Introduction To Ocean modelling Using CROCO And The CROCO_TOOLS

OBJECTIVES

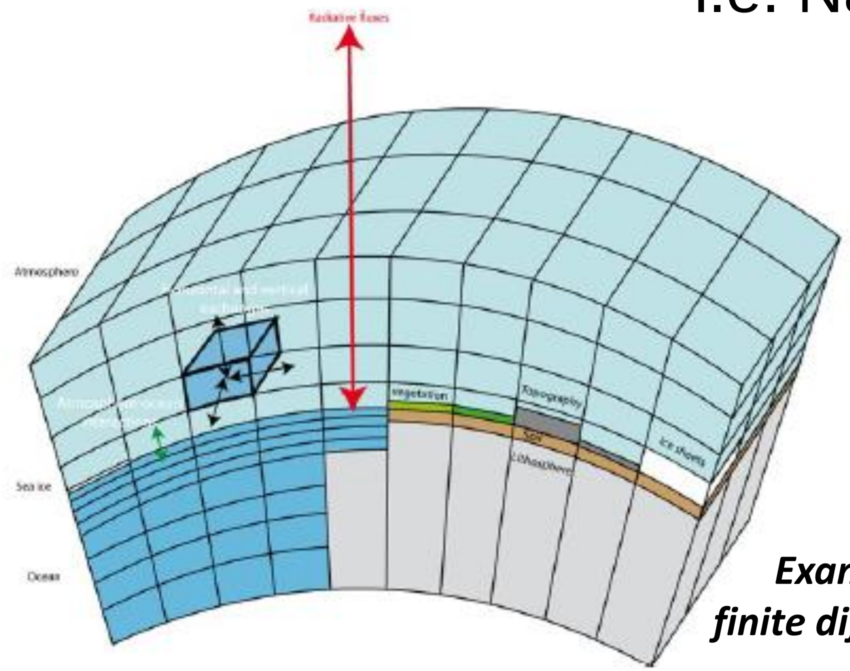
- Ocean Modelling Principle
- Ocean Modelling Advantages
- Methodology and primitive equations
- The CROCO model
- Program of basic week CROCO summer school

Introduction: Ocean modelling principle (0/3)

Introduction: Ocean modelling principle (1/3)

- Ocean model = simplified representation of physical processes that take place in the ocean.

- Ocean model = uses law of physics i.e. Navier Stokes equations



Example of a finite difference grid

- To do this, the ocean is divided into « small» boxes.

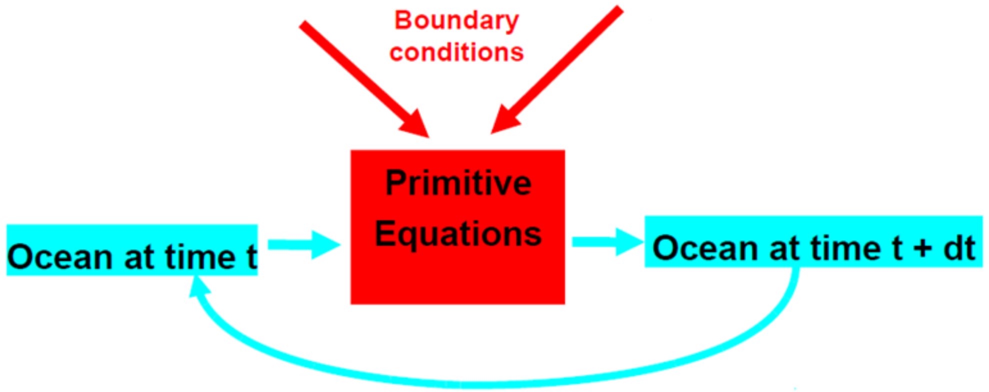
  ↳ **Discretization**

Introduction: Ocean modeling principle (2/3)

- If we know:

  - The **ocean state at time *t* :**
    u, v, T, S, …

  - **Boundary conditions** :
    surface, bottom, lateral sides



- We can **compute the ocean state at time *t+dt*** using **numerical approximations of Navier-Stokes Equations**

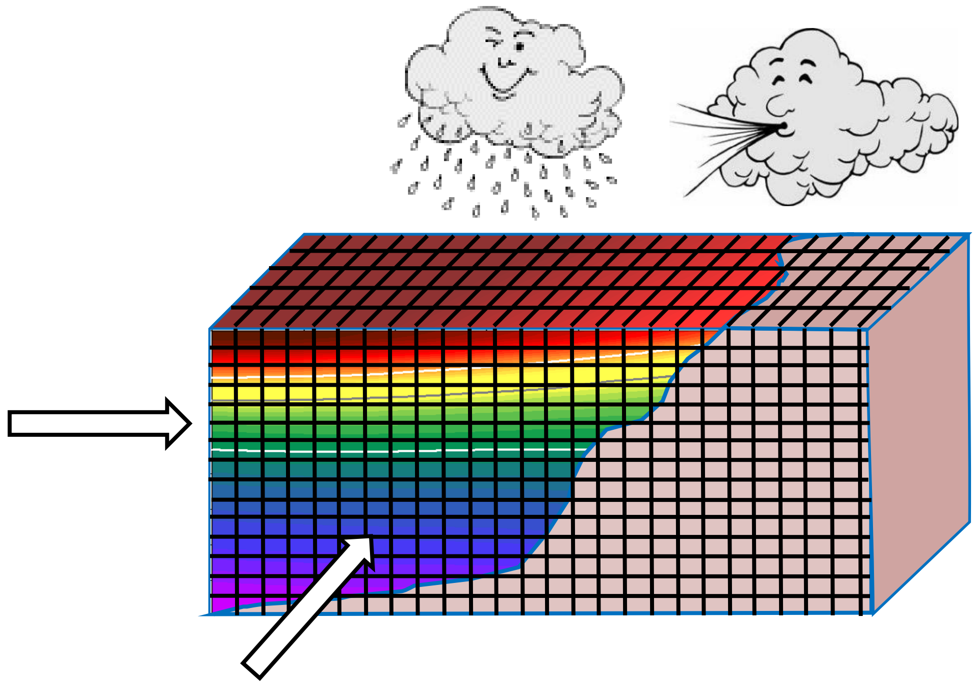
↳ For that we need to proceed to the **discretization** of the equations in **time** and **space**

Introduction: Ocean modelling principle (3/3)

- Let's compare the ocean model as a giant rectangular swimingpool

  - We know **ocean state at time *t***
  -> Filling the swimingpool

  - • **Boundary conditions** :
  -> surface
  •**->** Bottom
  •**->** lateral sides



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↳ For that we need to proceed to the **discretization** of the equations in time and space

Introduction: Ocean modeling, Objectives and Advantages

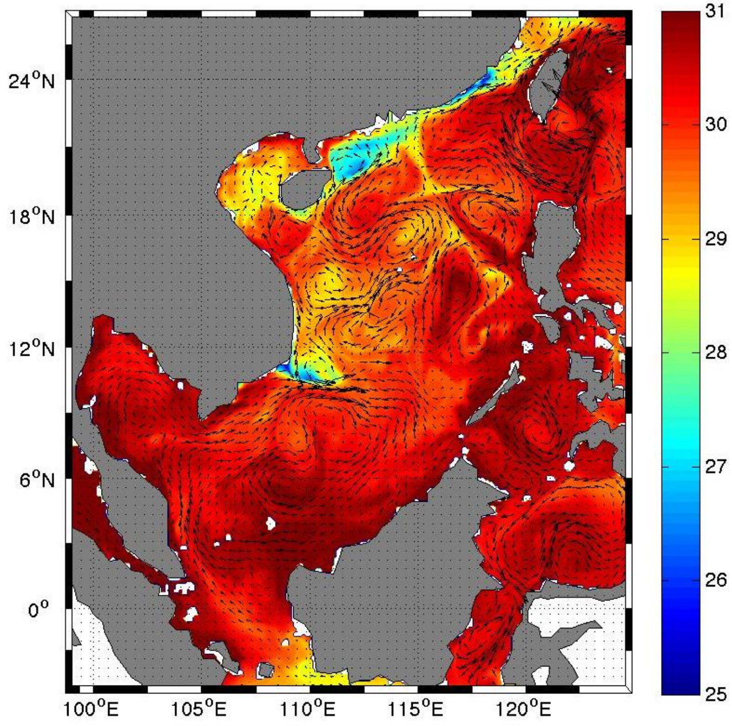
➢ Objectives:

