Conclusion

Here is the end of the manuscript, the time to take the stock of what has been achieved during this project. The goals of the PhD were

(1) to study the dynamics of mesoscale processes related to retention within the St Helena Bay nursery ground

(2) to develop a high resolution regional model to simulate the shelf circulation along the South and West coasts of South Africa.

The work could have been focused on the design of a 3D realistic model or on the study of a particular process of the system. The step by step approach chosen was more general: starting with a description of the system that has led to the selection of a few processes, concentrating on a specific process in St Helena Bay using both numerical and analytical approaches, and ending by a realistic simulation of the circulation of the Southern Benguela.

The barotropic study reveals that a wind driven equatorward current can generate a standing process in the lee of a cape. In the case of St Helena Bay, the numerical study shows that this process should take the form of a standing cyclonic eddy, controlled by a balance between advection and bottom friction. A length scale derived from this balance, which can be considered as an e-folding length scale, can then predict the size of the eddy as a function of the wind stress and the bottom friction parameter. Sensitivity tests reveal some discrepancies between this length scale and the size of the eddy, especially for smaller capes where the slope in the bay has gained importance. In the presence of bottom slope, standing shelf waves are more likely to develop. An analytical study shows that standing shelf waves can be excited by a mean current past a cape. The tracer, representing the age of the water, has been introduced in the model. It exhibits the retention induced by the standing recirculation process. Upwelling favorable winds can generate currents responsible for eggs and larvae dispersion. But, at the same time, these currents can induce recirculation in the lee of capes like Cape Columbine that can trap eggs and larvae in a favorable environment.

The particularity of the Benguela system, with the Agulhas Current retroflecting just South of the area of interest did not facilitate the implementation of a realist 3-D model of the region. Tests have been conducted using a low resolution configuration to set-up the open boundary conditions. The treatment of the bottom topography for this simulation gave an incorrect representation of the shelf circulation and the detachment of the Agulhas Current. For the high resolution experiment the solution is more satisfactory, and compares with observations for most of the processes. They include:

- The localized upwelling centers of Cape Peninsula, Cape Columbine, Namaqualand and Lüderitz.

- The upwelling eddies that are shed from the Cape Peninsula and Cape Columbine

- The upwelling plume that extend from Cape Columbine
- The filaments that extends from the upwelling front
- The equatorward baroclinic jet associated with the upwelling front
- The Columbine divide
- The poleward subsurface counter-current and the poleward undercurrent along the shelf break
- The poleward deep motion along the slope
- The weak circulation on the Agulhas Bank
- The convergent currents on the western margin of the Agulhas Bank that feed the Good Hope jet
- The cyclonic eddies shed from the Agulhas Current in the lee of the Agulhas Bank
- The shear edge eddies along the eastern and southern part of the Agulhas Bank
- The Agulhas retroflection

The major ingredients of Southern Benguela are present in the simulation. It is the first time that these local processes, described in numerous publications, have been modelized with this level of accuracy. Although the surface forcing is derived from a smooth monthly climatology, the mesoscale activity generates a significant high frequency variability. Its amplitude along the West Coast of South Africa compares quantitatively with observations. This result shows that the variability along the West Coast is more a consequence of intrinsic instability of the coastal ocean rather than a direct forcing from small scale wind variations. Some differences have also been noticed when comparing model results with data:

- The time-averaged modelized sea surface temperature along a coastal narrow band North of Cape Columbine is 2 to 3^o C smaller than the temperature observed from satellite imagery. It has been observed that the intensity of upwelling favorable wind stress is smaller along the coast North of Cape Columbine [*Jury,* 1988], but this pattern is not present in the dataset used to force the model. This can explain the difference between the model and the observations.
- The subsurface eddy kinetic energy is 2 times smaller than the eddy kinetic energy derived from altimeter data in the Agulhas retroflection area. There is 2 possible causes for this difference. Firstly, the Agulhas Current shows important variations that are generated upstream of the model domain and propagate with the flow, like the Natal pulses [*De Ruijter et al.,* 1999a, *Lutjeharms and Roberts,* 1988]. The seasonal time-averaged data set employed to force the Agulhas Current at the eastern open boundary does not inject this non-local variability into the model. Secondly, the western open boundary is close to the retroflection area and mights affect the Agulhas rings generation process.
- The cyclonic weak motion observed in St Helena Bay and analyzed in the second chapter is not present in the realistic model outputs. The treatment of bottom topography for this level of resolution enhanced the slope of the shelf, inhibiting the possible generation of this standing process.

A tracer, representing the probability of presence of an egg spawned on the western Agulhas Bank has been introduced to simulate the transport patterns between the Agulhas Bank and the West Coast of South Africa. It shows the negative effect of the upwelling favorable wind for the transfer from the Agulhas Bank to the West Coast and the positive effect of the mesoscale eddies and jet on the retention of the biological materials in the favorable areas. This is in agreement with the last result of the second chapter.

