INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team MOÏSE

Modelling, Observations, Identification for Environmental Sciences

Grenoble - Rhône-Alpes

THEME NUM

Activity Report

2007

Table of contents

1. Team

The MOISE project-team is a joint project between CNRS, UJF (Université Joseph Fourier, Grenoble 1), INPG (Institut National Polytechnique de Grenoble) and INRIA Rhône-Alpes. This project is located in the LJK laboratory.

Team Leader
Éric Blayo [Professor UJF, HdR]

Administrative assistant
Imma Presseguer [Assistant INRIA]

Research scientists
Didier Bresch [Research Director (DR) CNRS, University of Savoie, HdR]
Laurent Debreu [Research Associate (CR) INRIA]
Eugène Kazantsev [Research Associate (CR) INRIA]
François-Xavier Le Dimet [Professor UJF, détachement INRIA, HdR]
Antoine Rousseau [Research Associate (CR) INRIA]
Pierre Saramito [Research Associate (CR) CNRS, HdR]
Arthur Vidard [Research Associate (CR) INRIA]

Faculty members
Didier Auroux [Associate Professor IUT Toulouse]
Christine Kazantsev [Associate Professor UJF]
Jérôme Monnier [Associate Professor INPG, HdR]
Maëlle Nodet [Associate Professor UJF]

Post-doctoral fellows
Monika Krysta [CNRS fellowship]
Elise Nourtier-Mazauric [ANR contract]
Céline Robert [MERSEA European project]
Olivier Titaud [ANR contract, as of 01/02/2007]

Technical staff
Thomas Duhaut [Private Contract, as of 01/03/2007]
Marc Honnorat [Private Contract, as of 01/03/2007]
Joël Marin [Engineer Associate]

PhD students
Ibrahim Cheddadi [MESR fellowship]
Aymen Laadhari [BDI CNRS, as of 01/10/2007]
Florian Lemarié [MESR fellowship]
Bénédicte Lemieux-Dudon [LGGE Grenoble, ANR Contract]
Carine Lucas [MESR fellowship]
Thierry Mastrosimone [MESR fellowship, as of 01/10/2007]
Emilie Neveu [Regional Grant, as of 01/10/2007]
Ehouarn Simon [DGA fellowship]
Innocent Souopgui [SARIMA fellowship, codirection with University of Yaoundé, Cameroun]
Ange Toulougoussou [Regional Grant]

Interns
Amélie Martinez [6 months]
Alexandre Boilley [5 months]
Romain Biron [4 months]
David Cherel [2 months]

Visiting scientists
Genady Korotaev [Ukrainian Academy of Sciences]

Victor Shutyaev [Russian Academy of Sciences]

External collaborators

Laurence Viry [Research Engineer UJF]
Bernard Barnier [Research Director (DR) CNRS, LEGI, HdR]
Jacques Blum [Professor University of Nice, HdR]
Frédéric Parrenin [Researcher Associate (CR) CNRS, LGGE]
Jacques Verron [Research Director (DR) CNRS, LEGI, HdR]

2. Overall Objectives

2.1. Overall Objectives

MOÏSE is a research project in applied mathematics and scientific computing, focusing on the development of **mathematical and numerical methods for direct and inverse modelling in environmental applications** (mainly geophysical fluids). The scientific backdrop of this project is the **design of complex forecasting systems**, our overall applicative aim being to contribute to the improvement of such systems, especially those related to natural hazards: climate change, regional forecasting systems for the ocean and atmosphere, decision tools for floods, snow avalanches, mud or lava flows...

A number of specific features are shared by these different applications: interaction of different scales, multi-component aspects, necessity of combining heterogeneous sources of information (models, measurements, images), uniqueness of each event. The development of efficient methods therefore requires to take these features into account, a goal which covers several aspects, namely:

- Mathematical and numerical modelling
- Data assimilation (deterministic and stochastic approaches)
- Quantification of forecast uncertainties

Pluridisciplinarity is a key aspect of the project. The part of our work more related to applications is therefore being conducted in close collaboration with specialists from the different fields involved (geophysicists, etc).

3. Scientific Foundations

3.1. Introduction

Geophysical flows generally have a number of particularities that make it more difficult to model them and that justify the development of specifically adapted mathematical and numerical methods:

- Geophysical flows are non-linear. There is often a strong interaction between the different scales of the flows, and small-scale effects (smaller than mesh size) have to be modeled in the equations.
- Every geophysical episode is unique: a field experiment cannot be reproduced. Therefore the validation of a model has to be carried out in several different situations, and the role of the data in this process is crucial.
- Geophysical fluids are non closed systems, i.e. there is always interactions between the different components of the environment (atmosphere, ocean, continental water,etc.). Boundary terms are thus of prime importance.
- Geophysical flows are often modeled with the goal of providing forecasts. This has several consequences, like the usefulness of providing corresponding error bars or the importance of designing efficient numerical algorithms to perform computations in a limited time.

Given these particularities, the overall objectives of the MOÏSE project described earlier will be addressed mainly by using the mathematical tools presented in the following.

3.2. Numerical Modelling

Models allow a global view of the dynamics, consistent in time and space on a wide spectrum of scales. They are based on fluid mechanics equations and are very complex since they deal with the irregular shape of domains, and include a number of specific parameterizations (for example, to account for small-scale turbulence, boundary layers, or rheological effects). Another fundamental aspect of geophysical flows is the importance of non-linearities, i.e. the strong interactions between spatial and temporal scales, and the associated cascade of energy, which of course makes their modelling more complicated.

Since the behaviour of a geophysical fluid generally depends on its interactions with others (e.g. interactions between ocean, continental water, atmosphere and ice for climate modelling), building a forecasting system often requires **coupling different models**. Several kinds of problems can be encountered, since the models to be coupled may differ in numerous respects: time and space resolution, physics, dimensions. Depending on the problem, different types of methods can be used, which are mainly based on open and absorbing boundary conditions, multi-grid theory, domain decomposition methods, and optimal control methods.

3.3. Data Assimilation and Inverse Methods

Despite their permanent improvement, models are always characterized by an imperfect physics and some poorly known parameters (e.g. initial and boundary conditions). This is why it is important to also have **observations** of natural systems. Such observations are now increasingly numerous due, in particular, to satellite techniques. However, their accuracy is not always satisfactory, and the processing of such a quantity of data can be difficult. Moreover, observations provide only a partial view of reality, localized in time and space, and sometimes only very indirectly.

Since models and observations taken separately do not allow for a deterministic reconstruction of real geophysical flows, it is necessary to use these heterogeneous but complementary sources of information simultaneously, by using **data assimilation methods**. These tools for **inverse modelling** are based on the mathematical theories of optimal control and stochastic filtering. Their aim is to identify system parameters which are poorly known in order to correct, in an optimal manner, the model trajectory, bringing it closer to the available observations.

Variational methods are based on the minimization of a function measuring the discrepancy between a model solution and observations, using optimal control techniques for this purpose. The model inputs are then used as control variables. The Euler Lagrange condition for optimality is satisfied by the solution of the "Optimality System" (OS) that contains the adjoint model obtained by derivation and transposition of the direct model. It is important to point out that this OS contains all the available information: model, data and statistics. The OS can therefore be considered as a generalized model. The adjoint model is a very powerful tool which can also be used for other applications, such as sensitivity studies, identification, etc.

Stochastic filtering is the basic tool in the sequential approach to the problem of data assimilation into numerical models, especially in meteorology and oceanography. This approach, of a stochastic nature, is justified by the fact that the dynamical system is chaotic and thus behaves similarly to a stochastic system. Moreover, the (unknown) initial state of the system can be conveniently modeled by a random vector, and the error of the dynamical model can be taken into account by introducing a random noise term. The goal of filtering is to obtain a good approximation of the conditional expectation of the system state (and of its error covariance matrix) given the observed data. These data appear as the realizations of a random process related to the system state and contaminated by an observation noise.

The development of data assimilation methods in the context of geophysical fluids, however, is difficult for several reasons:

- the models are often strongly non-linear, whereas the theories result in optimal solutions only in the context of linear systems;

- the model error statistics are generally poorly known;
- the size of the model state variable is often quite large, which requires dealing with huge covariance matrices and working with very large control spaces;
- data assimilation methods generally increase the computational costs of the models by one or two orders of magnitude.

Such methods are now used operationally (after 15 years of research) in the main meteorological centers, but tremendous development is still needed to improve the quality of the identification, to reduce their cost, and to make them available for other types of applications.

3.4. Images in prediction models

Satellite images represent a large amount of data which are currently underused in numerical forecast systems. In particular, precursors of extreme meteorological events (like thunderstorms, fog, snow and frost, tidal waves, etc.) for which an early forecast is required are visible on these images. These data become of primary importance to improve the forecast quality.

Current data assimilation tools use three kinds of information:

1. Information of mathematical nature, provided by physical conservation laws. This generally corresponds to a complex set of non linear Partial Differential Equations
2. Information of physical nature, provided by in situ and remote measurements.
3. Information of statistical nature, based on a-priori knowledge of the dynamical system.

However, and despite their huge informative potential, images, including their dynamics, are only used in a qualitative way by forecasters, mainly because of the lack of an appropriate methodological framework. In order to extend data assimilation techniques to image data we need to be able to:

- identify and extract from images dynamics the relevant informations (for instance structures) about the model state variables evolution;
- link images dynamics with the underlying physical evolution processes;
- define functional spaces for images which have good topological properties;
- build observation operators which permit to map the model state variables space onto the aforementioned image space.

Integrating images in the data assimilation schemes further reinforces the heterogeneous and distributed nature of the information.

The use of images dynamics in numerical forecast systems is not restricted to meteorological applications: other scientific disciplines like hydrology (spatial observation of the main river bed during a flood), glaciology (radar exploration of polar ices, ice cover), medicine, etc. are interested in the development of such techniques.

3.5. Sensitivity Analysis - Quantification of Uncertainties

Due to the strong non-linearity of geophysical systems and to their chaotic behaviour, the dependence of their solutions on external parameters is very complex. Understanding the relationship between model parameters and model solutions is a prerequisite to design better models as well as better parameter identification. Moreover, given the present strong development of forecast systems in geophysics, the ability to provide an estimate of the uncertainty of the forecast is of course a major issue. However, the systems under consideration are very complex, and providing such an estimation is very challenging. Several mathematical approaches are possible to address these issues, using either variational or stochastic tools.

Variational approach In the variational framework, the sensitivity is the gradient of a response function with respect to the parameters or the inputs of the model. The adjoint techniques can therefore be used for such a purpose. If sensitivity is sought in the context of a forecasting system assimilating observations, the optimality system must be derived. This leads to the study of second-order properties: spectrum and eigenvectors of the Hessian are important information on system behaviour.

Global stochastic approach Unlike the variational approach to sensitivity, the response here is considered as the output of black-box functions, i.e. complex functions depending on many poorly-understood variables. Given such a function $f(x)$ for d-dimensional x, it is important to determine which variables, if any, dominate f and how they affect the function. Stochastic sensitivity analysis requires that the uncertainty about model inputs (parameters, initial values, boundary conditions, exogenous variables,etc.) be expressed in the form of a (joint) probability distribution of these inputs. Here, appropriate nonparametric methods for estimating joint density in high dimensional settings are required, such as nonlinear independent component analysis or other dimension-reduction methods. This is a preliminary step in sensitivity analysis.

After assessment of the uncertainty distribution of the inputs, functional ANOVA models may be used to decompose a square integrable f into a sum of lower dimensional component functions that depend on subsets of input variables. The variances of the component functions will then be used to identify important variables and interactions.

4. Application Domains

4.1. Introduction

Keywords: *Data assimilation*, *Glaciology*, *High Performance Computing*, *Hydrology*, *Inverse Problems*, *Meteorology*, *Mud Flows*, *Numerical Modelling*, *Oceanography*.

The evolution of natural systems, in the short, mid, or long term, has extremely important consequences for both the global earth system and humanity. Forecasting this evolution is thus a major challenge from the scientific, economic, and human viewpoints.

Humanity has to face the problem of **global warming**, brought on by the emission of greenhouse gases from human activities. This warming will probably cause huge changes at global and regional scales, in terms of climate, vegetation and biodiversity, with major consequences for local populations. Research has therefore been conducted over the past 15 to 20 years in an effort to model the earth's climate and forecast its evolution in the 21st century in response to anthropic action.

With regard to short-term forecasts, the best and oldest example is of course **weather forecasting**. Meteorological services have been providing daily short-term forecasts for several decades which are of crucial importance for numerous human activities.

There have also been a number of newer issues arising in recent years, one of the most important being the problem of **water resource management**. The availability of pure water is a problem of prime importance which is becoming a major concern even in countries which had no such difficulties in the past. Numerical tools play an important role in the design of hydrology management systems.

Numerous other problems can also be mentioned, like **seasonal weather forecasting** (to enable powerful phenomena like an El Niño event or a drought period to be anticipated a few months in advance), **operational oceanography** (short-term forecasts of the evolution of the ocean system to provide services for the fishing industry, ship routing, defense, or the fight against marine pollution), **air pollution** prediction systems, the prediction of **floods**, or the simulation of **mud flows** and **snow avalanches** for impact studies and regional planning.

As mentioned previously, mathematical and numerical tools are omnipresent and play a fundamental role in these areas of research. In this context, the vocation of MOISE is not to carry out numerical prediction, but to address mathematical issues raised by the development of prediction systems for these application fields, in close collaboration with geophysicists.

4.2. Oceanography and the Ocean-Atmosphere System

Keywords: *Atmosphere*, *Coupling Methods*, *Data Assimilation*, *Multi-resolution*, *Ocean*.

Participants: Eric Blayo, Didier Bresch, Laurent Debreu, Thomas Duhaut, Christine Kazantsev, Eugène Kazantsev, Monika Krysta, François-Xavier Le Dimet, Florian Lemarié, Carine Lucas, Maëlle Nodet, Elise Nourtier-Mazauric, Céline Robert, Antoine Rousseau, Ehouarn Simon, Arthur Vidard.

Understanding and forecasting the ocean circulation is currently the subject of an intensive research effort by the international scientific community. This effort was primarily motivated by the crucial role of the ocean in determining the earth's climate, particularly from the perspective of global change. In addition, important recent research programs are aimed at developing operational oceanography, i.e. near real-time forecasting of ocean circulation, with applications for ship routing, fisheries, weather forecasting, etc. Another related field is coastal oceanography, dealing for example with pollution, littoral planning, or the ecosystems management. Local and regional agencies are currently very interested in numerical modelling systems for coastal areas.

Both ocean-alone models and coupled ocean-atmosphere models are being developed to address these issues. In this context, the MOISE project conducts efforts mainly on the following topics:

- *Multi-resolution approaches and coupling methods*: Many applications in coastal and operational oceanography require high resolution local models. These models can either be forced at their boundaries by some known data, or be dynamically coupled with a large-scale coarser resolution model. Such model interactions require specific mathematical studies on open boundary conditions, mesh refinement methods, and coupling algorithms. The latter have also to be studied in the context of ocean-atmosphere coupled systems.
- *Advanced numerical schemes*: Most ocean models use simple finite difference schemes on structured grids. We are seeking for higher order schemes allowing both accuracy and good conservation properties, and dealing with irregular boundaries and bottom topography.
- *Parameterization and modelling of boundary layers*: A striking feature of ocean dynamics is the existence of several types of boundary layers, either lateral (near the coastlines), or vertical (near the ocean surface and bottom). Despite their relatively small size, these layers have an important role in the global dynamics, and must be accurately represented in the model. New modelling and numerical approaches to this problem are studied.
- *Data assimilation methods for ocean modelling systems*: The main difficulties encountered when assimilating data in ocean or atmosphere models are the huge dimension of the model state vector (typically 10^6-10^7), the strongly nonlinear character of the dynamics, and our poor knowledge of model error statistics. In this context, we are developing reduced order sequential and variational data assimilation methods addressing the aforementioned difficulties. We are also working on the assimilation of lagrangian data, and on the design of data assimilation methods for multi-resolution models and for coupled systems.

