Activity Report 2015

Team AIRSEA

mathematics and computing applied to oceanic and atmospheric flows

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Earth, Environmental and Energy Sciences

Table of contents

Team AIRSEA

Creation of the Team: 2015 January 01

Keywords:

Computer Science and Digital Science:

3.1.8. - Big data (production, storage, transfer)
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.4. - Statistical methods
6.2.6. - Optimization
6.2.7. - High performance computing
6.3.1. - Inverse problems
6.3.2. - Data assimilation
6.3.4. - Model reduction
7.1. - Parallel and distributed algorithms

Other Research Topics and Application Domains:

3.2. - Climate and meteorology
3.3.2. - Water: sea & ocean, lake & river
3.3.4. - Atmosphere
3.4.1. - Natural risks
4.2.2. - Hydro-energy
4.2.3. - Wind energy
9.9.1. - Environmental risks

1. Members

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Céline Hartweg [Univ. Lyon I, Associate Professor]
Gurvan Madec [CNRS, LOCEAN/Paris,Senior Researcher]
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2. Overall Objectives

2.1. Overall Objectives

The general scope of the AIRSEA project-team is to develop *mathematical and computational methods for the modeling of oceanic and atmospheric flows*. The mathematical tools used involve both *deterministic and statistical approaches*. The main research topics cover a) modeling and coupling b) model reduction for sensitivity analysis, coupling and multiscale optimizations c) sensitivity analysis, parameter estimation and risk assessment d) algorithms for high performance computing. The range of application is from climate modeling to the prediction of extreme events.

3. Research Program

3.1. Introduction

Recent events have raised questions regarding the social and economic implications of anthropic alterations of the Earth system, i.e. climate change and the associated risks of increasing extreme events. Ocean and atmosphere, coupled with other components (continent and ice) are the building blocks of the Earth system. A better understanding of the ocean atmosphere system is a key ingredient for improving prediction of such events. Numerical models are essential tools to understand processes, and simulate and forecast events at various space and time scales. Geophysical flows generally have a number of characteristics that make it difficult to model them. This justifies the development of specifically adapted mathematical methods:

- Geophysical flows are strongly non-linear. Therefore, they exhibit interactions between different scales, and unresolved small scales (smaller than mesh size) of the flows have to be **parameterized** in the equations.
- Geophysical fluids are non closed systems. They are open-ended in their scope for including and dynamically coupling different physical processes (e.g., atmosphere, ocean, continental water, etc). **Coupling** algorithms are thus of primary importance to account for potentially significant feedback.
- Numerical models contain parameters which cannot be estimated accurately either because they are difficult to measure or because they represent some poorly known subgrid phenomena. There is thus a need for **dealing with uncertainties**. This is further complicated by the turbulent nature of geophysical fluids.
- The computational cost of geophysical flow simulations is huge, thus requiring the use of **reduced models, multiscale methods** and the design of algorithms ready for **high performance computing** platforms.

Our scientific objectives are divided into four major points. The first objective focuses on developing advanced mathematical methods for both the ocean and atmosphere, and the coupling of these two components. The second objective is to investigate the derivation and use of model reduction to face problems associated with the numerical cost of our applications. The third objective is directed toward the management of uncertainty in numerical simulations. The last objective deals with efficient numerical algorithms for new computing platforms. As mentioned above, the targeted applications cover oceanic and atmospheric modeling and related extreme events using a hierarchy of models of increasing complexity.

3.2. Modeling for oceanic and atmospheric flows

Current numerical oceanic and atmospheric models suffer from a number of well-identified problems. These problems are mainly related to lack of horizontal and vertical resolution, thus requiring the parameterization of unresolved (subgrid scale) processes and control of discretization errors in order to fulfill criteria related to the particular underlying physics of rotating and strongly stratified flows. Oceanic and atmospheric coupled models are increasingly used in a wide range of applications from global to regional scales. Assessment of the reliability of those coupled models is an emerging topic as the spread among the solutions of existing models (e.g., for climate change predictions) has not been reduced with the new generation models when compared to the older ones.

Advanced methods for modeling 3D rotating and stratified flows The continuous increase of computational power and the resulting finer grid resolutions have triggered a recent regain of interest in numerical methods and their relation to physical processes. Going beyond present knowledge requires a better understanding of numerical dispersion/dissipation ranges and their connection to model fine scales. Removing the leading order truncation error of numerical schemes is thus an active topic of research and each mathematical tool has to adapt to the characteristics of three dimensional stratified and rotating flows. Studying the link between discretization errors and subgrid scale parameterizations is also arguably one of the main challenges.

Complexity of the geometry, boundary layers, strong stratification and lack of resolution are the main sources of discretization errors in the numerical simulation of geophysical flows. This emphasizes the importance of the definition of the computational grids (and coordinate systems) both in horizontal and vertical directions, and the necessity of truly multi resolution approaches. At the same time, the role of the small scale dynamics on large scale circulation has to be taken into account. Such parameterizations may be of deterministic as well as stochastic nature and both approaches are taken by the AIRSEA team. The design of numerical schemes consistent with the parameterizations is also arguably one of the main challenges for the coming years. This work is complementary and linked to that on parameters estimation described in 3.4.

Ocean Atmosphere interactions and formulation of coupled models State-of-the-art climate models (CMs) are complex systems under continuous development. A fundamental aspect of climate modeling is the representation of air-sea interactions. This covers a large range of issues: parameterizations of atmospheric and oceanic boundary layers, estimation of air-sea fluxes, time-space numerical schemes, non conforming grids, coupling algorithms ...Many developments related to these different aspects were performed over the last 10-15 years, but were in general conducted independently of each other.

The aim of our work is to revisit and enrich several aspects of the representation of air-sea interactions in CMs, paying special attention to their overall consistency with appropriate mathematical tools. We intend to work consistently on the physics and numerics. Using the theoretical framework of global-in-time Schwarz methods, our aim is to analyze the mathematical formulation of the parameterizations in a coupling perspective. From this study, we expect improved predictability in coupled models (this aspect will be studied using techniques described in 3.4). Complementary work on space-time nonconformities and acceleration of convergence of Schwarz-like iterative methods (see 7.1.1) are also conducted.

3.3. Model reduction / multiscale algorithms

The high computational cost of the applications is a common and major concern to have in mind when deriving new methodological approaches. This cost increases dramatically with the use of sensitivity analysis or parameter estimation methods, and more generally with methods that require a potentially large number of model integrations.

A dimension reduction, using either stochastic or deterministic methods, is a way to reduce significantly the number of degrees of freedom, and therefore the calculation time, of a numerical model.

Model reduction Reduction methods can be deterministic (proper orthogonal decomposition, other reduced bases) or stochastic (polynomial chaos, Gaussian processes, kriging), and both fields of research are very active. Choosing one method over another strongly depends on the targeted application, which can be as varied as real-time computation, sensitivity analysis (see e.g., section 7.3.1) or optimisation for parameter estimation (see below).

Our goals are multiple, but they share a common need for certified error bounds on the output. Our team has a 4-year history of working on certified reduction methods and has a unique positioning at the interface between deterministic and stochastic approaches. Thus, it seems interesting to conduct a thorough comparison of the two alternatives in the context of sensitivity analysis. Efforts will also be directed toward the development of efficient greedy algorithms for the reduction, and the derivation of goal-oriented sharp error bounds for non linear models and/or non linear outputs of interest. This will be complementary to our work on the deterministic reduction of parametrized viscous Burgers and Shallow Water equations where the objective is to obtain sharp error bounds to provide confidence intervals for the estimation of sensitivity indices.

