IN PARTNERSHIP WITH:
Université de Grenoble Alpes

Activity Report 2019

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

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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 6.1.2) 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 6.4) 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 6.3 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 (6.3.1). 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. New Software and Platforms

5.1. 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 2019, a new contract has been signed with CMEMS (Copernicus Marine Environment Moniroting Service) in order to extent the multiresolution capabilities of the AGRIF and its integration into the NEMO ocean system.

- 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

5.2. 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

5.3. 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 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: Arthur Vidard

5.4. 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

6. New Results

6.1. Modeling for Oceanic and Atmospheric flows

6.1.1. Numerical Schemes for Ocean Modelling

Participants: Eric Blayo, Matthieu Brachet, Laurent Debreu, Emilie Duval, Christopher Eldred, Nicholas Kevlahan, Florian Lemarié, Gurvan Madec, 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). As an example, the stabilization of the coupling between barotropic (fast) and baroclinic (slow) modes in a three dimensional ocean model is a source of large numerical dissipation. This has been studied in details in [6].
F. Lemarié and L. Debreu (with H. Burchard, K. Klingbeil and J. Sainte-Marie) have organized the international COMMODORE workshop on numerical methods for oceanic models (Paris, Sept. 17-19, 2018). https://commodore2018.sciencesconf.org/, see [12] for a summary of the scientific discussions. The next COMMODORE meeting is planned for February 2020 and will take place in Hamburg. https://www.conferences.uni-hamburg.de/event/76.

With the increase of resolution, the hydrostatic assumption becomes less valid and the AIRSEA group also works on the development of non-hydrostatic ocean models. The treatment of non-hydrostatic incompressible flows leads to a 3D elliptic system for pressure that can be ill conditioned in particular with non geopotential vertical coordinates. That is why we favour the use of the non-hydrostatic compressible equations that removes the need for a 3D resolution at the price of reincluding acoustic waves [29].
In addition, Emilie Duval started her PhD in September 2018 on the coupling between the hydrostatic incompressible and non-hydrostatic compressible equations.

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. In the context of the HEAT project, we worked on the analysis of dispersion analysis of continuous and discontinuous Galerkin methods of arbitrary degree of approximation ([31]), on compatible Galerkin schemes for shallow water model in 2D ([9]). In addition, we worked on the discrete formulation of the thermal rotating shallow water equations. This formulation, based on quasi-Hamiltonian discretizations methods, allows for the first time total mass, buoyancy and energy conservation to machine precision ([8]).

Accurate and stable implementation of bathymetry boundary conditions in ocean models remains a challenging problem. The dynamics of ocean flow often depend sensitively on satisfying bathymetry boundary conditions and correctly representing their complex geometry. Generalized (e.g.) terrain-following coordinates are often used in ocean models, but they require smoothing the bathymetry to reduce pressure gradient errors. Geopotential -coordinates are a common alternative that avoid pressure gradient and numerical diapycnal diffusion errors, but they generate spurious flow due to their “staircase” geometry. In [5], we introduce a new Brinkman volume penalization to approximate the no-slip boundary condition and complex geometry of bathymetry in ocean models. This approach corrects the staircase effect of -coordinates, does not introduce any new stability constraints on the geometry of the bathymetry and is easy to implement in an existing ocean model. The porosity parameter allows modelling subgrid scale details of the geometry. We illustrate the penalization and confirm its accuracy by applying it to three standard test flows: upwelling over a sloping bottom, resting state over a seamount and internal tides over highly peaked bathymetry features.

Figure (1) shows strong improvements obtained when the penalization method is used in comparison with traditional terrain following σ simulations. At 6km resolution, the penalization methods (Figure (1) d)), that takes into account details of bathymetry, allows to recover internal tide wave beams closed to the 3km simulation. (Figure (1) a)).

6.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, Florian Lemarié, Sophie Thery, Simon Clément.

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 [49]. 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 (see [21] for an overview). Our activities can be divided into four general topics

1. *Stability and consistency analysis of existing coupling methods*: in [49] 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 in [37] 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 the scope was on including the formulation of physical parameterizations in the theoretical analysis of the coupling, in particular the parameterization schemes to compute air-sea fluxes [56]. 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. This metamodel is more adequate to conduct the mathematical analysis of the coupling while being physically satisfactory [57]. More recently we have started to work specifically on the discretization methods for the parameterization of planetary boundary layers in climate models [51] which takes the form of an nonstationary nonlinear parabolic equation. The objective is to derive a discretization for which we could prove nonlinear stability criteria and show robustness to large variations in parabolic Courant number while being consistent with our knowledge of the underlying physical principles (e.g. the Monin-Obukhov theory in the surface layer).This work will continue in the framework of the PhD-thesis of C. Simon.

