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

Florian Lemarié, Hans Burchard, Knut Klingbeil, Laurent Debreu

To cite this version:

Florian Lemarié, Hans Burchard, Knut Klingbeil, Laurent Debreu. Challenges and prospects for dynamical cores of oceanic models across all scales. PDEs on the sphere, Apr 2019, Montreal, Canada. hal-02418199

HAL Id: hal-02418199
https://hal.inria.fr/hal-02418199

Submitted on 18 Dec 2019

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

florian.lemarie@inria.fr
[1] Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, LJK,
38000 Grenoble, France

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

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

A. Adcroft (Princeton, USA), A. Androsov (AWI, Ger.), H. Arango (Rutgers, USA), E. Audusse (LAGA, Fr.), S. Bachman (NCAR, USA), M. Bell (MetOffice, UK), R. Benshila (LEGOS, Fr.), M. Bentsen (Uni , Nor.), J. Berntsen (Bergen , Nor.), E. Blayo (UGA, Fr.), J.-M. Campin (MIT, USA), J. Chanut (Mercator, Fr.), E. Chassignet (COAPS, USA), S. Danilov (AWI, Ger.), C. Eldred (Inria, Fr.), D. Engwirda (Columbia, USA), R. Hallberg (GFDL, USA), M. Iskandarani (FSU, USA), T. Kärnä (FMI, Fin.) , N. Kevlahan (McMaster, Can.), P. Korn (MPI, Ger.), D. Le Roux (ICJ, Fr.), M. Losch (AWI, Ger.), G. Madec (LOCEAN, Fr.), G. Marques (NCAR, USA), P. Marsaleix (LA, Fr.), M. Petersen (LANL, USA), J. Sainte-Marie (Inria, Fr.), A. Shao (UVIC, Can.), P. Wolfram (LANL, USA), J. Zhang (VIMS, USA)

Context: the ocean model developers community has had the tendency to be split depending on target applications (global vs coastal) and on the type of horizontal grids (structured vs unstructured)

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**

  $\Longrightarrow$ Boussinesq approximation is valid ($\rightarrow$ 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

  $\Longrightarrow$ 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

  $\Longrightarrow$ Split-explicit treatment of 2D barotropic mode (+ consistency enforcement)
- 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 $L_x \approx 100\ \mathrm{km}$)

  $\Longrightarrow$ Strong constraint on the choice of vert. coord. & tracer advection/remapping schemes
- **Complex geometry (but no ”Pole problem”)**

  $\Longrightarrow$ Computational domain is bounded with irregular boundaries
- **Vacuum states (wetting and drying)**

  $\Longrightarrow$ 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 $\rho \rightarrow \rho_0$ except when associated with the gravitational term
- **Hydrostatic**
- **Thermodynamically consistent description of seawater** (Gibbs function)
  - Potential temperature θ is replaced by the conservative temperature $\Theta = h_0/c_p^0$.
- **Mode splitting**: fast surface gravity waves are integrated separately (depth independent barotropic mode approximation)

- Baroclinic (internal) mode

$$\left\{\begin{aligned} \frac{D\mathbf{u}_h}{Dt} &= -f\mathbf{k}\times\mathbf{u}_h - \frac{\boldsymbol{\nabla}_h p}{\rho_0} - g\boldsymbol{\nabla}_h\eta + \boldsymbol{\mathcal{F}}_{\mathrm{phys}} \\ \partial_z p &= -g\rho \\ \boldsymbol{\nabla}\cdot\mathbf{u} &= 0 \\ \frac{D\Theta}{Dt} &= \frac{1}{\rho_0 C_p}\partial_z\mathcal{I} + \mathcal{F}_\Theta; \qquad \frac{DS_{\mathrm{A}}}{Dt} = \mathcal{F}_{S_{\mathrm{A}}} \\ \rho &= \rho_{\mathrm{eos}}(\Theta, S_{\mathrm{A}}, z) \end{aligned}\right.$$

Kinematic surface boundary condition:

$$w|_{z=\eta} = \partial_t\eta + \mathbf{u}_h(z=\eta)\cdot\boldsymbol{\nabla}_h\eta + (E-P)$$

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

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

$\boldsymbol{\mathcal{F}}_{3D\rightarrow 2D}$: baroclinic-to-barotropic forcing.

