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Numerical Lagrangian study of typical pathways for water masses in the North Western Mediterranean

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Abstract

The numerical Lagrangian diagnostic tool Ariane is used to determine the main pathways in the North Western Mediterranean (NWM) and their associated transports . Quantitative and qualitative simulations are made for this region with Eulerian outputs from the ocean regional circulation model Symphonie for years 2001 to 2003. A clear correlation is shown between the mean position of the Northern Current and the bathymetry. The transport for the pathway linking Corsican waters and the Balearic channel is evaluated around 0.25 Sv. A strong recirculation in the Ligurian sea appears in our diagnostics. We named it the Ligurian Recirculation. The preliminary focus on it shows that water masses involved are centered around 500-meter depth. Future analysis on tracers (temperature and salinity) could allow us to link these results with specific water masses.

Un diagnostique lagrangien numérique de la circulation en Méditerranée Nord Occidentale (NWM) pour déterminer les principales circulations a été réalisé avec l'outil Ariane. Des simulations quantitatives et qualitatives ont été réalisées pour la NWM à partir des sorties eulériennes provenant du modèle de circulation régionale Symphonie pour les années 2001 à 2003. Une corrélation nette entre la position moyenne du Courant Nord et la bathymétrie a pu être mise en évidence. Le flux de masse d'eau entre la Corse et le canal des Baléares est évalué à 0.25 Sv. Une forte recirculation en mer ligure apparaît dans nos diagnostiques. Nous l'avons nommé recirculation ligurienne (LR). L'étude préliminaire sur cette recirculation montre que les masses d'eau concernées sont centrées autour de 500 de profondeur. De prochaines analyses avec les données de température et salinité devraient nous permettre de relier ces résultats avec les masses d'eau spécifiques de la Méditerranée Nord Occidentale.

Contents

Chapter 1

Introduction

The oceans and seas represent more than 70 % of the surface of the globe, but remain the least known natural environment. It is a surprising observation if we consider that more than 40 % of the worlds population live along the coasts. Sixty years after the birth of the modern oceanography, our vision of the oceans and seas have radically change. At first concentrate on the global ocean, studies tighten more and more on the coastal seas because of economical issues and the awareness of the influence of oceans on coastal region. Currently, the interest for the oceans and seas is reinforced because of their functions in the global warming and pollutant dispersion due to human activities. For these reasons, the knowledge of the water circulation in the different regions of the world need to be determine. The LATEX project, where this internship takes part, is a practical aspect of this will of a better knowledge of the circulation in a region which concerns us directly. For that the numerical study of the main pathways of the water masses in the North Western Mediterranean joins perfectly in this logic. The objectives of this study, apart to determine the main pathways of the water masses in the North Western Mediterranean, is the installation of a Lagrangian diagnostic tool, Ariane, in the LOPB (`http://www.com.univ-mrs.fr/LOB/`), and the development of methods to interpret its results.

Chapter 2

The *Centre d'Océanologie de Marseille*

2.1 Generalities

The *Centre d'Océanologie de Marseille* (COM) is a research unit of the *Centre National de Recherche Scientifique* (CNRS) and the *Université de la Méditerranée* that has the status of an Observatory (OSU) of the *Institut des Sciences de l'Univers* (INSU) working about physical and biogeochemical oceanography. It is composed of three laboratories, each of them specialized in distinct domains. It includes of 215 persons, distributed between researchers, professors, engineers, PhD student, administrative personnels. It is financed by the Université de la Méditerranée, the CNRS, the IRD and others organization (e.g. Agence National de Recherche or Framework Programs of European Union) for specific projects. The COM is situated on two different sites, Endoume since 1879 and Luminy since 1968, but will take up new premises in 2012. The COM works in partnership with many laboratories in France and around the world, and takes part in national and international meetings. The missions of the COM are various, from fundamental research to teaching, as well as valorization, vulgarization and expertise for administrations units.

2.2 The laboratories of the COM : DIMAR, LMGEM and LOPB

2.2.1 The DIMAR laboratory : *DIversité, évolution et écologie fonctionnelle MARine*

The main objective of DIMAR is to study the mechanisms which create and preserve the biodiversity in the seas and oceans. For that they study biodiversity at different temporal and biological scales. The origins of the erosion of the biodiversity are also a domain of study. The ambitious project of the laboratory is to combine researchers in biology, genetic, ecology and phylogeography. The laboratory possesses abilities necessary to do research about relationships between biological diversity and dynamic of the marin ecosystems. A particular attention is given to invasions of external species since the Mediterranean sea is one of the most affected region in the world. Five teams compose the laboratory. Two of them work on evolution and dynamic of the marine diversity, at different spatio-temporal scales. One evaluates the modifications of the biodiversity due to invasions and climate changes. One works on the impacts of terrestrial contributions on benthic community in delta regions. The last team works on the protection and conservation for different regions. A complete list of the opening and past project can be find on the web page of the laboratory : `http://www.com.univ-mrs.fr/DIMAR/presentation_UMR.htm`.

2.2.2 the LMGEM : *Laboratoire de Microbiologie,Géochimie et Ecologie Marine*

The activities of the LMGEM are orientated on the recycling of organic materials in the coastal and open ocean, in the water column and in the sediment. The objectives are concentrated on the molecular biology and microbiology: 1) the characterization of the molecular components present as trace in the sea water. 2) the determination and characterization of cellular functions implied in the degradation processes. 3) the study of the oxydo-reduction potential. 4) the statisticalanalysis and mathematical modeling of the processes. The laboratory is organizedin thematic teams. A complete list of the opening and past project can be find on the web page of the laboratory :`http://www.com.univ-mrs.fr/LMGEM/presentation/index.php3`

2.2.3 The LOPB : *Laboratoire d'Océanographie Physique et Biogéochimique*

The LOPB is specialized in physical and biogeochemical oceanography. Its main region of study is the Mediterranean sea, but some people work on the oceans throughout the world (especially the Antarctic Ocean) and on different lagoons. The abilities in the laboratory are various, and extend from physical modeling and in situ measurements. The laboratory is organized in two thematic teams. The physical team, which works mainly about the coastal hydrodynamic, and particularly about the circulation in the Gulf of Lion and on the eddies with modeling and experimentation from buoys and boat campaigns. The aims of this team is to better understand the hydrodynamic in the interfaces : continent/coastal ecosystem, sediments/water column and boundaries between continental shelves/general circulation. The biogeochemical team works mainly on the transfers of food nutriments in the different parts of the Mediterranean sea and the impact of their on the biodiversity. Collaboration between the two teams can focus on the effect of hydrodynamic on the transfers. Moreover the modeling approach units working on the physical and biogeochemical coupling with the ECO3M model (Ecological Modular Mechanistic Model) which have been created in the laboratory.

The main recent projects of the laboratory are:

- SESAME (Southern European Seas : Assessing and Modelling Ecosystem changes): its goal is to evaluate and predict the changes for the ecosystems of the Mediterranean and Black seas and the changes in the capacity of these ecosystems to produce resources and services.

- BOUM (Biogeochemistry from the Oligotrophic to the Ultra oligotrophic Mediterranean): its goal is to dispose of a better representation of the interactions between the Planktonic organisms and the cycles of biogenic elements for scales from the processes to the entire Mediterranean sea.

- JEST (Joint Environmental Study of the Terminos Lagoon): its goal is to determine the impact of anthropic effect and sustain solutions for the management of the Terminos lagoon (Mexico).

- LATEX is further detailed in part 3.1 since it is the project in which this internship takes part. More can be found on the web page : `http://www.com.univ-mrs.fr/LOB/`

Chapter 3

Context of the study

3.1 The Lagrangian Transport EXperiment project (LATEX)

LATEX is an innovative project which aims to study the influence of coupled dynamics on heat and matter transfer between coastal zones and the open ocean, combining all analysis methods available : satellite data, numerical simulations with Eulerian and Lagrangian approaches, in situ experimentation and measurements with buoys and moorings. This 3-year (2008-10) project was initialized with the LATEX00 pilot project in 2007. The main objective is to determine the interactions between mesoscale eddies, present in the western Gulf of Lions and the Northern Current and their impacts on the evolution of conservative or biogeochemical tracer's distribution.

This project will concentrate on three points :
- to increase knowledge on mesoscale eddies in the western Gulf of Lions
- to couple physics and biogeochemistry in a Lagrangian approach
- to quantify the coast-offshore exchanges for the process studied during the Lagrangian survey and to compare them with the matter and energy fluxes obtained with numerical coupled physical and biogeochemical modeling.

All the bibliography can be find on the LATEX website : `http://www.com.univ-mrs.fr/~petrenko/latex.htm`.

