INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team IDOPT

Systems optimization and identification in physics and environment

Rhône-Alpes

THEME NUM

Activity Report

2005

Table of contents

1. Team

The IDOPT project is a joint project between the CNRS (SPM department), Joseph Fourier University (Grenoble 1), INPG and INRIA Rhône-Alpes. This project is located in the LMC-IMAG laboratory.

Team leader

François-Xavier Le Dimet [Professor, UJF]

Administrative assistant

Imma Presseguer

Research scientists

Didier Bresch [CNRS]
Isabelle Charpentier [CNRS]
Laurent Debreu [INRIA]
Evgueni Kasantzev [INRIA]
Jérôme Monnier [Associate professor, INPG - délégation]
Dinh Tuan Pham [CNRS]
Pierre Saramito [CNRS]

Faculty members

Anestis Antoniadis [Professor, UJF]
Eric Blayo [Professor, UJF]
Jacques Blum [Professor, university of Nice]
Christine Kazantsev [Associate professor, UJF]
Patrick Witomski [Professor, UJF]

Post-doctoral fellows

Igor Gejadze [regional project]
Jianwei Ma [ACI Assimage]
Elise Nourtier [SHOM contract]
Céline Robert [MERSEA European project]

Technical staff

Cyril Mazauric [Mercator national project]

PhD students

William Castaings [European contract]
Marc Honnorat [CNRS BDI - CNES fellow]
Claire Lauvernet [CNRS-INRA fellow - defended april 2005]
Florian Lemarié [MESR fellow]
Carine Lucas [MESR fellow]
Wu Lin [French Embassy fellow, China - defended april 2005]
Maëlle Nodet [Universiy of Nice- defended november 2005]
Denis Quelo [ENPC, Paris]
Ehouarn Simon [DGA fellow]

Visiting scientists

Genady Korotaev [Ukrainian academy of sciences]
Victor Shutyaev [Professor, Russian Academy of sciences]

Exterior collaborators

Gérard Grégoire [Professor, Grenoble 2 university]
Jacques Verron [CNRS Research Director, LEGI]
Alain Le Breton [Professor, Grenoble 1 university]

2. Overall Objectives

2.1. Overall Objectives

Many systems in physics, mechanics and environmental sciences are modelled by partial differential equations with distributed parameters. These equations describe the behavior in space and/or in time of the system variables. From this general formulation two problems arise :

Identification The usual *direct approach* consists in solving the model equations. However it is frequent that some parameters or some functions appearing in the model are totally or partially unknown (e.g. diffusion coefficients in parabolic equations, source and sink terms in fluid dynamics, initial and/or boundary conditions...). *Inverse problems* are dedicated to the estimation of these unknown parameters using the information provided by experimental observations of the system. Solving inverse problems is useful for physicists: in many cases an approximation only of the unknown parameters is available, and these parameters cannot be measured by devices, either because they are used to parameterize small scale phenomena (e.g. turbulence in fluids) or because the measurement is expensive (e.g. measurements inside the solid earth or in the deep ocean). This point of view is essential in many domains of physics.

Optimization The physical systems described above may have some inputs (e.g. forcing terms) which can be controlled by an operator. A problem is : how to control the inputs in order to optimize the behavior of the system? The related mathematical problem is the estimation of these optimal inputs in open loop or closed loop (stabilizing feedback).

3. Scientific Foundations

3.1. Optimal control

For identification and optimization problems, we have to minimize a functional depending on the solution of a system of Partial Differential Equations (PDEs). The identification problem can be formulated as the minimization of the quadratic difference between the experimental observations and the corresponding quantities calculated by solving the system of PDEs. The control variables are, in this case, the parameters or the functions to be identified. The minimization of functionals depending on the solution of a PDE (e.g. through the initial conditions, the boundary conditions...) follows the optimal control theory [81].

3.2. Data Assimilation

A mathematical model alone is not sufficient to predict the evolution of a geophysical flow. Neither are data alone. Providing a forecast requires to retrieve the state of the flow at some initial time, and that this retrieved field be in agreement with the physical properties of the flow (i.e. satisfies the governing equations). Data Assimilation covers the techniques dedicated to use jointly the mathematical information provided by the equations, the physical information obtained by observation, and the statistical information, in order to retrieve at best the state of the flow. At the present time there exists two basic techniques: variational methods and filtering methods.

3.2.1. Variational methods

Participants: François-Xavier Le Dimet, Jacques Blum, Eric Blayo, Victor Shutyaev.

Variational methods are based on the minimization of a function measuring the discrepancy between a solution of the model and the observation. Le Dimet [80] has suggested to use optimal control techniques for this purpose. The inputs of the model are then used as control variables. The Euler Lagrange condition for optimality is found 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. Therefore the OS can be considered as a generalized model.

The adjoint model is a very powerful tool, which allows to conduct sensitivity studies, identification, etc. Despite its high computational cost, this technique has been adopted by the main operational meteorological centers (e.g. MeteoFrance, European Center for Medium Range Weather Forecast).

During these last years the main contributions of IDOPT have addressed the following topics :

- *Reduced order methods* In actual geophysical applications, the size of the control space is often huge, with a poor knowledge of the error statistics. Therefore the minimization can be quite difficult. An interesting alternative can be to try to define some low dimension control space, which contains the main directions of variability of the system. This point has been investigated in the PhD theses of S. Durbiano [67] and C. Robert [87].
- *Study of second order properties, with application to sensitivity studies* A major problem in the forecast of the evolution of the physical environment is to estimate the quality of the prediction, or in other words the impact of model and data uncertainties on the prediction. A so called second order adjoint has been introduced, which allows to extract the second order properties of the OS [78]. It is shown that predictibility properties, i.e. the impact of both model and observation errors, are linked to the properties of the Hessian of the cost function. Using the second-order adjoint it is possible to follow the impact of uncertainties from its source to the prediction [17]. The application to underwater propagation is described in [79].
- *Control of the model error* Another way to take into account the model error is to add an extra term to the model and to control this term in order to reduce the discrepancy with the observation. Such a study was conducted during the PhD of A. Vidard [90], and then in a more recent paper [89].
- *Adequation between models and data* An important topic is the adequation of models and data. It has been demonstrated that, for the same set of data, the best prediction is not necessarily associated to the best model. Improving the quality of a model may damage the prediction.
- *Assimilation of new types of data* A lot of observational information cannot be easily linked to model variables, and is not used so far for data assimilation. This is for example the case of lagrangian data or of satellite images. Studies are presently conducted on this subject.

3.2.2. Kalman filtering

Participants: Alain Le Breton, Dinh Tuan Pham, Jacques Verron.

Filtering is the basic tool in the sequential approach to the problem of data assimilation into numerical models, especially in meteorology and in oceanography. This approach, of stochastic nature, is justified by the fact that the dynamical system is chaotic and thus behaves similarly to a stochastic system. Moreover, the (unknown) initial state of the system can be conveniently modelled 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 also 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. In applications to meteorology and oceanography, the above filtering approach has encountered two major difficulties. The first one is the nonlinearity of the dynamical equations, which leads to the use of a suboptimal filter, the extended Kalman filter, in which the above equations are linearized around the current estimate of the system state. Such a filter however can be unstable and can sometimes diverge totally. The second difficulty is the very large dimension of the system state vector. The application of the filter would lead to prohibitive calculations. Furthermore this large size poses the problem of adequately specifying the statistical characteristics of the errors.

Our goal in this project is to investigate in depth the possibility of applying the above filtering approach to real data. To this end, we have developed a new filter of extended Kalman type, based on the use of a singular low-rank filter error covariance matrix. The filter operates according to the principle of making no correction along the directions of natural attenuation of the error. The corrections are made only along directions belonging to a subspace, which is constructed initially by the method of empirical orthogonal functions (EOFs), and which evolves in time according to the model equations. This filter is thus called *Singular Evolutive Extended Kalman* [85], [86]. It has been first tested in a reduced configuration based on a quasi-geostrophic ocean model, which yielded very satisfying results [85], [86]. It has been then successfully experimented for the assimilation of altimetric data in the realistic framework of a primitive equation model of the tropical Pacific ocean [88], [84].

Recently, we have worked towards the improvement of the filter, on the one hand to reinforce its robustness with regard to the system nonlinearity, and on the other hand to reduce its computational cost without noticeable degradation of its performance.

On the first point, the idea is to drop the linearization in the extended Kalman filter and to use a Monte-Carlo procedure and an interpolation. In this way, we have developed another filter called SEIK (*Singular Evolutive Interpolated Kalman*) [82], [84], which appears to be both more robust with regard to nonlinearities, and simpler to implement. Moreover, we have explored advanced stochastic filtering techniques to overcome the difficulties related to strong nonlinearities of the system [83].

On the second point, the idea is to enrich the correction basis by addition of some local basis vectors, and to simplify the evolution of the basis by letting only the global basis vectors evolve. This way the correction basis can contain more vectors, better captures the errors, and requires less computation as it is only "semi-evolutive". Such kind of filters have been experimented in various realistic ocean model settings, yielding quite satisfactory results [68], [69] [71], [70].

In addition to this work centered on the stochastic approach to the data assimilation, an activity of more theoretical nature is also performed in the domain of filtering, control and identification for stochastic systems with dynamical noise of fractional type [73], [76], [77], [75], [74]. These studies can lead to interesting perspectives in modelling since the eventual phenomenon of long range dependence in the dynamics can be taken into account.

3.3. Statistical inverse problems

Participants: Anestis Antoniadis, Theofanis Sapatinas, Felix Abramovich, Jeremie Bigot.

Wavelets are mathematical building blocks that can be used to represent functions and data sets. They combine useful modeling features such as locality and varying degrees of smoothness. As modeling and analyzing tools they allow us to "zoom-in" on the problem at various scales and therefore are part of what is called "multiscale" and "multiresolution" analyses. In particular, wavelets are a powerful tool for dealing with some inverse problems.