Reduced models for coupling applications Global and regional high-resolution oceanic models are either coupled to an atmospheric model or forced at the air-sea interface by fluxes computed empirically preventing proper physical feedback between the two media. Thanks to high-resolution observational studies, the existence of air-sea interactions at oceanic mesoscales (i.e., at $\mathcal{O}(1km)$ scales) have been unambiguously shown. Those interactions can be represented in coupled models only if the oceanic and atmospheric models are run on the same high-resolution computational grid, and are absent in a forced mode. Fully coupled models at high-resolution are seldom used because of their prohibitive computational cost. The derivation of a reduced model as an alternative between a forced mode and the use of a full atmospheric model is an open problem.

Multiphysics coupling often requires iterative methods to obtain a mathematically correct numerical solution. To mitigate the cost of the iterations, we will investigate the possibility of using reduced-order models for the iterative process. We will consider different ways of deriving a reduced model: coarsening of the resolution, degradation of the physics and/or numerical schemes, or simplification of the governing equations. At a mathematical level, we will strive to study the well-posedness and the convergence properties when reduced models are used. Indeed, running an atmospheric model at the same resolution as the ocean model is generally too expensive to be manageable, even for moderate resolution applications. To account for important fine-scale interactions in the computation of the air-sea boundary condition, the objective is to derive a simplified boundary layer model that is able to represent important 3D turbulent features in the marine atmospheric boundary layer.

Reduced models for multiscale optimization The field of multigrid methods for optimisation has known a tremendous development over the past few decades. However, it has not been applied to oceanic and atmospheric problems apart from some crude (non-converging) approximations or applications to simplified and low dimensional models. This is mainly due to the high complexity of such models and to the difficulty in handling several grids at the same time. Moreover, due to complex boundaries and physical phenomena, the grid interactions and transfer operators are not trivial to define.

Multigrid solvers (or multigrid preconditioners) are efficient methods for the solution of variational data assimilation problems. We would like to take advantage of these methods to tackle the optimization problem in high dimensional space. High dimensional control space is obtained when dealing with parameter fields estimation, or with control of the full 4D (space time) trajectory. It is important since it enables us to take into account model errors. In that case, multigrid methods can be used to solve the large scales of the problem at a lower cost, this being potentially coupled with a scale decomposition of the variables themselves.

3.4. Dealing with uncertainties

There are many sources of uncertainties in numerical models. They are due to imperfect external forcing, poorly known parameters, missing physics and discretization errors. Studying these uncertainties and their impact on the simulations is a challenge, mostly because of the high dimensionality and non-linear nature of the systems. To deal with these uncertainties we work on three axes of research, which are linked: sensitivity analysis, parameter estimation and risk assessment. They are based on either stochastic or deterministic methods.

Sensitivity analysis Sensitivity analysis (SA), which links uncertainty in the model inputs to uncertainty in the model outputs, is a powerful tool for model design and validation. First, it can be a pre-stage for parameter estimation (see 3.4), allowing for the selection of the more significant parameters. Second, SA permits understanding and quantifying (possibly non-linear) interactions induced by the different processes defining e.g., realistic ocean atmosphere models. Finally SA allows for validation of models, checking that the estimated sensitivities are consistent with what is expected by the theory. On ocean, atmosphere and coupled systems, only first order deterministic SA are performed, neglecting the initialization process (data assimilation). AIRSEA members and collaborators proposed to use second order information to provide consistent sensitivity measures, but so far it has only been applied to simple academic systems. Metamodels are now commonly used, due to the cost induced by each evaluation of complex numerical models: mostly Gaussian processes, whose probabilistic framework allows for the development of specific adaptive designs, and polynomial chaos not only in the context of intrusive Galerkin approaches but also in a black-box approach. Until recently, global SA was based primarily on a set of engineering practices. New mathematical and methodological developments have led to the numerical computation of Sobol' indices, with confidence intervals assessing for both metamodel and estimation errors. Approaches have also been extended to the case of dependent entries, functional inputs and/or output and stochastic numerical codes. Other types of indices and generalizations of Sobol' indices have also been introduced.

Concerning the stochastic approach to SA we plan to work with parameters that show spatio-temporal dependencies and to continue toward more realistic applications where the input space is of huge dimension with highly correlated components. Sensitivity analysis for dependent inputs also introduces new challenges. In our applicative context, it would seem prudent to carefully learn the spatio-temporal dependences before running a global SA. In the deterministic framework we focus on second order approaches where the sought sensitivities are related to the optimality system rather than to the model; i.e., we consider the whole forecasting system (model plus initialization through data assimilation).
All these methods allow for computing sensitivities and more importantly a posteriori error statistics.

Parameter estimation Advanced parameter estimation methods are barely used in ocean, atmosphere and coupled systems, mostly due to a difficulty of deriving adequate response functions, a lack of knowledge of these methods in the ocean-atmosphere community, and also to the huge associated computing costs. In the presence of strong uncertainties on the model but also on parameter values, simulation and inference are

closely associated. Filtering for data assimilation and Approximate Bayesian Computation (ABC) are two examples of such association.
Stochastic approach can be compared with the deterministic approach, which allows to determine the sensitivity of the flow to parameters and optimize their values relying on data assimilation. This approach is already shown to be capable of selecting a reduced space of the most influent parameters in the local parameter space and to adapt their values in view of correcting errors committed by the numerical approximation. This approach assumes the use of automatic differentiation of the source code with respect to the model parameters, and optimization of the obtained raw code.

AIRSEA assembles all the required expertise to tackle these difficulties. As mentioned previously, the choice of parameterization schemes and their tuning has a significant impact on the result of model simulations. Our research will focus on parameter estimation for parameterized Partial Differential Equations (PDEs) and also for parameterized Stochastic Differential Equations (SDEs). Deterministic approaches are based on optimal control methods and are local in the parameter space (i.e., the result depends on the starting point of the estimation) but thanks to adjoint methods they can cope with a large number of unknowns that can also vary in space and time. Multiscale optimization techniques as described in 7.2.2 will be one of the tools used. This in turn can be used either to propose a better (and smaller) parameter set or as a criterion for discriminating parameterization schemes. Statistical methods are global in the parameter state but may suffer from the curse of dimensionality. However, the notion of parameter can also be extended to functional parameters. We may consider as parameter a functional entity such as a boundary condition on time, or a probability density function in a stationary regime. For these purposes, non-parametric estimation will also be considered as an alternative.

Risk assessment Risk assessment in the multivariate setting suffers from a lack of consensus on the choice of indicators. Moreover, once the indicators are designed, it still remains to develop estimation procedures, efficient even for high risk levels. Recent developments for the assessment of financial risk have to be considered with caution as methods may differ pertaining to general financial decisions or environmental risk assessment. Modeling and quantifying uncertainties related to extreme events is of central interest in environmental sciences. In relation to our scientific targets, risk assessment is very important in several areas: hydrological extreme events, cyclone intensity, storm surges...Environmental risks most of the time involve several aspects which are often correlated. Moreover, even in the ideal case where the focus is on a single risk source, we have to face the temporal and spatial nature of environmental extreme events. The study of extremes within a spatio-temporal framework remains an emerging field where the development of adapted statistical methods could lead to major progress in terms of geophysical understanding and risk assessment thus coupling data and model information for risk assessment.

Based on the above considerations we aim to answer the following scientific questions: how to measure risk in a multivariate/spatial framework? How to estimate risk in a non stationary context? How to reduce dimension (see 3.3) for a better estimation of spatial risk?

Extreme events are rare, which means there is little data available to make inferences of risk measures. Risk assessment based on observation therefore relies on multivariate extreme value theory. Interacting particle systems for the analysis of rare events is commonly used in the community of computer experiments. An open question is the pertinence of such tools for the evaluation of environmental risk.
Most numerical models are unable to accurately reproduce extreme events. There is therefore a real need to develop efficient assimilation methods for the coupling of numerical models and extreme data.

