IN PARTNERSHIP WITH:
Université de Grenoble Alpes

Activity Report 2017

Project-Team AIRSEA

mathematics and computing applied to oceanic and atmospheric flows

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Earth, Environmental and Energy Sciences

Table of contents

Project-Team AIRSEA

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Keywords:

Computer Science and Digital Science:

A3.1.8. - Big data (production, storage, transfer)
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.2. - Stochastic Modeling (SPDE, SDE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.4. - Statistical methods
A6.2.6. - Optimization
A6.2.7. - High performance computing
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation
A6.3.4. - Model reduction

Other Research Topics and Application Domains:

B3.2. - Climate and meteorology
B3.3.2. - Water: sea & ocean, lake & river
B3.3.4. - Atmosphere
B3.4.1. - Natural risks
B4.3.2. - Hydro-energy
B4.3.3. - Wind energy
B9.9.1. - Environmental risks

1. Personnel

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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 7.1.2) 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 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 (7.2.1). 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

5.1.1. Awards

M. Nodet and J. Erhel won the first prize of the second Imaginary Mathematics for Planet Earth competition with their web module entitled "Simulating the melting of ice caps" [26].

E. Arnaud was granted by a CRCT (Congé pour recherches ou conversions thématiques) by the CNU in 2016/2017.

6. New Software and Platforms

6.1. AGRIF

Adaptive Grid Refinement In Fortran
KEYWORD: Mesh refinement
SCIENTIFIC 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.
NEWS OF THE YEAR: In 2017, the multiresolution capabilities of the AGRIF software have been extended to be able to treat a much larger number of grids. In particular, the load balancing algorithms have been greatly improved.

- Participants: Roland Patoum and Laurent Debreu
- Contact: Laurent Debreu
- Publications: Numerical and experimental approach for a better physical description of submesoscale processes : A north-western Mediterranean Sea case - AGRIF: Adaptive Grid Refinement in Fortran
- 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: Patrick Vidard

6.3. DassFlow

- Participants: Jerome Monnier, Joel Marin and Marc Honnorat
- Contact: Eric Blayo-Nogret

6.4. DiceDesign

Designs of Computer Experiments

FUNCTIONAL DESCRIPTION: This package is useful for conducting design and analysis of computer experiments.

- Contact: Céline Hartweg
- URL: https://cran.r-project.org/web/packages/DiceDesign/index.html

6.5. DiceEval

Construction and Evaluation of Metamodels

FUNCTIONAL DESCRIPTION: This package is useful for conducting design and analysis of computer experiments. Estimation, validation and prediction of models of different types : linear models, additive models, MARS,PolyMARS and Kriging.

- Contact: Céline Hartweg
- URL: https://cran.r-project.org/web/packages/DiceEval/index.html

6.6. 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 var 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: Patrick Vidard

6.7. 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. Numerical Schemes for Ocean Modelling

Participants: Eric Blayo, Laurent Debreu, Florian Lemarié, Christopher Eldred, Farshid Nazari.

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). A review paper on coastal ocean models has been written with German colleagues and will be published in Ocean Modelling early 2018 ([34]).
Ocean models usually rely on a mode splitting procedure which separates the fast external gravity waves with the slower internal waves. A paper on the stability of the mode splitting has been submitted to Journal of Computational Physics ([21])
The team is involved in the HEAT (Highly Efficient ATmospheric Modelling) ANR project. This project aims at developing a new atmospheric dynamical core (DYNAMICO) discretized on an icosahedral grid. This project is in collaboration with Ecole Polytechnique, Meteo-France, LMD, LSCE and CERFACS. This year we worked on dispersion analysis of compatible Galerkin schemes for a 1D shallow water model ([8]).

7.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, Laurent Debreu, Florian Lemarié, Charles Pelletier, Antoine Rousseau, Sophie Thery.

