CROCO – training 2024

Introduction to CROCO model

CROCO
Coastal and Regional Ocean COmmunity model

Outline

Coastal and Regional Ocean COmmunity model

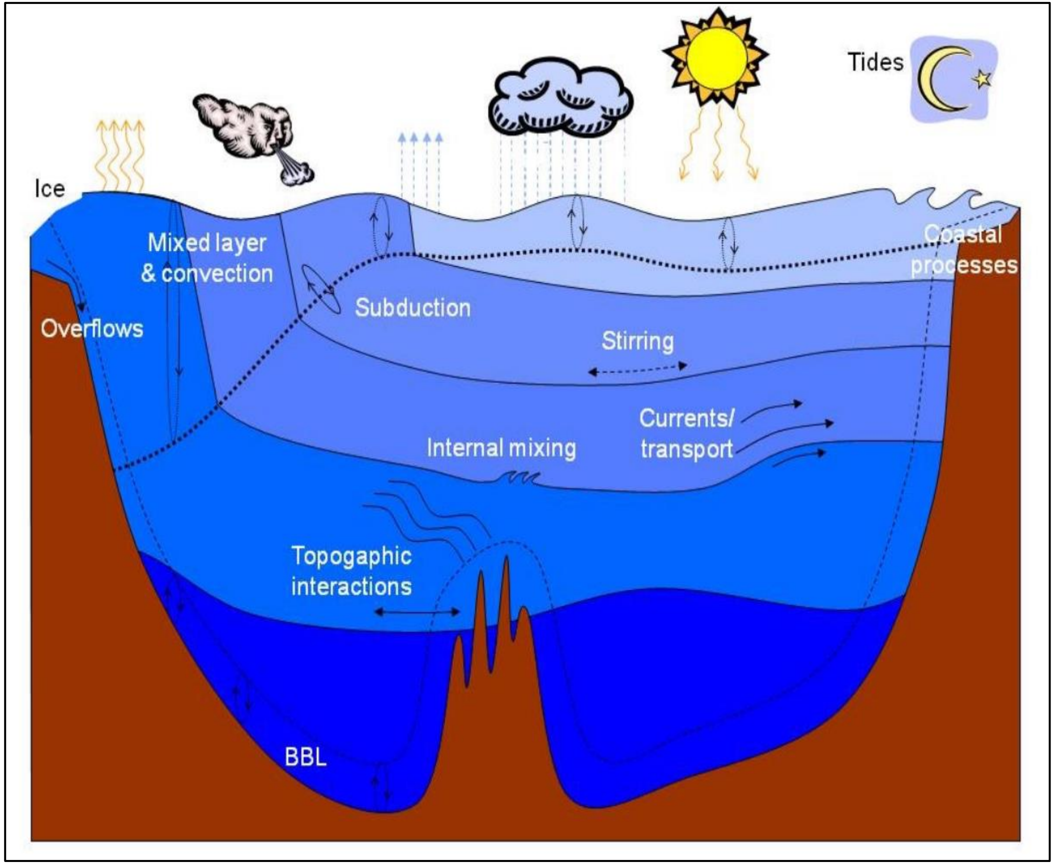
- ➢ Ocean processes: brief outline
- ➢ Ocean Modelling Principle
- ➢ CROCO model equations
- ➢ CROCO performances (nesting,coupling…)

Sea level variability causes

The fluctuations in sea level reflect a variety of phenomena related to ocean dynamics .

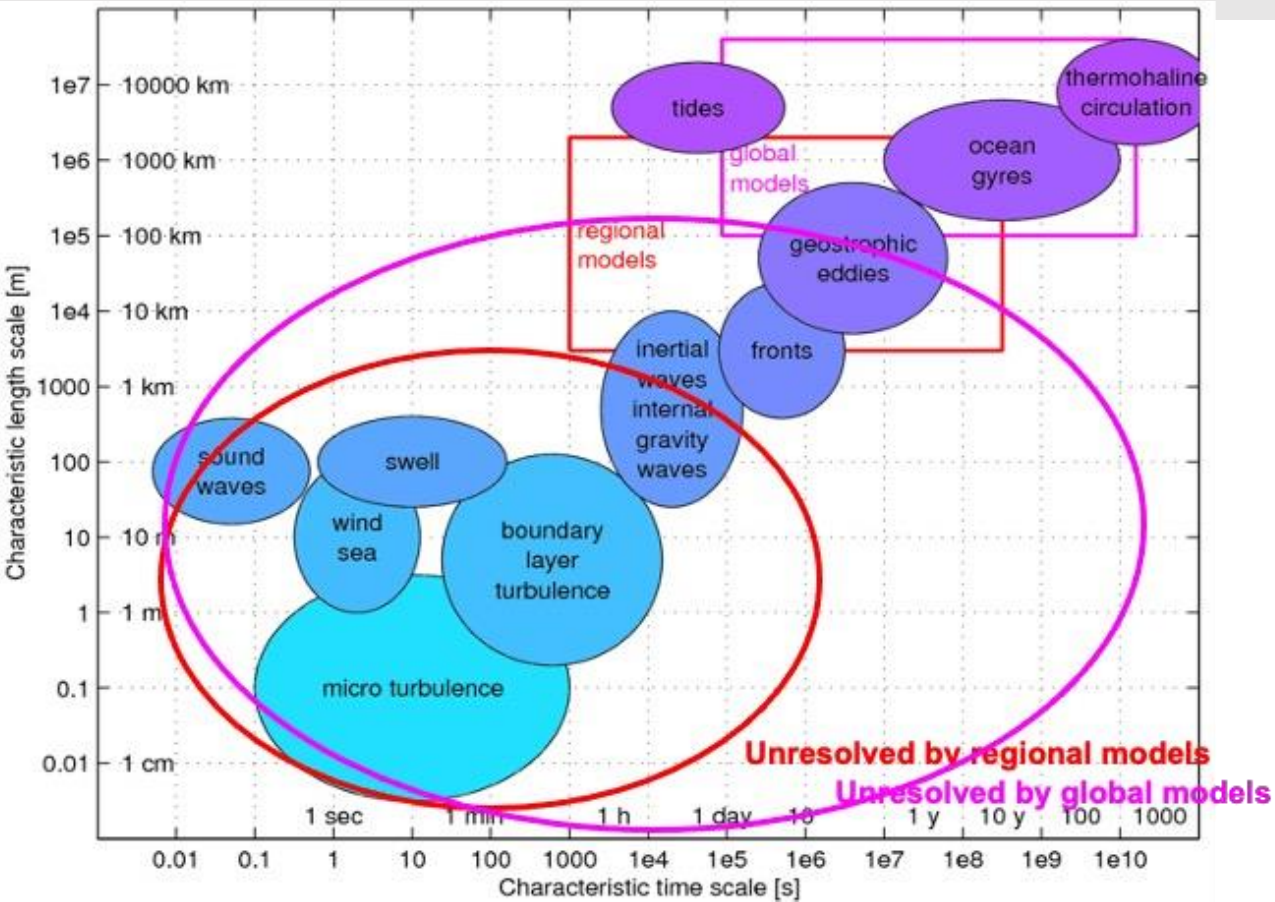
These fluctuations can be due to:

