INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team MOISE

Modelling, Observations, Identification for Environmental Sciences

Grenoble - Rhône-Alpes

THEME NUM

Activity Report

2008

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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-team is located in the LJK laboratory.

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2. Overall Objectives

2.1. Overall Objectives

MOISE is a research project-team 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-team 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-team. 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 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 MOISE project-team 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 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 behavior 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. However, observations provide only a partial (and sometimes very indirect) view of reality, localized in time and space.

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.

Stochastic filtering is the basic tool in the sequential approach to the problem of data assimilation into numerical models, especially in meteorology and oceanography. 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 and oceanographic 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.

A challenge of particular interest consists in developing methods for assimilating image data. Indeed, images and sequences of images represent a large amount of data which are currently underused in numerical forecast systems. For example, precursors of extreme meteorological events like thunderstorms, for which an early forecast is required, are visible on satellite images.

However, despite their huge informative potential, images 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 information (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.

The use of images dynamics in numerical forecast systems is not restricted to meteorological or oceanographic 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.

3.4. Sensitivity Analysis - Quantification of Uncertainties

Due to the strong non-linearity of geophysical systems and to their chaotic behavior, 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 behavior.

Global stochastic approach. Using the variational approach to sensitivity leads to efficient computations of complex code derivatives. However, this approach to sensitivity remains local because derivatives are generally computed at specific points. The stochastic approach of uncertainty analysis aims at studying global criteria based on a joint probability distribution functions modelling of the problem variables. The obtained sensitivity indices describe the global variabilities of the phenomena. For example, the Sobol sensitivity index is given by the ratio between the output variance conditionally to one input and the total output variance. The computation of such quantities leads to statistical problems. For example, the sensitivity indices have to be efficiently estimated from a few runs, using semi or non-parametric estimation techniques. The stochastic modelling of the input/output relationship is another solution.

4. Application Domains

4.1. Introduction

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, David Cherel, Laurent Debreu, Thomas Duhaut, Marc Honnorat, Christine Kazantsev, Eugène Kazantsev, Monika Krysta, François-Xavier Le Dimet, Florian Lemarié, Carine Lucas, Emilie Neveu, Maëlle Nodet, Elise Nourtier-Mazauric, Antoine Rousseau, 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-team 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, refinement methods (like mesh refinement or stochastic downscaling), 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 better 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: 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.

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 represents 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: Joël Marin, Jérôme Monnier.

DASSFLOW[1] is a river hydraulics simulation software designed for variational data assimilation. The forward models include 1D - 2D shallow-water equations (with topography and friction terms), transport and sediments equations. Time discretisation is the explicit Euler scheme, space discretisation is based on well-balanced finite volume schemes. 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.
The full code has been distributed to our collaborators (for ex., it is used in the context of few PhDs).
The code and the forge have been maintained by Joël Marin, assistant engineer (2006-08).

5.2. SDM toolbox

Participants: Claire Chauvin, Antoine Rousseau.

The computation of the wind at small scale and the estimation of its uncertainties is of particular importance for applications such as wind energy resource estimation. To this aim, we develop a new method based on the combination of an existing numerical weather prediction model providing a coarse prediction, and a Lagrangian Stochastic Model adapted from a pdf method introduced by S.B. Pope for turbulent flows. This Stochastic Downscaling Method (SDM[2]) is thus aimed to be used as a refinement toolbox of large-scale numerical models. SDM requires a specific modelling of the turbulence closure, and involves various simulation techniques whose combination is totally new (such as Poisson solvers, optimal transportation mass algorithm, original Euler scheme for confined Langevin stochastic processes, and stochastic particle methods).

5.3. Adaptive Grid Refinement

Participants: Laurent Debreu, Florian Lemarié.

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

AGRIF (Adaptive Grid Refinement In Fortran, [10], [67]) 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 ([25], [70]), OPA-NEMO ocean modelling system (a general circulation model used by the French and European scientific community, [16], [6], [7]).

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 have been developed within the framework of the COMMA project and will soon be released.

5.4. 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. Sedimentation models

The work with E. Fernández-Nieto and J. D. D. Zabsonré devoted to theoretical studies of viscous sedimentation models has been completed by the set of numerical experiments described in [31]. We have written a new model which is stable and energetically consistent.
Sedimentation phenomenon has also been studied in collaboration with the UCLA team. A model based on the multiscale analysis has been written. Its implementation is now in progress.