Paper [59] is an important paper in the field. It is a joint work with Felix Abramovich, Theofanis Sapatinas and Brani Vidakovic. The paper considers the testing problem in fixed-effects functional analysis of variance (FANOVA) models. We show how the existing optimal (in the minimax sense) testing procedures for testing a zero signal in a "signal+noise" model can be adapted for FANOVA and we derive optimal procedures for testing the significance of the components of the FANOVA model. The resulting tests are based on the empirical wavelet coefficients of the data. We performed a simulation study to illustrate the behaviour of these tests and applied them also to a real-life data arising from physiological experiments.

The techniques developed in the above mentioned work were further applied by Jérémie Bigot, a PhD student at the LMC, to address the problem of the alignment of multiple sets of curves and their comparison with FANOVA techniques. In paper [63], a non-parametric approach is proposed to estimate the zero-crossing lines of the continuous wavelet transform of a 1-D signal observed with noise. A new tool, the "structural intensity", is introduced to represent the locations of the significant landmarks of an unknown curve via a probability density function. This technique yields an automatic landmark-based registration method to synchronize a set of curves. A fixed-effects FANOVA model is then used to test the significance of main/interaction effects and to show the usefulness of curve alignment.

4. Application Domains

4.1. Identification and Optimization in Physics

Keywords: *Optimal control*, *electromagnetism*, *free surface flows*, *inverse problems*, *microfluidics*, *nuclear fusion*, *plasma*, *wetting*.

The applications are the plasma physics (nuclear fusion), the coating processes and biotechnologies. In each of these topics, an optimization is performed in order to identify a physical quantity, to minimize an energy or to compute an optimal Shape.

4.1.1. Real time identification problem in plasma physics

Participant: Jacques Blum.

A method of numerical identification of the plasma current density in a Tokamak fusion reactor from experimental measurements is proposed. This problem consists in the identification of a non-linearity in a semi-linear 2D elliptic equation from Cauchy boundary measurements, from integrals of the magnetic field over several chords and from measurements of magnetic field at specific points.

The problem is solved using fixed-point optimization algorithm based on the finite element method, followed by object-oriented C++ implementation aiming at real-time use as diagnostic at JET and other tokamaks (TORE SUPRA, ITER).

4.1.2. Microfluidics and wetting hydrodynamics

Participant: Jérôme Monnier.

We study mathematical and numerical models treating of liquid droplets spreading on solid surfaces. Such models are required for biotechnologies processes and coating technologies. The important phenomena of these free surface flows are interfacial (surface tension, curvature forces, surfactant) and local behavior in the vicinity of the triple line. These studies are led in collaboration with the PIM project-team, lab LEGI (Grenoble).

4.2. Data and Models in Environmental Sciences

Keywords: *Adaptive Meshing*, *Data assimilation*, *Domain Decomposition*, *Filtering*, *High Performance Computing*, *Hydrology*, *Inverse Problems*, *Meteorology*, *Oceanography*, *Optimal Control*.

The use of numerical models for meteorological prediction has been proposed by Charney and Von Neuman in the '40s. This practice became operational in the '60s. Generally geophysical flows have several particularities requiring mathematical and algorithmic developments:

- Geophysical flows are nonlinear. Therefore there is an interaction between the different scales of the models. The small scale effects (smaller than the mesh size) will have to be estimated by some additionnal terms in the equations. These terms cannot be measured by a physical experiment. This is a typical inverse problem.
- Every geophysical episode is unique: a field experiment cannot be reproduced. Therefore the validation of the model has to be carried out with several situations, all different, and the role of the data in this process is crucial.
- The geophysical fluids are non closed i.e. there is always interaction between the components of the environment. The ocean interacts with the atmosphere, the atmosphere interacts with continental water interacting with the ocean. A consequence is that boundary terms, associated to the interactions, will have to be provided in a model dedicated to one component of the environment. The quantitative estimation and parameterization of this term is also a typical inverse problem.

There has been a strong and increasing societal demand for a precise prediction in meteorology, oceanography and hydrology for a few years. Following meteorology, an operational center for oceanic prediction (MERCATOR) and a center for flood prediction (SHARPI) have been recently opened in Toulouse. The development of numerical prediction rises many mathematical and algorithmic problems. The vocation of IDOPT is not to carry out numerical prediction but to be a support for the mathematical problems raised by this approach. In this sense the basic components of the water cycle modelling are studied in IDOPT. Worldwide very few research groups have this particularity.

4.2.1. Oceanography

Participants: Eric Blayo, Didier Bresch, Jacques Blum, Laurent Debreu, Christine Kazantsev, Evgueni Kazantsev, François-Xavier Le Dimet, Florian Lemarié, Carine Lucas, Cyril Mazauric, Maelle Nodet, Dinh Tuan Pham, Céline Robert, Ehouarn Simon, Jacques Verron.

Understanding and forecasting the ocean circulation is presently the subject of an intensive research effort from the international scientific community. This effort was primarily motivated by the crucial role of the ocean in the earth climate, in the perspective of global change. Moreover important recent research programs aim at developing operational oceanography, i.e. a near real-time forecasting of ocean circulation, with applications to shipping, fisheries, weather forecasting... Another related field is coastal oceanography, dealing for example with pollution, littoral planning, or management of ecosystems. Essential tools for such goals are modelling systems, which require the development of performant numerical models and data assimilation methods. In this context, the IDOPT project conducts efforts on the following topics :

- *Multiresolution 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. From a mathematical and numerical point of view, such model interactions demand specific studies on open boundary conditions, mesh refinement methods, and coupling algorithms.
- *Advanced numerical schemes*: Most ocean models make use of simple second order finite difference schemes on structured grids. We are seeking for higher order schemes allowing both accuracy and good conservation properties, and dealing with irregular boundaries and bottom topography.
- *Parameterization and modelling of boundary layers*: A striking feature of ocean dynamics is the existence of several types of boundary layers, either lateral (near the coastlines), or vertical (near the ocean surface and bottom). Despite their relatively small size, these layers have an important role in the global dynamics, and must be accurately represented in the model. New modelling and numerical approaches to this problem are studied.
- *Data assimilation methods for ocean modelling systems*: As in atmospheric models, the main difficulties encountered when assimilating data in ocean models are the huge dimension of the model state vector (typically 10^6-10^7), the strongly nonlinear character of the dynamics, and our poor knowledge of model error statistics. In this context, we are developing reduced order sequential and variational data assimilation methods addressing the aforementioned difficulties. We are also working on the assimilation of lagrangian data, and on the design of data assimilation methods for multiresolution models.

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

4.2.2. *Hydrology and river hydraulics*

Participants: William Castaings, Igor Gejadze, Marc Honnorat, François-Xavier Le Dimet, Jérôme Monnier.

Floods prevention and prediction are critical issues. Flooding is the result of complex interactions of the water cycle between meteorology, hydrology and hydraulics. Mathematical and numerical modelling is becoming accepted as a standard engineering practice for both prevention and prediction of those catastrophic events. The models (1-D and 2-D shallow water equations) and the industrial softwares (e.g. Telemac2D, Carima1D) are quite satisfying for some configurations. Nevertheless for real applications, initial and boundary conditions (observed water level and discharge) are very partial and difficult to prescribe, also empirical parameters (e.g. land roughness) are calibrated manually using hydraulic expertise. Realistic and reliable forecasting of those catastrophic events requires a completely integrated approach with all components (models and data) integrated in a consistent manner into an hydro-meteorological prediction chain with affordable computational cost.

Data assimilation methods, that have shown their potential in other geosciences like meteorology and oceanography, are now in the forefront in hydrology. This prediction chain is far from being operational.

The problems adressed in IDOPT related to data assimilation for catchment scale hydrology and river hydraulics are part of the investigations to be carried out. The current research topics conducted in IDOPT are the following.

- *Image Data assimilation*. M. Honnorat began his PhD in October 2003, treating of image data assimilation for flood models. A crucial problem to tackle in image data assimilation is to work out the correspondance between some characteristics of the data and model variables.
  The two mathematical problems considered are: i) the reconstruction of the river flow dynamics (inflow discharge, land roughness and topography) using measures in-situ and video images of trajectories at surface flow; ii) assimilation of local fronts into models.
  This study is funded by CNES and CNRS.
- *Coupling 1D-2D models and data assimilation*. I. Gejadze began his 10 months postdoc in March 2005. It concerns the coupling of 1D and 2D shallow water models, while at same time assimilating some observed data. The configuration considered is a 2D overflowing flow laterally to a 1D river flow (flood extension). This approach should improve the classical 1D storage area models. It is funded by region Rhône-Alpes.
- *Sensitivity analysis for rainfall-runoff models*. Flash flood events are usually generated by heavy convective precipitation over a relatively small area but catchment hydrology plays a major role in their occurrence. Important factors like initial soil moisture and infiltration parameters govern rainfall abstractions and therefore control the partition of rainwater between infiltration and runoff. Adjoint sensitivity analysis and data assimilation are investigated by W. Castaing for an event-based distributed flash flood model. This work is done in collaboration with Toulouse Fluid Mechanics Institute (IMFT) in the framework of PACTES project.

All these studies are led in the framework of different projects with numerous collaborations.

- The regional project (Région Rhône-Alpes) “Numerical Prevention for Floods”, led by J. Monnier, conducts researches in data assimilation, coupling and parameter fitting methods, and uncertainties propagation. The collaborators are applied mathematicians and numericians (team-project IDOPT), hydrologists (Cemagref and LMFA Lyon), satellite image analysts (Cemagref Montpellier and Maison de la Télédétection), computer scientists (team-project TROPICS) and research engineers (Sogreah Company).
- The former european project ANFAS (1st Jan. 2000 - 31 March 2003) was dedicated to the design of a Decision Support System for flood prevention and protection. During this project, hydraulics models (1D/2D) were adapted to the Loire pilot site.

