INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team moise

Modelling, Observations, Identification for Environmental Sciences

Grenoble - Rhône-Alpes

Theme : Observation and Modeling for Environmental Sciences

Activity Report

2010

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

This project-team is located in the LJK laboratory.

1. Team

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2. Overall Objectives

2.1. Overall Objectives

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

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

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

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

3. Scientific Foundations

3.1. Introduction

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

- Geophysical flows are non-linear. There is often a strong interaction between the different scales of the flows, and small-scale effects (smaller than mesh size) have to be modelled in the equations.
- Every geophysical episode is unique: a field experiment cannot be reproduced. Therefore the validation of a model has to be carried out in several different situations, and the role of the data in this process is crucial.

- Geophysical fluids are non closed systems, i.e. there are always interactions between the different components of the environment (atmosphere, ocean, continental water, etc.). Boundary terms are thus of prime importance.
- Geophysical flows are often modeled with the goal of providing forecasts. This has several consequences, like the usefulness of providing corresponding error bars or the importance of designing efficient numerical algorithms to perform computations in a limited time.

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

3.2. Numerical Modelling

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

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

3.3. Data Assimilation and Inverse Methods

Despite their permanent improvement, models are always characterized by an imperfect physics and some poorly known parameters (e.g. initial and boundary conditions). This is why it is important to also have **observations** of natural systems. However, observations provide only a partial (and sometimes very indirect) view of reality, localized in time and space.

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

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

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

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

- the models are often strongly non-linear, whereas the theories result in optimal solutions only in the context of linear systems;
- the model error statistics are generally poorly known;
- the size of the model state variable is often quite large, which requires dealing with huge covariance matrices and working with very large control spaces;
- data assimilation methods generally increase the computational costs of the models by one or two orders of magnitude.

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

A challenge of particular interest consists in developing methods for assimilating image data. Indeed, images and sequences of images represent a large amount of data which are currently underused in numerical forecast systems. However, despite their huge informative potential, images are only used in a qualitative way by forecasters, mainly because of the lack of an appropriate methodological framework.

3.4. Sensitivity Analysis - Quantification of Uncertainties

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

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

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

4. Application Domains

4.1. Introduction

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

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

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

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

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

4.2. Oceanography and the Ocean-Atmosphere System

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

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

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

- *Multi-resolution approaches and coupling methods*: Many applications in coastal and operational oceanography require high resolution local models. These models can either be forced at their boundaries by some known data, or be dynamically coupled with a large-scale coarser resolution model. Such model interactions require specific mathematical studies on open boundary conditions, refinement methods (like mesh refinement or stochastic downscaling), and coupling algorithms. The latter have also to be studied in the context of ocean-atmosphere coupled systems.
- *Advanced numerical schemes*: Most ocean models use simple finite difference schemes on structured grids. We are seeking for better schemes allowing both accuracy and good conservation properties, and dealing with irregular boundaries and bottom topography.
- *Data assimilation methods for ocean modelling systems*: The main difficulties encountered when assimilating data in ocean or atmosphere models are the huge dimension of the model state vector (typically 10^6-10^7), 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, of sequences of images, and on the design of data assimilation methods for multi-resolution models and for coupled systems.

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

4.3. Glaciology

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

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

In another respect, ice streams represent an important feature of ice flows since they account for most of the ice leaving the ice sheet (in Antarctic, one estimates that ice streams evacuate more than 70% of the ice mass in less than 10% of the coast line). Furthermore, recent observations showed that some important ice streams are presently accelerating. Thus, we seek to improve models of ice sheets, by developing data assimilation approaches in order to calibrate them using available observations.

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

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

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

4.4. River Hydraulics

Participants: Eric Blayo, Antoine Rousseau, Manel Tayachi.

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

5. Software

5.1. Adaptive Grid Refinement

Participant: Laurent Debreu.

AGRIF (Adaptive Grid Refinement In Fortran, [62]) is a Fortran 90 package for the integration of full adaptive mesh refinement (AMR) features within a multidimensional finite difference model written in Fortran. Its main objective is to simplify the integration of AMR potentialities within an existing model with minimal changes. Capabilities of this package include the management of an arbitrary number of grids, horizontal and/or vertical refinements, dynamic regridding, parallelization of the grids interactions on distributed memory computers. AGRIF requires the model to be discretized on a structured grid, like it is typically done in ocean or atmosphere modelling. As an example, AGRIF is currently used in the following ocean models: MARS (a coastal model developed at IFREMER-France), ROMS (a regional model developed jointly at Rutgers and UCLA universities), OPA-NEMO ocean modelling system (a general circulation model used by the French and European scientific community) and HYCOM (a regional model developed jointly by University of Miami and the French Navy).
AGRIF is licensed under a GNU (GPL) license and can be downloaded at its web site (http://ljk.imag.fr/MOISE/AGRIF/index.html).

MSFF, a Multi-Scale Open Source CFD Code, based on AGRIF, developed in the context of the COMMA project has been released (http://www-gmm.insa-toulouse.fr/~poncet/comma/comma.html).

5.2. SDM toolbox

Participants: Claire Chauvin, Antoine Rousseau.

The computation of the wind at small scale and the estimation of its uncertainties is of particular importance for applications such as wind energy resource estimation. To this aim, we develop a new method based on the combination of an existing numerical weather prediction model providing a coarse prediction, and a Lagrangian Stochastic Model adapted from a pdf method introduced by S.B. Pope for turbulent flows. This Stochastic Downscaling Method (SDM http://sdm.gforge.inria.fr/) is thus aimed to be used as a refinement toolbox of large-scale numerical models. SDM requires a specific modelling of the turbulence closure, and involves various simulation techniques whose combination is totally new (such as Poisson solvers, optimal transportation mass algorithm, original Euler scheme for confined Langevin stochastic processes, and stochastic particle methods). In 2010, among numerous modifications, the code has been improved in order to take horizontal periodic boundary conditions into account: in this framework validation and comparison with large eddy simulations are currently underway.

