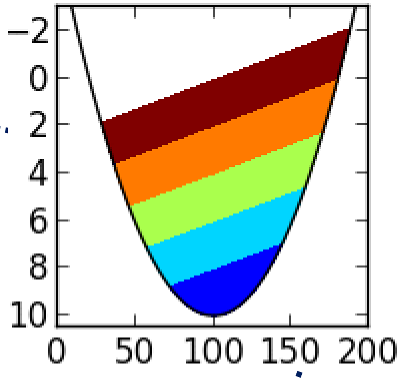
Upwelling

Lock exchange

Interaction current-topography

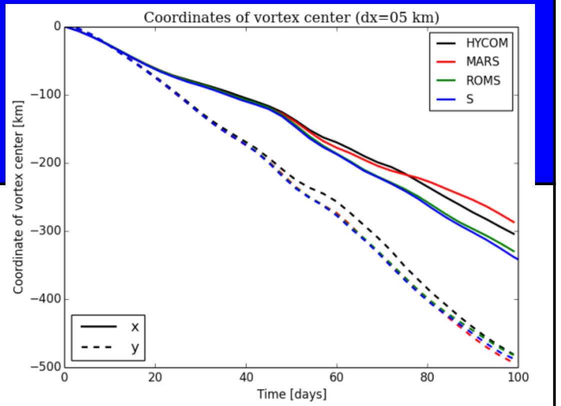
Internal wave

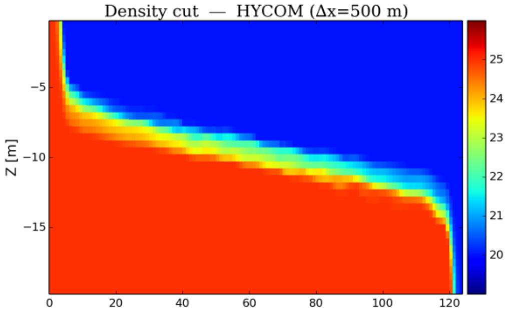
Thacker’s bowl

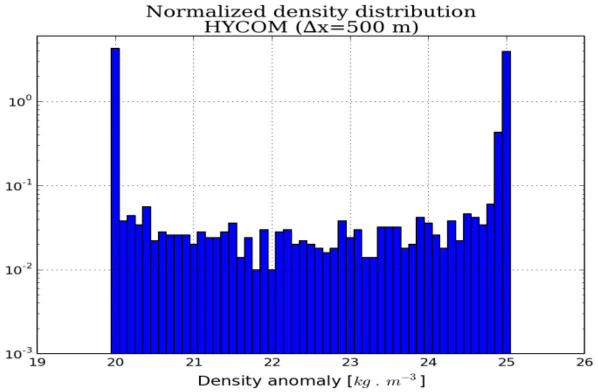


Vertical coordinates

Test case	HYCOM	MARS	NEMO	ROMS	S	Pycomodo tool : Python graphs of the test case results
Instable jet	✓	✓	✓	✓	✓	✓
Baroclinic vortex	✓	✓	✓	✓	✓	✓
Lock exchange	✓	✓	✓	✓	✓	✓
Passive lenses of tracer	-	✓				
Internal wave	✓			✓		
Thacker	✓	✓	-	✓		✓
Upwelling	✓	✓	✓	✓		✓
Interaction current-topography			✓		✓	
Traj. bt vortex						
Jet – mixing layer ?		✓	✓			



