RESEARCH CENTRE

Rennes - Bretagne Atlantique

IN PARTNERSHIP WITH:

INRAE, Université Rennes 1

2020

ACTIVITY REPORT

Project-Team

FLUMINANCE

Fluid Flow Analysis, Description and Control from Image Sequences

IN COLLABORATION WITH: Institut de recherche mathématique de Rennes (IRMAR)

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

Contents

Project-Team FLUMINANCE

Creation of the Project-Team: 2009 July 01

Keywords

Computer sciences and digital sciences

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Other research topics and application domains

B3.2. – Climate and meteorology

B3.3. – Geosciences

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1 Team members, visitors, external collaborators

Research Scientists

- Etienne Mémin [Team leader, Inria, Senior Researcher, HDR]
- Jocelyne Chaux [Inria, Emeritus, HDR]
- Christophe Collewet [Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, Researcher, HDR]
- Evgueni Dinvay [Inria, Starting Research Position, from Sep 2020]
- Camilla Fiorini [Inria, Starting Research Position, from Sep 2020]
- Dominique Heitz [Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, Researcher, HDR]
- Noe Lahaye [Inria, Researcher, from Oct 2020]
- Gilles Tissot [Inria, Researcher]

Faculty Member

- Roger Lewandowski [Univ de Rennes I, Professor, HDR]

PhD Students

- Mohamed Yacine Ben Ali [CSTB Nantes]
- Benjamin Dufee [Inria, from Sep 2020]
- Berenger Hug [Inria, from Sep 2020]
- Long Li [Univ de Rennes I]
- Francesco Tucciarone [Inria, from Oct 2020]

Technical Staff

- Pranav Chandramouli [Inria, Engineer, until Jan 2020]

Administrative Assistant

- Huguette Bechu [Inria]

2 Overall objectives

The research group that we have entitled FLUMINANCE from a contraction between the words "Fluid" and "Luminance" is dedicated to the extraction of information on fluid flows from image sequences and to the development of tools for the analysis and control of these flows. The objectives of the group are at the frontiers of several important domains that range from fluid mechanics to geophysics. One of the main originality of the FLUMINANCE group is to combine cutting-edge researches on data-assimilation and flow numerical modeling with an ability to conduct proper intensive experimental validations on prototype flows mastered in laboratory. The scientific objectives decompose in four main themes:

- **Fluid flows characterization from images**
  In this first axis, we aim at providing accurate measurements and consistent analysis of complex fluid flows through image analysis techniques.The application domain ranges from industrial processes and experimental fluid mechanics to environmental sciences. This theme includes also the use of non-conventional imaging techniques such as Schlieren techniques, Shadowgraphs, holography. The objective will be here to go towards 3D dense velocity measurements.

- **Coupling dynamical model and image data**
  We focus here on the study, through image data, of complex and partially known fluid flows involving complex boundary conditions, multi-phase fluids, fluids and structures interaction problems. Our credo is that image analysis can provide sufficiently fine observations on small and medium scales to construct models which, applied at medium and large scale, account accurately for a wider range of the dynamics scales. The image data and a sound modeling of the dynamical uncertainty at the observation scale should allow us to reconstruct the observed flow and to provide efficient real flows (experimental or natural) based dynamical modeling. Our final goal will be to go towards a 3D reconstruction of real flows, or to operate large motion scales simulations that fit real world flow data and incorporate an appropriate uncertainty modeling.

- **Control and optimization of turbulent flows**
  We are interested on active control and more precisely on closed-loop control. The main idea is to extract reliable image features to act on the flow. This approach is well known in the robot control community, it is called visual servoing. More generally, it is a technique to control a dynamic system from image features. We plan to apply this approach on flows involved in various domains such as environment, transport, microfluidic, industrial chemistry, pharmacy, food industry, agriculture, etc.