- The former national project PACTES (Prévention Anticipation des Crues au moyen des Techniques Spatiales) was initiated by the French Space Agency (CNES) and the French Ministry of Research, in order to improve the operational management of floods, through a joint approach involving the operational users, scientific laboratories and industry. Scoping interactions in terms of models and data with the continental water cycle, available gauged watersheds for evaluation and validation developed collaborations with the French hydro-meteorogical community (Meteo France, CETP, LTHE).

4.2.3. Mud flows and snow avalanches in mountains

Participant: Pierre Saramito.

The prevention of hazards in mountains, from snow avalanches to mud flows, requires advanced numerical simulations. Such simulations are based on sophisticated rheological and mechanical laws for describing complex materials, such as yield stress fluids and granular materials. Moreover, numerical simulations use sophisticated numerical methods : conservative finite volumes or finite elements, adaptive unstructured mesh generation, in a dynamical context. While dense snow avalanche prevention is quite advanced, the prediction of powder-snow avalanche phenomena is more delicate.

5. Software

5.1. Microfluidics/Droplet Impact

Participant: Jérôme Monnier.

MICRALEFE (MICRofluidics ALE Finite Element) is a C++ finite element software solving 2D axisymmetric Navier-Stokes flow with free surface dynamics and curvature forces. It treats of a droplet impact on a solid substrate (spreading and recoiling phases). The free surface dynamic is described using an ALE formulation (Arbitrary Lagrangian Eulerian). The code is based on the Rheolef C++ finite element library.
Micralefe capabilities include the triple line dynamics (liquid-gas-solid) and variable surface tension source terms.

5.2. River hydraulics

Participants: Igor Gejadze, Marc Honnorat, Jérôme Monnier.

DASSFLOW is a river hydraulics simulation software designed for variational data assimilation. The model is based on the shallow-water equations, solved by the finite volume method using the HLLC approximate Riemann solver. The adjoint code is available, as well as all the optimization framework that is necessary to easily build up new data assimilation experiments. The software is written in Fortran 90. Two versions are currently available.
The first one is 2D model taking into account Lagrangian data (local particles trajectories) for assimilation of video images.
The second one includes a coupling algorithm between 1D and 2D shallow water models (flood extension model), while at same time assimilating in-situ measurements.
Further features including front assimilation, mixed unstructured meshes, interfacing with professional pre and post-processors (ArcInfo) are under devolpment. This last feature will enable us to consider real test cases including satellite data (XiJun Lai's PostDoc, starting in february 2006).
T2DINVERSE is a reduced research version of software Telemac2D (Telemac2D is an industrial code developed by EDF R&D and distributed by Sogreah Co). This version is basically meant for automatic differentiation by Tapenade, aiming conditions and parameter identification of river flow models. Some of the simulation capabilities kept in T2DInverse involve flooding events with wetting and drying, dam break disasters, flows through flumes, breakwaters, bridge piers and other hydraulic works.

The code needs further developments in order to be operational, and be able to treat variational data assimilation problems with real configurations.

5.3. Wavelet Denoising MATLAB Toolbox

Participants: Anestis Antoniadis, Jeremie Bigot, Theofanis Sapatinas.

A wavelet toolbox and an accompanying paper “Gaussian Wavelet Denoising Matlab Toolbox” was jointly developed by A. Antoniadis, J. Bigot and T. Sapatinas, where various wavelet shrinkage and wavelet thresholding estimators in nonparametric regression appearing in the literature are discussed in detail and implemented. These estimators arise from a wide range of classical and empirical Bayes methods treating either individual or blocks of wavelet coefficients. See http://www.jstatsoft.org/v06/i06.

5.4. Adaptive Grid Refinement

Participants: Laurent Debreu, Florian Lemarié, Cyril Mazauric.

AGRIF (Adaptive Grid Refinement In Fortran, [66], [65]) 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, [18]). Cyril Mazauric works on the implementation of AGRIF in the standard version of the OPA ocean modelling system (a general circulation model used by the French and European scientific community).
Several developments/improvements have been added to the AGRIF software during this last year.

- Treatment of Fortran 90 codes : Previous versions of the AGRIF software were not able to deal with numerical models programmed in the Fortran 90 language. This limitation has been removed.
- More efficient computational performance: both at compile and run time levels. A strong effort has been done on the improvement of the computational performance of the codes compiled with the AGRIF library. In particular, optimization of parallel communications during update/interpolations steps has been conducted.
- Coding of flux conservations routines: Flux conservations routines have been added to the library. These procedures help the user in storing and using flux arrays defined at the coarse/fine grids interfaces.
- New interpolation schemes including a PPM (Piecewise Parabolic method) and an ENO (Essentially Non Oscillatory) scheme.

AGRIF is licensed under a GNU (GPL) license and can be downloaded at its web site (http://www-lmc.imag.fr/IDOPT/AGRIF). More than two hundred downloads of the software have been done during the last year.

6. New Results

6.1. Microfluidics and wetting hydrodynamics

Participant: Jérôme Monnier.

In collaboration with Iulian Cotoi (former postodoc and now at Montreal), we continue to develop the software Micralef modeling a droplet impact onto a solid substrate. Special attention is paid on the recoiling phase and local flow patterns near the triple line.

6.2. Ocean modelling

6.2.1. Mathematical modelling of the ocean dynamics

Participants: Didier Bresch, Christine Kazantsev, Carine Lucas.

6.2.1.1. Small-Scale induced effects in the oceans

The ocean bottom topography and coasts vary over a wide range of scales, the smallest ones being unresolved in numerical computations. There is a need for the development of simplified models that account implicitly for the impact of the small-scale topography on the large-scale ocean circulation. We have recently developped such nonlinear models in idealized case for the quasigeostrophic system. This gives for instance some nonlinear pde's which governs the western boundary layer extending in some sense the linear one proposed by H.W. Munk (Munk layer). We are now looking at more general cases (other pde's, more general topography and coasts). We also try to see with physicists (LEGI) how such expansions can be used in actual applications.

6.2.1.2. Mathematical justification of asymptotics

The mathematical justifications of formal asymptotics encountered in geophysics are not straigtforward. They depend on the domain, the data, the pde's that we considered. For instance, we have looked at western intensification of currents for domains with islands, that we have to add a corrector to the Sverdrup relation in this case. We have also considered rotating fluids in a cylinder showing that the Rossby waves are damped if the lateral section is not a disk (this result is linked to the Schiffer conjecture). This paper concerns ill prepared datas. We have also obtained the first justification of the planetary geostrophic equations from the Primitive one. This problem concerns singular perturbations with an operator which is not skew symmetric as it was in mathematical papers.

6.2.1.3. Influence of the viscous terms (Reynolds closure)

We have proposed new diffusive capillary models of Korteweg type and discuss their mathematical properties. More precisely, we introduce viscous models which provide with some additional behavior of the density close to vacuum. We actually prove that if some compatibility conditions and capillarity are satisfied, some extra regularity information on a quantity involving the density is available. We obtain a non-trivial equality deduced from the special structure of the momentum equations. This result allows for instance to justify the link between the viscous shallow water equations and the viscous quasi-geostrophic equations or the viscous lake equations. A numerical study of such properties is currently in progress.

6.2.2. Sensitivity of an ocean model to topography perturbations

Participant: Eugène Kazantsev.

The bottom topography has a strong influence on the ocean circulation. Therefore it is interesting to quantify the sensitivity of an ocean model flow to the representation of this topography. Even if the real bathymetry is well described, its representation on the model grid is not obvious, because of the limited resolution. It is known for 30 years that, requiring the large scale ocean flow to be well represented, one has to smooth the topography in order to retain only its large-scale components. In this case, the influence of topographic subgrid-scales has to be parameterized, which is far from obvious.

A possible way to adapt the real bathymetry to a particular numerical model is to perform some data assimilation with the topography as the control parameter. In order to proceed, we need to evaluate first the sensitivity of a model to the topography variations. In this work we are looking especially to the most sensitive and to the most insensitive modes of the solution with respect to small variations of the topography.

The existence of modes to which the solution is not sensitive helps us to understand whether there exists a unique possibility to reconstruct the topography from observations of the model solution. If the solution exhibits no sensitivity to some particular mode, this shows that this mode can be used to perturb the topography without any change in the model flow. Mathematically speaking, this mode belongs to the null space of the sensitivity operator. The dimension of this null space determines the number of independent topography variations resulting in the same observable flow. In this work we try to estimate its dimension and to find a simple relationship between configurations of the flow and modes in the null space.

On the other hand, the most sensitive modes will form the sensitive space. Any small perturbation of the topography by a function from this space will result in a drastic change of the flow. Concerning the data assimilation procedure, it is this space that has to be controlled in the best way. The dimension of this space shows the minimum number of functions participating to the cost functional.

The model used in our work is a simple barotropic vorticity equation over topography. It is used in two configurations: a square basin with a flat bottom, and a coarse resolution North Atlantic basin with realistic topography. We discuss both the steady state solution and the non-stationary flow.

The quantitative measure is influenced essentially by the error growing time. The longer the time period during which we analyze the sensitivity, the greater the sensitivity. This conclusion is consistent with numerous studies of the model sensitivity to other parameters. Thus, the predictability studies analyzing the sensitivity to initial conditions, reveal the exponential (or close to) growth rate. In this work, we show that at short time scales the sensitivity to topography may differ from the sensitivity to initial conditions. But, for the long time limit, the sensitivity of the solution to any source of perturbation is the same. The intrinsic model instability dominates at these time scales and the source of the perturbation does not matter any longer.

The analysis of the patterns of the most sensitive modes reveals that the solution is more sensitive to the topographic perturbations in regions where the flow is turbulent, whereas the solution exhibits little sensitivity in regions where the flow is laminar. For example, the solution of our barotropic model of the North Atlantic is not sensitive to topography near the european coast. All sensitivity modes corresponding to vanishing eigenvalues are concentrated in this region. This means that performing the procedure of reconstruction of the topography using this model solution would not work in this region, because all modes belong to the null space. One would need an additional information.