3.2 Assessment of the knowledge for the North Western Mediterranean (NWM) and the Northern Current (NC)

The Northern Current holds its name from its position in the western basin of the Mediterranean sea. Its represents the northern branch of the main loop of circulation in the western basin. It flows from the east to the west following the bathymetry [Lopez-Garcia et al. 1994; Millot 1999]. In the Ligurian sea, the NC is the result of the convergence of the eastern and western branches of the Corsican Current (respectively ECC for Eastern Corsican Current and WCC for Western Corsican Current) [Astraldi et al. 1990]. Offshore from the GOL, the NC presents more variability, with intrusions in the GOL, but globally stays between the 200-meter and the 2000-meter isobaths in geostrophic equilibrium [Conan and Millot 1995]. South of the Ebro delta, the NC divides in two parts. The most important part follows the Spanish coast whereas the rest forms the Balearic Recirculation (BR) which flows north of the Balearic islands and constitute a second loop of circulation in the north-western Mediterranean sea [Pinot et al. 2002]. The NC is associated with a dome structure of isopycnes in the Ligurian sea and the GOL, and a front of density [Nyffeler et al. 1980; Crepon and Boukthir 1987; Alberola et al. 1995; Conan and Millot 1995]. According to seasons, the NC presents different attributes, wide (35-50 km), shallow ($<$ 250 m) with maximum speed around 30-50 cm/s from May to November while narrower (20-30 km), shallower (250-500 m) and with higher maximum speed (around 60-80 cm/s) from January to March [Castellon et al. 1990; Alberola et al. 1995; Conan and Millot 1995; Albérola and Millot 2003a; Petrenko 2003]. Its flow is high during the winter and weak during the summer with maximum and minimum respectively in July and November/December. The intensification of the NC during the winter seems to come from the intensification of the ECC at the beginning of the winter and of the WCC at the end of the winter [Astraldi et al. 1990]. At this season it is possible to measure flux around 1.5 and 2 Sv ($1Sv = 10^6 m^3/s$). During the summer the flux is smaller than precedently [Alberola et al. 1995], around or inferior to 1 Sv.

3.3 The Symphonie Eulerian code

Symphonie is an Eulerian tridimensional coastal model developed in the Laboratoire d'Aérologie de Toulouse, member of the Pôle d'Océanographie Côtière de l'Observatoire Midi-Pyrénées. This model is used in the LOPB in the frame of the LATEX project to simulate the north western Mediterranean from 2001 to 2008. The implementation of the model was made by Hu et al.[2009]. The domain is composed by a 3 km grid for all the north western Mediterranean, and includes a nested grid with a resolution of 1 km for the GOL. The grid has an inclination of 31°compared to the equatorial direction to adjust with the bathymetry. The reader is invited to refer to Fig. 4.1 in section 4.3 to see the domain. This model takes into account the hypotheses of Bousinesq incompressibility and hydrostatic equilibrium. Velocity field, temperature, salinity, density and water elevation are computed on an Arakawa C-grid [Arakawa 1972] with an hybridization of sigma and z coordinates. Several studies were based on Symphonie in realistic conditions for the North Western Mediterranean (NWM): the Rhône River plume [Marsaleix et al. 1998; Estournel et al. 2001; Reffray et al. 2004], the dense water formation on the continental shelf and its impact [Dufau-Julliand 2004], effects of storms [Ulses et al. 2008], the sedimentary transport [Ulses 2005], circulations due to the wind [Estournel et al. 2005; Petrenko et al. 2008], intrusions in the center of the GOL [Estournel et al. 2003], eastern intrusions in the GOL [Auclair et al. 2001; Petrenko et al. 2005] and eddies detection in the western part of the GOL [Hu et al. 2009]. This model is appropriate to the study of the NWM and gives robust and realistic simulations. Daily outputs from January 2001 to December 2003 are available in the database of the LOPB.

The discretization of the domain : 339 cells in the zonal direction, 115 cells in the meridional direction and 40 levels in the vertical direction for the parent grid. The main particularity of the Eulerian model Symphonie is the vertical discretization of the domain. Indeed it uses an hybridization of the sigma and z coordinates. The hybrid coordinate is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models.

A complete description of this model can be find in the web site of the model: `http://poc.obs-mip.fr`, as well as in Hu et al.[2009] and references therein.

Chapter 4

A Lagrangian diagnostic tool: Ariane

4.1 Introduction

The diagnostic tool for Lagrangian experimentation : Ariane has been developed in the Laboratoire de Physique des Océans (LPO) in Brest by Bruno Blanke and Nicolas Grima. This code is under the free license CeCILL (CNRS) and can be used by anyone with respect to the license. Since the earlier development in 1992 [Speich 1992] Ariane has been used for Lagrangian diagnostics about the mass transfer for global ocean [Blanke et al. 2001], but also to study the warm water path in the Equatorial Atlantic [Blanke and Raynaud 1999], to determine the flux of the Equatorial Under Current [Blanke and Arhan 1997], to determine the origin of the Sicilian Current and the formation of the Northern Current [Pizzigali et al. 2007]. It is a code which temporally integrates the velocity field to compute trajectories. The package contains the FORTRAN 95 code and Matlab tools for graphic outputs and calculation of the stream function. All the information about Ariane can be consulted on the website : `http://www.univ-brest.fr/lpo/ariane`.

It is the first time Ariane is used for operational diagnostics with Symphonie outputs. The implementation was made with several steps. A first installation of the diagnostic tool was made on a desktop computer to run test simulations. These test simulations are examples provided with Ariane and diagnostics made with Symphonie outputs. I did this work to learn to use and parametrize Ariane correctly. A comparison between my results and results provided with Ariane shows small differences due to the accuracy of the computer, but behaviors of particles are similar for all simulations. During this evaluation, some bugs appeared. One concerns the interpolation of temperature and salinity on the initial positions of particles in the option that uses only the closest temperature grid point. As it is more accurate to use the option that interpolates physical parameters from all the temperature grid points around the particle, this bug is not a problem. Another problem appears when outputs from Symphonie do not contain information about temperature and salinity. Indeed Ariane needs a 3D mask for land or water grid points, whereas Symphonie contain just a 2D mask. To compute a 3D mask from Symphonie outputs, Ariane computes this mask from temperature and salinity outputs. One solution to fix this problem is to built a complete 3D mask for Symphonie. Currently Ariane is operational on the new cluster of the LOPB, which contains 16 processors and a lot of memory. The use of the cluster is made with SGE and I developed some scripts was developed to launch simulations and transfer outputs.

4.2 Hypothesis and equations

A Lagrangian diagnostic tool is used to compute trajectories from an OGCM in integrating the 3 dimensional velocity field from an initial point in the grid of the OGCM. For that, the velocity field must be interpolated at each location of the particles during their trajectories. Ariane takes advantage of the C-grid used to discretize the Symphonie model to compute analytically trajectories from model outputs. The algorithm of Ariane is detailed in [Blanke and Arhan 1997] and compute true trajectories for a given velocity field through the exact computation of 3 dimensional streamlines.

The 3 components of the velocity field are known over the six faces of each cell. The non divergence of the velocity field ensures continuous trajectories within this cell. The divergence of the velocity field is expressed as

$$\triangle V = \frac{1}{b}[\partial_i(e_2e_3)U + \partial_j(e_1e_3)V + \partial_k(e_1e_2)W] \tag{4.1}$$

where $n = i, j, k$ refers to the grid index for the three axes; ∂_n refers to the corresponding finite difference; e_1, e_2 and e_3 are the scale factors computed at each velocity grid point; and b is the product $e_1e_2e_3$ computed at the center of the cell (temperature grid point).

For each cell of the grid, the non divergence of the flow can be written as :

$$\partial_i F + \partial_j G + \partial_k H = 0 \tag{4.2}$$

where F, G and H represent the transport in the 3 directions, with $F = e_2 e_3 U$, etc.