- **Fundamental research** : understand ocean functioning
- **Applied research, operational oceanograpy** : ocean forecast, pollution, water quality …

➢ Advantages:

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

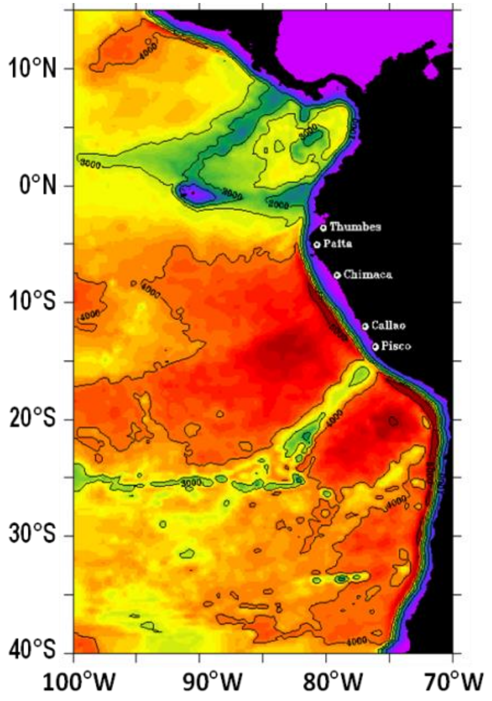
Sea Surface Temperature (SST) and surface current on 24/07/1992 ROMS 1/8°



Introduction: Ocean modeling, Objectives and Advantages

What are the forcing mechanisms of the intraseasonal SST variability off Peru ?

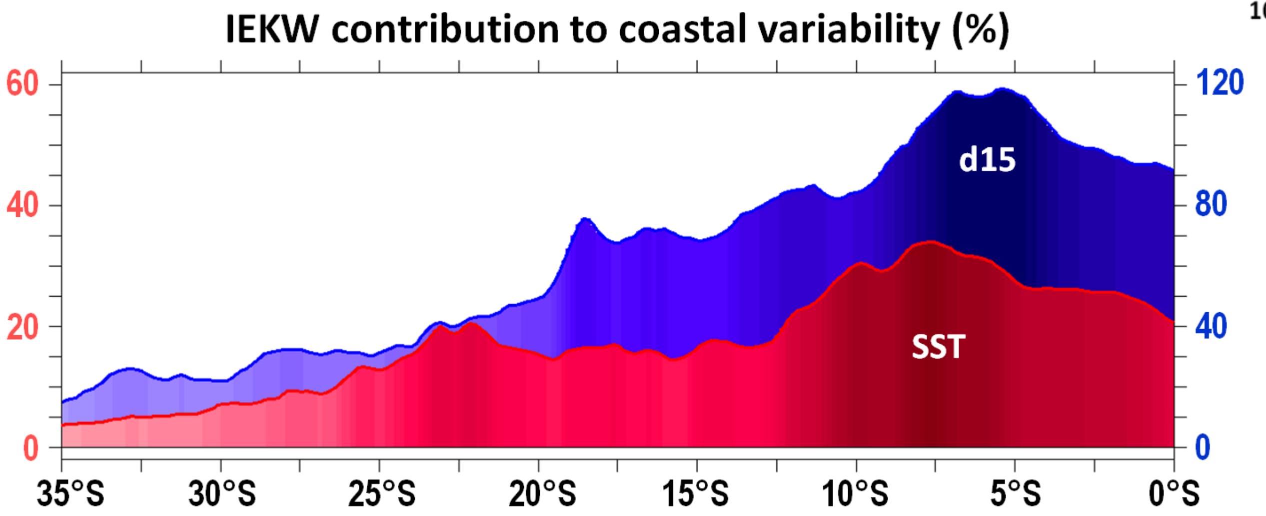
- *Remote – Connection with the equatorial variability ?*
- *Locally forced – Wind stress, Heat Fluxes ?*



- **Sensitivity experiments:**

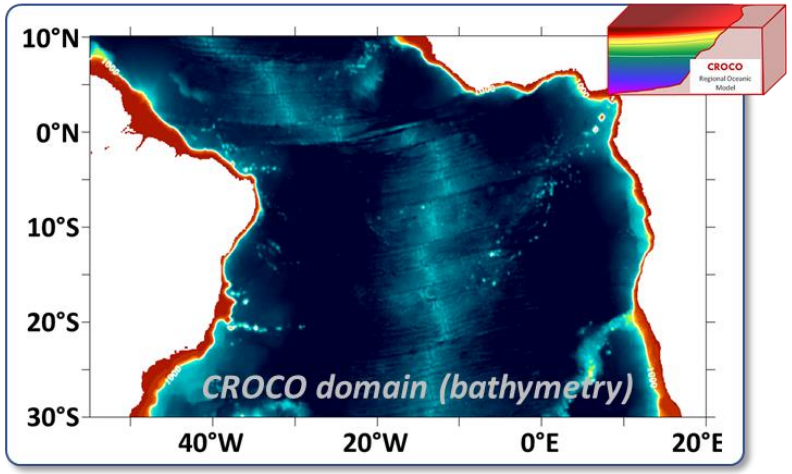
EXP-Name	SODA OBC (E)	QS Wind Stress (W)	HF Bulk fields (Q)
ROMS^{CR}	Total	Total	Total
ROMS^{E}	Total	Climatology	Climatology
ROMS^{WQ}	Climatology	Total	Total

➡ *Connection with the remote equatorial variability represents only ~20% of the intraseasonal SST variability off Central Peru in 2000-2008 !*



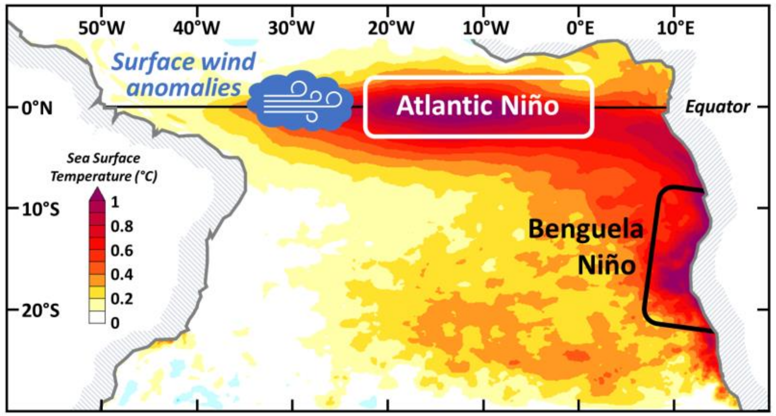
Introduction: Ocean modeling, Objectives and Advantages

Why does the Benguela Niño events precede the Atlantic Niños?



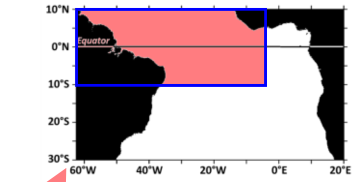
Benguela Niños stop earlier due to the development of coastal wind anomalies associated with a **convergent anomalous circulation located on the warm Atlantic Niño event**.