Turning attention to more realistic problems, a number of difficulties can be encountered. Using 3-D multi-level models leads to dealing with baroclinic components, which can change the sensitivity of the model, and with different geometries at each level. Moreover, this study gives no information about particular schemes of parameterization of topography. Numerous modern schemes like partial step or shaved cells cannot be distinguished in this work as well as different horizontal grids like Arakawa's ones.

This problem is addressed in details in [72].

6.2.3. Multiresolution approaches and coupling methods in oceanography

Participants: Eric Blayo, Laurent Debreu, Florian Lemarié, Cyril Mazauric, Elise Nourtier, Céline Robert.

The implementation of high-resolution local models can be performed in several ways. An usual way consists in designing a local model, and in using some external data to force it at its open boundaries. These data can be either climatological or issued from previous simulations of a large-scale coarser resolution model. The main difficulty in that case is to specify relevant open boundary conditions (OBCs). By performing a critical review of previous related works either in oceanography or applied mathematics, we have shown that such relevant OBCs must be based on the incoming characteristic variables (in the hyperbolic sense) of the model equations, with a consistent use of the external data. Numerical experiments in realistic 2-D ocean models, in collaboration with F. Vandermeirsch, have confirmed this result. The extension to 3-D realistic primitive equation models is presently underway.

Another way of designing such local models is to locally increase the resolution of a large-scale model. The design of local mesh refinement methods requires appropriate boundary conditions at the boundaries between coarse and fine mesh. Main difficulties rely on the treatment of distinct discrete boundary (e.g. due to different topography in ocean modelling) and the preservation of conservation properties. When the refinement is adaptive, the initialization procedure is also of tremendous importance ([16]). Last the computer implementation of efficient local mesh refinement involves dynamic memory management, use of structured types and can be even harder when operated on parallel computers. The AGRIF software, presented in section 5.4, has been developed in the IDOPT project and is increasingly used in realistic ocean models.

An interest of the local refinement approach is the two-way interaction between local and global models. However a limitation is that the physics remains (at least nearly) unchanged from the global to the local scale, while it is well-known that large scale physics may be inadequate for representing local phenomena. Therefore a more general approach consists in coupling different models, with possibly different resolutions, numerics, and even physics. We can then use the framework of global-in-time Schwarz domain decomposition methods to derive efficient algorithms with relevant interface conditions.

Our approach is twofold : on one hand, we conduct rigourous mathematical studies on simplified models, in collaboration with applied mathematicians from LAGA - Paris 13 (L. Halpern, C. Japhet, V. Martin). Exact and approximate absorbing interface conditions have been computed for tracer equations and for the 2-D linearized shallow-water system. Corresponding numerical experiments have also been performed.
On the other hand, a realistic configuration for coupling experiments has been realized in collaboration with oceanographers from LEGI - Grenoble (B. Barnier, S. Cailleau). It consists in the coupling of a regional high resolution model of the bay of Biscay with a coarser resolution model of the north Atlantic. Several numerical simulations, with different coupling algorithms, have been realized. They illustrate the pros and cons of each method, from the point of view of the quality of the interior and interface solutions. In particular, the improvement due to the feedback from the regional model onto the global model is clearly shown.
This work is funded by the national MERCATOR program and by the french navy (SHOM).

6.2.4. Mode and wavenumber inversion for shallow water system

Participant: Isabelle Charpentier.

Modes and wavenumbers are the main ingredients that characterize the pressure field in an oceanic waveguide. However, wavenumber and mode inversions are well-known to be a difficult task in underwater acoustics. Moreover, this double inversion has never been performed simultaneously from the same configuration of emitters and receivers. We present a new approach to this problem in a shallow water environment between two vertical arrays of sources and receivers. Starting from a classical modal decomposition of the pressure field, our algorithm focuses on a specific treatment of phase and amplitude variables. The key idea is to run a three-stage optimization by working separately on the phase and amplitude of the acoustic field. The high number of variables of the problem is turned into an advantage by using an adjoint code generated by an Automatic Differentiation software. Numerical results in the presence of noise show that modes and wavenumbers are estimated with high accuracy.

6.3. Data assimilation methods for ocean models

Participants: Didier Auroux, Eric Blayo, Jacques Blum, Laurent Debreu, François-Xavier Le Dimet, Maëlle Nodet, Dinh Tuan Pham, Céline Robert, Ehouarn Simon, Jacques Verron.

6.3.1. Synthesis of reduced-order methods

Following several studies led these last years in the IDOPT project on sequential and variational reduced order data assimilation methods, the PhD thesis of C. Robert (defended in december 2004) has consisted in drawing some synthesis of these methods (reduced order 4DVar and SEEK filter). A comparison of their applicability and performances in a realistic oceanic context (assimilation of in situ temperature data in a 3-D model of the tropical Pacific) has been performed for the first time. In the context of twin experiments (the model being supposed perfect), the smoothing nature of the variational approach appears to be an important aspect to correct the model solution for errors linked to propagating waves generated outside the observed area. In the context of the assimilation of real data (i.e. with an imperfect model), a mixed low-rank/full-rank 4DVar method led to the best results.

Finally, a first implementation of an hybrid method has been performed. In this method, the background error covariance matrix used in the variational approach evolves in time using the sequential filter. The preliminary results seem to show that this joint approach can improve further the solution.

6.3.2. Assimilation of lagrangian data.

This work is motivated by the Argo program, which aims at deploying a network of 3000 profiling floats over the world ocean. Argo is part of the international GODAE experiment (Global Ocean Data Assimilation Experiment). These profilers drift at a typical depth of 1500m, and perform a vertical profile of temperature and salinity every ten days. Their position is known every ten days, which gives a set of lagrangian data. We have developped a variational method in order to assimilate such data. Twin experiments are performed within the OPAVAR model, in an idealized configuration. The first results are available and they show that our method is successful. We presently test the impact on the assimilation of the parameters of the floats network : impact of the frequency of the data, impact of the drifting depth, impact of the number of floats. This work is the subject of the PhD Thesis of Maëlle Nodet which was defended in Nice on November 18.

6.3.3. Assimilation in multiresolution systems.

The objectives are to study the mathematical formulation of data assimilation methods for embedded grids (multiresolution systems) and to conduct numerical experiments for validation. This study is divided into two parts: the selection of the assimilated observations as a function of the grid resolution (definition of criteria and sensitivity analysis), and integration of the grid interactions in the assimilation system (the assimilation scheme should allow new types of grid interactions by taking advantage of the iterative minimization procedure to add additional constraints at the coarse/fine grid interfaces). The derivation of the exact adjoint of the multiresolution system has been proposed and numerical experiments in a 1D shallow water model show promising results [45]. More complex experiments are part of Ehouarn Simon's PhD thesis. We also try to compare this approach with the direct application of local multigrid methods for the solution of the optimality system. This work is granted by the national PATOM and MERCATOR programs.

6.3.4. Variational data assimilation for identification of the optimal topography

Participant: Eugène Kazantsev.

After the study of the sensitivity of an ocean model's solution to the representation of the bottom topography, we focus our attention on the data assimilation procedure, which allows us to find the optimal topography pattern.

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

The assimilation procedure has been tested for the simple barotropic ocean model that was used in the sensitivity study. Special attention was payed for choosing the assimilation interval or the quantity of assimilated external information. Artificial observational data generated by the same model were used in experiments. This allowed us to estimate exactly the accuracy of reconstruction of the topography pattern.

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

The obtained results show the linear dependence of the error in reconstructed topography on the amplitude of the pollution. Hence, we can get a good accuracy on the optimal topography assimilating observational data with relatively low errors.

The influence of the space grid of the model has also been considered. When the artificial observational data are generated by a high resolution model, it contains the small scale information, that cannot be assimilated by a low resolution model. The problem of interpolation and smoothing of the high resolution data is discussed and the assimilation error is analysed.

6.4. Data Assimilation in Agronomy

Participants: François-Xavier Le Dimet, Wu Lin, Claire Lauvernet.

Agronomy is an important field of application for modelling. In this field IDOPT has developped two collaborations. One with the Chinese Academy of Sciences (Institute of Automatics), CIRAD and INRIA Rocquencourt (Philippe de Reffye). The purpose of this collaboration is to insert observational measurements into individual plants models in order to calibrate the models and to optimize plants growths by controlling watering and/or fertilizing, a general methodology which can be applied to a general model of plant growth. This work is carried out in Wu Lin's Ph.D.
At the other end of the scale, in collaboration with INRA Avignon (Frederic Barret) growth of plants, to predict the harvest, is studied at the level of plot. Data are provided by space imagery (SPOT Satellite). This theme is also developped in the framework of ASSIMAGE.

6.4.1. GreenLab - a plant functional-structural model

Started in Beijing in 1998, the GreenLab project aims at a mathematical description of plant growth, especially for the plant functional-structural characteristics. During this year we introduced variational methods to FSPM, and obtained preliminary results in the applications of identification of environmental parameters, optimal control of irrigation, assimilation of model initial conditions and environmental conditions of light and temperature for the functional-structural plant model - GreenLab.
Wu Lin's thesis has been defended in 2005.

6.4.2. Data Assimilation for Vegetation

For fifty years, crop functioning models grew in number and performances to better describe the state and production of vegetation. Those models use soil, climate and vegetation related data. Some of those characteristics vary in space and time and they are thus difficult to evaluate. Remote sensing observations would allow to better quantify these characteristics through assimilation techniques.

The objective of this study is to develop a method to estimate canopy state variables in time and space using assimilation of high temporal frequency Spot data into vegetation process models. This work belongs to the ADAM project (Assimilation of Data within Agronomic Models), including CNES, INRA, Romanian Soil Science Institute and several other French and Romanian institutes (http://medias.obs-mip.fr/adam/).

Three main studies were conducted this year: the calculation of a complex agronomic model adjoint, SAIL radiative transfert model inversion to study remote sensing data, and development of a new way to consider spatial properties of the crop within the assimilation technique.

