IN PARTNERSHIP WITH:
CNRS

Institut polytechnique de Grenoble

Université Joseph Fourier (Grenoble 1)

Activity Report 2011

Project-Team MOISE

Modelling, Observations, Identification for Environmental Sciences

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Observation and Modeling for Environmental Sciences

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Project-Team MOISE

Keywords: Environment, Model Coupling, Data Assimilation, Inverse Problem, Ocean, Atmosphere, Glaciology

The MOISE project-team, LJK-IMAG laboratory (UMR 5224), is a joint project between CNRS, INRIA, Institut Polytechnique de Grenoble (Grenoble INP), Joseph Fourier University (UJF) and Pierre-Mendès-France University (UPMF). Team leader is Eric Blayo.

This project-team is located in the LJK laboratory.

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Bénédicte Lemieux-Dudon [and INRIA as of September 1st]

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Igor Gejadze [University of Strathclyde, Scotland, 1 month]
Robert Miller [COAS, Oregon State University, 1 year]
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Mikhail Tolstykh [Russian Academy of Sciences,1 week]

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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, 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).

2.2. Highlights

F.-X. Le Dimet was elected Fellow of the American Meteorological Society (October 2011).

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 modelled 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 are 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. 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.

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 describing 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 modeling 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.

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

Participants: Eric Blayo, Vincent Chabot, Claire Chauvin, David Cherel, Laurent Debreu, Christine Kazantsev, Eugène Kazantsev, François-Xavier Le Dimet, Bénédicte Lemieux-Dudon, Maëlle Nodet, Antoine Rousseau, Arthur Vidard, Franck Vigilant.

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.
- *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 10^6-10^8), 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, of sequences of images, 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. Glaciology

Participants: Eric Blayo, Bertrand Bonan, Bénédicte Lemieux-Dudon, Maëlle Nodet, Habib Toye Mahamadou Kele.

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 another 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 ice sheets, by developing data assimilation approaches in order to calibrate 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.

By gaining and loosing mass, glaciers and ice-sheets are playing a key role in the sea level evolution. This is obvious when regarding past as, for example, collapse of the large northern hemisphere ice-sheets after the Last Glacial Maximum has contributed to an increase of 120 m of sea level. This is particularly worrying when the future is considered. Indeed, recent observations clearly indicate that important changes in the velocity structure of both Antarctic and Greenland ice-sheets are occurring, suggesting that large and irreversible changes may have been initiated. This has been clearly emphasized in the last report published by the Intergovernmental Panel on Climate Change (IPCC). IPCC has further insisted on the poor current knowledge of the key processes at the root of the observed accelerations and finally concluded that reliable projections of sea-level rise are currently unavailable. In this context, our general aim is to develop data assimilation methods related to ice flow modelling purpose, in order to provide accurate and reliable estimation of the future contribution of ice-sheets to Sea Level Rise.

Development of ice flow adjoint models is by itself a scientific challenge. This new step forward is clearly motivated by the amount of data now available at both the local and the large scales.

4.4. River Hydraulics

Participants: Eric Blayo, Antoine Rousseau, Manel Tayachi.

Shallow Water (SW) models are widely used for the numerical modeling of river flows. Depending on the geometry of the domain, of the flow regime, and of the level of accuracy which is required, either 1D or 2D SW models are implemented. It is thus necessary to couple 1D models with 2D models when both models are used to represent different portions of the same river. Moreover, when a river flows into the sea/ocean (e.g. the Rhône river in the Mediterranean), one may need to couple a 2D SW with a full 3D model (such as the Navier-Stokes equations) of the estuary. These issues have been widely addressed by the river-engineering community, but often with somehow crude approaches in terms of coupling algorithms. This may be improved thanks to more advanced boundary conditions, and with the use of Schwarz iterative methods for example. We want to tackle these issues, in particular in the framework of a partnership with the French electricity company EDF.

5. Software

5.1. Adaptive Grid Refinement

Participants: Laurent Debreu, Marc Honnorat.

AGRIF (Adaptive Grid Refinement In Fortran, [71]) 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), OPA-NEMO ocean modelling system (a general circulation model used by the French and European scientific community) and HYCOM (a regional model developed jointly by University of Miami and the French Navy).
In 2011, a new contract has been signed with IFREMER to optimize parallel capabilities of the software. AGRIF is licensed under a GNU (GPL) license and can be downloaded at its web site (http://ljk.imag.fr/MOISE/AGRIF/index.html).

5.2. DatIce

Participants: Bénédicte Lemieux-Dudon, Habib Toye Mahamadou Kele.

The Datice code ([76], [77]) is designed to estimate consistent chronologies of several deep ice cores (i.e., depth-age relationships of the ice matrix and trapped gas). A cost function derived from Bayes theorem puts in competition the chronological constraints brought by heterogeneous observations (stratigraphic links between cores, gas and ice age markers, delta-depth markers, etc.), and the background dating scenarios simulated with glaciological models (firn densification and ice flow models). The minimization of the cost function provides optimal estimations of three key quantities from which dating scenarios can be derived: the past accumulation rate, the close-off depth which is the depth where the gas is trapped into ice, and the total thinning function. Uncertainties of the analysed dating scenarios (key quantities and chronologies) are assessed on the basis of the Bayesian formulation. This approach is innovative because:

- it relies on data assimilation techniques to calculate ice core chronologies and uncertainties;
- it applies to a large number of heterogeneous observations;
- it ensures consistency between the chronologies of several cores and the consistency between the gas and ice age scales.

The code has been used in several recent publications (see [68], [87] for example).

5.3. SDM toolbox

Participant: 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 http://sdm.gforge.inria.fr/) 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). In 2011, we worked on the comparison of the SDM model (endowed with a physical geostrophic forcing and a wall log law) with simulations obtained with a LES method (Méso-NH code) for the atmospheric boundary layer (from 0 to 750 meters in the vertical direction), in the neutral case, see [58].

5.4. CompModSA package

Alexandre Janon is a contributor of the package CompModSA - Sensitivity Analysis for Complex Computer Models (see http://cran.r-project.org/web/packages/CompModSA/index.html). This package is useful for conducting sensitivity analysis of complex computer codes when model evaluations are somewhat expensive (e.g. take longer than a couple of seconds to run) but a reasonable number (50 or more) of model evaluations can be obtained at sampled input values.

5.5. NEMO-TAM

Tangent and adjoint models for the NEMO platform of the oceanic modelling that have been delopped by the MOISE team have been published now under Cecill license and distributed by the NEMO consortium.

6. New Results

6.1. Mathematical Modelling of the Ocean Dynamics

6.1.1. Beyond the traditional approximation on the Coriolis force

Participant: Antoine Rousseau.

Formerly, A. Rousseau has performed some theoretical and numerical studies around the derivation of quasi-hydrostatic models. With C. Lucas, he proved that it is sometimes necessary to take into account the cosine part of the Coriolis force (which is usually neglected, leading to the so-called Traditional Approximation). They have also shown that the non-traditional terms do not raise any additional mathematical difficulty in the primitive equations: well-posedness for both weak and strong solutions.
In 2011, A. Rousseau and J. McWilliams (UCLA) proposed in [62] a mathematical justification of the tilt of convective plumes in the quasi-geostrophic regime, thanks to the account of the complete Coriolis force in the so-called quasi-hydrostatic quasi-geostrophic (QHQG) model. The new model has been presented in several international conferences [26], [49].

6.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, David Cherel, Laurent Debreu, Antoine Rousseau, Manel Tayachi.

6.1.2.1. Interface conditions for coupling ocean models

Many 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, a study on the derivation of interface conditions for 2-D $x-z$ Navier-Stokes equations is currently underway (D. Cherel's PhD thesis). It has been shown theoretically that several usual conditions lead to divergent algorithms, and that a convergent algorithm is obtained when using transmission conditions given by a variational calculation. Moreover the impact of two numerical schemes (a projection method, and a direct method [67]) on the implementation of the domain decomposition method has been discussed.
Using the direct method in a 2D $x-z$ Navier-Stokes model, D. Cherel has implemented a Schwarz-based domain decomposition method, for which he used the so-called *transmission* boundary conditions that mix the velocity and pressure variables on an Arakawa-C grid. The numerical results confirm the rate of convergence that has been obtained theoretically, thanks to a Fourier analysis of the semi-discretized problem. A paper is in preparation.

6.1.2.2. Coupling dimensionally heterogeneous models

The coupling of different types of models is gaining more and more attention recently. This is due, in particular, to the needs of more global models encompassing different disciplines (*e.g.* multi-physics) and different approaches (*e.g.* multi-scale, nesting). Also, the possibility to assemble different modeling units inside a friendly modelling software platform is an attractive solution compared to developing more and more global complex models. More specifically one may want to couple 1D to 2D or 3D models, such as Shallow Water and Navier Stokes models: this is the framework of our partnership with EDF in the project MECSICO. In her PhD, M. Tayachi is aimed to build a theoretical and numerical framework to couple 1D, 2D and 3D models for river flows.
This year, she obtained both numerical and theoretical results on a Laplace equation in a domain that suggests a domain decomposition method with two sub-domains that do not have the same space dimension (see Figure 1). A paper is in preparation.