6.1.1.2. 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, it is sometimes necessary to take into account the cosine part of the Coriolis force (which is usually neglected).

The study of the cosine part of the Coriolis force has been continued by writing a better model from a physical point of view. Shallow Water model with eddy viscosities has been derived in [20]. From this new system, we deduced the Quasi-Geostrophic Shallow Water equation for which numerical experiments show that the so-called 'cosine effect' depends on the topography and cannot be predicted.

6.1.1.3. Multiscale approximations for ocean equations.

We study a stationary Quasi-Geostrophic type equation in one or two dimensional spaces, with a quickly varying topography. We consider an asymptotic expansion of this equation on several space and time scales. At each expansion's order, we split the approximated solution into an interior function, which represents the solution far from the western boundary, and a corrector function that takes into account the boundary layer. We derive systems at each order for both functions and prove mathematical properties on these systems. Then we present numerical tricks and results, with and without topography, in the one and two dimensional cases. The method is very efficient compared to classical ones (finite differences, finite elements) which are very expensive due to quickly varying topography and thin boundary layer. A paper is in preparation.

6.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, David Cherel, Laurent Debreu, Florian Lemarié, Elise Nourtier-Mazauric, 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).

In the case of 2D shallow-water equations, we have continued a work in collaboration with V. Martin (LAMFA (Amiens) and F. Vandermeirsch (IFREMER Brest) on the development of OBCs approximating exact non local absorbing conditions. Exact absorbing conditions, avoiding any reflection of errors on the boundaries, have been determined for the 1-D linearized shallow-water system, taking into account advection, Coriolis terms, bottom topography and friction. Different local approximations have been proposed, depending on the dominant terms in the equations. These approximations have now to be tested numerically.

Pursuing earlier works, we considered in [27] the 3D linear primitive equations model in the case of a density which varies linearly with depth. The results that were obtained in lower dimensions have been extended to the 3D case. A review paper [56] has also been published in a special volume of the *HandBook of Numerical Analysis*.

6.1.2.2. Nesting methods

A common way to locally increase the resolution of a model consists in embedding a local high resolution grid in a coarser one covering a larger domain. If the interaction between the soutions on both grids is only one-way (i.e. with no feedback from the local solution to the large scale solution), the situation is similar to the open boundary problem. However better results are generally obtained in the case of two-way interactions. A review of the main numerical issues encountered in that case has been published in [9].

6.1.2.3. Interface conditions for coupling ocean models

Other physical situations require coupling two models with not only different resolutions, but also different physics. Such a coupling can be studied within the framework of global-in-time Schwarz methods. However, the efficiency of these iterative algorithms is strongly dependent on interface conditions. As a first step towards coupling a regional scale primitive equations ocean model with a local Navier-Stokes model, we started a study on the derivation of interface conditions for 2-D $x - z$ Navier-Stokes. It has been shown that several usual conditions lead to divergent algorithms, and that a convergent algorithm is obtained when using transmission conditions obtained by a variational calculation.

6.1.2.4. Ocean-atmosphere coupling

Many applications in regional oceanography and meteorology require high resolution regional models with accurate air-sea fluxes. Separate integrations of oceanic and atmospheric model components in forced mode (i.e. without any feedback from one component to the other) may be satisfactory for numerous applications. However, two-way coupling is required for analyzing energetic and complex phenomena (e.g. tropical cyclones, climate studies, ...). In this case, connecting the two model solutions at the air-sea interface is a difficult task, which is often addressed in a 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 shown that usual methods used by the physicists can be rewritten as one single iteration of a Schwarz coupling algorithm, with particular non optimal interface conditions. In order to see the impact of leading the iterative procedure to convergence, he performed a comparison between the converged and non converged solutions in the realistic test case of the simulation of the Tropical cyclone Erica using the atmospheric model WRF and the oceanic model ROMS (collaboration with P. Marchesiello, IRD Nouméa). Significant differences have been observed, that have now to be diagnosed from a physical point of view.

In order for the iterative Schwarz coupling method to be tractable in a realistic context, the number of iterations must be as small as possible. This question has been addressed on the model problem of coupling two non-stationary 1-D diffusion equations with different coefficients. This problem retains indeed an important part of the true physics of the air-sea interface phenomena.
In the simplified case of constant diffusion coefficients on each sub-domain, the study of the convergence rate of the global-in-time Schwarz algorithm has been carried out, and new optimal Neumann-Robin and Robin-Robin interface conditions have been derived. Then 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. The convergence of the Schwarz algorithm has been studied analytically, using an ad hoc expansion into eigenfunctions of an associated Sturm-Liouville problem, and again new optimal interface conditions have been proposed 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.
These works are partially supported by the ANR (COMMA project).