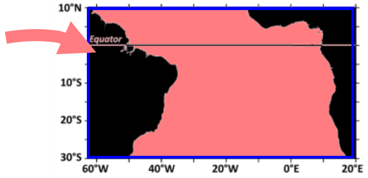
Tropical Atlantic interannual events



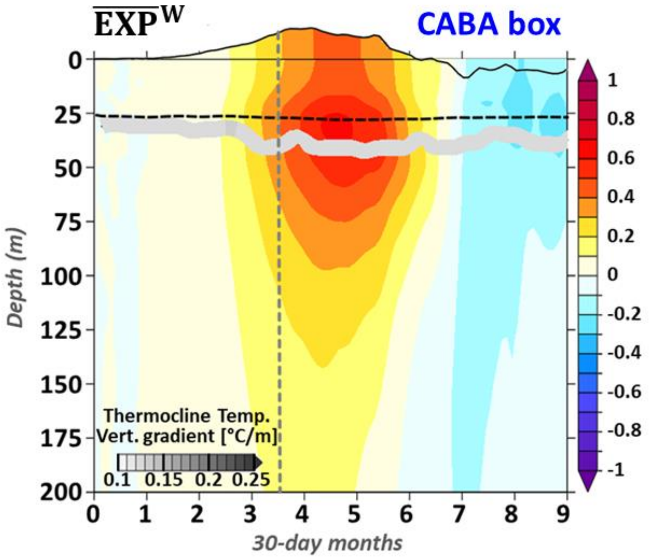
- **Sensitivity experiments:**

EXP-Name	Wind stress Perturbation
$\overline{EXP}$	×
$\overline{EXP}^{W}$	Restritect to the West
$\overline{EXP}^{A}$	Everywhere





COASTAL WIND-STRESS SWITCHED OFF



Introduction: Ocean modeling, Objectives and Advantages

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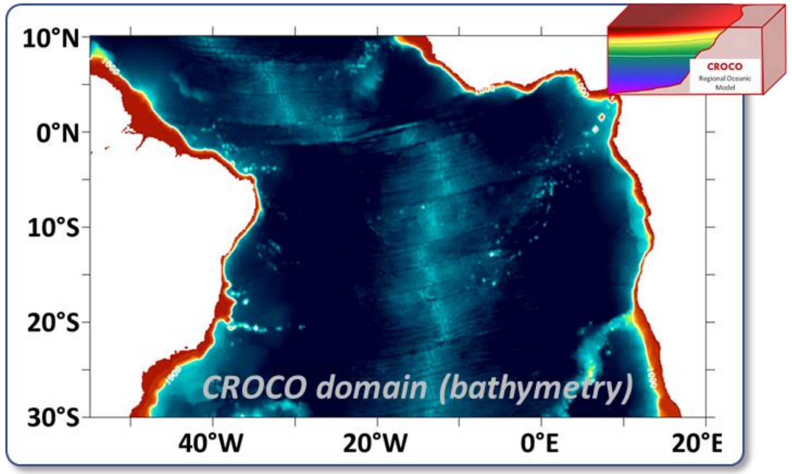

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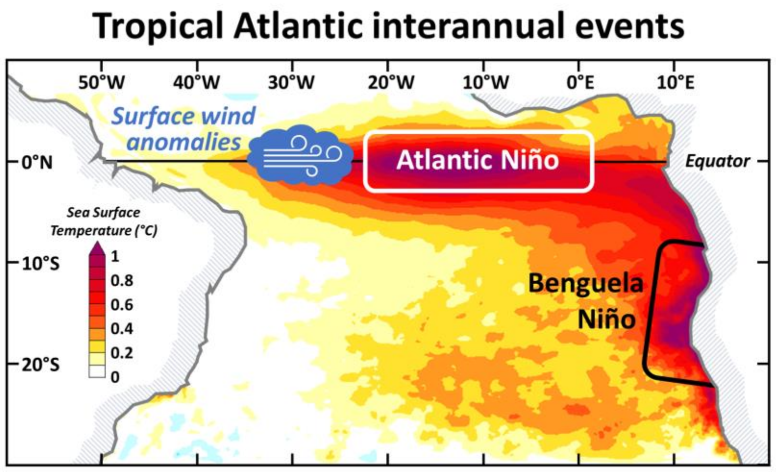

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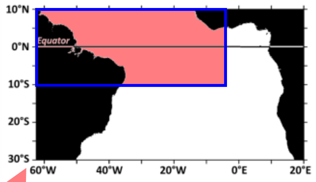

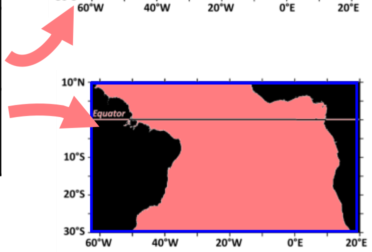

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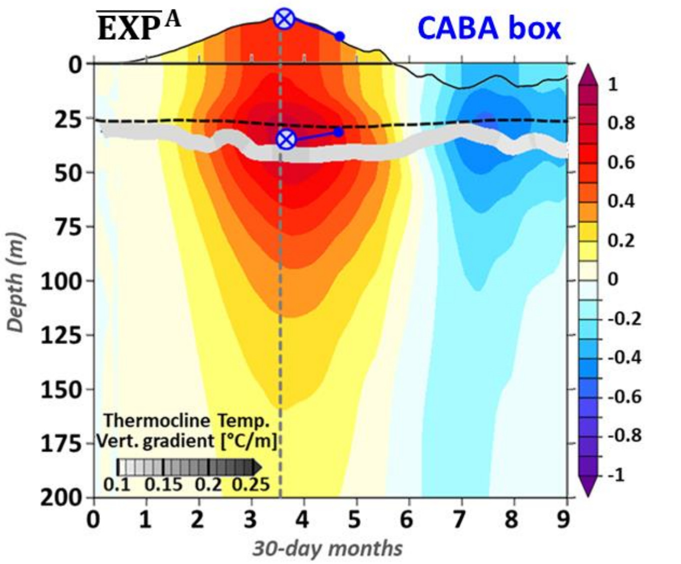


Introduction: Methodology

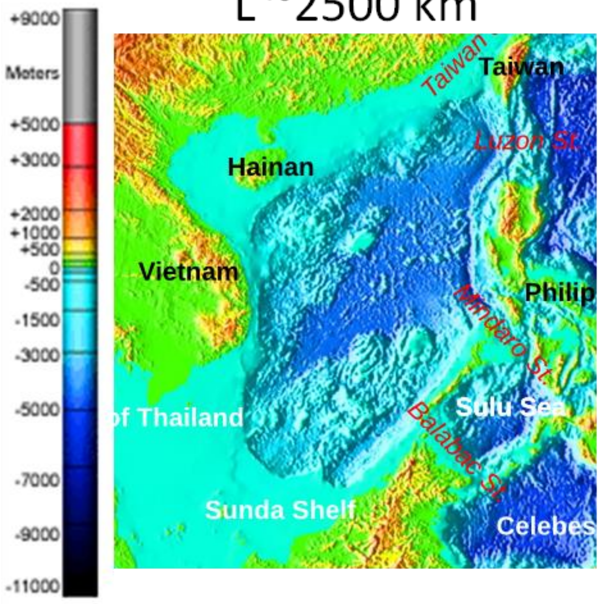
- Equations to solve: **Navier-Stokes equations**

The **Millennium Prize Problems** are seven problems in mathematics that were stated by the Clay Mathematics Institute in 2000. As of October 2014, six of the problems remain unsolved. A correct solution to any of the problems results in a US $1,000,000 prize (sometimes called a *Millennium Prize*) being awarded by the institute. The Poincaré conjecture was solved by Grigori Perelman, but he declined the award in 2010.

We make some **approximations** !