Most of these studies are led in strong interaction with geophysicists, in particular from the Laboratoire des Ecoulements Géophysiques et Industriels (LEGI, Grenoble).

4.3. Hydrology and River Hydraulics

Keywords: *Coupling/Superposition of Models*, *Data Assimilation*, *Floods*, *Hydrology*, *Richards' equations*, *Sensitivity Analysis*, *Shallow-water equations*.

Participants: William Castaings, Marc Honnorat, François-Xavier Le Dimet, Joël Marin, Jérôme Monnier, Maëlle Nodet.

Water resources and floods are critical issues. They are the result of complex interactions within the water cycle between meteorology, hydrology and hydraulics. Mathematical and numerical modelling is becoming accepted as a standard engineering practice for prevention and prediction.

Concerning river hydraulics, forward models based on 1-D and 2-D shallow water equations and the corresponding industrial softwares (e.g. Telemac2D, Carima1D) are satisfying for many situations. Nevertheless for real applications, initial and boundary conditions (basically, water level and discharge) are very partially measured hence difficult to prescribe. Empirical parameters (e.g. land roughness) are calibrated manually with difficulties. Also, coupling between 1D net-model and local 2D configurations is a-priori not feasible using the standard computational softwares.
Concerning soil infiltration and rainfall-runoff phenomena, on one hand forward models have still to be improved (e.g. 3D Richards' equations), and on the other hand, empirical parameters are numerous and very difficult to prescribe.
Realistic and reliable numerical prediction requires an integrated approach with all components (different models coupled together and corresponding measured data), with affordable computational cost. Sensitivity analysis and data assimilation methods, that have shown their potential in other geosciences like meteorology and oceanography, are now in the forefront in hydrology. This prediction chain is far from being operational in hydrology and river hydraulics.
The problems addressed in MOISE are related to the coupling/superposition of models, more efficient forward solvers, sensitivity analysis and data assimilation for catchment scale hydrology and/or river hydraulics.
The current research topics conducted in MOISE are the following:

- *Image data assimilation*. Images potentially contain a huge amount of information which could be used in conjunction with numerical models. A major difficulty is to develop convenient "observation operators", linking images and model variables. On one hand, we consider remote sensed observations such as surface trajectories (lagrangian data assimilation); on the other hand, we consider eulerian observations extracted from a satellite image (flood plain extension).
- *Coupling between 1D and 2D models, with data assimilation*. We elaborate the concept of a zoom model locally superposed on a 1D network global model. The zoom model (2D shallow-water equations) describes the flow dynamics inside the storage areas described in the 1D global model (1.5D shallow-water equations). Both models are coupled simultaneously with the variational data assimilation process (optimal control); thus allowing to assimilate local 2D observations into the 1D global model.
- *Soil water transfer modelling*.
- *Sensitivity analysis for rainfall-runoff models*.

4.4. Direct simulation of complex fluid flows

Keywords: *Finite Element Method*, *Mesh Adaptation*, *Non-Newtonian Fluids*.

Participants: Pierre Saramito, Ibrahim Cheddadi, Aymen Laadhari.

Complex fluids present behaviors that are dramatically different than ordinary fluids. These behaviors depend upon the microscopic structure of the fluid material. Most of complex fluids contain microscopic entities that are rigid or deformable particles. Applications cover the environment problems (mud and debris flows, snow avalanches, volcanic aerosols), biology (red cells in blood) and industry (macro-molecules in plastic material process). Liquid foams play a special role in this context since it represent a model fluid for such flow problem: the micro-structure (the bubble) is easily apparent for experiments and comparisons between numerical predictions and experiments could be performed at a finer level. Our methodology retains actually five axes of researches:

1. Numerical prediction of liquid foams
2. Direct simulation of the motions of particle in flowing liquids
3. Numerical analysis of viscoelastic fluid models
4. Numerical resolution of viscoplastic flow problems
5. Applications to debris and volcanic lava flows

4.5. Glaciology

Keywords: *Asymptotic Analysis (Shallow Ice)*, *Coupling*, *Data Assimilation*, *Glaciology*, *Inverse Methods*, *Non-Newtonian Stokes Model with Free Surface*, *Optimal Control*.

Participants: Eric Blayo, François-Xavier Le Dimet, Bénédicte Lemieux-Dudon, Joël Marin, Thierry Mastrosimone, Jérôme Monnier.

The study of past climate is a means of understanding climatic mechanisms. Drillings in polar ice sheets provide a huge amount of information on paleoclimates: correlation between greenhouse gases and climate, fast climatic variability during the last ice age, etc. However, in order to improve the quantitative use of the data from this archive, numerous questions remain to be answered because of phenomena occurring during and after the deposition of snow. An important research aim is therefore to optimally model ice sheets in the vicinity of drilling sites in order to improve their interpretation: age scale for the ice and for the gas bubbles, mechanical thinning, initial surface temperature and accumulation when snow is deposited, spatial origin of ice from the drilling.

In other respect, ice streams represent an important feature of ice flows since they account for most of the ice leaving the ice sheet (in Antarctic, one estimates that ice streams evacuate more than 70% of the ice mass in less than 10% of the coast line). Furthermore, recent observations showed that some important ice streams are presently accelerating. Thus, we seek to improve models of marine ice sheets, on one hand by coupling global and local ice flow models (shallow-ice and full Stokes 3D non-newtonian), and on the other hand by calibrating them using available observations.

Another objective is the evaluation of the state of the polar ice caps in the past, and their interactions with the other components of the earth climate, in order to forecast their evolution in the forthcoming centuries. The joint use of models and data, through data assimilation techniques, to improve system description is relatively new for the glaciological community. Therefore inverse methods have to be developed or adapted for this particular purpose.

5. Software

5.1. River Hydraulics

Participants: Marc Honnorat, Joël Marin, Jérôme Monnier.

DASSFLOW[1] is a river hydraulics simulation software designed for variational data assimilation, [90]. The forward models are based on the 1.5D and 2D shallow-water equations in conservative form with topography and friction terms. Time discretization is the explicit Euler scheme, space discretization is based on well-balanced finite volume schemes (HLLC approximate Riemann solver with source term i.e. topography). The mesh is unstructured, mix of triangles-quadrangles. Many boundary conditions, including characteristics ones, are available. The code is written in Fortran 90, and the adjoint code is automatically generated using the automatic differentiation tool Tapenade. Benchmarks related to the forward model and to some identification problems are available. It is interfaced with a few free and commercial pre and post-processors (SIG tools, mesh generators, visualization tools), which allows using Dassflow for real data. A twin experiment mode is included.
A stable version is available on the web via a Forge tool (the forward solver is freely distributed, GPL license, while the full code is distributed to collaborators only). Extra modules, which are more experimental, includes the additional following features:

1. assimilation of Lagrangian data (local particles trajectories extracted from video images for example),
2. different coupling algorithms between a 1D global model with storage area and local 2D models, with combined assimilation of data.

[1] http://dassflow.gforge.inria.fr/

The forward code has been distributed to many laboratories worldwide. The full code has been distributed to our collaborators. Today, it is used (or planned to be used) in the context of few PhDs (INRIA Opale, univ. Berkeley, univ. Toulouse x 2).
This code should evolves soon to a common platform (DassHydro) with our european partners from Politecnico Milano (E. Miglio), Sevilla (E. Fernandez-Nieto) and Malaga (C. Pares).
The code and the forge are currently maintain by Joël Marin, assistant engineer (2006-08).

5.2. Adaptive Grid Refinement

Participants: Laurent Debreu, Florian Lemarié.

AGRIF (Adaptive Grid Refinement In Fortran, [31], [97]) is a Fortran 90 package for the integration of full adaptive mesh refinement (AMR) features within a multidimensional finite difference model written in Fortran. Its main objective is to simplify the integration of AMR potentialities within an existing model with minimal changes. Capabilities of this package include the management of an arbitrary number of grids, horizontal and/or vertical refinements, dynamic regridding, parallelization of the grids interactions on distributed memory computers. AGRIF requires the model to be discretized on a structured grid, like it is typically done in ocean or atmosphere modelling. As an example, AGRIF is currently used in the following ocean models: MARS (a coastal model developed at IFREMER-France), ROMS (a regional model developed jointly at Rutgers and UCLA universities, [100]), OPA-NEMO ocean modelling system (a general circulation model used by the French and European scientific community).
AGRIF is licensed under a GNU (GPL) license and can be downloaded at its web site (http://ljk.imag.fr/MOISE/AGRIF/index.html). More than two hundred downloads of the software have been done during the last year.
Implementations of new features for adaptive mesh refinement in lagrangian models are planned within the framework of the COMMA project.

5.3. Rheolef: a C++ Finite Element Environment

Keywords: *Adaptive Meshes*, *C++*, *Finite Elements*, *Numerical Simulation*, *Partial Derivative Equations*.

Participant: Pierre Saramito.

Home page: http://ljk.imag.fr/membres/Pierre.Saramito/rheolef
Current stable version: 5.18
The license is GPL.
Rheolef is a computer environment that serves as a convenient laboratory for computations, involving finite element-like methods. It provides a set of unix commands and C++ algorithms and classes.
Classes covers first the classic graph data structure for sparse matrix formats and finite element meshes. A higher level of abstraction is provided by classes related to approximate finite element spaces, discrete fields and bilinear forms.

Current applications cover:

- Poisson problems in 1D, 2D and 3D with P1 or P2 elements,
- Stokes problems in 2D and 3D, with P2-P1 or P1 bubble-P1 elements,
- linear elasticity in 2D and 3D, with P1 and P2 elements, including the incompressible and nearly incompressible elasticity,
- characteristic method for convection-diffusion, time-dependent problems and Navier-Stokes equations,
- self-adaptive mesh based for 2D problems,
- axisymmetric problems,
- multi-regions and non-constant coefficients.

Input and output support various file formats for meshes generators and numerical data visualization systems (mayavi and vtk, plotmtv, gnuplot).
Both reference manual and user's guide are available. Distributions are available both in source form as a tar.gz pack and as binaries (debian and rpm packs).

6. New Results

6.1. Ocean Modelling

6.1.1. Mathematical Modelling of the Ocean Dynamics

Participants: Didier Bresch, Christine Kazantsev, Carine Lucas, Antoine Rousseau.

6.1.1.1. Numerical simulations and finite volume schemes

In the framework of a regional project devoted to viscous shallow water equations and their applications to environment, we have developed tsunami and sub-marine avalanches models and established well balanced finite volume schemes. This is a collaboration with E. Fernandez Nieto, and more generally Sevilla and Malaga teams. We also developed appropriate finite volume schemes for pollutant propagation in collaboration with J. Monnier, and appropriate schemes for viscous sedimentation models with E. Fernandez-Nieto and J.D.D. Zabsonré.

6.1.1.2. Influence of the viscous terms (Reynolds closure)

In the framework of compressible flows, we have introduced viscous models which provide additional behavior of the density close to vacuum. We actually proved that, if some compatibility conditions between the viscosities are satisfied and if the domain is periodic in space, some additional regularity information on a quantity involving the density is available. We obtained a non-trivial equality deduced from the special structure of the momentum equations. This result allows for instance to justify the link between the viscous Shallow Water equations and the viscous Quasi-Geostrophic equations or the viscous lake equations. Using this new mathematical entropy that has been introduced by D. Bresch and B. Desjardins (called now BD entropy in the literature), we obtained the first result of global existence of weak solutions to the full compressible Navier-Stokes equations with heat conductivity. This extends the result obtained by J. Leray on incompressible flows and P.-L. Lions on barotropic compressible flows. This gives a first answer to this open problem. Note that this technic leads also to the existence of global weak solutions for barotropic compressible Navier-Stokes equations with non-constant viscosity coefficients. It supplements, in some sense, the result by P.L. Lions since the two approaches cover different cases. Recently we have also extended such results to domains bounded in space, and we also have proved that similar BD entropies may be used to establish well defined viscous sedimentation models.

6.1.1.3. Polytropic Navier Stokes equations

In collaboration with B. Desjardins and E. Grenier, we are looking at the low mach number limit process justification on the polytropic Navier-Stokes equations. We intend to justify mathematically this limit even if crossing eigenvalues occurs. The first part of the work was to develop adequate tools to control the resonant set, and has been published in [24].

6.1.1.4. Small-scale induced effects in the oceans

Ocean bottom topography and coastlines vary over a wide range of scales, the smallest ones being unresolved in numerical computations. There is a need for the development of simplified models that implicitly account for the impact of the small-scale topography on the large-scale ocean circulation. We have recently developed such nonlinear models in idealized cases for the quasi-geostrophic system and the lake equations. This leads for instance to some nonlinear PDEs which govern the western boundary layer, extending in some sense the linear one proposed by H.W. Munk (Munk layer). It also provides some models with memory effects. Recently a mathematical derivation has been performed using two-scale convergence technics and defect measures control. We have also worked on the effect of fast oscillating topography in quasi-geostrophic equations and proposed some numerical implementation tools to simulate such flows. We are now looking at more general cases (other PDEs, more general topography and coastlines) and are trying to transfer these developments to actual applications (collaboration with geophysicists at LEGI). A collaboration with R. Klein on small scale bottom effects around shallow water system is still in progress.

6.1.1.5. Influence of the cosine terms of the Coriolis force

Recently, C. Lucas has performed some studies around the derivation of Shallow Water equations (namely the effects of the tensor and the boundary conditions). She proved that some terms have been omitted in some previous works made by other authors. More precisely, see [35], [36], it is sometimes necessary to take into account the cosine part of the Coriolis force (which is usually neglected). This gives a new Shallow Water system from which the Quasi-Geostrophic Shallow Water equation can be deduced. The influence of these new cosine terms in the latter equation has been numerically studied in collaboration with A. Rousseau, [78]. We proved that these terms can modify a double-gyre circulation (a simplified Gulf-Stream model). Numerical experiments show (see Figure 1) that this effect depends on the topography and cannot be predicted.

6.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Bernard Barnier, Eric Blayo, Laurent Debreu, Florian Lemarié, Elise Nourtier-Mazauric, Céline Robert, Antoine Rousseau.

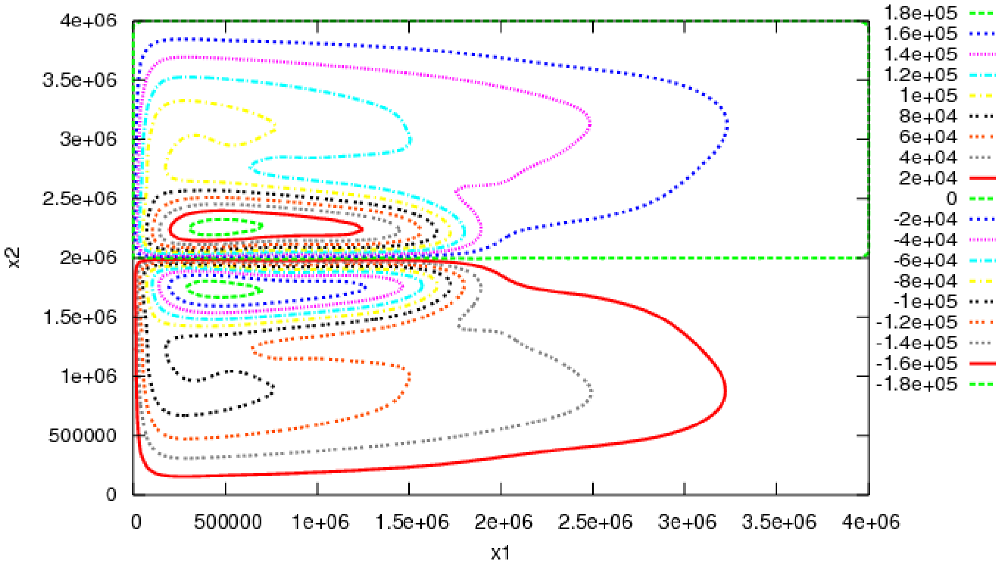
6.1.2.1. Open boundary conditions

The implementation of high-resolution local models can be performed in several ways. An usual way consists in designing a local model, and in using some external data to force it at its open boundaries. These data can be either climatological or issued from previous simulations of a large-scale coarser resolution model. The main difficulty in that case is to specify relevant open boundary conditions (OBCs).
Pursuing earlier works, we suggested a simplified 3D model (actually denoted as a 2.5D model [30]) for the inviscid Primitive Equations for which we introduced open boundary conditions. The corresponding boundary value problem leads to a well-posed problem. The full 3D linear model has also been considered in [40], and the results that have been obtained in lower dimensions have been extended to the 3D case.

