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Spécialité : Océanographie Physique

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Sujet de la thèse :

A numerical study of the Southern Benguela circulation with an application to fish recruitment.

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Introduction

The Benguela ecosystem, along the South-west coast of Africa is, with the California Current, the Peru-Chile and the North African upwelling systems, one of the world's 4 major ecosystems driven by an upwelling along the eastern margin of the Oceans. Their combined total area accounts only for 0.1 % of the total surface of the world oceans, but they provide almost 30 % of the world's total fish catch [*Durand et al.,* 1998]. Furthermore, their yearly fluctuations explain most of the inter-annual variability of the total marine fish catch. These fluctuations, showing years of high abundance and dramatic collapses, result from the variability of the recruitment (which is the number of young fish produced each year). The vulnerability of the fish larvae during the first weeks of their lives when their displacement capabilities are limited, leaving them at the mercy of the ocean for food accessibility or transportation, explains this large variability in recruitment. This critical period implies that the number in a year class is determined at a very early stage [*Hjort,* 1914, *Hjort,* 1926]. During this period, the environment has a major impact on the survival rate of larvae. Bakun [1993] has identified 3 classes of environmental processes that combine together to create a favorable environment for recruitment:

- The processes of enrichment which supply the beginning of the food chain with nutrients. They involve upwelling and vertical mixing.
- The processes of concentration, that aggregate food, eggs and larvae together. These can occur in convergence areas such as fronts or when vertical stratification inhibits vertical movement.
- The processes of retention that keep eggs, larvae and juveniles in a favorable area for their survival.

In upwelling areas, the existence of multi-variable and non-linear relationships between recruitment and upwelling intensity is a recurrent pattern resulting from the interaction between several environmental process [*Cury and Roy,* 1989, *Cury et al.,* 1995, *Durand et al.,* 1998]. The competition between these different processes (enrichment, mixing, dispersion...) leads to an "Optimal Environmental Window" that gives a maximum for pelagic fish recruitment success in upwelling areas for a limited averaged wind range ($\sim$ 5-7 m.s^{-1}) [*Cury and Roy,* 1989].

The Benguela upwelling system is a highly dispersive environment, where a strong equatorward wind along the coast induces an offshore displacement of the surface waters. Although important for the enrichment of the ecosystem in nutrients, this divergence can have a detrimental effect on the recruitment: eggs and larvae are then carried offshore, away from their coastal habitat. In the Southern Benguela, sardines and anchovies, the most abundant pelagic species, have adapted their reproductive strategies to the environmental constraints. They migrate to spawn on the western Agulhas Bank, upstream of the food sources. Eggs and larvae are advected by the currents towards the productive areas of the West Coast of South Africa. St Helena Bay, in the North of Cape Columbine, is recognized as the most important nursery ground of the West Coast of South Africa [*Hutchings,* 1992]. This area shelters the biggest fishing industry of the country. The loss of biological material during transport from the Agulhas Bank to the West Coast and the retention inside the nursery ground of St Helena Bay are supposed to be the principal factors affecting the recruitment of sardines and anchovies [*Hutchings et al.,* 1998].

The work presented in this manuscript is part of the VIBES (Viability of exploited pelagic fish resources in the Benguela Ecosystems and Stocks in relation with the environment) project. VIBES is a pluridisciplinary research project involving IRD (Institut de Recherche pour le Développement, France), UCT (University of Cape Town, South Africa), MCM (Marine and Coastal Management, South Africa) and LPO (Laboratoire de Physique des Océans, France). One of the scientific goals of VIBES is to improve our understanding of the spatial dynamics of the pelagic marine resources, the fisheries and the environment through modeling. The present work concentrates on the modeling and the understanding of the physical oceanic processes affecting pelagic fish recruitment in the Southern Benguela upwelling system.

To carry out this study, we use numerical tools in order to simulate the complex physical patterns observed in the Southern Benguela. We follow a step by step approach. We start by setting up idealized experiments in order to provide an understanding of the peculiarities of the circulation in St Helena Bay. At a later stage, a 3-dimensional realistic model is implemented to reproduce the dynamics of the ocean around the South western corner of Africa. The key processes of the dynamics of the Southern Benguela will be identified from idealized and realistic experiments. An analysis of these processes and a quantification of their impact on the transport, retention and dispersion of the biological material are performed in order to obtain the characteristic patterns affecting recruitment. The South western corner of Africa has been much studied because of the global climate implication of the inter-ocean exchanges that occur in this area. A high resolution model of this region might also give new insights on the physical processes involved in the South Atlantic-Indian Ocean exchange of properties.