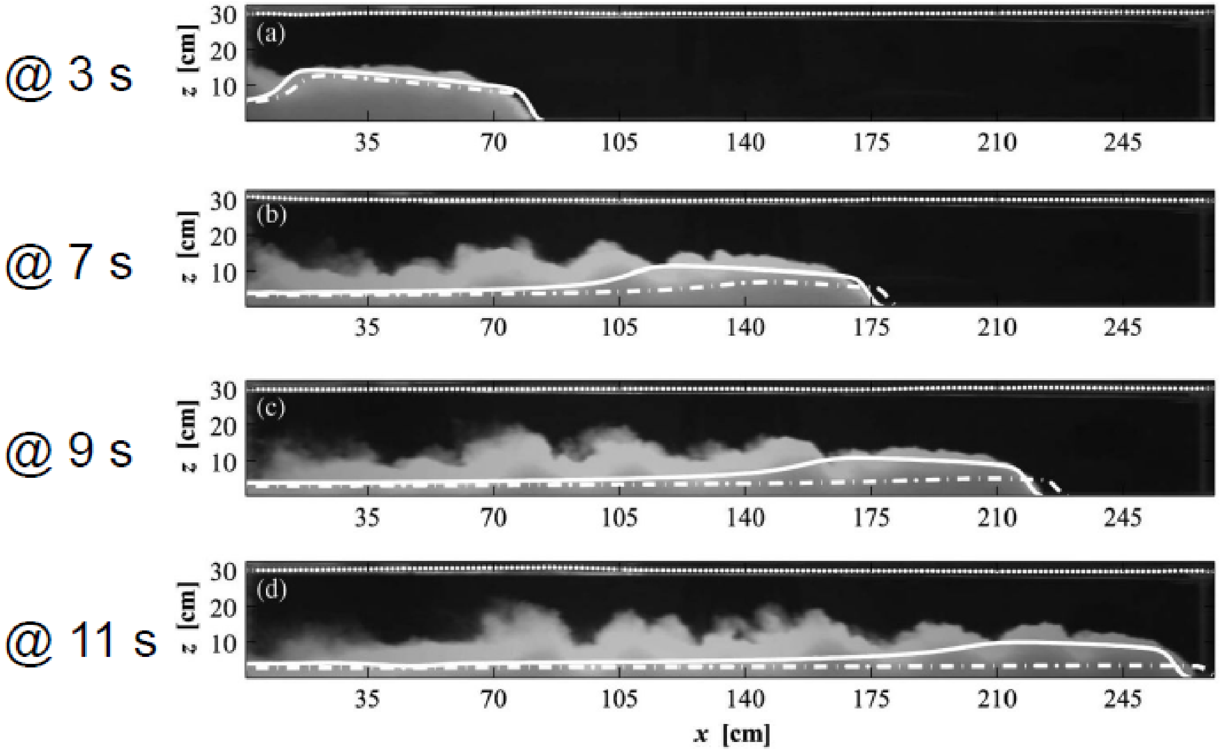




Lab experiment

Using experimental data allows to compare code outputs to a reference given a metric.

- **Convergence study**
- **Numerical comparison**
- **Sensitivity studies** (schemes, resolution viscosity)
- **Parameterization tests** e.g. TKE



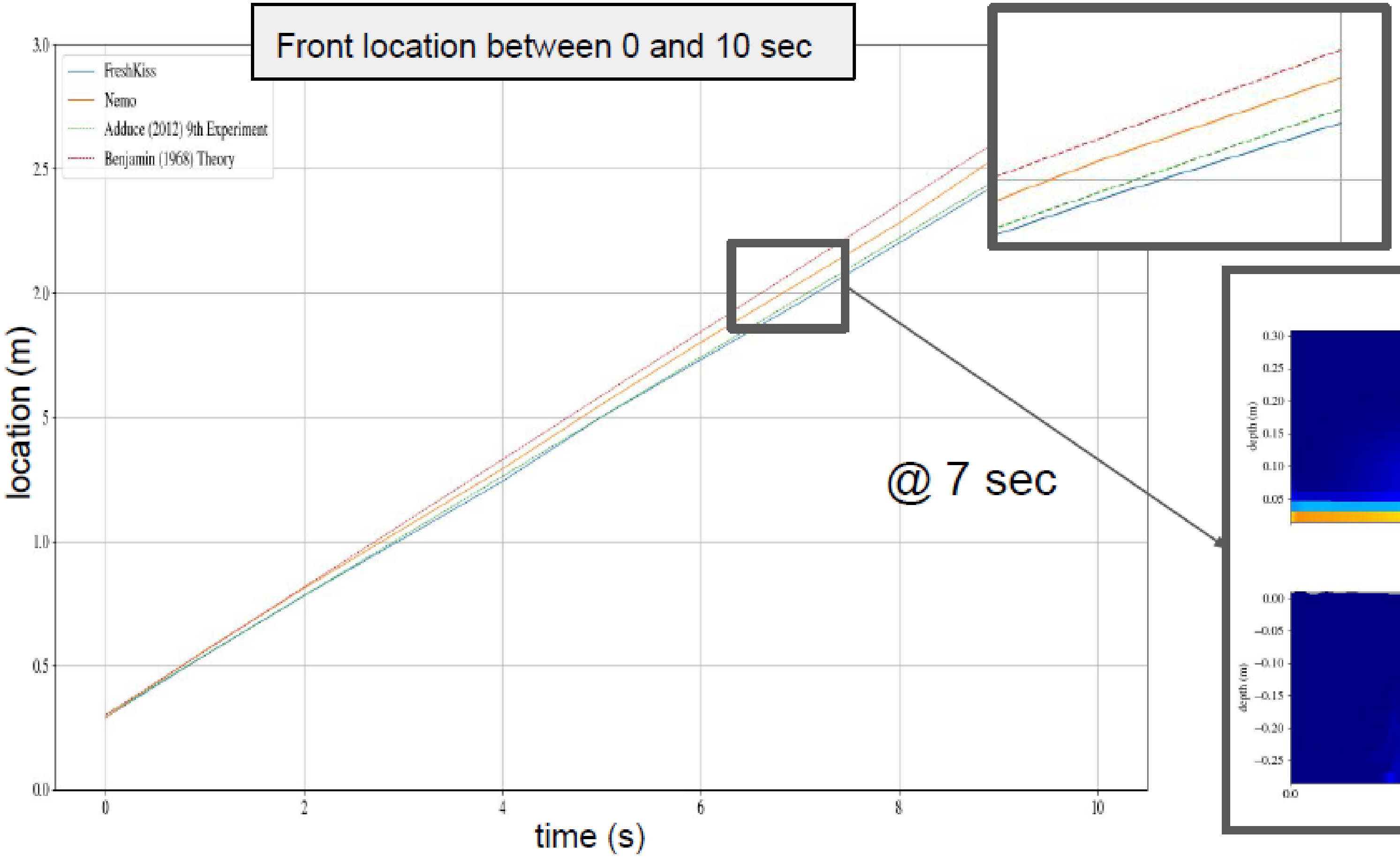
Literature shows various Lock Exchange experiments, we used **Adduce Sciortino and Proietti (2012)** results.