Following our preceding work, we have implemented characteristic (in the hyperbolic sense) OBCs in two different 3-D primitive equation ocean models, MARS (collaboration with F. Vandermeirsch, IFREMER Brest) and OPA-NEMO, in realistic configurations. Our results confirmed the fact that characteristics-based OBCs are relevant for the barotropic (i.e. depth-averaged) dynamics, and lead to clear improvements with regard to usual OBCs. For the baroclinic (i.e. fully 3-D) part of the dynamics, characteristic OBCs are based on a local decomposition into vertical modes. Such OBCs had never been implemented before in such realistic models. Our first results show that this approach seems robust and leads to improved results with regard to usual OBCs. However the present formulation of the free surface dynamics in the OPA-NEMO code makes it difficult to implement. This work is presently being continued.

6.1.2.2. Interface conditions for coupling ocean models

Another way of designing such local models consists in coupling a high resolution local model with some coarser resolution outer model. Such a coupling between two models with possibly different resolutions, numerics, and even physics, can be performed within the framework of global-in-time Schwarz domain decomposition methods. However, the efficiency of these algorithms is strongly dependent on interface conditions. In collaboration with applied mathematicians from LAGA (Paris 13) and LAMFA (Amiens) (L. Halpern, C. Japhet, V. Martin, E. Audusse, B. Merlet), we carry on mathematical studies on the development of absorbing conditions for the usual systems of equations encountered in ocean and atmosphere modelling. The absorbing conditions approach can be seen as a generalization of the characteristics method. Exact absorbing conditions, avoiding any reflection of errors on the boundaries, have been determined for different kind of tracer equations (with either laplacian or bi-laplacian diffusion operators), and for the 1-D and 2-D linearized shallow-water system, taking into account advection, Coriolis terms, bottom topography and friction. These exact conditions are non local both in space and in time, and need therefore to be approximated. Two approaches have been investigated for this purpose: (1) optimization of the convergence rate of the Schwarz algorithm (by controlling parameters involved in the expression of the boundary condition), (2) approximation



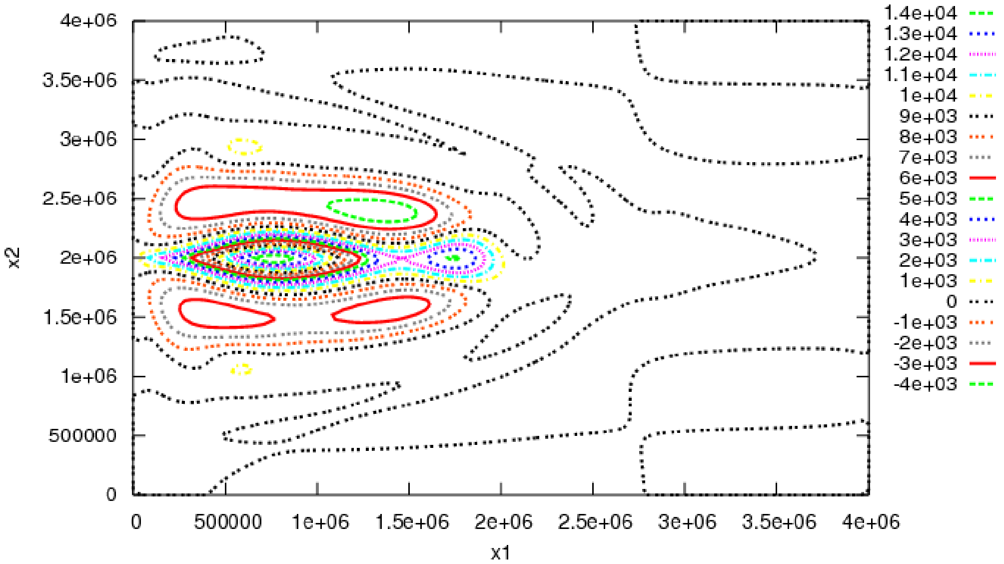


Figure 1. Time average of the stream function over 1600 years and difference due to the cosine effect, for a flat bottom.

based on mathematical coherence constraints and/or physical properties. Efficient boundary conditions have been computed by the first approach for tracer equations, and by the second approach for the shallow-water system.

6.1.2.3. Ocean-atmosphere coupling

Many applications in coastal and operational oceanography require high resolution local models, for which ocean-atmosphere interactions must be properly taken into account. A simple use in a "forced" mode (i.e. without any retroaction from the ocean onto the atmosphere) is often satisfactory for numerous ocean applications. However some applications do require a two-way coupling between an oceanic model and an atmospheric model (e.g. tropical cyclones, climate studies...). In that case, connecting the two model solutions at the air-sea interface is a difficult problem, which is presently often addressed in a quite crude and simplified way from a mathematical point of view. In this context, domain decomposition methods provide flexible and efficient tools for coupling models with non-conforming time and space discretizations.

In the framework of his PhD thesis, F. Lemarié has addressed the problem of flux exchanges between ocean and atmosphere in coupled models. A scale analysis of the various terms in primitive equations shows that a coupling between two non-stationary 1D diffusion equations with different coefficients would be relevant to capture most of the air-sea interface phenomena.

As a preliminary step, the study of the convergence rate of the global-in-time Schwarz algorithm with discontinuous (but constant on each sub-domain) diffusion coefficients has been carried out by taking explicitly into account the finiteness of the sub-domains. Those results have been compared to the few existing studies.

Then in a more realistic way, the more difficult case of coefficients which are both discontinuous at the air-sea interface and spatially variable in each sub-domain has been considered. In this case, the convergence of the Schwarz algorithm has been studied analytically, using an ad hoc expansion into eigenfunctions of an associated Sturm-Liouville problem. An important interest of this approach is that it is general enough to deal with different parameterizations of vertical mixing processes. On top of that a new formulation of transmission conditions has been introduced to take into account turbulent boundary layer processes near air-sea interface.

A realistic application making use of these new concepts is currently being implemented. It will consist in a 2D vertical y-z configuration with MAR (Modèle Atmosphérique Régional) and ROMS (Regional Ocean Modelling System) numerical models, for the simulation of Hadley cell circulation and sub-equatorial currents. These works are partially supported by the ANR (COMMA project).

6.2. Development of New Methods for Data Assimilation Methods

Participants: Didier Auroux, Eric Blayo, Laurent Debreu, Eugène Kazantsev, François-Xavier Le Dimet, Ehouarn Simon, Arthur Vidard, Emilie Neveu, Monika Krysta, Jacques Verron.

6.2.1. Variational data assimilation for locally nested models.

Participants: Eric Blayo, Laurent Debreu, Ehouarn Simon, Emilie Neveu.

The objectives are to study the mathematical formulation of variational data assimilation for locally nested models and to conduct numerical experiments for validation.

The state equations of the optimality system have been written for the general case of two embedded grids, for which several kinds of control (initial conditions, boundary conditions) have been proposed. Both one way and two way interactions have been studied. This last year, we worked on integration of non linear grid interactions in the algorithm. Additionally, the problem of specification of background error covariances matrices has been studied. These results are detailed in the Ph.D of Ehouarn Simon (to be defended in November).

Finally, Emilie Neveu has worked on comparison of this approach to the more traditional use of multi-grid methods for solving the optimization problem. During her training period, she derived convergence conditions for the application of the FAS (Full Approximation Scheme) to the optimization problem. She will continue on this subject during her Ph.D.
This work is granted by the french DGA.

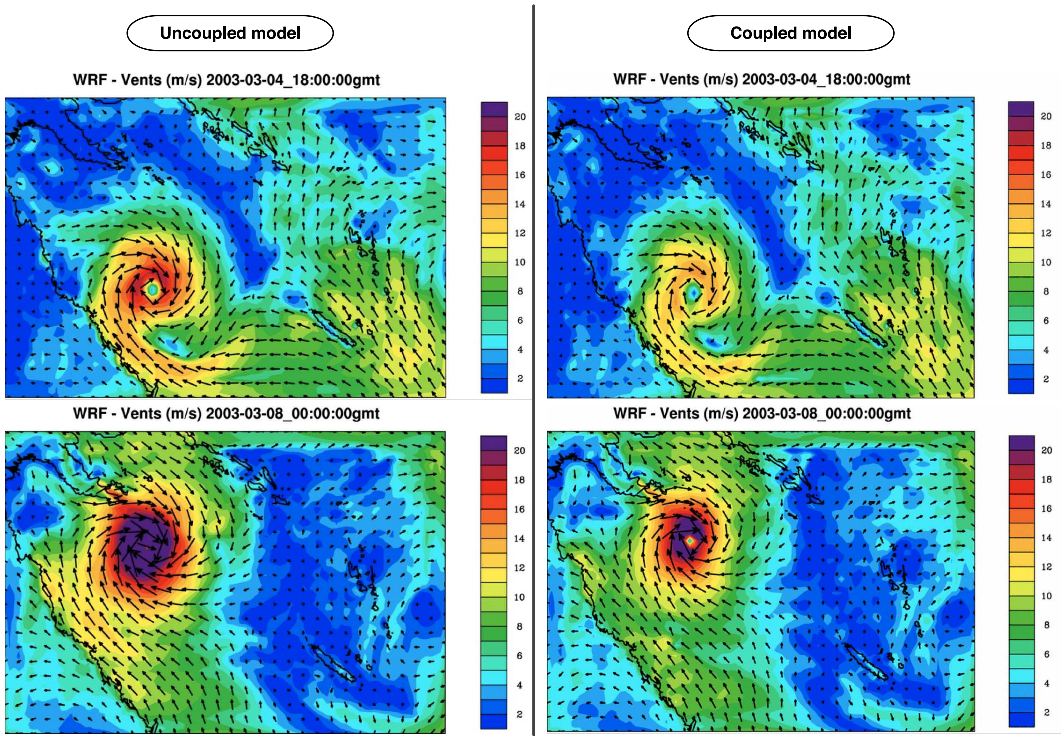


Figure 2. Wind speed and wind vectors at 10m height given by WRF atmospheric model during tropical Cyclone Erica in March 2003. The uncoupled simulation (left) using SST from NCEP reanalysis exhibits an overestimation of the cyclone intensity. On the contrary a 2-way coupled simulation with ROMS oceanic model (right) tends to a more realistic representation of wind speed. This improvement is mainly due to the feedback of the ocean onto atmosphere which is properly taken into account in the coupled simulation.

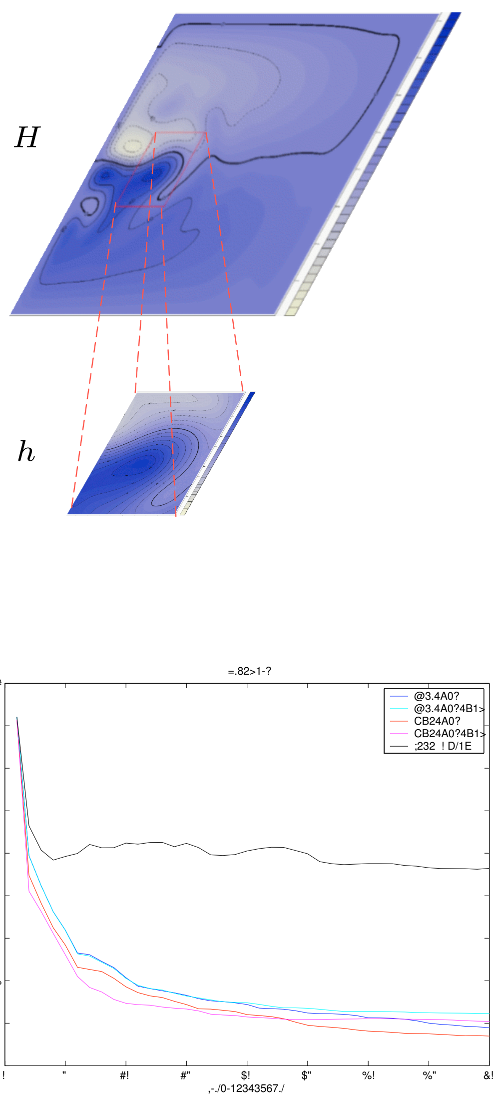


Figure 3.

(left) Nested Models - (right) High resolution RMS error during the minimization

In the context of variational data assimilation in regional models, the use of nested models allows a clear improvement of the solution with regard to a "classical" monogrid 4D-Var for which boundary conditions are controlled.

6.2.2. Control of the boundary layer parametrization by data assimilation

Participant: Eugène Kazantsev.

One of the obvious ways to reduce the number of discretization points of a numerical model and to reproduce the impact of small scales on the large scale processes consists in using improved numerical techniques, namely high order schemes. This kind of schemes is widely used in atmospheric modeling. In particular, compact schemes of fourth, fifth and higher order have shown their great ability to reproduce complex physical phenomena in models at relatively low resolution.

However, the major difficulty in using high-order schemes in ocean modeling is due to the presence of boundary conditions. Indeed, periodical boundaries in atmospheric models greatly simplify the implementation of high-order compact schemes.

It was shown previously that the use of high order schemes in a shallow water model for large oceanic scales results in a deformed solution due to a lack of explicit resolution in the boundary layers. It seems to be the only way to use these kind of schemes in a model in a bounded domain is to proceed by data assimilation in order to control the parametrization of the boundary layer. This may help us to find the optimal discretization, adapted to the given model and allow to use high-order scheme in the interior of the domain.

First experiments show the control to be efficient tool in creating of the optimal parametrization of the boundary layer. Assimilating the data of the high-resolution model with the same parameters, we can discretize all operators near boundaries in the way to get high order approximation in the inner points and optimal discretization near the boundary. This provides us with the low resolution model which behavior is close to the high resolution one.

A paper analyzing this problem is in preparation.

6.2.3. Variational Data Assimilation with Control of Model Error

Participant: Arthur Vidard.

One of the main limitation of the current operational variational data assimilation techniques is that they assume the model to be perfect mainly because of computing cost issues. Numerous researches have been carried out to reduce the cost of controlling model errors by controlling the correction term only in certain privileged directions or by controlling only the systematic and time correlated part of the error.

Both the above methods consider the model errors as a forcing term in the model equations. Trémolet (2006) describes another approach where the full state vector (4D field : 3D spatial + time) is controlled. Because of computing cost one cannot obviously control the model state at each time step. Therefore, the assimilation window is split into sub-windows, and only the initial conditions of each sub-window are controlled, the junctions between each sub-window being penalized. One interesting property is that, in this case, the computation of the gradients, for the different sub-windows, are independent and therefore can be done in parallel.

Y. Trémolet (ECMWF) spent one month in 2006 visiting the MOISE project and we successfully implemented the control of the full state vector within the OPAVAR framework. There was however some unresolved numerical issues at that time, mainly the need of the inverse of some operators that prevented us to use it in a realistic framework. In the meantime we developed another version of this scheme using a simpler shallow-water model and the PALM coupler to illustrate its nice parallelization properties described above.

We recently sorted out the problems mentioned above and we plan to test this method in a realistic framework very soon. Two testbeds are considered: Oceanic applications using OPAVAR/NEMOVAR and application sto laboratory experiments with image assimilation in the framework of ADDISA (see 6.5.1).

6.2.4. Data Assimilation for Coupled Models

Participant: Arthur Vidard.

One can see the method described in the previous section as a coupling of several assimilation windows with perfect model hypothesis. This can then be extended to the coupling of different models.

