Open boundary conditions and coupling methods for ocean flows

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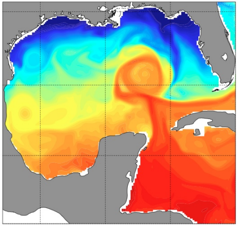
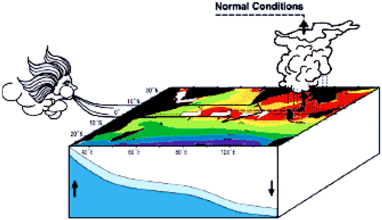
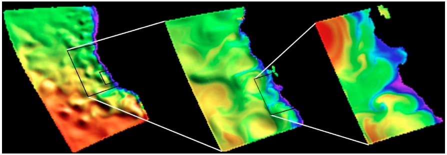
Context

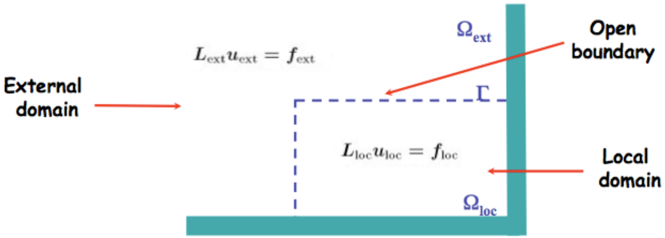
- limited area models
- multiscale and/or nested systems
- coupled systems







Formalization of the problem



A correct formulation could be :

Find u_{loc} and u_{ext} that satisfy

$$\begin{cases} L_{\text{loc}} u_{\text{loc}} = f_{\text{loc}} & \text{in } \Omega_{\text{loc}} \times [0,T] \\ L_{\text{ext}} u_{\text{ext}} = f_{\text{ext}} & \text{in } \Omega_{\text{ext}} \times [0,T] \\ u_{\text{loc}} = u_{\text{ext}} \text{ and } \dfrac{\partial u_{\text{loc}}}{\partial n} = \dfrac{\partial u_{\text{ext}}}{\partial n} & \text{on } \Gamma \times [0,T] \end{cases}$$

Formalization of the problem (2)

But :

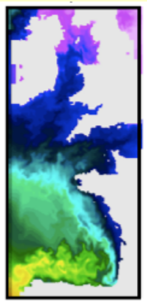
- There is not always an external model.
- The external model is not always available for online interaction.
- The external model is not defined on Ω_{ext} only, but on $\Omega_{\text{ext}} \cup \Omega_{\text{loc}}$ (overlapping).

$\longrightarrow$ **Actual applications do not address the correct theoretical problem, but more or less approaching formulations.**

Formalization of the problem (3)

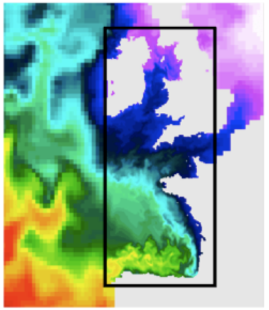
Open boundary problem

Which boundary conditions for regional models ?



Two-way interaction

How can we connect two models in a mathematically correct way ?



Outline

1. The open boundary problem
   - Classification of the methods
   - Application to a shallow water model
   - A way to go further: absorbing boundary conditions
2. Model coupling
   - Formalization and usual methods
   - Schwarz methods
3. Conclusion

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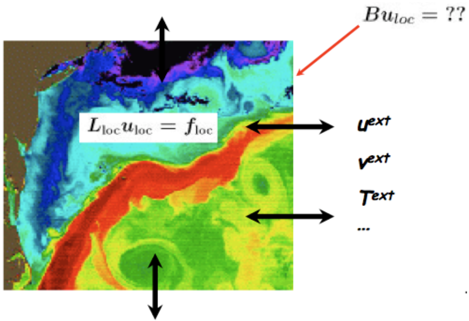
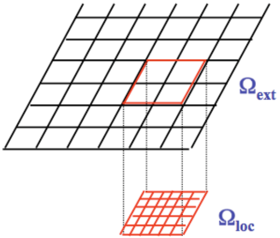
The open boundary problem



A particular case :
one-way nesting



Goal : choose the partial differential operator B in order to

- evacuate the outgoing information
- bring some external knowledge on incoming information

What is done usually

Old problem in ocean-atmosphere modelling : abundant literature, numerous conditions proposed, often with no clear conclusions. However **a few OBCs are often recommended** in comparative studies : radiation conditions, Flather condition, sponge layer. . .

When looking into details, basically **two families** :

- **relaxation** terms towards u_{ext} and/or **damping** terms (locally increased numerical viscosity) $\longrightarrow$ **model independent**
- **characteristic based** approaches $\longrightarrow$ **model dependent**

Literature review

The performances of usual conditions are fully consistent with the following criterion : $Bw = Bw_{\text{ext}}$ for each incoming characteristic variable w of the hyperbolic part of the equations (Blayo and Debreu, *Ocean Modelling*, 2005).