- **Numerical models for geophysical flows simulation and analysis** Numerical models are very useful for environmental applications. Several difficulties must be handled simultaneously, in a multidisciplinary context. For example, in geophysics, media are highly heterogeneous and only few data are available. Stochastic models are often necessary to describe unresolved physical processes. Computational domains are characterized by complex 3D geometries, requiring adapted space discretization. Equations modeling flow and transport are transient, requiring also adapted time discretization. Moreover, these equations can be coupled together or with other equations in a global nonlinear system. These large-scale models are very time and memory consuming. High performance computing is thus required to run these types of scientific simulations. Supercomputers and clusters are quite powerful, provided that the numerical models are written with a parallel paradigm.

3 Research program

3.1 Estimation of fluid characteristic features from images

The measurement of fluid representative features such as vector fields, potential functions or vorticity maps, enables physicists to have better understanding of experimental or geophysical fluid flows. Such measurements date back to one century and more but became an intensive subject of research since the emergence of correlation techniques [48] to track fluid movements in pairs of images of a particles laden fluid or by the way of clouds photometric pattern identification in meteorological images. In computer vision, the estimation of the projection of the apparent motion of a 3D scene onto the image plane, referred to in the literature as optical-flow, is an intensive subject of researches since the 80's and the seminal work of B. Horn and B. Schunk [59]. Unlike to dense optical flow estimators, the former approach provides techniques that supply only sparse velocity fields. These methods have demonstrated to be robust and to provide accurate measurements for flows seeded with particles. These restrictions and their inherent discrete local nature limit too much their use and prevent any evolutions of these techniques towards the devising of methods supplying physically consistent results and small scale velocity measurements. It does not authorize also the use of scalar images exploited in numerous situations to visualize flows (image showing the diffusion of a scalar such as dye, p ollutant, light index refraction, fluorescein,...). At the opposite, variational techniques enable in a well-established mathematical framework to estimate spatially continuous velocity fields, which should allow more properly to go towards the measurement of smaller motion scales. As these methods are defined through PDE's systems they allow quite naturally constraints to be included such as kinematic properties or dynamic laws governing the observed fluid flows. Besides, within this framework it is also much easier to define characteristic features estimation procedures on the basis of physically grounded data model that describes the relation linking the observed luminance function and some state variables of the observed flow. The Fluminance group has allowed a substantial progress in this direction with the design of dedicated dense estimation techniques to estimate dense fluid motion fields. See [7] for a detailed review. More recently problems related to scale measurement and uncertainty estimation have been investigated [53]. Dynamically consistent and highly robust techniques have been also proposed for the recovery of surface oceanic streams from satellite images [50]. Very recently parameter-free approaches relying on uncertainty concept has been devised [51]. This technique outperforms the state of the art.

3.2 Data assimilation and Tracking of characteristic fluid features

Real flows have an extent of complexity, even in carefully controlled experimental conditions, which prevents any set of sensors from providing enough information to describe them completely. Even with the highest levels of accuracy, space-time coverage and grid refinement, there will always remain at least a lack of resolution and some missing input about the actual boundary conditions. This is obviously true for the complex flows encountered in industrial and natural conditions, but remains also an obstacle even for standard academic flows thoroughly investigated in research conditions.

This unavoidable deficiency of the experimental techniques is nevertheless more and more compensated by numerical simulations. The parallel advances in sensors, acquisition, treatment and computer efficiency allow the mixing of experimental and simulated data produced at compatible scales in space and time. The inclusion of dynamical models as constraints of the data analysis process brings a guaranty of coherency based on fundamental equations known to correctly represent the dynamics of the flow (e.g. Navier Stokes equations) [11]. Conversely, the injection of experimental data into simulations ensures some fitting of the model with reality.