- Wind action
- Atmospheric pressure
- Heat flux
- Tidal forces



Spatial and time scale for different ocean process

Coastal and Regional Ocean COmmunity model

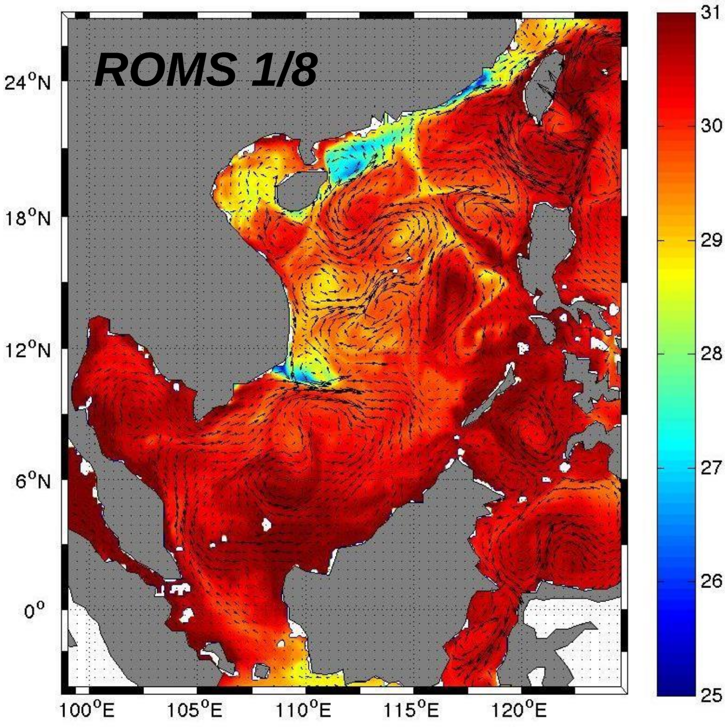


Why modelling ?

Coastal and Regional Ocean COmmunity model

Advantages:

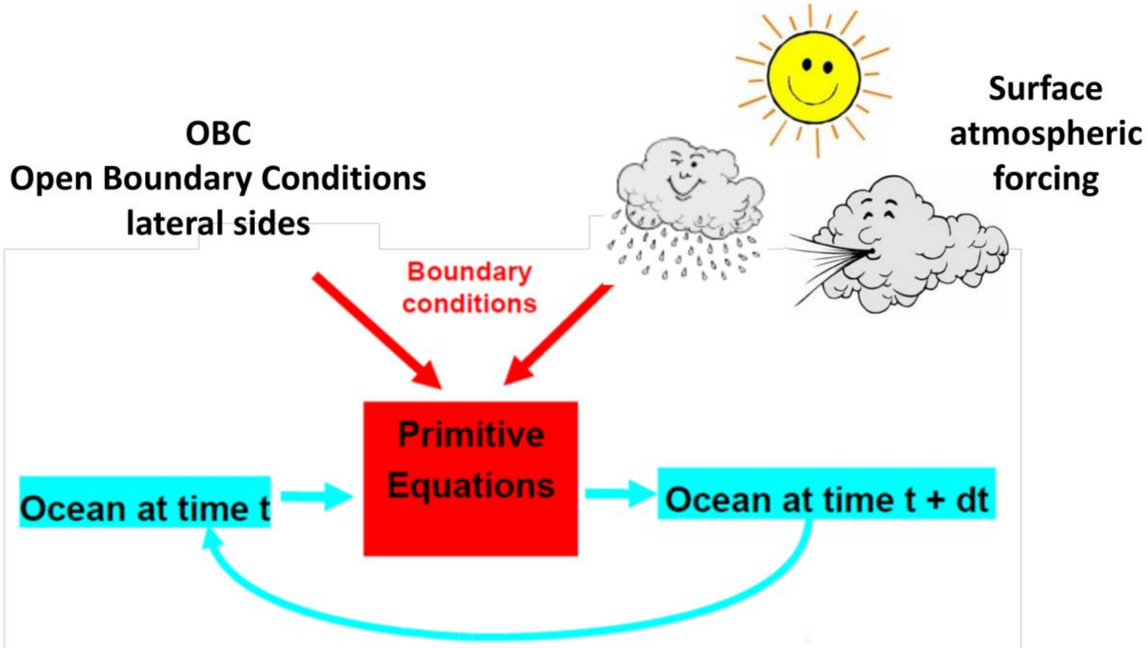
- Cost effective
- Synoptic 4D view
- Test hypothesis
- Hindcast and forecast
- Coupling with different models
- …