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Usual methods

Radiation conditions

Based on the Sommerfeld condition: $$\frac{\partial \phi}{\partial t} + c\,\frac{\partial \phi}{\partial x} = 0$$

$+$ local adaptive evaluation of c (Orlanski-like methods)

$c = -\dfrac{\partial\phi/\ \partial t}{\partial\phi/\ \partial x}$ leads for instance to $c_B^n = \dfrac{\Delta x}{\Delta t}\,\dfrac{\phi_{B-1}^{n-1} - \phi_{B-1}^{n-2}}{\phi_{B-1}^{n-1} - \phi_{B-2}^{n-1}}$

Performances:

- OK for simple idealized testcases
- For complex flows: addition of a relaxation term towards external data

$$\begin{cases} \phi = \phi^{\text{ext}} & \text{if } c \text{ is incoming} \\[2ex] \dfrac{\partial \phi}{\partial t} + c\,\dfrac{\partial \phi}{\partial x} = -\,\dfrac{\phi - \phi^{\text{ext}}}{\tau} & \text{if } c \text{ is outgoing} \end{cases}$$

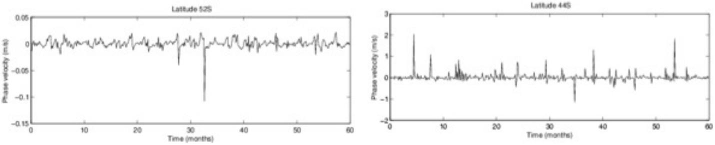
$\longrightarrow$ Results are "weakly successful"

Radiation conditions (2)

Justification:

- OK for $\pm$ monochromatic flows, because $w = \dfrac{\partial \phi}{\partial t} + c\,\dfrac{\partial \phi}{\partial x}$ is the incoming characteristic for the wave equation.

- For complex flows: the adaptive estimation of c makes the condition non-linear, and does not make physical sense (Tréguier et al., 2001; Durran, 2001).



The job is done mainly by the relaxation terms.

Usual methods

Flather condition

For free surface 2-D flows (case of an eastern open boundary) :

Sommerfeld condition for free surface: $\dfrac{\partial h}{\partial t} + \sqrt{gh_0}\,\dfrac{\partial h}{\partial x} = 0$

1-D approximation of the continuity equation: $\dfrac{\partial h}{\partial t} + h_0\,\dfrac{\partial u}{\partial x} = 0$

Combination + integration through Γ: $u - \sqrt{\dfrac{g}{h_0}}\,h = u^{\text{ext}} - \sqrt{\dfrac{g}{h_0}}\,h^{\text{ext}}$

$\longrightarrow$ good results in all comparative studies

Interpretation: $w_1 = w_1^{\text{ext}}$ (incoming characteristic variable of the shallow-water system)

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Example: the shallow water model

$$\left\{ \begin{array}{l} \dfrac{\partial u}{\partial t} + u\,\dfrac{\partial u}{\partial x} + v\,\dfrac{\partial u}{\partial y} - fv + g\,\dfrac{\partial h}{\partial x} + D(u) = F_x \\ \dfrac{\partial v}{\partial t} + u\,\dfrac{\partial v}{\partial x} + v\,\dfrac{\partial v}{\partial y} + fu + g\,\dfrac{\partial h}{\partial y} + D(v) = F_y \\ \dfrac{\partial h}{\partial t} + u\,\dfrac{\partial h}{\partial x} + v\,\dfrac{\partial h}{\partial y} + h\left(\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y}\right) = 0 \end{array} \right.$$

After local linearization :

$$\frac{\partial \Phi}{\partial t} + A_1\,\frac{\partial \Phi}{\partial x} + A_2\,\frac{\partial \Phi}{\partial y} + A_0\Phi + D(\Phi) = F$$

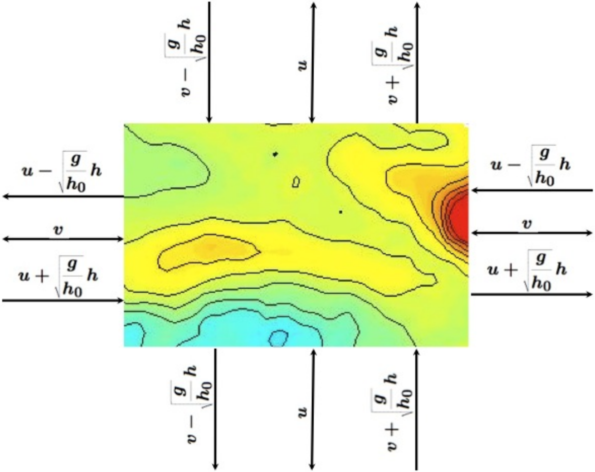
with $\quad \Phi = \begin{pmatrix} u \\ v \\ h \end{pmatrix}$ and $A_1 = \begin{pmatrix} u_0 & 0 & g \\ 0 & u_0 & 0 \\ h_0 & 0 & u_0 \end{pmatrix}$

Eigendecomposition of A_1 $\rightarrow$ characteristic variables (Eastern boundary):

$$w_1 = u - \sqrt{\frac{g}{h_0}}h \quad (u_0 - c)\ ,\ w_2 = v \quad (u_0)\ ,\ w_3 = u + \sqrt{\frac{g}{h_0}}h \quad (u_0 + c)$$

Example: the shallow water model

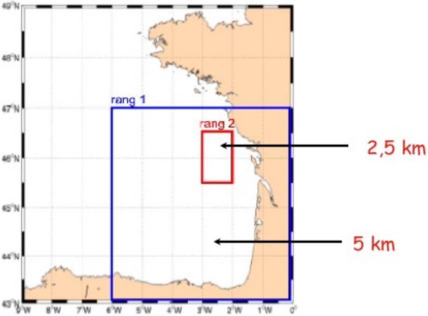
Information through the open boundaries:



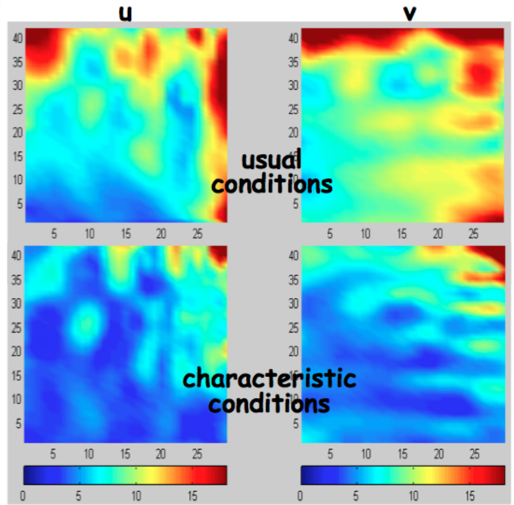
Numerical tests

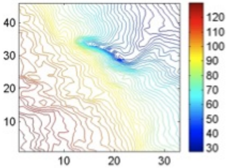
MARS model (IFREMER)

(collaboration: F. Vandermeirsch)



Numerical tests

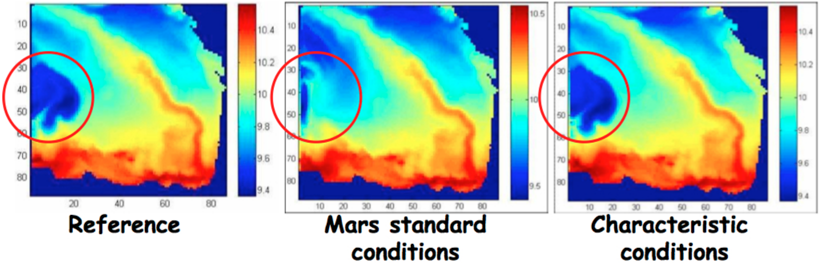




Rms error integrated over 2 months

Numerical tests

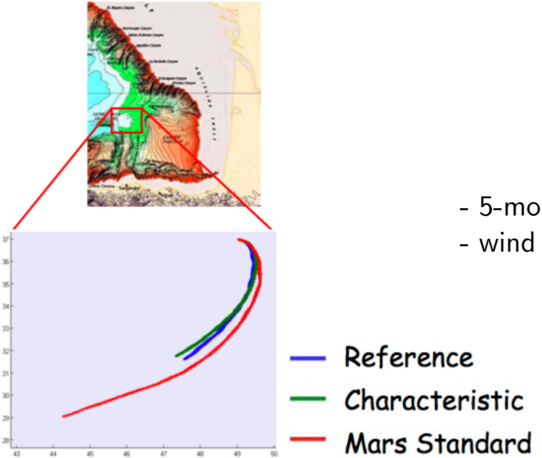
Propagation of a temperature anomaly



Solution after 2 months

Numerical tests

Float trajectories



- 5-month simulation
- wind forcing

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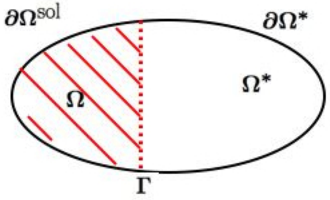
Taking into account “non hyperbolic” terms



Reference solution (unknown):

$$\begin{cases} Lu^* = f & \text{in } \Omega^* \times [0,T] \\ Bu^* = g & \text{on } \partial\Omega^* \times [0,T] \\ u^*(t=0) = u_0 \end{cases}$$

u^{ext}: external data (approximation of u^*)

One is looking for u solution of

$$\begin{cases} Lu = f & \text{in } \Omega \times [0,T] \\ Bu = g & \text{on } \partial\Omega^{\text{sol}} \times [0,T] \\ Cu = Cu^{\text{ext}} & \text{on } \Gamma \times [0,T] \\ u(t=0) = u_0 & \text{in } \Omega \end{cases}$$

$e = u - u^*$ error on u
$e^{\text{ext}} = u^{\text{ext}} - u^*$ error on the data

$$\begin{cases} Le = 0 & \text{in } \Omega \times [0,T] \\ Be = 0 & \text{on } \partial\Omega^{\text{sol}} \times [0,T] \\ Ce = Ce^{\text{ext}} & \text{on } \Gamma \times [0,T] \\ e(t=0) = 0 & \text{in } \Omega \end{cases}$$

$\rightarrow$ If one chooses C such that $Ce^{\text{ext}} = 0$, then $e = 0$ (i.e. $u = u^*$ on Ω)

If one assumes that $Lu^{\text{ext}} \simeq f$, then $Le^{\text{ext}} \simeq 0$.

To be solved:

Find C such that $Ce^{\text{ext}} = 0$ on Γ, given that $Le^{\text{ext}} = 0$ on $\Omega^* \setminus \Omega$

$\longrightarrow$ definition of an absorbing condition (Engquist & Majda, 1977)

On our equations: Halpern, 1986; Nataf et al., 1995; Lie, 2001...