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	`https://sourceforge.net/p/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

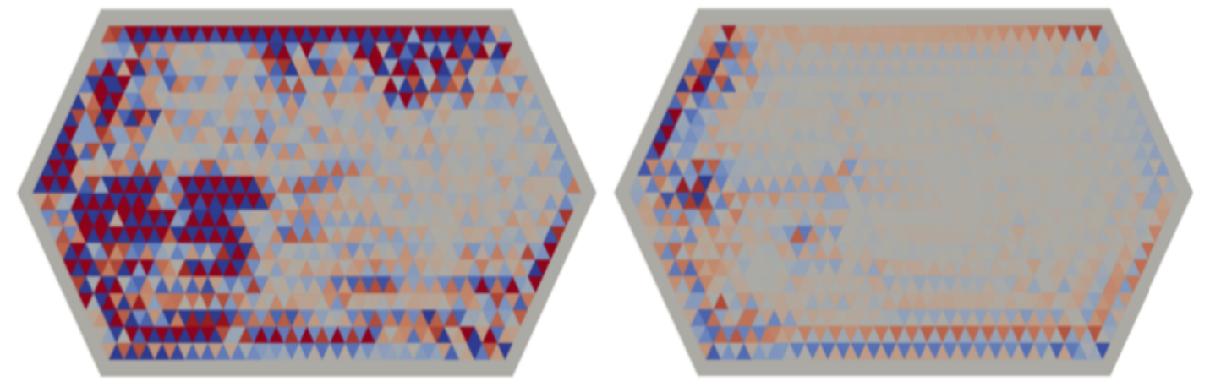
Table 2 : Overview of the main characteristics of some unstructured grid models.

4 - Some prospects for oceanic dynamical cores

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

Korn & Danilov, 2017

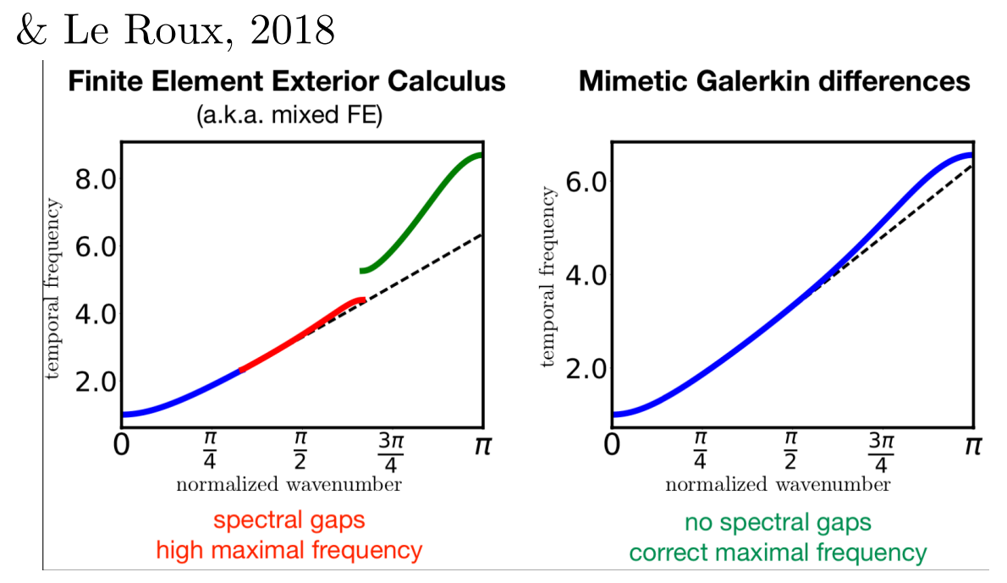
Vertical velocity after 1 year (Wind-driven experiment)