One solution to interpolate the 3 components of the transport in the cell with respect to the 3 dimensional non divergence of the flow is to pose that the transport vary linearly between 2 opposite faces (F depends linearly of i, etc.). i, j and k are considered as fractional within the cell with an extension from $i = 0$ to $i = 1$. One can write for F :

$$F(r) = F_0 + r \triangle F \tag{4.3}$$

with $r \in [0, 1]$ and $F(0) = F_0$, and where $\triangle F = F(1) - F(0)$. One can link position and velocity, $dx/dt = U$ for the transport:

$$\frac{dr}{ds} = F \tag{4.4}$$

where $s = (e_1 e_2 e_3)^{-1} t$ and $x = e_1 r$. With $r = 0$ for $s = 0$ and the combination of 4.3 and 4.4, we can find the time dependency of r within the cell :

$$r = \frac{F_0}{\triangle F}[exp(\triangle F s) - 1] \tag{4.5}$$

Similar relationships are obtained along both directions. The preceding equation applies only for a particular cell, and we need to determine the time when a given particle reach another cell (the time where r is equal to an exit value, $r = 1$). The time dependency is obtained from :

$$ds = \frac{dr}{F} \tag{4.6}$$

Using 4.3, we obtain the following equation :

$$ds = \frac{dF}{F \triangle F} \tag{4.7}$$

A crossing time can be obtained if $F(1)$ and $F(0)$ have the same sign, this implying $F \neq 0$. If this condition is not verified for F, the non divergence equation ensures that at least one direction satisfies it. If this condition is checked for the zonal direction, the pseudo time s is related to the transport F by :

$$\triangle s = \frac{1}{\triangle F} ln(\frac{F}{F_0}) \tag{4.8}$$

The crossing time corresponds to the moment when the transport reaches the exit face value, $F(1)$:

$$\triangle s = \frac{1}{\triangle F} ln(\frac{F_1}{F_0}) \tag{4.9}$$

Similar equations are obtained for other directions. The shorter crossing time defines the traveling time in the considered cell and the positions in the other directions are deduced from the equation of trajectories using $s = \triangle s$. After that, computation are done for the next cell, with a starting point equal to the exit point of the previous one. The age of the particle is the sum of the expressions obtained for $\triangle s$. This method ensures a constant transport along the trajectories and is both fast and accurate.

Ariane uses two different methods to allocate memory during simulations : sequential and non-sequential. The non-sequential mode stores in memory all the input data. In this case particles are integrated one by one during all the period of study until they go out the domain. The sequential mode reads sequentially one time step of the input data at a time and integrates all particles during this period, before reading the next time step.

Two temporal integrations are available, forward and backward integrations.

4.3 Qualitative and quantitative simulations

The diagnostic tool Ariane possesses two different modes, qualitative and quantitative. The qualitative mode uses individual particles to compute realistic trajectories. The quantitative mode uses thousands or more particles to compute the stream function and determine current transports. In each case, the objectives are different. The goal of this section is to describe qualitative and quantitative experimentations as well as corresponding technical characteristics. For this reason, the two following sections of this chapter can seem very technical during the first reading for people who have never used Ariane. For more details about the different steps of a simulation, the reader can refer to the tutorial and the manual "How to write an Ariane namelist file" on the Ariane's web page.

4.3.1 Qualitative experiment

The qualitative mode is used to determine trajectories in the domain during a given period. This mode is useful to simulate numerically the trajectory of individual Lagrangian drifters or buoys ([Pizzigali et al. 2007]). The maximum duration of the particle drift corresponds to the duration of stored data. Ariane computes 3D trajectories in using the three components of the velocity field. It is also possible to use only the horizontal velocity field to determine 2D trajectories. In the latter case, particles initialized at a given depth stay at this depth during the simulation.

To initialize the particles in the domain, Ariane uses five parameters, three spatial ones, a temporal one and a parameter which is read but not used in qualitative mode (it is present for consistency with the quantitative mode inputs). The spatial parameters are given in number of cell grid, i.e. we do not indicate longitude, latitude and depth but the corresponding cells grid. The grid of the model is the same as the one for the Eulerian diagnostic [Blanke and Arhan 1997]. To be sure that the Lagrangian simulation is robust, particles must not be initialized on the corner or faces of a temperature grid cell (it is also true for the qualitative experiment, but in this case the particles are initialized automatically). In fact the characteristics of the C grid and of the under mesh formulation imply that the velocity is imperfectly defined on the corners and faces of a grid cell. In these latter cases Ariane does not know which grid cell must be used. As a consequence, the index of grid cell used to initialize particles must not be an integer but a "non-integer", like 8.5 or 153.9 to indicate that the particles is positioned inside the temperature grid cell (but not at the corners of the grid cell). Hence positioning particles is accurate in zonal, meridional and vertical directions in shallow and deep water. For the time parameter, an integer value corresponds to the center of the period covered by the stored data. Thus, with a daily velocity field, a value of 5 for the time parameter corresponds to the 5^{th} day of the simulation at 12 hours. For example, it is possible to initialize the particle at 06:00 am of the 5^{th} day with an "non-integer" value : 5.25, like for the spatial position. Finally the last parameter can be chosen arbitrary as it is not used in qualitative mode.

To use the qualitative mode, it is also necessary to define three temporal parameters for the outputs. At first a time step (given in seconds) must be chosen. It represents the interval between two outputs. The second value corresponds to the frequency of the outputs. Its value depends on the interval chosen before. For example, with an interval of

86,400 seconds (one day), a frequency of 1 implies a daily output whereas a frequency of 30 implies a monthly output. Finally the maximum number of outputs for the simulation must be defined. The product of the three parameters gives the duration of the simulation.

The outputs of this mode give us physical and numerical information about particles used for the simulation. Particles are identified by an index given in the order of the initialization. This information allows us to follow any of the particles and study its parameters during its trajectory. Six values are saved as outputs: 1) three spatial indexes (given in longitude, latitude and depth), 2) one temporal value (corresponding to the particle age) and 3) three physical values (temperature, salinity and density).

4.3.2 Quantitative experiment

The quantitative mode is used to compute the stream function and the mass transport transfered by a vein of current, from the velocity field given by an OGCM [Blanke and Arhan 1997; Blanke and Raynaud 1999]. The stream function is computed on the horizontal plan of a non-divergent flow, diagnosed by the movement of particles each associated with a weight (volume of water in m^3). In this mode, particles are initialized on a section defined by longitude, latitude and depth limits and intercepted by the same section or other ones. The ensemble of sections must form a closed domain to ensure that a quantitative diagnostic is possible. Three different types of section are used : 1) one vertical section to initialize all the particles used during the experiment (which is always the first one defined) and also to intercept particles, 2) several vertical sections to intercept all the particles initialized, 3) a lid section (thus horizontal) covering the domain to intercept particles going out of the domain because of evaporation. To define these sections, it is necessary to indicate the grid cell limits in x, y and z directions. A section can be defined with several parts (joined or not). To define diagonal sections, it is enough to define it like stairs, with a sum of several small sections. The extension in each direction is limited by the grid. With the sequential mode, detailed simulations for the domain can be made in chaining partial simulations. When the sections are changed between two successive simulations, at least one must come from the preceding simulation, becoming the section for initialization in the following simulation.

Like for the qualitative experiment, the quantitative one only needs the 3D velocity field for the computation of trajectories. Temperature and salinity allow to study the thermohaline characteristics of particles reaching the different sections. For the density, two options are available : to use values present in the data or to compute them with temperature, salinity and the equation of state for sea water. As the calculation of the Lagrangian stream function only need the knowledge of the velocity fields, to use or not the physical data set have no influence about the stream function and the transport.

Two criteria must be defined for a correct quantitative simulation : 1) a spatial or/and physical criterion for their initialization which allows to limit the initialization of particles with spatial or physical parameters. (for example, it is possible to initialize particles if their temperature is higher than a certain level only, or the speed, or the depth etc.), 2) a temporal criterion which corresponds to the life expectancy of the particles. When a particle is initialized in the domain, it is advected during a duration depending on the speed of the current/recirculation. It signifies that each particle reaches a section independently of the others, i.e. two particles initialized at the same time, and very close one to the other, can reach the same section at different locations after different times and trajectories. Furthermore, a number of particles can be advected in the domain without reaching a section. These particles imply that it is not possible to compute the Lagrangian stream function because mass conservation is not respected and thus the transport field is 2D divergent. This situation is not possible for the non-sequential mode, but appears with the sequential mode. Hence the following explanation concerns only the sequential mode. Particles do not reach a section (hereafter lost) at the end of the simulation when they do not have enough time to be integrated all the way to a section. The time criterion allows to intercept the lost particles. If no lost particles are present in the simulation, the mass conservation is respected and the transport field is 2D non-divergent. Hence the computation of the Lagrangian stream function is possible. As the time criterion corresponds to the life expectancy of particles, all the particles initialized have the same temporal probability to reach a section. This time criterion must be chosen with consideration of the time of residence of the particles in the domain. If the time criterion is smaller than this time of residence, particles do not have enough time to reach the sections. But the time criterion is not sufficient by itself and must be used with other time parameters of Ariane : *lmin*, *lmax* and *lmt*. *lmin* and *lmax* represent respectively the first and the last time steps to initialize particles. *lmt* represents the total number of time steps of the simulation. To be sure that all the particles have the same life expectancy, their initialization must be stopped when the remaining time steps are not sufficient. For that, *lmax* must be equal to the *lmt* of the simulation minus the time criterion. For example, if the life expectancy of particles is 7 days and the simulation covers 20 days, particles can be initialized from the first day to the 13th but not after.