6.1.3. Numerical schemes for ocean modelling

Participants: Laurent Debreu, Jeremie Demange.

Reducing the traditional errors in terrain-following vertical coordinate ocean models (or sigma models) has been a focus of interest for the last two decades. The objective is to use this class of model in regional domains which include not only the continental shelf, but the slope and deep ocean as well. Two general types of error have been identified: 1) the pressure-gradient error and 2) spurious diapycnal diffusion associated with steepness of the vertical coordinate. In a recent paper [78], we have studied the problem of diapycnal mixing. The solution to this problem requires a specifically designed advection scheme. We propose and validate a new scheme, where diffusion is split from advection and is represented by a rotated biharmonic diffusion scheme with flow-dependent hyperdiffusivity satisfying the Peclet constraint.

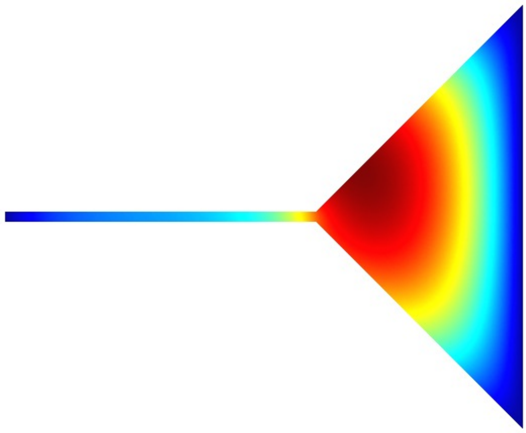

Figure 1. Numerical solution of a coupled 1D-2D system in a specific domain

In 2011, in collaboration with F. Lemarié at UCLA, this work has been extended in order to render the biharmonic diffusion operator scheme unconditionaly stable (paper submitted to ocean modelling). This is particularly needed when the slopes between coordinates lines and isopycnals surfaces are important so that the rotation of the biharmonic leads to strong stability condition along the vertical coordinate where the grid size is relatively small. This work also extends more classical results on the stability of laplacian diffusion with mixed derivatives.

In his Ph'D, Jeremie Demange begins a work on advection-diffusion schemes for ocean models (Supervisors : L. Debreu, P. Marchesiello (IRD)). His work will focus on the link between tracers (temperature and salinity) and momentum advection and diffusion in the non hyperbolic system of equations typically used in ocean models (the so called primitive equations with hydrostatic and Boussinesq assumptions).

Salinity at 1000 m in the Southwest Pacific ocean is shown in figure 2. The use of traditional upwind biased schemes (middle) exhibits a strong drift in the salinity field in comparison with climatology (left). The introduction of high order diffusion rotated along geopotential surfaces prevents this drift while maintaining high resolution features (right).

6.2. Development of New Methods for Data Assimilation

6.2.1. Variational Data Assimilation with Control of Model Error

Participants: Bénédicte Lemieux-Dudon, 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.

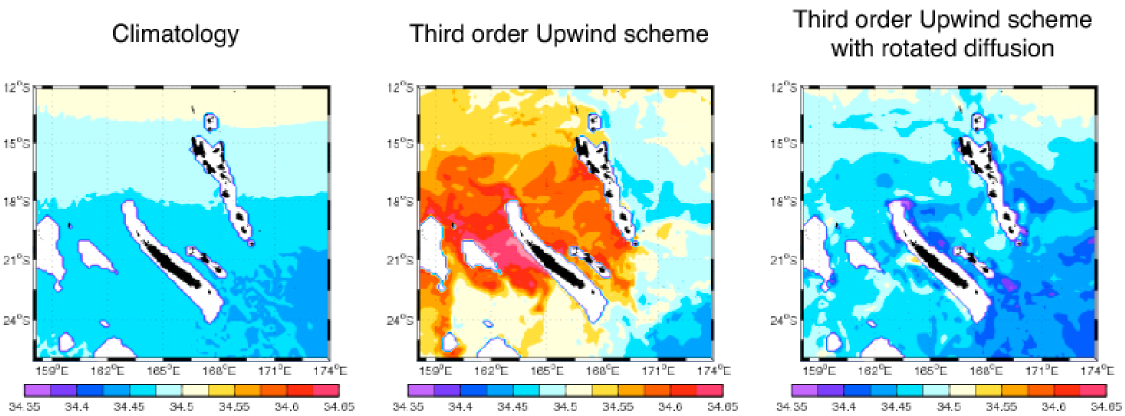

Figure 2. Salinity at 1000m in the Southwest Pacific ocean.

We are implementing this method in a realistic Oceanic framework using OPAVAR/ NEMOVAR as part of the VODA ANR project. An extensive documentation is being produced and should be available along with a first prototype early 2012.

6.2.2. Variational Data Assimilation and Control of the Boundary Conditions

Participant: Eugène Kazantsev.

A variational data assimilation technique applied to the identification of the optimal discretization of interpolation operators and derivatives in the nodes adjacent to the boundary of the domain is discussed in the context of the shallow water model. It was shown in [8] 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 schemes obtained in this way may not approximate derivatives in a common sense. This may lead to another model physics, violating, for example, impermeability boundary condition.

Experiments with a full non-linear shallow water model in [7] show that controlling the discretization of operators near a rigid boundary can bring the model solution close to observations as in the assimilation window and beyond the window. This type of control allows also to improve climatic variability of the model. These properties have been studied in two different configurations: an academic case of assimilation of artificially generated observational data in a square box configuration and assimilation of real observations in a model of the Black sea [30].

The sensitivity of the shallow water model in the previously described configurations has been studied in detail in [9]. It is shown in both experiments that the boundary conditions near a rigid boundary influence the solution higher than the initial conditions. This fact points out the necessity to identify optimal boundary approximation during a model development.

In order to illustrate the influence of optimal discretization of operators near the boundary we compare this influence with now classical data assimilation for identification of the optimal initial conditions of the model. The norm of the difference between the model solution and real observational data is plotted in figure 3. Observed sea surface elevation of the Black sea was assimilated during 50 days (May–Juin 1992) to identify optimal initial and boundary conditions. After that, models have been integrated forward for 500 days and their solutions have been compared with data. One can see that, starting from optimal initial point, the model remains close to observations during less than 100 days while optimal optimal discretization of operators allows the model to be always closer than the model with default parameters.

Adjoint models, necessary to variational data assimilation have been produced by the TAPENADE software, developed by the TROPICS team.

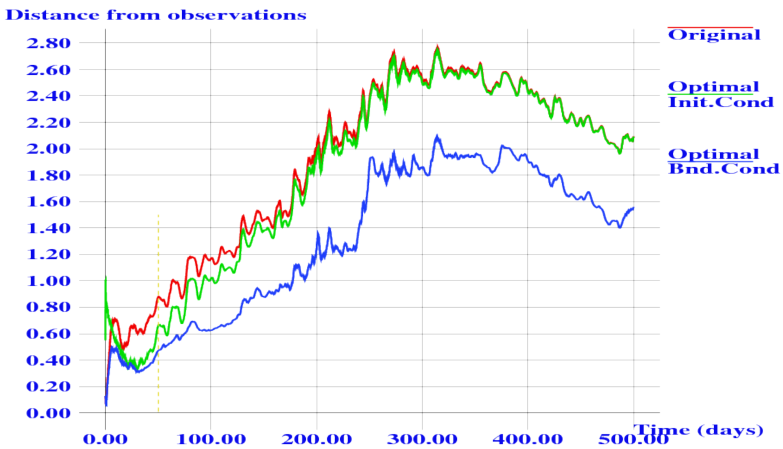

Figure 3. Evolution of the difference "model–observations".

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

Participants: Didier Auroux, Jacques Blum, Maëlle Nodet.

The Back and Forth Nudging (BFN) algorithm (see [63]) has been recently introduced for simplicity reasons, as it does not require any linearization, nor adjoint equation, or minimization process in comparison with variational schemes. Nevertheless it provides a new estimation of the initial condition at each iteration.

Previous theoretical results [65] showed that BFN was often ill-posed for viscous partial differential equations. To overcome this problem, we proposed a new version of the algorithm, which we called the Diffusive BFN [2], and which showed very promising results on one-dimensional viscous equations. Experiments on more sophisticated geophysical models, such as Shallow-Water equations and NEMO ocean model are still in progress, in collaboration with University of Nice.

6.2.4. Variational Data Assimilation for locally nested models.

Participants: Eric Blayo, Laurent Debreu, François-Xavier Le Dimet, 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 (see [85]).