H ~3000 m

L ~2500 km



- <u>Hypothesis</u>:
  - ✓ Hydrostatic : H/L <<1 (aspect ratio low)
    - neglect vertical acceleration
    - neglect Coriolis term associated to vertical velocities
  - ✓ Incompressibility
  - ✓ Boussinesq : $\rho=\rho_o=cste$ for horizontal gradient pressure

Primitive equations

Primitive Equations (1/3)

Momentum conservation equation

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

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

Hydrostatic equation

$$\boxed{0 = -\frac{\partial P}{\partial z} - \rho g}$$

Continuity equation

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

Tracer conservation

$$\boxed{\begin{aligned}\frac{\partial T}{\partial t} + \vec{u}.\nabla T &= \nabla_h\left(K_{Th}.\nabla_h T\right) + \frac{\partial}{\partial z}\left(K_{Tv}\frac{\partial T}{\partial z}\right)\\ \frac{\partial S}{\partial t} + \vec{u}.\nabla S &= \nabla_h\left(K_{Sh}.\nabla_h S\right) + \frac{\partial}{\partial z}\left(K_{Sv}\frac{\partial S}{\partial z}\right)\end{aligned}}$$

Equation of state

$$\boxed{\rho = \rho(S, T, p)}$$

Primitive Equations (2/3)

- **Initial conditions**

- **Surface boundary conditions (z=η):**

$$\frac{\partial \eta}{\partial t} = w$$ Kinematic

$$K_{Mv}\frac{\partial u}{\partial z} = \frac{\tau_x}{\rho_0}$$

$$K_{Mv}\frac{\partial v}{\partial z} = \frac{\tau_y}{\rho_0}$$

Wind stress

$$K_{Tv}\frac{\partial T}{\partial z} = \frac{Q}{\rho_0 C_p}$$ Heat flux

$$K_{Sv}\frac{\partial S}{\partial z} = \frac{S(E-P)}{\rho_0}$$ Salt flux : evap - rain

- **Bottom boundary conditions (z=-H):**

$$\vec{u}.\nabla(-H) = w$$ Kinematic

$$K_{Mv}\frac{\partial u}{\partial z} = \frac{-C_d|\vec{u}|u}{\rho_0}$$

$$K_{Mv}\frac{\partial v}{\partial z} = \frac{-C_d|\vec{u}|v}{\rho_0}$$

Bottom friction

$$K_{Tv}\frac{\partial T}{\partial z} = 0$$

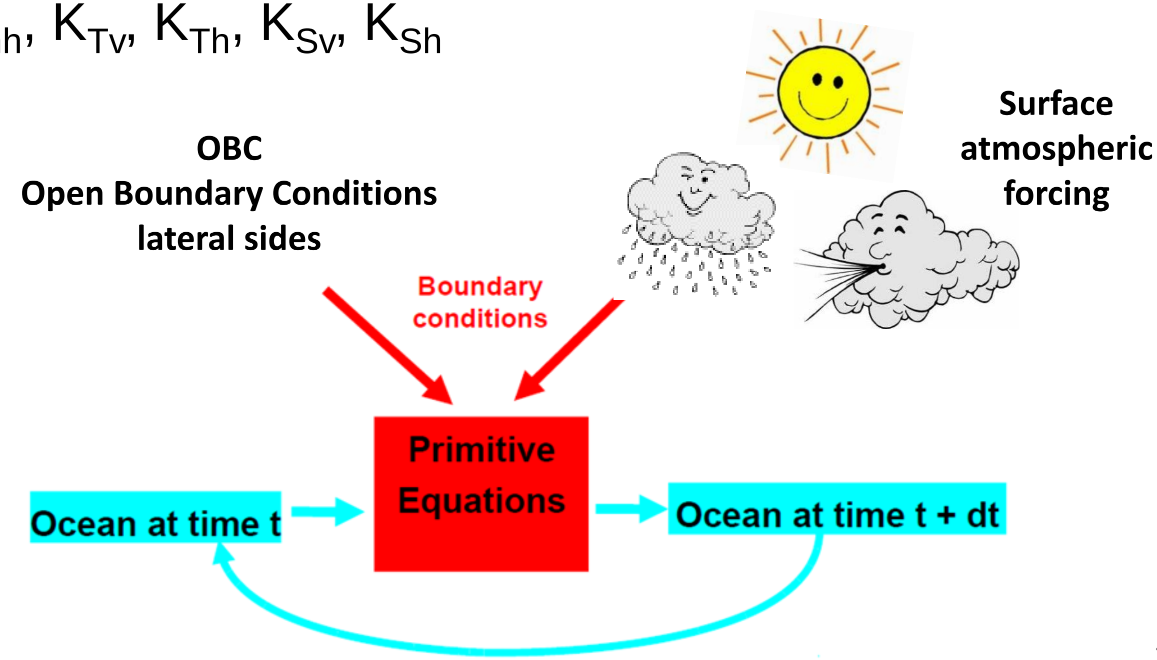
$$K_{Sv}\frac{\partial S}{\partial z} = 0$$

Bottom-flux

Primitive Equations (3/3)

- Solving the primitive equations
  + the boundary conditions on a discretised grid
- Unknowns : **Prognostic variables** at **time t+dt** : u, v, T, S, η
  We then compute the **diagnostic variables** : w, P, ρ
- Knowns : • Pronostic variable at time t
  • Boundary conditions
  • Model parameters : K_{mv}, K_{mh}, K_{Tv}, K_{Th}, K_{Sv}, K_{Sh}