6.2. Development of New Methods for Data Assimilation

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

Participants: Didier Auroux, Jacques Blum, Maëlle Nodet.

The back and forth nudging algorithm (see [3], [1]), has been recently introduced for simplicity reasons, as it does not require any linearization, or adjoint equation, or minimization process in comparison with variational schemes, but nevertheless it provides a new estimation of the initial condition at each iteration.

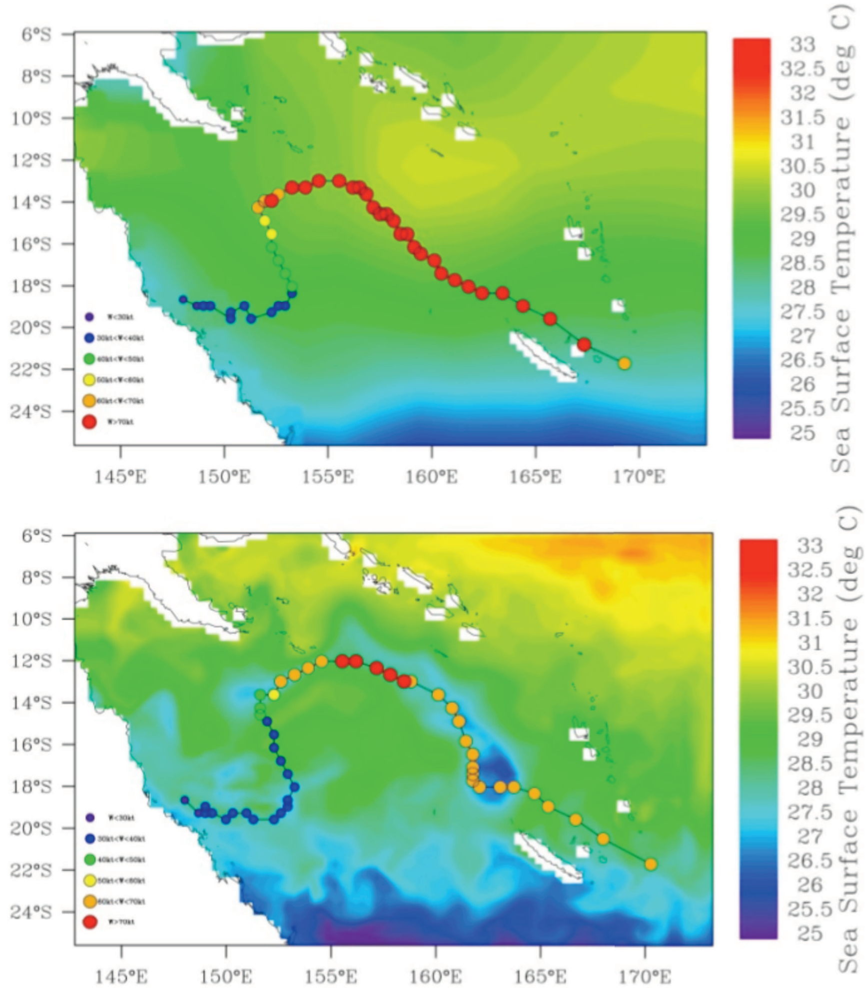

Figure 1. Simulated path and intensity (colored dots) of Cyclone Erica moving over New Caledonia in March 2003, superimposed on a map of the sea surface temperature : forced simulation (top) and coupled simulation (bottom). Note that in the case of two-way coupling, cold waters are produced on the cyclone track due to strong surface mixing induced by the hurricane winds; the cold water induces a negative feedback on the cyclone, which is weaker (and more realistic).

We have studied its convergence properties as well as its efficiency in the case of numerical experiment with a 2D shallow water model. Comparisons with the 4D-VAR have been performed. Finally, we also studied a hybrid method, by considering a few iterations of the BFN algorithm as a preprocessing tool for the 4D-VAR algorithm. We have shown that the BFN algorithm is extremely powerful in the very first iterations, and also that the hybrid method can both improve notably the quality of the identified initial condition by the 4D-VAR scheme and reduce the number of iterations needed to achieve convergence [57].