In the ANR MSDAG project and 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. The work includes the analysis of the ellipticity of the optimization problem [12], the comparison of different multigrid methods (Gauss-Newton multigrid method and Full Approximation Scheme) and specific developments for highly non linear problems. To extend previous work on Burgers equation, the Full Approximation Scheme (FAS) and the Newton Multigrid algorithm have been compared in a more complex shallow water model. The results shows good performance of the FAS and also put more interest in the design of the background error covariance matrix.

6.3. Data Assimilation for Ocean Models

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

Participants: Arthur Vidard, Franck Vigilant, Claire Chauvin, Bénédicte Lemieux-Dudon, Pierre-Antoine Bouttier, Laurent Debreu.

We are heavily involved in the development of NEMOVAR (Variational assimilation for NEMO). From 2006, we built a working group (coordinated by A. Vidard) in order to bring together various NEMOVAR 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. It has led to the creation of the VODA (Variational Ocean Data Assimilation for multi scales applications) ANR project
The project aims at delivering a common NEMOVAR platform based on NEMO platform for 3D and 4D variational assimilation. Following 2009-10 VODA activities, a fully parallel version of NEMOTAM (Tangent and Adjoint Model for NEMO) is now available for the community in the standard NEMO version. This version is based on the released 3.0 version of NEMO. Two upgrades were done to follow NEMO standard development race. As a consequence, NEMOVAR is also available for NEMO version 3.2, 3.2.1 and 3.2.2 both offer fully parallel features. The local group has developed a python interface engine (PIANO) to perform test and run on NEMO. A constant support to NEMOVAR project is ensured to deliver a focused response on dedicated issue (internal and external interaction).

We are also investigating variational data assimilation methods applied to high resolution ocean numerical models. This part of the project is now well advanced and encouraging preliminary results are available on an idealized numerical configuration of an oceanic basin (see Figure 4).

A new topic has been explored this year in the framework of VODA: data assimilation in a framework of nested models. It makes full use of the AGRIF capabilities of NEMO and follows previous work done on a toy model during the PhD thesis of E. Simon. Some early results are available with a global ocean 2 degrees configuration including a 1/2 degree zoom on the Agulhas region (see Figure 5).

As a side project we collaborate with Mercator-Ocean in order to use the adjoint to perform sensitivity analysis with the fourth of a degree global model used for the reanalysis. This collaboration that includes both heavy software developments and challenging scientific investigation, has been going on for 2 years now and is producing interesting results for both part that still need to be published.
Apart from the VODA ANR project, the NEMOVAR working group gets additional financial support by LEFE-Assimilation and the Mercator National Programs.

6.3.2. Variational data assimilation into highly nonlinear ocean models

Participants: Pierre-Antoine Bouttier, Eric Blayo, Jacques Verron.

The purpose of this study is to explore the behaviour of variational data assimilation methods in a non-linear ocean model. In an eddy-permitting or eddy-resolving ocean model, controlling mesoscale eddies activity is crucial for data assimilation methods. Our goal is to highlight the impact of these non-linearities on the assimilation system. To illustrate this, test experiments are performed with a double-gyre NEMO configuration at different resolutions (1/4°, 1/12°) which mimics Gulfstream-like behaviour in term of eddy system, and an incremental 4D-VAR formulation for the assimilation system.

First, we are mainly interested in observing the impact of the length of assimilation window on the quality of the analyzed trajectory. For that, we are doing twin experiments with 1/4° model, using simulated altimeter data, for different lengths of assimilation window. Helped by diagnoses on error scales, we also attempt to link the non-linear phenomena and error structures observed after assimilation quantitatively and qualitatively.

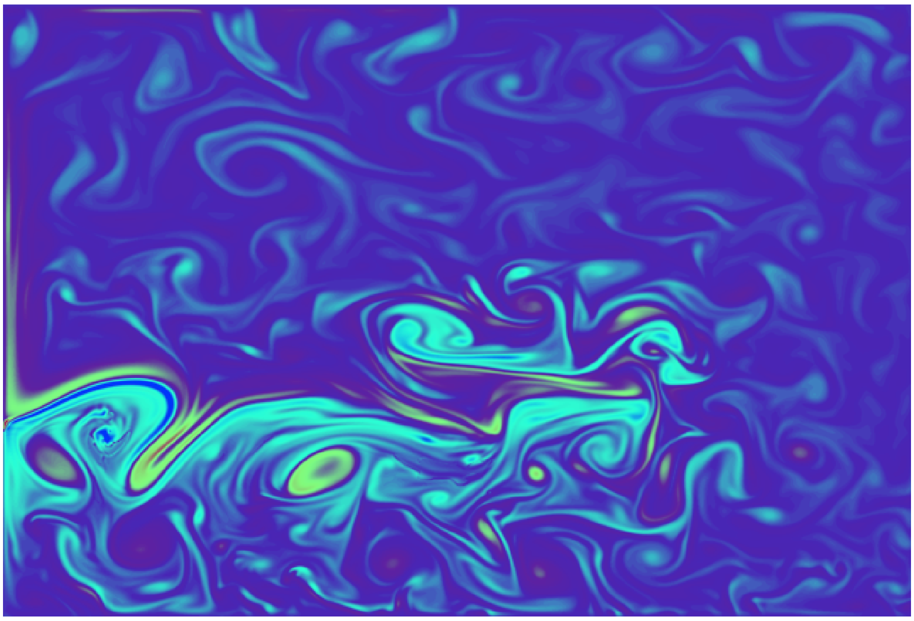

Figure 4. Surface relative vorticity of a 1/24th of a degree NEMO configuration

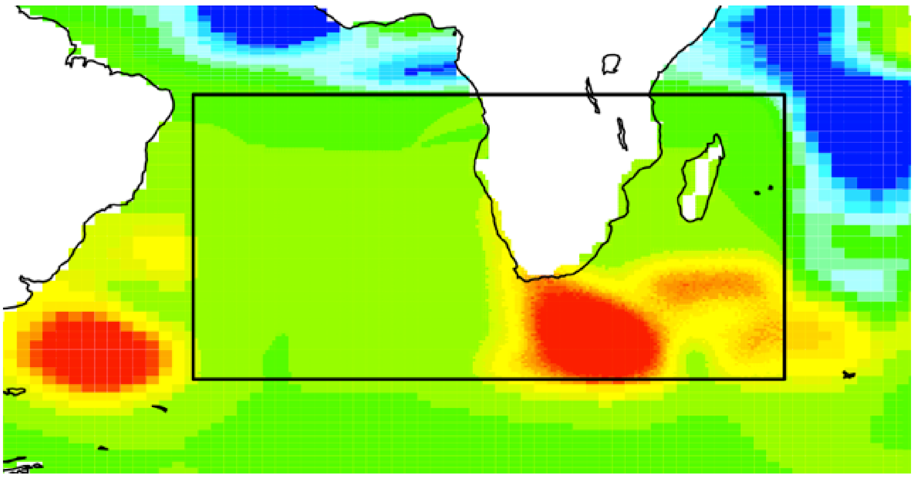

Figure 5. Temperature increment at 200m around the zoom on the Agulhas region

Then, by increasing the model resolution (and consequently mesoscale eddy activity), we bring to light the sensitivity of our assimilation system to non-linearity by repeating the same experiments on the length of assimilation window, and the same diagnoses about error structures.

6.3.3. Assimilation of Lagrangian Data

Participants: Claire Chauvin, Maëlle Nodet, Arthur Vidard.

When an observation is given at a sequence of positions along the fluid flow, then it can be defined as Lagrangian, from a mathematical point of view. From this sequence of positions (for instance the profiling drifting floats of Argo program), one can deduce important information on the stream that transports the drifters. Such an information has not yet been exploited in an operational framework, although previous works [82] have shown the interest of assimilating this new type of data.

A task of the ANR VODA has thus been defined in order to develop the tools for the variational assimilation of Lagrangian data in the context of NEMOVAR. C. Chauvin is an engineer working on this task. She first constructed the observation operator, which requires the interpolation of the velocity at any point of the domain. This interpolation operator is not linear for the general grids used in NEMO, implying heavy tangent and adjoint operators.

Tangent and adjoint procedures associated to this interpolation method have been developed, as well as the tests of these procedures on the main test configurations GYRE and ORCA2. Their implementation in NEMOVAR has required a specific application, in order to be consistent with the conventions and data structures already present in NEMOVAR. We also performed extensive numerical experiments to assess the impact of Lagrangian data assimilation, and its complementarity with other types of data, and we prepare an article to sum up the results. Preliminary results have been presented at EGU [34].

6.4. Assimilation of Image Data

6.4.1. Direct assimilation of sequences of images

Participants: François-Xavier Le Dimet, Maëlle Nodet, Nicolas Papadakis, Arthur Vidard, Vincent Chabot.