1. The STICS model will be used in the variational assimilation process. STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard, [64]) is a crop model that simulates canopy functioning, taking into account climate, soil characteristics, crop properties and cultural practices. Its large number of discontinuities did not permit to derive it quickly and easily.
2. Remote sensing data permits to evaluate canopy biophysical properties using different techniques to translate reflectance. Three inversion techniques have been compared with the help of soil measurements: multi-linear regression, vegetation indices and inversion of a canopy radiative transfert model with iterative methods. This model, SAIL (Scattering by Arbitrary Inclined Leaves) radiative transfer model, with leaf, soil and canopy optical properties, is able to simulate the SPOT data. Its inversion, using radiometric data, permits to include optical properties into the canopy functioning model.

3. In most agronomic studies on assimilation, model parameters are estimated by traditional pixel-based approaches. This means that, at a given date, a radiometric value gives a canopy biophysical characteristics (for exemple Leaf Area Index LAI) on one pixel, which is then assimilated. This technique generates at least 3 critical points:

    – spatial structures relations are not taken into account;
    – the inverse problem is certainly ill-posed;
    – the same work is repeated a large number of times, certainly unnecessarily, and generates a non optimal cost.

    In many inverse problems, the computational cost is a large obstacle, and reducing this cost becomes an additional aim. In order to take into account spatial properties within the assimilation of satellite images, another work has been conducted on a more simple model. The following questions then arise naturally:

    1. *Which space structures to exploit to reduce the problem size and to make it invertible?* This has been possible by associating *spatial dependance levels* to parameters: one will speak for example about *cultivar* parameter when this one is equal in all the cases to the same value : for example phenologic stages or leaves properties. With a lower degree, some parameters follow an *in-field* variability, like cultural practices. Finally, other parameters depend on the *pixel* level, like soil parameters or ones without any physical meaning.
    2. *How to transform the traditional assimilation scheme to an ensemble of pixels?* This can be done by the creation of a new agronomic model, taking into account all constraints, and which adjoint is calculated. LAI is now considered as a function of 3 groups of parameters: x is cultivar dependent, y is in-field variable, and z is pixel dependent: LAI $= \mathrm{f}(x, y, z)$, where the parameters x are constrained to be equal on all pixels of the same cultivar, and the parameters y must be equal on the same field. This "macro-model" and an associated cost function should be derived in function of as many parameters as there are pixels on the satellite image.

Our main results are the following :

1. The adjoint model of STICS has been calculated though its large number of discontinuities, and will now permit to develop many results: sensitivity analysis, estimation of soil and crop properties, as well as cultural practices, evaluation of the effects of high temporal frequency on the parameter estimation ...within papers quite soon.
2. The three methods used to transform canopy reflectance to its biophysical properties revealed the good precision of vegetation indices (NDVI particularly : Normalized Difference Vegetation Index) as well as the SAIL inversion method. The precision of the latter depends a lot on prior information about soil properties and view and illumination angles in cost function minimized, which is not always easy to determine. Finally regression gives the best results, but its coefficients are only valid in the particular case of ADAM experiment, though NDVI and inversion could be translated to another region.

3. The space constraints add robustness to the method particularly when less observations are available. They make it possible to obtain a result quite as satisfactory as the traditional pixel-based assimilation, in terms of state variable (LAI) estimation, but with a *calculation N times less costly*, where N is the number of pixels (meanly: 30 iterations to converge against 3000 for 100 pixels used). In addition, for a much smaller number of bservations, they give better results than pixel-based assimilation, and much *more stable face to the change of satellite revisit frequency*. Lastly, the twin experiments made it possible to show that taking into account the constraints, whatever the frequency of revisits, improves the identification of model parameters, which corresponds in general to the main objective of data assimilation.

Claire Lauvernet's thesis has been defended in 2005.

6.5. Hydrology

Participants: William Castaings, Igor Gejadze, Marc Honnorat, François-Xavier Le Dimet, Youssef Loukili, Jérôme Monnier.

6.5.1. Lagrangian Data Assimilation for River Hydraulic Models

M. Honnorat began his PhD in October 2003, addressing the problem of the assimilation of image type data for flood models.
Dynamic images (a series of still images, or a video) of a river flow, contain informations that can be used in a data assimilation process for the identification of model parameters, such as topography and land roughness.
Numerical experiments have shown that observed trajectories of passive individual tracers on the free surface of a river flow (lagrangian data) can bring valuable information on the flow velocity for the reconstruction of inflow discharge, very local topography and manning coefficients. Such computations based on video images of flows in a canal are under consideration (collaboration with N. Rivière, LMFA Lyon, and E. Huot, CLIME team-project). The continuation of this approach results in considering the assimilation of a water front, or coherent structures evolving on the surface flow.
This PhD is supervised by J. Monnier and F.-X. LeDimet; it is funded by CNES and CNRS.

6.5.2. Coupling 1D-2D Models and Data assimilation

Igor Gejadze, postdoctoral researcher, joined our team-project in April 2005, and stays untill June 2006. He studied and implemented into DassFlow a new algorithm coupling 1D and 2D shallow water models, while at same time assimilating the available data. This algorithm should be usefull for river overflowing and flood extension prediction. It improves the classical 1D storage area model. This work is funded by Région Rhône-Alpes.

6.5.3. Assimilation of flood satellite images

XiJun Lai, young researcher at Chinese Academy of sciences, will reach our team-project during the period February-December 2006. He will study the contribution of a satellite image of flood event and adapt the data assimilation algorithms. This work is done in collaboration with C. Puech (Cemagref Montpellier, Maison de la télédétection); it is funded by Région Rhône-Alpes.

6.5.4. Data assimilation into a flash flood model

W. Castaing began his PhD in spring 2002. A large part of this work is devoted to a general approach for sensitivity analysis and data assimilation applied to rainfall-runoff models. Flash flood events are usually generated by heavy convective precipitation over a relatively small area, but catchment hydrology plays a major role in their occurrence. An event-based flash flood model was developed by Institut de Mécanique des Fluides de Toulouse (IMFT). A model is not sufficient to carry out a prediction because it requires the prescription of initial and boundary conditions. Furthermore it includes many parameters without a direct physical meaning. They have therefore to be identified by additional information such as direct or remote measurements. In fact, important factors like initial soil moisture and infiltration parameters govern rainfall

abstractions and therefore control the partition of rainwater between infiltration and runoff. Since the model is devoted to be integrated into a hydrometeorogical prediction chain, its interaction in terms of models and data was scoped and the direct model slightly modified. After a review of the application of data assimilation to hydrology, adjoint sensitivity analysis and variational data assimilation was initiated.
The work of William Castaings puts in light a very fundamental point in environmental modelling about the link between sources of information. It is shown that the improvement of models is not necessary if the quality of the available data remains poor. An improvement of the model can even downgrade the quality of the forecast if the same set of data is kept. This remark is also the object of a cooperative research with Florida State University.

6.6. Snow avalanches and mud flows

Participant: Pierre Saramito.

The prediction of natural hazards in mountain, from snow avalanches to mud flows, requires sophisticated numerical simulations and complex rheological laws for non-linear materials, such as yield stress fluids or granular flows. This simulation requires also specific numerical methods, in order to solve the corresponding large non-linear set of equations in a time-dependent context: finite elements or finite volume, automatic mesh adaptation.

Our work is splitted into four axes: i) theoretical modelling of snow avalanches (aerosols) (with LEGI), ii) development of numerical solvers, iii) validation using experimental results (with CEMAGREF), and iv) visualization (virtual reality) (with GRAVIR).

Moreover, we are presently developing robust higher order schemes, in order to solve efficiently such time dependent flow problems, since simple implicit first order schemes are often insufficient for such problems.

6.7. Models of plinian columns

Participant: Isabelle Charpentier.

Many of the processes involved in volcanic eruptive columns may be described through physical models based on conservation laws in which a physical parameterization, called the entrainment function, plays an important role. Among the purposes of these models, the solution of inverse problems and the estimation of the characteristics of ancient eruptions, for instance, require a better knowledge of the characteristics and properties of this function. The first part of the study shows that the three usual shapes chosen for this function yield apparently the same behaviour of the column. However, we prove that a piecewise constant shape may be unsuitable in optimization processes based on gradient methods. It also turns out that the parameters defining the entrainment function cannot be considered as constant.

In the second part of the study, the unique parameter of the remaining two functions is viewed as dependent on the boundary conditions and specified with respect to them. A calibration of the entrainment function with respect to real data is achieved through a power law established between column height and discharge, the latter being related to velocity, radius and bulk density at the vent. According to a discussion on eruptive data, the construction of a mathematical parameterization, with respect to boundary conditions and the heights of the vent and the tropopause, appears to be an unwarranted and difficult task since any new addition in the observed data will definitely modify the power law.

A 4-dimensional data base covering the range of boundary conditions usually found in plinian eruptions, together with an interpolation operator, is constructed in order to provide an approximated parameter for any set of boundary conditions in the range considered. Numerical results with a data base of dimension 9^4 show that the approximated parameter allows one to recover column height very accurately.

6.8. Statistical inverse problems

Participants: Anestis Antoniadis, Theofanis Sapatinas, Felix Abramovich, Jeremie Bigot.

Paper [59] extends our previous results to the class of functional mixed-effects models. Functional mixed-effects models are very useful in analyzing functional data. The work considers a general functional mixed-effects model that inherits the flexibility of linear mixed-effects models in handling complex designs and correlation structures. Wavelet decomposition approaches are used to model both fixed-effects and random-effects in the same functional space, which helps in interpreting the resulting model as a functional data model since it does not contradict the intuition that, if each outcome is a curve, which is the basic unit in functional data analysis, then the population-average curve and the subject-specific curves should have the same smoothness property (i.e., they should lie in the same functional space). A linear mixed-effects representation is then obtained that is used for estimation and inference in the general functional mixed-effects model. Adapting recent methodologies in linear mixed-effects and nonparametric regression models, hypothesis testing procedures are provided for both fixed-effects (testing whether certain fixed-effects functional components or contrasts are equal to zero) and random-effects (testing whether the random-effects functional components are equal to zero). The usefulness of the proposed estimation and testing procedures is illustrated by means of two real-life datasets arising from endocrinology and physiology.