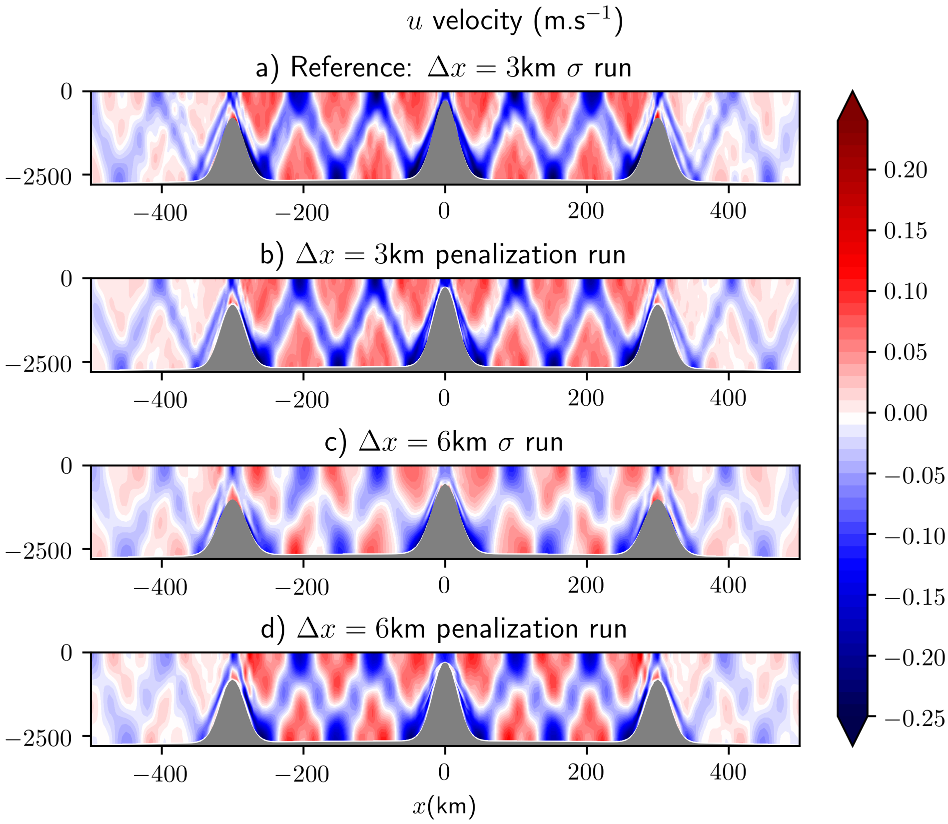

Figure 1. u velocity. Instantaneous solutions of the internal tide test case after 12 M2 tidal cycles of integration. (a) The reference σ coordinate run at 3 km resolution. (b) The penalized run at 3 km resolution. (c) The σ-coordinate run at 3 km resolution. (d) The penalized run at 6 km resolution.

3. *A simplified atmospheric boundary layer model for oceanic purposes*: Part of our activities within the IMMERSE project is dedicated to the development of a simplified model of the marine atmospheric boundary layer of intermediate complexity between a bulk parameterization and a full three-dimensional atmospheric model and to its integration to the NEMO general circulation model [24]. A constraint in the conception of such a simplified model is to allow an apt representation of the downward momentum mixing mechanism and partial re-energization of the ocean by the atmosphere while keeping the computational efficiency and flexibility inherent to ocean only modeling. A paper is in preparation and will be submitted in early 2020.
4. *Analysis of air-sea-wave 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. [50]) in large-scale realistic ocean-atmosphere coupled simulations [16], [53]. Moreover, within the ALBATROS project [23], we have contributed to the development of a 2-way coupling between an ocean global circulation model (NEMO) with a surface wave model (WW3). Such coupling is not straightforward to implement since it requires modifications of the governing equations, boundary conditions and subgrid scale closures in the oceanic model. A paper is currently under open discussion in Geoscientific Model Development journal on that topic [4].
5. *Efficient coupling methods*: we have been developing coupling approaches for several years, based on so-called Schwarz algorithms. In particular, we addressed the development of efficient interface conditions for multi-physics problems representative of air-sea coupling [61] (paper in preparation). This work is done in the framework of S. Théry PhD (started in fall 2017). During the internship of C. Simon, efficient interface conditions have been derived at a (semi)-discrete level and can thus be systematically compared with the ones obtained from the continuous problem.

These topics are addressed through strong collaborations between the applied mathematicians and the climate community (Meteo-France, Ifremer, LMD, and LOCEAN). Our work on ocean-atmosphere coupling has steadily matured over the last few years and has reached a point where it triggered interest from the climate community. Through the funding of the COCOA ANR project (started in January 2017, PI: E. Blayo), Airsea team members play a major role in the structuration of a multi-disciplinary scientific community working on ocean-atmosphere coupling spanning a broad range from mathematical theory to practical implementations in climate models. An expected outcome of this project should be the design of a benchmark suite of idealized coupled test cases representative of known issues in coupled models. Such idealized test cases should motivate further collaborations at an international level. In this context, a single-column version of the CNRM climate models has been designed and several coupling algorithms have been implemented (work done by S. Valcke, CERFACS). This model will be used to illustrate the relevance of our theoretical work in a semi-realistic context.

6.1.3. 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 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. Results shows significant improvement compared to the usual approach on this simple system. 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.

Following this line of research, CASIS, a collaborative project with Mercator Océan started late 2017 until end of 2019 in order to extend these developments to iterative Kalman smoother data assimilation scheme, in the framework of a coupled ocean-atmospheric boundary layer context.