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

- Eulerian information as radiance measurements: the radiative properties of the earth and its fluid envelops. 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 them 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 was the leader of the ANR ADDISA project dedicated to the assimilation of images, and is a member of its current follow-up GeoFluids (along with EPI FLUMINANCE and CLIME, and LMD, IFREMER and Météo-France)

During the ADDISA project we developed Direct Image Sequences Assimilation (DISA) and proposed a new scheme for the regularization of optical flow problems [86], [90]. Thanks to the nonlinear brightness assumption, we proposed an algorithm to estimate the motion between two images, based on the minimization of a nonlinear cost function [45]. We proved its efficiency and robustness on simulated and experimental geophysical flows [64]. As part of GeoFluids, we are investigating new ways to define distance between a couple of images. One idea was to define this distance as the norm of the apparent motion between two images. This has been done thanks to optical flow methods which turned out to need a specific parametrization for each couple of images. Another idea, currently under investigation, consists in comparing mains structures within each image. This can be done using, for example, a wavelet representation of images. We are also part of TOMMI, another ANR project started mid 2011, where we are investigating the possibility to use optimal transportation based distances for images assimilation.

6.4.2. Assimilation of ocean images

Participants: Vincent Chabot, Maëlle Nodet, Nicolas Papadakis, Arthur Vidard.

In addition with the direct assimilation approach previously described, a particular attention has been given to the cloud occlusion and the representation of the observation errors in the context of ocean image data. Such works will be intensified with the post-doctorate Alexandros Makris that will start his activities in December. The assimilation of images (SST and chlorophyll) provided by geostationary satellites is also studied with the oceanographers of the Laboratoire des Écoulements Géophysiques et Industriels. The objective is here to take benefit from the correlation that exists between image gradients and ocean flow discontinuities that can be exhibited through the computation of Lyapunov coefficients and vectors from numerical ocean models [70].

6.5. Quantifying Uncertainty

6.5.1. Propagation of uncertainties

Participants: François-Xavier Le Dimet, Victor Shutyaev.

Basically, 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 errors of 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. 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 model [16]. We expect to extent the numerical experiments to a semi-operational model in cooperation with ECMWF.

6.5.2. Sensitivity analysis for West African monsoon

Participants: Anestis Antoniadis, Céline Helbert, Clémentine Prieur, Laurence Viry.

6.5.2.1. Geophysical context

The West African monsoon is the major atmospheric phenomenon which drives the rainfall regime in Western Africa. Therefore, this is the main phenomenon in water resources over the African continent from the equatorial zone to the sub-Saharian one. Obviously, it has a major impact on agricultural activities and thus on the population itself. The causes of inter-annual spatio-temporal variability of monsoon rainfall have not yet been univocally determined. Spatio-temporal changes on the see surface temperature (SST) within the Guinea Gulf and Saharian and Sub-Saharian Albedo are identified by a considerable body of evidences as major factors to explain it.

The aim of this study is to simulate the rainfall by a regional atmospheric model (RAM) and to analyze its sensitivity to the variability of these inputs parameters. Once precipitations from RAM are compared to several precipitation data sets we can observe that the RAM simulates the West African monsoon reasonably.

6.5.2.2. *Statistical methodology*

As mentioned in the previous paragraph, our main goal is to perform a sensitivity analysis for the West African monsoon. Each simulation of the regional atmospheric model (RAM) is time consuming, and we first have to think about a simplified model. We deal here with spatio-temporal dynamics, for which we have to develop functional efficient statistical tools. In our context indeed, both inputs (albedo, SST) and outputs (precipitations) are considered as time and space indexed stochastic processes. A first step consists in proposing a functional modeling for both precipitation and sea surface temperatures, based on a new filtering method. For each spatial grid point in the Gulf of Guinea and each year of observation, the sea surface temperature is measured during the active period on a temporal grid. A Karhunen-Loève decomposition is then performed at each location on the spatial grid [91]. The estimation of the time dependent eigenvalues at different spatial locations generates great amounts of high-dimensional data. Clustering algorithms become then crucial in reducing the dimensionality of such data.

Thanks to the functional clustering performed on the first principal component at each point, we have defined specific subregions in the Gulf of Guinea. On each subregion, we then choose a referent point for which we keep a prescribed number of principal components which define the basis functions. The sea surface temperature at any point in this subregion is modeled by the projection on this truncated basis. The spatial dependence is described by the coefficients of the projection. The same approach is used for precipitation. Hence for both precipitation and sea surface temperatures, we obtain a decomposition where the basis functions are functions depending on time and whose coefficients are spatially indexed and time independent. Then, the most straightforward way to model the dependence of precipitation on sea surface temperatures is through a multivariate response linear regression model with the output (precipitation) spatially indexed coefficients in the above decomposition and the input (SST) spatially indexed coefficients being predictors. A naive approach consists in regressing each response onto the predictors separately; however it is unlikely to produce satisfactory results, as such methods often lead to high variability and over-fitting. Indeed the dimensions of both predictors and responses are large (compared to the sample size).

We apply a novel method recently developed by [83] in integrated genomic studies which takes into account both aspects. The method uses an ℓ_1-norm penalty to control the overall sparsity of the coefficient matrix of the multivariate linear regression model. In addition, it also imposes a *group* sparse penalty. This penalty puts a constraint on the ℓ_2 norm of regression coefficients for each predictor, which thus controls the total number of predictors entering the model, and consequently facilitates the detection of important predictors. The dimensions of both predictors and responses are large (compared to the sample size). Thus in addition to assuming that only a subset of predictors enter the model, it is also reasonable to assume that a predictor may affect only some but not all responses. By the way we take into account the complex and spatio-temporal dynamics. This work has been published in [1].

6.5.2.3. *Distributed Interactive Engineering Toolbox*

An important point in the study described above is that the numerical storage and processing of model inputs/outputs requires considerable computation resources. They were performed in a grid computing environment with a middleware (DIET) which takes into account the scheduling of a huge number of computation requests, the data-management and gives a transparent access to a distributed and heterogeneous platform on the regional Grid CIMENT (http://ciment.ujf-grenoble.fr/).

Thus, a different DIET module was improved through this application. An automatic support of a data grid software (http://www.irods.org) through DIET and a new web interface designed for MAR was provided to physicians.
These works involve also partners from the INRIA project/team GRAAL for the computational approach, and from the Laboratory of Glaciology and Geophysical Environment (LGGE) for the use and interpretation of the regional atmospheric model (RAM).

6.5.3. *Tracking for mesoscale convective systems*

Participants: Anestis Antoniadis, Céline Helbert, Clémentine Prieur, Laurence Viry, Roukaya Keinj.

6.5.3.1. Scientific context

In this section, we are still concerned with the monsoon phenomenon in western Africa and more generally with the impact of climate change. What we propose in this study is to focus on the analysis of rainfall system monitoring provided by satellite remote sensing. The available data are micro-wave and IR satellite data. Such data allow characterizing the behaviour of the mesoscale convective systems. We wish to develop stochastic tracking models, allowing for simulating rainfall scenari with uncertainties assessment.

6.5.3.2. Stochastical approach

The chosen approach for tracking these convective systems and estimating the rainfall intensities is a stochastic one. The stochastic modeling approach is promising as it allows developping models for which confidence in the estimates and predictions can be evaluated. The stochastic model will be used for hydro-climatic applications in West Africa. The first part of the work will consist in implementing a model developed in [88] on a test set to evaluate its performances, our ability to infer the parameters, and the meaning of these parameters. Once the model well fitted on toy cases, this algorithm should be run on our data set, and compared with previous results by [80] or by [79]. The model developed by [88] is a continuous time stochastic model to multiple target tracking, which allows in addition to birth and death, splitting and merging of the targets. The location of a target is assumed to behave like a Gaussian Process when it is observable. Targets are allowed to go undetected. Then, a Markov Chain State Model decides when the births, death, splitting or merging of targets arise. The tracking estimate maximizes the conditional density of the unknown variables given the data. The problem of quantifying the confidence in the estimate is also addressed. Roukaya Keinj started working on this topic with a two years postdoctoral position in November 2011.

6.5.4. Sensitivity analysis for forecasting ocean models

Participants: Eric Blayo, Maëlle Nodet, Clémentine Prieur, Gaëlle Chastaing, Alexandre Janon, Jean-Yves Tissot.

6.5.4.1. Scientific context

Forecasting ocean systems require complex models, which sometimes need to be coupled, and which make use of data assimilation. The objective of this project is, for a given output of such a system, to identify the most influential parameters, and to evaluate the effect of uncertainty in input parameters on model output. Existing stochastic tools are not well suited for high dimension problems (in particular time-dependent problems), while deterministic tools are fully applicable but only provide limited information. So the challenge is to gather expertise on one hand on numerical approximation and control of Partial Differential Equations, and on the other hand on stochastic methods for sensitivity analysis, in order to develop and design innovative stochastic solutions to study high dimension models and to propose new hybrid approaches combining the stochastic and deterministic methods.