We considered from a theoretical point of view the case of 1-dimensional transport equations, either viscous or inviscid, linear or not (Bürgers' equation). We showed that for non viscous equations (both linear transport and Bürgers), the convergence of the algorithm holds under observability conditions. Convergence can also be proven for viscous linear transport equations under some strong hypothesis, but not for viscous Bürgers' equation. Moreover, the convergence rate is always exponential in time. We also notice that the forward and backward system of equations is well posed when no nudging term is considered [60]. Several comparisons with the 4D-VAR and quasi-inverse algorithms have also been performed on this equation in [35].

Finally, within the standard nudging framework, we considered the definition of an innovation term that takes into account the measurements and respects the symmetries of the physical model. We proved the convergence of the estimation error to zero on a linear approximation of the system (a 2D shallow-water model). It boils down to estimating the fluid velocity in a water-tank system using only SSH measurements. The observer is very robust to noise and easy to tune. The general nonlinear case has been illustrated by numerical experiments, and the results have been compared with the standard nudging techniques [58].

6.2.2. 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).

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 has been implemented in a shallow water model which mimics a double-gyre circulation of the North Atlantic. It has been shown that evolving the covariance matrix leads to improved identification when the initial basis is rather poor, and especially when the model is not considered as perfect. Moreover, from a practical point of view, it is probably not necessary to make the whole basis evolve: some main directions can be kept unchanged, which decreases the cost of the method.

6.2.3. Variational Data Assimilation and Control of model's parameters and numerical schemes.

Participant: Eugène Kazantsev.

Following a previous study on the sensitivity of the solution of an ocean model to the representation of the bottom topography [61], we focused our attention on the data assimilation techniques devoted to identification of external model's parameters and parametrisations.

First, the attention was paid to control the bottom topography by variational data assimilation in frames of time-dependent motion governed by non-linear barotropic ocean model [17]. Assimilation of artificially generated data allows to measure the influence of various error sources and to classify the impact of noise that is present in observational data and model parameters. The choice of assimilation window is discussed. Assimilating noisy data with longer windows provides higher accuracy of identified topography. The topography identified once by data assimilation can be successfully used for other model runs that start from other initial conditions and are situated in other parts of the model's attractor.

Second, the numerical scheme of the shallow-water model at the boundary was controlled by assimilating data of a high resolution model [42]. It was shown that control of approximation of boundary derivatives and interpolations can increase the model's accuracy in boundary regions and improve the solution in general. On the other hand, optimal boundary schemes obtained in this way, may not approximate derivatives in a common sense. Particular study was performed on the example of one-dimensional wave equation to understand this phenomenon. In this simple case, we see that the control changes the interval's length (and, consequently, all approximations of derivatives) in order to compensate numerical error in the wave velocity.

6.2.4. Variational data assimilation for locally nested models.

Participants: Eric Blayo, Laurent Debreu, 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.

In Emilie Neveu's PhD, we continue to work on the subject. Our main interest is on the use of multiscale optimization methods for data assimilation. The idea is to apply a multigrid algorithm to the solution of the optimization problem. One of the focus is on the design of resolution dependent observation operators. The other key point is in the adaptation of the original FAS (Full Approximation Scheme) multigrid algorithm to local mesh refinement. The applications will be done in the context of the assimilation of images (see 6.4).

6.2.5. 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.

We recently sorted out the problems mentioned above and we continued to implement this method in a realistic Oceanic framework using OPAVAR/ NEMOVAR.

6.2.6. 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 using a simplified configuration of NEMO coupled with the SPEEDY model.

6.3. Data Assimilation for Ocean Models

6.3.1. 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. 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.
A paper presenting the grounding theory of this method has been submitted, see [64].
This project is currently under development and is granted by the Mercator program and the LEFE-INSU program.

6.3.2. 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 .

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-team) and ECMWF (Parallelization). This project aimed at avoiding duplication of effort, and at developing a common NEMOVAR platform.
The project is now well advanced, an efficient 3D variational system is now available. The transition from 3D to 4D requires the availability of the Tangent linear and Adjoint Model (NEMOTAM) of OPA9. A first parallel version of NEMOTAM (with a limited number of options) is being finalized
The NEMOVAR working group gets financial support by LEFE- Assimilation and Mercator National Programs.