5.3. DatIce

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

The Datice code ([13], [41]) is designed to estimate consistent chronologies of several deep ice cores (i.e., depth-age relationships of the ice matrix and trapped gas). A cost function derived from Bayes theorem puts in competition the chronological constraints brought by heterogeneous observations (stratigraphic links between cores, gas and ice age markers, delta-depth markers, etc.), and the background dating scenarios simulated with glaciological models (firn densification and ice flow models). The minimization of the cost function provides optimal estimations of three key quantities from which dating scenarios can be derived: the past accumulation rate, the close-off depth which is the depth where the gas is trapped into ice, and the total thinning function. Uncertainties of the analysed dating scenarios (key quantities and chronologies) are assessed on the basis of the Bayesian formulation. This approach is innovative:

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

The code has been used in several recent publications (see [60], [68] for example).

6. New Results

6.1. Mathematical Modelling of the Ocean Dynamics

6.1.1. Beyond the traditional approximation on the Coriolis force

Participant: Antoine Rousseau.

Recently, A. Rousseau and C. Lucas have performed some theoretical and numerical studies around the derivation of quasi-hydrostatic models. They proved that it is sometimes necessary to take into account the cosine part of the Coriolis force (which is usually neglected, leading to the so-called Traditional Approximation). After a first paper published in 2008 [64], they presented their new results in an international conference on mathematical oceanography, [15]. They have also shown that the non-traditional terms do not raise any additional mathematical difficulty in the primitive equations: well-posedness for both weak and strong solutions (as in [61] were obtained for the fully nonlinear 3D system, see [14], [29] In order to investigate the importance of the non-traditional terms in operational circumstances, A. Rousseau has visited UCLA (Jim McWilliams team) in December 2010.

6.1.2. Coupling Methods for Oceanic and Atmospheric Models

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

6.1.2.1. Open boundary conditions

The implementation of high-resolution local models can be performed in several ways. An usual way consists in designing a local model, and in using some external data to force it at its open boundaries. These data can be either climatological or issued from previous simulations of a large-scale coarser resolution model. The main difficulty in that case is to specify relevant open boundary conditions (OBCs).

In collaboration with V. Martin (LAMFA Amiens), we are working on the analysis of the impact of the imperfection of the external data on the design of efficient OBCs. A full theoretical analysis has been performed in a simple one-dimensional test case, and validated by numerical experiments. Its extension to a two-dimensional shallow water system is presently underway.

6.1.2.2. Interface conditions for coupling ocean models

Many physical situations require coupling two models with not only different resolutions, but also different physics. Such a coupling can be studied within the framework of global-in-time Schwarz methods. However, the efficiency of these iterative algorithms is strongly dependent on interface conditions. As a first step towards coupling a regional scale primitive equations ocean model with a local Navier-Stokes model, a study on the derivation of interface conditions for 2-D $x - z$ Navier-Stokes equations is currently underway (D. Cherel's PhD thesis). It has been shown theoretically that several usual conditions lead to divergent algorithms, and that a convergent algorithm is obtained when using transmission conditions given by a variational calculation. Moreover the impact of two numerical schemes (a projection method, and a direct method [59]) on the implementation of the domain decomposition method has been discussed.

In addition, A. Rousseau has started to collaborate with mathematicians and physicists in Montpellier in the framework of coastal oceanography, and in particular the coupling of coastal models with regional oceanographic models. This activity has just started and should grow in 2011.

6.1.2.3. Ocean-atmosphere coupling

Many applications in regional oceanography and meteorology require high resolution regional models with accurate air-sea fluxes. Separate integrations of oceanic and atmospheric model components in a forced mode (i.e. without any feedback from one component to the other) may be satisfactory for numerous applications. However, two-way coupling is required for analyzing energetic and complex phenomena (e.g. tropical cyclones, climate studies, etc). In this case, connecting the two model solutions at the air-sea interface is a difficult task, which is often addressed in a simplified way from a mathematical point of view. In this context, domain decomposition methods provide flexible and efficient tools for coupling models with non-conforming time and space discretizations.

F. Lemarié, in his PhD thesis (2008), addressed the application of such methods to this ocean-atmosphere coupling problem. In the continuity of this work, ensemble simulations have been performed in the realistic context of the simulation of a tropical cyclone, using WRF atmospheric model and ROMS oceanic model. These simulations seem to demonstrate that using an iterative Schwarz method suppresses a source of numerical error in the system.
These works are partially supported by the ANR (COMMA project).

6.1.3. Numerical schemes for ocean modelling

Participants: Laurent Debreu, Thomas Duhaut.

Reducing the traditional errors in terrain-following vertical coordinate ocean models (or sigma models) has been a focus of interest for the last two decades. The objective is to use this class of model in regional domains which include not only the continental shelf, but the slope and deep ocean as well. Two general types of error have been identified: 1) the pressure-gradient error and 2) spurious diapycnal diffusion associated with steepness of the vertical coordinate. In a recent paper [65], we have studied the problem of diapycnal mixing. The solution to this problem requires a specifically designed advection scheme. We propose and validate a new scheme, where diffusion is split from advection and is represented by a rotated biharmonic diffusion scheme with flow-dependent hyperdiffusivity satisfying the Peclet constraint.
This work is supported by a contract with IFREMER and now focuses on the derivation of multidimensional monotonic advection schemes adapted to this problem of diapycnal diffusion.

Salinity at 1000 m in the Southwest Pacific ocean is shown in figure 1. The use of traditional upwind biased schemes (middle) exhibits a strong drift in the salinity field in comparison with climatology (left). The introduction of high order diffusion rotated along geopotential surfaces prevents this drift while maintaining high resolution features (right).

6.2. Development of New Methods for Data Assimilation

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

Participants: Didier Auroux, Jacques Blum, Maëlle Nodet.

The back and forth nudging algorithm (see [56]) has been recently introduced for simplicity reasons, as it does not require any linearization, nor adjoint equation, or minimization process in comparison with variational schemes, but nevertheless it provides a new estimation of the initial condition at each iteration.