When a first run shows that some particles have been intercepted by the time criterion or the lid, a second run with the same parametrization and where these specific particles are deleted must be made to obtain a truly non-divergent transport field.

To determine the mean transport for each section, a simple method consists in running simulations for each section in forward and backward integrations as suggested by [Blanke and Arhan 1997]. Indeed there is a methodological error due to Lagrangian calculations realized with discrete particles. Combining the two modes of integration allows to average the results from each simulation and determine the error associated with the transport. Details of the methods are given in Appendix 4.1.

The outputs of the quantitative experiment contain the following information for each particle : spatial position, age, time steps for initialization and interception, physical properties and the volume of water. The volume of water for each particle is constant during the simulation. As these parameters are registered for initialization and interception, we can determine the origin and the destination of particles and make statistics. Outputs also give us information about the mean transport and the mean position of interception for each section and the global transport for the entire domain.

4.4 Ariane implementation for the North Western Mediterranean (NWM)

To use the quantitative analysis for the NWM, we must define the sections to initialize and intercept particles. On the basis of the knowledge of the NWM circulation and of the NC, we choose a configuration with 3 boundaries at the south-eastern limit of the domain. In fact, to avoid the sponge layer, 20 cells have been cut off in the y direction from the south-east boundary. For the starting section, we choose the region where the NC is formed. [Astraldi et al. 1990] show that the origin of the NC is the convergence of the WCC and ECC north of the Corsica. We cut this section in two parts (Corsica 1 & 2). Corsica 1 joins the Italian coast and the Corsican coast between 43°and 43.5°N. Corsica 2

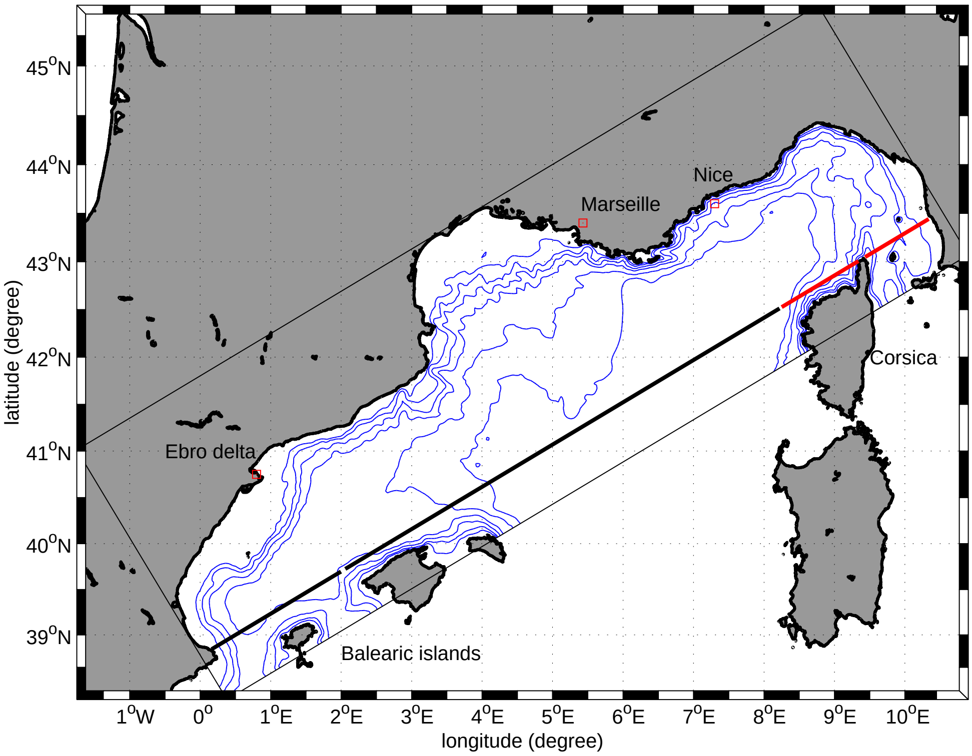

Figure 4.1: Domain used for the Lagrangian diagnostic. The red line represents the section on initialization for the upstream diagnostic. The black line represents the sections of interception for this diagnostic. The isobaths presented on this figure are : -100 -200 -500 -1000 -2000 and -2500 meter

joins the western Corsican coast and the 2500 meters isobath between 42.5°and 43°N. The 2500-meter isobath was chosen to make sure that the entire WCC flows in this section. The second section we define is the one between Spain and the Balearic islands. This choice corresponds to the main exit out of our domain for the Northern Current. Another portion of the NC takes part in the Balearic recirculation (BR) which flows northward of the Balearic islands. The last section joins the two preceding ones, thus between Corsica and the Balearic islands. The domain can be seen on Fig. 4.1

The time step and date of the simulation must be chosen because they determine the phenomena we can observe. Our simulation covers a period from the January 9, 2001 to the December 17, 2003. Thus we have a 1078 days Lagrangian diagnostic for the north-western Mediterranean. We choose a time criterion equal to 539 days. It signifies that a particle, after its initialization, have a life expectancy of 539 days. Although it is possible to specify a spatial or physical criterion to initialize particles, we choose not to use such a criterion for the moment. Nonetheless we must define a maximum value for the water volume which can be attributed to each particle. A large value does not permit to have an optimal accuracy, but gives a good time for calculation. A small value gives a better accuracy because more particles are initialized (thus statistics are better) but a very long time of calculation. To adjust this value, we make two simulations : one with a maximum value for the water volume for each particle equal to 10^8 m^3/s and one with 10^2 m^3/s. The comparison between the results of these tests shows that the difference for total transport between both simulation is smaller than 10^{-2} m^3/s. For both the mean position of initialization and interception, differences are smaller than 10^{-3} degree and 10 meters respectively for longitude/latitude and depth. Table 4.1 shows results for the Balearic Channel after a run in forward integration. The only significant difference is the time of calculation with our cluster, some hours for the first case and four days for the second. In sight of these results, we assume that a maximum transport for each particle of 10^8 m^3/s is the best choice for a good compromise between time of calculation and accuracy.

max trans.(m^3/s)/particle	trans.(Sv)	lon.(°)	lat.(°)	depth(m)
10^8	0.2521	1.009	39.253	-189.683
10^2	0.2499	1.009	39.253	-189.671

Table 4.1: Mean positions and transports for the Balearic channel after forward integration.

To have results as accurate as possible, we make upstream and downstream simulations, where the initialization is on the Corsican sections and on the Balearic channel respectively, both in forward and backward mode. Table 4.2 gives information about all the runs made for the diagnostic of the NWM. Finally, the reference dot for the stream function calculation is on land (6.5°E and 43.2°N), where the stream function is null.

runs	region of initialization	mode	integration	particles initialization	particles filtering
run_1	upstream	quantitative	forward	automatic	temporal criterion & lide
run_2	upstream	quantitative	backward	from run_1	temporal criterion & lid
run_3	upstream	quantitative	backward	from run_1	meanders & offshore
run_4	downstream	quantitative	backward	automatic	temporal criterion & lide
run_5	downstream	quantitative	forward	from run_4	temporal criterion & lid
run_6	downstream	quantitative	forward	from run_4	meanders & offshore
run_7	upstream	qualitative	forward	from run_1	temporal criterion & lid
run_8	upstream	qualitative	forward	from run_1	temporal criterion & lid

Table 4.2: list of runs made for the Lagrangian diagnostic of the NWM

Chapter 5

A Lagrangian diagnostic for the north-western Mediterranean, years 2001 to 2003

5.1 General results

In this section I will present results from the upstream and downstream quantitative simulations for the NWM. Fig. 5.1 shows the results of the stream function calculations. This figure brings to ligth the general circulation in the NW Mediterranean : 1) the NC, 2) the BR (Balearic Recirculation), 3) the LR (Ligurian Recirculation). For all the domain, values of the stream function are negative; it implies that the circulation occurs around the vertical axis counterclockwise from the north-east to the south-west.