6.1.4. Optimal control of grids and schemes for ocean model.

Participants: Laurent Debreu, Eugene Kazantsev.

In [28], variational data assimilation technique is applied to a simple bidimensional wave equation that simulates propagation of internal gravity waves in the ocean in order to control grids and numerical schemes. Grid steps of the vertical grid, Brunt-Vaisala frequency and approximation of the horizontal derivative were used as control parameters either separately or in the joint control. Obtained results show that optimized parameters may partially compensate errors committed by numerical scheme due to insufficient grid resolution.

Optimal vertical grid steps and coefficients in horizontal derivative approximation found in the variational control procedure allow us to get the model solution that is rather close to the solution of the reference model. The error in the wave velocity on the coarse grid is mostly compensated in experiments with joint control of parameters while the error in the wave amplitude occurs to be more difficult to correct.

However, optimal grid steps and discretization schemes may be in a disagreement with requirements of other model physics and additional analysis of obtained optimized parameters from the point of view of they agreement with the model is necessary.

6.1.5. Machine learning for parametrisation of the model dissipation.

Participants: Laurent Debreu, Eugene Kazantsev, Arthur Vidard, Olivier Zahm.

Artificial intelligence and machine learning may be considered as a potential way to address unresolved model scales and to approximate poorly known processes such as dissipation that occurs essentially at small scales. In order to understand the possibility to combine numerical model and neural network learned with the aid of external data, we develop a network generation and learning algorithm and use it to approximate nonlinear model operators. Beginning with a simple nonlinear equations like transport-diffusion and Burgers ones, we use artificially generated external data to learn the network by Adam algorithm [47]. Results show the possibility to approximate nonlinear, and even discontinuous dissipation operator with a quite good accuracy, however, several millions iterations are necessary to learn.

6.1.6. Nonhydrostatic Modeling

Participants: Eric Blayo, Laurent Debreu, Emilie Duval.

In the context of the French initiative CROCO (Coastal and Regional Ocean COmmunity model, https://www.croco-ocean.org) for the development of a new oceanic modeling system, Emilie Duval is working on the design of methods to couple local nonhydrostatic models to larger scale hydrostatic ones (PhD started in Oct. 2018). Such a coupling is quite delicate from a mathematical point of view, due to the different nature of hydrostatic and nonhydrostatic equations (where the vertical velocity is either a diagnostic or a prognostic variable). A prototype has been implemented, which allows for analytical solutions in simplified configurations and will make it possible to test different numerical approaches.

6.2. Assimilation of spatially dense observations

Participants: Elise Arnaud, François-Xavier Le Dimet, Arthur Vidard, Long Li, Emilie Rouzies.

6.2.1. 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 in the framework of a Long Li's Phd in co-supervision with Jianwei Ma.

6.2.2. Observation error representation

Accounting for realistic observations errors is a known bottleneck in data assimilation, because dealing with error correlations is complex. Following a previous study on this subject, we propose to use multiscale modelling, more precisely wavelet transform, to address this question. In [3] we investigate the problem further by addressing two issues arising in real-life data assimilation: how to deal with partially missing data (e.g., concealed by an obstacle between the sensor and the observed system); how to solve convergence issues associated to complex observation error covariance matrices? Two adjustments relying on wavelets modelling are proposed to deal with those, and offer significant improvements. The first one consists in adjusting the variance coefficients in the frequency domain to account for masked information. The second one consists in a gradual assimilation of frequencies. Both of these fully rely on the multiscale properties associated with wavelet covariance modelling.

A collaborative project started with C. Lauvernet (IRSTEA) in order to make use of this kind of assimilation strategies on the control of pesticide transfer and it led to the co supervision of E. Rouzies PhD, starting in Dec 2019.

6.2.3. 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. This has been extended to water pollutant tracking as part of Long Li's PhD and published in [13]

6.3. Model reduction / multiscale algorithms

6.3.1. Parameter space dimension reduction and Model order reduction

Participants: Mohamed Reda El Amri, Arthur Macherey, Youssef Marzouk, Clémentine Prieur, Alessio Spantini, Ricardo Baptista, Daniele Bigoni, Olivier Zahm.

Numerical models describing the evolution of the system (ocean + atmosphere) contain a large number of parameters which are generally poorly known. The reliability of the numerical simulations strongly depends on the identification and calibration of these parameters from observed data. In this context, it seems important to understand the kinds of low-dimensional structure that may be present in geophysical models and to exploit this low-dimensional structure with appropriate algorithms. We focus in the team, on parameter space dimension reduction techniques, low-rank structures and transport maps techniques for probability measure approximation.

In [25], we proposed a framework for the greedy approximation of high-dimensional Bayesian inference problems, through the composition of multiple low-dimensional transport maps or flows. Our framework operates recursively on a sequence of “residual” distributions, given by pulling back the posterior through the previously computed transport maps. The action of each map is confined to a low-dimensional subspace that we identify by minimizing an error bound. At each step, our approach thus identifies (i) a relevant subspace of the residual distribution, and (ii) a low-dimensional transformation between a restriction of the residual onto this sub-space and a standard Gaussian. We prove weak convergence of the approach to the posterior distribution, and we demonstrate the algorithm on a range of challenging inference problems in differential equations and spatial statistics.