We have considered from a theoretical point of view the case of 1-dimensional transport equations, either viscous or inviscid, linear or not (Burgers' equation). We showed that for non viscous equations (both linear transport and Burgers), the convergence of the algorithm holds under observability conditions. Convergence can also be proven for viscous linear transport equations under some strong hypothesis, but not for viscous Burgers' equation. Moreover, the convergence rate is always exponential in time. We also noticed that the forward and backward system of equations is well posed when no nudging term is considered [2]. Several comparisons with the 4D-VAR and quasi-inverse algorithms have also been performed on this equation in a submitted paper. The application of the BFN algorithm to OPA-NEMO ocean model is currently under investigation. The first experiments are very encouraging.

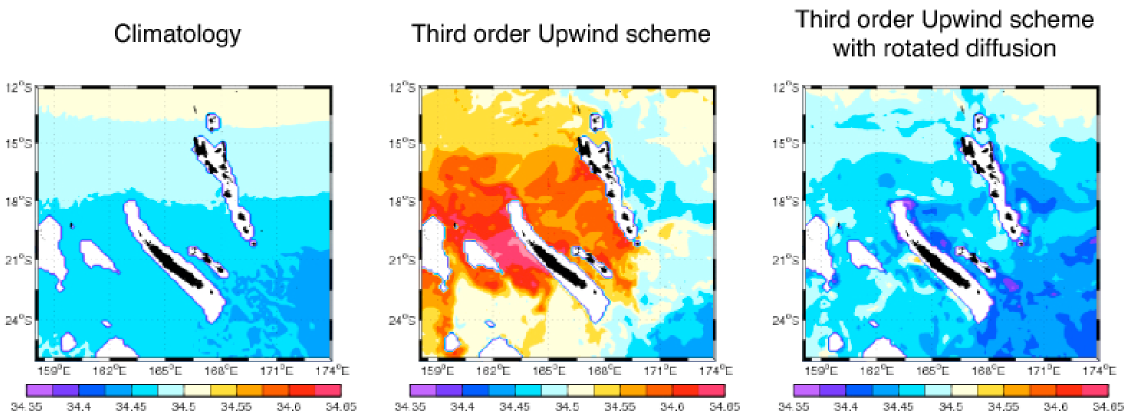

Figure 1. Salinity at 1000m in the Southwest Pacific ocean.

Still on Burgers equation, we also studied the discretized problem of data assimilation [55]. It is indeed crucial to be able to find correct discretizations of the continuous data assimilation problem.

Finally, within the standard nudging framework, we considered the definition of an innovation term that takes into account the measurements and respects the symmetries of the physical model. We proved the convergence of the estimation error to zero on a linear approximation of the system (a 2D shallow-water model). It boils down to estimating the fluid velocity in a water-tank system using only SSH measurements. The observer is very robust to noise and easy to tune. The general nonlinear case has been illustrated by numerical experiments, and the results have been compared with the standard nudging techniques [57].

6.2.2. Variational Data Assimilation with Control of Model Error

Participants: Pierre-Antoine Bouttier, Bénédicte Lemieux-Dudon, Arthur Vidard.

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

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

We are implementing this method in a realistic Oceanic framework using OPAVAR/ NEMOVAR as part of the VODA ANR project.

6.2.3. Variational Data Assimilation for locally nested models.

Participants: Eric Blayo, Laurent Debreu, François-Xavier Le Dimet, Emilie Neveu.

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

The state equations of the optimality system have been written for the general case of two embedded grids, for which several kinds of control (initial conditions, boundary conditions) have been proposed. Both one way and two way interactions have been studied. This last year, we worked on integration of non linear grid interactions in the algorithm. Additionally, the problem of specification of background error covariances matrices has been studied (see [18]).

In the ANR MSDAG project and Emilie Neveu's PhD, we continue to work on the subject. Our main interest is on the use of multiscale optimization methods for data assimilation. The idea is to apply a multigrid algorithm to the solution of the optimization problem. The work includes the analysis of the ellipticity of the optimization problem [31], the comparison of different multigrid methods (Gauss-Newton multigrid method and Full Approximation Scheme) and specific developments for highly non linear problems.

6.2.4. Variational Data Assimilation and Control of the Boundary Conditions.

Participant: Eugène Kazantsev.

A variational data assimilation technique applied to the identification of the optimal discretization of interpolation operators and derivatives in the nodes adjacent to the boundary of the domain is discussed in the context of the shallow water model. It was shown in [11] that control of approximation of boundary derivatives and interpolations can increase the model's accuracy in boundary regions and improve the solution in general. On the other hand, optimal schemes obtained in this way, may not approximate derivatives in a common sense. This may lead to another model physics, violating, for example, impermeability boundary condition. A particular study was performed in [10] on the example of one-dimensional wave equation to understand this phenomenon. In this simple case, we see that the control changes the interval's length (violating, consequently, the physical statement of the problem) in order to compensate numerical error in the wave velocity.

Experiments with a full non-linear shallow water model in [9] show that controlling the discretization of operators near a rigid boundary can bring the model solution close to observations as in the assimilation window and beyond the window. This type of control allows also to improve climatic variability of the model. These properties have been studied in two different configurations: an academic case of assimilation of artificially generated observational data in a square box configuration and assimilation of real observations in a model of the Black sea.

In order to illustrate the influence of optimal discretization of operators near the boundary we compare this influence with now classical data assimilation for identification of the optimal initial conditions of the model. The norm of the difference between the model solution and real observational data is plotted in figure 2. Observed sea surface elevation of the Black sea was assimilated during 50 days (May–Juin 1992) to identify optimal initial and boundary conditions. After that, models have been forwarded for 500 days and their solutions have been compared with data. One can see that starting from optimal initial point the model remains close to observations during less than 100 days while optimal optimal discretization of operators allows the model to be always closer than the model with default parameters.