Conventional C-grid

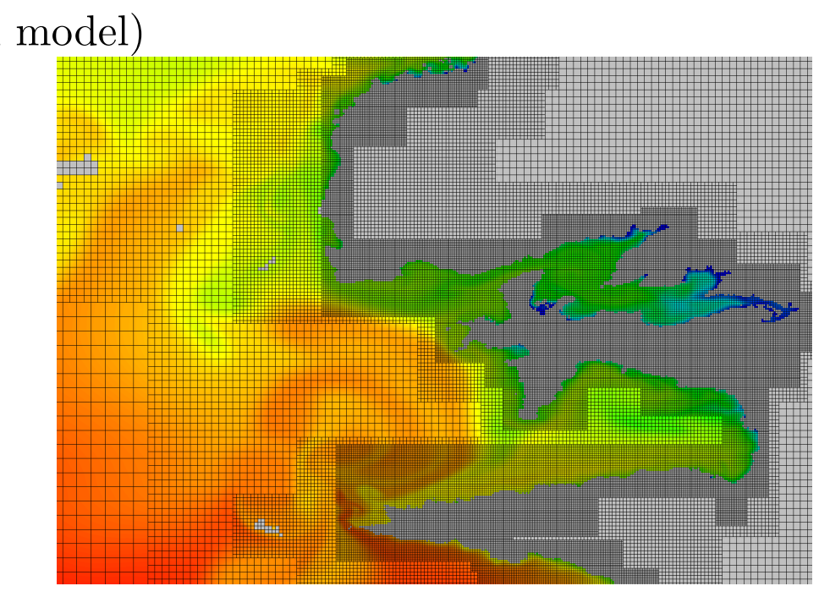
ICON-O discretization

Eldred & Le Roux, 2018

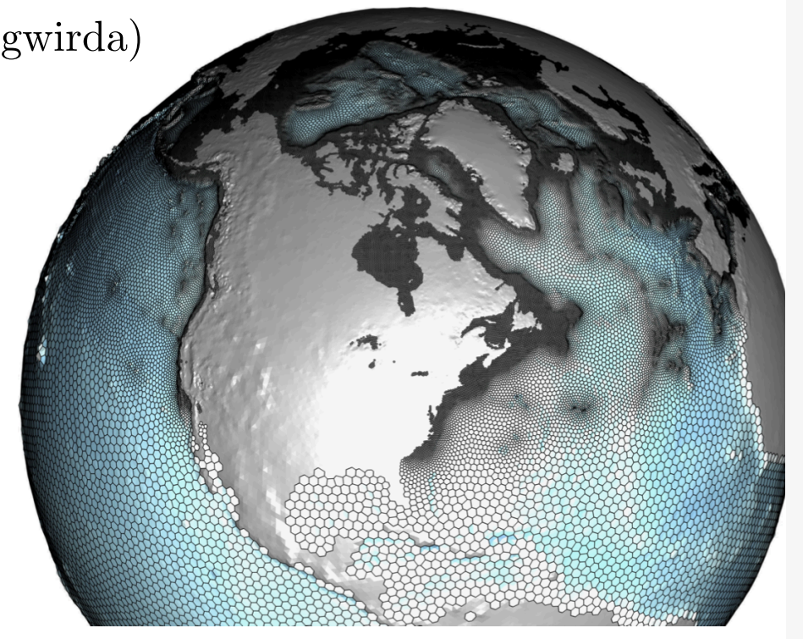


Multi-resolution strategies

Block structured mesh refinement
(Croco Ocean model)