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 [61]. For the last few years we have been actively working on the analysis of ocean-atmosphere coupling both in terms of its continuous and numerical formulation.Our activities over the last few years can be divided into four general topics

1. *Stability and consistency analysis of existing coupling methods*: in [61] 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. This last remark was further studied recently in [1] and it turned out to be a major source of instability in atmosphere-snow coupling.
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, in particular the parameterization schemes to compute air-sea fluxes [18]. To do so, a metamodel representative of the behavior of the full parameterization but with a continuous form easier to manipulate has been derived thanks to a sensitivity analysis based on Sobol' indexes. This metamodel has the advantage to be more adequate to conduct the mathematical analysis of the coupling while being physically satisfactory. This work is in revision for publication in Quarterly Journal of the Royal Meteorological Society and has been presented in various conferences [69], [24], [20], [17]. In parallel we have contributed to a general review gathering the main international specialists on the topic [53].
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. Last year the single column oceanic and atmospheric components have been developed and coupled during the PhD-thesis of Rémi Pellerej and in the framework of the SIMBAD project. A publication describing this model and its interfacing with the OOPS software to allow the implementation of various data assimilation techniques is currently in preparation for the Geoscientific Model Development journal.
4. *Analysis of air-sea interactions in realistic high-resolution realistic simulations*: part of our activity has been in collaboration with atmosphericists and physical oceanographers to study the impact on some modeling assumptions (e.g. [62]) in large-scale realistic ocean-atmosphere coupled simulations [70], [66], [12].

These four topics are addressed through strong collaborations between the applied mathematicians and the climate community.

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. First results have been presented during international conferences [22], [23] and a publication is currently in preparation. Another industrial contract named ALBATROS is also funded by (from June 2016 to June 2019) to couple SIMBAD with the NEMO global ocean model and a wave model called WW3.

An ANR project COCOA (COmprehensive Coupling approach for the Ocean and the Atmosphere, P.I.: E. Blayo) has been funded in 2016 and has officially start in January 2017.

7.1.3. 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 and will defend it early 2018. So far, three general data assimilation algorithms, based on variational data assimilation techniques, have been developed and applied to a single column coupled model. 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 [68], [25]. The aforementioned system has been coded within the OOPS framework (Object Oriented Prediction System) in order to ease the transfer to more complex/realistic models.

The second contribution to ERACLIM2 was to investigate the importance of the quality of the data assimilation scheme in the ocean in the coupled system. It led to the proposition of cost effective approximations either in term of resolution reduction or equation simplifications, along with a metric to asses the quality of said approximations [35]

Finally, CASIS, a new collaborative project with Mercator Océan has started late 2017 in order to extend developments to iterative Kalman smoother data assimilation scheme, in the framework of a coupled ocean-atmospheric boundary layer context.

7.1.4. Parameterizing subgrid scale eddy effects

Participant: Eugene Kazantsev.

Basing on the maximum entropy production principle, the influence of subgrid scales on the flow is presented as the harmonic dissipation accompanied by the backscattering of the dissipated energy. This parametrization is tested on the shallow water model in a square box. Two possible solutions of the closure problem are compared basing on the analysis of the energy dissipation-backscattering balance. Results of this model on the coarse resolution grid are compared with the reference simulation at four times higher resolution. It is shown that the mean flow is correctly recovered, as well as variability properties, such as eddy kinetic energy fields and its spectrum [33].

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 [57], 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 [58]. In [55], 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 [59].

When considering parameter-dependent PDE, it happens that the quantity of interest is not the PDE’s solution but a linear functional of it. In [56], we have proposed a probabilistic error bound for the reduced output of interest (goal-oriented error bound). By probabilistic we mean that this bound may be violated with small probability. The bound is efficiently and explicitly computable, and we show on different examples that this error bound is sharper than existing ones.

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 [59]. In [60], we propose a generalization of the probabilistic goal-oriented error estimation in [56] to parameter-dependent nonlinear problems. One aims at applying such results in the previous context of sensitivity of a controlled system.

7.3. Dealing with uncertainties

7.3.1. Sensitivity Analysis

Participants: Eric Blayo, Laurent Gilquin, François-Xavier Le Dimet, Elise Arnaud, Maëlle Nodet, Clémentine Prieur, Laurence Viry.

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. 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 [54] in the case where input parameters are correlated. Clémentine Prieur supervised Gaëlle Chastaing's PhD thesis on the topic (defended in September 2013) [41]. We obtained first results [42], 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 [40], [43]. We also considered the estimation of groups Sobol' indices, with a procedure based on replicated designs [52]. 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 [64]. The whole methodology proposed during the PhD is presented in [65].