Sea Surface Temperature (SST)and surface current on 24/07/1992

Ocean modelling principle

Coastal and Regional Ocean COmmunity model

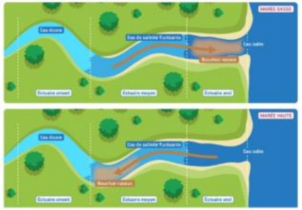


If we know: The **ocean state at time *t* :u,v,T,S..**we can **compute the ocean state at time *t+dt*** using **numerical approximations of Navier-Stokes Equations.**

=> **discretization** of the equations in **time** and **space**

Various type of ocean model depending on space discretization techniques

Coastal and Regional Ocean COmmunity model



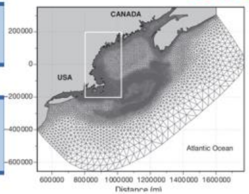
Beach, lagoon, estuary

Coast, continental shelf, regional

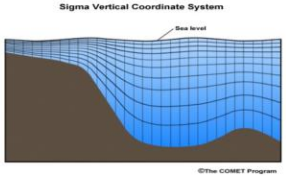
Offshore, ocean

Finite elements — **Coherens, Telemac …**

Finite Volumes — **FVCOM, MIKE3, MOHID…**

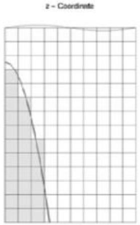


Finite Differences



Sigmas coordinates
MARS3D, CROCO, …

ROMS



Finite Differences

Z coordinates
NEMO, MITgcm, …

Isopycnal or hybrid coordinates **HYCOM**

CROCO MODEL

CROCO brief history

CROCO
Coastal and Regional Ocean COmmunity model

SCRUM

ROMS Rutgers

ROMS UCLA

ROMS : Regional Oceanic Modeling System

ROMS AGRIF
Including Agrif nesting library

+
MUSTANG sediment module of MARS

+
Non Hydrostaic and non boussinesq kernels of Symphonie

CROCO

Coastal and Regional Ocean COmmunity model

CROCO philosophy

CROCO
Coastal and Regional Ocean COmmunity model

Open-source Community

•CROCO is open-source and developed by an active community of users and developers. Contributions are managed through a Git repository, ensuring continuous updates and improvements.

•Stable versions of the model are released every 1 to 1.5 years.

•A community forum is available for discussions, troubleshooting…

Pre- and Post-processing Tools

•Tools are provided to simplify the configuration of the model and visualize output data

CROCO Model equations

Coastal and Regional Ocean COmmunity model

Momentum conservation

$$\frac{\partial u}{\partial t} + \vec{u}.\nabla u - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \nabla_h \left(K_{Mh}.\nabla_h u\right) + \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + \vec{u}.\nabla v + fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \nabla_h \left(K_{Mh}.\nabla_h v\right) + \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial v}{\partial z}\right)$$

advection Coriolis Pressure gradient Horizontal diffusion Vertical diffusion

Continuity

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

Tracer conservation

$$\frac{\partial T}{\partial t} + \vec{u}.\nabla T = \nabla_h \left(K_{Th}.\nabla_h T\right) + \frac{\partial}{\partial z}\left(K_{Tv}\frac{\partial T}{\partial z}\right)$$

$$\frac{\partial S}{\partial t} + \vec{u}.\nabla S = \nabla_h \left(K_{Sh}.\nabla_h S\right) + \frac{\partial}{\partial z}\left(K_{Sv}\frac{\partial S}{\partial z}\right)$$

Equation of state

$$\rho = \rho(S, T, p)$$

Boussinesq hystrostatic mode, and non-hydrostatic, non-Boussinesq mode (NBQ) available

CROCO boundary conditions

- At the surface (z = ξ)

$$K_{Mv}\frac{\partial u}{\partial z} = \frac{\tau_s^x}{\rho_0}(x,y,t)$$

$$K_{Mv}\frac{\partial v}{\partial z} = \frac{\tau_s^y}{\rho_0}(x,y,t)$$

$$\kappa_{Tv}\frac{\partial T}{\partial z} = \frac{Q_T}{\rho_0 C_P} + \frac{1}{\rho_0 C_P}\frac{dQ_T}{dT}(T - T_{ref})$$

$$\kappa_{Sv}\frac{\partial S}{\partial z} = \frac{(E-P)S}{\rho_0} \qquad ; w = \frac{\partial \xi}{\partial t}$$

- At the bottom(z = -H)

$$K_{Mv}\frac{\partial u}{\partial z} = \tau_b^x(x,y,t)$$

$$K_{Mv}\frac{\partial v}{\partial z} = \tau_b^y(x,y,t)$$

$$\kappa_T\frac{\partial T}{\partial z} = 0$$

$$\kappa_S\frac{\partial S}{\partial z} = 0$$

$$-w + \vec{v}\vec{\nabla}h = 0$$

Variables	**Description**
τ_s^x , τ_s^y	Wind stress
Q_T	Net heat flux
E –P	Evaporation minus rain
τ_b^x, τ_b^y	Bottom stress
T_{ref}	Reference Temperature

CROCO Model equations

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Momentum conservation

$$\frac{\partial u}{\partial t} + \vec{u}.\nabla u - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \nabla_h\left(K_{Mh}.\nabla_h u\right) + \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + \vec{u}.\nabla v + fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \nabla_h\left(K_{Mh}.\nabla_h v\right) + \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial v}{\partial z}\right)$$

advection *Coriolis* *Pressure gradient* *Horizontal diffusion* *Vertical diffusion*

depends on turbulent closure scheme used (KPP , GLS scheme…)