6.3. Data Assimilation for Ocean Models

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

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

We are heavily involved in the development of NEMOVAR (Variational assimilation for NEMO). From 2006, we built a working group (coordinated by A. Vidard) in order to bring together various NEMOVAR user-groups with diverse scientific interests (ranging from singular vector and sensitivity studies to specific issues in variational assimilation), and to get technical and scientific support from Inria Sophia (Automatic adjoint derivation, TROPICS project-team) and ECMWF (Parallelization). This project aimed at avoiding duplication of effort, and at developing a common NEMOVAR platform. It has led to the creation of the VODA (Variational Ocean Data Assimilation for multi scales applications) ANR project

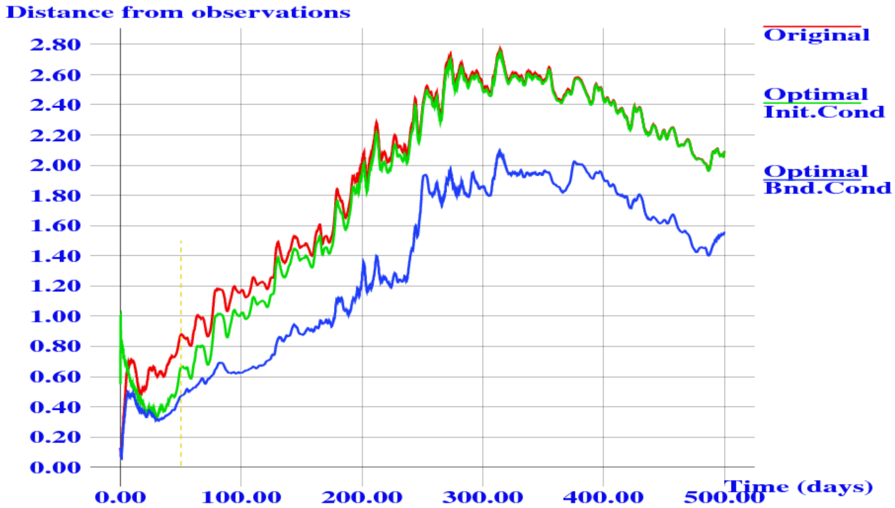

Figure 2. Evolution of the difference "model–observations".

The project aims at delivering a common NEMOVAR platform based on NEMO platform for 3D and 4D variational assimilation. Following 2009-10 VODA activities, a fully parallel version of NEMOTAM (Tangent and Adjoint Model for NEMO) is now available for the community in the standard NEMO version. This version is based on the released 3.0 version of NEMO. Two upgrades were done to follow NEMO standard development race. As a consequence, NEMOVAR is also available for NEMO version 3.2 and 3.2.1 both offer fully parallel features. The local group has developed a python interface engine (PIANO) to perform test and run on NEMO. The test modules for linear tangent part were upgraded to be compliant with PIANO. In addition, a test module is added to check tangent linear hypothesis according to user's configuration. A constant support to NEMOVAR project is ensured to deliver a focused response on dedicated issue (internal and external interaction). We were able to deliver a short-time support response to Met-Office partner on 3.2 NEMOVAR version.

We are also investigating variational data assimilation methods applied to high resolution ocean numerical models. This year was dedicated to take in hand software NEMO/NEMOVAR and to set up an idealized numerical configuration of an oceanic basin. Then, we have developed numerical and data assimilation frameworks around this model with the aim of leading variational data assimilation experiments.

As part of VODA, we are also working toward a NEMO-ASSIM framework. In collaboration with LEGI, we studied the feasibility of hosting non-variational DA tools in NEMO/NEMOVAR by integrating SESAM in the coding, building and execution environment.

As a side project we collaborated with Mercator-Ocean in order to use the adjoint to perform sensitivity analysis with the fourth of a degree global model used for the reanalysis.
Apart from the VODA ANR project, the NEMOVAR working group gets additional financial support by LEFE-Assimilation and the Mercator National Programs.

6.3.2. Assimilation of Lagrangian Data

Participants: Claire Chauvin, Maëlle Nodet, Arthur Vidard.

When an observation is given at a sequence of positions along the fluid flow, then it can be defined as Lagrangian, in a mathematical point of view. From this sequence of positions (for instance the profiling drifting floats of Argo program), one can deduce important information on the stream that transports the drifters. Such an information has not yet been exploited in an operational framework, although previous works [66] have shown the interest of assimilating this new type of data.

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

We used the method proposed by Daget, and called General Bilinear Remapping Interpolation (see http://www.cerfacs.fr/~daget/TECHREPORT/TR_CMGC_06_18_html). Interpolation on a point inside a mesh consists in finding weights associated to each face of the mesh. These weights are found thanks to an iterative scheme obtained by linearization.

One task was then to develop the tangent and adjoint procedures associated to this interpolation method, as well as the tests of these procedures on the main test configurations GYRE and ORCA2 . Their implementation in NEMOVAR has required a specific application, in order to be consistent with the conventions and data structures already present in NEMOVAR.

One aim of the development of these routines was to make the assimilation of Lagrangian Data possible for users of NEMOVAR. This has then required an implementation in the code with the same philosophy as the other observation operators, in terms of Fortran data structures as well as user interface. A reference manual has also been written [51].
On this subject a collaboration with K. Ide (University of Maryland) has been initiated. For a simple but highly nonlinear point-vortex model, we wish to compare sequential and variational methods to assimilate Lagrangian data. The work is still ongoing.

6.4. Assimilation of Image Data

6.4.1. Direct assimilation of sequences of images

Participants: François-Xavier Le Dimet, Arthur Vidard, Innocent Souopgui.

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

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

MOISE was the leader of the ANR ADDISA project dedicated to the assimilation of images, and is a member of its current follow-up GeoFluids (along with EPI FLUMINANCE and CLIME, and LMD, IFREMER and Météo-France)

During the ADDISSA project we developed Direct Image Sequences Assimilation (DISA) and proposed a new scheme for the regularization of optical flow problems [1], [19] . Thanks to the nonlinear brightness assumption, we proposed an algorithm to estimate the motion between two images, based on the minimization of a nonlinear cost function. We proved its efficiency and robustness on simulated and experimental geophysical flows [58]. As part of GeoFluids, we are investigating new ways to define distance between a couple of images. One idea was to define this distance as the norm of the apparent motion between two images. This has been done thanks to optical flow methods which turned out to need a specific parametrization for each couple of images. Another idea, currently under investigation, consists in comparing mains structures within each images. This can be done using, for example, a wavelet representation of images.