The figure taken from Adduce & al. paper shows a longitudinal section of the Lock Exchange lab experiment #9 ($\Delta\rho$ = 90 kg/m3) white lines are numerical models.

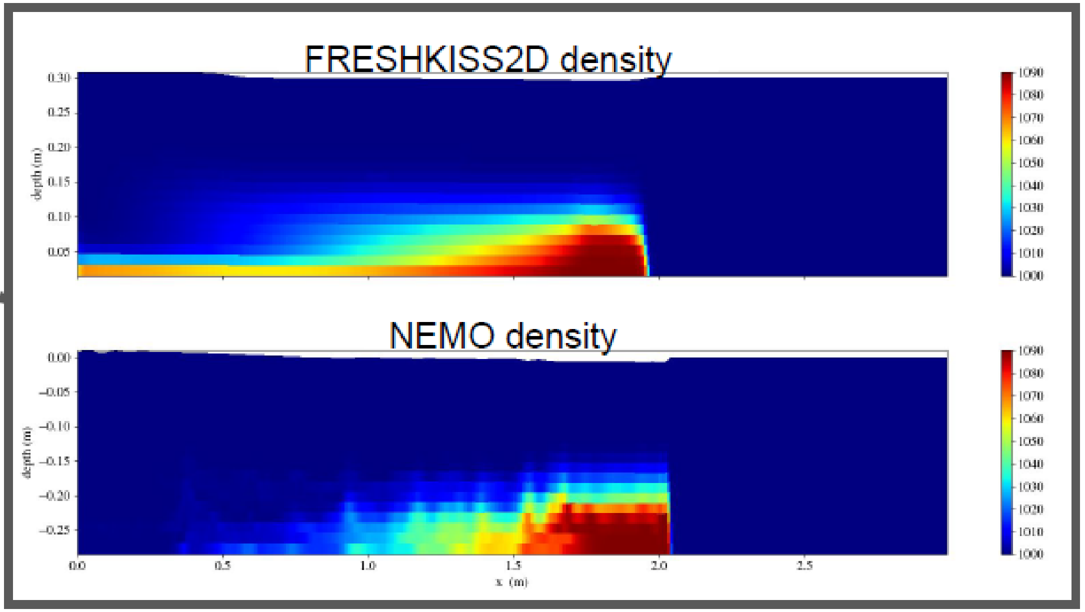
Sibylle Techene

Lab experiment - Lock Exchange

Navier-Stokes 2D hydrostatic equations with variable density and both incompressible and Boussinesq assumptions. Δx : 0.01 m, Δz : 0.015 m, viscosity : 10^{-4} m^2/s



Benjamin theory assumes energy conservation
Nemo less viscous than Freshkiss2d and real data
Lab experiment is expected
Freshkiss2d closed to lab experiment



Analytical solution

There are various configurations likely to be implemented in an global circulation model (hydrostatic or Boussinesq hypothesis for example).

Using analytical solutions for studying global circulation models offers

- a solid understanding in the numerical methods involved,
- a rigorous testing tool of the model ingredients,

$$\delta X/\delta t + \delta F(X)/\delta x = S(X)$$

$$X_{i,n+1} = X_{i,n} - \Delta t/\Delta x \, (F_{i+1/2} - F_{i-1/2}) + \Delta t \, S(X_{i,n})$$

- **convergence** study from discrete to continuous system
- **consistency** ensure to solve the proper equations
- **order and stability** shows the numerical scheme actual performance