6.5.4.2. Estimating sensitivity indices

A first task is to develop tools for estimated sensitivity indices. Among various tools a particular attention was paid to FAST and its derivatives. In [89], the authors present a general way to correct a positive bias which occurs in all the estimators in random balance design method (RBD) and in its hybrid version, RBD-FAST. Both these techniques derive from Fourier amplitude sensitivity test (FAST) and, as a consequence, are faced with most of its inherent issues. And up to now, one of these, the well-known problem of interferences, has always been ignored in RBD. After presenting in which way interferences lead to a positive bias in the estimator of first-order sensitivity indices in RBD, the authors explain how to overcome this issue. They then extend the bias correction method to the estimation of sensitivity indices of any order in RBD-FAST. They also give an economical strategy to estimate all the first-order and second-order sensitivity indices using RBD-FAST.

6.5.4.3. Intrusive sensitivity analysis, reduced models

Another point developed in the team for sensitivity analysis is model reduction. To be more precise regarding model reduction, the aim is to reduce the number of unknown variables (to be computed by the model), using a well chosen basis. Instead of discretizing the model over a huge grid (with millions of points), the state vector of the model is projected on the subspace spanned by this basis (of a far lesser dimension). The choice of the basis is of course crucial and implies the success or failure of the reduced model. Various model reduction methods offer various choices of basis functions. A well-known method is called proper orthogonal decomposition" or principal component analysis". More recent and sophisticated methods also exist and may be studied, depending on the needs raised by the theoretical study. Model reduction is a natural way to overcome difficulties due to huge computational times due to discretizations on fine grids. In [61], the authors present a reduced basis offline/online procedure for viscous Burgers initial boundary value problem, enabling efficient approximate computation of the solutions of this equation for parametrized viscosity and initial and boundary value data. This procedure comes with a fast-evaluated rigorous error bound certifying the approximation procedure. The numerical experiments in the paper show significant computational savings, as well as efficiency of the error bound. The present preprint is under review. When a metamodel is used (for example reduced basis metamodel, but also kriging, regression, ...) for estimating sensitivity indices by Monte Carlo type estimation, a twofold error appears : a sampling error and a metamodel error. Deriving confidence intervals taking into account these two sources of uncertainties is of great interest. We obtained results particularly well fitted for reduced basis metamodels [61]. Alexandre Janon obtained a best poster award on the topic [40]. An ongoing work deals also with asymptotic confidence intervals in the double limit where the sample size goes to infinity and the metamodel converges to the true model. Implementations have to be conducted on more general models such as Shallow-Water models.

6.5.4.4. Sensitivity analysis with dependent inputs

An important challenge for stochastic sensitivity analysis is to develop methodologies which work for dependent inputs. For the moment, there does not exist conclusive results in that direction. Our aim is to define an analogue of Hoeffding decomposition [75] in the case where input parameters are correlated. A PhD started in October 2010 on this topic (Gaëlle Chastaing). We obtained first results which should be submitted soon, deriving a general functional ANOVA for dependent inputs, allowing defining new variance based sensitivity indices for correlated inputs.

6.5.5. Quantification of uncertainty with Multi-fidelity computer experiments

Participants: Federico Zertuche, Céline Helbert, Anestis Antoniadis.

Propagation of uncertainties through computer codes is a hard task when dealing with heavy industrial simulators. Confidence intervals announced on predictions are often huge because of the lack of data. The context of the study here is the case of simulations when multiple levels of analysis (fast and slow) are available. In most cases the fast (but less trustworthy) and the slow (but more accurate) response values can be obtained independently. Thus, we can learn more about the response by additionally measuring the cheap function(s) on a large number of x 's. In most cases the relationship between cheap and expensive responses is modeled by an autoregressive Gaussian regression. This method is a natural extension of the kriging method in the sense that to build the surrogate one performs a Gaussian regression for the cheap data and one for the difference vector defined by the autoregressive relationship. The prediction error depends on the prediction error of the cheap and expensive surrogates. We can observe that this modeling greatly improves the traditional kriging method when the actual relationship between the cheap and expensive responses is somewhat linear. On another hand, this approach gives worse results when the relation between cheap and expensive is far to be linear. Therefore some improvements must be made on the models to take into account a more precise link between the two levels fidelity of the responses. Some other additional tasks concern the associated numerical designs (must the designs be absolutely nested ?) and the allocation of resources between low and fast runs. The work is currently the object of the thesis of Federico Zertuche that has just begun in October 2011.

6.5.6. Impact of the thermodynamics and chemical kinetics parameters at different scales for the models of CO2 storage in geological media

Participant: Céline Helbert.

In collaboration with Bernard Guy and Joharivola Raveloson (Ecole des Mines de Saint-Etienne) we study the water-gas-rock interactions in the case of CO2 storage in geological environment. The focus is on the scale of observation of geochemical phenomena while taking into account the heterogeneity of the reservoir. This heterogeneity at small and large scale helps to maintain a local variability of the chemical composition of the fluid and influence reaction rates at the pore as well as at the reservoir scale. We propose to evaluate the geostatistical characteristics of local variability thanks to simulations of reactive transport on a small scale in which parameters (namely the equilibrium constants log K and the rate constant k) are perturbed to represent local processes. This contribution is the following of a precedent study of the impact of the reservoir uncertainties on the CO2 storage [72].

6.6. Inverse methods for Glaciology

6.6.1. Dating ice matrix and gas bubbles

Participants: Eric Blayo, Bénédicte Lemieux-Dudon, Habib Toye Mahamadou Kele.

Dating ice matrix and gas bubbles of ice-cores is essential to study paleoclimates. Inverse modelling implemented on 1D ice flow models is being applied for a few years to construct the ice chronology of several deep ice cores. Such a method based on a Monte Carlo algorithm was implemented under the assumption of perfect ice flow models, for one core at a time, and without including the inverse modelling of the densification models, which enables to construct the gas age scale. This approach faces three issues: 1) frequent discrepancies between core chronologies (lack of stratigraphic links between cores as data constraints), 2) frequent failure to verify relevant data constraints (perfect model assumption is too strong), and 3) frequent inconsistency between gas and ice age scales.

A new approach was proposed during the B. Lemieux-Dudon's PhD to circumvent these restrictions. It introduces the model error in terms of correction functions on three key quantities from which one can calculate both the ice and gas age scales: a) the accumulation rate, b) the total thinning function, and c) the close-off depth in meters of ice equivalent (i.e. depth below the ice-sheet surface where the atmosphere is trapped). A variational formulation of the inverse problem is constructed. It includes several ice cores with background scenarios and paleo data as constraints, among which:

- stratigraphic links between pair of ice cores (methane, tephra, cosmogenic isotopes, etc.) to derive consistent dating between cores,
- ice and gas age markers, as well as delta-depth data (i.e., in situ depth interval between gas and ice of the same age), which enable to optimize the gas and ice age scales simultaneously.

The cost function includes covariance error matrices, and confidence intervals of the solution can be assessed. This method was applied to derive simultaneously a common age scale for the North Grip core and for the two EPICA cores (DML and DC). [76].

This method arouses some interest in the glaciological and paleo community ([68], [87]). Some further developments are however mandatory to ensure the robustness of the dating solution: (i) code optimization, (ii) diagnostics on the assimilation system, and (iii) calibration of the background error covariance matrices.

H. Toye Mahamadou Kele (a 2-year INRIA young engineer contract) joined the MOISE team to modify the code. During the first year, he implemented a shared memory parallelization of the code, and he currently works on the calibration of the covariance error matrices by implementing a posteriori diagnostics.

6.6.2. Inverse methods for large scale ice-sheet models

Participants: Bertrand Bonan, Maëlle Nodet, Catherine Ritz.

In collaboration with C. Ritz (CNRS, Laboratoire de Glaciologie et Geophysique de l'Environnement (LGGE), Grenoble), we aim to develop adjoint methods for ice cap models.

In the framework of global warming, the evolution of sea level is a major but ill-known phenomenon. It is difficult to validate the models which are used to predict the sea level elevation, because observations are heterogeneous and sparse.

Data acquisition in polar glaciology is difficult and expensive. Satellite data have a good spatial coverage, but they allow only indirect observation of the interesting data. We wish to make the most of all available data and evaluate where/when/what we have to add new observations. Sensitivity analysis, and in particular the adjoint method, allows to identify the most influential parameters and variables and can help to design the observation network.

The ANR project ADAGe started one year ago on this subject, and B. Bonan started his PhD in September 2010. During his master internship, he implemented the adjoint code of a simplified ice-sheet flow-line model, Winnie, developed by C. Ritz at LGGE. We then performed twin experiments of data assimilation. These preliminary results have been presented at two international conferences [32], [33].

We then implemented Ensemble Kalman Filter (EnKF) on Winnie, which we would like to compare to variational assimilation methods. Coding and testing for the EnKF are still in progress.