$\Longrightarrow$



CROCO model (1/5): History

SCRUM

ROMS UCLA / RUTGERS

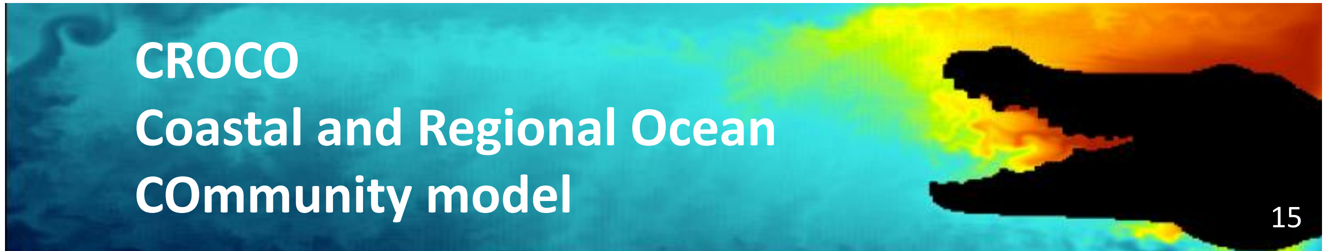
ROMS Regional Oceanic Modeling System

AGRIF

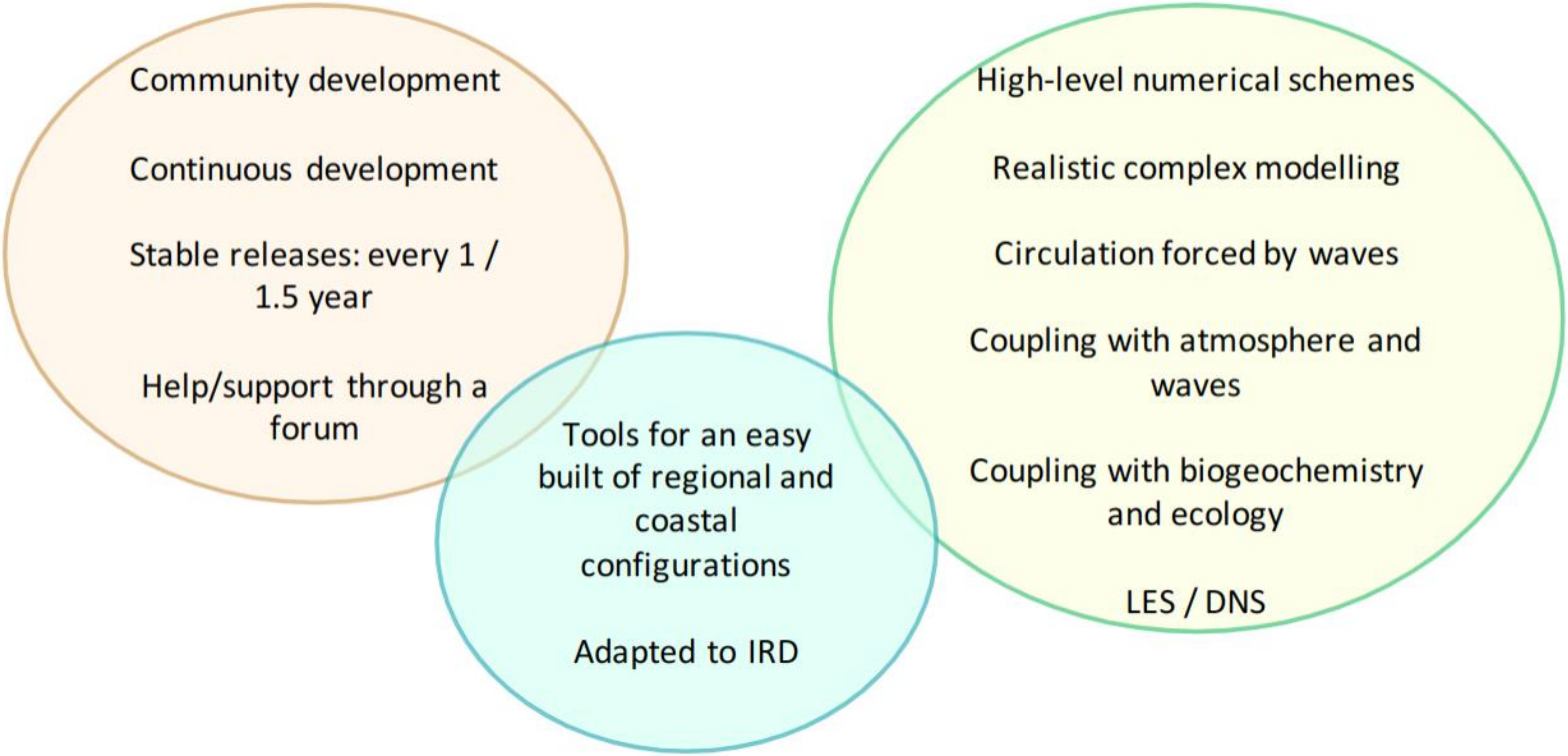
ROMS AGRIF

NH-NBQ of Symphonie-NH
Mutli-resolution
MUSTANG sediment module of MARS

Coastal and Regional Ocean COmmunity model

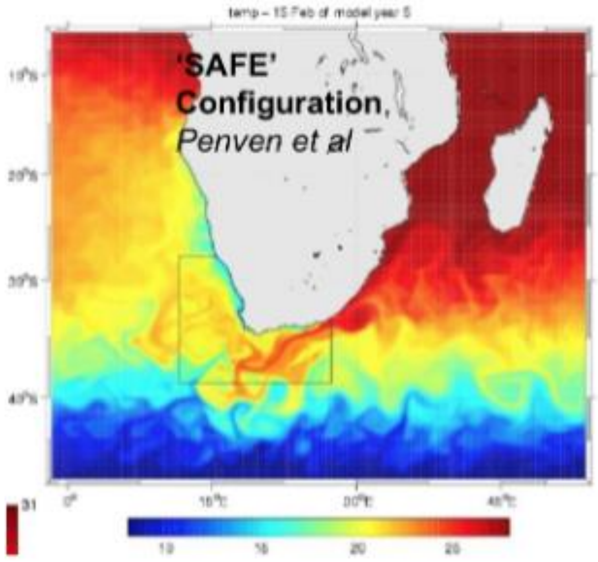


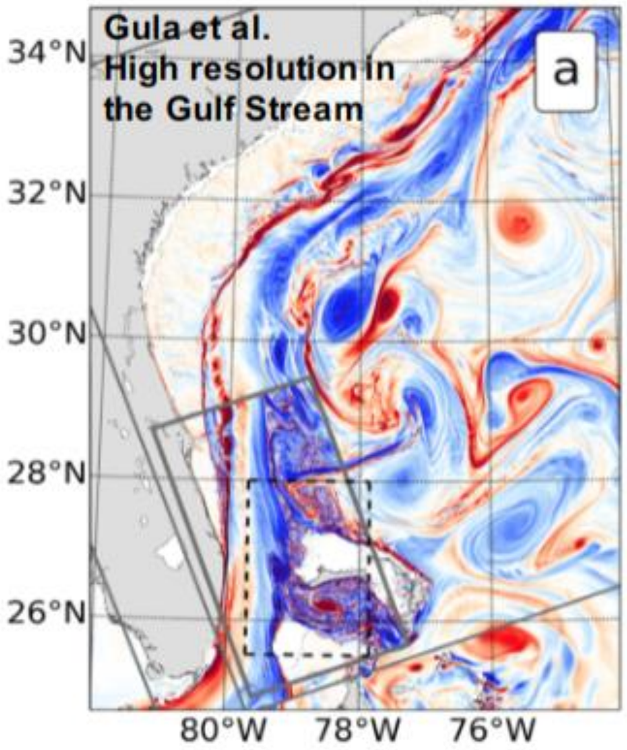
CROCO model (2/5): Philosophy

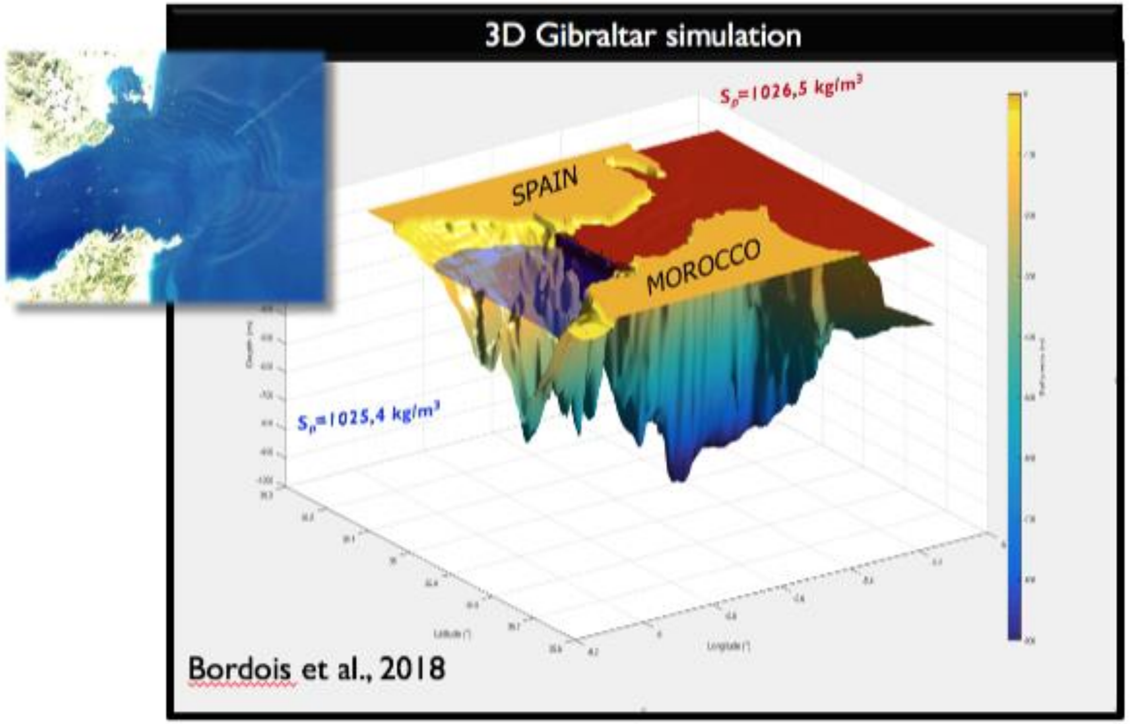


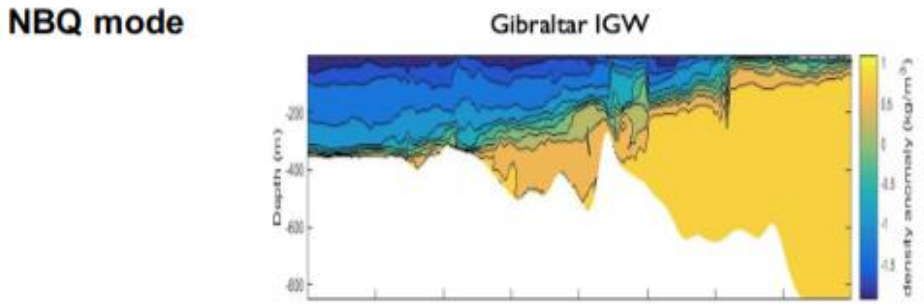
CROCO model (3/5): Examples

For starting, here are a few examples of use of CROCO



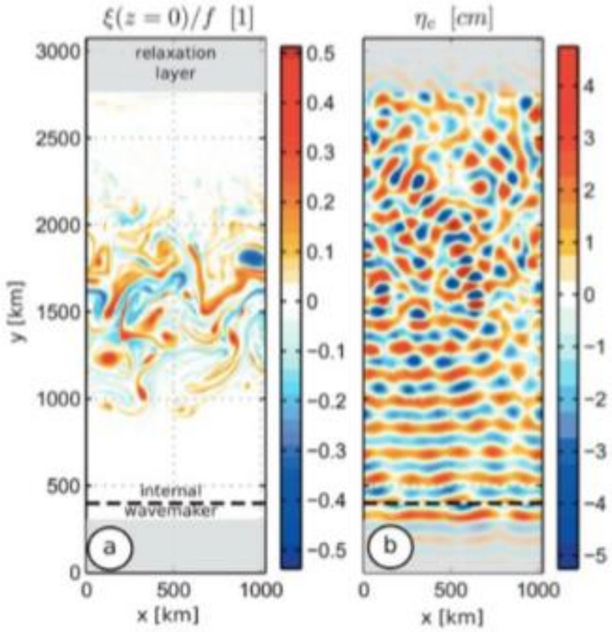




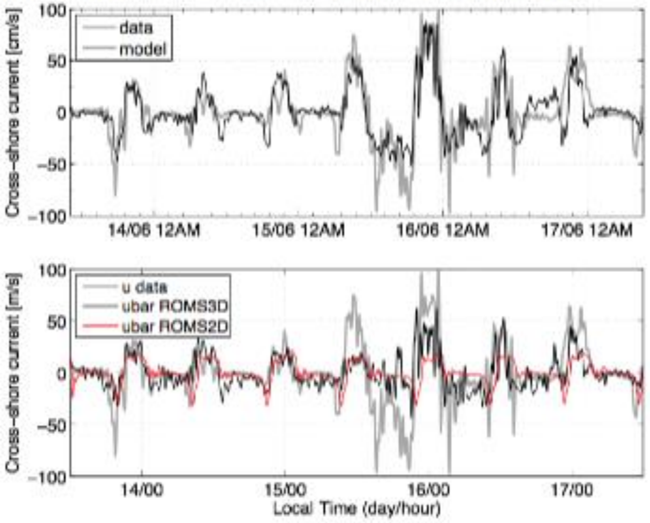


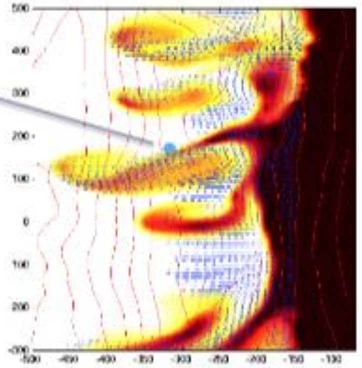
For starting, here are a few examples of use of CROCO