3.5. High performance computing

Methods for sensitivity analysis, parameter estimation and risk assessment are extremely costly due to the necessary number of model evaluations. This number of simulations require considerable computational resources, depends on the complexity of the application, the number of input variables and desired quality of approximations. To this aim, the AIRSEA team is an intensive user of HPC computing platforms, particularly grid computing platforms. The associated grid deployment has to take into account the scheduling of a huge number of computational requests and the links with data-management between these requests, all of these as automatically as possible. In addition, there is an increasing need to propose efficient numerical algorithms specifically designed for new (or future) computing architectures and this is part of our scientific objectives. According to the computational cost of our applications, the evolution of high performance computing platforms has to be taken into account for several reasons. While our applications are able to exploit space parallelism to its full extent (oceanic and atmospheric models are traditionally based on a spatial domain decomposition method), the spatial discretization step size limits the efficiency of traditional parallel methods. Thus the inherent parallelism is modest, particularly for the case of relative coarse resolution but with very long integration time (e.g., climate modeling). Paths toward new programming paradigms are thus needed. As a step in that direction, we plan to focus our research on parallel in time methods.

New numerical algorithms for high performance computing Parallel in time methods can be classified into three main groups. In the first group, we find methods using parallelism across the method, such as parallel integrators for ordinary differential equations. The second group considers parallelism across the problem. Falling into this category are methods such as waveform relaxation where the space-time system is decomposed into a set of subsystems which can then be solved independently using some form of relaxation techniques or multigrid reduction in time. The third group of methods focuses on parallelism across the steps. One of the best known algorithms in this family is parareal. Other methods combining the strengths of those listed above (e.g., PFASST) are currently under investigation in the community.

Parallel in time methods are iterative methods that may require a large number of iteration before convergence. Our first focus will be on the convergence analysis of parallel in time (Parareal / Schwarz) methods for the equation systems of oceanic and atmospheric models. Our second objective will be on the construction of fast (approximate) integrators for these systems. This part is naturally linked to the model reduction methods of section (7.2). Fast approximate integrators are required both in the Schwarz algorithm (where a first guess of the boundary conditions is required) and in the Parareal algorithm (where the fast integrator is used to connect the different time windows). Our main application of these methods will be on climate (i.e., very long time) simulations. Our second application of parallel in time methods will be in the context of optimization methods. In fact, one of the major drawbacks of the optimal control techniques used in 3.4 is a lack of intrinsic parallelism in comparison with ensemble methods. Here, parallel in time methods also offer ways to better efficiency. The mathematical key point is centered on how to efficiently couple two iterative methods (i.e., parallel in time and optimization methods).

4. Application Domains

4.1. The Ocean-Atmosphere System

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) or the prediction of **floods**.

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 AIRSEA 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.

5. Highlights of the Year

5.1. Highlights of the Year

Early 2015 AIRSEA team succeed MOISE in developing of *mathematical and computational methods for the modeling of oceanic and atmospheric flows*.

The substantial changes compared to the scientific objectives of the MOISE team include a redefinition of the domains of applications now centered on oceanic and atmospheric modeling (the latter is a new target application for the team), the increased focus on statistical methods and hybrid deterministic/statistical approaches, as well as an emphasis on the development of numerical algorithms for high performance computing.

5.1.1. Awards

Clémentine Prieur was awarded by the Prix Blaise Pascal of GAMNI-SMAI.

Jose R. Leon was granted by an International Inria Chair.

6. New Software and Platforms

6.1. AGRIF

Adaptive Grid Refinement In Fortran
FUNCTIONAL DESCRIPTION

AGRIF 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.

- Participants: Laurent Debreu, Marc Honnorat
- Contact: Laurent Debreu
- URL: http://www-ljk.imag.fr/MOISE/AGRIF

6.2. BALAISE

Bilbliothèque d'Assimilation Lagrangienne Adaptée aux Images Séquencées en Environnement
KEYWORDS: Multi-scale analysis - Data assimilation - Optimal control
FUNCTIONAL DESCRIPTION

BALAISE (Bilbliothèque d'Assimilation Lagrangienne Adaptée aux Images Séquencées en Environnement) is a test bed for image data assimilation. It includes a shallow water model, a multi-scale decomposition library and an assimilation suite.

- Contact: Arthur Vidard

6.3. NEMOVAR

Variational data assimilation for NEMO

KEYWORDS: Oceanography - Data assimilation - Adjoint method - Optimal control

FUNCTIONAL DESCRIPTION

NEMOVAR is a state-of-the-art multi-incremental variational data assimilation system with both 3D and 4D capabilities, and which is designed to work with NEMO on the native ORCA grids. The background error covariance matrix is modelled using balance operators for the multivariate component and a diffusion operator for the univariate component. It can also be formulated as a linear combination of covariance models to take into account multiple correlation length scales associated with ocean variability on different scales. NEMOVAR has recently been enhanced with the addition of ensemble data assimilation and multi-grid assimilation capabilities. It is used operationnaly in both ECMWF and the Met Office (UK)

- Partners: CERFACS - ECMWF - Met Office
- Contact: Arthur Vidard

6.4. Sensitivity

FUNCTIONAL DESCRIPTION

This package is useful for conducting sensitivity analysis of complex computer codes.

- Contact: Laurent Gilquin
- URL: https://cran.r-project.org/web/packages/sensitivity/index.html

7. New Results

7.1. Modeling for Oceanic and Atmospheric flows

7.1.1. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, Mehdi-Pierre Daou, Laurent Debreu, Florian Lemarié, Charles Pelletier, Antoine Rousseau.

7.1.1.1. Coupling heterogeneous models in hydrodynamics

The coupling of models of different kinds is gaining more and more attention, due in particular to a need for more global modeling systems encompassing different disciplines (e.g. multi-physics) and different approaches (e.g. multi-scale, nesting). In order to develop such complex systems, it is generally more pragmatic to assemble different modeling units inside a user friendly modelling software platform rather than to develop new complex global models.

In the context of hydrodynamics, global modeling systems have to couple models of different dimensions (1D, 2D or 3D) and representing different physics (Navier-Stokes, hydrostatic Navier-Stokes, shallow water…). We have been developing coupling approaches for several years, based on so-called Schwarz algorithms. Our recent contributions address the development of absorbing boundary conditions for Navier-Stokes equations [1], and of interface conditions for coupling hydrostatic and nonhydrostatic Navier-Stokes flows [2]. In the context of our partnership with with ARTELIA Group (PhD thesis of Medhi Pierre Daou), implementations of Schwarz coupling algorithms have been performed for hydrodynamics industrial codes (Mascaret, Telemac and OpenFoam), using the PALM coupling software. A first implementation has been realized in an academic test case, and a second one is presently under implementation in a much more realistic context.

7.1.1.2. Ocean-atmosphere coupling

Coupling methods routinely used in regional and global climate models do not provide the exact solution to the ocean-atmosphere problem, but an approximation of one [12]. For the last few years we have been actively working on the analysis of Schwarz waveform relaxation to apply this type of iterative coupling method to air-sea coupling [59], [60], [58]. In the context of the simulation of tropical cyclone, sensitivity tests to the coupling method have been carried out using ensemble simulations (through perturbations of the coupling frequency and initial conditions). We showed that the use of the Schwarz iterative coupling methods leads to a significantly reduced spread in the ensemble results (in terms of cyclone trajectory and intensity), thus suggesting that a source of error is removed w.r.t coupling methods en vogue in existing coupled models [61].