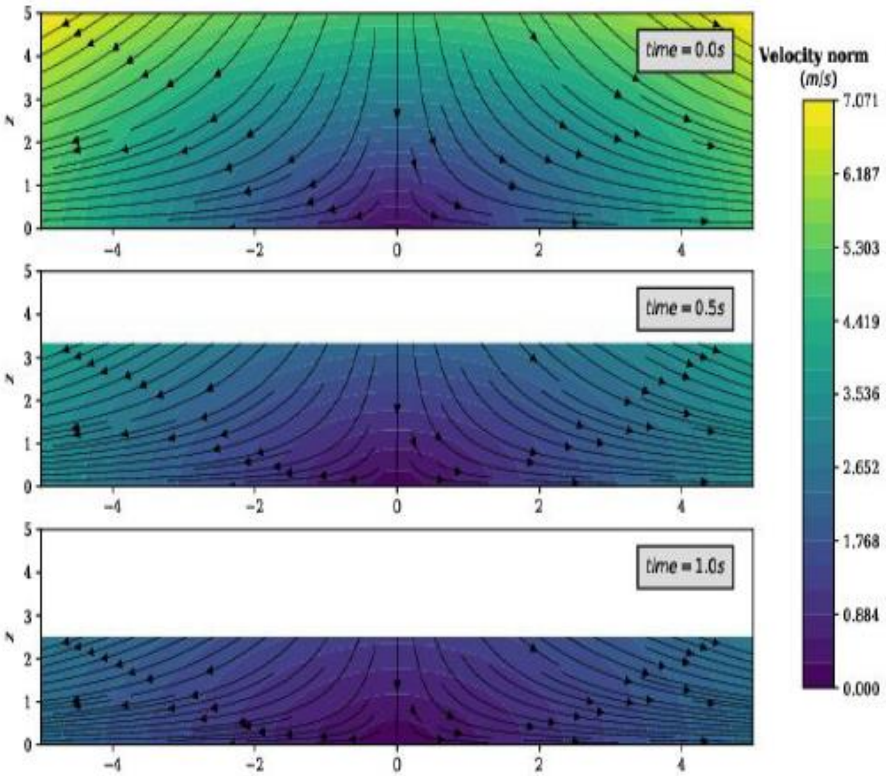
Analytical solution Example

Flat bottom emptying box solutions for **Navier-Stokes free surface non hydrostatic** equations.

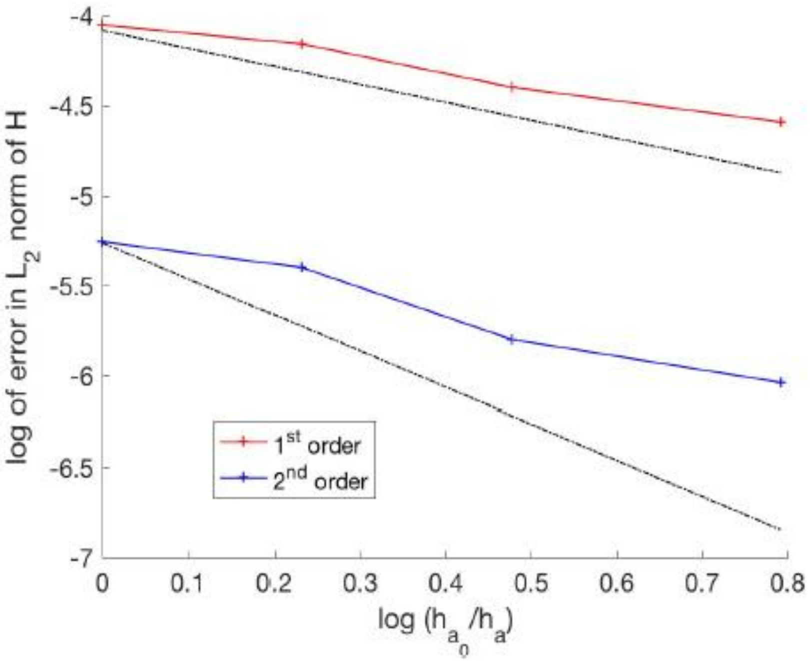
For some $\alpha \in \mathbb{R}_+$, $t_0 \in \mathbb{R}$, $t_1 \in \mathbb{R}_+^*$, $\phi_0 \in \mathbb{R}$, $\theta \in [0, 2\pi]/\{\pi\}$ let us consider the functions h, u, v, w, p, ϕ defined for $t \geqslant t_0$ by

$$\begin{aligned}
h(t,x,y) &= \alpha f(t),\\
u(t,x,y,z) &= f(t)\,(x\cos(\theta) + y\sin(\theta))\,,\\
v(t,x,y,z) &= f(t)\tan\left(\frac{\theta}{2}\right)(x\cos(\theta) + y\sin(\theta))\,,\\
w(t,x,y,z) &= f(t)\,(z_b - z)\,,\\
p(t,x,y,z) &= p^{a,0}(t) + g(h - (z - z_b)) + \left(h^2 - (z - z_b)^2\right) f(t)^2,\\
\phi(t,x,y,z) &= \frac{\phi_0}{L}(x\cos(\theta) + y\sin(\theta))\frac{z - z_b}{h_0},
\end{aligned}$$

where $f(t) = 1/(t - t_0 + t_1)$ and with a flat bottom $z_b(x,y) = z_{b,0} = cst$, $h_0 = h(t_0, x, y) = \alpha/t_1$ and $p^{a,0}(t)$ a given function.