To illustrate the direct assimilation of sequences of images, in figure 3 we show two images from the sequence produced by METEOSAT and the velocity field obtained assimilating this sequence.

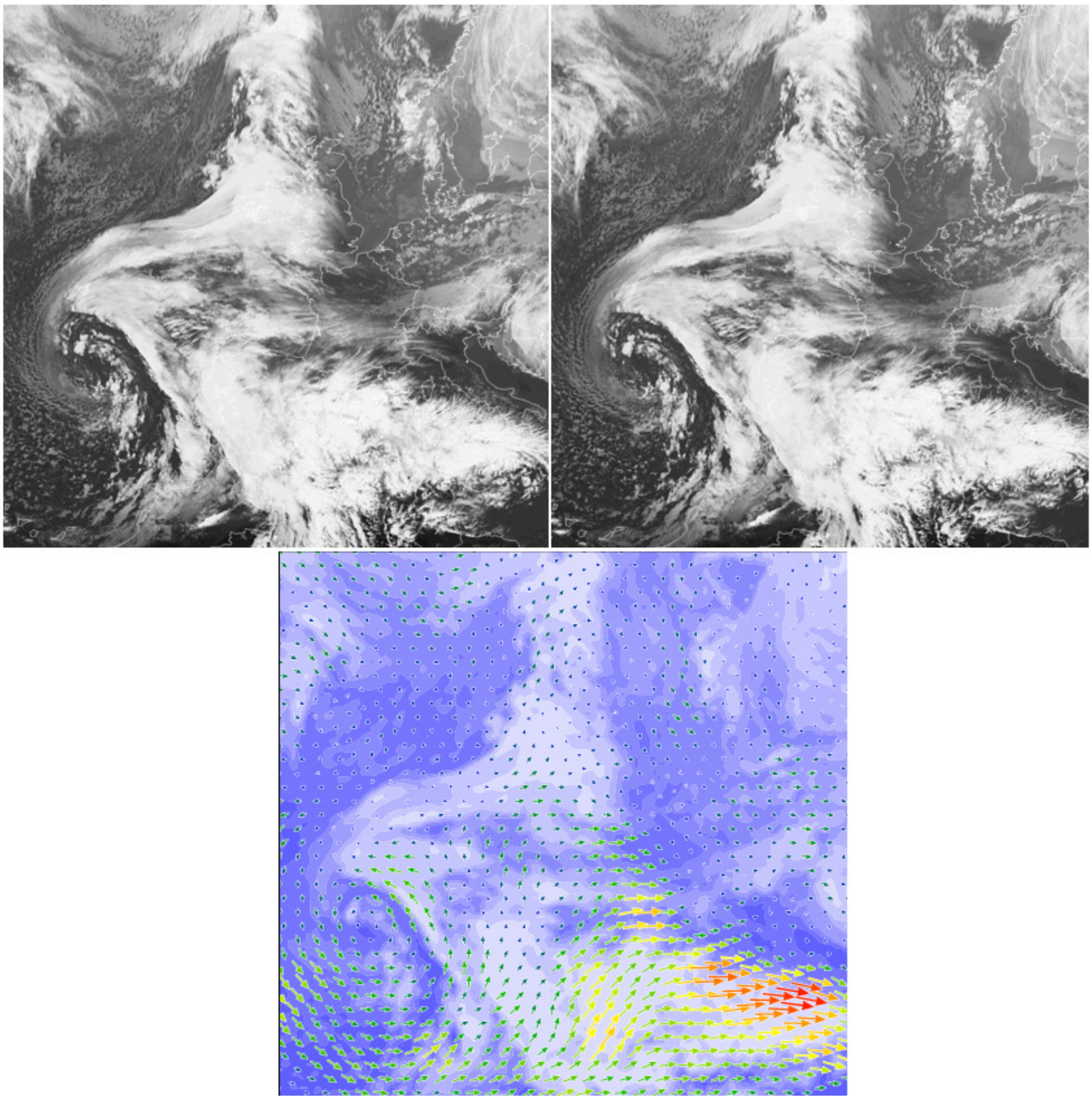

Figure 3. A sequence of Meteosat images and the velocity field obtained assimilating this sequence.

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

Participants: François-Xavier Le Dimet, Gennady Korotaev.

From the observation of sea surface imagery, the surface current velocity, at the mesoscale level, is extracted by using optimal control methods. It is assumed that the imagery contrast could be described by a transport diffusion equation. The method permits to retrieve an initial field of passive tracer together with surface current velocity from the sequence of images. The processing of AVHRR observations is carried out operationally in MHI (Marine Hydrophysical Institute, Sebastopol) now.

This work is done in collaboration with G. Korotaev (MHI) and I. Herlin, E. Huot (CLIME, Rocquencourt).

6.5. Inverse methods for Glaciology

6.5.1. Dating ice matrix and gas bubbles

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

Dating ice matrix and gas bubbles of ice-cores is essential to study paleoclimates. The conjunction of information brought by observations and flow models is now a commonly used approach to build the chronology of ice cores. Till now this technique has been applied: 1) to one core at a time, 2) to estimate the age of the ice but not of the gas (which is younger), 3) under the assumption of perfect glaciological models after the optimization of their parameters. This currently used methodology faces three problems: 1) for distinct cores the chronologies calculated separately usually show discrepancies, 2) chronologies sometimes fail to respect relevant data constraints precisely because models are imperfect (non well understood physical processes are omitted), at last 3) the gas and ice ages are not independent entities and some valuable observations contain information on both.

To go beyond these restrictions B. Lemieux-Dudon has proposed in her PhD a new inverse approach which takes into account the modelling errors. It aims at identifying the accumulation rate, the total thinning function and the close-off depth in meters of ice equivalent (i.e. depth below the surface where the gas is trapped), which are in best agreement with some prior guesses and with independent observations. This method operates on several cores simultaneously by the mean of stratigraphic links relating the gas or ice phase of two cores. The Bayesian framework of this method also enables to associate confidence intervals to the solution. This approach is applied to derive simultaneously a common age scale for the North Grip core and for the two EPICA cores (DML and DC). [13]. This method arouses some interest in the glaciological and paleo community ([60], [68]). Some further developments are however necessary: (i) optimization of the code, (ii) diagnostics on the assimilation system and (iii) calibration of the backgroung error covariance matrix. H. Toye Mahamadou Kele recently joined the MOISE team to work on the development of the code.