6.6.3. Inverse methods for full-Stokes glaciology models

Participants: Olivier Gagliardini, Maëlle Nodet, Catherine Ritz.

We are also interested in inverse modelling for another class of glaciology models, called full-Stokes models. Such a model is developed by LGGE and CSC in Finland, called Elmer/Ice. Contrary to large scale models, Elmer/Ice is based on the full Stokes equations, and no asumptions regarding aspect ratio are made, so that this model is well adapted to high resolution small scale modelling, such as glaciers (and more recently the whole Greenland ice-sheet).

In collaboration with O. Gagliardini, F. Gillet-Chaulet and C. Ritz (Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Grenoble), we investigated a new method to solve inverse problems for a Full-Stokes model of Groenland, which consisted in solving iteratively a sequence of Neumann and Dirichlet problems within a gradient descent algorithm. We also compared this method to an approximate variational algorithm, using the fact that the full Stokes equations are almost self-adjoint. These results have been submitted for publication and presented at EGU and AGU [36], [37].

With O. Gagliardini, F. Gillet-Chaulet and M. Jay-Allemand (LGGE), we also implemented these methods to study a complex phenomenon: the surge of Variegated glacier (Alaska). This glacier is indeed known to surge periodically, that is to accelerate suddenly during 1-2 years, and then come back to a quiescent phase during 10-20 years. Inverse modelling allowed us to infer changes in basal conditions from surface velocities, and to come to a better understanding of the surge phenomenon, as seen in Figure 6. These results have been published [6] and presented at AGU [42].

6.7. Image processing

6.7.1. Segmentation and assimilation of medical images

Participant: Nicolas Papadakis.

In collaboration with the Inria team MC2 of the Bordeaux-Sud-Ouest center, we investigate the application of image assimilation to medical issues. The objective is here to use MRI images in order to monitor EDP models dealing with tumor growth in lungs or brains. Using such images, we would like to define a patient specific process allowing to calibrate the numerical model with respect to the observed tumor. First works based on convex relaxation of the binary segmentation problem [81] have been realized in this direction by proposing a 3D segmentation method dedicated to glioblastomas from a set of MRI brain images. The obtained automatic segmentation results are very close to specialist manual segmentations (errors of 5%) and will be used as pseudo-observations for an assimilation system based on the numerical model describing the tumor growth. The final issue will be to define an observation operator linking images with the model in order to realize a direct assimilation.

6.7.2. Optimal transport

Participants: Maëlle Nodet, Nicolas Papadakis, Arthur Vidard.

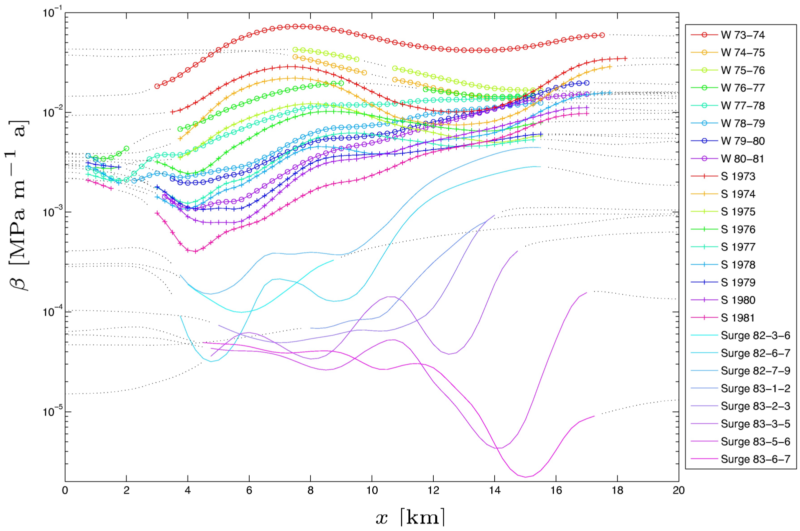

Figure 6. Distribution of the basal friction parameter along the central flow line for the 25 dates of measurements. Dotted curves indicate where measured surface velocities are missing. In the legend, W Y1-Y2 denotes the mean velocity for the winter from year Y1 to year Y2, S Y denotes the mean velocity for the summer of year Y and Surge Y-M1-M2 the mean velocity for year Y from month M1 to month M2.

A new activity on optimal transport has been started in collaboration with the EDP and MGMI teams of the Laboratoire Jean Kuntzmann, Grenoble and the MAP5 Laboratory, Paris, through a project funded by the ANR white program. The purpose is to define metric beween images involving the so-called Wasserstein distance. Such metric would be of particular interest in order to introduce pertinent observation operators for assimilating image data 6.4. Other applications including image morphing and histogram equalization are also studied for image processing purposes. First results has been obtained by adding spatial regularity to the transport map computed by the Benamou-Brenier algorithm [66]

6.7.3. Computer vision

Participant: Nicolas Papadakis.

In collaboration with Vicent Caselles (Pompeu Fabra University, Barcelona, Spain), different image processing works have been finalized: 3D reconstruction and novel view synthesis for soccer replays [13], stereo inpainting for 3D movie post-production [29]. Other works dedicated to object tracking in image sequences have also been proposed with Aurelie Bugeau (LABRI, Bordeaux) [14]. A main attention is now given to the problem of histogram equalization of different images [15]. Our aim is now to include spatial information on color repartition during the histogram transfer for inpainting and shadow removal purposes. A journal paper dealing with this issue has been recently accepted for publication.

6.8. Multivariate risk indicators

Participant: Clémentine Prieur.

In collaboration with Véronique Maume-Deschamps, Elena Di Bernardino (ISFA, Lyon 1) and Peggy Cenac (Université de Bourgogne), we are interested in defining and estimating new multivariate risk indicators. This is a major issue with many applications (environmental, insurance, ...). Two papers were accepted for publication and one other is submitted. The submitted one deals with the estimation of bivariate tails [56]. In [69] we propose to minimize multivariate risk indicators by using a Kiefer-Wolfowitz approach to the mirror stochastic algorithm. In [4] we present an estimation procedure for multivariate risk indicators making use of a plug-in estimation of level sets of bivariate cumulative distribution functions.

6.9. Stochastic Downscaling Method

Participant: Antoine Rousseau.

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. In this work, we consider a new approach for the downscaling in CFD, The local model that we propose is inspired from S.B. Pope's previous works on turbulence. We investigated a new numerical simulation method for the downscaling in CFD, with a strong orientation in applications to meteorology, particularly for the simulation of wind at small scales. The local model that we propose consists in modeling the fundamental equations of fluid motion by a stochastic Lagrangian model describing the behaviour of a fluid particle. Because of the both Lagrangian and stochastic nature of our model, it is discretized thanks to an interacting particle system, combining a time Euler scheme for stochastic differential equations and a Monte–Carlo approximation method. This model called *SDM* (Stochastic Downscaling Method) is adapted from previous works introduced by S.B. Pope [84] (see http://sdm.gforge.inria.fr/Accueil/index.en.php).

This year, we worked on the comparison of the SDM model (endowed with a physical geostrophic forcing and a wall log law) with simulations obtained with a LES method (Méso-NH code) for the atmospheric boundary layer (from 0 to 750 meters in the vertical direction), in the neutral case. This work allowed to deeply understand the contribution of each elements of the Lagrangian model in terms of the turbulence production and dissipation, we analyzed the returns of various closure parametrization approaches, including viscosity turbulent approach. We also investigated anisotropic effect, with the introduction of GLM model in SDM (see [84]), in particular the isotropic relaxation case. We gave our conclusions as a part of the final report for ADEME [58]. A paper is in preparation.

6.10. Mathematical modelling for CFD-environment coupled systems

Participant: Antoine Rousseau.

6.10.1. Minimal-time bioremediation of natural water resources

The objective of this work is to provide efficient strategies for the bioremediation of natural water resources. Based on a previous paper [74] that deals with an homogeneous resource in space (with a system of ODEs), we implement a coupled ODE-PDE system that accounts for the spatial non-homogeneity of pollution in natural resources. The main idea is to implement a Navier-Stokes model in the resource (such as a lake), with boundary conditions that correspond to the corresponding optimal discharge of a (small) bioreactor. A first mathematical model has been intoduced (see [48]) and a journal paper is ready to be submitted.

6.10.2. Mathematical modelling for the confinement of lagoons

This work deals with the concept of confinement of paralic ecosystems. It is based on the recent paper [73] that presents a modelling procedure in order to compute the confinement field of a lagoon.
In [59], A. Rousseau and E. Frénod (INRIA CALVI), improve the existing model in order to account for tide oscillations in any kind of geometry such as a non-rectangular lagoons with a non-flat bottom. The new model, that relies on PDEs rather than ODEs, is then implemented thanks to the finite element method. Numerical results confirm the feasibility of confinement studies thanks to the introduced model.