Tracer conservation

$$\frac{\partial T}{\partial t} + \vec{u}.\nabla T = \nabla_h\left(K_{Th}.\nabla_h T\right) + \frac{\partial}{\partial z}\left(K_{Tv}\frac{\partial T}{\partial z}\right)$$

$$\frac{\partial S}{\partial t} + \vec{u}.\nabla S = \nabla_h\left(K_{Sh}.\nabla_h S\right) + \frac{\partial}{\partial z}\left(K_{Sv}\frac{\partial S}{\partial z}\right)$$

Turbulent mixing schemes

Two types of mixing schemes

- Pronostic type like GLS : based on two differential equations: one governing TKE (Turbulent Kinetic Energy) and the other describing the turbulence length scale

$$\frac{\partial q^2}{\partial t} + \vec{u}.\vec{\nabla} q^2 = \underbrace{2K_{Mv}\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]}_{TKE\ production} + \underbrace{K_{Tv}\frac{2g}{\rho_0}\frac{\partial \rho_\theta}{\partial z}}_{flottability} + \underbrace{\frac{\partial}{\partial z}\left[K_q\frac{\partial q^2}{\partial z}\right]}_{TKE\ diffusion} - \underbrace{\frac{2q^3}{B_1\ell}}_{TKE\ dissipation}$$

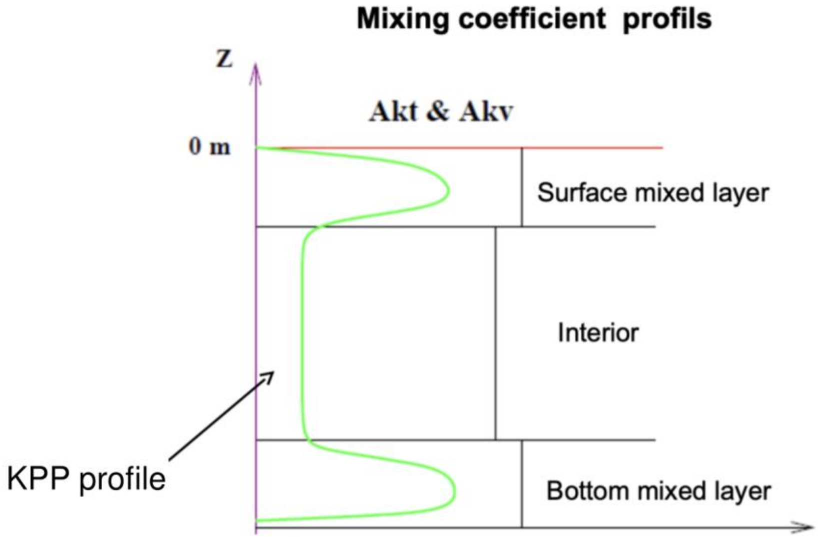
$$\frac{\partial \ell q^2}{\partial t} + \vec{u}.\vec{\nabla}\ell q^2 = E_1\ell\left\{K_{Mv}\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 + K_{Tv}\frac{g}{\rho_0}\frac{\partial \rho_\theta}{\partial z}\right]\right\} - \frac{q^3 W}{B_1} + \frac{\partial}{\partial z}\left[K_q\frac{\partial \ell q^2}{\partial z}\right]$$

ℓ: turbulent length scale q^2=2*TKE

Turbulent mixing schemes

- Non Pronostic type KPP: The vertical mixing in the ocean's surface layer can be described by a vertical diffusion profile. It relates turbulence to the density gradient, allowing diffusion coefficients to be calculated f

- KPP assumes that turbulence in the boundary layer is in equilibrium with surface and bottom fluxes => true for large scale models,
- for coastal applications, the scheme should : respond to local forcing, respond rapidly to surface and bottom fluxes => GLS-type scheme preferred



Open boundary conditions

CROCO Model integrates several OBC Schemes notably:

External mode

Oranski radiation condition for 2D momentum…

$$\frac{\partial \phi}{\partial t} + c_x \frac{\partial \phi}{\partial x} + c_y \frac{\partial \phi}{\partial y} = 0$$

Pronostic variable φ (φ can be T, S or $\vec{v}$ or 2D momentum speed)

Internal mode

Radiation, Orlansky (1976) , Kuo (1984).

$$\frac{\partial \phi}{\partial t} + c_x \frac{\partial \phi}{\partial x} + c_y \frac{\partial \phi}{\partial y} = 0$$

Adaptative mixed radiations/nudging open boundary conditions (Marchesiello et al, 2001).

$$\frac{\partial \phi}{\partial t} + c_x \frac{\partial \phi}{\partial x} + c_y \frac{\partial \phi}{\partial y} = -\frac{1}{\tau}(\phi - \phi_{ext})$$

$\vec{c}(c_x, c_y)$: phase speed

$$c_x = -\frac{\partial \phi}{\partial t} \frac{\frac{\partial \phi}{\partial x}}{\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2} \qquad c_y = -\frac{\partial \phi}{\partial t} \frac{\frac{\partial \phi}{\partial y}}{\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2}$$