Ponte & Klein, 2015,, internal tides and eddies

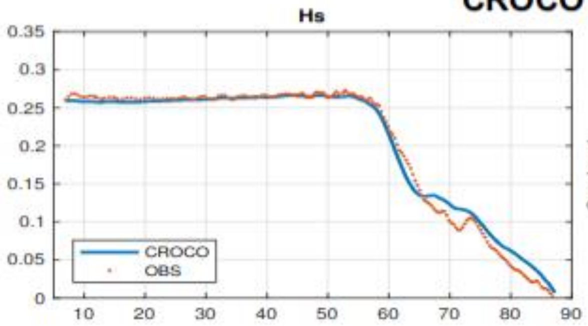


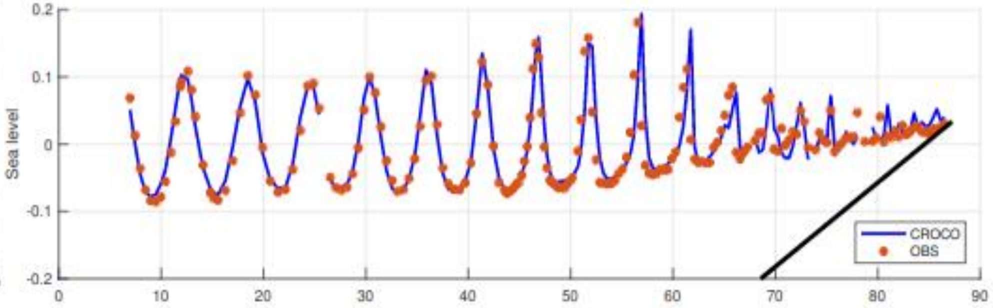
Marchesiello et al. 2015, Rip current





CROCO wave-to-wave (Marchesiello, Benshila)

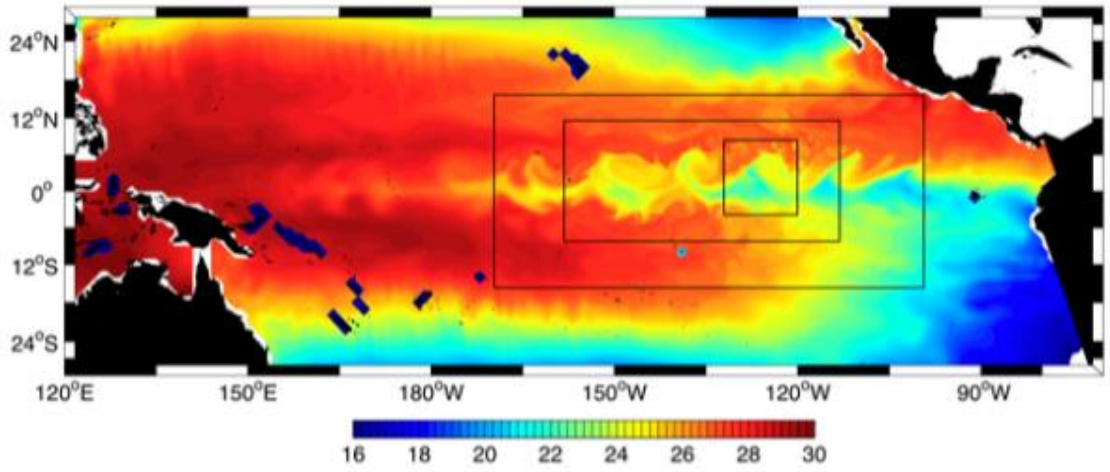




CROCO and more (1/2)

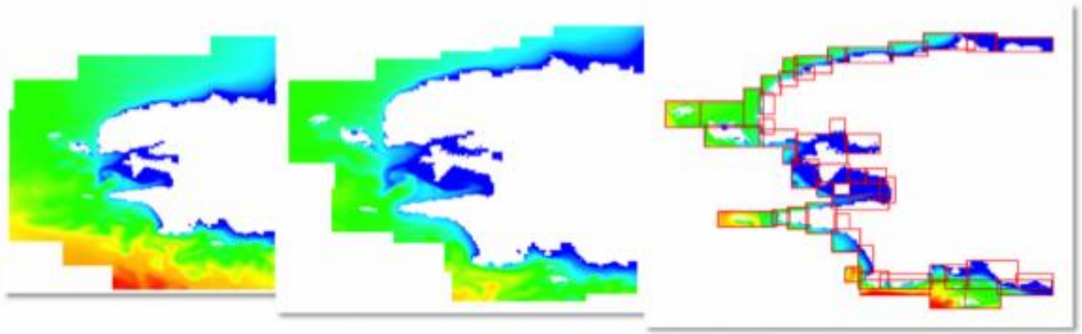
Nesting with AGRIF

- 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 and more (2/2)

- Rivers inputs and passive tracer evolution
- Wave-current interactions (WKB module, coupling with WW3)
- Current sediment interactions/Morphodynamics (USGS/MUSTANG modules)
- Ocean/Wave/Atmosphere coupling (using the OASIS-MCT coupler)
- Biogeochemistry (PISCES/BIOEBUS/NPZD modules)
- Coupling with Lagrangian and ecosystem modules.