Derivation of absorbing conditions

Example: 2-D advection-diffusion-reaction equation

$$Lu = \frac{\partial u}{\partial t} + a\frac{\partial u}{\partial x} + b\frac{\partial u}{\partial y} - \nu\Delta u + cu = f \quad \text{in } \mathbf{R}^2\times]0,+\infty[$$

Fourier transform: $\hat{w}(x,k,\omega) = \frac{1}{2\pi}\iint w(x,y,t)\, e^{-i(ky+\omega t)}\, dy\, dt$

$$Le = 0 \Longrightarrow \widehat{Le} = -\nu\,\frac{\partial^2 \hat{e}}{\partial x^2} + a\,\frac{\partial \hat{e}}{\partial x} + \left[c + \nu k^2 + i(\omega + bk)\right]\hat{e} = 0$$

Derivation of absorbing conditions

$$\begin{cases} \hat{e}^- = \alpha \; \exp(\lambda^+ x) \\ \hat{e}^+ = \beta \exp(\lambda^- x) \end{cases} \quad \text{with } \lambda^\pm = \frac{1}{2\nu}\left[a \pm \sqrt{a^2 + 4c\nu + 4\nu^2 k^2 + 4i\nu(\omega + bk)}\right]$$

$$\Longrightarrow \begin{cases} \dfrac{\partial \hat{e}^-}{\partial x} - \lambda^+ \hat{e}^- = 0 \Rightarrow \dfrac{\partial e^-}{\partial x} - \Lambda^+ e^- = 0 \\[2ex] \dfrac{\partial \hat{e}^+}{\partial x} - \lambda^- \hat{e}^+ = 0 \Rightarrow \dfrac{\partial e^+}{\partial x} - \Lambda^- e^+ = 0 \end{cases} \quad \text{with } \Lambda^\pm(e) = TF^{-1}(\lambda^\pm \hat{e})$$

$$\text{Ideally: } C = \begin{cases} \dfrac{\partial}{\partial x} - \Lambda^- & \text{if } \Omega = \mathbf{R}^- \\[2ex] \dfrac{\partial}{\partial x} - \Lambda^+ & \text{if } \Omega = \mathbf{R}^+ \end{cases}$$

But pseudo-differential operator (non local, both in time and space).

Derivation of absorbing conditions

$\Lambda^{\pm}$ can be approximated by differential operators, at different orders:

$$\lambda_0^{\pm} = \frac{a \pm p}{2\nu} \qquad \text{and} \qquad \lambda_1^{\pm} = \frac{a \pm p}{2\nu} \pm i(\omega + bk)\, q$$

i.e. $$\Lambda_0^{\pm} = \frac{a \pm p}{2\nu} Id \qquad \text{and} \qquad \Lambda_1^{\pm} = \frac{a \pm p}{2\nu} Id \pm q \frac{\partial}{\partial t} \pm bq \frac{\partial}{\partial y}$$

where p and q are coefficients to be determined.

Taylor expansion (assuming k and ω small) :

$$p = \sqrt{a^2 + 4c\nu} \qquad \text{and} \qquad q = 1/\sqrt{a^2 + 4c\nu}$$

Minimization of the reflection ratio $\rho = \dfrac{\text{reflected wave}}{\text{incident wave}}$

0th order: minimize $\rho(p)$ 1st order: minimize $\rho(p, q)$

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0th order: minimize $\rho(p)$ $\qquad$ 1st order: minimize $\rho(p, q)$

Example: shallow-water model

Work with V. Martin (LAMFA Amiens) and F. Vandermeirsch (IFREMER Brest)

- 0th order (i.e. flat bottom, without friction): $w_1 = 0$
  (we recover a classical method of characteristics)
- 1st order (different possible expansions):
  - flat bottom, weak bottom friction (r) : $\dfrac{\partial w_1}{\partial x} - \dfrac{r}{4c} w_3 = 0$
  - no friction, weak topographic slope (α) :
    $2c\dfrac{\partial w_1}{\partial t} - \alpha u_0 w_1 - \dfrac{\alpha(u_0 + c)}{2} w_3 = 0$
  - no friction, strong topographic slope (minimization of the reflection ratio): $a\dfrac{\partial w_1}{\partial t} + b w_1 - \dfrac{\alpha}{2} w_3 = 0$
    where a, b are solutions of a minmax problem.

On going work...

Outline

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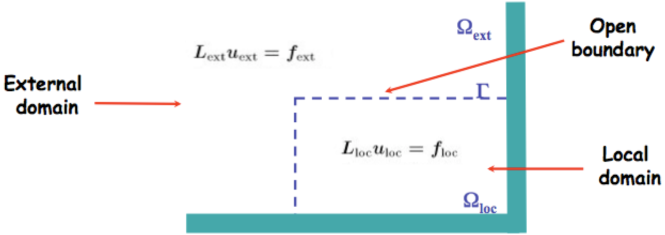
Formalization of the coupling problem

The two models are fully available.



A formulation of the problem could be:

Find u_{ext} and u_{loc} such that

$$\begin{cases} L_{loc} u_{loc} = f_{loc} & \text{in } \Omega_{loc} \times [0,T] \\ L_{ext} u_{ext} = f_{ext} & \text{in } \Omega_{ext} \times [0,T] \\ u_{loc} = u_{ext} \text{ et } \dfrac{\partial u_{loc}}{\partial n} = \dfrac{\partial u_{ext}}{\partial n} & \text{on } \Gamma \times [0,T] \end{cases}$$

However **usual coupling methods** are often **ad-hoc simple algorithms** in order to be computationally cheap.

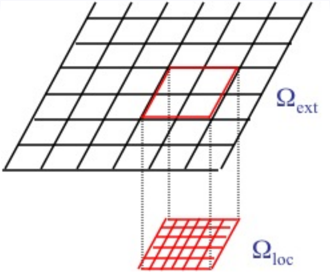
⇒ They are **not** fully **satisfactory from a mathematical point of view**.