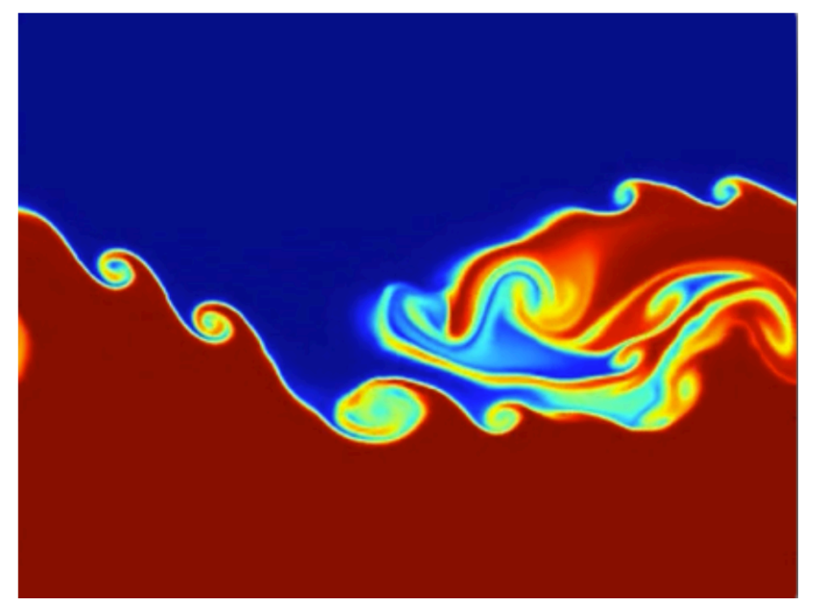


Variable resolution unstructured meshes
(Courtesy of D. Engwirda)