Spatial discretization

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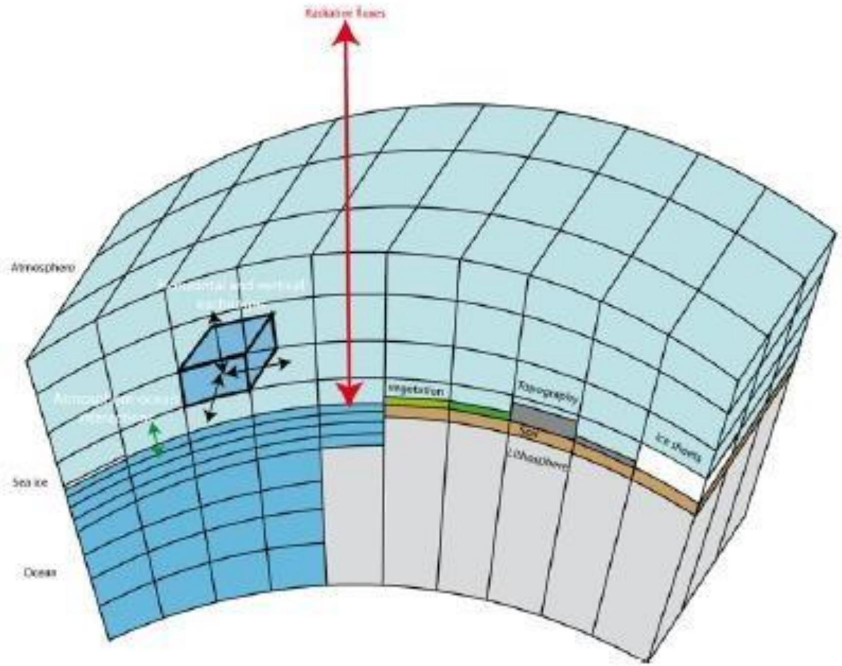
The model domain is devided into « small» boxes.



Example of a finite difference grid

CROCO Horizontal discretization

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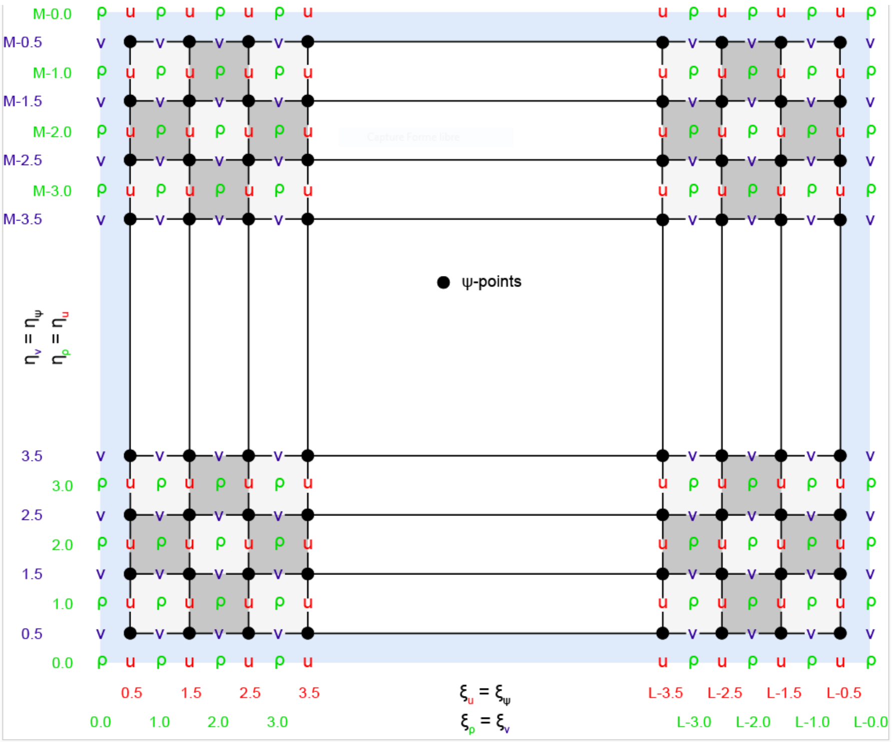
Horizontally: CROCO grid is discretized in curvilinear coordinates that follow the coastline and terrain, with a free surface. It uses an **Arakawa-C grid**, where variables are arranged in a specific way to improve the accuracy of fluid dynamics calculations



CROCO vertical descretisation

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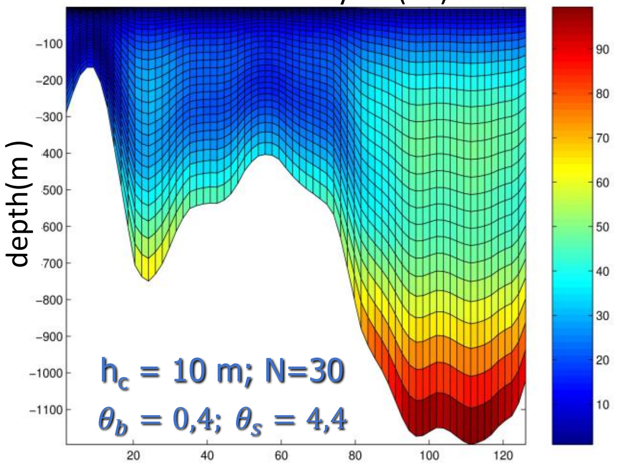
Vertically, CROCO uses sigma coordinates, allowing for stretched bathymetry and specific resolution at the surface or the bottom, depending on the application

Tickness of layers (m)



Distance (km) from the trasect origin

Free surface

Vertical stretching coordinate

Water column depth
(changed in sediment application with erosion/deposition)

$$z(x, y, \sigma, y) = \xi(1 + \sigma) + h_c\sigma + (h - h_c)C(\sigma)$$

parameter controlling stretching
between surface and bottom levels

Stretching function C=*f(**θ**s, **θ**b)*

CROCO Time stepping , numerics

CROCO is a free surface model that :

- resolves the dynamics associated with fast scales, which directly affect the free surface,
- resolves slow scales, related to the ocean's interior dynamics.

⇒ To handle these contrasting dynamics, CROCO adopts a time-splitting strategy.

- In Boussinesq mode the equations associated with fast scales (barotropic mode) are separated from the complete equations and integrated over time using an efficient time-stepping scheme, with a time step that is a sub-multiple of the main time step (baroclinic time step).