Question: can we **improve the physical solution** of the coupled model **by improving mathematical aspects** of the coupling method ?

Goals

1. Revisit usual coupling methods within a theoretical framework
2. Propose improved approaches
3. Test their practical implementation

In pratice: ad hoc method



$$L^H_{\text{ext}} u^H_{\text{ext}} = f^H_{\text{ext}} \quad \text{in } \Omega_{\text{ext}} \cup \Omega_{\text{loc}}$$

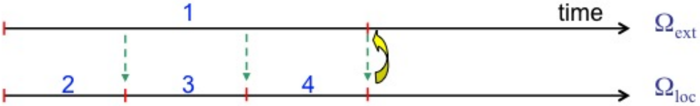
then

$$\begin{cases} L^h_{\text{loc}} u^h_{\text{loc}} = f^h_{\text{loc}} & \text{in } \Omega_{\text{loc}} \\ B^h u^h_{\text{loc}} = B^h I^h_H u^H_{\text{ext}} & \text{on } \Gamma \end{cases}$$

then

$$u^H_{\text{ext}} = I^H_h u^h_{\text{loc}} \quad \text{dans } \Omega_{\text{loc}}$$

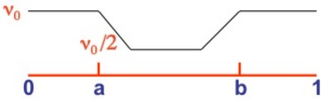
(possibly with flux correction)

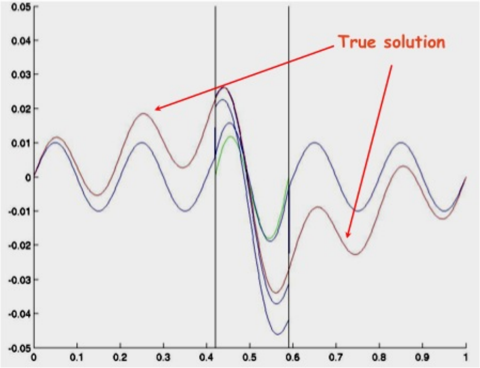


In pratice: ad hoc method

Which impact on the result ? a very simple example

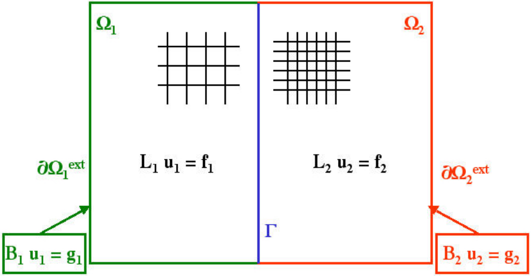
$$\begin{cases} -\nu(x)\, u"(x) + u(x) = \sin n\pi x \\ u(0) = u(1) = 0 \end{cases}$$





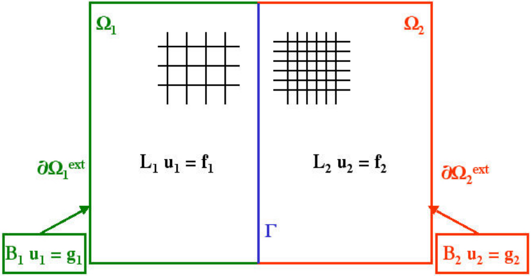
Outline

Framework: Schwarz methods



$$\begin{cases} L_1 u_1 & = f_1 & \Omega_1 \times [0,T] \\ u_1 & \text{given} & \text{at } t=0 \\ B_1 u_1 & = g_1 & \partial\Omega_1^{\text{ext}} \times [0,T] \\ C_1 u_1 & = C_1 u_2 & \Gamma \times [0,T] \end{cases} \qquad \begin{cases} L_2 u_2 & = f_2 & \Omega_2 \times [0,T] \\ u_2 & \text{given} & \text{at } t=0 \\ B_2 u_2 & = g_2 & \partial\Omega_2^{\text{ext}} \times [0,T] \\ C_2 u_2 & = C_2 u_1 & \Gamma \times [0,T] \end{cases}$$

Framework: Schwarz methods



$$\begin{cases} L_1 u_1^{n+1} = f_1 & \Omega_1 \times [0,T] \\ u_1^{n+1} \text{ given} & \text{at } t=0 \\ B_1 u_1^{n+1} = g_1 & \partial\Omega_1^{\text{ext}} \times [0,T] \\ C_1 u_1^{n+1} = C_1 u_2^{n} & \Gamma \times [0,T] \end{cases} \qquad \begin{cases} L_2 u_2^{n+1} = f_2 & \Omega_2 \times [0,T] \\ u_2^{n+1} \text{ given} & \text{at } t=0 \\ B_2 u_2^{n+1} = g_2 & \partial\Omega_2^{\text{ext}} \times [0,T] \\ C_2 u_2^{n+1} = C_2 u_1^{n} & \Gamma \times [0,T] \end{cases}$$

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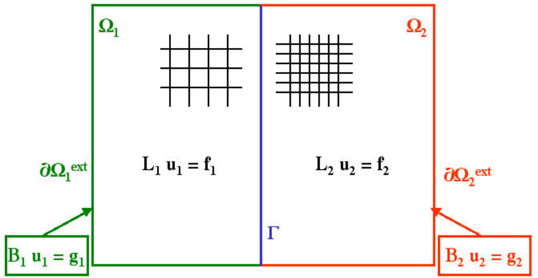

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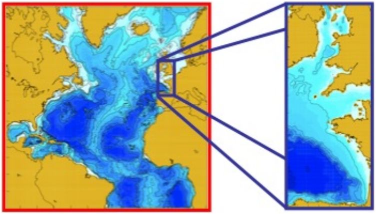
Questions:

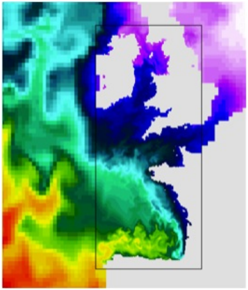
- Is it worth ? (is there an impact on the physics ?)
- How to reduce the computation cost ?