To enable data and models coupling to achieve its potential, some difficulties have to be tackled. It is in particular important to outline the fact that the coupling of dynamical models and image data are far from being straightforward. The first difficulty is related to the space of the physical model. As a matter of fact, physical models describe generally the phenomenon evolution in a 3D Cartesian space whereas images provides generally only 2D tomographic views or projections of the 3D space on the 2D image plane. Furthermore, these views are sometimes incomplete because of partial occlusions and the relations between the model state variables and the image intensity function are otherwise often intricate and only partially known. Besides, the dynamical model and the image data may be related to spatio-temporal scale spaces of very different natures which increases the complexity of an eventual multiscale coupling. As a consequence of these difficulties, it is necessary generally to define simpler dynamical models in order to assimilate image data. This redefinition can be done for instance on an uncertainty analysis basis, through physical considerations or by the way of data based empirical specifications. Such modeling comes to define inexact evolution laws and leads to the handling of stochastic dynamical models. The necessity to make use and define sound approximate models, the dimension of the state variables of interest and the complex relations linking the state variables and the intensity function, together with the potential applications described earlier constitute very stimulating issues for the design of efficient data-model coupling techniques based on image sequences.

On top of the problems mentioned above, the models exploited in assimilation techniques often suffer from some uncertainties on the parameters which define them. Hence, a new emerging field of research focuses on the characterization of the set of achievable solutions as a function of these uncertainties. This sort of characterization indeed turns out to be crucial for the relevant analysis of any simulation outputs or the correct interpretation of operational forecasting schemes. In this context, stochastic modeling play a crucial role to model and process uncertainty evolution along time. As a consequence, stochastic parameterization of flow dynamics has already been present in many contributions of the Fluminance group in the last years and will remain a cornerstone of the new methodologies investigated by the team in the domain of uncertainty characterization.

This wide theme of research problems is a central topic in our research group. As a matter of fact, such a coupling may rely on adequate instantaneous motion descriptors extracted with the help of the techniques studied in the first research axis of the FLUMINANCE group. In the same time, this coupling is also essential with respect to visual flow control studies explored in the third theme. The coupling between a dynamics and data, designated in the literature as a Data Assimilation issue, can be either conducted with optimal control techniques [60, 61] or through stochastic filtering approaches [54, 57]. These two frameworks have their own advantages and deficiencies. We rely indifferently on both approaches.

3.3 Optimization and control of fluid flows with visual servoing

Fluid flow control is a recent and active research domain. A significant part of the work carried out so far in that field has been dedicated to the control of the transition from laminarity to turbulence. Delaying, accelerating or modifying this transition is of great economical interest for industrial applications. For instance, it has been shown that for an aircraft, a drag reduction can be obtained while enhancing the lift, leading consequently to limit fuel consumption. In contrast, in other application domains such as industrial chemistry, turbulence phenomena are encouraged to improve heat exchange, increase the mixing of chemical components and enhance chemical reactions. Similarly, in military and civilians applications where combustion is involved, the control of mixing by means of turbulence handling rouses a great interest, for example to limit infra-red signatures of fighter aircraft.

Flow control can be achieved in two different ways: passive or active control. Passive control provides a permanent action on a system. Most often it consists in optimizing shapes or in choosing suitable surfacing (see for example [52] where longitudinal riblets are used to reduce the drag caused by turbulence). The main problem with such an approach is that the control is, of course, inoperative when the system changes. Conversely, in active control the action is time varying and adapted to the current system's state. This approach requires an external energy to act on the system through actuators enabling a forcing on the flow through for instance blowing and suction actions [64, 56]. A closed-loop problem can be formulated as an optimal control issue where a control law minimizing an objective cost function (minimization of the drag, minimization of the actuators power, etc.) must be applied to the actuators [49]. Most of the works of the literature indeed comes back to open-loop control approaches [63, 58, 62] or to forcing approaches [55] with control laws acting without any feedback information on the flow actual state. In order for these methods to be operative, the model used to derive the control law must describe as accurately as possible the flow and all the eventual perturbations of the surrounding environment, which is very unlikely in real situations. In addition, as such approaches rely on a perfect model, a high computational costs is usually required. This inescapable pitfall has motivated a strong interest on model reduction. Their key advantage being that they can be specified empirically from the data and represent quite accurately, with only few modes, complex flows' dynamics. This motivates an important research axis in the Fluminance group.

3.4 Numerical models applied to hydrogeology and geophysics

The team is strongly involved in numerical models for hydrogeology and geophysics. There are many scientific challenges in the area of groundwater simulations. This interdisciplinary research is very fruitful with cross-fertilizing subjects.