6.4. Assimilation of Image Data

At the present time the observation of Earth from space is done by more than thirty satellites. These platforms provide information two kinds of observations:

- Eulerian information as radiance measurements: the radiative properties of the earth and it's fluid envelopps. These data can be plugged into numerical models by solving some inverse problems.
- Lagrangian information: the movement of fronts and vortices give information on the dynamics of the fluid. Presently this information is scarcely used in meteorology by following small cumulus clouds and using then as Lagrangian tracers, but the selection of these clouds must be done by hand and the altitude of the selected clouds must be known, this is done by using the temperature of the top of the cloud.

MOISE is the leader of the ADDISA project selected and funded by Agence Nationale de la Recherche dedicated to the assimilation of images. The member of the ADDISA group are the INRIA project CLIME, Laboratoire des Ecoulements Géophysique et Industriels (CNRS,Grenoble), Institut de Mathématiques de Toulouse and MétéoFrance The principle is to link images and numerical models in order to retrieve the initial condition at best. Two basic techniques are tested:

- from images deduce pseudo-observation as the velocity of the flow, then assimilate these data as pseudo observations using a regular variational data assimilation scheme.
- Consider “objects" in the images (fronts, vortices) then compare with the same objects created by the model and inject them into a scheme of assimilation which take them into account.

The method is already used by MétéFrance to detect precursors of severe storms.

6.4.1. Assimilation of Images: the ADDISA project

Participants: François-Xavier Le Dimet, Didier Auroux, 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 : http://addisa.gforge.inria.fr

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. [68]).

D. Auroux works on the extraction of velocity fields from sequences of images, providing pseudo-observations of the fluid velocity [59].

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

Participants: François-Xavier Le Dimet, Gennady 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 permits 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.

6.5. Quantifying Uncertainty

6.5.1. Uncertainty analysis

Participants: Eric Blayo, Clémentine Prieur, Laurence Viry.

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 during a drought period of the Western African monsoon simulated by a regional atmospheric model to the uncertainties on some input parameters (albedo, sea surface temperature in the gulf of Guinea...). Some preliminary statistical data analysis has been performed, as well as the implementation of the model on different computers.

According to the knowledge of the physicians, we focus on the SST (sea surface temperature) parameter which has a major influence on precipitation. We wish to give a response surface for the SST. However we have to take into account its non stationarity property. To address this point, we build a random partition of the surface and we consider that on each element of the partition, the SST is stationary. The choice of the way to partition is crucial and has to be done carefully. Regression trees can be used for that purpose, as well as wavelets. The next step is then to study the global process, which is highly unstationary.

This sensitivity study will require rather huge computation resources, and will be run in a grid computing environment which takes into account the scheduling of a huge number of computation requests and links with data-management, all of this being performed as automatically as possible. We are in contact with the Graal project team (Eddy Caron) who helps us to find a solution to configure, deploy, run and monitor our application with his GridRPC-Middleware DIET (Distributed Interactive Engineering Toolbox).

6.5.2. Propagation of uncertainties

Participants: François-Xavier Le Dimet, Victor Shutyaev.

Basicaly geophysical models are suffering of two types of errors:

- errors in the model itself due to approximations of physical processes and their subgrid parametrization and also errors linked to the necessary numerical discretization.
- Errors in the observation because of the measurements and also errors due to sampling. For instance, many remote sensings observe only radiances, which are transformed into the state variables thanks to complex processes like the resolution of an inverse problem. This is, of course, a source of errors.

Estimating the propagation of errors is an important and costly (in term of computing resources) task for two reasons:

- the quality of the forecast must be estimated
- the estimation of the statistics of errors has to be included in the analysis to have an adequate norm, based on these statistics, on the forecast and also on the observation.

In the variational framework, models, observations, statistics are linked into the optimality system which can be considered as a “generalized" model containing all the available estimation. In works [29], [13], [41] the estimation of error covariances are estimated both from the second order analysis and the Hessian of the cost function. Numerical experiments have been carried out on a non-linear 1-D model, we expect to extent the numerical experiments to a semi-operational model in cooperation with ECMWF.

6.6. Glaciology

6.6.1. Coupling and variational sensitivities for ice flows

Participants: Joël Marin, Jérôme Monnier.

The studies described below are done in collaboration with O. Gagliardini and C. Ritz from LGGE - Grenoble. It is co-funded by INP-Grenoble (BQR support, J. Monnier) and CNRS-INSU dept (LEFE program, J. Monnier).
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) the elaboration of a finite element computational code of Stokes 2D Non-newtonian with free surface flows, including coupling and variational data assimilation.