More recently, the Shapley value, from econometrics, was proposed as an alternative to quantify the importance of random input variables to a function. Owen [67] derived Shapley value importance for independent inputs and showed that it is bracketed between two different Sobol' indices. Song et al. [72] recently advocated the use of Shapley value for the case of dependent inputs. In a very recent work [13], in collaboration with Art Owen (Standford's University), we show that Shapley value removes the conceptual problems of functional ANOVA for dependent inputs. We do this with some simple examples where Shapley value leads to intuitively reasonable nearly closed form values. We also investigated further the properties of Shapley effects in [31].

7.3.2. Non-Parametric Estimation for Kinetic Diffusions

Participants: Clémentine Prieur, Jose Raphael Leon Ramos.

This research is the subject of a collaboration with Chile and Uruguay. More precisely, we started working with Venezuela. Due to the crisis in Venezuela, our main collaborator on that topic moved to Uruguay.

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 [37] and when only partial observational data are available. A paper on the non parametric estimation of the drift has been accepted recently [38] (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 [38], in collaboration with J.R. Leon (Montevideo, Uruguay) and P. Cattiaux (Toulouse). Recursive estimators have been also proposed by the same authors in [39], also recently accepted. In a recent collaboration with Adeline Samson from the statistics department in the Lab, we considered adaptive estimation, that is we proposed a data-driven procedure for the choice of the bandwidth parameters.

In [5], we focused on damping Hamiltonian systems under the so-called fluctuation-dissipation condition. Idea in that paper were re-used with applications to neuroscience in [63].

Note that Professor Jose R. Leon (Caracas, Venezuela, Montevideo, Uruguay) was funded by an international Inria Chair, allowing to collaborate further on parameter estimation.

We recently proposed a paper on the use of the Euler scheme for inference purposes, considering reflected diffusions.This paper could be extended to the hypoelliptic framework.

We started a collaboration with Karine Bertin (Valparaiso, Chile) funded by a MATHAMSUD project. We are interested in new adaptive estimators for invariant densities on bounded domains, and would like to extend that results to hypo-elliptic diffusions.

7.3.3. 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 [44] for a review of recent extensions of the notion of return level to the multivariate framework. In the context of environmental risk, [71] 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 [45] 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 [46], [48], 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 [29].

Elena Di Bernardino, Véronique Maume-Deschamps (Univ. Lyon 1) and Clémentine Prieur also derived an estimator for bivariate tail [47]. The study of tail behavior is of great importance to assess risk.

With Anne-Catherine Favre (LTHE, Grenoble), Clémentine Prieur supervised 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 and was defended in February 2017. A first paper on data reconstruction has been accepted [73]. It was a necessary step as the initial series contained many missing data. A second paper is in revision, considering the modeling of precipitation amount with semi-parametric models, modeling both the bulk of the distribution and the tails, but avoiding the arbitrary choice of a threshold. We work in collaboration with Philippe Naveau (LSCE, Paris).

7.3.4. Extensions of the replication method for the estimation of Sobol' indices

Participants: Elise Arnaud, Laurent Gilquin, Clémentine Prieur.

Sensitivity analysis studies how the uncertainty on an output of a mathematical model can be attributed to sources of uncertainty among the inputs. Global sensitivity analysis of complex and expensive mathematical models is a common practice to identify influent inputs and detect the potential interactions between them. Among the large number of available approaches, the variance-based method introduced by Sobol' allows to calculate sensitivity indices called Sobol' indices. Each index gives an estimation of the influence of an individual input or a group of inputs. These indices give an estimation of how the output uncertainty can be apportioned to the uncertainty in the inputs. One can distinguish first-order indices that estimate the main effect from each input or group of inputs from higher-order indices that estimate the corresponding order of interactions between inputs. This estimation procedure requires a significant number of model runs, number that has a polynomial growth rate with respect to the input space dimension. This cost can be prohibitive for time consuming models and only a few number of runs is not enough to retrieve accurate informations about the model inputs.

The use of replicated designs to estimate first-order Sobol' indices has the major advantage of reducing drastically the estimation cost as the number of runs n becomes independent of the input space dimension. The generalization to closed second-order Sobol' indices relies on the replication of randomized orthogonal arrays. However, if the input space is not properly explored, that is if n is too small, the Sobol' indices estimates may not be accurate enough. Gaining in efficiency and assessing the estimate precision still remains an issue, all the more important when one is dealing with limited computational budget.