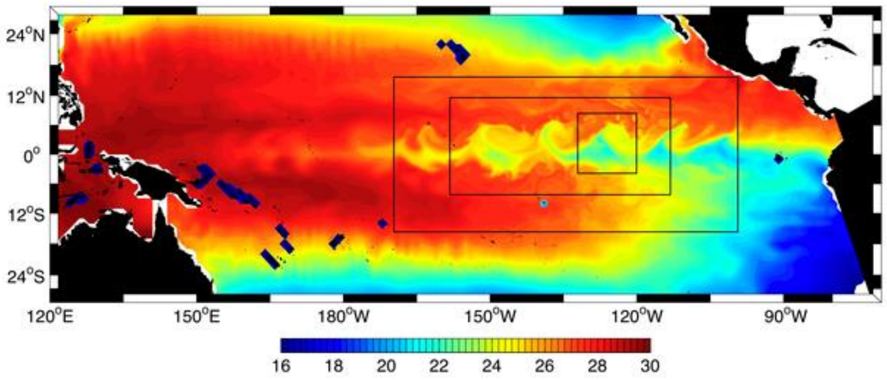
- For **Non-Boussinesq (NBQ) mode**, the barotropic mode solver is replaced by a fully 3D fast mode solver, which resolves all waves, including acoustic waves.

CROCO PERFORMANCES

CROCO nesting

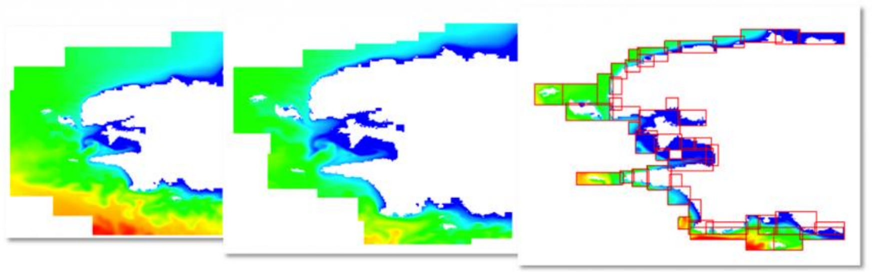
Nesting with AGRIF

- Grid refinement with the AGRIF library (developed at Inria)
- 1-way (coarse grid force the finer grid) and 2-way (feedback of the finer grid to the coarse grid) nesting capabilities



Towards multi-grid / multi-resolution (in dev.)

- Exchanges between grids of the same level
- Refinement criteria
- Good CPU load balance
- Management of numerous grid outputs



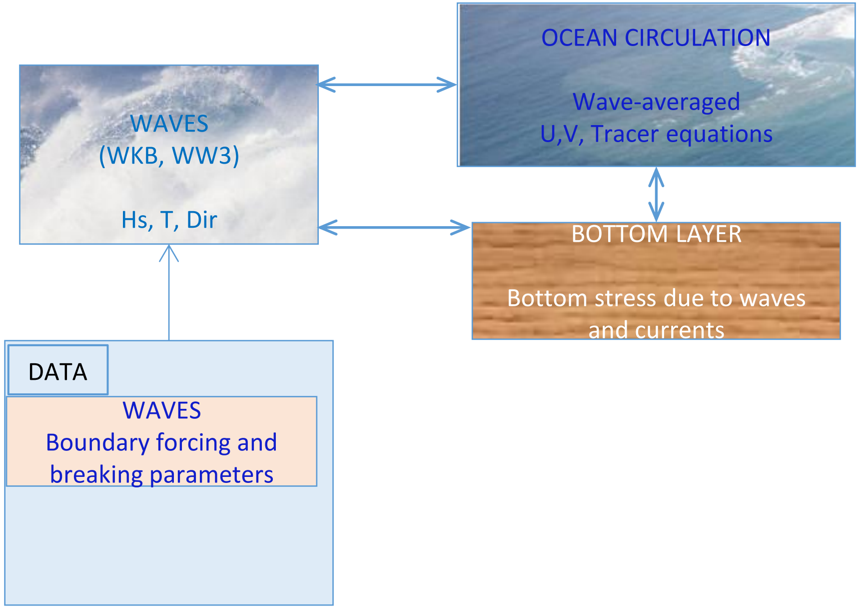
CROCO modules and coupling

Coastal and Regional Ocean COmmunity model

Wave-current interactions

- Based on the vortex force formalism (Uchiyama et al. 2010):
    - Impact of evolving water level on waves
    - Impact of current on waves evolution (refraction, etc)
    - Wave-induced circulation (stokes drift and transport, acceleration by breaking)
    - Enhanced mixing due to wave breaking
    - Surface and bottom streaming (wave-induced thin viscous boundary layer)
    - Mass flux due to wave rollers
    - Wave-induced pressure effects
    - Wave-induced additional diffusivity
    - Wave-induced setup

- WKB module
- Coupling with a wave model through OASIS3-MCT library (developed at CERFACS)