The paper [34] introduces a novel error estimator for the Proper Generalized Decomposition (PGD) approximation of parametrized equations. The estimator is intrinsically random: It builds on concentration inequalities of Gaussian maps and an adjoint problem with random right-hand side, which we approximate using the PGD. The effectivity of this randomized error estimator can be arbitrarily close to unity with high probability, allowing the estimation of the error with respect to any user-defined norm as well as the error in some quantity of interest. The performance of the error estimator is demonstrated and compared with some existing error estimators for the PGD for a parametrized time-harmonic elastodynamics problem and the parametrized equations of linear elasticity with a high-dimensional parameter space.

In the framework of Arthur Macherey’s PhD, we have also proposed in [26] algorithms for solving high-dimensional Partial Differential Equations (PDEs) that combine a probabilistic interpretation of PDEs, through Feynman-Kac representation, with sparse interpolation. Monte-Carlo methods and time-integration schemes are used to estimate pointwise evaluations of the solution of a PDE. We use a sequential control variates algorithm, where control variates are constructed based on successive approximations of the solution of the PDE. We are now interested in solving parametrized PDE with stochastic algorithms in the framework of potentially high dimensional parameter space. In [36], we consider gradient-based dimension reduction of vector-valued functions. Multivariate functions encountered in high-dimensional uncertainty quantification problems often vary most strongly along a few dominant directions in the input parameter space. In this work, we propose a gradient-based method for detecting these directions and using them to construct ridge approximations of such functions, in the case where the functions are vector-valued. The methodology consists of minimizing an upper bound on the approximation error, obtained by subspace Poincaré inequalities. We have provided a thorough mathematical analysis in the case where the parameter space is equipped with a Gaussian probability measure. We are now working on the nonlinear generalization of active subspaces. Reduced models are also developed In the framework of robust inversion. In [43], we have combined a new greedy algorithm for functional quantization with a Stepwise Uncertainty Reduction strategy to solve a robust inversion problem under functional uncertainties. An ongoing work aims at further reducing the number of simulations required to solve the same robust inversion problem, based on Gaussian process meta-modeling on the joint input space of deterministic control parameters and functional uncertain variable. These results are applied to automotive depollution. This research axis is conducted in the framework of the Chair OQUAIDO.

6.4. Sensitivity analysis

Participants: Elise Arnaud, Eric Blayo, Laurent Gilquin, Maria Belén Heredia, Adrien Hirvoas, François-Xavier Le Dimet, Henri Mermoz Kouye, Clémentine Prieur, Laurence Viry.

6.4.1. 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.

6.4.2. Global sensitivity analysis

Participants: Elise Arnaud, Eric Blayo, Laurent Gilquin, Maria Belén Heredia, Adrien Hirvoas, Alexandre Janon, Henri Mermoz Kouye, Clémentine Prieur, Laurence Viry.

6.4.2.1. Global sensitivity analysis with dependent inputs

An important challenge for stochastic sensitivity analysis is to develop methodologies which work for dependent inputs. Recently, the Shapley value, from econometrics, was proposed as an alternative to quantify the importance of random input variables to a function. Owen [54] derived Shapley value importance for independent inputs and showed that it is bracketed between two different Sobol' indices. Song et al. [60] recently advocated the use of Shapley value for the case of dependent inputs. In a recent work [55], 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 [30].

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

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 an approach to render the replication method iterative, enabling the required number of evaluations to be controlled. With this approach, more accurate Sobol' estimates are obtained while recycling previous sets of model evaluations. Its main characteristic is to rely on iterative construction of stratified designs, latin hypercubes and orthogonal arrays [45]

In [11] 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.

The replicated designs strategy for global sensitivity analysis was also implemented in the applied framework of marine biogeochemical modeling, making use of distributed computing environments [15]. It has allowed to perform a global sensitivity analysis with input space dimension more than eighty, without any screening preliminary step.

6.4.2.3. Green sensitivity for multivariate and functional outputs

Participants: María Belén Heredia, Clémentine Prieur.

Another research direction for global SA algorithm starts with the report that most of the algorithms to compute sensitivity measures require special sampling schemes or additional model evaluations so that available data from previous model runs (e.g., from an uncertainty analysis based on Latin Hypercube Sampling) cannot be reused. One challenging task for estimating global sensitivity measures consists in recycling an available finite set of input/output data. Green sensitivity, by recycling, avoids wasting. These given data have been discussed, e.g., in [59], [58]. Most of the given data procedures depend on parameters (number of bins, truncation argument...) not easy to calibrate with a bias-variance compromise perspective. Adaptive selection of these parameters remains a challenging issue for most of these given-data algorithms. In the context of María Belén Heredia's PhD thesis, we have proposed a non-parametric given data estimator for agregated Sobol' indices, introduced in [48] and further developed in [44] for multivariate or functional outputs. This last work should be submitted soon.

6.4.2.4. Global sensitivity analysis for parametrized stochastic differential equations

Participants: Henri Mermoz Kouye, Clémentine Prieur.