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

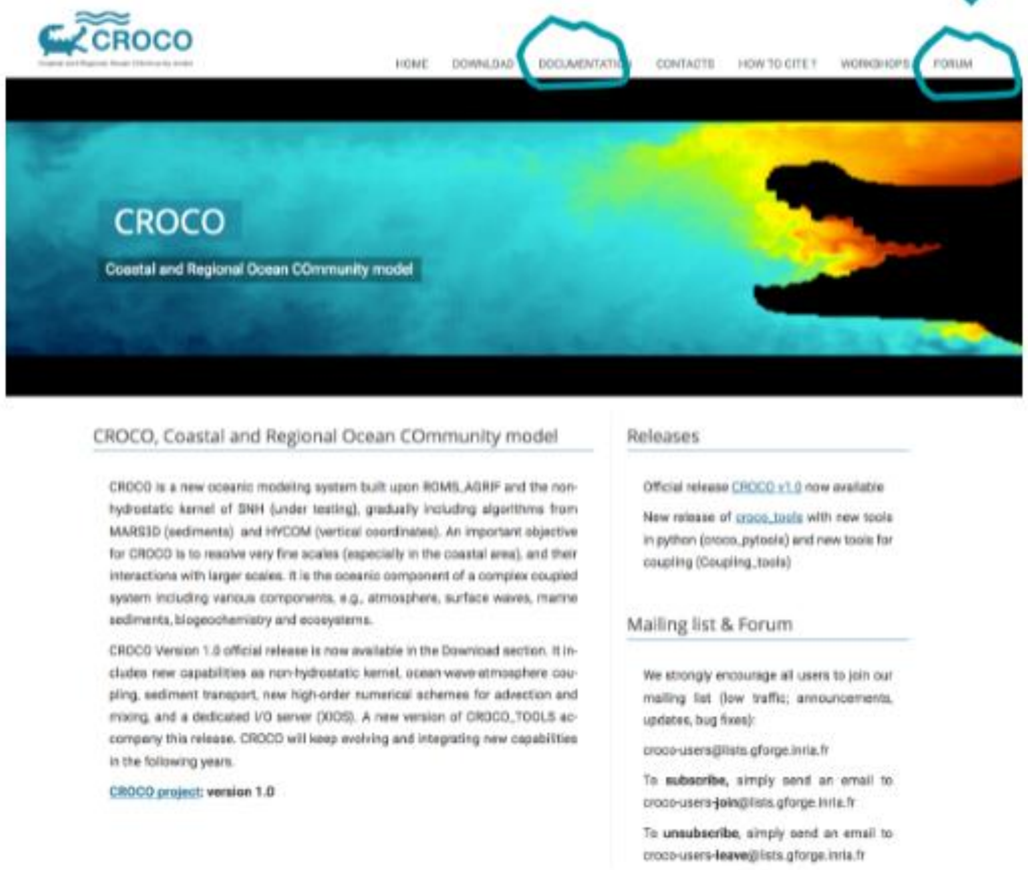
XIOS (dev. at ISPL)
- Outputs facilities
- Diagnostics facilities

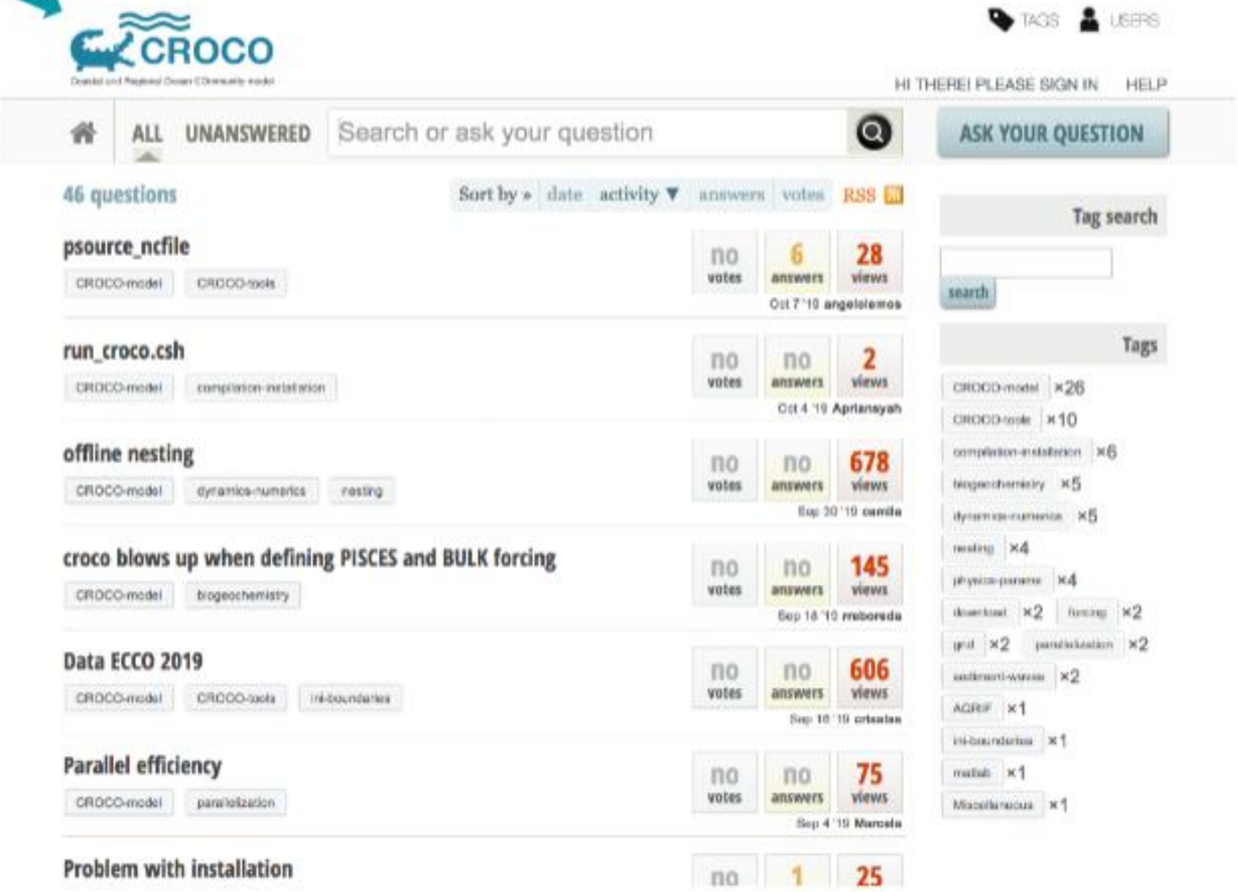
⇒ Need to download and compile XIOS

CROCO help

DOCUMENTATION

FORUM





Day 1 : Monday October 17th

MORNING

Forewords by Jennifer Veitch
Class: "Introduction to regional ocean modeling",
followed by a round-table discussion during which attendees will present their scientific objectives and their expectations for this class
Hands-on session : First connection on the Lengau cluster, and test Matlab

AFTERNOON

Class: Let's make our first CROCO grid
Hands-on session :
- Presentation of CROCO and CROCO_tools environment.
- Quick Linux and NetCDF recaps
- First preprocessing steps: model grid and work on the vertical sigma parameters

Example of support

TUTORIAL 01: CREATE THE WORKING ENVIRONEMENT

In this tutorial, we will review some basic instructions to **prepare the working environment**. We will work on the CHPC cluster called LENGAU. In this tutorial we will review the steps to log onto the super-computer. Then, we will copy some CROCO directories that are already stored on the super-computer (instead of downloading some archives from the CROCO website https://www.croco-ocean.org). At last, we will test our working environment.

STEP 1: Log onto the Lengau HPC cluster

→ To connect to the CHPC you must write, from a terminal/console, the following instruction:

```
ssh -X login@lengau.chpc.ac.za
```

Replace `login` with your corresponding account number.