Impact on the physics : ocean-ocean coupling

North Atlantic 1/3° - Bay of Biscay 1/15°

(Cailleau et al., *Ocean Modelling*, 2008)

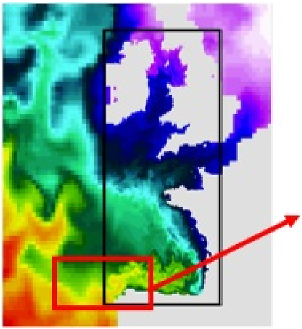


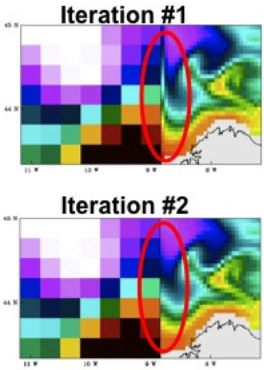


3-year simulation - primitive equation model NEMO

Impact on the physics : ocean-ocean coupling

Iterating leads to a solution with better regularity.

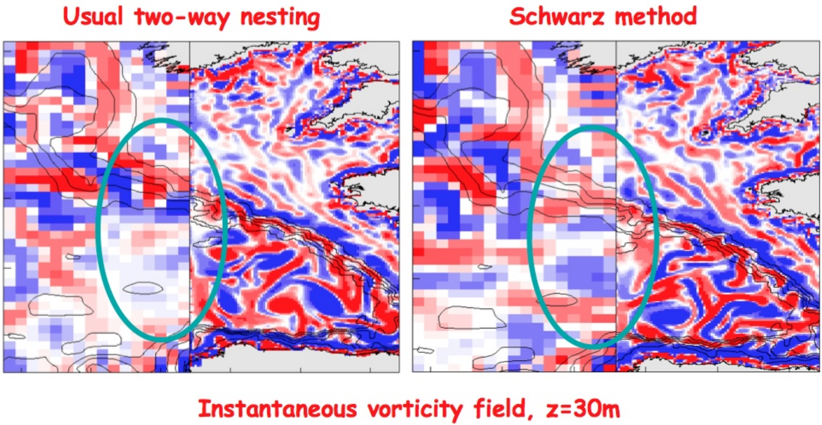




Temperature $z = 10m$

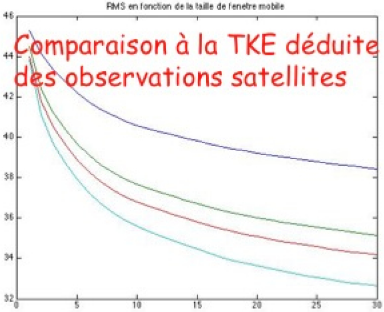
Impact on the physics : ocean-ocean coupling

Iterating leads to a solution with better regularity.



Impact on the physics : ocean-ocean coupling

Comparison to real observations (uncertain diagnostic, since models and forcing fields are imperfect)



The iterative method leads (or seems to lead) to a better solution:
→ perhaps not crucial if one is mostly interested in the statistics of the solution.
→ probably much more important for deterministic forecast.
→ Cost : $\times 5 - 7$ on average (not optimized)

Impact on the physics: simulation of a tropical cyclone

Simulation of the tropical cyclone Erica (2003) by coupling

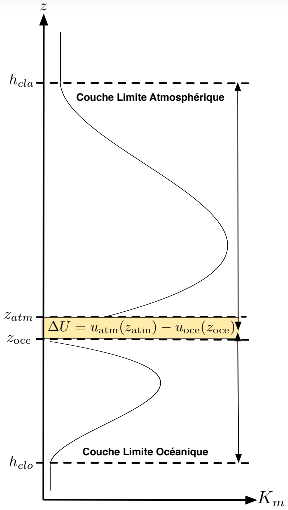
- ROMS: primitive equation ocean model (Shchepetkin-McWilliams, 2005)
- WRF: non hydrostatic atmospheric model (Skamarock-Klemp, 2007)

$\Delta x_a = 35$km, $\Delta t_a = 180$s
$\Delta x_o = 18$km, $\Delta t_o = 1800$s
15-day simulation

Boundary Conditions: vertical fluxes for $\vec{\tau}, Q_{\rm net}$ and F

$$\rho_a K_z^a \frac{\partial u_{\rm atm}}{\partial z}(0,t) = \rho_o K_z^o \frac{\partial u_{\rm oce}}{\partial z}(0,t) = F_{\rm oa}(u_{\rm atm}(0^+,t) - u_{\rm oce}(0^-,t))$$

Boundary layer parameterization



typical vertical viscosity profile

$$F_{\text{oa}}(\Delta U) = C_D(\mathbf{u}_\star)\,|\Delta U|\,\Delta U$$

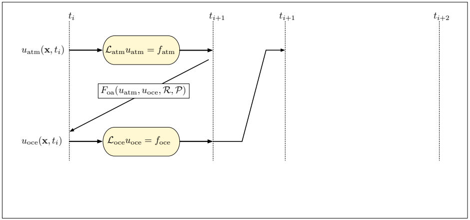
with $\mathbf{u}_\star$ solution of

$$\frac{\Delta U}{\mathbf{u}_\star} = \frac{1}{k}\left[\ln\left(\frac{z_{\text{atm}}}{z_0}\right) - \psi_m\left(\zeta(\mathbf{u}_\star)\right)\right]$$

Keywords: parameterization of Reynolds terms, K-profile schemes, Monin-Obukhov theory, bulk formulas...