Table 5.1 shows the repartition of the transport towards the different pathways of the

		Linking transport (Sv)		
sections of initialization	Time-averaged Eulerian transport (Sv)	Corsica 1 & 2	Balearic channel	offshore
Corsica 1 & 2	1.04	0.55	0.25	0.24
Balearic channel	1.3	0.28	0.55	0.47

Table 5.1: Transport computed for each section for upstream and downstream simulations

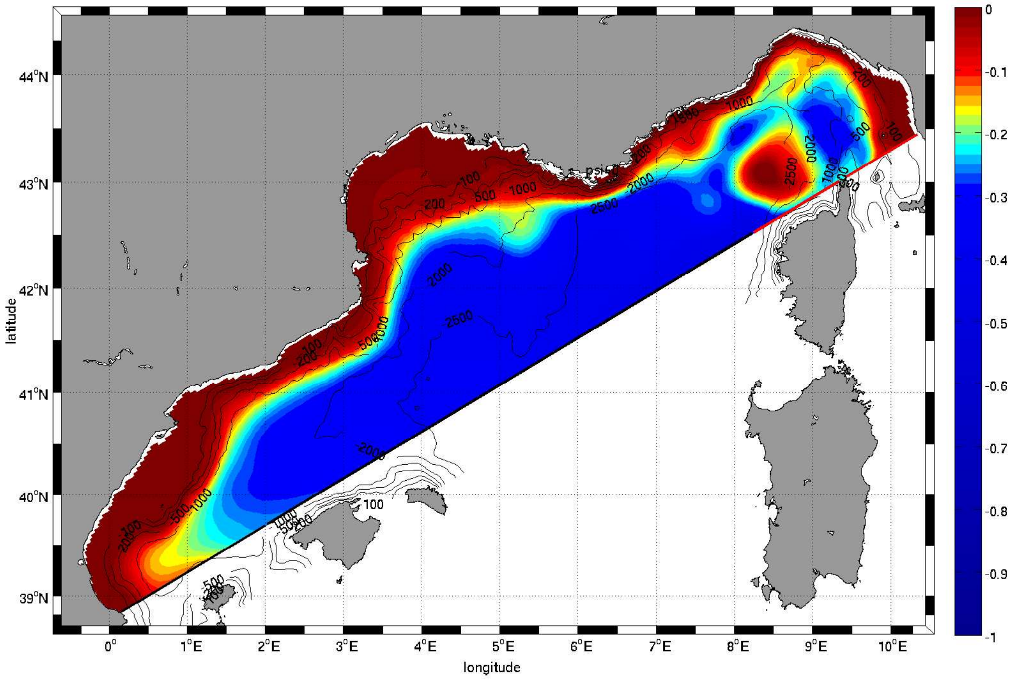

Figure 5.1: Stream function. The stream function presented on the figure come from run_1. The region with the higher gradient flowing along the coast represents the NC. Color are associated to the intensity of the stream function given in the colorbar. The reference dot for the stream function is positioned on the land.

NWM. Both total transports initialized either upstream on the Corsican sections or downstream in the Balearic Channel are on the order of a Sverdrup (1 Sv and 1.3 Sv respectively). We can observe that for both configuration of initialization, a majority of the initialized transport goes back through the section used for initialization. We can see that the transports for the pathway linking Corsica and the Balearic islands have the same order, around 0.25 Sv. Finally, 0.24 for the upstream case Sv and 0.47 Sv for the downstream case go out of the domain offshore. These results allows us to propose a quantification of the transport through the different pathways in the NWM.

5.2 Physical interpretation

5.2.1 The NC

Fig. 5.1 shows that the NC follows the bathymetry between the 200 m and 2500 m isobaths. It confirms the observation made by [Conan and Millot 1995]. The NC is present in the Ligurian sea, offshore of the GOL and along the continental shelf offshore of Spain. A bump can be observed offshore Nice, which corresponds to a submarine promontory well evidenced by the 2500-meter isobath in a region where the continental slope is otherwise regular. Offshore Marseille, two hypotheses could be proposed to explain an other bump : the bathymetric influence, but the 2500-meter isobath irregularity is upstream further to the west; and current instabilities probably due to a combination of the geostrophic equilibrium and the detachment of eddies at the entrance of the GOL [Echevin et al. 2003], but ,in this zone, eddies are more frequently observed inshore the NC [Allou, pers. communication]. In the western part of the GOL continental shelf, we can observe that the isoline 0.025 Sv of the stream function goes towards the north-east. Only a significant transport can explain this particularity. [Petrenko et al. 2008] emits the hypothesis that an eastward current can exist in the GOL, with a maximum speed of 25 cm/s, due to certain wind forcing during stratified conditions. This signature could be due to this eastward current, which could appear several times during the three years of our simulation. East of the Ebro delta, we observe a spreading of the NC, which divides in two parts : southward along the shoreline and eastward to form the BC northward of the Balearic islands ([Pinot et al. 2002]). A clear correlation can be observed between the streamlines and the spreading of the bathymetry.

	Transport for the pathway linking Corsican sections and the Balearic channel (in Sv)			
	forward	backward	mean	error
upstream	0.25	0.22	0.235	0.03
downstream	0.24	0.28	0.255	0.04
estimated transport (error)	0.25 ($\pm$0.07)			

Table 5.2: Transport for the pathway linking Corsican sections and the Balearic channel (in Sv). These values results from successive simulations with forward and backward integrations, as explain in appendix 4.1

The mean transport between the pathway linking the Corsican sections 1 & 2 and the Balearic channel via the NC computed from upstream and downstream simulation is equal to 0.25 $\pm$0.07 Sv (Table 5.2. Values computed for upstream and downstream simulation can be seen on table 5.2. This transport is smaller than the transport estimated by [Alberola et al. 1995] which is close to 1 Sv in the winter and close to 0.5 Sv for the summer. Fig. 5.1 clearly shows that, will our present calculations, transport can only diminish from upstream to downstream. Hence the values obtained for the linkage between the Corsican sections and the Balearic section is obviously smaller than values obtained during occasional cruises at specific locations. The origin of the NC is situated north of Corsica at a longitude of 9.2°E with a standard deviation of 0.7°, a latitude of 42.9 °N (with no standard deviation since the initialization is done on the chosen Corsican sections) and a depth of 160 m with a standard deviation of 200 m. In the BC, the mean position of interception of particles is at a longitude of 1.1°E with a standard deviation of 0.5°, a latitude of 39.3 °N and at a depth of 190 m with a standard deviation of 160 m (Fig. 5.2). In agreement with measurement made by [Castellon et al. 1990; Alberola et al. 1995; Conan and Millot 1995; Albérola and Millot 2003b], we confirm that the NC is a surface current, present between the surface and a depth of 500 m. Fig. 5.3 gives the repartition of the age of the particles which reach the BC. The mean duration of the travel is 75 $\pm$25 days. The incertitude associated to the mean duration is equal to 25 days. The maximum duration is equal to the time criterion. It possible that ,without this criterion, the maximum duration for the trajectories between CC and BC be longer. Fig. 5.3 presents a Rayleigh distribution, with a median value of 66 days. As this value is smaller than the average, we conclude that although less particles reach the BC after 76 days, they can reach the BC after a very long time, which increases the average for the age of particles. The choice of the time criterion seems to be adapted because we see on Fig. 5.3 that we have an entire Rayleigh distribution for the age, without having cut the extreme part of the distribution.

5.2.2 The Ligurian Recirculation

On Fig. 5.1 we can see a strong recirculation, situated north of the western coast of Corsica (8.3°E and 43.1°N for the center). We named it Ligurian Recirculation (hereinafter LR). This recirculation is cyclonic because it presents negative values of the stream function. The LR presents a diameter equal to 50 km for its larger dimension and is positioned west of the 2000 m isobath. We can see an asymmetry between the western and eastern sides of the LR : west the isotachs are tight whereas east they are spread. We have thus a western edge intensification, with a gradient of the stream function approximately twice that the one of the eastern edge, and thus a more important speed. As no section cuts this recirculation, it is difficult to determine the origin of the particles which contribute to its signature for the stream function, but we can make some hypothesis. The first constatation is that we do not know the depth of this recirculation and thus we cannot determine if particles come from the WCC or not. The statistics for the particles which reach the Corsican section could provide us some information. Indeed, half of the particles initialized go back through the Corsican section. As the LR is really close to the western edge of this section, it is possible that they come from the LR. This hypothesis is confirmed by initial and final positions of particles which reach the Corsican sections on Fig. 5.2. The fact that the mean duration for the travel is 23 days can be in correlation with a speed of the order of cm/s (an evaluation with a mean radius of 30 km and a travel duration of 23 days also gives a speed of the order of cm/s too). Particles reaching the Corsican section will be associated with the LR for a majority of them. We can suppose that the depth given by the statistics is approximately the depth of the LR. Statistics give a mean depth of 650 m for the initialization and 600 m for the interception, with standard deviation of 630 m and 530 m respectively (Fig. 5.2). The LR concerns the totality of the water column, from the surface to 1100 m depth. The transport associated to the Corsican section is 0.55 Sv. We can expect that a large part of the 0.55 Sv can be attributed to the LR. All these observations do not allow to determine