We designed approaches to render the replication method recursive, enabling the required number of evaluations to be controlled. With these approaches, more accurate Sobol' estimates are obtained while recycling previous sets of model evaluations. The estimation procedure is therefore stopped when the convergence of estimates is considered reached. One of these approaches corresponds to a recursive version of the replication method and is based on the iterative construction of stratified designs, latin hypercubes and orthogonal arrays [50]. A second approach combines the use of quasi-Monte Carlo sampling and the construction of a new stopping criterion [9] [32] .

In [30] a new strategy to estimate the full set of first-order and second-order Sobol' indices with only two replicated designs based on orthogonal arrays of strength two. Such a procedure increases the precision of the estimation for a given computation budget. A bootstrap procedure for producing confidence intervals, that are compared to asymptotic ones in the case of first-order indices, is also proposed.

7.3.5. Parameter control in presence of uncertainties: robust estimation of bottom friction

Participants: Victor Trappler, Elise Arnaud, Laurent Debreu, Arthur Vidard.

Many physical phenomena are modelled numerically in order to better understand and/or to predict their behaviour. However, some complex and small scale phenomena can not be fully represented in the models. The introduction of ad-hoc correcting terms, can represent these unresolved processes, but they need to be properly estimated.

A good example of this type of problem is the estimation of bottom friction parameters of the ocean floor. This is important because it affects the general circulation. This is particularly the case in coastal areas, especially for its influence on wave breaking. Because of its strong spatial disparity, it is impossible to estimate the bottom friction by direct observation, so it requires to do so indirectly by observing its effects on surface movement. This task is further complicated by the presence of uncertainty in certain other characteristics linking the bottom and the surface (eg boundary conditions). The techniques currently used to adjust these settings are very basic and do not take into account these uncertainties, thereby increasing the error in this estimate.

Classical methods of parameter estimation usually imply the minimisation of an objective function, that measures the error between some observations and the results obtained by a numerical model. In the presence of uncertainties, the minimisation is not straightforward, as the output of the model depends on those uncontrolled inputs and on the control parameter as well. That is why we will aim at minimising the objective function, to get an estimation of the control parameter that is robust to the uncertainties. In this work, a toy model of a coastal area has been modelled and implemented. The control parameter is the bottom friction, upon which classical methods of estimation are applied in a simulation-reestimation experiment. The model is then modified to include uncertainties on the boundary conditions in order to apply robust control methods. First, a sensitivity analysis of the objective function has been performed to assess the influence of each considered variable. Then, a study on the meaning of different concepts of robustness have been carried on. Typically, one then seeks an optimal parameter set that would minimise the variance or the mean of the original objective function. Various associated algorithms from the literature have been implemented. They all rely on surrogate models and black-box optimisation techniques to solve this estimation problem.

7.3.6. Sensitivity of a floating offshore wind turbine to uncertain parameters

Participants: Adrien Hirvoas, Elise Arnaud, Clémentine Prieur, Arthur Vidard.

In a fast-changing energy context, marine renewable energies in general and floating offshore wind energy in particular are a promising source of energy in France and aboard. The design of these structures is made in a specific regulated framework related to their environment. Floating offshore wind turbines are submitted to various continuous environmental loadings (wind, current, swell), which generate solicitations and fatigue in some components. Fatigue lifetime is estimated with a dedicated software that allows performing coupled multi-physics simulations of the system (hydrodynamics, aerodynamics, mechanics and controls). The inputs of these simulations necessarily include uncertainties regarding the environmental loadings and the physical parameters of the models as well. These uncertainties can have an influence on the simulated behaviour of the system. The core of this work consists in conducting a sensitivity analysis to assess, how the uncertainty on an output of a model can be attributed to sources of uncertainty among the inputs. The approach that is considered, is based on the calculation of Sobol indices with the FAST method, and a meta-model using Kriging. These indices are used to evaluate in what extend an input or group of inputs is responsible for the output variance. The perspectives of this study is to understand what king of measurements could be of interest to properly estimate the sensible parameters, and where these measurements should be monitored on the structure. Such an estimation will be performed with data assimilation approaches, which optimally combine numerical models and physical observations. This work in done in collaboration with IFPEN.