In geophysics, a main concern is to solve inverse problems in order to fit the measured data with the model. Generally, this amounts to solve a linear or nonlinear least-squares problem.

Models of geophysics are in general coupled and multi-physics. For example, reactive transport couples advection-diffusion with chemistry. Here, the mathematical model is a set of nonlinear Partial Differential Algebraic Equations. At each timestep of an implicit scheme, a large nonlinear system of equations arise. The challenge is to solve efficiently and accurately these large nonlinear systems.

3.5 Numerical algorithms and high performance computing

Linear algebra is at the kernel of most scientific applications, in particular in physical or chemical engineering. The objectives are to analyze the complexity of these different methods, to accelerate convergence of iterative methods, to measure and improve the efficiency on parallel architectures, to define criteria of choice.

4 Application domains

By designing new approaches for the analysis of fluid image sequences, data -model coupling and stochastic representation of fluid flows the Fluminance group contrinutes to several application domains of great interest for the community and in which the anaysis of complex turbulent flow is key. The group focuses on two broad application domains:

- Environmental sciences
- Experimental fluid mechanics and industrial flows

More recently a focus on ocean dynamics and indoor environmental flow has been operated.

5 New software and platforms

5.1 New software

5.1.1 2DLayeredMotion

Name: Estimation of 2D independent mesoscale layered atmospheric motion fields

Functional Description: This software enables to estimate a stack of 2D horizontal wind fields corresponding to a mesoscale dynamics of atmospheric pressure layers. This estimator is formulated as the minimization of a global energy function. It relies on a vertical decomposition of the atmosphere into pressure layers. This estimator uses pressure data and classification clouds maps and top of clouds pressure maps (or infra-red images). All these images are routinely supplied by the EUMETSAT consortium which handles the Meteosat and MSG satellite data distribution. The energy function relies on a data model built from the integration of the mass conservation on each layer. The estimator also includes a simplified and filtered shallow water dynamical model as temporal smoother and second-order div-curl spatial regularizer. The estimator may also incorporate correlation-based vector fields as additional observations. These correlation vectors are also routinely provided by the Eumetsat consortium.

URL: http://fluid.irisa.fr/index.html

Contact: Étienne Mémin

Participant: Étienne Mémin

5.1.2 3DLayeredMotion

Name: Estimation of 3D interconnected layered atmospheric motion fields

Functional Description: This software extends the previous 2D version. It allows (for the first time to our knowledge) the recovery of 3D wind fields from satellite image sequences. As with the previous techniques, the atmosphere is decomposed into a stack of pressure layers. The estimation relies also on pressure data and classification clouds maps and top of clouds pressure maps. In order to recover the 3D missing velocity information, physical knowledge on 3D mass exchanges between layers has been introduced in the data model. The corresponding data model appears to be a generalization of the previous data model constructed from a vertical integration of the continuity equation.

URL: http://fluid.irisa.fr

Contact: Étienne Mémin

5.1.3 DenseMotion

Name: Estimation of 2D dense motion fields

Functional Description: This code allows the computation from two consecutive images of a dense motion field. The estimator is expressed as a global energy function minimization. The code enables the choice of different data models and different regularization functionals depending on the targeted application. Generic motion estimators for video sequences or fluid flows dedicated estimators can be set up. This software allows in addition the users to specify additional correlation based matching measurements. It enables also the inclusion of a temporal smoothing prior relying on a velocity vorticity formulation of the Navier-Stoke equation for Fluid motion analysis applications.

URL: http://fluid.irisa.fr/index.html

Contact: Étienne Mémin

Participant: Étienne Mémin

5.1.4 Low-Order-Motion

Name: Estimation of low order representation of fluid motion

Functional Description: This code enables the estimation of a low order representation of a fluid motion field from two consecutive images.The fluid motion representation is obtained using a discretization of the vorticity and divergence maps through regularized Dirac measure. The irrotational and solenoidal components of the motion fields are expressed as linear combinations of basis functions obtained through the Biot-Savart law. The coefficient values and the basis function parameters are formalized as the minimizer of a functional relying on an intensity variation model obtained from an integrated version of the mass conservation principle of fluid mechanics.