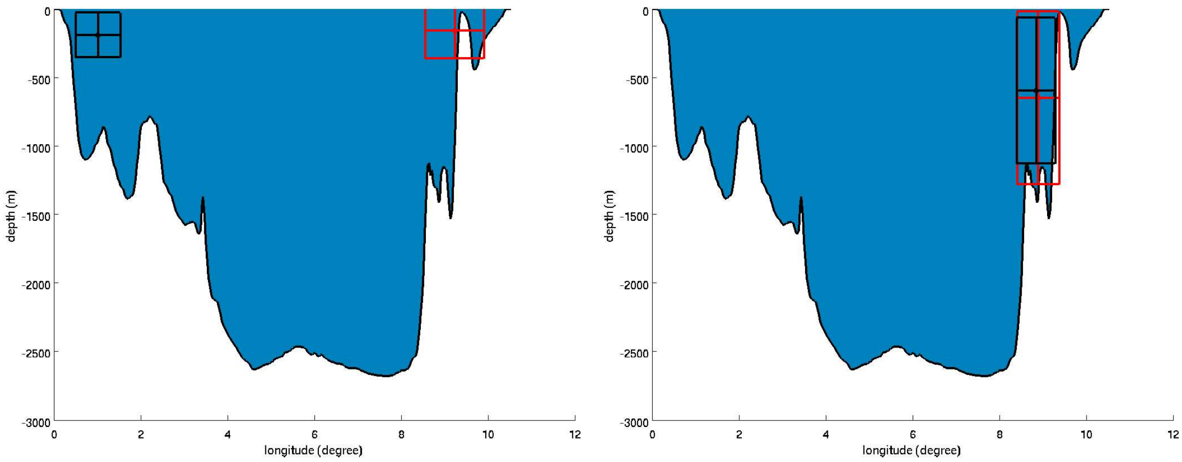

Figure 5.2: Mean initial and final positions of particles : on the right for the Balearic channel and on the left for the Corsican sections. The red rectangles represent the initial positions for particles and the black one the position of interception. The center of the rectangles represent the mean positions and the extension of the rectangles the standard deviation for longitude and depth.

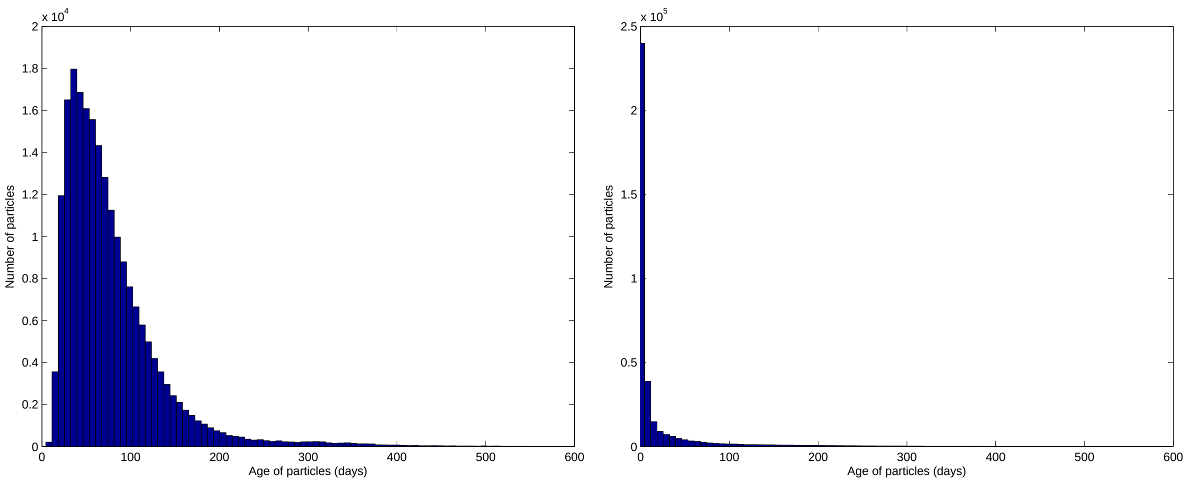

Figure 5.3: On the right the histogram presents age for particles reaching the Balearic channel and on the left it presents the age of particles reaching the Corsican sections. The histograms present the repartition of the particles age when they are intercepted. Each bar represents the number of particles intercepted during a 7-days period.

the origin of this LR. It can be one of these situations : 1) a recirculation presents during the three years with a medium transport ($\simeq$ 0.55Sv), 2) a recirculation with a short life expectancy, but an important transport (higher than 0.55 Sv), 3) successive short-lived recirculations summed up in the same region. The origins of this recirculation (LR) is investigated with Ariane qualitative tests.

5.3 Qualitative analysis of the main pathways

To visualize the main pathways determined with the quantitative diagnostic, we realize a qualitative diagnostic. This qualitative diagnostic uses one percent of the particles initialized during the run_1 experiment. Particles used for the qualitative diagnostic are chosen randomly, with an uniform distribution of the index of particles. This method of selection ensures that no discrimination is made for the spatial and temporal initialization of particles. Thus we initialize 7322 particles during 18 months on the Corsican sections. The visualization of trajectories for each particle allows us to determine 4 cases compare to the 3 described before: 1) the NC, 2) the BR, 3) the LR west, 4) the LR east. Between the Corsican sections and the Balearic channel, 2 pathways can be distinguished for all the duration of the diagnostic : 1) the part of the NC with flows southward along the Spanish coast, 2) the part of the NC which flows north of the Balearic islands to form the BR (Fig. 5.4). The 2 other pathways (3 & 4) are present in the Ligurian sea, and contribute to the LR. Contrary to the observation made in section 3.2.2, particles which flow in the LR do not only come from the WCC. The qualitative diagnostic shows us that particles in the LR come from both WCC and ECC in 2 distinct pathways. The particles coming from the ECC flow along the Italian coast and go southward offshore from Nice to the LR, whereas the particles coming from the WCC go northward directly to the LR (Fig. 5.4). These pathways can be observed during all the duration of the diagnostic, and support the hypothesis of a constant recirculation, present during the 3 years of our diagnostic, rather than successive recirculations in the same region. For both pathways, after various time, most particles in the LR exit this recirculation and go north-westward to the NC, whereas just a few of them go southward along the western Corsican coast. If we compare the trajectories with the position of the Corsica 2 section, we can observe that most of them cut the section. These particles represent the particles intercepted as "meanders" in the quantitative diagnostic run_1. It supports the hypothesis than the majority of the 0.55

Sv flowing through the Corsican sections come from the LR. However, as the majority of particles join the NC after having circulated in the LR, we can suppose that we probably under-estimate the transport between the Corsican sections and the Balearic channel. As we need to take in account the sponge layer in our quantitative diagnostics, we cannot modify the position of the sections. Only a numerical domain further extended to the south could allow us to correct this under-estimation.

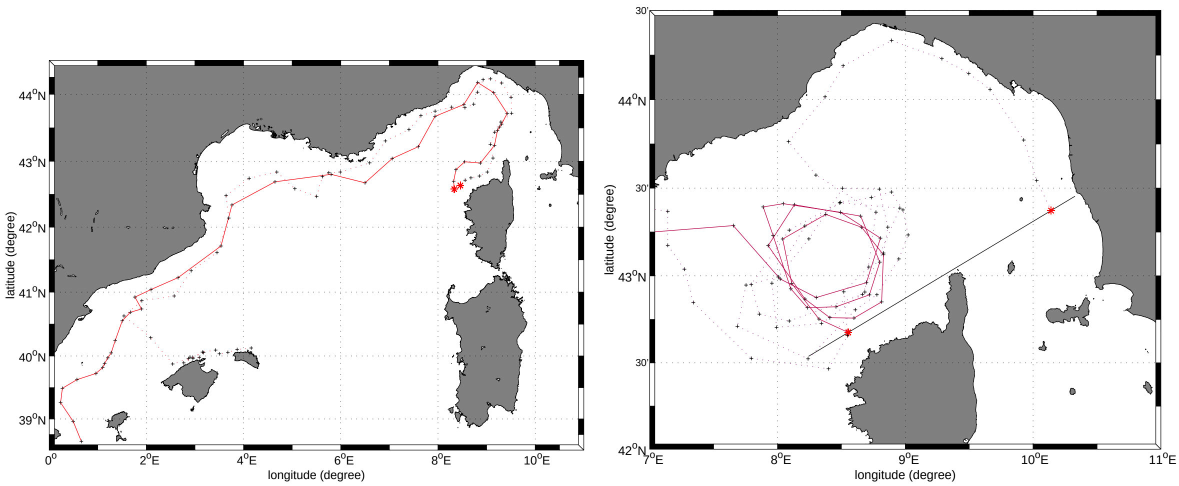

Figure 5.4: Main pathways of the NWM : on the right pathways 1) and 2) for the NC (continuous line) and the Balearic recirculation (dashed line), on the left pathways 3) and 4) for particles reaching the LR from WCC (continuous line) and ECC (dashed line). The red trajectory for pathways 1) and 2) signify that particles travel at the beginning of the 3 years of our diagnostic. The purple and blue color for the pathways 3) and 4) signify that particles travel during the middle and final time of our simulation. The red crosses represent the initial positions of particles. The black crosses show particles positions with a time step of one day.

