Simulation of plankton dynamics in the turbulent Benguela upwelling system.

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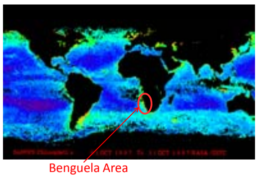
Abstract

We study the interplay of hydrodynamic transport and plankton dynamics in the Benguela upwelling system. A coupled system of oceanic flow and a simple biogeochemical model (NPZ type) is used. For the surface oceanic flow we use two different velocity fields: a) one derived from satellite data (altimeter and scatterometter) at ¼˚ to study the surface dynamics, and b) from a 3D numerical model at 1/12˚ resolution, which "includes" a vertical component. We study the effect of the horizontal transport on the dynamics of phytoplankton and compare simulations using both velocity fields. We compute horizontal Finite Size Lyapunov Exponents (FSLEs) as a proxy of horizontal mixing and analyze their correlations with phytoplankton concentrations.

Coupling hydrodynamical and biological models in the Benguela

- Coupling between hydrodynamical and biological models: advection-reaction-diffusion system. This system is resolved using a semi-Lagrangian algorithm.
- The biological model is derived from Sandulescu et al. [2008] and describes the interaction of a three-level trophic chain (NPZ) in the mixed layer of the ocean (see below).
- Horizontal transport is explicitly taken into account in the 2D flow from satellite at $1/4^0$ spatial resolution (Sudre and Morrow [2008]), and velocity data from the ROMS (Regional Ocean Modeling System) climatological numerical model at $1/12^0$ spatial resolution.
- The advection is performed in 2D (ocean surface only) for both systems.
- The nutrient supply due to vertical mixing mimics the upwelling, and it is modeled as a source term in the reaction part of nutrient equation.
- We add also an eddy diffusion process acting on plankton and nutrients concentrations to incorporate the small-scale turbulence, which is not explicitly taken into account by the velocity fields used. The diffusion coefficient, D, is given by Okubo's formula and the value is corresponding to the length scale of the velocity data (spatial resolution).
- The biological model needs a 2 months spin-up to reach its equilibrium.



Advection-Reaction-Diffusion Equations

$$\frac{\partial N}{\partial t} + \mathbf{v}\nabla N = F_N + D\nabla^2 N$$
$$\frac{\partial P}{\partial t} + \mathbf{v}\nabla P = F_P + D\nabla^2 P$$
$$\frac{\partial Z}{\partial t} + \mathbf{v}\nabla Z = F_Z + D\nabla^2 Z$$

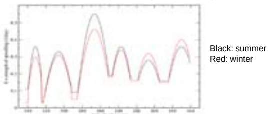
NPZ model

$$\frac{dN}{dt} = F_N = \Phi_N - \beta\frac{N}{\kappa_N + N}P + +\mu_N\left((1-\gamma)\frac{\alpha\eta P^2}{\alpha+\eta P^2}Z + \mu_P P + \mu_z Z^2\right)$$
$$\frac{dP}{dt} = F_P = \beta\frac{N}{\kappa_N + N}P - \frac{\alpha\eta P^2}{\alpha+\eta P^2}Z - \mu_P P$$
$$\frac{dZ}{dt} = F_Z = -\gamma\frac{\alpha\eta P^2}{\alpha+\eta P^2}Z - \mu_Z Z^2$$

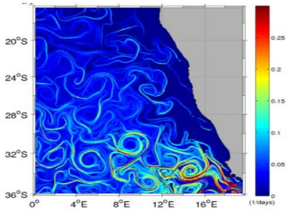
$$\Phi_N = S(x-y)(N_0 - N)$$

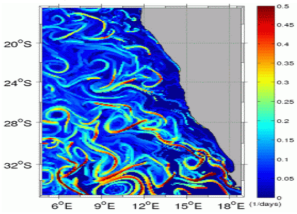
Mixing term

(S is the strength of the upwelling. We use seasonal values to mimic the upwelling cells along the coast)



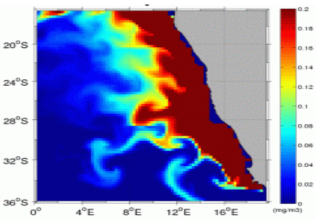
Spatial structures of computed FSLEs and modelled phytoplankton


A snapshot of backward FSLEs from Satellite ($1/4^0$)


A snapshot of backward FSLEs from ROMS ($1/12^0$)

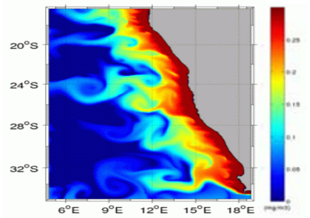
- Southern system more turbulent than the northern one.
- Higher mixing in ROMS than in Satellite velocity field.
- Complex spatial structures in plankton concentrations (dynamics of the turbulent medium and of the marine ecosystem).
- Using ROMS velocity field, the structures are clearer since the flow is more turbulent and the spatial resolution is finer than the satellite velocity field.