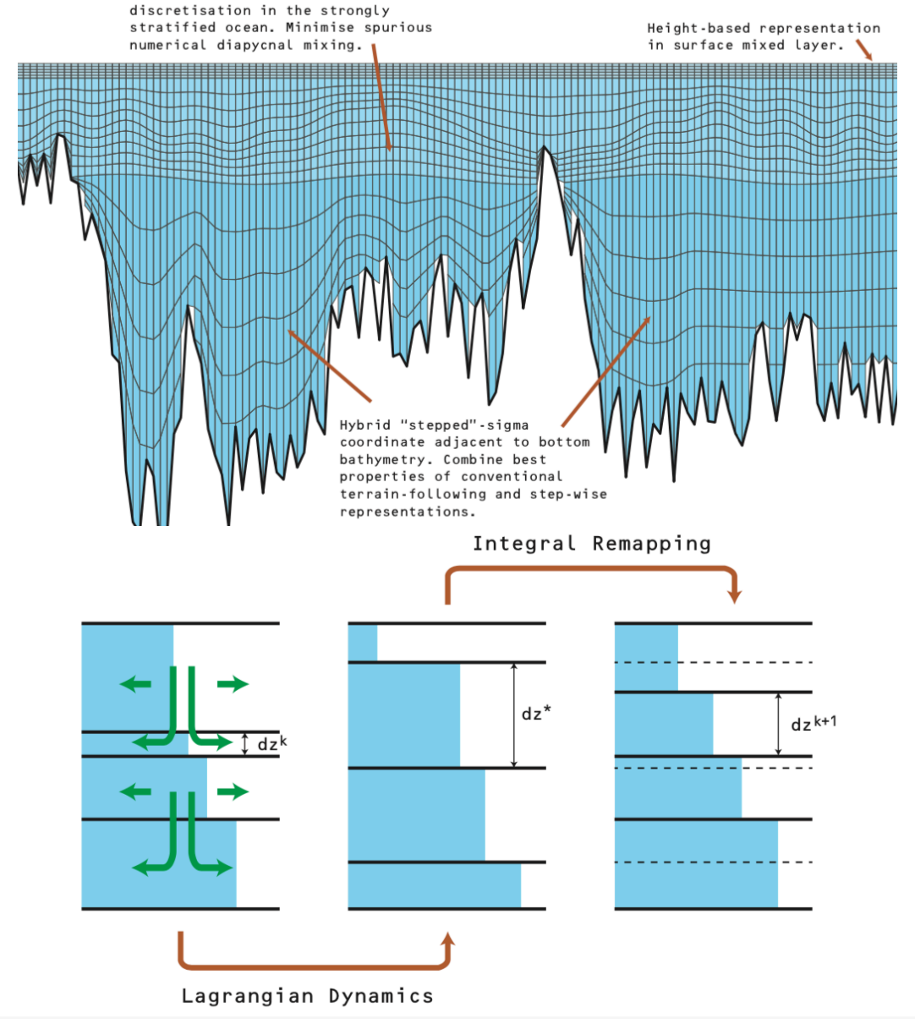


Inclusion of NH effects

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}



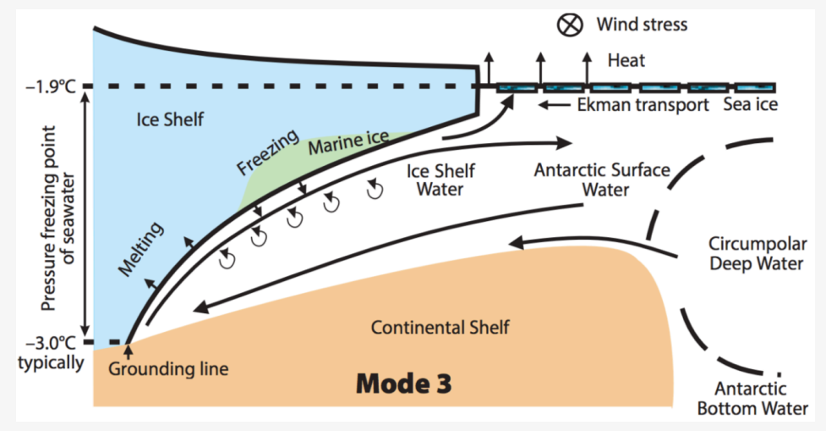
A.L.E. vertical coordinates



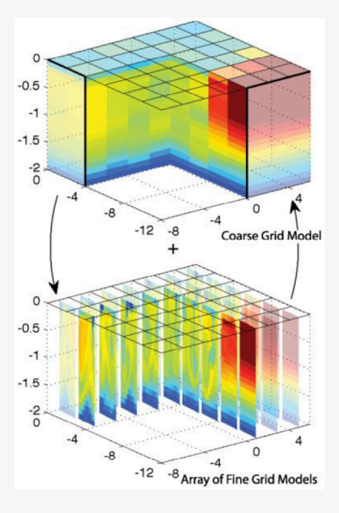
5 - Challenges

- **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**

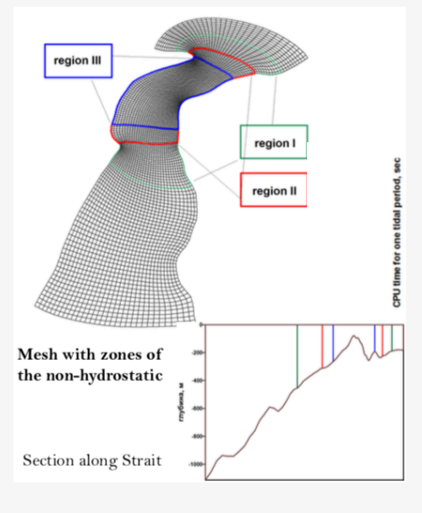
(e.g. interactions between ocean, sea ice and ice shelves)