7. Contracts and Grants with Industry

7.1. Contracts with Industry

- A 4-year contract named ReDICE (Re Deep Inside Computer Experiments) with EDF, CEA, IRSN, RENAULT, IFP on the thematic computer experiments
- A 3-year contract with EDF: project MeCSiCo (coupling methods for the simulation of river flows): see 4.4
- A 3-year contract with ADEME on the thematic "Stochastic Downscaling Method": see 6.9.
- A 1-year contract with IFREMER on the thematic “Optimization of the parallel performance of the AGRIF software": see 5.1

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Nicolas Papadakis is responsible of the ASIOME project (Assimilation de Structures d'Images Océanographiques et Modélisation d'Erreurs) funded by the Pôle Mathématiques Sciences et Technologies de l'Information et de la Communication (MSTIC) of the Joseph Fourier University, Grenoble. 6.4.2
- E.Blayo , M. Nodet are responsible for the workpackage "numerical modelling" within the regional project (Région Rhône-Alpes) "**Envirhonalp**" http://www.envirhonalp.fr.
- A. Rousseau leads the working group *Couplage Fluide/Vivant* in Montpellier for the study of coupled systems (fluid dynamics and life sciences) in nearshore regions. This research is funded by the Labex NUMEV in Montpellier.
- E. Blayo is a member of the scientific committee of the regional Institut des Sciences Complexes (IXXI) http://www.ixxi.fr.
- E. Blayo is a member of the scientific committee of the Pôle Alpin Risques Naturels http://www.risknat.org.

8.1.1. Collaborations with Various Regional Research Teams

- LGGE Grenoble, Edge team (C. Ritz, O. Gagliardini, F. Gillet-Chaulet), see paragraphs 6.6.2 and 6.6.3.
- LEGI, MEOM team : 6.4.2,6.1.2,6.2.3,6.3.1,6.4.1.
- LTHE : 6.5.2,6.5.3

8.2. National Initiatives

8.2.1. Interactions with other INRIA Project-Teams or Actions

Participants	**INRIA Project-Team**	**Research topic**	**Link**
N. Papadakis	MC2	Image segmentation and assimilation for tumor growth modeling	6.7.1
C.Prieur	GRAAL	Grid deployment for the study of West African Monsoon	6.5
A. Rousseau	TOSCA	Stochastic Downscaling Method	6.9

Participants	INRIA Project-Team	Research topic	Link
A. Rousseau	CALVI	Coupled systems in nearshore regions	6.10
A. Rousseau	MODEMIC	Bioremediation of natural resources	6.10
A. Vidard M. Nodet F.X. Le Dimet	CLIME, FLUMINANCE	Image assimilation	6.4
A. Vidard, M. Nodet, E.Kazantsev	TROPICS	Ocean Adjoint Modelling	6.3.1,6.2.2
L.Debreu, E.Blayo	CLIME, FLUMINANCE	Multiscale data assimilation	6.3.1

8.2.2. Collaborations with other Research Teams in France

Participants	INRIA Project-Team	Research topic	Link
N. Papadakis	(Labri, IMB, Bordeaux)	image processing problems (histogram equalization and image inpainting)	6.7
M. Nodet	Laboratoire Dieudonné (Université de Nice)	BFN data assimilation scheme	6.2.3
C. Prieur	IMT Toulouse, IFP Rueil, EDF, CEA Cadarache	Sensitivity analysis	6.5.2
C. Prieur	ISFA Lyon 1, Université de Bourgogne	Multivariate risk indicators	6.8
C. Prieur	LGGE	Statistical methodology	6.5.2
C. Helbert	Ecole des Mines St-Etienne, Universit de Berne, Telecom St-Etienne, EDF, CEA, IRSN, IFP, RENAULT	Computer Experiments	6.5.5
C. Helbert	Ecole des Mines St-Etienne	Quantification of Uncertainties in CO2 storage	6.5.6
A. Rousseau	Institut de Mathématiques et de Modélisation de Montpellier (I3M)	Modelling and simulation of coastal flows	6.1
A. Rousseau	Laboratoire de Météorologie Dynamique (Ecole Polytechnique), Centre d'Études Techniques de l'Équipement (Clermont-Ferrand)	Stochastic Downscaling Method	6.9
E.Blayo, A.Rousseau	LAMFA (Amiens), LAGA (Paris 13), IFREMER (Brest)	Coupling methods	6.1.2
A. Vidard	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (Toulouse), Mercator-Océan (Toulouse), Laboratoire de Physique des Océans (Brest),	Ocean Data Assimilation	6.3.1
A. Vidard	LOCEAN (Paris)	Ocean Adjoint Modelling	6.3.1
A. Vidard	LPO (Brest), CERFACS	Ocean data assimilation	6.3.1

8.2.3. MOISE team is implied in:

- A 4-year ANR contract: ANR ADAGe (Adjoint ice flow models for Data Assimilation in Glaciology, see paragraph 6.6) .
- A 4-year ANR contract: ANR Geo-FLUIDS (Fluid flows analysis and simulation from image sequences: application to the study of geophysical flows, see paragraph 6.4) .
- A 4-year ANR contract: ANR COSTA-BRAVA (Complex Spatio-Temporal Dynamics Analysis by Reduced Models and Sensitivity Analysis)http://www.math.univ-toulouse.fr/COSTA_BRAVA/index.html
- A 4-year ANR contract: ANR TOMMI (Transport Optimal et Modèles Multiphysiques de l'Image), see paragraphs 6.7.2,6.4.
- AST & Risk ANR project (white project selected in 2008). http://isfaserveur.univ-lyon1.fr/asterisk/
- A 3 years ANR contract: ANR MSDAG (Multiscale Data Assimilation in Geophysics) see paragraph 6.2.4)
- A 4 year ANR contract (2011-2015): ANR COMODO (Communauté de Modélisation Océanographique) on the thematic "Numerical Methods in Ocean Modelling". (coordinator L. Debreu) 6.1.3
- Nicolas Papadakis is involved in the SWOT-Ocean group in charge of the use of the high resolution data that will be provided by the future SWOT satellite (CNES/NASA mission). This work is realized in collaboration with Jacques Veron of the Laboratoire des Écoulements Géophysique et Industriels. 6.4.2
- M. Nodet is PI of the project "Méthodes inverses en glaciologie" supported by INSU-LEFE.
- 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 6.3.1. This project is granted by two INSU-LEFE and a Mercator-Ocean calls for proposals
- A. Vidard is coordinator of the ANR VODA (Variational Ocean Data Assimilation for multi-scales applications) 4-year contract.
- DATICE simulations are currently performed at LSCE (Laboratoire des Sciences de l'Environnement et du Climat) in the framework of a PhD thesis (Lucie Bazin supervised by Amaelle Landais), and at LGGE (Laboratoire de Glaciologie et de Géophysique de l'Environnement) in the framework of a postdoctoral work (Daniel Véres, supervised by Patricia Martinerie). Both works will contribute to calculate AICC2012, the future unified Antarctic ice core age scales (Special Issue in preparation in the *Climate of the Past* journal, Eric Wolff, CP co-editor-in-chief, British Antarctic Survey, Cambridge). An ANR proposal in preparation "Datation multi-archives" (where LGGE and LSCE are partners, and MOISE members intervene as experts) aims in particular at extending the mathematical method to marine sediment cores.
- E. Blayo is the co-chair (with M. Bocquet, EPI CLIME) of the CNRS-INSU research program on mathematical and numerical methods for ocean and atmosphere LEFE-MANU. http://www.insu.cnrs.fr/co/lefe
- E. Blayo was a member of the 2011 ANR evaluation panel "Earth, Environment, Space".
- L. Debreu is the coordinator of the national group COMODO (Numerical Models in Oceanography)
- L. Debreu organized a 3-day meeting on numerical ocean modelling (Villard de Lans, November 2011)

8.2.4. Participation to National Research Groups (GdR) CNRS

- M. Nodet is involved in GDR Calcul and GDR Ondes.
- C. Prieur chairs GdR MASCOT NUM, in which are also involved M. Nodet, E. Blayo, A. Rousseau, C. Helbert, L. Viry, A. Janon, J.-Y. Tissot and G. Chastaing. http://www.gdr-mascotnum.fr/doku.php

8.3. European Initiatives

8.3.1. Major European Organizations with which Moise has followed Collaborations

Partner: European Centre for Medium Range Weather Forecast. Reading (UK)

World leading Numerical Weather Centre, that include an ocean analysis section in order to provide ocean initial condition fo the coupled ocean atmosphere forecast. They play a significant role in the NEMOVAR project in which we are also partner.

Partner: Met Office (U.K) National British Numerical Weather and Oceanographic service. Exceter (UK).

We do have a strong collaboration with their ocean initialization team through both our NEMO, NEMO-ASSIM and NEMOVAR activities. They also are our partner in the NEMOVAR consortium.

Partner: Marine Hydrographic Institute, Natinal Ac.Sci. Ukraine, Sevastopol.