Paper [62] is devoted to a fast, wavelet-based, regression-type method for estimating the parameters of a stable distribution. Fourier domain representations, combined with a wavelet multiresolution approach, are shown to be effective and highly efficient tools for inference in stable law families.

Paper [60] considers regression problems with univariate design points. The design points are irregular and no assumptions on their distribution are imposed. The regression function is retrieved by a wavelet based reproducing kernel Hilbert space (RKHS) technique with the penalty equal to the sum of blockwise RKHS norms. Under relevant assumptions on design points the method achieves asymptotic optimality in a wide range of Besov spaces.

Finally paper [61] focusses on nonparametric estimators in inverse problems for Poisson processes involving the use of wavelet decompositions. Adopting an adaptive wavelet Galerkin discretization the proposed method combines the well know theoretical advantages of wavelet-vaguelette decompositions for inverse problems in terms of optimally adapting to the unknown smoothness of the solution, together with the remarquably simple closed form expressions of Galerkin inversion methods.

7. Contracts and Grants with Industry

7.1. National contracts

- A 2-year contract with MERCATOR on the thematic "coupling of ocean models"
- A 2-year contract with MERCATOR on the thematic "Assimilation of lagrangian data in OPAVAR"
- A 2-year contract with SHOM (french navy) on the thematic "coupling of ocean models"

7.2. International contracts

- IDOPT is a partner of the european MERSEA project (http://www.mersea.eu.org). This project is led by IFREMER, and aims at developing a european system for operational oceanography.
  Participants: Eric Blayo, Laurent Debreu, Florian Lemarié.
- IDOPT participates to the joint project with the Numerical Mathematics Institute of the russian academy of sciences "Variational data assimilation for geophysical models", co-directed by F.X. Le Dimet (France), V.Shutyaev (Russia) and G. Korotaev (Ukraine), and supported by EGIDE.
  Participants: François-Xavier Le Dimet, Eugène Kazantsev.
- Anestis Antoniadis is the coordinator of the French part of a research European network of the type "Interuniversity Attractions Poles", from 2002-2005, including 5 Belgian Universities (UCL, KUL, ULB, LUC, FUNP(NAMUR),), the UJF (LMC) and a German University (Aachen) on the theme "Statistical techniques and modeling for complex substantive questions with complex data".
  Participants: Anestis Antoniadis, Gerard Grégoire.

8. Other Grants and Activities

8.1. Regional action

Collaborations with various regional research teams:

- MEOM (Modélisation des Écoulements Océaniques et des Marées) team from Laboratoire d'Écoulements Géophysiques et Industriels (Grenoble) : oceanography.
- Laboratoire de Transferts en Hydrologie et Environnement (Grenoble): inverse problems in hydrology.
- Département d'études des matériaux, section d'études de la solidification : CENG (Centre d'Études Nucléaires de Grenoble).
- Institut Laue-Langevin, Institut de Biologie Structurale du CENG et ESRF (Synchrotron) : stochastic methods for inverse problems.
- Pechiney : Centre de recherche de Voreppe.
- Cemagref Lyon, Department Hydrology and Hydraulics.
- LEGI, PIM project-team (Particules Interfaces Microfluidique).
- The regional project (Région Rhône-Alpes) "Numerical Prevention for Floods", led by J. Monnier, conducts researches in data assimilation, coupling and parameter fitting methods, and uncertainties propagation. The collaborators are applied mathematicians and numericians (team-project IDOPT), hydrologists (Cemagref and LMFA Lyon), satellite image analysts (Cemagref Montpellier and Maison de la Télédétection), computer scientists (team-project TROPICS) and research engineers (Sogreah Company). Frequent meetings are organized.

8.2. National actions

F.-X. Le Dimet is in charge of the project ASSIMAGE, devoted to the assimilation of images in numerical models in the framework of the ACI "Données Massives".

Interactions with other INRIA projects or actions:

- PARA PROJECT: Operational inverse mode
- ESTIME PROJECT: Optimisation algorithm, operational inverse mode
- TROPICS ACTION: Adjoint code automatic differentiation (TAPENADE), operational inverse mode
- SINUS PROJECT : Operational inverse mode

Collaborations with other research teams in France :

- Participation to the national research programm MERCATOR (oceanography).
- Laboratory "Analyse, Géométrie et Applications" (Paris 13): Domain decomposition and coupling methods
- IFREMER Brest
- IRD Brest
- "Laboratoire de Météorologie Dynamique" in the ENS (Paris): data assimilation for environment
- CEA Cadarache
- Centre National de Recherche Météorologique, Météo-France (Toulouse): Data assimilation for atmospheric models

Participation to national research groups (GdR) CNRS :

- GdR SPARCH (simulation de faisceaux de particules chargées)
- GdR Optimal design
- GdR Fluids in interaction
- GdR EAPQ (Equations d'Amplitudes et Propriétés Qualitatives)

8.3. European actions

8.3.1. Western Europe

Collaboration of A. Antoniadis and G. Grégoire with the professors I. Gijbels and A. Kneip of the Institut de Statistique de Louvain-La-Neuve. Collaboration of A. Antoniadis with Dr. Umberto Amato of CNR Italien (Naples). Collaboration of A. Antoniadis with Dr. Sylvain Sardy (École Polytechnique Fédérale de Lausanne).
F.-X. Le Dimet participates to the European project ECRASE (modelling in hydrology) and to the European projet PIONEER (coastal oceanography). He is member of the ECMI Educational Board (European Consortium for Mathematics in Industry).
E. Blayo and L. Debreu participate to the European project MERSEA (operational oceanography).

8.4. International actions

On the thematic “plasma physics” : collaboration with M. Vogelius (Rutgers university).
On the thematic “environnement” : F.-X. Le Dimet is in charge of an action (ECCO-NET) of cooperation with Russia (Institute of Numerical Mathematics of the Russian Academy of Sciences) and Ukrain (Institute of Oceanography of the Ukrainian Academy of Sciences). The theme of this cooperation is data assimilation for geophysical flows. On this theme it exists also a strong cooperation with China (Institute of Atmospheric Physics of the Chinese A.S.) (Invitation of F.-X. Le Dimet, in 2004) and Vietnam (Institutes of Mathematics and Institute of Mechanics of the Vietnamese A.S.), (Invitations of F.-X. Le Dimet, in 2004)
IDOPT is in charge of the associated group "SEMINOLE" devoted to promote co-operative research between the Department of Computational Sciences and Information Technology at Florida State University and IDOPT. Several stays both in Grenoble and Tallahassee were carried out in the framework of the agreement. The theme of the agreement is "Data and models for geophysical flows".

9. Dissemination

9.1. Scientific community dissemination

A. Antoniadis is a member of the Editorial board of the *ISUP* journal since 1992.
A. Antoniadis is associate editor of the Journal of the French Statistical Society since 1998.
A. Antoniadis is Editor in Chief of the journal ESAIM: Probability & Statistics since 2001.
A. Antoniadis is associate editor of the Journal “Statistics and Computing” since 2002.
J. Blum is member of the scientific commitee of PSMN (Pôle de Simulation et de Modélisation Numérique) of the ENS Lyon.
D. T. Pham is editor in chief of the *Journal of Time Series Analysis* since 1992.
F.-X. Le Dimet is a member of the scientific commitee of the european project GIR ECOFOR.
F.-X. Le Dimet is a member of the Educational Board of ECMI
F.-X. Le Dimet is a member of the scientific commitee of the PNRH (Programme National de Recherches en Hydrologie, CNRS-INSU).
E. Blayo is a member of the scientific commitee of Mercator (French national program for operational oceanography).

9.2. Teaching

There exists a strong link with the MASTER in applied mathematics of the Joseph Fourier University and the Institut National Polytechnique de Grenoble (ENSIMAG). Most of the staff of the project give lectures in this formation, and our Master and PhD students come from this formation. Among all the lectures given by the staff of the project, we can cite:
- Models and data for geophysical flows (E. Blayo, L. Debreu, F.-X. Le Dimet)
- Domain decomposition and coupling methods for PDEs (E. Blayo)

- Inverse problems in medical imagery (A. Antoniadis)
- Control and optimization of systems governed by PDEs (J.Blum, master of the univ. of Nice)

Lectures given in international schools :

- Optimization and applications (Hue, Vietnam, co-organized by the Vietnamese Academy of Sciences and the university of Namur, 2005) : F.-X. Le Dimet.

9.3. conferences, workshops

The members of the team have participated to various conferences and workshops. See the bibliography.

10. Bibliography

Doctoral dissertations and Habilitation theses

[1] C. LAUVERNET. *Assimilation variationnelle des observations de télédétection dans les modèles de fonctionnement de la végétation : utilisation du modèle adjoint et prise en compte des contraintes spatiales*, Ph. D. Thesis, Université Joseph Fourier, April 2005.

[2] M. NODET. *Modélisation mathématique et assimilation de donnéees lagrangiennes pour l'océeanographie*, Ph. D. Thesis, Université de Nice, December 2005.

[3] L. WU. *Variational methods applied to plant functional-structural dynamics: parameter identification, control and data assimilation*, Ph. D. Thesis, Université Joseph Fourier, April 2005.

Articles in refereed journals and book chapters

[4] D. AUROUX, J. BLUM. *Back and forth nudging algorithm for data assimilation problems*, in "C. R. Acad. Sci. Paris, serie I", vol. 340, 2005, p. 873–878.

[5] E. BLAYO, L. DEBREU. *Nesting ocean models*, E. CHASSIGNET, J. VERRON (editors). , Springer, 2005.

[6] E. BLAYO, L. DEBREU. *Revisiting open boundary conditions from the point of view of characteristic variables*, in "Ocean Modelling", vol. 9, n^o 3, 2005, p. 231–252.