Many models are stochastic in nature, and some of them may be driven by parametrized stochastic differential equations. It is important for applications to propose a strategy to perform global sensitivity analysis (GSA) for such models, in presence of uncertainties on the parameters. In collaboration with Pierre Etoré (DATA department in Grenoble), Clémentine Prieur proposed an approach based on Feynman-Kac formulas [10]. The research on GSA for stochastic simulators is still ongoing, first in the context of the MATH-AmSud project FANTASTIC (Statistical inFerence and sensitivity ANalysis for models described by sTochASTIC differential equations) with Chile and Uruguay, secondly through the PhD thesis of Henri Mermoz Kouye, co-supervised by Clémentine Prieur, in collaboration with INRA Jouy.

6.5. Model calibration and statistical inference

6.5.1. Bayesian calibration

Participants: Maria Belén Heredia, Adrien Hirvoas, Clémentine Prieur.

Physically-based avalanche propagation models must still be locally calibrated to provide robust predictions, e.g. in long-term forecasting and subsequent risk assessment. Friction parameters cannot be measured directly and need to be estimated from observations. Rich and diverse data is now increasingly available from test-sites, but for measurements made along ow propagation, potential autocorrelation should be explicitly accounted for. In the context of María Belén Heredia's PhD, in collaboration with IRSTEA Grenoble, we have proposed in a comprehensive Bayesian calibration and statistical model selection framework with application to an avalanche sliding block model with the standard Voellmy friction law and high rate photogrammetric images. An avalanche released at the Lautaret test-site and a synthetic data set based on the avalanche were used to test the approach. Results have demonstrated i) the effciency of the proposed calibration scheme, and ii) that including autocorrelation in the statistical modelling definitely improves the accuracy of both parameter estimation and velocity predictions. In the context of the energy transition, wind power generation is developing rapidly in France and worldwide. Research and innovation on wind resource characterisation, turbin control, coupled mechanical modelling of wind systems or technological development of offshore wind turbines floaters are current research topics. In particular, the monitoring and the maintenance of wind turbine is becoming a major issue. Current solutions do not take full advantage of the large amount of data provided by sensors placed on modern wind turbines in production. These data could be advantageously used in order to refine the predictions of production, the life of the structure, the control strategies and the planning of maintenance. In this context, it is interesting to optimally combine production data and numerical models in order to obtain highly reliable models of wind turbines. This process is of interest to many industrial and academic groups and is known in many fields of the industry, including the wind industry, as "digital twin". The objective of Adrien Hirvoas's PhD work is to develop of data assimilation methodology to build the "digital twin" of an onshore wind turbine. Based on measurements, the data assimilation should allow to reduce the uncertainties of the physical parameters of the numerical model developed during the design phase to obtain a highly reliable model. Various ensemble data assimilation approches are currently under consideration to address the problem. In the context of this work, it is necessary to develop algorithms of identification quantifying and ranking all the uncertainty sources. This work in done in collaboration with IFPEN.

6.5.2. *Non-Parametric statistical inference 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 [39] and when only partial observational data are available. A paper on the non parametric estimation of the drift has been accepted recently [40] (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 [40], in collaboration with J.R. Leon (Montevideo, Uruguay) and P. Cattiaux (Toulouse). Recursive estimators have been also proposed by the same authors in [41], 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 [42], 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 [52].

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 also have a collaboration with Karine Bertin (Valparaiso, Chile), Nicolas Klutchnikoff (Université Rennes) and Jose R. León (Montevideo, Uruguay) funded by a MATHAMSUD project (2016-2017) and by the LIA/CNRS (2018). We are interested in new adaptive estimators for invariant densities on bounded domains [38], and would like to extend that results to hypo-elliptic diffusions.

6.6. Modeling and inference for extremes

Participants: Philomène Le Gall, Clémentine Prieur, Patricia Tencaliec.

In [19], we are 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 Anne-Catherine Favre (LGGE-Lab in Grenoble) and Philippe Naveau (LSCE, Paris).

In the context of Philomène Le Gall's PhD thesis, we are applying the aforementioned modeling of extreme precipitation with the aim of regionalizing extreme precipitation.

6.7. Land Use and Transport Models Calibration

Participants: 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 [46] and Thomas Capelle defended his in April 2017 and published his latest results in [2].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

A 3-year contract (from June 2016 to June 2019) named ALBATROSS with Mercator-Ocean on the topic « Interaction océan, vagues, atmosphère à haute résolution» (PI: F. Lemarié).

A 2-year contract with Mercator-Ocean on the thematic "The AGRIF software in the NEMO European ocean model": see 5.1

Contract with IFPEN (Institut Français du pétrole et des énergies nouvelles), for the supervision of a PhD (Adrien Hirvoas). Research subject: Development of a data assimilation method for the calibration and continuous update of wind turbines digital twins

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 [1] has been funded by OQUAIDO. The Chair is reconducted for one year in 2020 and then a new contract should be approved by all partners for a new 4-years period.