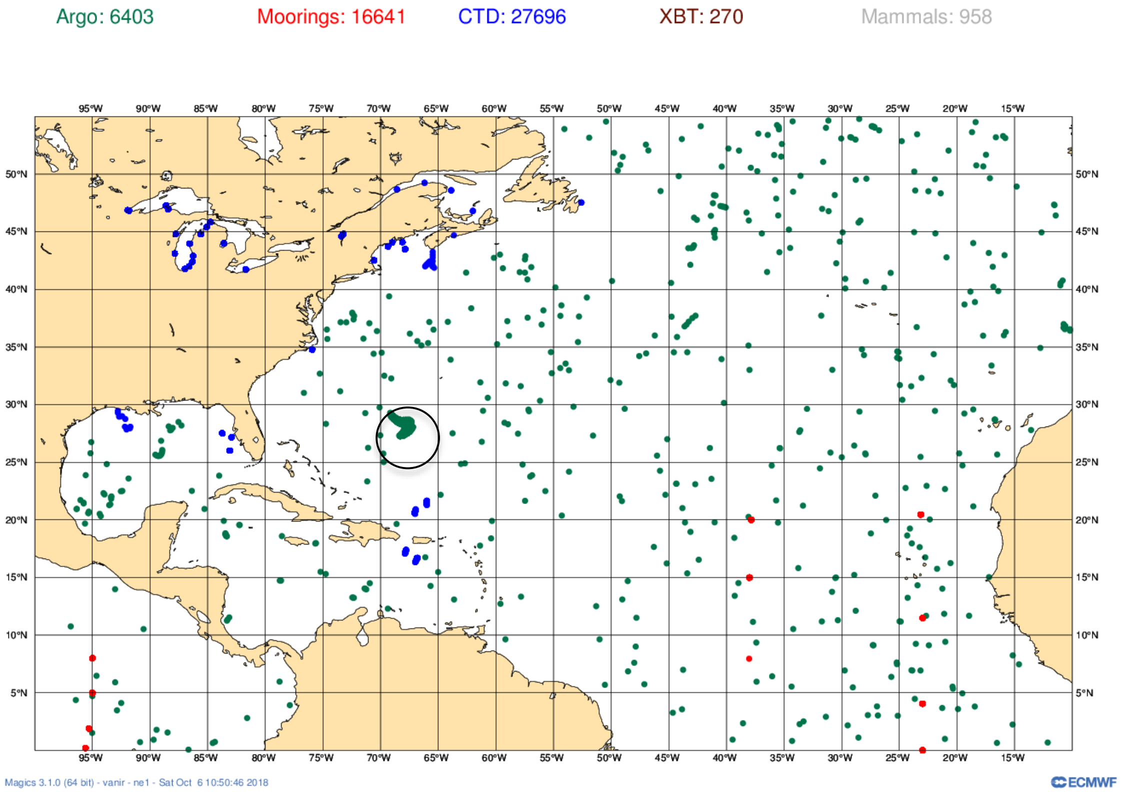
Vertical section of the analytical solution

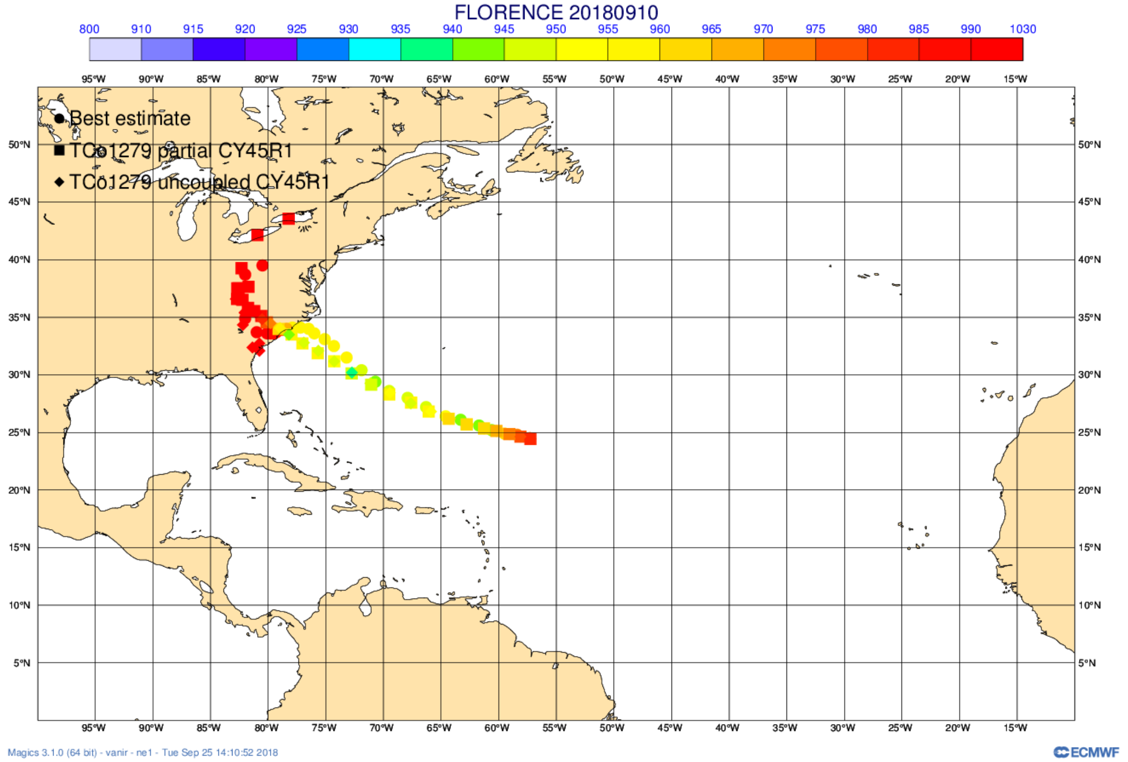


Convergence study

Observations – example
Alamo floats dropped in before Tropical Cyclone (TC) Florence