This is not a simple task: it involves the gathering of very heterogeneous information multi-scales, multi-fluids, multi-phases and numerous datatype)

This research is still at a really preliminary stage. To begin with, we developed a coupled toy model using Lorenz equations which behaves somewhat like a tropical ocean-atmosphere system, reproducing some El Niño-like behavior. We tested some of our ideas on this simple system. We are now in the process of building a more realistic testbed.

6.2.5. A Hybrid Variational-Stochastic Method for Data Assimilation

Participants: Eric Blayo, Monika Krysta, Jacques Verron.

A data assimilation method based on variational approach is currently being implemented. It consists in a coupling of the cost function of the variational approach with a fixed-interval optimal linear smoother. It is hence referred to as hybrid.

The background error covariance matrix of the usual variational framework remains unchanged. In the hybrid method, however, at each transition between the assimilation windows, it is replaced with the one delivered by the smoother. The latter is updated whenever new analyses or new background states are produced. Moreover, it can be shown that the background states issued from an incremental variational method and an appropriately built fixed-interval smoother are mathematically equivalent. This property ensures that the matrix injection into the cost function is done in a consistent manner (i.e., at each transition between the assimilation windows the background error covariance matrix provided by the smoother is precisely the one which describes the newly-computed variational background state).

The hybrid is expected to perform better than the 4D-Var but also better than a suboptimal hybrid based on a coupling between 4D-Var and Kalman filter. In fact, the hybrid method ensures the results of the same quality as those of the fixed-interval smoother. Nevertheless, for the models which are already equipped with the 4D-Var, the hybrid is far simpler to implement than the entire smoother. It is enough to add to the 4D-Var the evolution (forecast and analysis) of the error covariance matrix. In practice, the matrices are considered to be of a small rank, which simplifies their evolution furthermore, similarly to the SEEK filter approach.

The smoother-based hybrid is currently being implemented in a shallow water model which mimics a double-gyre circulation of the North Atlantic.

6.2.6. A Nudging-Based Data Assimilation Method: the Back and Forth Nudging

Participant: Didier Auroux.

The back and forth nudging algorithm, recently introduced in collaboration with J. Blum (University of Nice) in [94], consists in solving first the standard forward nudging equation and then the direct system backwards in time with a feedback term which is opposite to the one introduced in the forward equation. The "initial" condition of this backward resolution is the final state obtained by the standard nudging method. After resolution of this backward equation, one obtains an estimate of the initial state of the system. We repeat these forward and backward resolutions until convergence of the algorithm.

This work has been motivated by the fact that it is usually tiresome to derive the adjoint model. Our algorithm does not need to linearize the system, nor to have a powerful optimization algorithm. The backward system is not the adjoint equation but the direct system, with an extra feedback term that stabilizes the resolution of this ill-posed backward problem [94].

We have recently compared this algorithm to the 4D-VAR method on toy models such as the Lorenz' and 1D viscous Burgers' equations, but also on a layered quasi-geostrophic ocean model. The numerical convergence of the BFN algorithm is always achieved in a few iterations, and in the case of twin experiments, it provides a good estimation of the initial condition and very good forecasts (see Figure 4). This work is partly presented in [93].

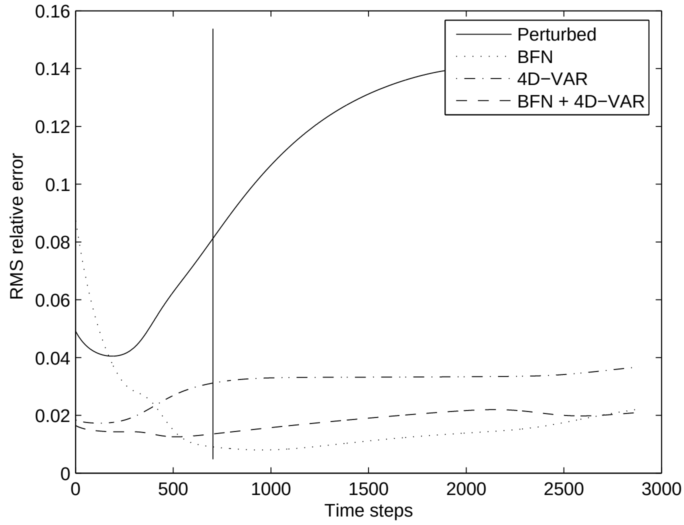


Figure 4. BFN on a Burgers model: evolution in time of the RMS difference between the reference trajectory and the perturbed trajectory derived from the noised observations of the system at time t=0 (plain line), and between the reference trajectory and the identified trajectories for the BFN (dotted line), the 4D-VAR (dash-dotted line) and the BFN-preprocessed 4D-VAR (dashed-line) algorithms.

We already proved the theoretical convergence for a linear compact operator, provided that some hypothesis on the spatial distribution of the observations and the observation operator were satisfied. We are currently working on the theoretical point of view for nonlinear models, and already obtained some a priori estimations on the Lorenz system. We are also doing many numerical experiments on a shallow water model (see Figure 5), and exhaustive comparisons with other data assimilation schemes on a Burgers model.

Figure 5. BFN on a shallow-water model: data assimilation period = 1 month, forecast period = 3 months; model states at the end of the forecast period: true state (left), no assimilation (center), BFN assimilation (right).

6.2.7. Generalization of the dual variational data assimilation algorithm to a nonlinear situation

Participant: Didier Auroux.

The idea of the dual variational data assimilation algorithm 4D-PSAS (Physical Space Analysis System) is to perform the minimization in the space of the observations, rather than in the model space as in the primal 4D-VAR scheme. Despite the formal equivalence between 4D-VAR and 4D-PSAS in a linear situation (both for model equations and observation operators), the dual method has several important advantages: in oceanographic cases, the observation space is smaller than the model space, which should improve the minimization process; for no additional cost, it provides an estimation of the model error; and finally, it does not have any singularities when the covariance error matrices tends to zero.

We proposed in [16] an extension of this algorithm to a fully nonlinear situation, as it has been done in the previous years with other classical data assimilation schemes: the 4D-VAR and the Kalman filter. For this purpose, we considered a nonlinear multi-layer quasi-geostrophic ocean model, which mimics quite well the mid-latitude circulation. We reported the results of extensive numerical experiments that have been carried out to compare this extended algorithm to the classical variational formulation, and to study its sensitivity to many parameters such as the nonlinearities, the number of available observations, the presence of an unknown term in the assimilation model, and to study the detection of the model error.

As a matter of fact, it is found that this extended algorithm has kept the same advantages as in the linear case (model error detection, smaller sensitivity to various perturbations, more efficient minimization process). All these experiments suggest that it is an efficient assimilation scheme for oceanographic problems.

6.3. Quantifying Uncertainty in Data Assimilation

6.3.1. Uncertainty analysis

Participants: Eric Blayo, David Cherel, Ange Toulougoussou, Laurence Viry.

In the framework of an internship, D. Cherel has compared two approaches, variational and stochastic, to assess the sensitivity of the response of a linear reaction-advection-diffusion equation to the uncertainty on its coefficients. The information brought by both methods, as well as their cost, have been compared. Moreover, its has been proven on this simple example that a reduced-order model can be used instead of the full model for conducting the sensitivity analysis at a much cheaper computational cost without significantly changing the results.

In collaboration with C. Messager (U. Leeds and LPO Brest), a sensitivity analysis has been started on a realistic testcase. The aim of the study is to analyze the sensitivity of the rainfall in western Africa simulated by an atmospheric model to the uncertainties on some input parameters (albedo, heat content of the upper ocean in the gulf of Guinea...). Some preliminary statistical data analysis has been performed, as well as the implementation of the model on different computers, see [88]. This sensitivity study will require rather huge computation resources, and will be run in a grid computing environment.

6.3.2. Error propagation in Variational Data Assimilation

Participants: François-Xavier Le Dimet, Victor Shutyaev.

In cooperation with the Institute of Numerical Mathematics (V. Shutyaev, Moscow) and the University of Strathclyde (I. Gezadje, UK).
The forecast of the evolution of geophysical fields make sense only if an evaluation of the error is provided. Most of the time this is done by Monte-Carlo techniques. In the framework of non linear models with non gaussian error there is no scientific justification for these methods. We have based the estimation of errors on a deterministic study of the equations.
The problem of variational data assimilation for a nonlinear evolution model is considered to identify the initial condition. The equation for the error of the optimal solution through the statistical errors of the input data is derived, based on the Hessian of the misfit functional and the second-order adjoint techniques.

The covariance matrix of the optimal solution error is expressed through the covariance matrices of the input errors. Numerical algorithms are developed to construct the covariance matrix of the optimal solution error using the covariance matrices of the input errors. Accepted for publication by SIAM Journal on Geophysics.

6.4. Data Assimilation for Ocean Models

Participants: Eugène Kazantsev, Maëlle Nodet, Arthur Vidard.

6.4.1. Assimilation of Lagrangian Data

Participant: Maëlle Nodet.

This work is motivated by the Argo program, which aims at deploying a network of 3000 profiling floats over the world ocean. Argo is part of the international GODAE experiment (Global Ocean Data Assimilation Experiment). These profilers drift at a typical depth of 1500m, and perform a vertical profile of temperature and salinity measurements every ten days. Their position is known every ten days, which gives a set of lagrangian data. We have developed a variational method in order to assimilate such data. Twin experiments were performed within the OPAVAR model, in an idealized configuration.
We currently have two directions of work. First, we are performing new sensitivity experiments, to assess the impact of the initial distribution of the floats (either homogeneous, or random, or else). Second, we which to address the problem of the representativeness error. To do that we generate high resolution data, and we assimilate them into a low resolution model.
This project is currently under development and is granted by the Mercator program and the LEFE-INSU program.

6.4.2. Variational Data Assimilation for the Identification of an Optimal Topography

Participant: Eugène Kazantsev.

Following a previous study on the sensitivity of the solution of an ocean model to the representation of the bottom topography, we focused our attention on the data assimilation procedure, which allows us to find an optimal topography pattern, corresponding to some optimality criterion.

The procedure is similar to data assimilation for the identification of an optimal initial condition of a model. In both cases we look for the model solution that minimizes the distance to the set of observations. However, the control parameter in this case is the model bottom topography rather than the initial condition.

This assimilation procedure has been tested for the simple barotropic ocean model that was previously used in the sensitivity study. Special attention was payed to the choice of the assimilation interval and of the amount of assimilated external information. Artificial observations generated by the same model were used in experiments. This allowed us to estimate the precision of the reconstruction of the topography pattern.

In order to estimate the influence of measurement errors that are present in real data, we performed a set of experiments of assimilation of polluted fields. The model with modified parameters is used to produce artificial observations in this case. The perturbation consists in a white noise added to the field at each grid point of the field. We first modify the model initial conditions, simulating the interpolation or assimilation errors. Second, we perturb the forcing of the model in order to simulate the different physics for real observations. And third, we add a white noise to the artificial observations at all grid-points and at all time steps in order to simulate the measurements errors.

The obtained results show the linear dependency of the error in the identified topography on the amplitude of the pollution. Hence, we can get the optimal topography with a good accuracy by assimilating observations.

The influence of the space grid of the model was also considered. When the artificial observational data are generated by a high resolution model, they contain small scale information that cannot be assimilated by a low resolution model. The problem of interpolation and smoothing of the high resolution data was discussed and the assimilation error was analyzed.

A paper has been submitted on this subject.

6.4.3. Development of a Variational Data Assimilation System for OPA9/NEMO

Participant: Arthur Vidard.

A new version of the french ocean model OPA (Ocean PArallèle), ocean component of the NEMO (Nucleus for European Modelling of the Ocean) framework was released in 2005. For the previous version of the OPA model (8.2) a variational data assimilation system, OPAVAR, was developed mainly by A. Weaver at CERFACS. However the OPA 9 model has been completely rewritten in Fortran 90 and the code structure is significantly different from the previous versions, making it quite difficult to update OPAVAR .

In early 2006 a collaborative project was initiated between MOISE project (A. Vidard), CERFACS (A. Weaver) and ECMWF (K. Mogensen) to develop NEMOVAR, a variational system for NEMO/OPA9.

Since a large community is interested in variational data assimilation with OPA9, we built a working group (coordinated by A. Vidard) in order to bring together various OPAVAR user-groups with diverse scientific interests (ranging from singular vector and sensitivity studies to specific issues in variational assimilation), and to get technical and scientific support from Inria Sophia (Automatic adjoint derivation, TROPICS project) and ECMWF (Parallelization). This project aimed at avoiding duplication of effort, and at developing a common NEMOVAR platform.
The project is now well advanced, a 3D variational system with limited capacity but fully parallel is now available. The transition from 3D to 4D requires the availability of the Tangent linear and Adjoint Model (NEMOTAM) of OPA9. A first version of NEMOTAM is being tested and will be released before the end of the year. However, a significant amount of work is still required to produce a suitable adjoint model for NEMOVAR.
NEMOTAM is developed in strong collaboration with the TROPICS team from INRIA Sophia-Antipolis.
The NEMOVAR working group gets financial support by LEFE-Assimilation and Mercator National Programs and this allowed to organize a NEMOVAR workshop in spring 2007.

6.4.4. Assimilation of Real Data in the Irminger Sea

Participant: Maëlle Nodet.

In collaboration with T. Haine (Johns Hopkins University, Baltimore, USA), we work on a NASA-funded project called "Estimating Arctic/Subarctic exchanges thanks to Data Assimilation". The Data Assimilation system, based on the MITgcm code, is currently under development. It will feature assimilation of real data such as satellite data and in-situ data (ships, moorings, floats).

6.5. Assimilation of Image Data

6.5.1. Assimilation of Images: the ADDISA project

Participants: François-Xavier Le Dimet, Innocent Souopgui, Olivier Titaud, Arthur Vidard, Laurent Debreu, Emilie Neveu.

ADDISA is a project coordinated by F.-X. Le Dimet and supported for three years (2007-2009) by the ANR

F.-X. Le Dimet, A. Vidard, O. Titaud and I. Souopgui implemented a shallow-water model coupled with an advection-diffusion model which simulates the drift of a vortex submitted to the Coriolis force. This simulation corresponds to some experiments performed by LEGI with the Coriolis platform where the motion of the vortex is focused by a passive tracer (cf. [98]). A 4D-Var method is being adapted to direct assimilation of images: the space of observations is a curvelet space (see [96]) and a corresponding operator is considered: it maps the space of state variables onto the image space. Twin experiences are considered before working on LEGI experiments. This work and the ADDISA project was presented by O. Titaud at the Russo-Franco-Ukrainian colloquium *Enhancement of data assimilation in the oceanographic models*, Marine Hydrophysical Institute, Sevastopol, Ukraine, 26-29 June 2007 (see [82]) and at the *Grand Colloque STIC 2007*, Cité des Sciences de la Villette, Paris, 5-7 November 2007 (see [57]). This work will be adapted to real Black Sea satellite images and oceanographic circulation model in collaboration with the Ukrainian *Marine Hydrophysical Institute* (proposal of an INRIA associated team *Advanced Data Assimilation Methods* *for the Sea*). Image Assimilation techniques was presented by F.-X. Le Dimet in various conferences (see bibliography). I. Souopgui presented active contours techniques for object localization and tracking in the MOISE workshop. Finally a two days workshop on assimilation of images was organized by O. Titaud at LJK in September 2007 (see http://addisa.gforge.inria.fr/2007_09_journees_ADDISA.php).

E. Neveu and L. Debreu are working on assimilation of images and trajectory in multi-resolution oceanographic models. The idea is to adapt the model resolution to the image scale and to perform information exchanges between models of different resolution.

6.5.2. Application of Variational Methods to the processing of space imagery

Participants: François-Xavier Le Dimet, Genady Korotaev.

In cooperation with the Institute of Oceanography (G. Korotiaev Ukrainian Academy of Sciences) and CLIME (I. Herlin, E. Huot, Rocquencourt).
From the observation of sea surface imagery the surface current velocity, at the mesoscale, level is extracted by using optimal control methods. It is assumed that the imagery contrast could be described by a transport diffusion equation. The method permots to retrieve an initial field of passive tracer together with surface current velocity from the sequence of images. Examples of processing of AVHRR observations and validations of results have been carried out.