Motivated by this encouraging result, our activities over the last year can be divided into three topics

1. *Stability and consistency analysis of existing coupling methods*: in [12] we showed that the usual methods used in the context of ocean-atmosphere coupling are prone to splitting errors because they correspond to only one iteration of an iterative process without reaching convergence. Moreover, those methods have an additional condition for the coupling to be stable even if unconditionally stable time stepping algorithms are used.
2. *Study of physics-dynamics coupling*: during the PhD-thesis of Charles Pelletier (funded by Inria) the scope is on including the formulation of physical parameterizations in the theoretical analysis of the coupling. The first months of this Ph-D were dedicated to the study of the parameterization schemes to compute air-sea fluxes. A thorough sensitivity analysis showed that several parameters within existing schemes have no influence on the resulting fluxes. A simplified scheme retaining most the complexity of complicated parameterizations has thus been designed. This new scheme has also the advantage to be more adequate to conduct the mathematical analysis of the coupling.
3. *Design of a coupled single column model*: in order to focus on specific problems of ocean-atmosphere coupling, a work on simplified equation sets has been started. The aim is to implement a one-dimensional (in the vertical direction) coupled model with physical parameterizations representative of those used in realistic models. Thanks to this simplified coupled model the objective is to develop a benchmark suite for coupled models evaluation.

These three topics are addressed through strong collaborations between the applied mathematics and the climate community As an illustration, the PhD-thesis of Charles Pelletier is in collaboration with the LSCE (Laboratoire des Sciences du Climat et de l'Environnement).

Moreover a PPR (*Projet à partenariat renforcé*) called SIMBAD (SIMplified Boundary Atmospheric layer moDel for ocean modeling purposes) is funded by Mercator-Ocean for the next three years (from march 2015 to march 2018). The aim of this project in collaboration with Meteo-France, Ifremer, LMD, and LOCEAN is to derive a metamodel to force high-resolution oceanic operational models for which the use of a full atmospheric model is not possible due to a prohibitive computational cost.

7.1.1.3. Data assimilation for coupled models

In the context of operational meteorology and oceanography, forecast skills heavily rely on proper combination of model prediction and available observations via data assimilation techniques. Historically, numerical weather prediction is made separately for the ocean and the atmosphere in an uncoupled way. However, in recent years, fully coupled ocean-atmosphere models are increasingly used in operational centers to improve the reliability of seasonal forecasts and tropical cyclones predictions. For coupled problems, the use of separated data assimilation schemes in each medium is not satisfactory since the result of such assimilation process is generally inconsistent across the interface, thus leading to unacceptable artefacts. Hence, there is a strong need for adapting existing data assimilation techniques to the coupled framework. As part of our ERACLIM2 contribution, R. Pellerej started a PhD on that topic late 2014. So far, three general data assimilation algorithms, based on variational data assimilation techniques, have been developed and applied to a simple coupled problem. The dynamical equations of the considered problem are coupled using an iterative Schwarz domain decomposition method. The aim is to properly take into account the coupling in the assimilation process in order to obtain a coupled solution close to the observations while satisfying the physical conditions across the air-sea interface. Preliminary results shows significant improvement compared to the usual approach on this simple system.

7.1.2. Numerical Schemes for Ocean Modelling

Participants: Eric Blayo, Laurent Debreu, Florian Lemarié.

In 2015, we worked on the stability constraints for oceanic numerical models ([13]). The idea is to carry a deep analysis of these constraints in order to propose new time stepping algorithms for ocean models. Except for vertical diffusion (and possibly the external mode and bottom drag), oceanic models usually rely on explicit time-stepping algorithms subject to Courant-Friedrichs-Lewy (CFL) stability criteria. Implicit methods could be unconditionally stable, but an algebraic system must be solved at each time step and other considerations such as accuracy and efficiency are less straightforward to achieve. Depending on the target application, the process limiting the maximum allowed time-step is generally different. In this paper, we introduce offline diagnostics to predict stability limits associated with internal gravity waves, advection, diffusion, and rotation. This suite of diagnostics is applied to a set of global, regional and coastal numerical simulations with several horizontal/vertical resolutions and different numerical models. We show that, for resolutions finer that 1/2°, models with an Eulerian vertical coordinate are generally constrained by vertical advection in a few hot spots and that numerics must be extremely robust to changes in Courant number. Based on those results, we review the stability and accuracy of existing numerical kernels in vogue in primitive equations oceanic models with a focus on advective processes and the dynamics of internal waves. We emphasize the additional value of studying the numerical kernel of oceanic models in the light of coupled space-time approaches instead of studying the time schemes independently from spatial discretizations. From this study, we suggest some guidelines for the development of temporal schemes in future generation multi-purpose oceanic models.

The increase of model resolution naturally leads to the representation of a wider energy spectrum. As a result, in recent years, the understanding of oceanic submesoscale dynamics has significantly improved. However, dissipation in submesoscale models remains dominated by numerical constraints rather than physical ones. Effective resolution is limited by the numerical dissipation range, which is a function of the model numerical filters (assuming that dispersive numerical modes are efficiently removed). In [16], we present a Baroclinic Jet test case set in a zonally reentrant channel that provides a controllable test of a model capacity at resolving submesoscale dynamics. We compare simulations from two models, ROMS and NEMO, at different mesh sizes (from 20 to 2 km). Through a spectral decomposition of kinetic energy and its budget terms, we identify the characteristics of numerical dissipation and effective resolution. It shows that numerical dissipation appears in different parts of a model, especially in spatial advection-diffusion schemes for momentum equations (KE dissipation) and tracer equations (APE dissipation) and in the time stepping algorithms. Effective resolution, defined by scale-selective dissipation, is inadequate to qualify traditional ocean models with low-order spatial and temporal filters, even at high grid resolution. High- order methods are better suited to the concept and probably unavoidable. Fourth-order filters are suited only for grid resolutions less than a few kilometers and momentum advection schemes of even higher-order may be justified. The upgrade of time stepping algorithms (from filtered Leapfrog), a cumbersome task in a model, appears critical from our results, not just as a matter of model solution quality but also of computational efficiency (extended stability range of predictor-corrector schemes). Effective resolution is also shaken by the need for non scale-selective barotropic mode filters and requires carefully addressing the issue of mode splitting errors. Possibly the most surprising result is that submesoscale energy production is largely affected by spurious diapycnal mixing (APE dissipation). This result justifies renewed efforts in reducing tracer mixing errors and poses again the question of how much vertical diffusion is at work in the real ocean.

7.1.3. Better Parameterization of the Coastline for Ocean Models

Participants: Eric Blayo, Eugene Kazantsev, Florian Lemarié, Pierre Marchand.

We aim at the development of finer approximations of lateral boundaries and boundary conditions for NEMO, by investigating and comparing analytical and optimal control approaches.

Regarding the analytical approach, we focused on a 2D shallow water formulation, and revisited the properties of the energy and enstrophy conserving schemes in the presence of a coastline. This led us to highlight a number of problems with the enstrophy conserving scheme (sensitivity to the choice of a slip or a noslip boundary condition, non conservation of the enstrophy, numerical instability). We also proposed a corrected scheme near the boundary for the continuity equation and new values for ghost points derived from the energy conservation in order for the energy conserving scheme to take into account a coastline with some inclination with regard to the numerical grid. We also investigated the viscous case, and proposed an implementation of slip and no slip boundary conditions for the viscous term in such a case of an inclined coastline.

These results are under comparison with the optimal control approach 7.3.2 realised for the Nemo model in a similar configuration.

7.2. Model reduction / multiscale algorithms

7.2.1. Intrusive sensitivity analysis, reduced models

Participants: Maëlle Nodet, Clémentine Prieur.

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 [55], 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.