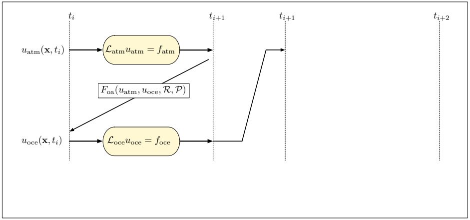
Impact on the physics: simulation of a tropical cyclone

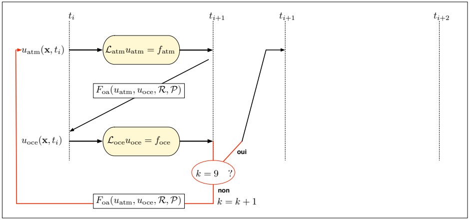
15-day simulation (60 6-hour time windows)



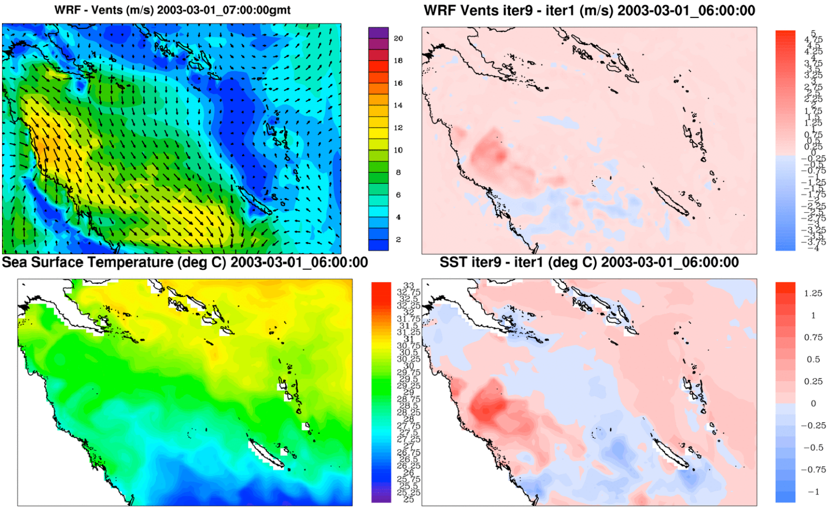
Impact on the physics: simulation of a tropical cyclone

15-day simulation (60 6-hour time windows)





Impact on the physics: simulation of a tropical cyclone



10-meter wind (m/s) and sea surface temperature (°C).

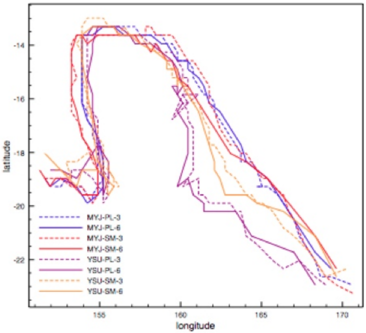
Impact on the physics: simulation of a tropical cyclone

What is the impact of the iterative method on the coupled solution ? $\longrightarrow$ ensemble simulations w.r.t. uncertain parameters

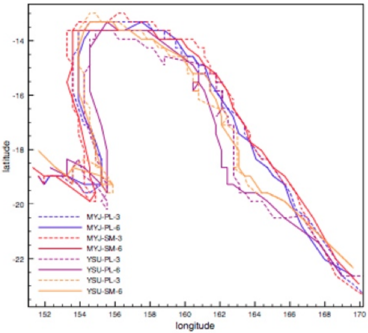
- **PBL/SL**: Mellor-Yamada-Janjic (MYJ) vs Yonsei University (YSU)
- **Microphysics** : Purdue Lin scheme vs Single-Moment 3-class scheme
- **Length of the time windows** : 6h vs 3h

Sensitivity of the trajectory of the cyclone

Usual method



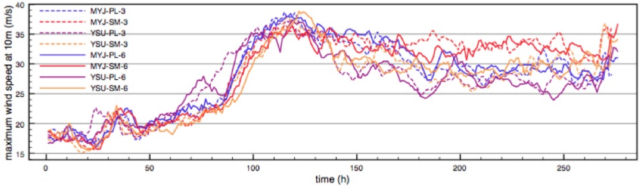
Schwarz method



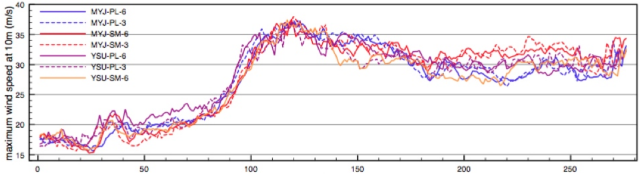
		3h	6h
1 itération	déviation moy	85km	94km
	déviation max	214km	238km
		3h	6h
9 itérations	déviation moy	66km	71km
	déviation max	167km	190km