6.6. Hydrology and River Hydraulics

Participants: William Castaings, Didier Bresch, Joël Marin, Marc Honnorat, François-Xavier Le Dimet, Jérôme Monnier.

6.6.1. Lagrangian Data Assimilation for River Hydraulic Models

Participants: Marc Honnorat, François-Xavier Le Dimet, Jérôme Monnier.

M. Honnorat has defended his PhD in october 2007, addressing the problem of the assimilation of image type data for flood models, [12]. This PhD has been supervised by J. Monnier and F.-X. Le Dimet, and funded by CNES and CNRS.
Dynamic images (a series of still images, or a video) of a river flow contain informations that can be used in a data assimilation process for the identification of model parameters, such as topography and land roughness.
Numerical experiments have shown that observed trajectories of passive individual tracers on the free surface of a river flow (lagrangian data) can bring valuable information on the flow velocity for the reconstruction of inflow discharge, very local topography and manning coefficients, [34].
The numerical method has been applied to a real flow in in a channel (rectangular cross section) with a broadcrested weir (wooden plank) placed on the bottom widthwise. As observations, we considered a video sequence of surface markers drifted by the water. This work has been done in collaboration with N. Rivière, LMFA Lyon (experiments) and E. Huot, CLIME team-project (image processing).
The objective of the data assimilation experiment is to identify the shape of the weir in the channel. The results we obtained seem promising since the shallow-water model reproduces correctly an equivalent topography, reproducing the broadcrested weir and the flow separations (recirculating zones), see Fig. 6.

6.6.2. Assimilation of a Flood Satellite Image

Participant: Jérôme Monnier.

In collaboration with X. Lai, researcher at Nanjing Institute of Geography and Limnology, Chinese Academy of sciences, who spent 10 months in our project-team in 2006 (fund Région Rhône-Alpes), R. Hostache (PhD Cemagref Montpellier) and C. Puech (DR Cemagref Montpellier, Maison de la télédétection), we investigated the contribution of one satellite image of a flood event (Moselle river) in 2D shallow-water flood model (variational data assimilation). To this end, we defined an extended cost function and adapted a temporal strategy to the classical variational data assimilation algorithm. Using our software (see 5.1), we showed that the satellite image allowed to improve the calibration of Manning roughness coefficients, see Figure 7. Furthermore, the identification of the inflow discharge has been investigated. These results are submitted or under redaction.

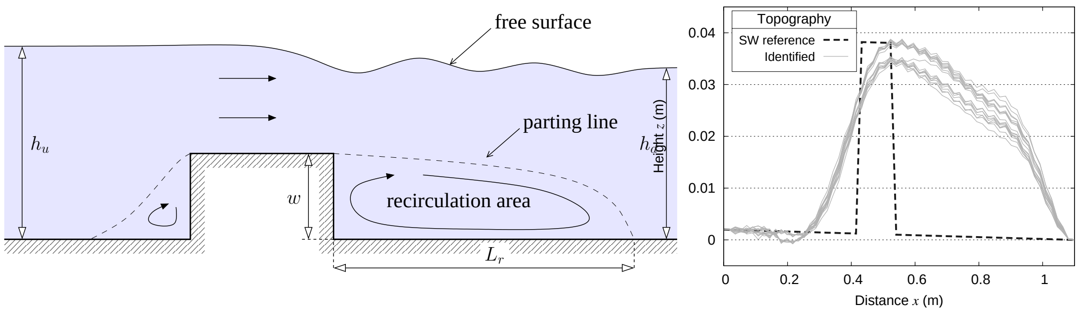


Figure 6. (a) Obs.: Schematic view of upstream and downstream recirculations around the obstacle. (b) Equivalent topography identified

6.6.3. Solvers for shallow-water equations: well-balanced schemes

Participants: Didier Bresch, Joël Marin, Jérôme Monnier.

In collaboration with E. Fernandez-Nieto (Ass. Prof., univ. Sevilla), we elaborated a HLLC well-balanced finite volume scheme for the 2D Shallow-Water equations with source term (or equivalently for the 1D shallow-water with transport of contaminant). A paper has been submitted on this subject. The scheme elaborated is based on a modification of the numerical flux which depends on the source term (the topography); it is not based on an upwinding of the source term. We obtain a well-balanced scheme and a consistent approximation of the intermediate wave speed. Numerical results show that a well-balanced scheme without such a consistent approximation of the intermediate wave speed can produce bad results.
In other respect, we considered the two shallow-water models 1.5D and 2D in order to couple them in a globally well-balanced way. We assume that their respective numerical scheme belong to a family of numerical solvers with extensions to non-homogeneous hyperbolic systems of Roe method, HLL, Russanov or numerical schemes using flux limiters. Then, we presented a technique to define the coupling terms such that the global scheme is well balanced, in the sense that it exactly preserves water at rest with or without over-flowing the 1D channel. Numerical tests show the efficiency of the coupling method using consistent grids or not. A paper on this subject is under progress (Fernandez-Nieto - Marin - Monnier).

6.6.4. Coupling 1D-2D river models: combined algorithms

Participants: Joël Marin, Jérôme Monnier.

In the continuity of our previous study [32], we improve the concept of a zoom model locally superposed on a 1D network global model. The zoom model (2D shallow-water equations) describes the flow dynamics inside the storage areas described in the 1D global model (1.5D shallow-water equations).
The improvement is done at all stage. First, the information transmitted from 1D to 2D has been rederived from the continuity equations; the classical 1.5D models (1D with storage area) become a particular case of the present (continuous) formulation. Second, upon work described in section 6.6.3, the finite volume schemes are builded in order to define a global well-balanced scheme. Third, we define a new sequential Joint Assimilation Coupling algorithm. The JAC algorithm consists to couple simultaneously with the data assimilation process (using the optimal control process). Thus this allows to assimilate local 2D observations into the 1D global model, while both models are coupled. This last version of JAC algorithm is more suitable if using existing computational softwares. Comparison of efficiency and CPU-time consuming are done between the two different versions of JAC algorithm, also accuracy is compared to a more classical Schwarz algorithm (global in time). An article is under preparation.

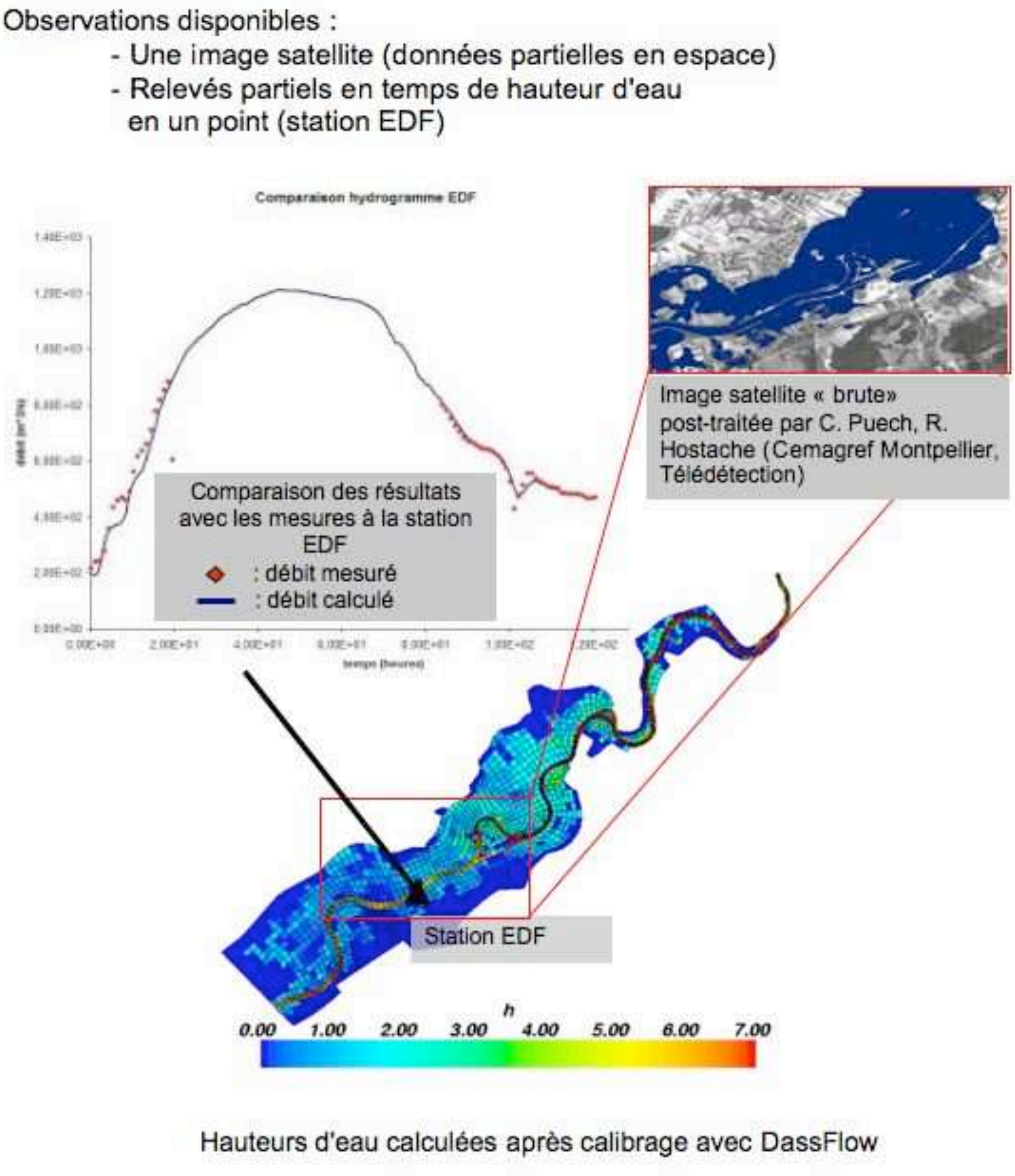


Figure 7. Flood of Mosel river: Assimilation of a partial satellite image and partial in-situ measurements.

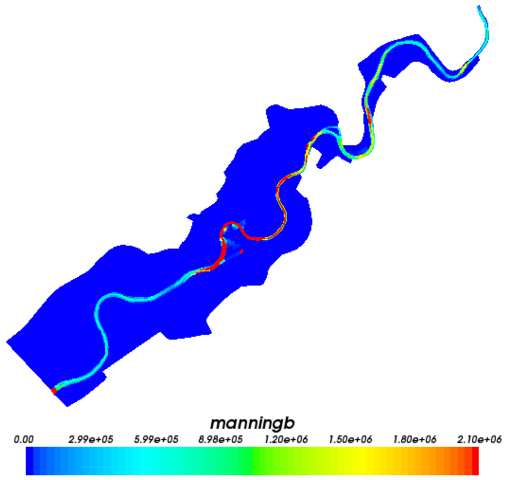


Figure 8. Flood of Mosel river: local sentivity wrt Manning values (10 land-uses).

6.6.5. Soil Water Transfer

Participants: Amélie Martinez, Jérôme Monnier, Maëlle Nodet.

In collaboration with I. Braud (Cemagref Lyon) and the start-up Hydrowide, we investigated numerical resolution of the Richards' equation. During her 6 months Master degree internship (supervisors: J. Monnier and M. Nodet), A. Martinez studied and implemented two numerical schemes to solve the one-dimensional Richards' equation: finite differences and finite volumes, both integrating saturated and unsaturated cases. A natural extension of these numerical schemes to the 3D case seems to be feasible, although CPU time consuming for (real) large scales. Next studies will address the reduction of models.

6.6.6. Adjoint sensitivity analysis and parameter estimation for hydrological modelling

Participants: William Castaings, François-Xavier Le Dimet.

During his PhD, W. Castaings investigated the potential of variational methods for some critical issues underlying the modelling of catchment scale hydrology.
The rainfall-runoff transformation is characterized by the complexity of the involved processes and by the limited observability of the atmospheric forcing, catchment properties and hydrological response. It is therefore essential to understand, analyze and reduce the uncertainty inherent to hydrological modelling (sensitivity and uncertainty analysis, data assimilation). Variational methods are widely used in other scientific disciplines (ex. Meteorology, oceanography) facing the same challenges. In this work, they were applied to hydrological models characterized by different modelling paradigms (reductionist vs. systemic) and runoff generation mechanisms (infiltration-excess vs. saturation excess). The potential and limitations of variational methods for catchment hydrology are illustrated with MARINE from the Toulouse Fluids Mechanics Institute (IMFT) and two models (event based flood model and continuous water balance model) based on TOPMODEL concepts developed at the Laboratory of Environmental Hydrology (LTHE). Forward and adjoint sensitivity analysis provide a local but extensive insight of the relation between model inputs and prognostic variables. The gradient of a performance measure (characterizing the misfit with observations), calculated with the adjoint model, efficiently drives a bound-constrained quasi-newton optimization algorithm for the estimation of model parameters. The results obtained are very encouraging and plead for an extensive use of the variational approach to understand and corroborate the processes described in hydrological models but

also estimate the model control variables (calibration of model parameters and state estimation using data assimilation).
The final version of the manuscript should be available early December 2007 (see [11]).

6.7. Direct simulation of complex fluid flows

Participants: Pierre Saramito, Ibrahim Cheddadi, Aymen Laadhari.

6.7.1. Numerical prediction of liquid foams

The numerical resolution of equations governing the elastoviscoplastic behavior of liquid foams [41], [53] is compared with available experimental data. Ibrahim Cheddadi (PhD student) develops the numerical simulation algorithms. This work is developed in collaboration with laboratoire de spectrométrie physique (LSP Grenoble): François Graner (DR CNRS), Philippe Marmottant (CR CNRS) and Christophe Raufaste (PhD student) perform experimental measurement and theoretical analysis. This action is supported by the PPF (Plan Pluri-formation *Fluides complexes*, U. Joseph Fourier).

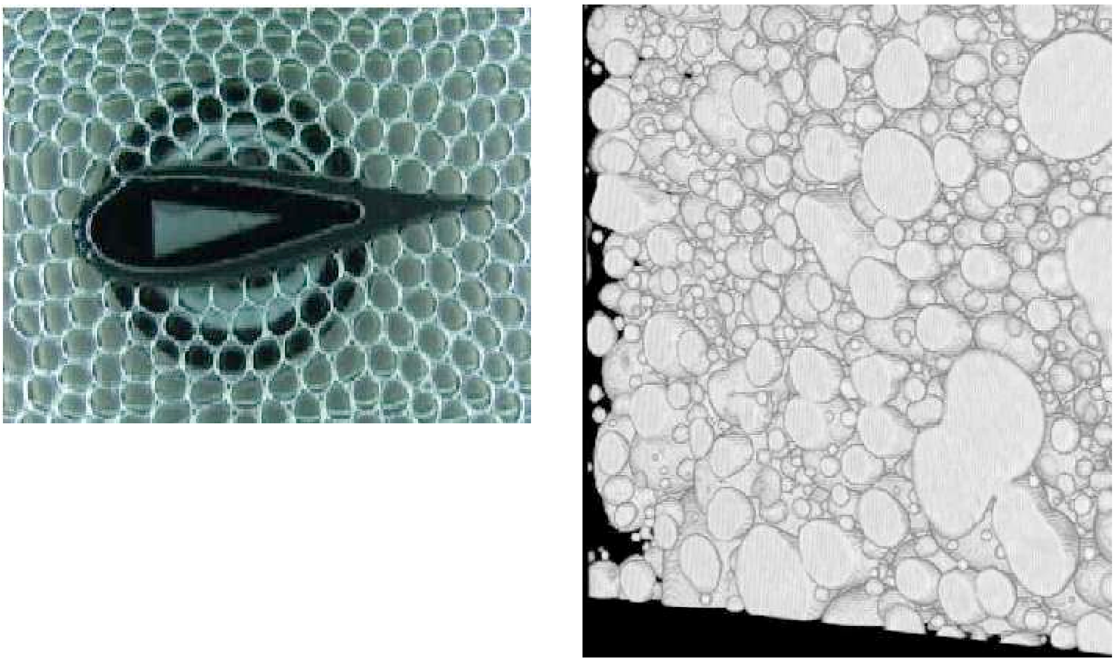


Figure 9. Foam flow : (Left) étirement des bulles autour d'un obstacle; (Right) structure 3D (LSP Grenoble / ESRF synchrotron).