[7] D. BRESCH, B. DESJARDINS. *The Rayleigh-Taylor instability and the Korteweg system*, in "Phys. Rev. E", 2005.

[8] D. BRESCH, B. DESJARDINS, B. DUCOMET. *Quasi neutral limit for a viscous capillary model of plasma*, in "Ann. Institut Poincaré, Anal. non linéaire", vol. 22, n^o 1, 2005, p. 1–9.

[9] D. BRESCH, B. DESJARDINS, E. GÉRARD-VARET. *Couches limites - Mathématiques marines*, in "La Recherche", vol. 384, 2005, p. 80–81.

[10] D. BRESCH, E. ESSOUFI, M. SY. *Effect of density dependent viscosities on multiphasic incompressible fluid models*, in "J. Math. Fluid Mech.", 2005.

[11] D. BRESCH, D. GÉRARD-VARET. *Roughness-induced effects on the quasi-geostrophic model*, in "Commun. Math. Phys.", vol. 253, n^o 1, 2005, p. 81–119.

[12] D. BRESCH, M. GISCLON, C. LIN. *An example of low Mach (Froude) number effects for compressible flows with nonconstant density (height) limit*, in "Math. Mod. Numer. Anal.", vol. 39, n° 3, 2005, p. 477–486.

[13] I. CHARPENTIER, J. ESPÍNDOLA. *A study of the entrainment function in models of Plinian columns: Characteristics and calibration*, in "Geophys. J. Int.", vol. 160, n° 3, 2005, p. 1123–1130.

[14] I. CHARPENTIER, J. ESPÍNDOLA. *Local sensitivity analysis of a numerical model of volcanic Plinian columns through automatic differentiation*, in "Math. Geol.", vol. 37, n° 1, 2005, p. 95–113.

[15] I. CHARPENTIER, N. JAKSE. *Phase diagram of complex fluids using an efficient integral equation method*, in "J. Chem. Phys.", 2005.

[16] L. DEBREU, C. VOULAND, E. BLAYO. *AGRIF: Adaptive Grid Refinement in Fortran*, in "Computers and Geosciences", 2005.

[17] F.-X. LE DIMET, V. SHUTYAEV. *On deterministic error analysis in variational data assimilation*, in "Nonlinear Processes in Geophysics", vol. 12, n° 4, 2005, p. 481–490.

[18] P. PENVEN, L. DEBREU, P. MARCHESIELLO, J. MCWILLIAMS. *Applications of the ROMS embedding procedure for the Central California Upwelling System*, in "Ocean Modelling", vol. 12, 2005, p. 157–187.

[19] C. ROBERT, S. DURBIANO, E. BLAYO, J. VERRON, J. BLUM, F.-X. LE DIMET. *A reduced order strategy for 4D-Var data assimilation*, in "Journal of Marine Systems", vol. 57, n° 1-2, 2005, p. 70–82.

[20] J. ÉTIENNE, E. J. HOPFINGER, P. SARAMITO. *Numerical simulation of high density ratio lock-exchange flows*, in "Phys. Fluids", vol. 17, n° 3, 2005, 036601.

[21] J. ÉTIENNE, P. SARAMITO. *Estimations d'erreur a priori de la méthode de Lagrange-Galerkin pour les équations de type Kazhikhov-Smagulov*, in "Comptes Rendus Mathématique", 2005.

[22] J. ÉTIENNE, P. SARAMITO, E. HOPFINGER. *Numerical simulations of dense clouds on steep slopes: application to powder-snow avalanches*, in "Annals of Glaciology", vol. 38, 2005, p. 379–392.

Publications in Conferences and Workshops

[23] A. ANTONIADIS, T. SAPATINAS. *Estimation and inference in functional wavelet mixed-effects models*, in "International Seminar on Nonparametric Inference, ISNI 2005, La Coruña, Spain", July 2005.

[24] E. BLAYO, L. DEBREU, B. BARNIER, S. CAILLEAU, V. FEDORENKO. *Nesting and coupling methods for ocean models*, in "International colloquium in honour of C. Le Provost, Toulouse", March 2005.

[25] E. BLAYO, L. DEBREU, V. FEDORENKO, S. CAILLEAU, B. BARNIER. *Nesting and coupling methods for atmospheric and oceanic models*, in "Assemblée générale de l'European Geophysical Union, Vienne", April 2005.

[26] D. BRESCH. *Effet de fond sur équations des lacs*, in "Workshop International de Mathématiques pour l'Océanographie "Modèles de nappes de pétrole", Calacuccia", May 2005.

[27] D. BRESCH. *Les équations des lacs peuvent être dégénérées*, in "Mathematical Methods in Hydrodynamics, Lille", June 2005.

[28] S. CAILLEAU, B. BARNIER, V. FEDORENKO, E. BLAYO, L. DEBREU. *Validation of open boundary conditions for ocean models: application to a regional model of Bay of Biscay*, in "Assemblée générale de l'European Geophysical Union, Vienne", April 2005.

[29] S. CAILLEAU, B. BARNIER, V. FEDORENKO, E. BLAYO, L. DEBREU. *Validation of open boundary conditions for ocean models: application to a regional model of the bay of Biscay*, in "International colloquium in honour of C. Le Provost, Toulouse", March 2005.

[30] W. CASTAINGS, D. DARTUS, M. HONNORAT, F.-X. LE DIMET, Y. LOUKILI, J. MONNIER. *Automatic Differenciation: a tool for variational data assimilation and adjoint sensitivity analysis for flood modeling*, in "Automatic Differentiation: Applications, Theory and Tools, proceedings of the 4th International Conference on Automatic Differentiation, AD2004, Chicago", M. BÜCKER, G. CORLISS, P. HOVLAND, U. NAUMANN, B. NORRIS (editors). , Lecture Notes in Computational Science and Engineering, vol. 50, Springer, July 2005.

[31] L. DEBREU, E. BLAYO, B. BARNIER. *A general adaptive multiresolution approach to ocean modelling. Experiments in a primitive equation model of the North Atlantic*, in "Adaptive Mesh Refinement - Theory and Applications, Chicago", T. PLEWA, T. LINDE, V. WEIRS (editors). , Lecture Notes in Computational Sciences and Engineering, vol. 41, Springer, September 2005.

[32] C. DOUCET, C. GUÉRIN, I. CHARPENTIER, J.-L. COULOMB. *Approche supernodale pour la résolution directe des grands systèmes linéaires creux issus de la modélisation éléments finis de phénomènes électromagnétiques*, in "2ème Congrès National de Mathématiques Appliquées et Industrielles, Evian", May 2005.

[33] M. HONNORAT, F.-X. LE DIMET, J. MONNIER. *On a river hydraulics model and Lagrangian data assimilation*, in "International Conference on Adaptive Modeling and Simulation, ADMOS'05, Barcelona", September 2005.

[34] N. JAKSE, J.-L. BRETONNET, I. CHARPENTIER, K. WU, S. LAI. *Integral equation approach to study the static structure factor of a charged colloidal suspension*, in "6th Liquid Matter Conference of the European Physical Society, Utrecht", July 2005.

[35] C. JAPHET, L. HALPERN, E. BLAYO. *Optimized Schwarz waveform relaxation algorithms with nonconforming time discretization for coupling convection-diffusion problems with discontinuous coefficients*, in "16th international conference on Domain Decomposition Methods, DD16, New-York", January 2005.

[36] C. LAUVERNET, F. BARET, D. BEAL, M. WEISS, K. PAVAGEAU, B. BERTHELOT, P. REGNER. *Improved estimates of vegetation biophysical variables from MERIS TOA images*, in "MERIS and (A)ATSR workshop ESRIN, Frascati, Italy", September 2005.

[37] C. LAUVERNET, F. BARET. *Improved estimates of vegetation biophysical variables from MERIS TOA images by using spatial and temporal constraints*, in "9th International Symposium on Physical Measurements and

Signatures in Remote Sensing, ISPMSRS, Beijing, China", October 2005.

[38] C. LAUVERNET, F. BARET, R. VINTILA, F.-X. LE DIMET. *Prise en compte des contraintes spatiales pour l'assimilation de données de télédétection dans un modèle de fonctionnement du couvert végétal*, in "Réunion plénière Assimage (Etude de techniques d'assimilations de données image dans des modéles de simulation de fluides géophysiques), Chamrousse", INRIA, February 2005.

[39] C. LAUVERNET. *Différentiation du modèle STICS pour réaliser des analyses de sensibilité*, in "Séminaire STICS, Carry-le-Rouet", Dpt Environnement et agronomie, March 2005, p. 71–74.

[40] J. MONNIER, P. WITOMSKI. *A shape inverse approach modelling electro-wetting*, in "6th World Congress on Structural and Multidisciplinary Optimization, WCSMO6, Rio de Janeiro", May 2005.

[41] M. NODET. *Variational assimilation of Lagrangian data in oceanography*, in "4th WMO International Symposium on Assimilation of Observations in Meteorology and Oceanography, Prague", April 2005.

[42] M. NODET. *Variational assimilation of Lagrangian data in oceanography*, in "Congress on Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics, Lerici", June 2005.

[43] C. ROBERT, E. BLAYO, J. VERRON. *Comparison of sequential and variational reduced-order data assimilation methods in the Tropical Pacific ocean*, in "International colloquium in honour of C. Le Provost, Toulouse", March 2005.

[44] C. ROBERT, E. BLAYO, J. VERRON. *Comparison of sequential and variational reduced-order data assimilation methods in the Tropical Pacific Ocean*, in "4th WMO International Symposium on Assimilation of Observations in Meteorology and Oceanography, Prague", April 2005.

[45] E. SIMON, L. DEBREU, E. BLAYO. *4D variational data assimilation for locally nested models*, in "4th WMO International Symposium on Assimilation of Observations in Meteorology and Oceanography, Prague", April 2005.

[46] R. VINTILA, F. BARET, C. LAUVERNET, N. ROCHDI, H. DE BOISSEZON, J.-C. FAVARD, C. RADNEA. *Monitoring crop status at field level using high revisit frequency satellite observations*, in "9th International Symposium on Physical Measurements and Signatures in Remote Sensing, ISPMSRS, Beijing, China", October 2005.