8. Partnerships and Cooperations

8.1. Regional Initiatives

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

8.2. National Initiatives

8.2.1. ANR

A 4-year contract : ANR COCOA (COmprehensive Coupling approach for the Ocean and the Atmosphere). PI: E. Blayo. (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.

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

A 4-year contract : ANR ADOM (Asynchronous Domain decomposition methods)

A 5-year contract : ANR MELODY (Bridging geophysics and MachinE Learning for the modeling, simulation and reconstruction of Ocean DYnamic)

A 5-year contract with the French Navy (SHOM) on the improvment of the CROCO ocean model http://www.croco-ocean.org.

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.

8.2.2. Inria Challenge

Sea Uncertainty Representation and Forecast (SURF),

Coord : Airsea (A. Vidard),

Partenaires Inria : Ange, Cardamom, Fluminance, Lemon, Mingus, Defi

Partenaires extérieurs: BRGM, Ifremer, SHOM

8.2.3. 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 5.3.

C. Prieur is co-advising the PhD thesis of Henri Mermoz Kouye, ine the framework of the Inria-INRA collaboration.

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 the group (co-chair). In particular, she will co-chair next GdR annual meeting in Aussois (May 2020). 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

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

H2020 project IMMERSE (Improving Models for Marine EnviRonment SErvices) is funded from 2018-12-01 to 2022-11-30 (Inria contact: Florian Lemarié, coordinator: J. Le Sommer, CNRS). The overarching goal of the project is to ensure that the Copernicus Marine Environment Monitoring Service (CMEMS) will have continuing access to world-class marine modelling tools for its next generation systems while leveraging advances in space and information technologies, therefore allowing it to address the ever-increasing and evolving demands for marine monitoring and prediction in the 2020s and beyond. See also https://cordis.europa.eu/project/rcn/218810/factsheet/fr and https://immerse-ocean.eu/

8.3.2. Collaborations in European Programs, Except FP7 & H2020

Program: C3S

Project acronym: ERGO

Project title: Enabling an Ensemble of Data Assimilation for the Ocean

Duration: Février 2019 - juillet 2021

Coordinator: Arthur Vidard

Other partners: Cerfacs (France), Met Office (U.K.), CMRE (int, Italie)

Abstract: The scope of this contract is to improve ocean data assimilation capabilities at ECMWF, used in both initialization of seasonal forecasts and generation of coupled Earth System reanalyses. In particular it shall focus on i) improving ensemble capabilities in NEMO and NEMOVAR and the use of their information to represent background error statistics; ii) extend NEMOVAR capabilities to allow for multiple resolution in multi-incremental 3D-Var; iii) make better use of ocean surface observations. It shall also involve performing scout experiments and providing relevant diagnostics to evaluate the benefit coming from the proposed developments.

8.3.3. 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 : SAMO board

SAMO board is in charge of the organization of the SAMO (sensitivity analysis of model outputs) conferences, every three years. It is strongly supporter by the Joint Research Center of the European Commission. In 2019, Clémentine Prieur, which is part of this board, as also co-chair of a satellite event on the future of sensitivity analysis. A position paper is under construction, as a synthesis of the discussions hold in Barcelona (autumn 2019).

8.4. International Initiatives

8.4.1. Inria Associate Teams Not Involved in an Inria International Labs

8.4.1.1. UNQUESTIONABLE

Title: UNcertainty QUantification is ESenTIal for OceaNic & Atmospheric flows proBLEms.

International Partner: Massachusetts Institute of Technology (United States) - Aerospace Computational Design Laboratory - Youssef Marzouk

Start year: 2018

See also: https://team.inria.fr/unquestionable/

The ability to understand and predict the behavior of geophysical flows is of greatest importance, due to its strong societal impact. Numerical models are essential to describe the evolution of the system (ocean + atmosphere), and involve a large number of parameters, whose knowledge is sometimes really poor. The reliability of the numerical predictions thus requires a step of parameter identification. The Inria-AIRSEA team has a strong expertise in variational approaches for inverse problems. An alternative is the use of particle filters, whose main advantage is their ability to tackle non-gaussian frameworks. However, particle filters suffer from the curse of dimensionality. The main objective of the collaboration we propose between the Inria-AIRSEA team and the MIT UQ group is the understanding of potential low-dimensional structure underlying geophysical applications, then the exploitation of such structures to extend particle filter to high-dimensional applications.

8.4.2. Inria International Partners

F. Lemarié and L. Debreu collaborate with Hans Burchard and Knut Klingbeil from the Leibniz-Institut für Ostseeforschung in Warnemünde (Germany) [32], [12].

C. Prieur collaborates with Jose R. Leon (Universdad de la república de Uruguay, Montevideo).

C. Prieur collaborates with K. Bertin (CIMFAV, Valparaíso).

F.-X. Le Dimet is a Honorary Professor of the Institut of Mechanics, Ac.Sci. Vietnam.

F.-X. Le Dimet is a Honorary Professor of the Institut of Numerical Mathematics, Russian Ac.Sci.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

Alistair Adcroft (Princeton Univ.) visited the team in Jan. 2019

Jose R. León was visiting the team during two weeks. He is working with Clémentine Prieur, in collaboration with Pierre Etoré and Adeline Samson (DATA department of LJK) on UQ for models described by SDE.