Sensitivity of the intensity of the cyclone

Usual method

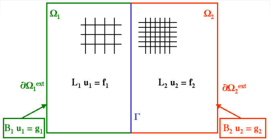


Schwarz method



		3h	6h
1 itération	déviation moy	2.49 m/s	2.46 m/s
	déviation max	3.03 m/s	3.19 m/s
		3h	6h
9 itérations	déviation moy	1.27 m/s	1.36 m/s
	déviation max	2.43 m/s	1.67 m/s

Decreasing the cost: absorbing boundary conditions

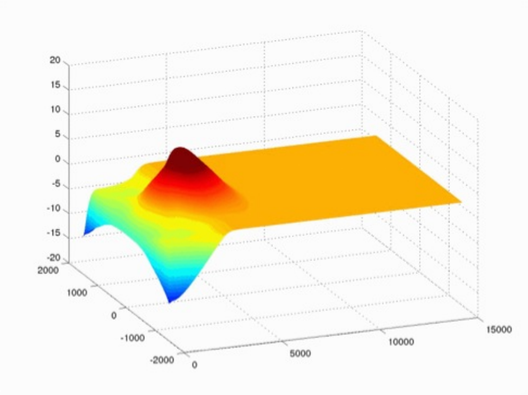


$$\left\{ \begin{array}{lll} L_1 u_1^{n+1} & = f_1 & \Omega_1 \times [0,T] \\ u_1^{n+1} & \text{given} & \text{at } t=0 \\ B_1 u_1^{n+1} & = g_1 & \partial\Omega_1^{\text{ext}} \times [0,T] \\ C_1 u_1^{n+1} & = C_1 u_2^n & \Gamma \times [0,T] \end{array} \right. \qquad \left\{ \begin{array}{lll} L_2 u_2^{n+1} & = f_2 & \Omega_2 \times [0,T] \\ u_2^{n+1} & \text{given} & \text{at } t=0 \\ B_2 u_2^{n+1} & = g_2 & \partial\Omega_2^{\text{ext}} \times [0,T] \\ C_2 u_2^{n+1} & = C_2 u_1^n & \Gamma \times [0,T] \end{array} \right.$$

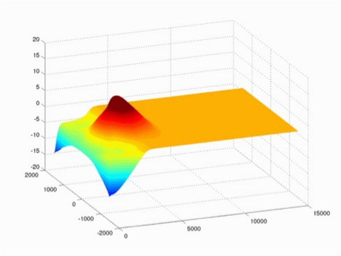
Systems satisfied by the errors:

$$\left\{ \begin{array}{lll} L_1 e_1^{n+1} & = 0 & \Omega_1 \times [0,T] \\ e_1^{n+1} & = 0 & \text{at } t=0 \\ B_1 e_1^{n+1} & = 0 & \partial\Omega_1^{\text{ext}} \times [0,T] \\ C_1 e_1^{n+1} & = C_1 e_2^n & \Gamma \times [0,T] \end{array} \right. \qquad \left\{ \begin{array}{lll} L_2 e_2^{n+1} & = 0 & \Omega_2 \times [0,T] \\ e_2^{n+1} & = 0 & \text{at } t=0 \\ B_2 e_2^{n+1} & = 0 & \partial\Omega_2^{\text{ext}} \times [0,T] \\ C_2 e_2^{n+1} & = C_2 e_1^n & \Gamma \times [0,T] \end{array} \right.$$

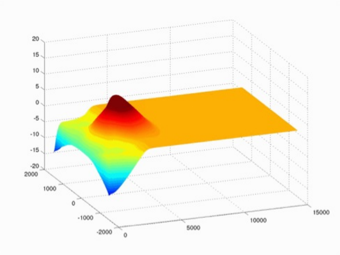
If one finds C_1, C_2 such that $C_1 e_2 = 0$ and/or $C_2 e_1 = 0$, then convergence in 2 iterations. $\longrightarrow$ **absorbing conditions**



shallow water - channel configuration (Martin, 2005)



Dirichlet-Dirichlet



optimized conditions

Solutions after 2 iterations

Some recent or ongoing works towards efficient interface conditions for ocean and atmosphere models

- Shallow water without advection (V. Martin, 2005)
- Shallow water with advection (V. Martin, E.B., on going work)
- Linearized primitive equations (E. Audusse, P. Dreyfuss and B. Merlet, 2009)
- Navier-Stokes (D. Cherel, A. Rousseau, E.B., on going work)
- Coupling between 3D Navier-Stokes and 2D shallow water (M. Tayachi, starting work with N. Goutal, V. Martin, A. Rousseau)
- 1-D advection-diffusion with variable and discontinuous coefficients $\longrightarrow$ ocean-atmosphere coupling (F. Lemarié, L. Debreu and E.B., 2010; C. Japhet, on going work)
- ...

Outline

Conclusion

- Open boundary and coupling problems are frequently encountered in the context of ocean and atmosphere, and more generally in hydrodynamics. Present methods are often *ad hoc* methods.
- More accurate methods exist, which may have some impact on the quality of the solution, at least for "deterministic" forecast (perhaps not for "statistical" solutions).

- **Open boundary problems**
  A 0th-order approach (method of characteristics) leads to clear improvements.
  Further improvements can be expected from the use of absorbing conditions.
- **Coupling problem**: global-in-time Schwarz methods
  - rather easy to implement
  - remaining difficulties:
    - quantify the impact in a fully realistic testcase (lack of a reference solution)
    - reduction of the cost (optimized conditions ? are 2-3 iterations enough ?)

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