[47] R. VINTILA, F. BARET, C. LAUVERNET, N. ROCHDI, H. DE BOISSEZON, J.-C. FAVARD. *Monitoring crop status using high revisit frequency satellite observations*, in "Soil, Water and Climate seminar, University of Minnesota, USA", Precision Agriculture Center. Soil, Water and Climate department, February 2005.

[48] J. ÉTIENNE, E. J. HOPFINGER, P. SARAMITO. *Simulations numériques à haute résolution d'écoulements gravitaires à fortes variations de densité*, in "Congrès Français de Mécanique, CFM 2005, Troyes, France", September 2005.

Internal Reports

[49] A. ANTONIADIS, E. PAPARODITIS, T. SAPATINAS. *A Functional Wavelet-Kernel Approach for*

Continuous-time Prediction, Research report, nº ccsd-00004891, 1074-M, LMC-IMAG, May 2005, http://hal.ccsd.cnrs.fr/ccsd-00004891.

[50] A. ANTONIADIS, T. SAPATINAS. *Estimation and Inference in fuctional mixed-effects models*, Research report, LMC, 2005.

[51] M. BENSAADA, D. ESSELAOUI, P. SARAMITO. *Estimation d'erreur pour la méthode des caractéristiques avec une dérivée d'Oldroyd sur un problème de transport tensoriel*, Technical report, 2005.

[52] D. BRESCH, D. GÉRARD-VARET, E. GRENIER. *Derivation of the planetary geostrophic equations*, Technical report, 2005.

[53] D. BRESCH, G. MÉTIVIER. *Global existence and uniqueness for the lake equations with vanishing topography: elliptic estimates for degenerate equations*, Technical report, 2005.

[54] I. CHARPENTIER, C. DAL CAPPELLO. *High order cross derivative computation for the differential cross section of double ionization of helium by electron impact*, Research report, nº 5546, INRIA, July 2005, http://www.inria.fr/RRRT/RR-5546.html.

[55] Y. LOUKILI, M. HONNORAT, J. MONNIER. *T2DInverse: Towards calibration and sensitivity analysis into Telemac2D using automatic differentiation*, Technical report, nº 5618, INRIA, July 2005, http://www.inria.fr/rrrt/rr-5618.html.

[56] J. MONNIER, P. CHOW-WING-BOM. *ElectroCap: A shape inverse model for an electro-capillarity process*, Research report, nº 5617, INRIA, July 2005, http://www.inria.fr/rrrt/rr-5617.html.

[57] J. MONNIER, P. WITOMSKI. *Numerical modelling of electro-wetting by a shape inverse approach*, Technical report, 2005.

[58] C. ROBERT, E. BLAYO, J. VERRON. *Comparison of reduced-order sequential, variational and hybrid data assimilation methods in the context of a Tropical Pacific ocean model*, Technical report, 2005.

Bibliography in notes

[59] F. ABRAMOVICH, A. ANTONIADIS, T. SAPATINAS, B. VIDAKOVIC. *Wavelet methods for testing in functional analysis of variance models*, in "International Journal on Wavelets and its applications", vol. 2, nº 4, 2004, p. 323–350.

[60] U. AMATO, A. ANTONIADIS, M. PENSKY. *Wavelet kernel penalized estimation for non-equispaced design regression*, in "Statistics and Computing", to appear.

[61] A. ANTONIADIS, J. BIGOT. *Poisson Inverse Problems*, in "Annals of Statistics", submitted.

[62] A. ANTONIADIS, A. FEUVERGER, P. GONCALVES. *Wavelet Based Estimation for Univariate Stable Laws*, in "Annals of the Institute of Mathematical Statistics", to appear.

[63] J. BIGOT. *Automatic landmark registration of 1D curves*, M. AKRITAS, D. POLITIS (editors). , Elsevier, 2003, p. 479–496.

[64] N. BRISSON, ET AL.. *STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parametrization applied to wheat and corn.*, in "Agronomie", vol. 18, 1998, p. 311–346.

[65] L. DEBREU, E. BLAYO. *AGRIF: Adaptive Grid Refinement In Fortran*, Technical report, INRIA, June 2002, http://www.inria.fr/rrrt/rt-0262.html.

[66] L. DEBREU, C. VOULAND, E. BLAYO. *AGRIF: Adaptive grid refinement in Fortran*, in "Computers and Geosciences", To appear, 2005.

[67] S. DURBIANO. *Vecteurs caractéristiques de modèles océaniques pour la réduction d'ordre en assimilation de données*, Ph. D. Thesis, Université Joseph Fourier, December 2001.

[68] I. HOTEIT, D. T. PHAM, J. BLUM. *A Semi-evolutive partially local filter for data assimilation*, in "Marine Pollution Bulletin", vol. 43, n° 7-12, 2001, p. 164–174.

[69] I. HOTEIT, D. T. PHAM, J. BLUM. *A simplified reduced order Kalman filtering and application to altimetric data assimilation in the Tropical Pacific*, in "Journal of Marine Systems", vol. 36, n° 1-2, 2002, p. 101–127.

[70] I. HOTEIT, D. T. PHAM, J. BLUM. *A semi-evolutive filter with partially local correction basis for data assimilation in oceanography*, in "Oceanologica Acta", vol. 26, n° 5-6, 2003, p. 511-524.

[71] I. HOTEIT, D. T. PHAM. *Evolution of the reduced state space and data assimilation scheme based on the Kalman filter*, in "J. Meteorological Soc. Japan", vol. 81, n° 1, 2003, p. 21–39.

[72] E. KAZANTSEV. *Sensitivity of a simple ocean model to the topography perturbations*, in "Nonlinear Processes in Geophysics", submitted, 2005.

[73] M. KLEPTSYNA, A. LE BRETON. *A Cameron-Martin type formula for general Gaussian processes – A filtering approach*, in "Stochastics Stochastics Rep.", vol. 72, n° 3-4, 2002, p. 229–250.

[74] M. KLEPTSYNA, A. LE BRETON. *Extension of the Kalman-Bucy filter to elementary linear systems with fractional Brownian noises*, in "Stat. Inference Stoch. Process.", vol. 5, n° 3, 2002, p. 249–271.

[75] M. KLEPTSYNA, A. LE BRETON. *Statistical analysis of the fractional Ornstein-Uhlenbeck type process*, in "Stat. Inference Stoch. Process.", vol. 5, n° 3, 2002, p. 229–248.

[76] M. KLEPTSYNA, A. LE BRETON, M. VIOT. *New formulas concerning Laplace transforms of quadratic forms for general Gaussian sequences*, in "J. Appl. Math. Stochastic Anal.", vol. 15, n° 4, 2002, p. 323–339.

[77] M. KLEPTSYNA, A. LE BRETON, M. VIOT. *About the linear-quadratic regulator problem under a fractional Brownian perturbation*, in "ESAIM, Probab. Stat.", vol. 7, 2003, p. 161–170.

[78] F.-X. LE DIMET, I. NAVON, D. DAESCU. *Second order information in data assimilation*, in "Monthly Weather Review", vol. 130, nº 3, 2002, p. 629–648.

[79] F.-X. LE DIMET, V. SHUTYAEV, J. WANG, M. MU. *The problem of data assimilation for soil water movement*, in "ESAIM-COCV", vol. 10, nº 3, 2004, p. 331–345.

[80] F.-X. LE DIMET, O. TALAGRAND. *Variational algorithms for analysis and assimilation of meteorological observations : theoretical aspect*, in "Tellus", 1986.

[81] J. LIONS. *Contrôle optimal de systèmes gouvernés par des équations aux dérivés partielles*, Dunod, 1968.

[82] D. T. PHAM. *A Singular Evolutive Interpolated Kalman Filter for Data Assimilation in Oceanography*, Technical report, nº 163, LMC-IMAG, September 1996.

[83] D. T. PHAM. *Stochastic methods for sequential data assimilation in strongly nonlinear systems*, Technical report, nº 3597, INRIA, December 1998, http://www.inria.fr/rrrt/rr-3597.html.

[84] D. T. PHAM, J. VERRON, L. GOURDEAU. *Filtres de Kalman singuliers évolutif pour l'assimilation de données en océnographie*, in "C. R. Acad. Sci., Paris, Sciences de la terre et des planètes", vol. 326, nº 4, 1998, p. 255–260.

[85] D. T. PHAM, J. VERRON, M.-C. ROUBAUD. *A Singular Evolutive Extended Kalman Filter for Data Assimilation in Oceanography*, Technical report, nº 162, LMC-IMAG, September 1996.

[86] D. T. PHAM, J. VERRON, M. C. ROUBAUD. *A Singular Evolutive Extended Kalman Filter for Data Assimilation in Oceanography*, in "Journal of Marine Systems", vol. 16, nº 3-4, 1998, p. 323–340.

[87] C. ROBERT. *Développement et comparaison de méthodes d'assimilation de données de rang réduit dans un modèle de circulation océanique : application à l'océan Pacifique tropical*, Ph. D. Thesis, Université Joseph Fourier, December 2004.

[88] J. VERRON, L. GOURDEAU, D. T. PHAM, R. MURTUGUDE, A. J. BUSALACHI. *An Extended Kalman Filter to Assimilate Satellite Altimeter Data into a Nonlinear Numerical Model of the Tropical Pacific Ocean: Method and validation*, in "J. Geophys. Res.", vol. 104, nº C3, 1999, p. 5441–5458.

[89] P.-A. VIDARD, A. PIACENTINI, F.-X. LE DIMET. *Variational data analysis with control of the forecast bias*, in "Tellus", vol. 56, nº 3, 2004, p. 177–188.

[90] P. VIDARD. *Vers une prise en compte de l'erreur modèle en assimilation de données 4D-variationnelle*, Ph. D. Thesis, Université Joseph Fourier, December 2001.