Nicholas Kevlahan, from McMaster University (Canada) was a visiting scientist of the AIRSEA team for 10 months in 2018-2019.

Victor Shutyaev, from the Institut of Numerical Mathematics (Moscow, Russian Ac.Sci.) was visiting the team during two weeks to collaborate with F.-X. Le Dimet [17].

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Journal

9.1.1.1. Member of the Editorial Boards

F. Lemarié is associate editor of the Journal of Advances in Modeling Earth Systems (JAMES)

9.1.1.2. Reviewer - Reviewing Activities

E. Blayo: reviewer for Ocean Modelling, Journal of Scientific Computing

F. Lemarié reviewed papers for Q. J. Roy. Meteorol. Soc. , Ocean Model. and J. Adv. Mod. Earth Sys.

9.1.2. Invited Talks

E. Blayo: Journées Tarantola : défis en géosciences, Paris, juin 2019

E. Blayo: Workshop Modélisation océan-atmosphère, Rennes, septembre 2019

F.-X. Le Dimet: The Mathematics of Climate and the Environment, IHP Paris 2019, Nov. 12-15

F. Lemarié has given an invited talk at the Banff International Research Station during the Physics-Dynamics Coupling in Earth System Models workshop [21]

9.1.3. Leadership within the Scientific Community

L. Debreu is the chair of the CNRS-INSU research program LEFE-MANU on mathematical and numerical methods for ocean and atmosphere https://insu.cnrs.fr/fr/methodes-mathematiques-et-numeriques-manu since April 2018.

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

9.1.4. Scientific Expertise

E. Blayo was the head of the HCERES evaluation committee for the Maison de la Simulation (Jan. 2019)

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

F. Lemarié is a member of the NEMO (https://www.nemo-ocean.eu/) Developers Committee as external expert.

9.1.5. Research Administration

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

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

E. Arnaud is in charge of the AMAC (Algorithmes, Modeles, Analyses, Calcul) department 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 Research Council of UGA.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: E. Blayo, Mathematical analysis, 80h, L1, University Grenoble Alpes, France

License: E. Arnaud, Mathematics for engineer, 50h, L1, University Grenoble Alpes, France.

License: E. Arnaud, statisctics for biologists, 40h, L2, University Grenoble Alpes, France.

Licence: C.Kazantsev, Mathematical tools for scientists and engineers, 100h, L1, University Grenoble Alpes, France

Licence: C.Kazantsev, Mathematics for engineer, 60h, L2, University Grenoble Alpes, France

Master: E. Blayo, Partial Differential Equations, 45h, M1, University Grenoble Alpes, France

Master: E. Arnaud, A. Vidard: Inverse problem and data assimilation, 28h, M2, Univ. Grenoble-Alpes, France

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

Doctorat: E. Blayo, A. Vidard, Introduction to Data Assimilation, 20h,University Grenoble Alpes, France

E-learning: E. Arnaud, Mathematics for engineer, L1, Pedagogical resources on http://math.u-ga.fr and videos for http://tinyurl.com/youtube-mat207

E-learning: E. Arnaud, Inverse problem and data assimilation, L2, Pedagogical resources on http://math.u-ga.fr

9.2.2. Supervision

Intern : Simon Clément, Study of discretized Schwarz waveform relaxation algorithms, M2R, applied mathematics, UGA, 6 months, E. Blayo and F. Lemarié

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

PhD in progress : Emilie Duval, Coupling hydrostatic and nonhydrostatic ocean circulation models. October 2018, L. Debreu and E. Blayo.

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

PhD in progress : Rishabh Batth, Asynchronousparallel in time schemes for data assimilation, December 2019, L. Debreu and A. Vidard.

PhD in progress : Simon Clément, Numerical analysis for reconciling in space and time the air-sea exchanges and their parameterization. October 2019, E. Blayo and F. Lemarié.

PhD in progress: Adrien Hirvoas, Development of a data assimilation method for the calibration and continuous update of wind turbines digital twins, May 2018, E. Arnaud, C. Prieur, F. Caleyron

PhD: Mohamed Reda El Amri, Analyse d'incertitudes et de robustesse pour les modèles à entrées et sorties fonctionnelles,[1], Univ.Grenoble Alpes, April, 29, 2019. Clémentine Prieur, Céline Helbert (Centrale Lyon), funded by IFPEN, in the OQUAIDO chair program.

Post Doc in progress : Anass El Aouni, Multi-resolution techniques for ocean data assimilation, October 2019, A. Vidard

9.2.3. Juries

Arthur Vidard

Feb. 2019: PhD thesis of Olivier Guillet, INPT Toulouse (reporter)

E. Blayo:

Feb. 12, 2019: PhD thesis of Benoît Pinier, University of Rennes (reporter)

Apr. 5, 2019: HDR thesis of Sophie Ricci, University of Toulouse (reporter)

Oct. 21, 2019: PhD thesis of Jai Chowdhry Beeman, University Grenoble Alpes (president)

Dec. 18, 2019: PhD thesis of Alexandre Devers, University Grenoble Alpes (president)

Arthur Vidard was part of Inria CRCN recruitment juries in Bordeaux–Sud-ouest and Lille-Nord Europe

E. Arnaud is in charge of ATER recruitment in computer sciences, University Grenoble Alpes

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

E.Kazantsev is a member of the Local Commission for Permanent Formation of Inria Grenoble - Rhône-Alpes.