The first part of the thesis concentrates on the description of the characteristic elements of the Benguela dynamics. Numerous articles related to surveys conducted in the Benguela upwelling system have been published during the last 30 years. Several reviews [*Nelson and Hutchings,* 1983, *Shannon,* 1985, *Shannon and Nelson,* 1996, *Shillington,* 1998] provide a broad outline of the observed dynamics of the Benguela. The bibliographic study conducted in this first part of the manuscript provides a general description of the actual understanding of the system and leads to the identification of key questions relevant to the thesis.

The second chapter presents the idealized experiments conducted to analyze the peculiarities of the shelf circulation in St Helena Bay. The bay is situated North of Cape Columbine, a step like variation of 100 km in the coastline. Associated with the cape, the shelf broadens from 50 to 150 km. These topographic variations should considerably alter the shelf dynamics. Two hypothesis are used to simplify the problem. Firstly, the gentle slope of the shelf should allow the neglect of processes related to stratification in the simulation of the shelf dynamics [*Clark and Brink,* 1985]. Secondly, spatial and temporal wind variations are assumed to be of secondary importance in comparison to the processes related to topography. Hence, barotropic experiments are conducted, forced by a constant wind. These experiments are conducted to test if a topographically induced process can balance the dispersion caused by the wind forced coastal currents. Diagnostic tools are designed to help in the understanding of the simulated process and a sensitivity analysis will explore the shelf dynamics response to a range of wind forcing, bottom friction parameter and size of the cape. An analytical solution in the form of standing shelf waves, illuminates this important behavior of the shelf dynamics. A tracer of water age is integrated into the model to quantify retention.

For the third chapter, a realistic regional model is implemented in order to produce a high resolution portrayal of the ocean dynamics surrounding the South-western corner of Africa and to explore the physical processes involved in the different biological stages leading to recruitment, from eggs to larvae and juveniles. A meeting organized at the beginning of the project and discussions with the different partners of the project allowed the selection of model requirements:

- The numerical model must be able to resolve the mesoscale features that develop over the coastal domain (like filaments, plumes, eddies, or coastal jets...).
- The model domain must include the main pelagic fish spawning and nursery grounds.
- It must be large enough to allow the relevant physical processes to fully develop, but small enough to obtain sufficient fine spatial resolution at a reasonable computational cost.

The Benguela upwelling system is unique in a way that the African continent ends at around 34^o S. This induces the highly energetic poleward termination of the western boundary current of the Indian Ocean, the Agulhas Current, to flow along the Agulhas Bank and somehow to interact with the Benguela upwelling system. It retroflects South of the Agulhas Bank to flow back into the Indian Ocean. One should note that the anticyclonic eddies shed at the retroflection area, the Agulhas rings, are the biggest coherent structures observed in the Ocean. The handling of these highly energetic structures and currents by a regional oceanic model of finite dimension is a challenge that require specific treatments. Recently, long term simulations (of more than 10 years) have been conducted using a regional oceanic model for the California Current System [*Marchesiello et al.,* 2000]. The model employed is ROMS, the Regional Ocean Modeling System. It uses a generalized nonlinear terrain-following coordinate, high order schemes and new parameterizations that have been especially implemented to resolve with a high level of accuracy the primitive equation of momentum along the shelf and the slope on a regional scale. Though there is no equivalent of the Agulhas Current along the West Coast of the United States, we expect to obtain long-term meaningful results using the same tool for the Benguela upwelling system. The validation of the model results will be done through comparison with data. The study of the variability of the system and of typical mesoscale processes will give insights for the understanding of the Benguela dynamics. Special attention is given to the model solution on the shelves along the South and West coasts, and comparison is also made with the results of the idealized experiments. If the realistic model solution is satisfactory, it will be possible to use the model to explore transport mechanisms from the Agulhas Bank to West Coast and retention processes in the coastal domain. This is done by introducing a passive tracer that simulates eggs and larvae transport behavior.

Following this approach, we expect to provide a better understanding of the dynamics of the Southern Benguela as well as necessary tools for the ongoing study of the dynamics of the recruitment.