Prospects

- The realistic 3D model has been developed in order to produce an accurate portrayal of the dynamics of the Southern Benguela to study the impact of the environment on the recruitment of small pelagics. An individual based model (IBM) has been developed by the VIBES group. This model allows the simulation of the path of fish eggs, larvae and juveniles when they are released in the model domain. The coupling of the IBM with the results of the physical model allows the simulation and analysis of transport processes affecting the recruitment of sardines and anchovies in the Southern Benguela. Specific scenarios (like strong upwelling or weak upwelling) can be undertaken to understand the impact of the variability of the environment on the living resources. The coupling of a coastal ocean model to an IBM constitutes a powerful tool for the understanding of ecosystem dynamics. This technique has been successfully applied to quantify the effects of advection on pollock larvae in Alaska [*Hermann et al.,* 1996] and on cod and haddock larvae on George Bank [*Werner et al.,* 1993].

- In the second chapter, we have shown the generation of a standing process in the barotropic case. Is it still valid when stratification is taken into account ? The comparison of the results with the observed circulation in St Helena Bay seems to maintain this hypothesis, but the advection by a mean current is not clear in the baroclinic case.

- The realistic model provides a large amount of information and specific processes that can been studied from the model outputs. The forcing of the poleward undercurrent and counter-current can be diagnosed by computing the different terms of the momentum and vorticity equations from the model outputs. Special attention can be given to the de-stabilization processes of the upwelling front along the West Coast of South Africa. The quantification of energy transformation mechanisms can lead to the indication of the type of instability process that is responsible of the de-stabilization of the front.

- Simplified models and analytical analysis, inspired by the work of Gill and Schumann [1979], of the shear edge eddies obtained on the Agulhas Bight could explain the reason for these recurrent features. This process should be also present on the coastal side of the other western boundary currents.

- The analysis of the results of the high resolution experiment allows us to identify directions to follow in the future, in order to improve the quality of the realistic simulation:

  - The topography on the shelf near Cape Peninsula and in St Helena Bay has been significantly altered during the smoothing process. The 100 m isobath passes through the Cape Peninsula and the exaggerated slope of the shelf in St Helena Bay can inhibit the generation of the cyclonic process, important for the retention of biological material in the coastal area. The algorithm of topography smoothing can be corrected in order to respect the general shape of the shelves. Simulation with higher spatial resolution can allow the use of a more realistic bottom topography, but at a larger numerical cost. A new pressure gradient scheme is still in development at UCLA [*Shchepetkin and McWilliams,* in preparation]. If this formulation gives the results expected, it could be possible to employ a more accurate bottom topography at the actual level of resolution.

  - The shedding of the Agulhas rings seems to have been constricted by the vicinity of the eastern open boundary. This boundary should be placed at a few hundred of kilometers offshore in order to allow a greater degree of freedom for the detachment of the Agulhas rings.
  - The level of eddy kinetic energy in the Agulhas area is 2 times smaller for the model than for the observations. Although an important source of variability for the Agulhas Current has been recognized to be the Mozambique channel [*Biastoch and Krauß,* 1999], thousands of km upstream of our domain, the displacement of the western boundary around 28^o E, where the Agulhas Current appears to be more stable, should enhance the simulation of the variability in the retroflection area. Another possibility could be the utilization of the direct outputs of AGAPE instead of using a seasonal climatology. In this case, the larger amount of data that should have to be treated to fit to the regional model grid dramatically increases the numerical cost of the preprocessing chain. We will rapidly reach the paradox that more cpu time should be necessary to prepare the experiments than to actually run them. In this case, in order to obtain a meaningful solution, it should be also necessary to enforce the compatibility of the surface forcing between the regional model and the AGAPE basin scale model.
  - A finer climatological dataset can be derived for the surface wind forcing to obtain a sea surface temperature closer to the observations along the west coast.

- Test experiments with low wind forcing, high wind forcing, warm water intrusion from the North, or using a more variable wind stress can allow the quantification of the response of the Benguela upwelling system on the interannual variability of the external forcing. This response can dramatically affect the recruitment.

- The use of realistic surface forcing and the comparison with the simulation obtained in the present work can give a quantification of the direct impact of the surface forcing on the variability of the Benguela system.

- The use of embedded grids, in one way and in two ways, can resolve one of the most important problem of coastal dynamics: the need for a high resolution solution in the coastal domain in opposition to the need for a proper representation of the effects induced by the large scale circulation. This method can be useful for the inclusion of processes such as the variability produced by eddies generated as far as the Mozambique Channel. Using these methods, it will also be possible to have fine scale high resolution subgrids for the areas of interest such as bays like St. Helena Bay, Saldanha Bay, or False Bay. It opens a wide field of non-academic applications of the model solution for coastal management, harbor and industrial installations, or pollutant dispersion studies.

Many other improvements can be added to the actual model to produce a better representation of the Benguela ecosystem, such as the assimilation of data, the introduction of tides, the modeling of the river outflows, or the modeling of the primary production... Each increase of the complexity of the modelized system, will result in an increase of the complexity of the solution. New tools should then be designed to help the understanding of the key processes that are structuring these solutions. Recently, an important effort has been conducted to understand the dynamics of coastal ecosystems, an example is the work conducted for the West Coast of the United States [*Miller et al.*, 1999]. The experience gained and the tools designed for the study of the Benguela ecosystem could be applied to other coastal domains of the world. Important fundamental insight could be obtained by comparing the dynamics of the different domains.