6.7.2. Direct simulation of the motions of particle in flowing liquids

Our aim is to predict, by using the direct numerical simulation, the flow of a fluid containing particles. While case of rigid bodies particles has been already addressed in the past by many researchers, the case of deformable particle is still few explored. Aymen Laadhari (PhD student) develops the numerical simulation algorithms. This work is developed in collaboration with laboratoire de spectrometry physique (LSP Grenoble): Chaouqi Misbah (DR CNRS) and Mourad Ismail (MdC UJF). This action is partially supported by the ANR project *Modélisation et simulation de fluides complexes biomimétiques* MOSICOB animated by Bertrand Maury (Pr, U. Orsay).

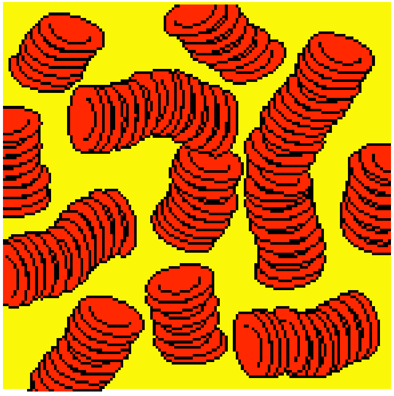


Figure 10. Blood flow: vesicules and agregate formation.

6.7.3. Numerical analysis of viscoelastic fluid models

Viscoelastic effects appears in numerous contexts: extrusion of polymers, molding and injection, inks, adhesion... These effects appears also for blood flows, in a time dependent context. The aim of this project is to develop robust high order schemes, in order to solve efficiently such time dependent flow problems: simple implicit one order schemes are often insufficient for such problems. This work is developed in collaboration with Marrocco (CNRS-DRI funding, 2003-2006). The coordination and the animation is assured by Pierre Saramito. Participants are Ibrahim Cheddadi (LJK, PhD student), Vuk Milisic (LJK, CR CNRS), Jocelyn Etienne (CR CNRS, LSP Grenoble), Ecole Centrale de Lyon : A. Zine (Pr) Mohammed Bensaada (PhD student, U. Kenitra, Marroco), Driss Esselaoui (Pr, U. Kenitra, Marroco), Al Moatassine (EC, U. Marrackech, Marroco), A. Machmoum (EC, U. Marrackech, Marroco).

6.7.4. Numerical resolution of viscoplastic flow problems

The prediction of natural hazards in mountain, from snow avalanches to mud flows and volcanic lava requires sophisticated numerical simulations and complex rheological laws for non-linear materials, such as yield stress fluids or granular flows. This simulation requires also specific numerical methods, in order to solve the corresponding large non-linear set of equations in a time-dependent context: finite elements or finite volume, automatic mesh adaptation. In collaboration with Nicolas Roquet (CR LCPC, Nantes), Pierre Saramito devellops new efficient numerical methods [39], [76], [81], [80] for the resolution of such flow problems.

6.7.5. Applications to debris and volcanic lava flows

Pierre Saramito develops a new collaboration with Yves Dumont and Claude Smutek (U. La Réunion) for the numerical prediction of volcanic lava flows. This work is funded by the La Réunion region (REAVOLC, 2007-2009). It is a conceptual continuation of a previous work animated by Pierre Saramito on debris flows and snow avalanches, in collaboration with Emil Hopfinger (DR CNRS, LEGI), Mohammed Naaim an Dominique Laigle (CEMAGREF), Marie-Paule Cani (PR UJF, LJK) and Fabrice Neyret (CR CNRS, LJK).

6.8. Glaciology

Participants: Eric Blayo, Joël Marin, Thierry Mastrosimone, Jérôme Monnier, Bénédicte Lemieux-Dudon.

6.8.1. Coupling and variational sensitivities for ice flows

Participants: Joël Marin, Thierry Mastrosimone, Jérôme Monnier.

Figure 11. Viscoplastic fluid flows: Volcanic lava flow, La Réunion, november 2002.

Thierry Mastrosimone started his PhD in applied mathematics at LJK in october 2007 (supervisors: J. Monnier, O. Gagliardini, fund: Bonus Qualité Recherche INP-G). Joël Marin (associate engineer INRIA, Sept. 06- Sept. 08) started to elaborate a forward solver for ice flows in september 2007. The studies described below are done in collaboration with O. Gagliardini and C. Ritz from LGGE - Grenoble and with MIDIGA project (F. Parrenin, E. Blayo). Also, an INSU - LEFE assimilation support has been asked in september 07.
This autumn, we started to address the following two problems: 1) the re-derivation of the asymptotic equations (shallow-ice, 2nd order) in presence of general friction basal boundary conditions;
2) an efficient finite element computational code of Stokes 2D Non-newtonian with free surface flows, differentiable by the Tapenade tool.
Then, we plan to develop some processes of identification / variational data assimilation and a combined weak superposition process, similar to those done in river hydraulics but applied to the present two models free-surface / asymptotic. The final objective being a reliable coupling between the local 3D model ("full Stokes") with the global asymptotic model (shallow-ice). Let us remark that the local high resolution model and the global one are solved on very different space-time grids, while variables are not the same.
Few questions will be addressed: what kind of boundary conditions must be prescribed on the open lateral boundaries? on the basal boundary (change of regime in marine ice-sheets) ? Are the asymptotic equations able to reproduce the relationship between sub glacial lakes and flattening of the free surface? Is it possible to use this feature to detect sub glacial lakes from the surface topography? etc
In a glaciology point of view, one of the final aim would be to obtain multi-scale calibrated ice flow models either in the neighborhood of the deep ice cores recently obtained in Antarctica or in the neighborhood of ice streams (marine ice-sheets).

6.8.2. Inverse methods for ice cores dating

Participants: Eric Blayo, Bénédicte Lemieux-Dudon, Frédéric Parrenin.

Data from deep ice cores provides substantial informations in order to study past climatic mechanisms. The calculation of precise core chronologies, i.e. depth-age relationship, is a prerequisite to infer climatic scenario from the analysis of the core records (i.e. gas composition, temperature proxy...). The main techniques used up to now to estimate these chronologies are based on the modeling of the ice flow as well as on the use of age markers (i.e. estimate of the age of layers by physicochemical measurements on ice material) but also (when feasible) on the counting of annual layers. The synchronization of distinct core chronologies is also a crucial step enabling the comparison of distinct core records. This synchronization is achieved using specific events (like volcanic or climatic events) which imprint several cores at the same time with a recognizable and common signature. In her PhD thesis, B. Lemieux-Dudon is developing a new inverse method which aims at combining these complementary informations in order to build a common and optimized chronology for several cores simultaneously. This method takes into account the model uncertainty which cannot be ignored in the context of simplified flow representation that are currently involved in the inversion process. This new approach enables to respect large sets of age markers and to determine robust confidence intervals on the solution. It relies on a bayesian framework and assumes lognormal error statistic for the control variables and some observations. This method has been tested on three cores simultaneously (EPICA DC, EPICA DML and Vostok) and more than 200 observations have been successfully assimilated. The sensitivity of the solution with respect to the background information, especially the error covariance matrix, has also been analyzed. This method will be used in the future to build a reference chronology for Quaternary polar records.

6.9. Downscaling stochastic method

Participant: Antoine Rousseau.

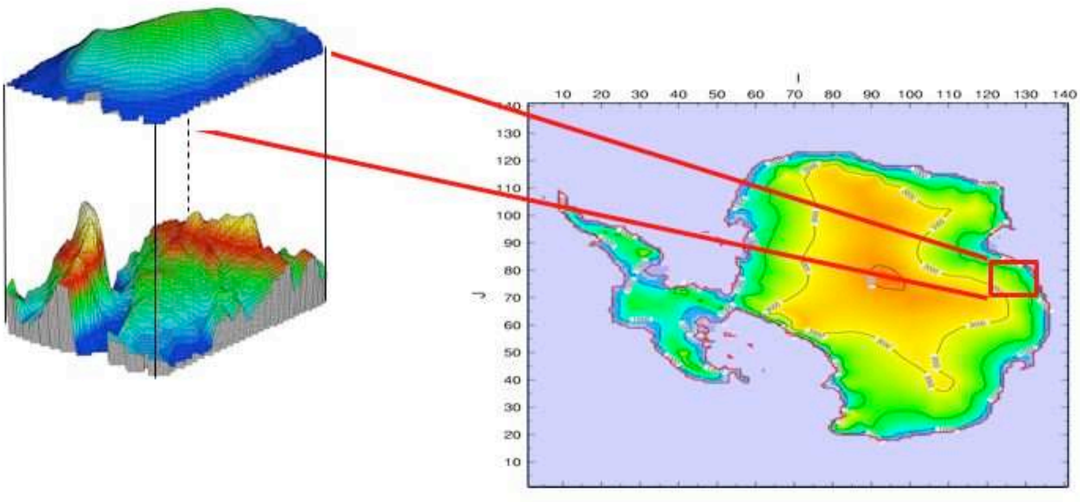


Figure 12. Ice-flows in Antarctic: superposition of a local high resolution model (Stokes with free-surface) and a global model (asymptotic equations).

In collaboration with TOSCA (Inria Sophia-Antipolis), LMD (Ecole Polytechnique) and CETE (Clermont-Ferrand), we investigate a new method for the numerical simulation of the wind at small scales. Thanks to boundary data provided at large scales by the weather forecasting code $MM5$, we propose a Langevin model that rules the behaviour of stochastic particles. This model called DSM (Downscaling Stochastic Method) is adapted from previous works introduced by S.B. Pope, [101], and has been presented in [77], [47]. This research program is funded by ADEME (Agence de Développement de l'Écologie et de la Maîtrise de l'Énergie).
During summer 2007, A. Rousseau managed a research program at CEMRACS, and the group adapted an algorithm from D. Bertsekas [95], in order to compute the solution of an optimal transport problem that concerns the particles involved in DSM: see [87]. This research program was funded by CEMRACS and INRIA (Service de Formation par la Recherche).

6.10. Control of the Wave Equation

Participant: Maëlle Nodet.

In collaboration with G. Lebeau, we investigate a new method to solve the problem of distributed control of the wave equations over a bounded domain. This problem has been addressed by J.-L. Lions [99] and the HUM method is well-known. G. Lebeau and B. Dehman (work in progress) propose a new method to theoretically resolve the HUM problem, avoiding the use of now-classic multi-grid approaches. M. Nodet started working on the numerical implementation of this method.

7. Contracts and Grants with Industry

7.1. Regional Contracts

Ongoing in 2007:

- A project within the GRAVIT (Grenoble Alpes Valorisation Innovation Technologies) framework on "Numerical Computations on heterogeneous clusters and application to weather forecasting".

7.2. National Contracts

Ongoing in 2007:

- A 15 months contract with IFREMER on the thematic "Numerical Methods in Ocean Modelling".
- A 3-year contract with ADEME on the thematic "downscaling stochastic method": see 6.9.
- A 1-year contract with MERCATOR on the thematic "Assimilation of lagrangian data in OPAVAR": see 6.4.1.
- A 6-months contract with Degreane-Horizon (6000Û)on the topic "Wind Field Estimation in the Vicinity of an Airport Using a Radar Profiler". Alexandre Boilley did his M2R internship in the MOISE project team (supervisor A. Vidard). A. Boilley is now starting a PhD in Meteo-France on this topic. A. Vidard and F.-X. le Dimet are part of the steering committee of this thesis.

8. Other Grants and Activities

8.1. Regional Actions

8.1.1. Regional Projects

- E. Blayo is the co-leader (with F. Desprez, ENS Lyon) of the regional project (Région Rhône-Alpes) "**Distributed High-Performance Computing**" 2005-2010, which conducts researches both in software and mathematical aspects of grid-computing. This project involves a dozen of regional research teams.
- F.X. Le Dimet is responsible for numerical modelling within a regional project (Région Rhône-Alpes) "**Envirhonalp**" 2005-2010. This project aims at gathering physicists, engineers and applied mathematicians to provide improved modelling and decision tools for environmental processes.
- J. Monnier is responsible of a 3-year contract with INP-G (BQR) on the thematic "Coupling and assimilation for ice flows": see 6.8.

8.1.2. Collaborations with Various Regional Research Teams

- MEOM (Modélisation des Écoulements Océaniques à Moyenne échelle) team from Laboratoire d'Écoulements Géophysiques et Industriels (Grenoble): oceanography: see 6.2.
- Laboratoire de Transferts en Hydrologie et Environnement (Grenoble): see 6.6.
- Cemagref Lyon, Department Hydrology and Hydraulics: 6.6.
- Laboratoire de mécanique des fluides et d'acoustique (Lyon): 6.6.
- LEGI, PIM project-team (Particules Interfaces Microfluidique): 6.2.
- LGGE, Laboratoire de Glaciologie, Géophysique et Environnement: 6.8.

8.2. National Actions

8.2.1. Interactions with other INRIA Projects or Actions

Participants	INRIA Project	Research topic	Link
J. Monnier, A. Vidard, F.X. Le Dimet	CLIME	Image Processing and Data Assimilation	6.6
A. Rousseau	TOSCA	Downscaling Stochastic Methods	6.9
J. Monnier, A. Vidard	TROPICS	Adjoint code automatic differentiation (TAPENADE) and operational inverse mode	6.6 6.4

8.2.2. Collaborations with other Research Teams in France

Participants	Research Team	Research topic	Link
[1]	MERCATOR-Ocean	Ocean Modelling and Data Assimilation	6.1 6.2 6.4
A. Vidard	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (Toulouse)	Ocean Data Assimilation	6.4.3
[2]	Laboratoire d'Analyse, Géométrie et Applications (Paris 13)	Domain Decomposition and Coupling Methods	6.1.2
[3]	IFREMER Brest	Ocean Modelling	6.1.2
J. Monnier	Cemagref Montpellier, Maison de la Télédétection	Image Processing	6.6
L. Debreu F. Lemarié	IRD Brest	Ocean Modelling Atmosphere-Ocean Coupling	6.1.2
F.-X. Le Dimet	Laboratoire de Météorologie Dynamique (ENS Paris)	Data Assimilation for Environment	6.5
A. Rousseau	Laboratoire de Météorologie Dynamique (Ecole Polytechnique)	Downscaling Stochastic Methods	6.9
A. Rousseau	Centre d'Études Techniques de l'Équipement	Downscaling Stochastic Methods	6.9
[4]	Cemagref Montpellier, Maison de la Télédétection	Data Assimilation of Flood Satellite Images	6.6.2
M. Nodet	Laboratoire Dieudonné (Université de Nice) (G. Lebeau)	Control of the Wave Equation	6.10
D. Auroux, M. Nodet	Laboratoire Dieudonné (Université de Nice) (J. Blum)	BFN data assimilation scheme	6.2.6

[1] : E. Blayo, L. Debreu, M. Nodet, C. Robert, A. Vidard.

[2] : E. Blayo, L. Debreu, F. Lemarié, E. Nourtier, C. Robert, A. Rousseau.

[3] : E. Blayo, L. Debreu, F. Lemarié, J. Marin, M. Nodet, E. Nourtier, C. Robert.

[4] : M. Honnorat, F.X. Le Dimet, J. Monnier.

8.2.3. Participation to National Research Groups (GdR) CNRS

- D. Bresch, C. Lucas and A. Rousseau participate to the GdR MOAD (Modelling Asymptotics and nonlinear Dynamics) managed by S. Benzoni and to the GdR CHANT managed by F. Castella.
- D. Auroux participates to the GdR MOMAS (Modélisations Mathématiques et Simulations numériques liées aux problèmes de gestion des déchets nucléaires).