9.3.2. Education

Ch. Kazantsev and E. Blayo are strongly involved in the creation and dissemination of pedagogic suitcases with mathematical activities designed for primary and secondary school (used by 10,000 – 12,000 pupils in 2018-2019). This is done in collaboration with the Rectorat de Grenoble.

E. Arnaud has animation of a "laboratoire des mathématiques", Pablo Neruda School, Saint Martin d'Hères

C. Kazantsev is a member of an IREM group for creation of scientific activities for professional development of secondary schools teachers.

C. Kazantsev is a member of an International Inter-IREM commission, which work on the multi-languages problem for children in the mathematical learning. Three meetings take place in Paris during the year, the first was on September 28.

C. Kazantsev participated to the collaboration program with the Ecole Normale Supérieure de Bamako, Mali. She spent ten days in Bamako to present the modelisation teaching and the purpose and activities of "La Grange des Maths" group. Bamako, ENSup, January, 13-25

C. Kazantsev participated to the "Colloque du cinquantenaire des IREM" with a presentation of the activities of "La Grange des Maths", Besançon, May, 9-11

9.3.3. Interventions

National events:

Ch. Kazantsev and E. Blayo are strongly involved in the creation of "La Grange des maths", a science popularization 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 participated at the "Culture and mathematical games Salon", Place St Sulpice, Paris, 23-26 May.

Ch. Kazantsev and E. Blayo participated in the "Fête de la Science", October, 12.

E. Arnaud. gave a presentation "(Se) tromper avec les chiffres" at the conference "Sciences et esprit critique, interroger les certitudes", Maison pour la sciences, Acadèmie de Grenoble, 8 nov. 2018, Grenoble.

Public exhibitions

C.Kazantsev participated in the "Oriel des Maths" and in the "Forum des associations" with the presentation of the "La Grange des Maths" center and its activities. Varces, March, 10.

C.Kazantsev participated at the "Remue-méninges festival" with the presentation of the "Maths à modeler" activities. Echirolles, April, 11.

C.Kazantsev participated to the "Sou des écoles", with the presentation of the "La Grange des Maths" activities. Varces, June, 15.

C.Kazantsev participated at the "Raout de Domène" with the presentation of mathematical animations. Domene, September, 1.

In educational institutions

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

C.Kazantsev presented mathematical animations to pupils of the Jean Mermoz scholl in Poisat for about 80 children during 3 hours. Poisat, May, 29.

E. Arnaud gave a talk "(Se) tromper avec les chiffres" for pupils of secondary schools on the 8th of March 2019 and the 2nd of May 2019.

9.3.4. Creation of media or tools for science outreach

C.Kazantsev participated in the edition of the Teachers notebooks which explain and advise how to use the "La Grange Suitcases" (sets of mathematical games, problems and animations) destined for primary and secondary schools teachers as well as for the general public.

C.Kazantsev participated in the creation of mathematical activities that can be autonomously used by schoolchildren of primary and secondary schools and by the general public.

E. Arnaud, in charge of the UGA Idex project math@uga : implementation of a collaborative moodle platform http://math.u-ga.fr to share pedagogical resources within teachers and towards students.

E. Arnaud, participation to UGA Idex projects Caseine and data@ugat

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

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Articles in International Peer-Reviewed Journals

[2] T. CAPELLE, P. STURM, A. VIDARD, B. MORTON. *Calibration of the Tranus Land Use Module: Optimisation-Based Algorithms, their Validation, and Parameter Selection by Statistical Model Selection*, in "Computers, Environment and Urban Systems", September 2019, vol. 77, pp. 101146:1-13 [*DOI :* 10.1016/J.COMPENVURBSYS.2017.04.009], https://hal.inria.fr/hal-01519654

[3] V. CHABOT, M. NODET, A. VIDARD. *Multiscale Representation of Observation Error Statistics in Data Assimilation*, in "Sensors", 2019, pp. 1-19, forthcoming, https://hal.inria.fr/hal-02421699

[4] X. COUVELARD, F. LEMARIÉ, G. SAMSON, J.-L. REDELSPERGER, F. ARDHUIN, R. BENSHILA, G. MADEC. *Development of a 2-way coupled ocean-wave model: assessment on a global NEMO(v3.6)-WW3(v6.02) coupled configuration*, in "Geoscientific Model Development Discussions", August 2019, pp. 1-36 [*DOI :* 10.5194/GMD-2019-189], https://hal.inria.fr/hal-02267188

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Invited Conferences

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Conferences without Proceedings

[22] E. BLAYO, F. LEMARIÉ, C. PELLETIER, S. THÉRY. *Toward an improved simulation of ocean-atmosphere interactions*, in "2019 - conférence Modélisation Océan-Atmosphère", Rennes, France, September 2019, https://hal.inria.fr/hal-02415136

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