When a metamodel is used (for example reduced basis metamodel, but also kriging, regression, ...) for estimating sensitivity indices by Monte Carlo type estimation, a twofold error appears: a sampling error and a metamodel error. Deriving confidence intervals taking into account these two sources of uncertainties is of great interest. We obtained results particularly well fitted for reduced basis metamodels [56]. In [54], the authors provide asymptotic confidence intervals in the double limit where the sample size goes to infinity and the metamodel converges to the true model. These results were also adapted to problems related to more general models such as Shallow-Water equations, in the context of the control of an open channel [8].

Let us come back to the output of interest. Is it possible to get better error certification when the output is specified. A work in this sense has been accepted, dealing with goal oriented uncertainties assessment [7].

A collaboration has been started with Christophe Prieur (Gipsa-Lab) on the very challenging issue of sensitivity of a controlled system to its control parameters [8].

7.2.2. Multigrid Methods for Variational Data Assimilation.

Participants: Laurent Debreu, François-Xavier Le Dimet, Arthur Vidard.

In order to lower the computational cost of the variational data assimilation process, we investigate the use of multigrid methods to solve the associated optimal control system. On a linear advection equation, we study the impact of the regularization term on the optimal control and the impact of discretization errors on the efficiency of the coarse grid correction step. We show that even if the optimal control problem leads to the solution of an elliptic system, numerical errors introduced by the discretization can alter the success of the multigrid methods. The view of the multigrid iteration as a preconditioner for a Krylov optimization method leads to a more robust algorithm. A scale dependent weighting of the multigrid preconditioner and the usual background error covariance matrix based preconditioner is proposed and brings significant improvements. This work is summarized in ([5]).

7.3. Dealing with uncertainties

7.3.1. Sensitivity Analysis for Forecasting Ocean Models

Participants: Eric Blayo, Laurent Gilquin, Céline Helbert, François-Xavier Le Dimet, Elise Arnaud, Simon Nanty, Maëlle Nodet, Clémentine Prieur, Laurence Viry, Federico Zertuche.

7.3.1.1. Scientific context

Forecasting geophysical 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.

7.3.1.2. Estimating sensitivity indices

A first task is to develop tools for estimated sensitivity indices. In variance-based sensitivity analysis, a classical tool is the method of Sobol' [68] which allows to compute Sobol' indices using Monte Carlo integration. One of the main drawbacks of this approach is that the estimation of Sobol' indices requires the use of several samples. For example, in a d-dimensional space, the estimation of all the first-order Sobol' indices requires $d+1$ samples. Some interesting combinatorial results have been introduced to weaken this defect, in particular by Saltelli [66] and more recently by Owen [64] but the quantities they estimate still require $O(d)$ samples.

In a recent work [71] we introduce a new approach to estimate all first-order Sobol' indices by using only two samples based on replicated latin hypercubes and all second-order Sobol' indices by using only two samples based on replicated randomized orthogonal arrays. We establish theoretical properties of such a method for the first-order Sobol' indices and discuss the generalization to higher-order indices. As an illustration, we propose to apply this new approach to a marine ecosystem model of the Ligurian sea (northwestern Mediterranean) in order to study the relative importance of its several parameters. The calibration process of this kind of chemical simulators is well-known to be quite intricate, and a rigorous and robust — i.e. valid without strong regularity assumptions — sensitivity analysis, as the method of Sobol' provides, could be of great help. The computations are performed by using CIGRI, the middleware used on the grid of the Grenoble University High Performance Computing (HPC) center. We are also applying these estimates to calibrate integrated land use transport models. As for these models, some groups of inputs are correlated, Laurent Gilquin extended the approach based on replicated designs for the estimation of grouped Sobol' indices [6].

We can now wonder what are the asymptotic properties of these new estimators, or also of more classical ones. In [54], the authors deal with asymptotic properties of the estimators. In [52], the authors establish also a multivariate central limit theorem and non asymptotic properties.

7.3.1.3. 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 [53] in the case where input parameters are correlated. Clémentine Prieur supervised Gaëlle Chastaing's PhD thesis on the topic (defended in September 2013) [44]. We obtained first results [45], deriving a general functional ANOVA for dependent inputs, allowing defining new variance based sensitivity indices for correlated inputs. We then adapted various algorithms for the estimation of these new indices. These algorithms make the assumption that among the potential interactions, only few are significant. Two papers have been recently accepted [43], [46]. We also considered (see the paragraph 7.3.1) the estimation of groups Sobol' indices, with a procedure based on replicated designs. These indices provide information at the level of groups, and not at a finer level, but their interpretation is still rigorous.

Céline Helbert and Clémentine Prieur supervised the PhD thesis of Simon Nanty (funded by CEA Cadarache, and defended in October, 2015). The subject of the thesis is the analysis of uncertainties for numerical codes with temporal and spatio-temporal input variables, with application to safety and impact calculation studies. This study implied functional dependent inputs. A first step was the modeling of these inputs, and a paper has been submitted [63]. The whole methodology proposed during the PhD is under advanced revision [36].

7.3.1.4. Multy-fidelity modeling for risk analysis

Federico Zertuche's PhD concerns the modeling and prediction of a digital output from a computer code when multiple levels of fidelity of the code are available. A low-fidelity output can be obtained, for example on a coarse mesh. It is cheaper, but also much less accurate than a high-fidelity output obtained on a fine mesh. In this context, we propose new approaches to relieve some restrictive assumptions of existing methods ([57], [65]): a new estimation method of the classical cokriging model when designs are not nested and a nonparametric modeling of the relationship between low-fidelity and high-fidelity levels. The PhD takes place in the REDICE consortium and in close link with industry. The first part of the thesis was also dedicated to the development of a case study in fluid mechanics with CEA in the context of the study of a nuclear reactor.

The second part of the thesis was dedicated to the development of a new sequential approach based on a course to fine wavelets algorithm. Federico Zertuche presented his work at the annual meeting of the GDR Mascot Num in 2014 [72].

7.3.1.5. Data assimilation and second order sensitivity analysis

Basically, in the deterministic approach, a sensitivity analysis is the evaluation of a functional depending on the state of the system and of parameters. Therefore it is natural to introduce an adjoint model. In the framework of variational data assimilation the link between all the ingredients (observations, parameters and other inputs of the model is done through the optimality system (O.S.), therefore a sensitivity will be estimated by deriving the O.S. leading to a second order adjoint. This is done in the paper [15] in which a full second order analysis is carried out on a model of the Black Sea.

This methodology has been applied to

- **Oil Spill**. These last years have known several disasters produced by wrecking of ships and drifting platforms with severe consequences on the physical and biological environments. In order to minimize the impact of these oil spills its necessary to predict the evolution of oil spot. Some basic models are available and some satellites provide images on the evolution of oil spots. Clearly this topic is a combination of the two previous one: data assimilation for pollution and assimilation of images. A theoretical framework has been developed with Dr. Tran Thu Ha (iMech).
- **Data Assimilation in Supercavitation (with iMech)**. Some self propelled submarine devices can reach a high speed thanks to phenomenon of supercavitation: an air bubble is created on the nose of the device and reduces drag forces. Some models of supercavitation already exist but are working on two applications of variational methods to supercavitation:
  - Parameter identification : the models have some parameters that can not be directly measured. From observations we retrieve the unknown parameters using a classical formalism of inverse problems.
  - Shape Optimization. The question is to determine an optimum design of the shape of the engine in order to reach a maximum speed.

7.3.2. Optimal Control of Boundary Conditions

Participants: Christine Kazantsev, Eugene Kazantsev.

A variational data assimilation technique is applied to the identification of the optimal boundary conditions for a simplified configuration of the NEMO model. A rectangular box model placed in mid-latitudes, and subject to the classical single or double gyre wind forcing, is studied. The model grid can be rotated on a desired angle around the center of the rectangle in order to simulate the boundary approximated by a staircase-like coastlines. The solution of the model on the grid aligned with the box borders was used as a reference solution and as artificial observational data. It is shown in [9], [10] that optimal boundary has a rather complicated geometry which is neither a staircase, nor a straight line. The boundary conditions found in the data assimilation procedure bring the solution toward the reference solution allowing to correct the influence of the rotated grid (see fig. 1).