7.3.7. Uncertainty and robustess analysis for models with functional input/output.

Participants: Mohammed Reda El Amri, Clémentine Prieur.

Numerical models are commonly used to study physical phenomena. They imply many inputs parameters, and potentially provide a large number of quantities of interest as outputs. Practitioners are not only interested in the response of their model for a given set of inputs (forward problem) but also in recovering the set of inputs values leading to a prescribed value or range for the quantity of interest (inversion problem). In collaboration with IFP Energies nouvelles, we develop data-driven strategies for robust inversion under functional uncertainties. Reda El Amri's PhD thesis aim at developping such tools with application to pollutant emission control.

7.4. Assimilation of Images

Participants: Elise Arnaud, François-Xavier Le Dimet, Maëlle Nodet, Arthur Vidard, Nelson Feyeux.

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.

Our current developments are targeted at the use of « 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. This approach is being applied to the tracking of oceanic oil spills [10]

A collaborative project started with C. Lauvernet (IRSTEA) in order to make use of our image assimilation strategies on the control of pesticide transfer.

7.4.2. Optimal transport for image assimilation

We investigate the use of optimal transport based distances for data assimilation, and in particular for assimilating dense data such as images. The PhD thesis of N. Feyeux studied the impact of using the Wasserstein distance in place of the classical Euclidean distance (pixel to pixel comparison). In a simplified one dimensional framework, we showed that the Wasserstein distance is indeed promising. Data assimilation experiments with the Shallow Water model have been performed and confirm the interest of the Wasserstein distance. Results have been presented at conferences and seminars and a paper is under minor revision at NPG [49].

7.5. 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. Laurent Gilquin defended his PhD in October 2016 [51] and Thomas Capelle defended his in April 2017 and published his latest results in [4].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Contract with IFPEN (Institut Français du pétrole et des énergies nouvelles), for the supervision of Adrien Hirvoas. Research subject: Sensitivity of a floating offshore wind turbine to uncertain parameters and identification of observable variables for data assimilation.

The Chair OQUAIDO – for "Optimisation et QUAntification d'Incertitudes pour les Données Onéreuses" in French – is the chair in applied mathematics held at Mines Saint-Étienne (France). It aims at gathering academical and technological partners to work on problems involving costly-to-evaluate numerical simulators for uncertainty quantification, optimization and inverse problems. This Chair, created in January 2016, is the continuation of the projects DICE and ReDICE which respectively covered the periods 2006-2009 and 2011-2015. Reda El Amri's PhD thesis is funded by OQUAIDO.

A 1-year contract with NOVELTIS on the thematic "Développement de démonstrateurs avec AGRIF": see 6.1

A 3-year contract named ALBATROS with Mercator-Ocean on the topic « Interaction océan, vagues, atmosphère à haute résolution ».

9. Partnerships and Cooperations

9.1. Regional Initiatives

STAREX - Clémentine Prieur obtained a 8kE two-years funding for a local project on risk by the Labex Persyval. Philippe Naveau (from LSCE, Paris) visited the team during one month in spring 2017 in this context.

C. Prieur is co-leader of work-package 3 of the cross-disciplinary-project Trajectories from Idex Grenoble.

9.2. National Initiatives

9.2.1. ANR

COCOA: COmprehensive Coupling approach for the Ocean and the Atmosphere. PI: E. Blayo. Duration: 4 years (Jan. 2017 - Dec. 2020). Other partners: Laboratoire des Sciences du Climat et de l'Environnement (UMR8212, Gif-sur-Yvette), Laboratoire de Météorologie Dynamique (UMR8539, Paris), Laboratoire d'Océanographie Physique et Spatiale (UMR6523, Brest), Centre National de Recherche Météorologique (UMR3589, Toulouse), Cerfacs (Toulouse). This project aims at revisiting the overall representation of air-sea interactions in coupled ocean-atmosphere models, and particularly in climate models, by coherently considering physical, mathematical, numerical and algorithmic aspects.

C. Prieur and E. Arnaud are involved as experts in project High-Tune http://www.agence-nationale-recherche.fr/Projet-ANR-16-CE01-0010 funded by ANR.