Using velocities from Satellite ($1/4^0$)



Phytoplankton t = 360 days

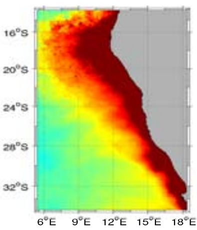
Using velocities from ROMS ($1/12^0$)



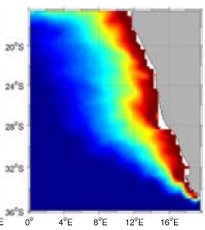
Phytoplankton t = 360 days

Spatial variability: comparison between modelled Phytoplankton and Chlorophyll from SeaWiFS

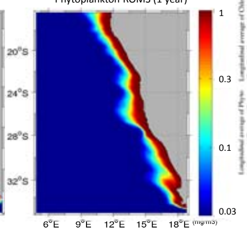
Seawifs average (3 years)

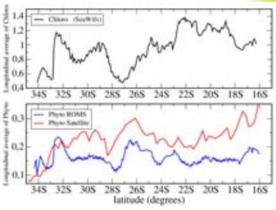


Phytoplankton sat (3 years)



Phytoplankton ROMS (1 year)



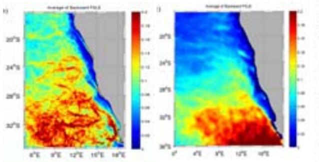


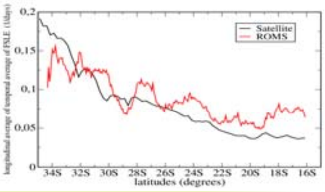
- Slightly better agreement using ROMS velocity field (blue line).

- Higher concentrations of chlorophyll at the coast, decreasing offshore. Chlorophyll concentrations are higher in the north than in the south.
- General pattern quite well reproduced, but large differences in the range of chlorophyll concentrations (underestimation of the model).
- Low latitude: underestimation of the model (effect of the PAR not taken into account?)

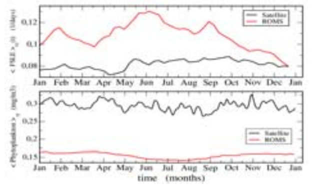
Spatial variability: surface horizontal mixing from Finite Size Lyapunov Exponents (FSLEs)

- Higher horizontal mixing in the southern Benguela than in the north in both velocity fields. .
- Higher spatial averaged mixing in ROMS than in the satellite velocity field.
- Latitudinal variations of mixing in agreement between both velocity field (although different spatial resolution).
- High chloro / low mixing (north) and low mixing / high chloro (south): it suggests a spatial negative correlation between phytoplankton (Chlorophyll) and horizontal mixing (*Rossi et al [2008]*).



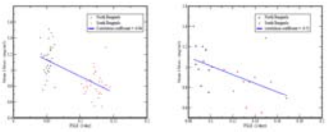


Correlation FSLE - phytoplankton concentrations: Effect of the velocity field?

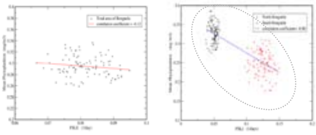


- Negative correlation exists also in the annual cycle: winter = max mixing / min chlorophyll (lower nutrients input).
- Exists within a simulation (although different ranges) and also comparing both simulations together.

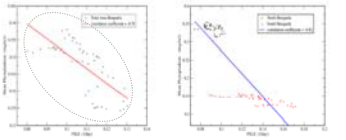
Correlation FSLE / observed Chloro (SeaWiFS)



Correlation FSLE / modelled Chloro (satellite)



Correlation FSLE / modelled Chloro (ROMS)



- The negative correlation between horizontal mixing and phytoplankton concentrations appears almost everywhere: robust inverse relationship.
- It is stronger when using satellite velocity field per subsystem → particular intrinsic hydrodynamic signature of the 2 subsystems not reproduced in the model?
- It is stronger when using ROMS velocity field over the whole area → importance of the vertical dynamics? Scale effect (resolution of the velocity field)?
- Quite large difference of the relation just by using different velocity field.
- Sensitivity of the relationship to the resolution of the velocity field and the dominant term (advection/diffusion/reaction)?

Conclusions & Perspectives

- We reproduced the spatial and temporal variability of phytoplankton concentrations due to both dynamics of the flow and of the marine ecosystem.
- The model yields a spatial distribution of phytoplankton quite similar to the chlorophyll given by SeaWiFS. However the range of concentration is underestimated: parameters of the biological model? Initialization values? PAR effect? Introduction of a sinking term (varying spatially)?
- Horizontal mixing is higher in the south than in the north / chlorophyll concentrations are larger in the north than in the south Benguela.
- A negative correlation between horizontal mixing and phytoplankton concentrations is confirmed using the chlorophyll data as well as the modelled chlorophyll. However, this correlation is changing depending on the velocity field used and the area considered. Which processes are responsible? Effect of spatial resolution of the velocity field? Vertical dynamical constraints? Mixing intensity? Compressibility of the flow?
- Sensitivity studies were initiated: advection and reaction parts appeared to be the most important.

References:
- *Sudre, J. and Morrow, R.*: Global surface currents: a high resolution product for investigating ocean dynamics, Ocean Dyn., 58(2), 101-118, 2008.
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- *Rossi, V., López, C., Sudre, J., Hernández-García, E. and Garçon, V.*: Comparative study of mixing and biological activity of the Benguela and Canary upwelling systems, Geophys. Res. Lett., 35, L11602, doi:10.1029/2008GL033610, 2008.