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).
T. Mastrosimone has participated to the project during his first year of his PhD (till July'08). J. Marin (associate engineer INRIA, Sept. 06- Apr. 08) has contributed to the code development.

6.6.2. Dating ice matrix and gas bubbles

Dating ice matrix and gas bubbles of ice-cores is essential to study paleoclimates. The conjunction of information brought by observations and flow models is now a commonly used approach to build the chronology of ice cores. Till now this technique has been applied: 1) to one core at a time, 2) to estimate the age of the ice but not of the gas (which is younger), 3) under the assumption of perfect glaciological models after the optimization of their parameters. This currently used methodology faces three problems: 1) for distinct cores the chronologies calculated separately usually show discrepancies, 2) chronologies sometimes fail to respect relevant data constraints precisely because models are imperfect (not well understood physical processes are omitted), at last 3) the gas and ice ages are not independent entities and some valuable observations contain information on both. To go beyond these restrictions B. Lemieux-Dudon has proposed in her PhD a new inverse approach which takes into account the modelling errors. It aims at identifying the accumulation rate, the total thinning function and the closeoff depth of ice equivalent (i.e. depth below the surface where the gas is trapped) which are in best agreement with some prior guesses and with independent observations. This method operates on several cores simultaneously by the mean of stratigraphic links relating the gas or ice phase of two cores. The Bayesian framework of this method also enables to associate confidence intervals to the solution. This approach is applied to derive simultaneously a common age scale for the NorthGrip core and for the two EPICA cores (DML and DC)

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 [28], [8], [24] 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).

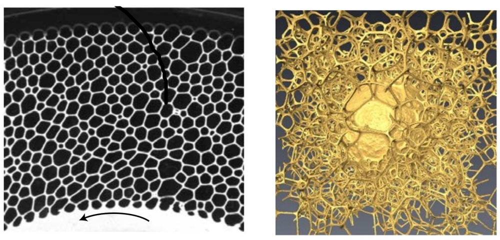

Figure 2. Foam flow: (Left) Couette flow (Right) 3D structure arround a sphere (LSP Grenoble / ESRF synchrotron 2008).

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 Spectrométrie 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).

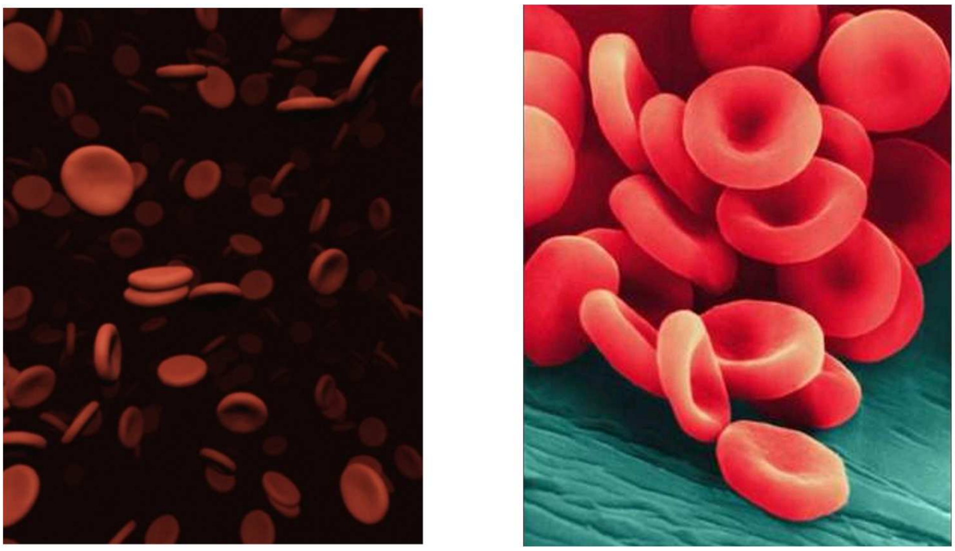

Figure 3. Blood flow: (left) flow of red cells (right) formation of agregate of cells.

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 appear 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 first order schemes are often insufficient for such problems. This work is developed in collaboration with Morocco (CNRS-DRI funding, 2003-2006). The coordination and the animation is ensured 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, Morocco), Driss Esselaoui (Pr, U. Kenitra, Morocco), Al Moatassine (EC, U. Marrackech, Morocco), A. Machmoum (EC, U. Marrackech, Morocco).

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 develops new efficient numerical methods [26] for the resolution of such flow problems.