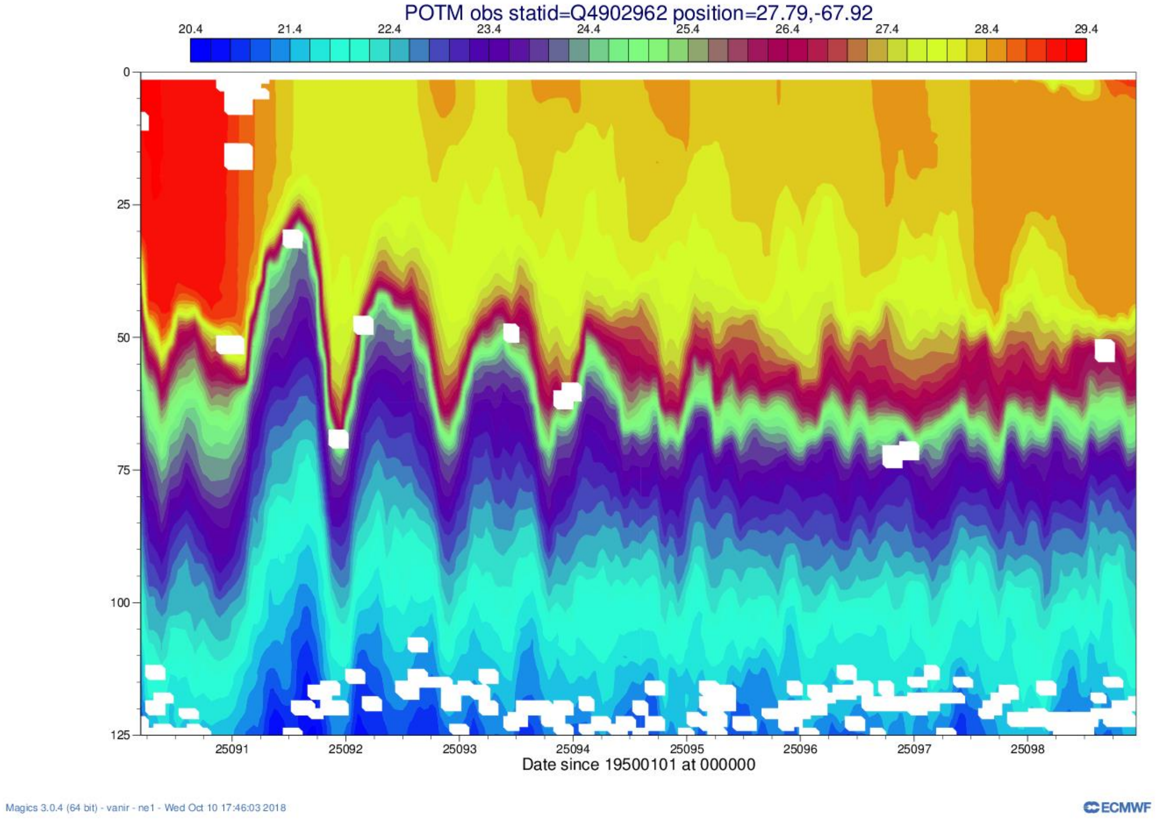
K. Mogensen

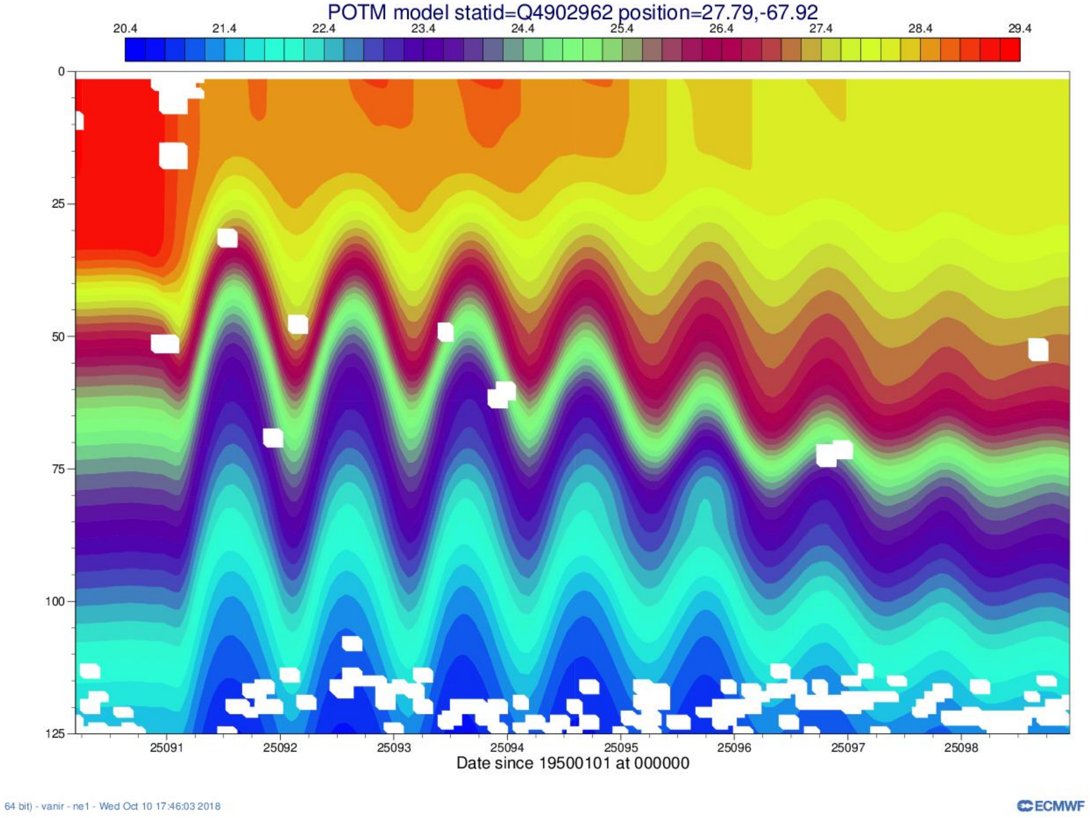




Observations – example
Alamo floats dropped in before TC Florence 9 km atmosphere

K. Mogensen





Cooling not strong enough: too weak winds or errors in the ocean model?

Challenges and prospects for dynamical cores of oceanic models across all scales

Florian Lemarié[1], Hans Burchard, Knut Klingbeil, and Laurent Debreu

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COMMODORE

Community for the numerical modeling of the global, regional and coastal ocean

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FIRST COMMODORE WORKSHOP: COMMUNITY FOR THE NUMERICAL MODELING OF THE GLOBAL, REGIONAL, AND COASTAL OCEAN

WHAT: A total of 47 participants from 9 countries representing 15 different oceanic numerical models met to review our current understanding of future challenges in the design of oceanic dynamical cores.

WHEN: 17–19 September 2018

WHERE: Paris, France

1 - Major differences compared to atmospheric modeling

	Atmosphere	Ocean
Horizontal velocities U	$10\ \mathrm{m\,s^{-1}}$	$0.1\ \mathrm{m\,s^{-1}}$
Sound speed c_s	$\sim 340\ \mathrm{m\,s^{-1}}$	$\sim 1500\ \mathrm{m\,s^{-1}}$
External gravity waves c_0	$\sim \mathbf{300}\ \mathrm{m\,s^{-1}}$	$\sim \mathbf{100}\ \mathrm{m\,s^{-1}}$
Internal gravity waves c_1	$\sim \mathbf{100}\ \mathrm{m\,s^{-1}}$	$\sim \mathbf{1}\ \mathrm{m\,s^{-1}}$
First deformation radius	O($100\ \mathrm{km}$)	O($10\ \mathrm{km}$)

- Density variations are quite small compared to the mean density
  → Boussinesq approximation is valid (i.e. no acoustic modes)
- Validity of hydrostatic balance ($\delta^2 \mathrm{Fr}^2 \ll 1$) : in the ocean the hydrostatic balance is violated approximately for $L < 1\ \mathrm{km}$ and weak stratification
  → Oceanic non-hydrostatic models are at an early development stage