A 4-year contract : ANR HEAT (Highly Efficient ATmospheric modelling) http://www.agence-nationale-recherche.fr/?Project=ANR-14-CE23-0010.

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 6.6.

C. Prieur chaired GdR MASCOT NUM 2010-2017, in which are also involved M. Nodet, E. Blayo, C. Helbert, E. Arnaud, L. Viry, S. Nanty, L. Gilquin. She is still strong involved in thie group (co-chair) http://www.gdr-mascotnum.fr/doku.php.

LEFE/GMMC CASIS, Coupled Assimilation Strategies for the Initialisation of an ocean- atmospheric boundary layer System, A. Vidard. en collaboration avec Mercator océan

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 6.6.

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 Center 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

F. Lemarié is involved in the Inria associate team NEMOLOCO with Santiago University (Chile)

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

C. Prieur collaborates with Jose R. Leon (UCV, Central University of Caracas), who was funded by the international Inria chair program. He moved in June 2017 to Montevideo, Uruguay, and the collaboration goes on.

C. Prieur is collaborating with AC Favre (LTHE, Grenoble) in the framework of a two-years canadian funding from CFQCU (Conseil franco-québécois de coopération universitaire) 2015-2016.

F. Lemarié and L. Debreu collaborate with Hans Burchard from the Leibniz-Institut für Ostseeforschung in Warnemünde (Germany).

F. Lemarié and L. Debreu collaborate with Knut Klingbeil from the Dept. of Mathematics of the University of Hamburg (Germany).

9.4.2. Participation in Other International Programs

9.4.2.1. International Initiatives

SIDRE

Title: Statistical inference for dependent stochastic processes and application in renewable energy

International Partners:

Universidad de Valparaiso (Chile) - CIMFAV - Facultad de Ingeniería - Karine Bertin

Universidad Central de Venezuela (Venezuela) - Departamento de Matemáticas - Jose León

Duration: 2016 - 2017

Start year: 2016

See also: http://sidre.cimfav.cl/

We want to develop, apply and study the properties of statistical tools in several non-parametric models, segmentation models, time series and random fields models, and to study some classes of long-range dependent processes, for their possible application in renewable energies and other domains. In particular non-parametric statistical procedure in Markov switching non-linear autoregressive models, finite mixture, non-parametric functional test and non-parametric estimators in stochastic damping Hamiltonian systems will be considered. Statistical tools for segmenting dependent multiples series, censoring processes in time series models and a new model interpolation scheme will be studied.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Werner Bauer (Imperial College, London) spent one week in the AIRSEA team from October 9th to October 13th to work on mimetic schemes for atmospheric models.

9.5.1.1. Internships

Gino Rivano from the university of Valparaiso (Chile) : « High-resolution numerical modeling of the oceanic circulation in central Chile: application to larvae dispersal » (advisor: F. Lemarié), 3 months in the framework of the Inria MERIC center of excellence.

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

C. Prieur visited during two weeks Karine Bertin in Chile. CIMFAV – Facultad de Ingeniería Universidad de Valparaíso.

F.-X. Le Dimet visited Florida State University, Dpt of Mathematics during two weeks in May 2017

F.-X. Le Dimet visited Harbin Institute of Technology, Dpt of Mathematics during 10 days in July 2017

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

E. Blayo and M. Nodet were in the organizing committee of a one-day meeting: Teaching mathematical and numerical methods to students in geosciences (Paris, December 21, 2017).

E. Blayo, E. Cosme and A. Vidard organize a one-week school “Introduction to data assimilation” for doctoral students.

F. Lemarié was the convener of the session « Recent developments in numerical atmospheric, oceanic and sea-ice models: towards global cloud and eddy resolving simulations on exascale supercomputers » during the 2017 European Geosciences Union General Assembly in Vienna (http://meetingorganizer.copernicus.org/EGU2017/session/23945).