CROCO modules and coupling

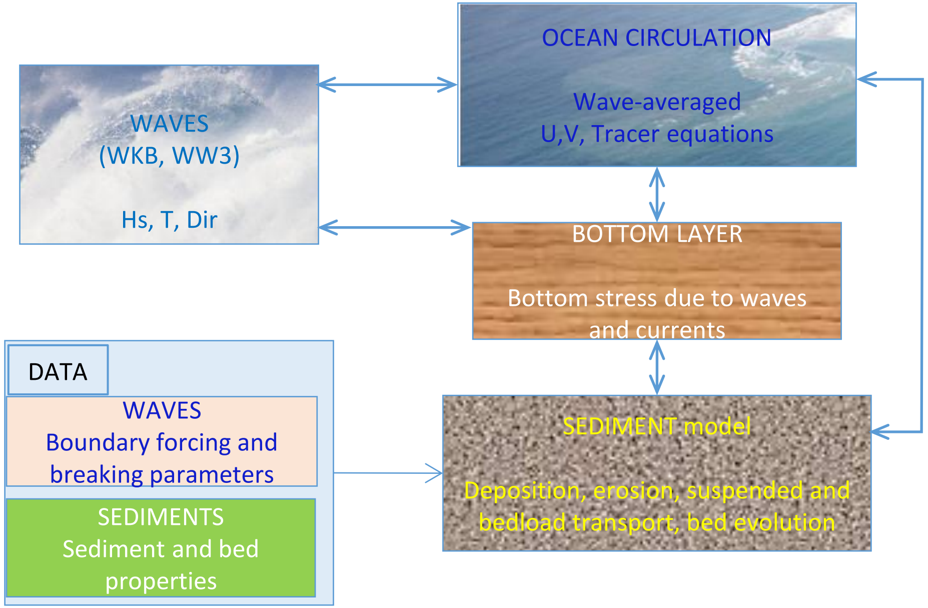
Sediment modules

- USGS Sediment model (Blaas et al. (2007); Warner et al. (2008)
  - Wave input (specified, WKB, or WW3)
  - Wave-current combined bottom stress (Soulsby, 1995)
  - Erosion (armoring), deposition, suspended transport
  - Bedload transport and flux divergence
  - Bed model (sand, mud, or mixed)
  - Morphological evolution (with acceleration factor)
  - Wetting and drying
  - Positive-definite advection schemes (WENO,TVD)
  - Sediment influence on density
- MUSTANG (Mud and Sand Transport Modeling, Le Hir et al., 2011 by Ifremer/DHYSED)

Morphodynamics

Currents-sediment coupling (Warner et al. 2008):

- Volume and constancy preserving scheme
- Speed-up equilibration: morpho. factor (Roelvink, 2006)



CROCO modules and coupling

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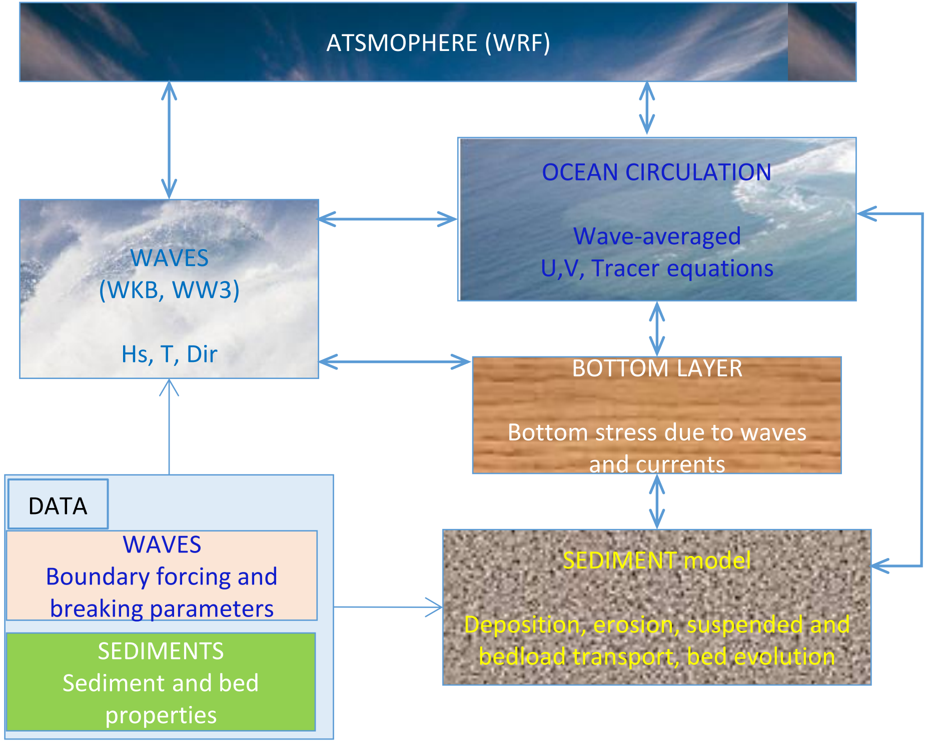
Ocean-wave-atmosphere coupling

- Current feedback (CFB) option available
- Coupling with an atmospheric model through **OASIS3-MCT library** (developed at CERFACS)

  ⇒ Need to download and compile OASIS and coupled models



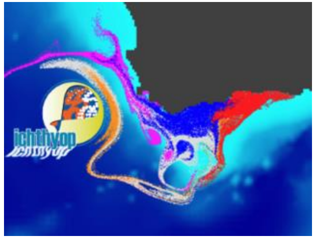
CROCO modules and coupling

Biogeochemistry

- PISCES module (Aumont and Bopp, 2006)
- BioEBUS module (Gutknecht et al., 2013)
- NPZD

Coupling with lagrangian and ecosystemic models

- ARIANE
- Tracmass
- ICHTYOP
- Ltrans
- OSMOSE
- APECOSM



CROCO tools and facilities

Matlab CROCO_TOOLS

- Climatological pre-processing
- Interannual pre-processing
- Visualization

Python CROCO_TOOLS

- Pre-processing: in dev.
- Visualization

Online diagnostics

- Online temperature / vorticity / energy balance

XIOS (dev. at ISPL)

- Outputs facilities
- Diagnostics facilities

⇒ Need to download and compile XIOS

Modeling package

CROCO_TOOLS

- Aforc_NCEP
- Aforc_QuikSCAT
- Diagnostic_tools
- Nesting_tools
- Opendap_tools
- Opendap_tools_no_loaddap
- RUNOFF_DAI
- Tides
- Town
- UTILITIES
- Visualization_tools
- croco_pytools
- croco_pyvisu
- start.m
- Oforc_OGCM
- Aforc_CFSR
- Aforc_ECMWF
- Coupling_tools
- Rivers
- crocotools_param.m
- Preprocessing_tools
- readme_crocotools.txt,
- Forecast_tools