6.5.2. Adjoint methods for glaciology modelling

Participants: Eric Blayo, Bertrand Bonan, Maëlle Nodet, Catherine Ritz.

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

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

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

The ANR project ADAGe started a year ago on this subject, and B. Bonan started his PhD last September. During his master internship, he implemented the adjoint code of a simplified ice-sheet flow-line model, Winnie, developed by C. Ritz at LGGE. We then performed twin experiments of data assimilation. These preliminary results have been presented at two national conferences [36], [35].

In collaboration with O. Gagliardini, C. Ritz and F. Gillet-Chaulet (LGGE), we also investigated a new method to solve inverse problems for a Full-Stokes model of Groenland, which consisted in solving iteratively a sequence of Neumann and Dirichlet problems within a gradient descent algorithm. These results have been presented at two conferences [39], [40].

6.6. Quantifying Uncertainty

6.6.1. Propagation of uncertainties

Participants: François-Xavier Le Dimet, Victor Shutyaev.

Basically, geophysical models are suffering of two types of errors:

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

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

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

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

6.6.2. Sensitivity analysis for West African monsoon

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

6.6.2.1. Geophysical context

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

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

6.6.2.2. Statistical methodology

As mentioned in the previous paragraph, our main goal is to perform a sensitivity analysis for the West African monsoon. Each simulation of the regional atmospheric model (RAM) is time consuming, and we first have to think about a simplified model. We deal here with spatio-temporal dynamics, for which we have to develop functional efficient statistical tools. In our context indeed, both inputs (albedo, SST) and outputs (precipitations) are considered as time and space indexed stochastic processes. A first step consists in proposing a functional modeling for both precipitation and sea surface temperatures, based on a new filtering method. For each spatial grid point in the Gulf of Guinea and each year of observation, the sea surface temperature is measured during the active period on a temporal grid. A Karhunen-Loève decomposition is then performed at each location on the spatial grid [69]. The estimation of the time dependent eigenvalues at different spatial locations generates great amounts of high-dimensional data. Clustering algorithms become then crucial in reducing the dimensionality of such data.

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

We apply a novel method recently developed by [67] in integrated genomic studies which takes into account both aspects. The method uses an ℓ_1-norm penalty to control the overall sparsity of the coefficient matrix of the multivariate linear regression model. In addition, it also imposes a *group* sparse penalty. This penalty puts a constraint on the ℓ_2 norm of regression coefficients for each predictor, which thus controls the total number of predictors entering the model, and consequently facilitates the detection of important predictors. The dimensions of both predictors and responses are large (compared to the sample size). Thus in addition to assuming that only a subset of predictors enter the model, it is also reasonable to assume that a predictor may affect only some but not all responses. By the way we take into account the complex and spatio-temporal dynamics.

6.6.2.3. Distributed Interactive Engineering Toolbox

The study described above still requires rather huge computation resources, and will be run in a grid computing environment which takes into account the scheduling of a huge number of computation requests and links with data-management, all of this as automatically as possible.
These works involve also partners from the INRIA project/team GRAAL for the computational approach, and from the Laboratory of Glaciology and Geophysical Environment (LGGE) for the use and interpretation of the regional atmospheric model (RAM).

6.6.3. Sensitivity analysis for forecasting ocean models

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

6.6.3.1. Scientific context

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

6.6.3.2. Estimating sensitivity indices

A first task is to develop tools for estimated sensitivity indices. Among various tools a particular attention was paid to FAST and its derivatives. In [53], the authors present a general way to correct a positive bias which occurs in all the estimators in random balance design method (RBD) and in its hybrid version, RBD-FAST. Both these techniques derive from Fourier amplitude sensitivity test (FAST) and, as a consequence, are faced with most of its inherent issues. And up to now, one of these, the well-known problem of interferences, has always been ignored in RBD. After presenting in which way interferences lead to a positive bias in the estimator of first-order sensitivity indices in RBD, the authors explain how to overcome this issue. They then extend the bias correction method to the estimation of sensitivity indices of any order in RBD-FAST. They also give an economical strategy to estimate all the first-order and second-order sensitivity indices using RBD-FAST.

6.6.3.3. Intrusive sensitivity analysis, reduced models

Another point developed in the team for sensitivity analysis is model reduction. To be more precise regarding model reduction, the aim is to reduce the number of unknown variables (to be computed by the model), using a well chosen basis. Instead of discretizing the model over a huge grid (with millions of points), the state vector of the model is projected on the subspace spanned by this basis (of a far lesser dimension). The choice of the basis is of course crucial and implies the success or failure of the reduced model. Various model reduction methods offer various choices of basis functions. A well-known method is called “proper orthogonal decomposition” or “principal component analysis”. More recent and sophisticated methods also exist and may be studied, depending on the needs raised by the theoretical study. Model reduction is a natural way to overcome difficulties due to huge computational times due to discretizations on fine grids. In [52], the authors present a reduced basis offline/online procedure for viscous Burgers initial boundary value problem, enabling efficient approximate computation of the solutions of this equation for parametrized viscosity and initial and boundary value data. This procedure comes with a fast-evaluated rigorous error bound certifying the approximation procedure. The numerical experiments in the paper show significant computational savings, as well as efficiency of the error bound. Perspectives are now to get bounds when estimating sensitivity indices from such reduced models. First results are under study and seem rather interesting. Implementations have to be conducted on more general models such as Shallow-Water models.

6.6.3.4. Sensitivity analysis with dependent inputs

An important challenge for stochastic sensitivity analysis is to develop methodologies which work for dependent inputs. For the moment, there does not exist conclusive results in that direction. Our aim is to define an analogue of Hoeffding decomposition [63] in the case where input parameters are correlated. A PhD started in October on this topic (Gaëlle Chastaing).