- **Multi-resolution strategies with local adaptation of model equations**

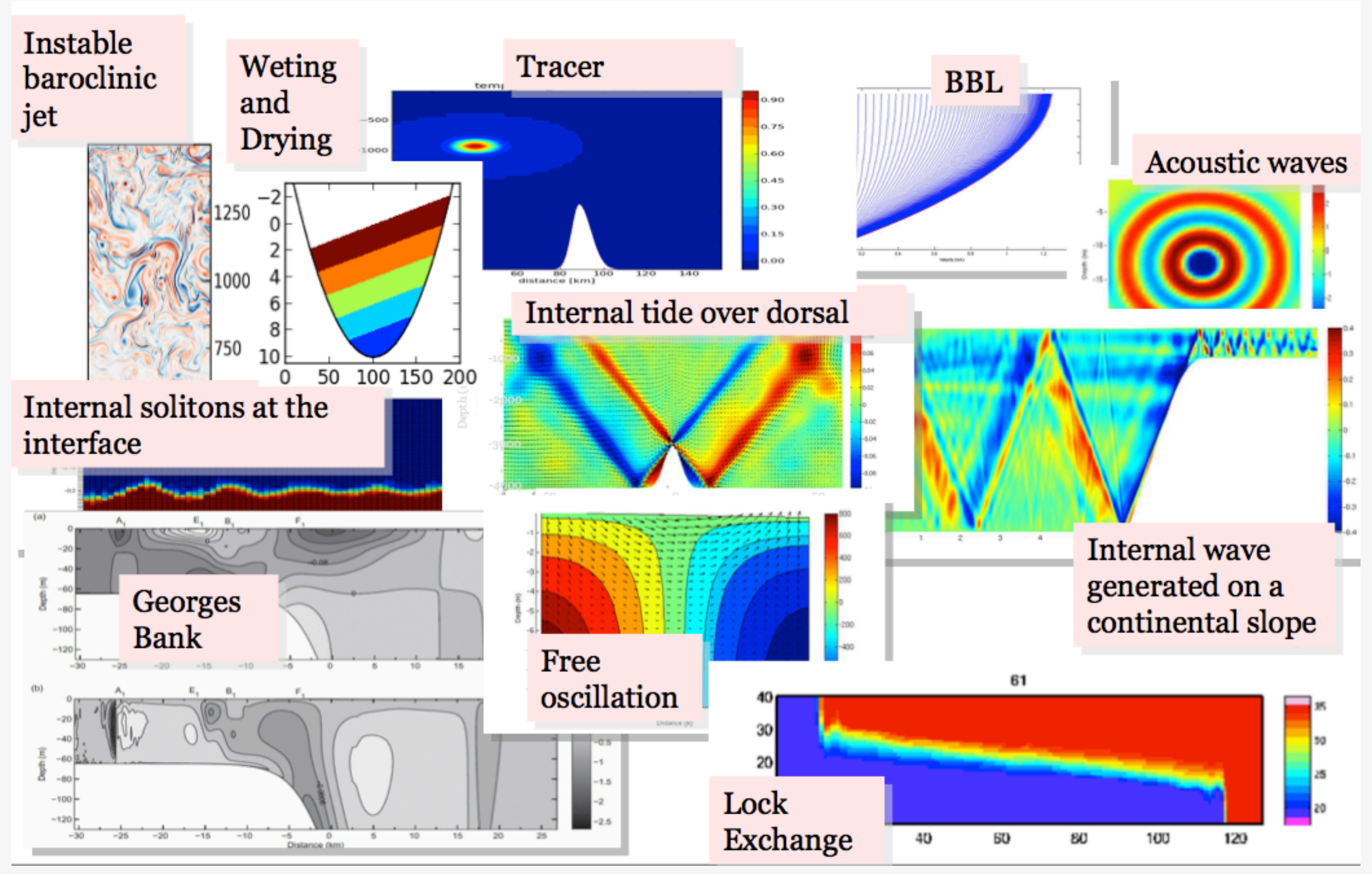


via super-parameterization
(Campin et al., 2011)



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

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



Any suggestion for semi-idealized testcases are welcome

References

- Eden, C., 2016. Closing the energy cycle in an ocean model. Ocean Modell. 101, 30 – 42.
- Griffies, S., Adcroft, A., 2008. Formulating the Equations of ocean models, in: Hecht, M., Hasumi, H. (Eds.), Ocean Modeling in an Eddying Regime. AGU, USA. volume 177 of *Geophysical Monograph Series*, p. 350.
- IOC, SCOR and IAPSO, 2010. The international thermodynamic equation of seawater - 2010: Calculation and use of thermodynamic properties. Technical Report. Intergovernmental Oceanographic Commission. UNESCO.
- Klingbeil, K., Lemarié, F., Debreu, L., Burchard, H., 2018. The numerics of hydrostatic structured-grid coastal ocean models: State of the art and future perspectives. Ocean Modell. 125, 80 – 105.
- Lemarié, F., Burchard, H., Debreu, L., Klingbeil, K., Sainte-Marie, J., 2019. Advancing dynamical cores of oceanic models across all scales. Bull. Amer. Meteorol. Soc. 100(3), ES109–ES115.