Adjoint models, necessary to variational data assimilation, have been produced by the TAPENADE software, developed by the SCIPORT team. This software is shown to be able to produce the adjoint code that can be used in data assimilation after a memory usage optimization.

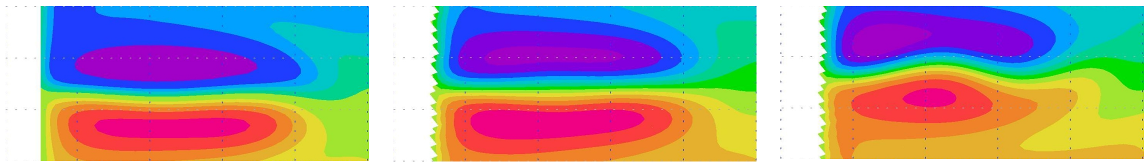

Figure 1. Sea surface elevation: reference solution on the aligned grid (left), solutions on the 30° *rotated grid with optimal (center) and conventional (right) boundary conditions.*

7.3.3. Non-Parametric Estimation for Kinetic Diffusions

Participants: Clémentine Prieur, Jose Raphael Leon Ramos.

This research is the subject of a collaboration with Venezuela and is partly funded by an ECOS Nord project.

We are focusing our attention on models derived from the linear Fokker-Planck equation. From a probabilistic viewpoint, these models have received particular attention in recent years, since they are a basic example for hypercoercivity. In fact, even though completely degenerated, these models are hypoelliptic and still verify some properties of coercivity, in a broad sense of the word. Such models often appear in the fields of mechanics, finance and even biology. For such models we believe it appropriate to build statistical non-parametric estimation tools. Initial results have been obtained for the estimation of invariant density, in conditions guaranteeing its existence and unicity [40] and when only partial observational data are available. A paper on the non parametric estimation of the drift has been accepted recently [41] (see Samson et al., 2012, for results for parametric models). As far as the estimation of the diffusion term is concerned, a paper has been accepted [41], in collaboration with J.R. Leon (Caracas, Venezuela) and P. Cattiaux (Toulouse). Recursive estimators have been also proposed by the same authors in [42], also recently accepted.20

Note that Professor Jose R. Leon (Caracas, Venezuela) is now funded by an international Inria Chair and will spend one year in our team, allowing to collaborate further on parameter estimation.

7.3.4. Multivariate Risk Indicators

Participants: Clémentine Prieur, Patricia Tencaliec.

Studying risks in a spatio-temporal context is a very broad field of research and one that lies at the heart of current concerns at a number of levels (hydrological risk, nuclear risk, financial risk etc.). Stochastic tools for risk analysis must be able to provide a means of determining both the intensity and probability of occurrence of damaging events such as e.g. extreme floods, earthquakes or avalanches. It is important to be able to develop effective methodologies to prevent natural hazards, including e.g. the construction of barrages.

Different risk measures have been proposed in the one-dimensional framework . The most classical ones are the return level (equivalent to the Value at Risk in finance), or the mean excess function (equivalent to the Conditional Tail Expectation CTE). However, most of the time there are multiple risk factors, whose dependence structure has to be taken into account when designing suitable risk estimators. Relatively recent regulation (such as Basel II for banks or Solvency II for insurance) has been a strong driver for the development of realistic spatio-temporal dependence models, as well as for the development of multivariate risk measurements that effectively account for these dependencies.

We refer to [47] for a review of recent extensions of the notion of return level to the multivariate framework. In the context of environmental risk, [67] proposed a generalization of the concept of return period in dimension greater than or equal to two. Michele et al. proposed in a recent study [48] to take into account the duration and not only the intensity of an event for designing what they call the dynamic return period. However, few studies address the issues of statistical inference in the multivariate context. In [49], [51], we proposed non parametric estimators of a multivariate extension of the CTE. As might be expected, the properties of these estimators deteriorate when considering extreme risk levels. In collaboration with Elena Di Bernardino (CNAM, Paris), Clémentine Prieur is working on the extrapolation of the above results to extreme risk levels.

Elena Di Bernardino, Véronique Maume-Deschamps (Univ. Lyon 1) and Clémentine Prieur also derived an estimator for bivariate tail [50]. The study of tail behavior is of great importance to assess risk.

With Anne-Catherine Favre (LTHE, Grenoble), Clémentine Prieur supervises the PhD thesis of Patricia Tencaliec. We are working on risk assessment, concerning flood data for the Durance drainage basin (France). The PhD thesis started in October 2013. A first paper on data reconstruction has been accepted [18]. It was a necessary step as the initial series contained many missing data.

7.4. Assimilation of Images

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

7.4.1. Direct assimilation of image sequences

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 follow-up GeoFluids (along with EPI FLUMINANCE and CLIME, and LMD, IFREMER and Météo-France) that ended in 2013.

During the ADDISA project we developed Direct Image Sequences Assimilation (DISA) and proposed a new scheme for the regularization of optical flow problems [69], which was recently extended [17]. 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 [38]. As part of the ANR project GeoFluids, we are investigating new ways to define distance between a couple of images. One idea is to compare the gradient of the images rather than the actual value of the pixels. This leads to promising results. Another idea, currently under investigation, consists in comparing main structures within each image. This can be done using, for example, a wavelet representation of images. Both approaches have been compared, in particular their relative merits in dealing with observation errors, in a paper published early 2015 [4] and presented in several international conferences [21], [28].

In recent developments [11] we have also used "Level Sets" methods to describe the evolution of the images. The advantage of this approach is that it permits, thanks to the level sets function, to consider the images as a state variable of the problem. We have derived an Optimality System including the level sets of the images.

7.4.2. *Optimal transport for image assimilation*

Within the optimal transport project TOMMI funded by the ANR white program (started mid 2011), a new optimization scheme based on proximal splitting method has been proposed to solve the dynamic optimal transport problem. We investigate the use of optimal transport based distances for data assimilation. The study is still under investigation in the framework of N. Feyeux's PhD, but preliminary encouraging results have already been presented in [20] and an article is in preparation on this topic.

7.5. Tracking of Mesoscale Convective Systems

Participant: Clémentine Prieur.

We are interested in the tracking of mesoscale convective systems.A particular region of interest is West Africa. Data and hydrological expertise is provided by T. Vischel and T. Lebel (LTHE, Grenoble).

A first approach involves adapting the multiple hypothesis tracking (MHT) model originally designed by the NCAR (National Centre for Atmospheric Research) for tracking storms [70] to the data for West Africa. With A. Makris (working on a post-doctoral position), we proposed a Bayesian approach [62], which consists in considering that the state at time t is composed on one hand by the events (birth, death, splitting, merging) and on the other hand by the targets' attributes (positions, velocities, sizes, ...). The model decomposes the state into two sub-states: the events and the targets positions/attributes. The events are updated first and are conditioned to the previous targets sub-state. Then given the new events the target substate is updated. A simulation study allowed to verify that this approach improves the frequentist approach by Storlie et al. (2009). It has been tested on simulations [62] and investigated in the specific context of real data on West Africa [35]. Using PHD (probability hypothesis density) filters adapted to our problem, generalizing recent developments in particle filtering for spatio-temporal branching processes (e.g. [39]) could be an interesting alternative to explore. The idea of a dynamic, stochastic tracking model should then provide the base for generating rainfall scenarios over a relatively vast area of West Africa in order to identify the main sources of variability in the monsoon phenomenon.