Figure 4. Talus: the critical angle where avalanche (i.e. geophysical flow) appears is of about 30 degrees.

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. Experimental study of the control operator for the Wave Equation

Participant: Maëlle Nodet.

In collaboration with G. Lebeau (Université de Nice), 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 [69] and the HUM method is well-known. Following theoretical new results by B. Dehman and G. Lebeau, we performed an experimental study of the properties of the HUM control operator.
A paper with new theoretical and experimental numerical results has been submitted, see [66].

6.9. Stochastic Downscaling Method

Participants: Antoine Rousseau, Claire Chauvin.

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 behavior of stochastic particles. The development of this model, called SDM (Stochastic Downscaling Method), is funded by ADEME (Agence de Développement de l'Écologie et de la Maîtrise de l'Énergie).
After spending 6 months (January-June) in Sophia-Antipolis (EPI TOSCA), Claire Chauvin joined MOISE in July 2008. Together with Antoine Rousseau and co-authors, they obtained some encouraging numerical results on SDM that have been published in [5].

7. Contracts and Grants with Industry

7.1. Regional Contracts

Ongoing in 2008:

- 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 2008:

- A 15 months contract with IFREMER on the thematic "Numerical Methods in Ocean Modelling".
- A 1-year contract with MERCATOR on the thematic "Assimilation of lagrangian data in OPAVAR": see 6.3.1.
- A 3-year contract with ADEME on the thematic "stochastic downscaling method": see 6.9.
- A 2-year contract with MERCATOR on the thematic "Variational data assimilation for OPA/NEMO".

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 6.6.

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 5.1.
- Cemagref Lyon, Department Hydrology and Hydraulics: 5.1.
- Laboratoire de mécanique des fluides et d'acoustique (Lyon): 5.1.
- LEGI, PIM project-team (Particules Interfaces Microfluidique): 6.2.
- LGGE, Laboratoire de Glaciologie, Géophysique et Environnement: 6.6.
- Laboratoire de Spectrométrie Physique (LSP Grenoble) 6.7.

8.2. National Actions

8.2.1. Interactions with other INRIA Project-Teams or Actions

Participants	INRIA Project-Team	Research topic	Link
A. Rousseau	TOSCA	Stochastic Downscaling Method	6.9
A. Vidard	TROPICS	Ocean Adjoint Modelling	6.3.2
A. Vidard F.X. Le Dimet	CLIME	Image assimilation	6.4.1

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 6.3
A. Vidard	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (Toulouse)	Ocean Data Assimilation	6.3.2
[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
A. Vidard	LOCEAN (Paris)	Ocean Adjoint Modelling	6.3.2
A. Vidard	Laboratoire de Physique des Océans (Brest)	Ocean Data Assimilation	6.3.2
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	6.4
M. Nodet	Laboratoire Dieudonné (Université de Nice) (G. Lebeau)	Experimental study of the control operator for the Wave Equation	6.8
D. Auroux, M. Nodet	Laboratoire Dieudonné (Université de Nice) (J. Blum)	BFN data assimilation scheme	6.2.1
A. Rousseau	Mathématiques et Applications, Physique Mathématique d'Orléans (MAPMO)	Cosine Effect in Geophysical Fluid Dynamics	6.1
A. Rousseau	Laboratoire de Météorologie Dynamique (Ecole Polytechnique)	Stochastic Downscaling Method	6.9
A. Rousseau	Centre d'Études Techniques de l'Équipement	Stochastic Downscaling Method	6.9
J. Monnier	D. Dartus and H. Roux (IMF-Toulouse)	co-supervisor of Don N'Guyen 's PhD, (08-11).	5.1
P. Saramito	N.Roquet (CR LCPC, Nantes)	Viscoplastic flow problems	6.7.4

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

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[3] : E. Blayo, L. Debreu, M. Honnorat.