5.4 Characterization of the Ligurian Recirculation

After the general observations made with the first diagnostic and observation of the LR, additional diagnostics were made to complement our understanding of the LR. The objectives of these diagnostics are to evaluate which of the ECC, the WCC or both, contribute to the LR, its variability, its position in the water column and its physical properties and vorticity. On Fig. 5.5 (page 34) we can see the stream function for particles initialized in the western and eastern Corsican sections of the Cap Corse respectively. These stream functions show that for years 2001 to 2003, the ECC do not contribute to the LR because we do not see isolines corresponding to the LR. For the WCC, we can observe the LR northward Corsica. The fact that only the WCC contributes to the LR allow us to analyse easily its properties because particles come from the same region. Fig. 5.6 (page 35) shows the stream function for different depth with an initialization on th west of Corsica. We can see that for the four depth-dependent sections chosen (0-200m, 200-500m, 500-1000m and 1000-2500m) an anticyclonic circulation is present at the same longitude and latitude. The conclusion is that the LR is present involving particles throughout the water column. The difference in the intensity we can see for the four figures comes from the fact that it represents the stream function for sections with different extensions in depth, and hence sections through different fluxes. Fig. 5.7 (page 36) shows the stream function for years 2001, 2002 and 2003. For these diagnostics, the initialization of the particles is made during the first six months of each year and the life expectancy for particles is half a year (170 days). We can observe a great variability of the circulation northward of Corsica. In 2001, a cyclonic circulation is observed on the north-east of the position expected for the LR. The LR does not exists in 2001. In 2002, we can see an anticyclonic circulation northwest of Corsica, but smaller and with a more specific shape than for the three years diagnostic. However, its position corresponds to the LR, hence we conclude that we observe the LR in year 2002. The shape of this circulation, compared with Fig. 5.6 allows us to conclude that it concerns all the water column. In 2003, a strong cyclonic circulation can be seen where the LR is expected. Compared with the circulation in 2002, the circulation is bigger and has a circular form and it turns in an opposite direction. As no more diagnostics could be made, we cannot know if this cyclonic circulation concerns all the water column or not. It appears through these results from years 2001 to 2003 that the circulation northwest of Corsica is extremely variable, as well in its position, more or less close to Corsica, as in its direction, cyclonic or anticyclonic. A first hypothesis to explain this variability is the physical properties of sea water in the Ligurian sea during each year. However it appears that between 2002 and 2003, temperature and salinity for particles contributing to the circulation have the same properties (13.42-13.49 °C and 38.29-38.35 psu in average for initialization and interception). But as we cannot know the temperature evolution during particles circulation, but only for initialization and interception, it is possible that the variations of these characteristics for years 2002 and 2003 are different and induce this variability. A more detailed diagnostic with Eulerian results from Symphonie and other Lagrangian diagnostics may answer this question in the future. An other difference between 2002 and 2003 is the transport which can be associated to the respective circulations. In 2002, a major part of the 0.53 Sv intercepted by the western Corsican section can be associated to the LR, whereas in 2003, it is the major part of 0.28 Sv which can be associated to it. We have thus a very important variability. As the physical properties do not explain the appearance of the LR, we have to make some hypothesis to explain it. The different figures in this section show that the LR is canalized by the bathymetry, like for the NC, and its position and shape can be explained with this observation. Indeed the LR cannot be more to the east because it cannot pass the continental shelf. That is why, in 2001, 2002 or 2003, the circulation is always along the continental slope. For the cyclonic or anticyclonic circulations, we can built two schemes which need to be evaluated. For the cyclonic circulation, we can suppose that water masses throughout the water column are carried to the north by the ECC in the east and by the WCC in the south. The result is a cyclonic circulation in the Ligurian Sea, which is constrained by the NC. For the anticyclonic circulation, we can suppose that it appears closer to Corsica, and thus that such circulation is not constrained by the NC, but by other circulation. During some periods in the years, a part of the ECC flows north along the eastern Corsican coast, goes around Cap Corse and flows southward along the western side of northern Corsica. When this happens, the WCC flows always north-eastward of Corsica. During such periods, an anticyclonic circulation can appear between these currents northest of Corsica. However, such a scenario seems limited to explain the important flux computed for the anticyclonic circulation in 2002. The last supposition we made is that the anticyclonic circulation found with the stream function is the result of a sum of several small cyclonic circulations, like for corotary eddies.

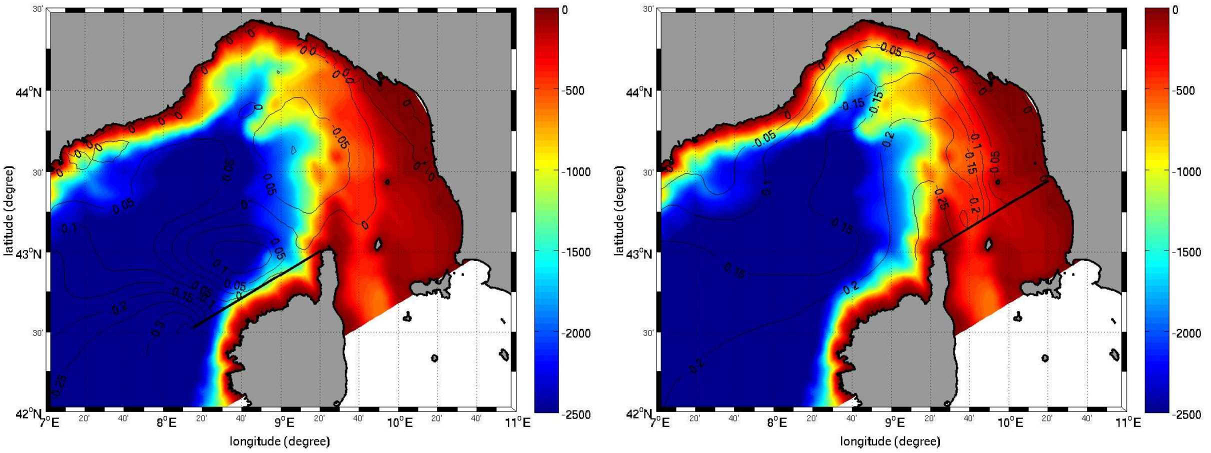

Figure 5.5: Stream function computed from section Corsica 1 (top) & 2 (bottom). Black lines represent the isolines (values ?indicated on the plot) of the stream function. The colorbar represents the bathymetry.