7.6. Land Use and Transport Models Calibration

Participants: Thomas Capelle, Laurent Gilquin, Clémentine Prieur, Arthur Vidard, Peter Sturm, Elise Arnaud.

Given the complexity of modern urban areas, designing sustainable policies calls for more than sheer expert knowledge. This is especially true of transport or land use policies, because of the strong interplay between the land use and the transportation systems. Land use and transport integrated (LUTI) modelling offers invaluable analysis tools for planners working on transportation and urban projects. Yet, very few local authorities in charge of planning make use of these strategic models. The explanation lies first in the difficulty to calibrate these models, second in the lack of confidence in their results, which itself stems from the absence of any well-defined validation procedure. Our expertise in such matters will probably be valuable for improving the reliability of these models. To that purpose we participated to the building up of the ANR project CITiES led by the STEEP EPI. This project started early 2013 and two PhD about sensitivity analysis and calibration were launched late 2013. This work led to conference papers [24], [23] and a two published journal paper [3], [6]

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- A 4-year contract named ReDICE (Re Deep Inside Computer Experiments) with EDF, CEA, IRSN, RENAULT, IFP on the thematic computer experiments.

- A 3-year contract with ARTELIA Group: funding for the PhD thesis of M.P. Daou (CIFRE)
- A 1-year contract with NOVELTIS on the thematic "Développement de démonstrateurs avec AGRIF": see 6.1
- A 1-year contract with IFREMER on the thematic "Evolution de la librairie de raffinement de maillage en Fortran (AGRIF) : amélioration de la prise en compte du trait de côte et des frontiéres ouvertes en contexte paralléle MPI/OpenMP" : see 6.1

9. Partnerships and Cooperations

9.1. Regional Initiatives

- Clémentine Prieur is a member of the project "Soutien à l'Excellence et à l'Innovation Grenoble INP MEPIERA (MEthodologies innovantes Pour l'Ingénierie de l'Eau et des Risques Associés) leaded by A.- C. Favre (LTHE).
- N. Feyeux PhD is sponsored by the action ARC3 Environment of the Region Rhone-Alpes.

9.2. National Initiatives

9.2.1. ANR

- A 3.5 year ANR contract: ANR CITiES (numerical models project selected in 2012). https://team.inria.fr/steep/projects/
- A 4-year ANR contract: ANR TOMMI (Transport Optimal et Modèles Multiphysiques de l'Image), see paragraphs 7.4.2,7.4.
- A 5 year ANR contract (2011-2016): ANR COMODO (Communauté de Modélisation Océanographique) on the thematic "Numerical Methods in Ocean Modelling". (coordinator L. Debreu) 7.1.2

9.2.2. Other Initiatives

- 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.
- C. Prieur chairs GdR MASCOT NUM, in which are also involved M. Nodet, E. Blayo, C. Helbert, E. Arnaud, L. Viry, S. Nanty, L. Gilquin. http://www.gdr-mascotnum.fr/doku.php
- C. Prieur is the leader of the LEFE/MANU project MULTIRISK (2014-2016) on multivariate risk analysis, which gathers experts from Lyon 1 University, CNAM, LSCE and Grenoble University mainly.
- E.Kazantsev, E.Blayo, F. Lemarié participate in the project "PACO - Vers une meilleure paramétrisation de la côte et des conditions limites dans les modèles d'océan" supported by LEFE-GMMC and LEFE-MANU .

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. ERA-CLIM2

Type: COOPERATION

Instrument: Specific Targeted Research Project

Program: Collaborative project FP7-SPACE-2013-1

Project acronym: ERA-CLIM2

Project title: European Reanalysis of the Global Climate System

Duration: 01/2014 - 12/2016

Coordinator: Dick Dee (ECMWF, Europe)

Other partners: Met Office (UK), EUMETSAT (Europe), Univ Bern (CH), Univ. Vienne (AT), FFCUL (PT), RIHMI-WDC (RU), Mercator-Océan (FR), Météo-France (FR), DWD (DE), CERFACS (FR), CMCC (IT), FMI (FI), Univ. Pacifico (CL), Univ. Reading (UK), Univ. Versailles St Quentin en Yvelines (FR)

Inria contact: Arthur Vidard

9.3.2. Collaborations with Major European Organizations

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

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

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

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

Partner: University of Reading, Department of Meteorology, Department of Mathematics

Subject: Data assimilation for geophysical systems.

9.4. International Initiatives

C. Prieur collaborates with Jose R. Leon (UCV, Central University of Caracas).

C. Prieur is leader of a project ECOS Nord with Venezuela (2012-2015).

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Jose-Raphael Leon-Ramos, Caracas University, has been granted by the Inria international chair.

Victor Shutyaev, Russian Academy of Sciences, 2 weeks.

Pierre Ngnepieba, Florida Agricultural & Mechanical University, 2 weeks.

9.5.2. Visits to International Teams

F.-X Le Dimet has been invited two times by the Department of Mathematics at Florida State University (one week in April and 2 weeks in october). In USA he was also invited at NASA Stennis Space center (Mississipi) by NRL (Navy Resarch lab) He delivered seminars in this place.

F.-X Le Dimet has been invited by Nanjing University (Department of Meteoroly) , one week in May 2015 to give a 6 -hours tutorial on Variational Data Assimilation.

F.-X. Le Dimet and E.Kazantsev were invited by the Institute of Numerical Mathematics of the Russian Academy of Sciences to present a communication at the G.Marchuk's memorial jubilee [34].

F.-X. Le Dimet has presented a communication at the SIAM meetng on Scientific Computing held in Salt Lake city in April 2015

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific events organisation

A.Vidard was a member of the organizing committee of the Summer school “Traitement du signal et des images”, Peyresq, juin 2015

C.Prieur was a member of the organizing committee of the Journées MAS 2016, Grenoble http://mas2016.sciencesconf.org/

E. Blayo and L. Debreu have organized a mini-symposium “Mathématiques et prévision climatique" within the SMAI 2015 conference (Les Karellis, June 2015).

L. Debreu have organized the international workshop "DRAKKAR" on global ocean modelling with the NEMO system (January 2015).

F. Lemarié and L. Debreu have organized a mini-symposium entitled "Recent algorithmic developments in oceanic models : numerical schemes and test-cases for model assessment" at the European Geosciences Union General Assembly, Vienne, April 2015.

10.1.2. Scientific events selection

C.Prieur was a member of the program committee of the SAMO 2016 La Réunion http://samo2016.univ-reunion.fr/

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing activities

E. Blayo: reviewer for Mathematics and Computers in Simulation, Ocean Modelling.

L. Debreu:reviewer for Ocean Modelling, Ocean Dynamics, Geophysical Model Development.

F. Lemarié : reviewer for Ocean Modeling, Dynamics of Atmospheres and Oceans, SIAM Journal on Scientific Computing

E. Kazantsev: reviewer for International Journal for Numerical Methods in Fluids.

10.1.4. Leadership within the scientific community

E. Blayo is the chair of the CNRS-INSU research program LEFE-MANU on mathematical and numerical methods for ocean and atmosphere . http://www.insu.cnrs.fr/co/lefe

C. Prieur chairs GdR MASCOT NUM, in which are also involved M. Nodet, E. Blayo, C. Helbert, E. Arnaud, L. Viry, S. Nanty, L. Gilquin. http://www.gdr-mascotnum.fr/doku.php

L. Debreu is the coordinator of the national group COMODO (Numerical Models in Oceanography)

10.1.5. Scientific expertise

F.-X. Le Dimet is reviewer for the PRACE consortium (scientific computing)

10.1.6. Research administration

C.Prieur is an elected member of CNU20

C.Prieur is a member of CS of SMF

C.Prieur is a member of the Committee of Statistical Mathematics Group of SFdS

E.Arnaud is a member of the executive committee of IXXI (complex system institute) http://www.ixxi.fr

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: A.Vidard, Mathématiques pour l’ingénieur, 26h, L1, Universités Grenoble-Alpes, France

License: E. Arnaud, Statistics for biologist, 20h, L1, University of Grenoble, France.