8.2.3. Participation to National Research Groups (GdR) CNRS

- D. Auroux participates to the GdR MOMAS (Modélisations Mathématiques et Simulations numériques liées aux problèmes de gestion des déchets nucléaires).
- 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.
- E.Blayo, C.Prieur, M. Nodet and A. Rousseau participate to the GDR MASCOT NUM (Méthodes d'analyse stochastiques pour les codes et traitements numériques

8.2.4. Other National Actions

- F.X. Le Dimet is in charge of the project ADDISA (http://addisa.gforge.inria.fr, see 6.4.1) 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 project-team 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) which is chaired by S. Benzoni Gavage.
- D. Auroux is in charge of the project PROSSDAG (Probing new sequential schemes for retrospective data assimilation in geophysics) supported by ANR. This project started in November 2007 and will end in November 2010.
- Numerous members of the team are also supported by IDRIS (French national super-computing center) and get computing hours on parallel and vectorial supercomputers.
- A. Vidard leads a group of projects gathering multiple partners in France and UK on the topic "Variational Data Assimilation for the NEMO/OPA9 Ocean Model", see 6.3.2. This project is granted by two INSU-LEFE and a Mercator-Ocean calls for proposals
- 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.
- M. Nodet is in charge of a 2-year contract with LEFE-INSU on the thematic "Assimilation of lagrangian data in OPAVAR": see 6.3.1.
- Florian Lemarié is involved in the ANR project "Cyclônes and climate" led by Christophe Menkes (LOCEAN,IRD Nouméa) and Jean-François 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.
- 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

- MOISE 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 Spanish project with E. Fernandez-Nieto (University of Sevilla) and C. Pares (Univ. Malaga), on river and flood modeling.
- A. Vidard collaborates with ECMWF (Reading, UK) on the development of a variational data assimilation system for the NEMO ocean model.
- A. Vidard, F.-X. Le Dimet, I. Souopgui and O. Titaud are part of the ADAMS associated team and the ECO-NET project ADOMENO, both co-led by A. Vidard and E. Huot (CLIME project team). They gather scientists from INRIA (MOISE and CLIME), MHI (Sevastopol, Ukraine), INM (Moscow, Russia) and MNI (Tbilissi, Georgia) and aim at developing advanced data assimilation methods applied to the Black Sea.
- 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.
- 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

- 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.
- E.Blayo, L.Debreu, M. Nodet, F. Lemarié, D.Bresch, C.Lucas participate to the INRIA Program “Equipe associées", creating the joint team NMOM (Numerical Methods for Ocean Modelling) with UCLA, Department of Atmospheric and Oceanic Sciences (J.McWilliams).
- 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.).
- 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 is involved in a Chinese project with X. Lai (Chin. Ac. Sc., Nanjing Institute of Geography and Limnology) on data assimilation for shallow flows.
- 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.
- A. Rousseau collaborates with Roger Temam (French Académie des Sciences and 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.

9. Dissemination

9.1. Scientific Community Animation

- 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.
- A. Rousseau is in charge of EDP/MOISE weekly seminar, see http://ljk.imag.fr/ This workshop generally features a talk from a member of a french lab (sometimes from abroad) that interests, or may interest, some of the Moise team-members.
- A. Rousseau was in charge of the evaluation of applications issued in Rhône-Alpes region for the national "Fête de la Science" 2008.
- Half of the team members have participated in the Festival of Sciences “Remue-Méninges 2008" http://www.inrialpes.fr/1213114337681/0/fiche___actualite/&RH=ACCUEIL. Environnemental modeling, observations of the nature accompanied by physical experiments have been explained for more than 1000 school-children of the Isere department.

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-team also participate to teaching activities.

9.2.2. Lectures Given in International Schools and Foreign Universities

- F.-X. Le Dimet has delivered a serie of lecture on " Data Assimilation in Hydrology" at the Institute of Mechanics on the invitation of the Academy of Sciences of Vietnam. March 2009.
- D. Auroux gave 3 lectures on Data Assimilation in Bangalore, India (in both the Indian Institute of Science, and the Tata Institute for Fundamental Research). He also organized a graduated course on Data Assimilation at the National Engineering School of Tunis, Tunisia.
- Antoine Rousseau gave 4 lectures in International Fall School on Modelling in French Guyana. This school was organized by the AOC lab, Guadeloupe, French Carribean (27-31 oct 2008).

9.3. Conferences and Workshops

- The members of the team have participated to various conferences and workshops (see the bibliography).
- E. Blayo and M. Nodet organized (in collaboration with E. Cosme, LEGI) a graduate course "Introduction to Data Assimilation: Methods and Applications". In 2008, around fifty persons from various fields attended this winter course, half of them coming from Grenoble, and the others from research centers in France. This course was also given by M. Nodet in Marseille for oceanographers.
- M. Nodet helped with MOISE/CLIME stand during the Salon Européen de la Recherche which was held in Paris in June.
- L.Debreu participated in organization of the 2008 ROMS/TOMS European Workshop http://www.myroms.org/index.php?page=events&id=6.

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