8.2.4. Other National Actions

- F.X. Le Dimet is in charge of the project ADDISA (http://addisa.gforge.inria.fr, see 6.5.1) devoted to the assimilation of images in numerical models in the framework of the ANR "Masse de données et Connaissances Ambiantes". ADDISA began in January 2007 and will end in december 2009. A. Vidard, L. Debreu, D. Auroux, E. Neveu, I. Souopgui and O. Titaud are also involved in ADDISA. Four other national partners are involved in ADDISA : INRIA team-project Clime ; Groupe d'études de l'Atmosphère Météorologique (GAME) URA CNRS - Météo-France 1357 ; Laboratoire des Ecoulements Géophysiques et Industriels (LEGI), UMR CNRS 5519 ; Institut de Mathématiques de Toulouse, UMR CNRS 5219. ADDISA has an international extension called ADDISAAF (see section 8.4)

- E. Blayo is a member of the scientific committee of Mercator-Ocean (French national center for operational oceanography)
- E. Blayo is a member of the scientific committee of LEFE-ASSIM (national research program on data assimilation)
- D. Bresch is a member of the scientific committee of GdR CNRS MOAD (Modélisation, Asymptotique et Dynamique) who is chaired by S. Benzoni Gavage.
- M. Nodet and D. Auroux are involved in Jacques Blum's project "Un nouvel observateur: le back and forth nudging (BFN) - Études théoriques, numériques et applications" supported by INSU-LEFE.
- A. Vidard leads a project gathering multiple partners in France and UK on the topic "Variational Data Assimilation for the NEMO/OPA9 Ocean Model", see 6.4.3. This project is granted by INSU-LEFE.
- M. Nodet is in charge of a 2-year contract with LEFE-INSU on the thematic "Assimilation of lagrangian data in OPAVAR": see 6.4.1.
- Numerous members of the team are also supported by IDRIS (French national super-computing center) and get computing hours on parallel and vectorial supercomputers.
- D. Auroux is in charge of the project PROSSDAG (Probing new sequential schemes for retrospective data assimilation in geophysics) supported by ANR. This project will begin end of 2007.
- Florian Lemarié is involved in the ANR project "Cyclônes and climate" led by Christophe Menkes (LOCEAN,IRD Nouméa) and Jean-Franois Royer (CNRM Météo-France). One of the main objectives of this project is to tackle present and future cyclone activity and its relation with the ENSO phenomenon (El Nino Southern Oscillation), not only in climate models but also in regional downscaling performed with high resolution regional oceanic and atmospheric models.
- 2003-2007: P. Saramito participates to the project MOSICOB, *Modélisation et simulation de fluides complexes biomimétiques*, supported by the ANR (See 6.7.2).
- 2007-2010: P. Saramito : Plan pluri-formation (PPF) *Dynamique des systèmes complexes* (DYSCO), UJF (See 6.7.1).
- 2007-2009: P. Saramito : REAVOLC with *La Réunion region* (See 6.7.5).

8.3. European Actions

- MOÏSE is a partner of the european MERSEA project (http://www.mersea.eu.org). This project is led by IFREMER, and aims at developing a European system for operational oceanography (participants : E. Blayo, L. Debreu, C. Robert).
- J. Monnier is involved in a joint work with E. Fernandez-Nieto (University of Sevilla), C. Pares (Univ. Malaga), E. Miglio and L. Bonaventura (Politecnico Milano) (development of a common computational platform dedicated to surface flows). He also collaborated with I. Gejadze (University of Strathclyde).
- D. Bresch collaborates with F. Guillen-Gonzalez and E. Fernandez-Nieto in Sevilla on shallow water modeling, with J. Videman in Lisboa on multi-scale analysis.
- D. Bresch, C. Lucas and A. Rousseau collaborate with R. Klein (Potsdam Institute of Climatology) in Germany.
- A. Vidard collaborates with ECMWF (Reading, UK) on the development of a variational data assimilation system for the NEMO ocean model. Yannick Trémolet from ECMWF spent one month visiting our team. He worked with A. Vidard on implementing new ideas about control of model errors in variational data assimilation with the OPA ocean general circulation model.

- F.X Le Dimet collaborates with I. Gejadze (Dept. of Civil Engineering, University of Strathclyde, Scotland) and V. Shutyaev (Institute of Numerical Mathematics, Russian Academy of Sciences) on propagation and control of the error in data assimilation and on evaluation of error covariance by deterministic method.

8.4. International Actions

- F.-X. Le Dimet is in charge of an action (ECCO-NET) of cooperation with Russia (Institute of Numerical Mathematics of the Russian Academy of Sciences) and Ukrain (Institute of Oceanography of the Ukrainian Academy of Sciences). The theme of this cooperation is the data assimilation for geophysical flows. This cooperation will end in december 2007.
- L. Debreu, F.X. Le Dimet, A Vidard O. Titaud, E. Neveu and I. Souopgui are involved in the international project ADDISAAF (ADDISA for Africa), coordinated by E . Kamgnia (University of Yaoundé I) and I. Herlin (INRIA Clime). Other partner is: Ecole Nationale d'Ingénieurs de Tunis, Tunisia.
- There also exists a strong cooperation on this theme with China (Institute of Atmospheric Physics of the Chinese A.S.) and Vietnam (Institute of Mathematics and Institute of Mechanics of the Vietnamese A.S.).
- In collaboration with Carl Wunsch Team at Earth Atmosphere and Planetary Sciences department at MIT, MOISE is in charge of a contract of cooperation France-MIT.
- MOISE belongs to the SARIMA project for cooperation in computer Sciences and Applied Mathematics between France and Africa. This project funds the PhD of Innocent Souopgui, which started in 2006.
- J. Monnier collaborates with X. Lai (Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences) on data assimilation of floods.
- A. Rousseau collaborates with Roger Temam (Indiana University) and Joe Tribbia (NCAR) on the theoretical and numerical studies of open boundary conditions for the primitive equations of the ocean: see 6.1.1.
- M. Nodet collaborates with Tom Haine about "Estimating Arctic/Subarctic exchanges thanks to Data Assimilation" (see 6.4.4). She visited Thomas Haine (Earth and Planetary Sciences department) at the Johns Hopkins University (Baltimore USA) for two weeks in October.
- D. Auroux is involved in an IFCPAR project (Indo-French center for the promotion of advanced research) and a collaboration with India (Indian Institute of Science, Bangalore). This project deals with the control and forecast of systems of partial differential equations and started in October 2007.

9. Dissemination

9.1. Scientific Community Dissemination

- E. Nourtier (and recently M. Nodet) is in charge of MOISE fortnightly workshop, see http://ljk.imag.fr/MOISE/Seminars/gdt_moise.php. This workshop generally features a talk from either a member of the team, or scientists working on subjects of interest for us, especially physicists from Rhône-Alpes region.

9.2. Teaching

9.2.1. Teaching at Grenoble University

Half of the team members are faculty, and give lectures in the Master in applied mathematics of the Joseph Fourier University and the Institut National Polytechnique de Grenoble (ENSIMAG). The non-faculty (INRIA/CNRS) members of the project also participate to teaching activities.

F.-X. Le Dimet and M. Nodet organized (in collaboration with E. Cosme, LEGI) a graduate course "Introduction to Data Assimilation: Methods and Applications". In 2007, most of the attendees were from Grenoble, and a couple of them were from other research centers in France. This course will be reorganized (with E. Blayo) in 2008 and extended to a national audience.

9.2.2. Lectures Given in International Schools and Foreign Universities

- F.-X. Le Dimet gave lectures on Data Assimilation to PhD students of the Institute of Mechanics, Academy of Sciences of Vietnam (February 2007) and University of Yaoundé, Cameroon (July 2007)

9.3. Conferences and Workshops

- The members of the team have participated to various conferences and workshops (see the bibliography).
- F.X. Le Dimet co-organized the following summer schools or tutorials on Data Assimilation for Geosciences:
  - Institute of Mechanics, Hanoi, Vietnam, March 2006,
  - Universidade de Chile, Santiago, Chile, October 2006,
  - Université de Ahomey, Bénin, November 2006.
- J. Monnier organized a one day international workshop entitled "Numerical Modelling for Floods" at LMC-IMAG, supported by the regional project Rhône-Alpes (8th february 2006).
- A. Rousseau co-organized the SMAI 2007 workshop in Praz-sur-Arly, june 2007.
- O. Titaud organized a meeting of the ADDISA partners on Image Assimilation at LJK, Grenoble (Sept. 2007)

10. Bibliography

Major publications by the team in recent years

[1] E. Blayo, L. Debreu. *Revisiting open boundary conditions from the point of view of characteristic variables*, in "Ocean Modelling", vol. 9, 2005, p. 231-252, http://hal.inria.fr/inria-00134856/fr/.

[2] D. Bresch, B. Desjardins. *On the existence of global weak solutions to the Navier-Stokes equations for viscous compressible and heat conducting fluids*, in "J. Math. Pures et Appl.", vol. 57, n^{o} 9, 2007, p. 57-90.

[3] L. Debreu, C. Vouland, É. Blayo. *AGRIF: Adaptive Grid Refinement in Fortran*, in "Computers and Geosciences", to appear, 2007.

[4] J. Etienne, P. Saramito, E. Hopfinger. *Numerical simulations of dense clouds on steep slopes: application to powder-snow avalanches*, in "Annals of Glaciology", vol. 38, 2005, 379—392.

[5] M. Honnorat, J. Monnier, F.-X. Le Dimet. *Lagrangian data assimilation for river hydraulics simulations*, in "Comput. Visual. Sc. (CVS)", 2007.

[6] M. Jianwei, A. Antoniadis, F.-X. Le Dimet. *Curvelet-Based Snake for Multiscale Detection and Tracking of Geophysical Fluids*, in "IEEE Transaction on Geoscence and Remote Sensing", to appear, 2006.

[7] F.-X. LE DIMET, V. SHUTYAEV. *On Determinisitic Error Analysis in Data Assimilation*, in "Nonlinear Processes in Geophysics", vol. 12, 2005, p. 481-490.

[8] M. NODET. *Variational assimilation of Lagrangian data in oceanography*, in "Inverse Problems", vol. 22, 2006, p. 245-263, http://hal.inria.fr/inria-00173069/fr/.

[9] C. ROBERT, S. DURBIANO, E. BLAYO, J. VERRON, F.-X. LE DIMET. *A reduced order strategy for 4D-Var data assimilation*, in "Journal of Marine Systems", vol. 57, 2005, p. 70-82.

[10] A. ROUSSEAU, R. TEMAM, J. TRIBBIA. *The 3d primitive equations in the absence of viscosity: boundary conditions and well-posedness in the linearized case*, in "J. Math. Pures Appl. (9)", to appear, 2007, http://hal.inria.fr/inria-00179961/fr/.

Year Publications

Doctoral dissertations and Habilitation theses

[11] W. CASTAINGS. *Sensitivity analysis and parameter estimation for hydrological modelling: Sensitivity analysis and parameter estimation for hydrological modelling: potential and limitations of variational methods*, Ph. D. Thesis, Université Joseph Fourier, 2007.

[12] M. HONNORAT. *Assimilation de données Lagrangiennes pour la simulation numérique en hydraulique fluviale*, Ph. D. Thesis, Institut National Polytechnique - Grenoble, 2007.

[13] C. LUCAS. *Effets de petites échelles, du tenseur des contraintes, des conditions au fond et à la surface sur les équations de Saint-Venant*, Ph. D. Thesis, Université Joseph Fourier, 2007.

[14] J. MONNIER. *Modèles numériques directs et inverses d'écoulements de fluides*, Habilitation à Diriger des Recherches, Institut National Polytechnique - Grenoble, 2007.

[15] E. SIMON. *Assimilation variationnelle de données pour des modèles emboîtés*, Ph. D. Thesis, Université Joseph Fourier, 2007.

Articles in refereed journals and book chapters

[16] D. AUROUX. *Generalization of the dual variational data assimilation algorithm to a nonlinear layered quasi-geostrophic ocean model*, in "Inverse Problems", vol. 23, n° 6, 2007, p. 2485–2503, http://hal.inria.fr/inria-00189641/fr/.

[17] M. BALMASEDA, D. ANDERSON, A. VIDARD. *Impact of ARGO on analyses of the global ocean.*, in "Geophysical Research Letters", vol. 34, 2007, http://hal.inria.fr/inria-00181749/en/.

[18] M. BALMASEDA, D. DEE, A. VIDARD, D. ANDERSON. *A Multivariate Treatment of Bias for Sequential Data Assimilation: Application to the Tropical Oceans*, in "Quarterly Journal- Royal Meteorological Society", vol. 133, 2007, p. 167–179, http://hal.inria.fr/inria-00176159/en/.

[19] M. BALMASEDA, G. SMITH, K. HAINES, D. ANDERSON, T. PALMER, A. VIDARD. *Historical reconstruction of the Atlantic Meridional Overturning Circulation from the ECMWF operational ocean reanalysis*, in "Geophysical Research Letters", To appear, 2007, http://hal.inria.fr/inria-00181739/en/.

[20] H. BESSIÈRE, H. ROUX, F.-X. LE DIMET, D. DARTUS. *Assimilation de données*, in "Guide OMM Hydrologie", J.-M. TANGUY (editor), to appear, 2007.

[21] É. BLAYO, L. HALPERN, C. JAPHET. *Optimized Schwarz waveform relaxation algorithms with nonconforming time discretization for coupling convection-diffusion problems with discontinuous coefficients*, in "Domain Decomposition Methods in Science and Engineering XVI", O. B. WIDLUND, D. E. KEYES (editors), Lecture Notes in Computational Science and Engineering, vol. 55, Springer, 2007, http://hal.inria.fr/inria-00187555/fr/.

[22] D. BRESCH, B. DESJARDINS. *On the existence of global weak solutions to the Navier-Stokes equations for viscous compressible and heat conducting fluids*, in "J. Math. Pures et Appl.", vol. 57, n^{o} 9, 2007, p. 57-90.

[23] D. BRESCH, B. DESJARDINS, M. GISCLON, R. SART. *The Rayleigh-Taylor instability and the Korteweg system*, in "Ann. Univ. Ferrara", to appear, 2007.

[24] D. BRESCH, B. DESJARDINS, E. GRENIER. *Crossing of eigenvalues: Measure type estimates*, in "J. Diff. Equations", vol. 241, n^{o} 2, 2007, p. 207–224.

[25] D. BRESCH, E. H. ESSOUFI, M. SY. *Effect of density dependent viscosities on multiphasic incompressible fluid models*, in "J. Math. Fluid Mech.", vol. 9, n^{o} 3, 2007, p. 377–397.

[26] D. BRESCH, D. GÉRARD-VARET. *On some homogeneization problems from shallow water equations*, in "Appl. Math. Lett.", vol. 20, n^{o} 5, 2007, p. 505-510.

[27] S. CAILLEAU, V. FEDORENKO, B. BARNIER, É. BLAYO, L. DEBREU. *Comparison of different numerical methods used to handle the open boundary of a regional ocean circulation model of the Bay of Biscay*, in "Ocean Modelling", to appear, 2007.

[28] W. CASTAINGS, D. DARTUS, F.-X. LE DIMET, G.-M. SAULNIER. *Sensitivity Analysis and Parameter Estimation for the distributed modeling of infiltration excess overland flow*, in "Hydrol. Eart Syst. Sci.", vol. 4, 2007, p. 1-42.

[29] J. CHANUT, B. BARNIER, W. LARGE, L. DEBREU, T. PENDUFF, J.-M. MOLINES. *Mesoscale eddies in the Labrador Sea and their contribution to convection and restratification*, in "Journal of Physical Oceanography", to appear, 2007.

[30] Q. CHENG, J. LAMINIE, A. ROUSSEAU, R. TEMAM, J. TRIBBIA. *A 2.5D Model for the Equations of the Ocean and the Atmosphere*, in "Analysis and Applications", vol. 5, n^{o} 3, 2007, p. 199–229, http://hal.inria.fr/inria-00172578/fr/.

[31] L. DEBREU, C. VOULAND, É. BLAYO. *AGRIF: Adaptive Grid Refinement in Fortran*, in "Computers and Geosciences", to appear, 2007.