- Stiffness ($c_0 \gg c_1$): fast modes are meteorologically important (i.e. accuracy matters) and propagate horizontally
  → Split-explicit treatment of 2D barotropic mode + consistency enforcement between barotropic and baroclinic modes
- Away from boundary layers, tracers are stirred and mixed preferentially along isopycnal surfaces : $\kappa_{\mathrm{dia}} \approx 10^{-5}\ \mathrm{m^2\,s^{-1}}$ (e.g. Ledwell et al., 1993); $\kappa_{\mathrm{iso}} \approx 10^3\ \mathrm{m^2\,s^{-1}}$ (for $L_x \approx 100\ \mathrm{km}$)
  → Strong constraint on the choice of vert. coord. & tracer advection/remapping schemes
- Complex geometry (but no "Pole problem")
  → Computational domain is bounded with irregular boundaries
- Vacuum states (wetting and drying)
  → Volume-conserving treatment of dry states and non-negativity of water heights

2 - Overview of equations and associated modeling assumptions

- Geometric assumptions:
  - spherical geoid, traditional shallow-fluid
  - fixed bathymetry ($-H(x,y) \leq z \leq \eta(x,y,t)$)
- Boussinesq
  - *in-situ* density $\rho \to \rho_0$ except when associated with the gravitational term
- Hydrostatic
- Thermodynamically consistent description of seawater via a Gibbs function (TEOS10)
  - Potential temperature θ is replaced by the conservative temperature $\Theta = h_0/c_p^0$.
- Mode splitting: fast surface gravity waves are integrated separately (under a depth-independent barotropic mode approximation)

- Baroclinic (internal) mode

A completer

- Barotropic (external) mode ($\overline{\mathbf{u}} = \int_{-H}^{\eta} \mathbf{u}_h\, \mathrm{d}z$)

$$\begin{cases} \partial_t \eta = -\boldsymbol{\nabla}_h \cdot (D\overline{\mathbf{u}}) - (E-P) \\ \partial_t (D\overline{\mathbf{u}}) = -Df\mathbf{k} \times \overline{\mathbf{u}} - gD\boldsymbol{\nabla}_h \eta + D\boldsymbol{\mathcal{F}}_{3D\to 2D} \end{cases}$$