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

- C. Prieur is associate editor of the journal Computational and Applied Mathematics

10.1.2.2. Reviewer - Reviewing Activities

F. Lemarié: reviewer for Ocean Modeling, Geoscientific Model Development

10.1.3. Invited Talks

C. Prieur was invited to give a tutorial for the opening workshop of the SAMSI program on QMC. https://www.samsi.info/programs-and-activities/year-long-research-programs/2017-18-program-quasi-monte-carlo-high-dimensional-sampling-methods-applied-mathematics-qmc/

L. Debreu gave an invited talk in the session "Emerging methods for scalable atmosphere and ocean modelling", SCICADE 2017, University of Bath, September 2017

L. Debreu gave an invited talk at the conference "An overview on free surface flows", Paris, November 2017.

L. Debreu gave an invited talk at the conference "Numwave", Montpellier, December 2017.

F. Lemarié has been invited for a talk at the 3rd international workshop on « Energy transfers in Atmosphere and Ocean » in Hamburg (Germany) [17]

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).

L. Debreu is a member of the steering committee of the CROCO ocean model https://www.croco-ocean.org

10.1.5. Scientific Expertise

F. Lemarié is a member of the CROCO (https://www.croco-ocean.org/) scientific committee in charge of the « numerical methods » topic.

10.1.6. Research Administration

E. Blayo is a deputy director of the Jean Kuntzmann Lab.

C. Prieur is a member of the Scientific Council of the Mathematical Society of France (SMF).

C. Prieur is a member of the Committee of Statistical Mathematics Group of the French Statistical Society (SFdS).

E. Arnaud has been a member of the executive committee of IXXI (complex system institute) until July 2017 http://www.ixxi.fr

E. Arnaud is in charge of the MAD (Modèles et algorithmes déterministes) department of Laboratoire Jean Kuntzmann

L. Debreu is a member of the scientific evaluation committee of the French Research Institute for Development (IRD).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

License: E. Arnaud, Mathématiques pour l'ingénieur, 50h, L1, University Grenoble Alpes, France.

License: E. Arnaud, Algorithmique, 18h, L2, University Grenoble Alpes, France.

License: V. Trappler, Méthodes statistiques pour la biologie, 18h, L2, University Grenoble Alpes, France.

Licence: E. Blayo, Analyse approfondie, 80h, L1, Univ. Grenoble Alpes.

Licence: M. Nodet, Outils mathematiques pour l'ingenieur, 80h, Univ. Grenoble Alpes

Master: E. Arnaud, Tutorat d'apprentis MIAGE, 28h, M2, University Grenoble Alpes, France.

Master: E. Arnaud, Data assimilation and inverse problem, 38h, M2, University Grenoble Alpes, France.

Master: E. Blayo, PDEs and numerical methods, 43h, M1, Univ. Grenoble Alpes and Ensimag engineer school.

Master: M. Nodet, Partial differential equations, 20h, Univ. Grenoble Alpes

Master: M. Nodet, Inverse methods, 30h, Univ. Grenoble Alpes

Doctorat: E. Blayo and A. Vidard, Introduction to data assimilation, 20h, Univ. Grenoble Alpes

Doctorat: F.-X. Le Dimet, Data Assimilation for Geophysical Fluids, 16h, Harbin Institute of Technology, Summer School in Pure and Applied Mathematics.

Doctorat: L. Debreu co-organized a one week doctoral training session on numerical modelling of atmospheric and oceanic flows (with F. Hourdin (LMD, Paris), G. Roullet (UBO, Brest) and T. Dubos (Ecole Polytechnique, Paris)).)

E-learning

E-learning, SPOC: E. Arnaud, M. Nodet, E. Blayo, A. Vidard 10 weeks, moodle platform http://tinyurl.com/uga-mat207, University Grenoble Alpes, L1, 150 students

Pedagogical resources : all documents for problem-based learning including videos http://tinyurl.com/youtube-mat207

10.2.2. Supervision

Intern: Victor Trappler, Robust Estimation of bottom friction ; Parameter control in presence of uncertainties, M2, DTU Aqua, National Institute of Aquatic Resources, Technical University of Denmark, 6 months, E. Arnaud, L. Debreu and A. Vidard.

Intern: Adrien Hirvoas, Sensitivity of a floating offshore wind turbine to uncertain parameters and identification of observable variables for data assimilation, M2, University Grenoble Alpes, IFPEN, 6 months, E. Arnaud, C. Prieur, A. Vidard, F. Caleyron.

PhD in progress: Rémi Pellerej, Étude et développement d'algorithmes d'assimilation de données variationnelle adaptés aux modèles couplés océan-atmosphère, October 2014, A. Vidard, F. Lemarié.