We have a long term collaboration about data assimilation with the Black Sea. This collaboration is getting to a new level with their plan to adopt NEMO and NEMOVAR for their operational forecasting system. On our side, we will benefit from their expertise on the Black Sea dynamics, that is an excellent test case for our developments and methods.

Partners: David Vaugham, British Antarctic Survey (UK). Tony Payne, University of Bristol (UK)

Subject: Ice-sheet inverse modelling to assess sea-level change.

Partners: V. Shutyaev (Institute of Numerical Mathematics, Russian Academy of Sciences), I. Gejadze (Dept. of Civil Engineering, University of Strathclyde, Scotland)

Subject: propagation and control of the error in data assimilation and on evaluation of error covariance by deterministic method.

Partner: GDR-E CONEDP

Subject: Control of Partial Differential Equations.

Partner: Vicent Caselles of the Pompeu Fabra University, Barcelona Spain

Subject: Image processing problems such as 3D reconstruction [13], histogram transfer [15] or image inpainting [29]. 6.7

8.4. International Initiatives

- C. Prieur collaborates with Antonio Galves (University Sao Paulo) and Jose R. Leon (UCV, Central University of Caracas). She is a member of a USP-COFECUB project on the study of stochastic models with variable length memory (2010-2013) with University of Sao Paulo.
- F.-X. Le Dimet was invited in Jet Propulsion Laboratory, NASA, Pasadena, USA, 1 week, (1 conférence)
- F.-X. Le Dimet was invited in CICESE , Ensenada Mexique 2 weeks, février 2011 (2 conférences)
- F.-X. Le Dimet was invited in Ewu University, Seoul Korea, August 2011, 2 weeks.
- F.-X. Le Dimet was invited in Florida State University : 6 weeks.
- F.-X. Le Dimet was invited in Caltech , Pasadena, California 1 week, 1 conference.
- F.-X. Le Dimet was invited in NASA (JPL) 1 week.

8.4.1. Visits of International Scientists

- Professor Robert Miller (College of Oceanic and Atmospheric Sciences, Oregon State University) has been visiting our team from October 2010 to September 2011. He worked in particular with us on Ensemble Kalman filtering and on error filtering in variational data assimilation.

9. Dissemination

9.1. Animation of the scientific community

- C. Kazantsev is the Director of the Grenoble branch of the National Research Institute for Mathematics Teaching http://www-irem.ujf-grenoble.fr/irem/accueil/.
- N Papadakis is in charge of EDP/MOISE fortnightly seminar, see http://ljk.imag.fr/MOISE/Seminaires/seminaires.php. This seminar 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.
- N. Papadakis co organizes the working group Optimal Transport and Image Processing, see http://ljk.imag.fr/MOISE/Seminaires/seminaires.php that consists of a presentation given by a member of the LJK or invited scientists.
- N. Papadakis developped a graphic interface of [15] for the 2011 "Fête de la science" event.
- M. Nodet and D. Auroux organized the conference Problèmes Inverses : des Plasmas à l'Océanographie (Nice, June 2011), in honor of J. Blum 60th birthday.
- Clémentine Prieur organized the annual meeting of the GDR MASCOT NUM in Villard de Lans in March 2011. It was in honor of Professor A. Antoniadis and many international guest stars were invited.
- Clémentine Prieur was one of the three invited editors of a special number of the Journal de la Société Française de Statistiques on sensitivity analysis http://smf4.emath.fr/Publications/JSFdS/152_1/html/
- Céline Helbert participated to the organization of a special topic session "industrial and business statistics in France" in the 11th annual ENBIS conference that aims to bring together professionals who are involved in business and industrial statistics. They offer opportunities to meet each other and to share ideas and best practices. The accepted contributions are from a wide range of applications, including industry, manufacturing, administration, business and risk management, marketing, sales, logistics and service.
- A. Rousseau gave a plenary lecture to the National Conference of Mathematics Teachers (APMEP) on the basics of mathematical modelling for environmental sciences.
- A. Rousseau is a member of Evaluation Committee at INRIA.
- M. Nodet and A. Rousseau are members of the national board of the *Agrégation externe de mathématiques*.
- A. Rousseau participated in a career fair at MIT with M. Thonnat (Deputy Scientific Director at INRIA), A. Theis-Viémont and E. Chareyre (Human Resources at INRIA). The European Career Fair is an annual recruiting event, organized by the MIT European Club, that connects employers from Europe with the most talented candidates that live in the US.
- A.Vidard organized the conference "Inversion et l'Assimilation d'Images" in frames of the program INSU/LEFE-ASSIM, of the GDR ISIS and of CCT-TSI of the CNES in Paris the 16th of June 2011.
- In the framework of MaiMoSiNE, "Maison de la Modélisation et de la Simulation Nanosciences et Environnement", a training course was organised on the DATICE code (http://maimosine.fr/fiche_formation/26), gathering participants from LGGE (Grenoble), LSCE (Saclay), and BAS (British Antarctic Survey Cambridge) institutes.

- E. Blayo has co-organized (with S. Charles (UCB Lyon) and D. Bicout (UJF Grenoble)) a one-day (October 10, 2011) conference "Sensitivity analysis for environmental sciences".

9.2. Teaching

Licence, Master, Doctorat:

Licence : Mathematics for engineers, 72h, L1, UJF
Licence : Descriptive Statistics, 71h, L1, UPMF
Licence : Statistics studies 2, 30h, L1, UPMF
Licence : Quality, 24h, L2, UPMF
Licence : Plans of experiences, 30h, L2, UPMF
Licence : Data mining, 16h, L2, UPMF
Licence : Quality, 10h, L3, UPMF
Master : Numerical modelling for coastal oceanography, 18H, M2, UBO and ENSTA Bretagne, Brest, France
Master : Finite element method, 45h, M1, UJF
Master : Model coupling, 27h, M2, UJF and G-INP
Master : Inverse methods, 27h, M2, UJF and G-INP
Master : Modelling and control of PDEs, 20h, M2, G-INP
Doctorat : Introduction to data assimilation, 14h, University of Grenoble
Doctorat : Méthodes de couplage de modèles pour la décomposition de domaines, 20h, Université de Montpellier 2, France
Doctorat : Introduction to data assimilation, Grenoble University, France

PhD & HdR

PhD in progress : Pierre-Antoine Bouttier, Variational data assimilation into highly nonlinear ocean models, October 2009, E. Blayo and J. Verron
PhD in progress: Bertrand Bonan, Inverse methods for large scale ice-sheet models, Sept. 2010, Advisors: M. Nodet and C. Ritz (LGGE).
PhD in progress : David Cherel, Couplage de modèles en mécanique des fluides océaniques, 01/10/2008, E. Blayo & A. Rousseau
PhD in progress : Manel Tayachi, Couplages de modèles hydrologiques et océanographiques, 01/05/2010, E. Blayo & A. Rousseau
PhD in progress : Laurent Violeau (EPI TOSCA), Stochastic Lagrangian Models and Applications to Downscaling in Fluid Dynamics, 01/10/2010, M. Bossy (EPI TOSCA, INRIA Sophia) & A. Rousseau
PhD in progress : Vincent Chabot, Assimilation de données pour l'estimation de structures 2D et 3D dans des séquences d'images, 01/10/2010, A.Vidard, M.Nodet.
PhD in progress Jean-Yves Tissot, Approches stochastiques et variationnelles pour l'analyse de sensibilité et la quantification d'incertitude - Application à un système de prévisions des circulations océaniques. Début oct. 2009, C. Prieur and E. Blayo.
PhD in progress Alexandre Janon, Analyse de sensibilité et réduction de dimension, application à l'océanographie. Début oct. 2009, C. Prieur and M. Nodet.
PhD in progress Gaelle Chastaing, Estimation des indices de sensibilite sous conditions de dependance. Début oct. 2010, C. Prieur, F. Gamboa.
PhD in progress: Jeremie Demange, Schémas numériques d'advection-diffusion en océanographie, Feb. 2011, Advisors: E. Blayo, L. Debreu, P. Marchesiello (IRD, Toulouse)
PhD in progress: Xavier Meunier, La circulation des courants océaniques de bords ouest : un verrou de modélisation océanique pour les modèles de prévision climatique, Sept. 2011, Advisors, B. Barnier (LEGI), L. Debreu, J. LeSommer (LEGI)
PhD in progress: Federico Zertuche, Exploitation des simulateurs multifidelites pour l'analyse de risque. Début 1er octobre 2011, Advisor Céline Helbert

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

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[2] D. AUROUX, J. BLUM, M. NODET. *Diffusive Back and Forth Nudging algorithm for data assimilation*, in "Comptes Rendus de l Académie des Sciences - Series I - Mathematics", 2011, vol. 349, p. 849-854 [*DOI :* 10.1016/J.CRMA.2011.07.004], http://hal.inria.fr/inria-00617571/en.

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