→ When entering the LENGAU super-computer, you will see something similar to this in your terminal:

```
Last login: Mon Sep 12 13:28:23 2022 from XX.XXX.XX.XXX

Welcome to LENGAU

##################################################################################
#                                                                                #
# In order to receive notifications via email from the CHPC all users should     #
# be subscribed to the CHPC user distribution list. If you are not part of the   #
# distribution list you can subscribe at the following link:                     #
# https://lists.chpc.ac.za/mailman/listinfo/chpc-users                           #
#                                                                                #
##################################################################################
[login@login2 ~]$
```

This will take you to your directory on your home directory on Lengau: `/home/login`

> You should **NOT** use your home directory to save large datasets or run CROCO!
> You should go to your directory on `lustre` (there is a link to it in your `/home/login` directory) to do all the processing and saving of data.

→ To list the files and directories inside your home directory, just type the Linux command `ls`:

```
[login@login2 ~]$ ls
lustre
[login@login2 ~]$
```

→ To know where your home directory is, just type the Linux command **pwd**:

```
[login@login2 ~]$ pwd
/home/login
[login@login2 ~]$
```

→ Go directly on your `lustre` directory by executing the Linux change directory command cd:

```
[login@login2 ~]$ cd lustre
[login@login2 lustre]$ pwd
/home/login/lustre
[login@login2 lustre]$ ls
```

TUTORIAL 02: CREATE MY CROCO GRIDS

In this tutorial, we do the step to prepare our first model grid. We will connect to the super-computer LENGAU, and run Matlab to do the first CROCO pre-processing step. We will then analyse CROCO sigma vertical coordinate system.

STEP 1: Log onto the Lengau HPC cluster

→ From a terminal/konsole, execute the following instruction:

```
ssh -X login@lengau.chpc.ac.za
```

Replace `login` with your corresponding account number.

→ Reserve one processor to do this pre-processing step (see Step 4 from #TUTORIAL01):

```
[login@login2 ~]$ qsubi1
[login@cnode0220 ~]$
```

→ Go directly into your `lustre` directory:

```
[login@cnode0220 ~]$ cd lustre
[login@cnode0220 lustre]$ ls
croco-v1.2.1 croco tools
[login@cnode0220 lustre]$
```

STEP 2: Create the work directory of your first CROCO configuration

The simplest example of CROCO configuration is the configuration called **BENGUELA_LR** which corresponds to a domain in the Benguela upwelling zone of the coasts of Namibia and South-Africa with a relatively Low Resolution (LR). This configuration is the one that comes by default in the CROCO code and it is similar to the one described in Penven et al. (2001). Before creating your own configuration, let's begin by recreating the BENGUELA_LR Grid.

→ Go into the `croco` source code directory `croco-v1.2.1`:

```
[login@cnode0220 ~]$ cd croco_v1.2.1
[login@cnode0220 croco v1.2.1]$ ls
 AGRIF               DOC SPHINX                OCEAN       SCRIPTS
 create config.bash  MPI NOLAND preprocessing  PISCES      TEST CASES
 CVTK                MUSTANG                   README.md   XIOS
[login@cnode0220 croco_v1.2.1]$
```

→ Edit the file `create_config.bash` using the Linux command `vi`:

```
[login@cnode0220 croco v1.2.1]$ vi create config.bash
[login@cnode0220 croco v1.2.1]$
                              :
# Configuration name
# ------------------
MY CONFIG NAME=Run

# Home and Work configuration directories
# ---------------------------------------
                              :
```

Day 2 : Tuesday October 18th

MORNING

Class: "Numerical aspects I "Finite differences: Spatial and temporal discretization

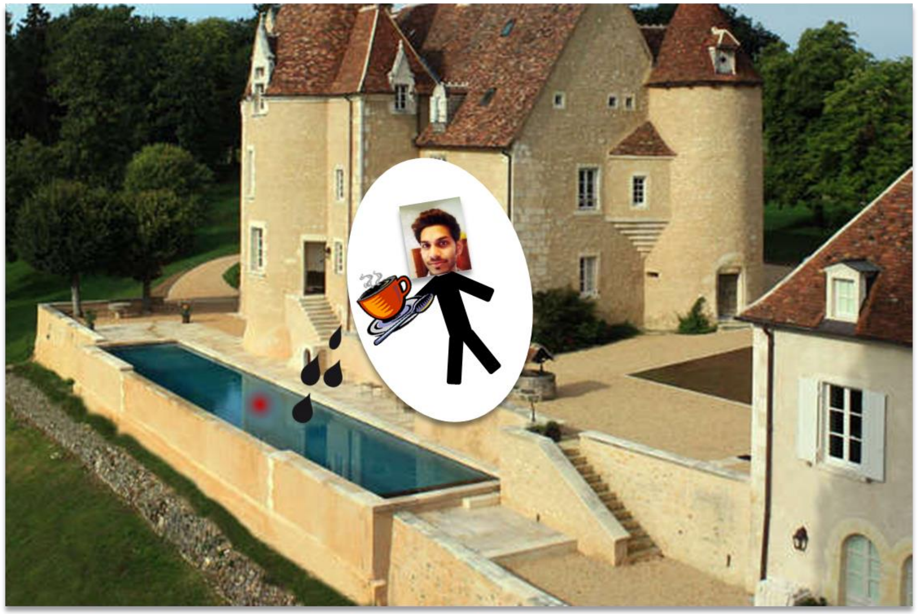
Hands-on session : Finite differences - Solving a simple case, the 1-D Diffusion equation

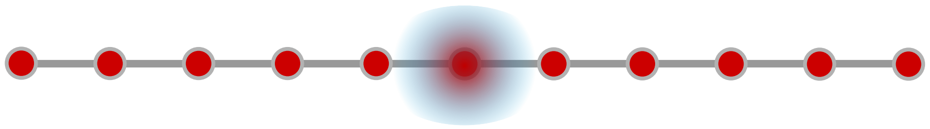
AFTERNOON

Class: Forcing and Open Lateral Boundary conditions

Hands-on session: • Creation of all CROCO forcing inputs (climatological forcing)

• Launch of the model (climatological configuration)



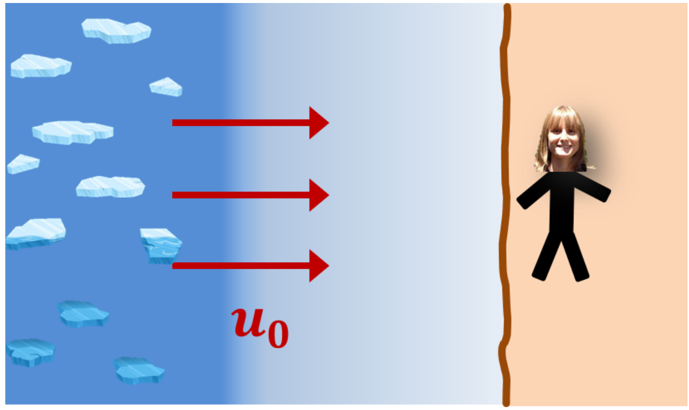


Day 3 : Wednesday October 19th

MORNING

Class: "Numerical aspects II " • Consistency and stability of a numerical scheme
• Introduction to CFL condition
• Quick overview of Sigma coordinates and truncation error

Hands-on session : • Model outputs analysis with CROCO_gui



AFTERNOON

Class: Introduction to the online nesting with AGRIF

Hands-on session : • Creation of all CROCO Forcings inputs (climatological forcing) for a zoom (with nestgui)
• Launch of the model (climatological configuration) with a zoom

Day 4 : Thursday October 20th

MORNING

Role game in order to give a complete understanding of the model input files, with an emphasis on how the model handles the time“

Hands-on session : • Model outputs analysis with CROCO_gui

AFTERNOON

Class: Running an inter-annual simulation“

Hands-on session: • Preparation of an inter-annual simulation input files
• Launch of the inter-annual simulation
• Notions of optimization of the I/O

Day 5 : Friday October 21th

MORNING

Class: How to take into account the river run-off?
Hands-on session: Let’s put river in one of your configurations

Class: Notion of model validations. Example: Taylor diagram presentation

AFTERNOON

Hands-on session: Introduction to offline floats propagation
Class: Introduction to LiveCROCO