UTILITIES:

- air_sea
- export_fig
- m_map1.4h
- mask
- mex60
- mexcdf
- netcdf_matlab_60
- netcdf_x86_64

CROCO : Fortran source code

- AGRIF
- CVTK
- OCEAN
- PISCES
- Run
- XIOS
- create_config.bash

DATA_SETS : Global datasets to build the regional forcing

CARS2009, COADS05, GOT99.2, m_map1.4f, QuikSCAT_clim, RUNOFF_DAI, SeaWifs, SST_pathfinder, Topo, TPXO6, TPXO7, WOA2009, WOAPISCES

SYSTEM REQUIREMENTS

OS: LINUX or UNIX

CROCO : fortran program ~ (55000 lines of FORTRAN code)

CROCOTOOLS : Matlab (Octave) scripts + datasets (18 Gb)

PC configuration:

- Fortran Compiler : gfortran, Intel Fortran Compiler
- NetCDF : http://www.unidata.ucar.edu
- OpenMPI : http://www.open-mpi.org
- Matlab (or Octave)

Additional software

- Ncview, NCO,Ferret,Octave-3.6.1 + netcdf …

HOW TO GET CROCO AND CROCO TOOLS

CROCO
Coastal and Regional Ocean COmmunity model

http://www.croco-ocean.org

In the download section

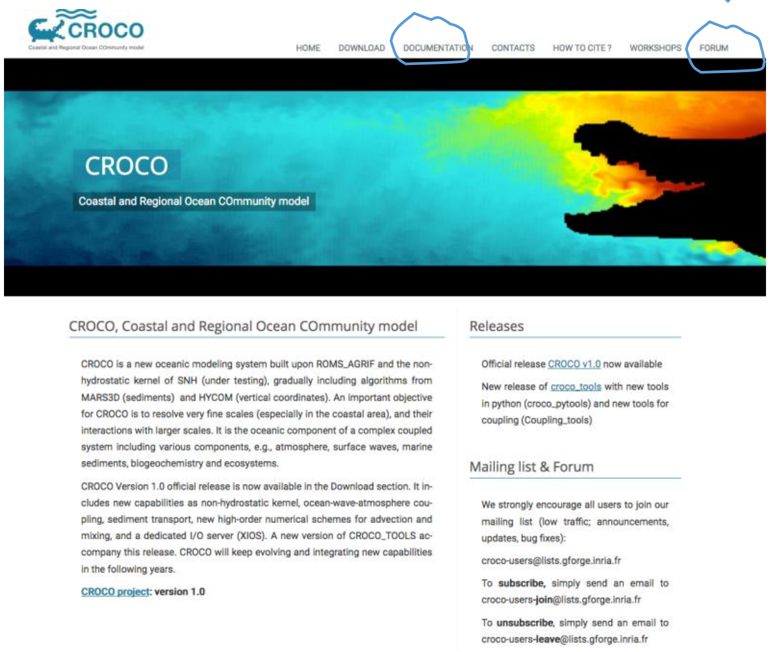
- **CROCO** : Fortran source code
- **CROCO_TOOLS** : Pre- and post processing toolbox (Matlab)
- **DATASETS** [18 Gb] : the global datasets needed by the CROCO_TOOLS
- **UTILITIES** : netCDF library, mapping toolbox etc …

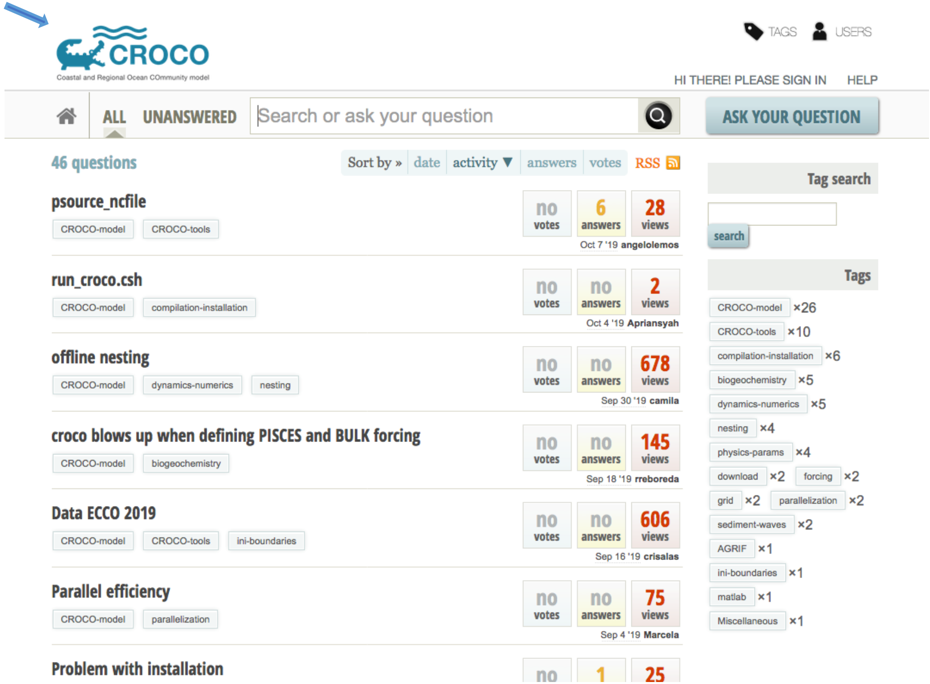
CROCO help

CROCO
Coastal and Regional Ocean COmmunity model

DOCUMENTATION

FORUM





CROCO team

Coastal and Regional Ocean COmmunity model

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