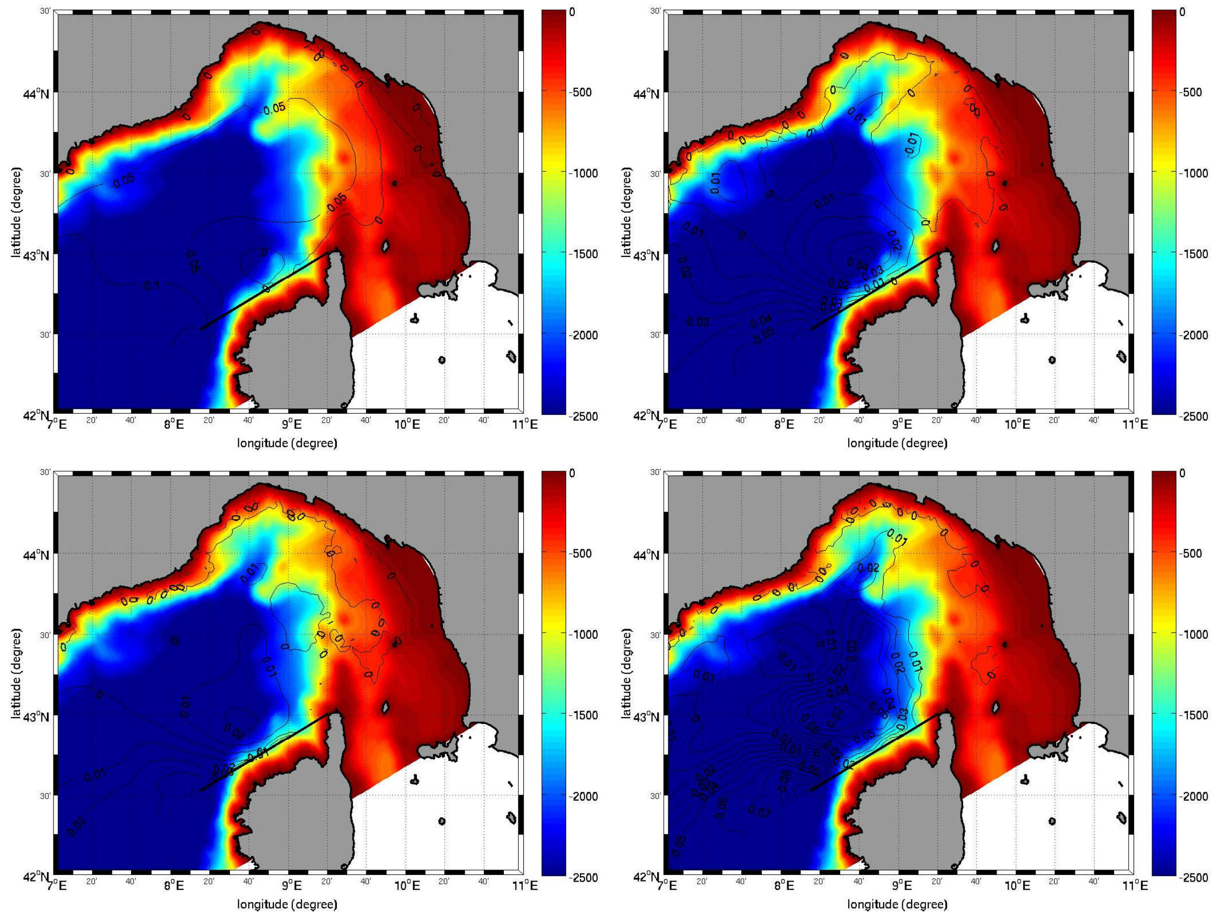

Figure 5.6: Stream function computed from section Corsica 1 (west of Corsica). On top-left the streamfunction for depth between 0 and 200m. On top-right the streamfunction for depth between 200 and 500m. On bottom-left the streamfunction for depth between 500 and 1000m. On bottom-right the streamfunction for depth between 1000 and 2500m. Black lines represent the isolines of the stream function. The colorbar represents the bathymetry.

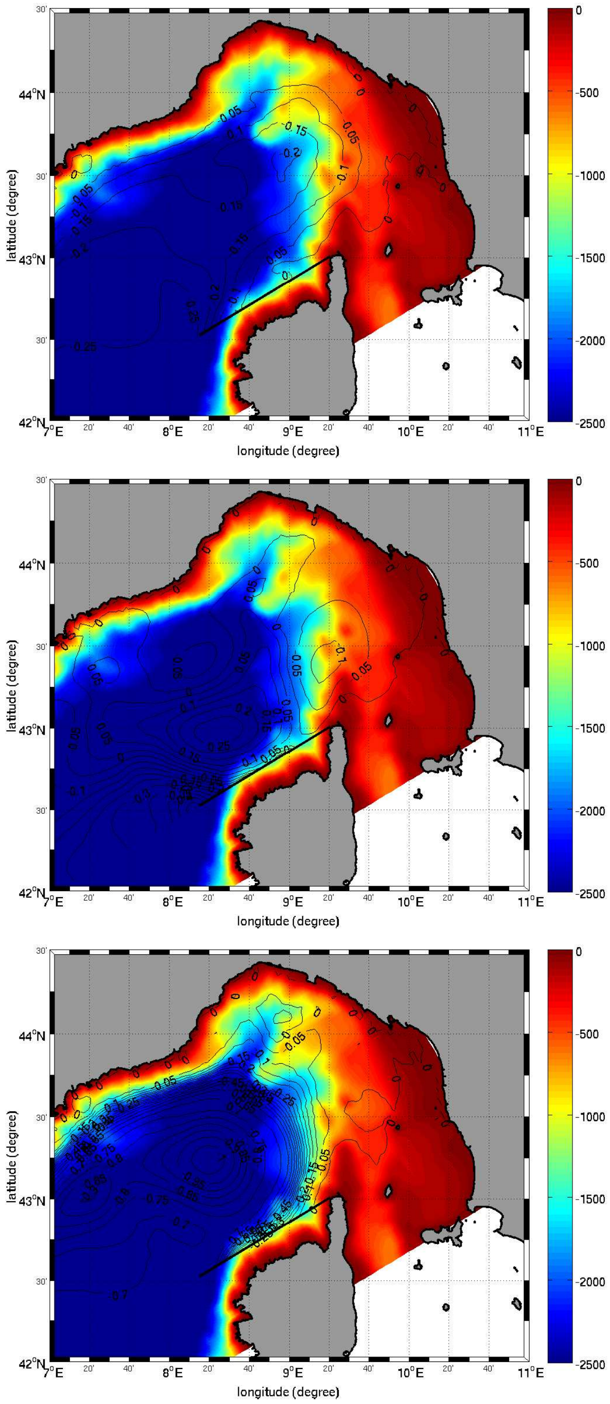

Figure 5.7: Stream function computed from section Corsica 1 (west of Corsica) for each year 2001 to 2003. Figure on the top is year 2001, figure on the middle is 2002 and figure on the bottom is 2003. Black line represents the isolines of the stream function. The colorbar represents the bathymetry.

Chapter 6

Conclusion and perspectives

The first Lagrangian diagnostic made with Ariane allowed us to bring to light the regional circulation in the NWM. We were able to show clearly the influence of the bathymetry on the circulation of the NC and its division in two branches north of the Balearic islands and the presence of a strong recirculation in the Ligurian sea, due to water from WCC. This circulation in the Ligurian sea has a great variability in its characteristics. A first estimation of the global transport between the different parts of the NWM allowed us to show the main destination of the water coming from the WCC and the ECC, and to evaluate the transport for the pathway linking Corsica and the Balearic channel. However we could not determine the origin and the destination of the different water masses because we did not use information about temperature and salinity in our diagnostic.
Ariane is currently totally operational at the LOPB. The diagnostic for the NWM allowed us to develop adapted methods for Lagrangian diagnostics and tools to use Ariane at its best and to analyze its outputs.
This preliminary study opens several axes of reflexion for the following months :
- Lagrangian diagnostics for the different water masses, to determine their destination and physical evolution,
- Lagrangian diagnostic for the GOL, to quantify potential intrusions of the NC and evaluate the circulation in the GOL,
In a longer term, perspectives are Lagrangian diagnostics for longer periods, and analysis of the inter-annual variability of the different circulations.

Chapter 7

Appendix

Determination of the error of the Eulerian transport

The error associated with the evaluation of the Eulerian transport can be evaluated estimating the volumes, and hence variability or "transfer" of volumes between simulations. A transfer of volume can be determined from two simulations, one with a forward integration and one with a backward one. This difference in the volume of water tranfered during simulations, which cover the same period, gives a difference in term of transport by the current. The following part of this section gives the methodology to determine the transport and the associated error in non-sequential and sequential modes. For the non-sequential mode, we can define two sections : A and B, run a forward integration from A and determine the transport in B; run a backward integration from B and determine the transport in A. After, we can compare the transport values and calculate their mean and standard deviation. The difference must converge to 0 when the number of particles increase. For the sequential mode, the approach is similar but it is necessary to isolate the transport we want to compare. In this case, particles are not integrated with all the time steps [*1,lmt*] but with the fraction [*lmin,lmax*]. For the forward integration, where particles are integrated from section A, *lmin* must be equal to 1 and *lmax* inferior to *lmt*. Then the time of integration is limited by *lmt-lmax*. Particles are integrated on section A. For the backward integration, where particles are integrated from section B, *lmt* must be equal to *1+lmt-lmax* and *lmax* must be equal to *lmt*. It is the difference of transport between section A (between the time steps *1* and *lmax*) and section B (between the time steps *1+lmt-lmax* and *lmt*), which gives the error of the method. As not all particles in the forward integration reach section B after the time step *1+lmt-lmax*, the ones not reaching B must be filtered to ensure the correspondence between forward and backward integrations.

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