License: E. Arnaud, Mathematics upgrade, 14h, L1, University of Grenoble, France.

Licence: E. Blayo, Mathématiques pour l’ingénieur, 66h, L1, UJF Grenoble.

Licence: E. Blayo, Méthodes statistiques pour la biologie, 39h, L2, UJF Grenoble.

License: M.Nodet, Outils maths pour les scientifiques et ingénieurs, 90h, L1, UJF Grenoble.

License: M.Nodet, Projet anglophone pour les L2 math info international 18h, L2, UJF Grenoble.

License: Ch. Kazantsev, Mathematiques pour les sciences de l'Ingenieur, L1, 60h UJF Grenoble.

Master: E. Arnaud, Advising students on apprenticeship, 28h, M2, University of Grenoble, France.

Master: E. Arnaud, Image processing, 18h, M2, University of Grenoble, France.

Master: E. Blayo, Méthode des éléments finis, 47h, M1, UJF Grenoble

Master: E. Blayo, Modelling and control of PDEs, 17h, M2, UJF Grenoble

Master: E. Blayo, F. Lemarié, Model coupling, 27h, M2, UJF Grenoble

Master: F. Lemarié, E. Blayo, An introduction to Schwarz domain decomposition methods, 24h, M2, Grenoble

Master: M.Nodet, Méthodes numériques, 15h, M1, UJF Grenoble

Master: M.Nodet, Méthodes inverses assimilation de données, 36h,M2, UJF Grenoble

Doctorat: E. Blayo, M. Nodet, A. Vidard, Introduction to data assimilation, 20h, University of Grenoble

Doctorat : Laurent Debreu, Formation doctorale nationale Modélisation numérique de l'océan et de l'atmosphère, 16-20 novembre 2015, Brest, France. With T. Dubos (LMD/Ecole Polytechnique, Paris), G. Roullet (Brest University), F. Hourdin (LMD/CNRS, Paris)

E-learning

Elise Arnaud, Maëlle Nodet, Mathematics for engineer, L1, University of Grenoble,

Pedagogical resources : http://tinyurl.com/youtube-mat126

10.2.2. Supervision

HDR : Laurent Debreu, Modélisation numérique de l'océan, Université Grenoble Alpes, 17 décembre 2015.

PhD : Simon Nanty, Quantification des incertitudes et analyse de sensibilité pour codes de calcul à entrées fonctionnelles et dépendantes, Université Grenoble-Alpes,15 octobre 2015, Clémentine PRIEUR, Céline Helbert

PhD in progress : Nelson Feyeux, Application du transport optimal pour l'assimilation de données images, novembre 2013, A. Vidard, M. Nodet

PhD in progress : Thomas Capelle, Calibration of LUTI models, octobre 2013, P. Sturm (EPI STEEP), A.Vidard

PhD in progress : Rémi Pellrej, Assimilation de données pour les modèles couplés, octobre 2014, A. Vidard, F. Lemarié

PhD in progress : Laurent Gilquin, Sensitivity analysis of a macroeconomic LUTI model, started in October 2013, E. Arnaud and C. Prieur

PhD in progress : Patricia Tencaliec, Approches stochastiques pour la gestion des risques environnementaux extrêmes, October 2013, Clémentine Prieur, Anne-Catherine Favre (LTHE)

PhD in progress: Mehdi-Pierre Daou, Développement d'une méthodologie de couplage multimodèles avec changements de dimension. Validation en dynamique littorale. May 2013, E. Blayo and A. Rousseau.

PhD in progress: Charles Pelletier, Etude mathématique et numérique de la formulation du couplage océan-atmosphère dans les modèles de climat. December 2014, E. Blayo, F. Lemarié and P. Braconnot.

PhD in progress: Alexis Ropiquet, Parameter estimation for subgrid modelling, Sept.2015, C.Prieur and E. Blayo.

10.2.3. Juries

E. Blayo

- 4 May 2015 - HDR thesis of Emmanuel Witrant, University of Grenoble (president)
- 12 May 2015 - PhD thesis of Sébastien Barthélémy, University of Toulouse (reporter)
- 26 Jun 2015 - PhD thesis of Romain Casati, University of Grenoble (president)
- 30 Jun 2015 - HDR thesis of Isabelle Herlin, University Pierre et Marie Curie, Paris (examiner)
- 2 Dec 2015 - PhD thesis of Lucie Rottner, University of Toulouse (reporter)
- 17 Dec 2015 - HDR thesis of Laurent Debreu, University of Grenoble (examiner)

F. Lemarié : 4 novembre 2015 - PhD thesis of Aimie Moulin, University of Grenoble (examiner)

M. Nodet : jury de bac technologique 2015

F.-X. Le Dimet : 17 Dec 2015 - HDR thesis of Laurent Debreu, University of Grenoble (president)

10.3. Popularization

- A.Vidard has Animated the stand Inria at the exposition “Solutions - COP 21", December,9, 2015
- A.Vidard has given a Conference «Le numérique au service de l’observation et de l’anticipation des changements climatiques» at the Exposition “Solutions - COP 21", December,9, 2015
- C.Prieur has given an interview to Interctices.info https://interstices.info/jcms/p_86521/mieux-modeliser-le-climat-grace-aux-statistiques
- E. Blayo participated to a Journée numérique, at the French Senate (Paris), on Feb. 11th, 2015. http://www.senat.fr/evenement/journee_numerique_inria.html
- E. Blayo gave several outreach talks, in particular for high school students and for groups of teachers.
- M. Nodet co-organises a year-round weekly math club in two secondary schools, where pupils research open mathematical problems.
- M. Nodet organised a two-month weekly meeting at a secondary school to explain mathematical research, in particular modelling for ocean and climate.
- M. Nodet gave an outreach talk about maths and oceanic currents in a secondary school during the mathematical week 2015.
- M. Nodet wrote, with J. Ehrel, two outreach papers for Interstices about glaciology and inverse problems [32], [31].
- M. Nodet gave an outreach talk about mathematical modelling for the environment at the IREM Lille 2015 conference [33].
- Several members of the AIRSEA team have contributed to the 2015 Science Festival through an information stand entitled "Understanding oceanic and atmospheric circulations".
- Since 2010, Ch. Kazantsev is the Director of the IREM of Grenoble http://www-irem.ujf-grenoble.fr/irem/accueil/. The Institute is under rapid development now, joining about 50 teachers of primary and secondary schools of the Grenoble region and 15 university professors. They work together 16 times a year on the development of the teaching strategy for the educational community. In addition to this, IREM is the editor of two journals: "Grand N" destined to primary schools teachers and "Petit x" – to the secondary schools.
- Ch. Kazantsev and E. Blayo participate in the creation of "La Grange des maths" in Varces
- Ch. Kazantsev has organized two stages of one or two days for children 14 or 15 years old during the holidays in the framework of "MathC2+", participation in these stages for one or two animations (in calculus and in modelisation), 2x2h for each animation

- A.Vidard gave an outreach talk at the Summer school “Traitement du signal et des images”, Peyresq, juin 2015
- M. Nodet and Ch.Kazantsev are involved in an IREM group which aims to bring interdisciplinarity into secondary school curriculum and proposes activities for teachers.
- M. Nodet co-organised a two day training session for secondary and high school teachers, about modelling and mathematics for the newly created Maison Pour la Science Alpes Dauphiné.
- M. Nodet is involved in various events and groups related to pedadogy at university levels.

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

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