PhD in progress: Long Li, Assimilation d'image pour le suivi de polluants, September 2017, A. Vidard, J.-W. Ma (Harbin University, China).

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 and F. Lemarié.

PhD in progress: Sophie Thery, Numerical study of coupling algorithms and boundary layer parameterizations in climate models. October 2017, E. Blayo and F. Lemarié.

PhD in progress: Victor Trappler, Parameter control in presence of uncertainties, October 2017, E. Arnaud, L. Debreu and A. Vidard.

PhD in progress: Reda El Amri, Analyse d'incertitudes et de robustesse pour les modèles à entrées et sorties fonctionnelles, April 2016, Clémentine Prieur, Céline Helbert (Centrale Lyon), funded by IFPEN, in the OQUAIDO chair program.

PhD in progress: Maria Belén Heredia, a generic Bayesian approach for the calibration of advanced snow avalanche models with application to real-time risk assessment conditional to snow conditions, October 2017, Nicolas Eckert (IRSTEA Grenoble), Clémentine Prieur, funded by the OSUG@2020 Labex.

PhD: Patricia Tencaliec, Approches stochastiques pour la gestion des risques environnementaux extrêmes, October 2013 - February 2017, Clémentine Prieur, Anne-Catherine Favre (LTHE).

PhD : Thomas Capelle, Calibration of LUTI models, UGA, April 2017, P. Sturm (EPI STEEP), A.Vidard, [36].

10.2.3. Juries

E. Blayo:

- October 13, 2017: PhD thesis of Olivier Passalacqua, Univ. Grenoble Alpes (president);
- November 9, 2017: HDR thesis of Matthieu Plu, University of Toulouse (referee);
- December 14, 2017: PhD thesis of Marina Duran Moro, Univ. Grenoble Alpes (president).

C. Prieur:

- 18 décembre 2017: PhD thesis of Eliott Tixier, UPMC (referee);
- June 28, 2017: PhD thesis of Claire Delplancke, Univ. of Toulouse (referee);
- June 13, 2017: PhD thesis of Angie Pineda, Univ. of Caracas, Venezuela (president);

- March 1, 2017: PhD thesis of Nabil El Moçayd, Univ. of Toulouse (referee);
- February 1, 2017: PhD thesis of Patricia Tencaliec, Univ. Grenoble Alpes (directrice);
- February 16, 2017: HDR thesis of N. Eckert, Univ. Grenoble Alpes (referee).

F.-X. Le Dimet: PhD thesis of Hind Oubanas, Univ. of Toulouse (referee);

E. Arnaud: juries of M2 thesis and M2 Miage apprentices.

10.3. Popularization

M. Nodet and J. Erhel won the first prize of the second Imaginary Mathematics for Planet Earth competition with their web module entitled "Simulating the melting of ice caps" [26].

E. Blayo gave several outreach talks, in particular for middle school and high school students, and for more general audiences.

Ch. Kazantsev and E. Blayo are strongly involved in the creation of “La Grange des maths", a science center that will be located in Varces (south of Grenoble), which will offer a huge variety of mathematical hands-on exhibits. See http://www.la-grange-des-maths.fr/.

Ch. Kazantsev leads two IREM groups. One of them works in frames of the center “La Grange des maths" and prepares "The Mathematical box", a set of 23 games and mathematical activities designed to allow children to study mathematics in an original and autonomous way. Since October, these box are available to rent by secondary schools. Another group organizes "The Sunday Math Club" that teaches mathematics in a researchers way by proposing interesting mathematical problems to children from 10 to 17 years old.

M. Nodet and E. Arnaud co-organises a year-round weekly math club in two secondary schools, part of the national network "Math en Jeans", where pupils research open mathematical problems.

M. Nodet takes part in training modelling in mathematics to secondary school maths teachers through the regional "Maison pour la Science"

M. Nodet is in charge of an IREM group about building interdisciplinary projects for secondary school classes. Part of their work has been accepted for publication in the IREM national journal [28].

M. Nodet is a member of "Les Emulateurs", a group of Grenoble University professors meeting once a month around the subjects of innovative pedagogy and its applications to universities.

M. Nodet co-autored, with other Univ. Grenoble Alpes teachers, a paper at the Pedagogy conference QPES [27] and offered a 3h practical work session during this conference about "Peer assessment in education".

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