6.7. Multivariate risk indicators

Participant: Clémentine Prieur.

In collaboration with VÃ©ronique Maume-Deschamps, Elena Di Bernardino (ISFA, Lyon 1) and Peggy Cenac (UniversitÃ© de Bourgogne), we are interested in defining and estimating new multivariate risk indicators. This is a major issue with many applications (environmental, insurance, ...) Two papers were submitted. The first one deals with the estimation of bivariate tails [48]. The second one [49] proposes to minimize multivariate risk indicators by using a Kiefer-Wolfowitz approach to the mirror stochastic algorithm.

6.8. Stochastic Downscaling Method

Participants: Antoine Rousseau, Claire Chauvin.

In collaboration with TOSCA (Inria Sophia-Antipolis), LMD (Ecole Polytechnique) and CETE (Clermont-Ferrand), we investigate a new method for the numerical simulation of the wind at small scales. Thanks to boundary data provided at large scales by the weather forecasting code $MM5$, we propose a Langevin model that rules the behavior of stochastic particles. The development of this model, called SDM (Stochastic Downscaling Method), is funded by ADEME (Agence de Développement de l’Écologie et de la Maîtrise de l’Énergie).

In 2010, the paper [3] has been published: this work improves the theoretical understanding of the new method and then focuses on some numerical properties of the scheme, such as the confinement. The code has been modified in order to take horizontal periodic boundary conditions into account: in this framework validation and comparison with large eddy simulations are presently underway.

7. Contracts and Grants with Industry

7.1. Contracts with Industry

Ongoing in 2010:

- A 3-year contract with EDF: project MeCSiCo (coupling methods for the simulation of river flows): see 4.4
- A 3-year contract with ADEME on the thematic "Stochastic Downscaling Method": see 6.8.
- A 2-year (2009-2010) contract with CNES on the thematic "development of the tangent and adjoint models for NEMO": see 6.3.1
- A 1-year contract with Alyotech on the thematic “Integration of the AGRIF software in the HYCOM ocean model": see 5.1

8. Other Grants and Activities

8.1. Regional Initiatives

- E.Blayo is responsible for the workpackage "numerical modelling" within the regional project (Région Rhône-Alpes) "**Envirhonalp**".
- E. Blayo is a member of the scientific committee of the regional Institut des Sciences Complexes (IXXI).
- E. Blayo is a member of the scientific committee of the Pole Grenoblois des Risques Naturels.

8.1.1. Collaborations with Various Regional Research Teams

- LEGI, MEOM team : 6.1.2,6.2.1,6.3.1,6.4.1.
- CERFACS 6.3.1.
- LGGE Grenoble, Edge team (C. Ritz, O. Gagliardini), see paragraph 6.5.2.

8.2. National Initiatives

8.2.1. Interactions with other INRIA Project-Teams or Actions

Participants	**INRIA Project-Team**	**Research topic**	**Link**
A. Rousseau	TOSCA	Stochastic Downscaling Method	6.8
C.Prieur	GRAAL	Grid deployment for the study of West African Monsoon	6.6
L.Debreu, E.Blayo	CLIME, FLUMINANCE	Multiscale data assimilation	
A. Vidard F.X. Le Dimet	CLIME, FLUMINANCE	Image assimilation	6.4
A. Vidard	TROPICS	Ocean Adjoint Modelling	6.3.1

8.2.2. Collaborations with other Research Teams in France

Participants	Research Team	Research topic	Link
M. Nodet	Laboratoire Dieudonné (Université de Nice)	BFN data assimilation scheme	6.2.1
C. Prieur	IMT Toulouse, IFP Rueil, EDF, CEA Cadarache	Sensitivity analysis	6.6.2
C. Prieur	ISFA Lyon 1, UniversitÃ© de Bourgogne	Multivariate risk indicators	6.7
C. Prieur	LGGE	Statistical methodology	6.6.2
A. Rousseau	Institut de Mathématiques et de Modélisation de Montpellier (I3M)	Modelling and simulation of coastal flows	6.1
A. Rousseau	Mathématiques et Applications, Physique Mathématique d'Orléans (MAPMO)	Quasi-hydrostatic models in geophysical fluid dynamics	6.1
A. Rousseau	Laboratoire de Météorologie Dynamique (Ecole Polytechnique), Centre d'Études Techniques de l'Équipement (Clermont-Ferrand)	Stochastic Downscaling Method	6.8
E.Blayo, A.Rousseau	LAMFA (Amiens), LAGA (Paris 13), IFREMER (Brest)	Coupling methods	6.1.2
A. Vidard	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (Toulouse), Mercator-Océan (Toulouse), Laboratoire de Physique des Océans (Brest),	Ocean Data Assimilation	6.3.1
A. Vidard	LOCEAN (Paris)	Ocean Adjoint Modelling	6.3.1

8.2.3. Participation to National Research Groups (GdR) CNRS

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

8.2.4. Other National Actions

- C. Kazantsev is the Director of the Grenoble branch of the national Research Institute for Mathematics Teaching http://www-irem.ujf-grenoble.fr/irem/accueil/.
- E. Blayo is the co-chair (with M. Bocquet, EPI CLIME) of the CNRS-INSU research program on data assimilation LEFE-ASSIM. http://www.insu.cnrs.fr/co/lefe/assim
- M. Nodet and D. Auroux are involved in J. Blum's project "Un nouvel observateur: le back and forth nudging (BFN) - Études théoriques, numériques et applications" supported by INSU-LEFE.
- A. Vidard leads a group of projects gathering multiple partners in France and UK on the topic "Variational Data Assimilation for the NEMO/OPA9 Ocean Model", see 6.3.1. This project is granted by two INSU-LEFE and a Mercator-Ocean calls for proposals
- A. Vidard is coordinator of the ANR VODA (Variational Ocean Data Assimilation for multi-scales applications) 4-year contract.
- L. Debreu is the coordinator of the national group COMODO (Numerical Models in Oceanography)
- L. Debreu organized a 3-day meeting on numerical ocean modelling (Autrans, March 2010)

MOISE team is implied in:

- A 4-year ANR contract: ANR ADAGe (Adjoint ice flow models for Data Assimilation in Glaciology, see paragraph 6.5.2) .
- A 4-year ANR contract: ANR Geo-FLUIDS (Fluid flows analysis and simulation from image sequences: application to the study of geophysical flows, see paragraph 6.4) .
- A 4-year ANR contract: ANR COSTA-BRAVA (Complex Spatio-Temporal Dynamics Analysis by Reduced Models and Sensitivity Analysis)http://www.math.univ-toulouse.fr/COSTA_BRAVA/index.html
- AST & Risk ANR project (white project selected in 2008). http://isfaserveur.univ-lyon1.fr/asterisk/
- A 12 months contract with IFREMER on the thematic "Numerical Methods in Ocean Modelling". 6.1.3
- A 3 years ANR contract: ANR MSDAG (Multiscale Data Assimilation in Geophysics) see paragraph 6.2.3)

8.3. European Initiatives

- M. Nodet is involved in European GDR CONEDP (Control of Partial Differential Equation).
- C. Prieur is implied in the IAP project on Statistical Analysis of Association and Dependence in Complex Data. The IAP research network in statistics is a network of 9 research teams 9. Five of them are Belgian and 4 are European, non-Belgian teams. http://www.stat.ucl.ac.be/IAP/PhaseVI/description.html
- F.-X. Le Dimet collaborates with I. Gejadze (Dept. of Civil Engineering, University of Strathclyde, Scotland) and V. Shutyaev (Institute of Numerical Mathematics, Russian Academy of Sciences) on propagation and control of the error in data assimilation and on evaluation of error covariance by deterministic method.
- A. Vidard collaborates with ECMWF (Reading, UK) on the development of a variational data assimilation system for the NEMO ocean model.
- A. Vidard, F.-X. Le Dimet, E. BLayo and I. Souopgui are part of the ADAMS associated team and the ECO-NET project ADOMENO, both co-led by A. Vidard and E. Huot (CLIME project team). They gather scientists from INRIA (MOISE and CLIME), MHI (Sevastopol, Ukraine), INM (Moscow, Russia) and MNI (Tbilissi, Georgia) and aim at developing advanced data assimilation methods applied to the Black Sea.

8.4. International Initiatives

- M. Nodet and A. Vidard developed a collaboration with K. Ide (University of Maryland, formerly UCLA) about Lagrangian and Images data assimilation, see paragraph 6.3.2 et 6.4.
- C. Prieur collaborates with Antonio Galves (University Sao Paulo) and Jose R. Leon (UCV, Central University of Caracas). She is a member of a USP-COFECUB project on the study of stochastic models with variable length memory (2010-2013) with University of Sao Paulo.
- L. Debreu, F.X. Le Dimet, A Vidard O. Titaud, E. Neveu and I. Souopgui are involved in the international project ADDISAAF (ADDISA for Africa), coordinated by E . Kamgnia (University of Yaoundé I) and I. Herlin (INRIA Clime). Other partner is: Ecole Nationale d'Ingénieurs de Tunis, Tunisia.
- E.Blayo, L.Debreu, M. Nodet and A. Rousseau participate to the INRIA Program “Equipes associées", creating the joint team NMOM (Numerical Methods for Ocean Modelling) with UCLA, Department of Atmospheric and Oceanic Sciences (J.McWilliams), and CICESE, Ensenada (J. Scheinbaum).

- E.Blayo, F.-X. Le Dimet, I. Souopgui and A. Vidard participate to the INRIA Program “Equipes associées", within the joint team ADAMS (Méthodes avancées d’assimilation des données de la Mer) with MHI, Ukraine (G.Korotaev), INM, Russia, (V.Shutyaev) and M.Nodia Geophysical Institute, Georgia, (A. Kordzadze).
- There also exists a strong cooperation on this theme with China (Institute of Atmospheric Physics of the Chinese A.S.) and Vietnam (Institute of Mathematics and Institute of Mechanics of the Vietnamese A.S.).

9. Dissemination

9.1. Animation of the scientific community

- The members of the team have participated to various conferences and workshops (see the bibliography).
- A. Rousseau (until July) and C. Kazantsev (since then) are in charge of EDP/MOISE fortnightly seminar, see http://ljk.imag.fr/MOISE/Seminaires/seminaires.php. This seminar generally features a talk from either a member of the team, or scientists working on subjects of interest for us, especially physicists from Rhône-Alpes region.
- M. Nodet gave a talk to the National Conference of Mathematics Teachers (APMEP) on the basics of Numerical Weather Prediction.
- A. Rousseau participated in a career fair at MIT with C. Puech, A. Theis-Viémont and E. Chareyre (INRIA). The *European Career Fair* is an annual recruiting event, organized by the MIT European Club, that connects employers from Europe with the most talented candidates that live in the US. Some candidates they met at MIT joined INRIA teams in 2009.
- A. Rousseau is part of the *wide audience group* at the french SMAI, and manned the mathematical stand of the 2010 "Salon de l’Education" in Paris.
- A. Rousseau participated with 1000 French scientists to the publication "1000 chercheurs parlent d’avenir", see [54] and http://www.maraval.org/spip.php?article237.
- E. Blayo and A. Vidard gave, in collaboration with E. Cosme (LEGI), a doctoral one-week course on data assimilation. 40 participants, January 2010. http://www-meom.hmg.inpg.fr/Web/pages-perso/Cosme/info_cours_AD2010.html
- E. Blayo, A. Vidard and A. Pierson have organized, in collaboration with E. Cosme (LEGI), the 3rd French national conference on data assimilation. 100 participants, Grenoble, December 9-10, 2010. http://sama.ipsl.jussieu.fr/Fr/events/workshops/2010_12_09_CNA2010.html
- E. Blayo, L. Debreu, F.-X. Le Dimet and A. Vidard organized and gave lectures to the CIMPA school on data assimilation in Wuhan, China http://www.cimpa-icpam.org/spip.php?article209
- L. Debreu is a member of the scientific committee of Mercator Ocean (French national program for operational oceanography)

9.2. Teaching

9.2.1. Teaching at Grenoble University

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

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