[32] I. GEJADZE, J. MONNIER. *On a 2D zoom for 1D shallow-water model: coupling and data assimilation*, in "Comp. Meth. Appl. Mech. Engnr. (CMAME)", to appear, 2007.

[33] I. GEJADZE, F.-X. LE DIMET, V. SHUTYAEV. *On analysis error covariance in optimal control problem*, in "SIAM Journal on Scientific Computing", to appear, 2007.

[34] M. HONNORAT, F.-X. LE DIMET, J. MONNIER. *Lagrangian data assimilation for river hydraulics simulations*, in "Comput. Visu. Sc. (CVS)", to appear, 2007.

[35] C. LUCAS. *Cosine Effect on Shallow Water Equations and Mathematical Properties*, in "Quarterly of Applied Mathematics", to appear, 2007, http://hal.inria.fr/inria-00186560/en/.

[36] C. LUCAS. *Effet cosinus sur un modèle visqueux de type Saint-Venant et ses équations limites de type quasi-géostrophique et lacs*, in "C. R. Acad. Sci. Paris, Ser. I", vol. 345, 2007, p. 313–318.

[37] J. MONNIER, A. BENSELAMA, I. COTOI. *Flow patterns in the vicinity of triple line dynamics arising from a local surface tension model*, in "Int. J. Comput. Multiscale Comput. Eng. (IJCMCE)", to appear, 2007.

[38] P. PENVEN, P. MARCHESIELLO, L. DEBREU, J. LEFÈVRE. *Sotfware tools for pre- and post-processing of oceanic regional simulations*, in "Environmental Modelling and Software", to appear, 2007.

[39] N. ROQUET, P. SARAMITO. *An adaptive finite element method for viscoplastic flows in a square pipe with stick-slip at the wall*, in "J. Non Newtonian Fluid Mech.", To appear, 2007.

[40] A. ROUSSEAU, R. TEMAM, J. TRIBBIA. *The 3d primitive equations in the absence of viscosity: boundary conditions and well-posedness in the linearized case*, in "J. Math. Pures Appl. (9)", to appear, 2007, http://hal.inria.fr/inria-00179961/fr/.

[41] P. SARAMITO. *A new constitutive equation for elastoviscoplastic fluid flows*, in "J. Non Newtonian Fluid Mech.", vol. 145, n^{o} 1, 2007, p. 1-14.

[42] A. VIDARD, D. ANDERSON, M. BALMASEDA. *Impact of Ocean Observation Systems on Ocean Analysis and Seasonal Forecasts*, in "Monthly Weather Review", vol. 135, 2007, p. 409–429, http://hal.inria.fr/inria-00176154/en/.

Publications in Conferences and Workshops

[43] E. AUDUSSE, É. BLAYO, L. HALPERN, C. JAPHET, V. MARTIN, É. NOURTIER-MAZAURIC. *Des conditions d'interface efficaces pour le couplage de modèles océaniques*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly, Grenoble", 4–8 juin 2007, 217.

[44] E. AUDUSSE, É. BLAYO, L. HALPERN, C. JAPHET, V. MARTIN, É. NOURTIER-MAZAURIC. *Efficient interface conditions for the coupling of ocean models*, in "Computational Methods for Coupled Problems in Science and Engineering II, Barcelona, Spain", E. OÑATE, M. PAPADRAKAKIS, B. SCHREFLER (editors), International Center for Numerical Methods in Engineering (CIMNE), May 2007, p. 528–531, http://hal.inria.fr/inria-00180920/fr/.

[45] D. AUROUX. *Back and forth nudging algorithm for data assimilation problems*, in "SPARC Data Assimilation Workshop, Toronto, Canada", September 2007.

[46] D. AUROUX, J. BLUM. *Back and forth nudging algorithm for data assimilation problems*, in "European Geophysical Union, Vienna, Austria", April 2007.

[47] F. BERNARDIN, M. BOSSY, A. ROUSSEAU, T. SALAMEH, P. DROBINSKI. *Local wind simulation using a stochastic particle method*, in "SciCADE 2007, International Conference on SCientific Computation and Differenttial Equations, Saint-Malo, France", 2007.

[48] É. BLAYO. *Direct and inverse modelling in environmental sciences*, in "Understanding and solving multiphysics problems for industry and society with large scale simulation, Montbonnot", Congrès Franco-Finlandais, 2007.

[49] É. BLAYO. *Open boundary conditions*, in "Workshop on Numerical Methods in Ocean Models, Bergen, Norway", 2007.

[50] É. BLAYO, L. DEBREU, F. DUMAS, V. GARNIER, J. MARIN, C. ROBERT, F. VANDERMEIRSCH. *Investigation of 2-D and 3-D characteristic-based open boundary conditions for regional ocean models*, in "Congrès de l'European Geophysical Union, Vienne", 2007.

[51] É. BLAYO, C. ROBERT, J. VERRON. *Reduced order approaches for variational data assimilation in a model of the Tropical Pacific ocean*, in "SIAM Conference on Computational Science and Engineering, Costa Mesa", 2007.

[52] C. CHAUVIN, P. SARAMITO, C. TROPHIME. *Estimation d'erreur a posteriori et adaptation de maillage pour le problème du thermistor*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly", June 2007.

[53] I. CHEDDADI, P. SARAMITO, F. GRANER. *Modélisation numérique des écoulements de mousse*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly", June 2007.

[54] I. CHEDDADI, P. SARAMITO, F. GRANER, P. MARMOTTANT, C. RAUFASTE. *Couette flow of a foam: numerical simulation and experiments*, in "Visco-plastic fluids: from theory to application, Monte Verità (Tessin), Switzerland", October 2007.

[55] L. DEBREU. *Two-Way Nesting*, in "Workshop on Numerical Methods in Ocean Models, Bergen, Norway", august 2007.

[56] I. GEJADZE, J. MONNIER. *Superposition of a local zoom model using optimal control. Application to 1D-2D river flows*, in "ECCOMAS 'Coupled problems'. Ibiza", May 2007.

[57] E. HUOT, O. TITAUD. *ADDISA, Assimilation de Données Distribuées et Images Satellites*, in "Grand Colloque STIC 2007", 2007, http://colloque-stic.info/.

[58] M. KRYSTA, É. BLAYO, E. COSME, C. ROBERT, J. VERRON, A. VIDARD. *Hybrid method for data assimilation in oceanography*, in "IUGG (International Union of Geodesy and Geophysics) XXIV General Assembly, Perugia, Italie", Juillet 2007.

[59] M. KRYSTA, E. COSME, J. VERRON, É. BLAYO, C. ROBERT, A. VIDARD. *Une approche hybride variationnelle-stochastique pour l'assimilation de données*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly", Juin 2007.

[60] F. LEMARIÉ, L. DEBREU. *NEMO/AGRIF, theoretical and practical aspects*, in "Workshop on the DRAKKAR global ocean model at 1/4 $\circ$ resolution, IFREMER, Brest, France", September 2007.

[61] F. LEMARIÉ, L. DEBREU, É. BLAYO. *Méthodes mathématiques et numériques pour le couplage océan-atmosphère*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly", June 2007.

[62] B. LEMIEUX-DUDON, F. PARRENIN, É. BLAYO. *A new inverse method to construct a common and optimal ice chronology for several ice cores simultaneously*, in "2nd International Workshop on Physics of Ice Core Records, Sapporo", 2007.

[63] F.-X. LE DIMET, É. BLAYO. *Assimilation of Images for Geophysical Fluids*, in "SIAM Conference on Computational Geosciences, Santa Fe, USA", February 2007.

[64] F.-X. LE DIMET. *Data Assimilation : A paradigm for complex systems*, in "ICTMA13, Katmandoo, Nepal", June 2007.

[65] F.-X. LE DIMET. *Toward Assimilation of images*, in "General Assembly of the American Meteorological Society, San Antonio, USA", January 2007.

[66] F.-X. LE DIMET. *Vers l'assimilation d'images*, in "SMAI 2007, Praz-sur-Arly, France", June 2007.

[67] F.-X. LE DIMET, S. PARK. *Variational Methods a Global approach*, in "AOGS, Sasaki Symposium, Bangkok, Thailand", September 2007.

[68] F.-X. LE DIMET, V. SHUTYAEV, I. GEJADZE. *Assimilation of images in geophysical models*, in "5ICIP, Volga River, Russia", April 2007.

[69] F.-X. LE DIMET, V. SHUTYAEV, I. GEJADZE. *On Optimal Error Analysis in Variational Data Assimilation*, in "5ICIP, Volga River, Russia", April 2007.

[70] F.-X. LE DIMET, V. SHUTYAEV, I. GEJADZE. *On optimal solution error in variational data assimilation*, in "European Geophysical Union, Vienna, Austria", March 2007.

[71] J. MONNIER, M. HONNORAT, X. LAI, F.-X. LE DIMET. *Assimilation of remote sensed data for river hydraulic simulations*, in "ICIAM Zurich", July 2007.

[72] J. MONNIER, M. HONNORAT, X. LAI, F.-X. LE DIMET. *Assimilation of remote sensing data for river flows*, in "MAMERN'07 Granada", July 2007.

[73] M. NODET. *Assimilation de données lagrangiennes en océanographie*, in "Congrès national de mathématiques appliquées et industrielles (SMAI), Praz-sur-Arly", June 2007.

[74] M. NODET. *Assimilation of Lagrangian Data into an ocean model*, in "ICIAM 07, Zurich Suisse", 2007, http://hal.inria.fr/inria-00177517/en/.

[75] M. NODET. *Variational assimilation of Lagrangian Data*, in "SIAM Dynamical Systems, Snowbird, Utah États-Unis d'Amérique", 2007, http://hal.inria.fr/inria-00177515/en/.

[76] N. ROQUET, P. SARAMITO. *Résolution du glissement à seuil à la paroi pour les écoulements viscoplastiques en conduite droite de section constante par éléments finis adaptatifs*, in "Congrès français de mécanique, Grenoble", August 2007.

[77] A. ROUSSEAU, F. BERNARDIN, M. BOSSY, P. DROBINSKI, T. SALAMEH. *Stochastic Particle Method Applied to Local Wind Simulation*, in "Proc. IEEE International Conference on Clean Electrical Power, Capri, Italy", IEEE, 2007, p. 526–528, http://hal.inria.fr/inria-00172503/fr/.

[78] A. ROUSSEAU. *Effet Cosinus sur les équations quasi-géostrophiques*, in "Journées EDP Rhône-Alpes Auvergne", S. BENZONI (editor), Institut Camille Jordan, nov 2007.

[79] A. ROUSSEAU, R. TEMAM, J. TRIBBIA. *Numerical simulations of the inviscid primitive equations in a limited domain*, in "Analysis and Simulation of Fluid Dynamics", C. CALGARO, J.-F. COULOMBEL, T. GOUDON (editors), Advances in Mathematical Fluid Mechanics, Birkhäuser, 2007, http://hal.inria.fr/inria-00172561/fr/.

[80] P. SARAMITO. *Adaptive meshing in viscoplasticity*, in "Visco-plastic fluids: from theory to application, Monte Verità (Tessin), Switzerland", October 2007.

[81] P. SARAMITO. *Numerical methods for viscoelastic and viscoplastic non-Newtonian fluids*, in "Congrès français de mécanique, Grenoble", August 2007.

[82] O. TITAUD, I. SOUOPGUI. *Image Assimilation for Geophysical Fluids: the ADDISA project. Active contours and Vortex Motion*, in "Enhancement of data assimilation in the oceanographic models, Sevastopol, Ukraine", June 2007.

[83] A. VIDARD. *Altimeter Assimilation in a Global Ocean General Circulation Model*, in "Enhancement of Data Assimilation in the Oceanographic Models", 2007, http://hal.inria.fr/inria-00176163/en/.

Internal Reports

[84] D. ANDERSON, M. BALMASEDA, T. STOCKDALE, L. FERRANTI, F. VITART, K. MOGENSEN, F. MOLTENI, F. DOBLAS-REYES, A. VIDARD. *Development of the ECMWF seasonal forecast System 3*, Technical report, ECMWF, 2007, http://hal.inria.fr/inria-00176170/en/.

[85] M. BALMASEDA, A. VIDARD, D. ANDERSON. *The ECMWF System 3 ocean analysis*, Technical report, ECMWF, 2007, http://hal.inria.fr/inria-00176165/en/.

[86] A. BENSELAMA, J. MONNIER. *Navier-Stokes ALE free surface flow with generalized Navier slip conditions. Droplet impact and attempt using Comsol Multiphysics 3.2*, Research Report, n^{o} RR-6175, INRIA, 2007, http://hal.inria.fr/inria-00144007.

[87] C. CHAUVIN, S. HIRSTOAGA, P. KABELIKOVA, F. BERNARDIN, M. BOSSY, A. ROUSSEAU. *Solving the Uniform Density Constraint in a Downscaling Stochastic Model*, Technical report, Cemracs, Luminy, august 2007.

[88] D. CHEREL. *Implementation and comparison of a variational method and a stochastic method for estimating the sensitivity of a model to its parameter*, Technical report, ENSIMAG, 2007.

[89] E. FERNANDEZ-NIETO, D. BRESCH, J. MONNIER. *HLLC solver for non-homogeneous Shallow Water equations with pollutants. Well-balanced problem in the intermediate wave speed*, Technical report, 2007.

[90] M. HONNORAT, J. MARIN, J. MONNIER, X. LAI. *DassFlow v1.0: a variational data assimilation software for river flows*, Research Report, n° RR-6150, INRIA, 2007, http://hal.inria.fr/inria-00137447.

[91] E. NOURTIER-MAZAURIC. *Efficient interface conditions for the coupling of ocean models based on shallow-water equations and advection-diffusion equations*, Technical report, INRIA, 2007.

[92] M.-H. TBER, L. HASCOËT, A. VIDARD, B. DAUVERGNE. *Building the Tangent and Adjoint codes of the Ocean General Circulation Model OPA with the Automatic Differentiation tool TAPENADE*, Research Report, n° 6372, INRIA, 2007, https://hal.inria.fr/inria-00192415.

References in notes

[93] D. AUROUX. *Several data assimilation methods for geophysical problems*, in "Ind. J. Pure Appl. Math.", vol. 37, n° 1, 2006, p. 41–58, http://hal.inria.fr/inria-00176180/fr/.

[94] D. AUROUX, J. BLUM. *Back and forth nudging algorithm for data assimilation problems*, in "C. R. Acad. Sci. Paris, Ser. I", vol. 340, 2005, p. 873–878, http://hal.inria.fr/inria-00189644/fr/.

[95] D. BERTSEKAS. *Auction Algorithms*, in "Encyclopedia of Optimization (C.A. Floudas and P.M. Pardalos, Eds), Kluwer Academic Publishers, Vol. 1, pp. 73-77", 2001.

[96] E. J. CANDÈS, D. L. DONOHO. *New tight frames of curvelets and optimal representations of objects with piecewise C^2 singularities*, in "Pure Appl. Math.", n° 57, 2004, p. 219–226.

[97] L. DEBREU, É. BLAYO. *AGRIF: Adaptive Grid Refinement In Fortran*, Technical report, INRIA, June 2002, http://hal.inria.fr/inria-00069912.

[98] J.-B. FLÓR, I. EAMES. *Dynamcis of monopolar vortices on a topographic beta-plane*, in "J. Fluid Mech", n° 456, 2002, p. 353–376.

[99] J.-L. LIONS. *Exact controllability, stabilization and perturbations for distributed systems.*, in "SIAM Rev.", vol. 30, n° 1, 1988, p. 1-68.

[100] P. PENVEN, L. DEBREU, P. MARCHESIELLO, J. C. MCWILLIAMS. *Evaluation and application of the ROMS 1-way embedding procedure to the central California upwelling system*, in "Ocean Modelling", vol. 12, n° 1-2, 2006, p. 157–187.

[101] S. B. POPE. *Lagrangian pdf methods for turbulent flows*, in "Annu. Rev. Fluid Mech.", vol. 26, 1994, p. 23-63.