$\boldsymbol{\mathcal{F}}_{3D\to 2D}$: baroclinic-to-barotropic forcing term kept frozen

3 - Brief overview of some existing dynamical cores

Acronym	website	Primary target application	horiz. grid	NH option
Croco	https://www.croco-ocean.org/	coastal	structured	Yes
FESOM	https://fesom.de/	global	unstructured	
GETM	https://getm.eu/	coastal	structured	Yes
Hycom	https://hycom.org/	global	structured	
ICON-O	https://www.mpimet.mpg.de/en/science/models/icon-esm/icon-o/	global	unstructured	
MITgcm	http://mitgcm.org/	global	structured	Yes
MOM6	https://github.com/NOAA-GFDL/MOM6-examples/wiki	global	structured	
MPAS-O	https://mpas-dev.github.io/	global	unstructured	
NEMO	https://www.nemo-ocean.eu/	global	structured	
Roms-Rutgers	https://www.myroms.org/	coastal	structured	
SCHISM	http://ccrm.vims.edu/schismweb/	coastal	unstructured	
Suntans		coastal	unstructured	Yes
Symphonie	http://sirocco.obs-mip.fr/ocean-models/s-model/	coastal	structured	Yes
Thetis	http://thetisproject.org/	coastal	unstructured	

Table 1 : Summary of realistic oceanic models widely used by the research and operational community.

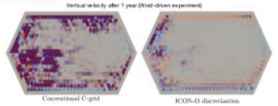
Model	Variables arrangement	Discretization technique	FE pair	Stabilization	Mesh	Mode splitting
FESOM	triangular B-grid	FV	-	-	Arbitrary	SPI
ICON-O	triangular C-grid	FE	modified $\mathrm{RT}_0 - P_0$	No	Orthogonal	SPI
MPAS-O	hexagonal C-grid	FV	-	-	Orthogonal	SPE
SCHISM	triangles or quads	FE	$P_1 - P_1^{\mathrm{NC}}$	No	Arbitrary	No
Thetis	triangles or quads	FE	$P_1^{\mathrm{DG}} - P_1^{\mathrm{DG}}$	Roe	Orthogonal	SPI

Table 2 : Overview of the main characteristics of some unstructured grid models.

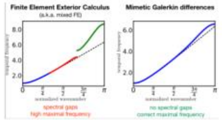
4 - Some prospects for oceanic dynamical cores

Control of spurious modes & spectral gaps (with FE methods)

Korn & Danilov, 2017

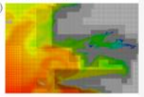


Eldred & Le Roux, 2018

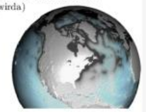


Multi-resolution strategies

Block structured mesh refinement (Croco Ocean model)

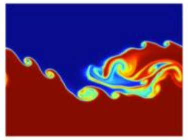


Variable resolution unstructured meshes (Courtesy of D. Engwirda)

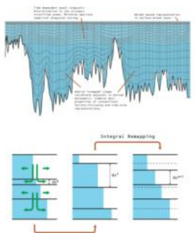


Inclusion of NH effects

1. Pseudo-compressible approach (Auclair et al., 2018) {Croco, SNH}
2. Incompressible pressure projection/correction approach {MITGcM, Suntans}
3. Artificial compressibility method (ACM) (Lee et al., 2006) {Symphonie}
4. Diagnostic approach for NH pressure (Klingbeil and Burchard, 2013) {GETM}



A.L.E. vertical coordinates

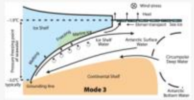


5 - Challenges

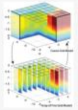
- Challenges for unstructured meshes: High-order methods and Local time-stepping
- Energy consistency and resolved/unresolved scales coupling
  - Discrete closing of the energy budget
  - Design of energy-conserving space and time discretizations
- Control of energy, non-negativity and dry states for nonlinear scalar conservation laws

- Stable and consistent coupling with other Earth-system compartments

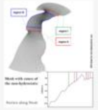
(e.g. interactions between ocean, sea ice and ice shelves)



- Multi-resolution strategies with local adaptation of model equations

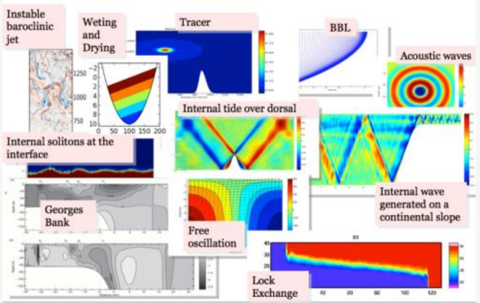


via super-parameterization (Campin et al., 2011)



via automatic selection of NH zones (Androsov et al.)

6 - Toward a "DCMIP-like" test-case suite



References

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COMMODORE

- Partners ?
  - INRIA
  - IPSL
  - UKMO
  - GFDL
  - AWE
  - MPI
  - ECMWF
  - …
- Endorsed by WGNE ?
- Fast-track initiative ?
- Financial support for networking ?
- Summer school / Hackathon involving students ?

COMMODORE workshop

Community for the numerical modeling of the global, regional and coastal ocean

Hamburg: 28th-31st January 2020

Additional slides