URL: http://fluid.irisa.fr

Contact: Étienne Mémin

Participants: Anne Cuzol, Étienne Mémin

5.1.5 TYPHOON

Keyword: Fluid mechanics

Functional Description: Typhoon is a fluid motion estimator from image sequences. It is almost real-time dedicated to the measurement of LIDAR sequences, multi-scale, fast and precise to make a fine scale analysis of fluid flows with applications in the fields of energy, transport and environment.

URL: https://phys.csuchico.edu/lidar/typhoon/

Authors: Pierre Dérian, Christopher Mauzey, Étienne Mémin

Contact: Étienne Mémin

Participants: Christopher Mauzey, Étienne Mémin, Pierre Dérian

Partner: CSU Chico

5.1.6 H2OLab

Keywords: Simulation, Energy, Contamination, Groundwater, Hydrogeology, Heterogeneity, Uncertainly, Multiscale

Scientific Description: The software platform contains a database which is interfaced through the web portal H2OWeb. It contains also software modules which can be used through the interface H2OGuilde. The platform H2OLab is an essential tool for the dissemination of scientific results. Currently, software and database are shared by the partners of the h2mno4 project.

Functional Description: The software platform H2OLab is devoted to stochastic simulations of groundwater flow and contaminant transport in highly heterogeneous porous and fractured geological media.

-Modeling and numerical simulation of aquifers -Porous and fractured heterogeneous media -Flow with mixed finite elements -Solute transport with a Lagrangian method -Stochastic modeling for data uncertainty.

URL: http://h2olab.inria.fr/

Contact: Jocelyne Erhel

Participants: Géraldine Pichot, Grégoire Lecourt, Jean-Raynald De Dreuzy, Jocelyne Erhel

Partners: Université de Rennes 1, CNRS, Université de Lyon, Université de Poitiers

5.1.7 PALMTREE

Keyword: Monte-Clarlo

Functional Description: We present an easy-to-use package for the parallelization of Lagrangian methods for partial differential equations. In addition to the reduction of computation time, the code aims at satisfying three properties:

simplicity: the user just has to add the algorithm governing the behaviour of the particles. portability: the possibility to use the package with any compiler and OS. action-replay: the ability of the package to replay a selected batch of particles.

The last property allows the user to replay and capture the whole sample path for selected particles of a batch. This feature is very useful for debugging and catching some relevant information.

Authors: Lionel Lenôtre, Géraldine Pichot, Lionel Lenôtre, Lionel Lenôtre

Contacts: Jocelyne Erhel, Géraldine Pichot

5.1.8 GRT3D

Name: Global Reactive Transport in 3D

Keywords: Geochemistry, Dispersion, Scientific calculation, Simulation, Advection

Scientific Description: Participants : Édouard Canot, Jocelyne Erhel [correspondant] .

Version: version 2.0, April 2014

APP: registered

Programming language: C

Abstract: Reactive transport modeling has become an essential tool for understanding complex environmental problems. It is an important issue for MoMaS and C2S@EXA partners (see sections 8.2.5 , 8.2.3), in particular Andra. We have developed a method coupling transport and chemistry, based on a method of lines such that spatial discretization leads to a semi-discrete system of algebraic differential equations (DAE system). The main advantage is to use a complex DAE solver, which controls simultaneously the timestep and the convergence of Newton algorithm. The approach SIA uses a fixed-point method to solve the nonlinear system at each timestep, whereas the approach SNIA uses an explicit scheme.

The software suite GRT3D has four executable modules:

SIA1D: Sequential Iterative Approach for 1D domains,

GDAE1D: Global DAE approach for 1D domains,

SNIA3D: Sequential Non Iterative Approach for 1D, 2D or 3D domains.

GDAE3D: Global DAE approach for 1D, 2D or 3D domains. This module has three variants: the original one with logarithms, an optimized one still with logarithms, an optimized one which does not use logarithms.

Current work: extension of the chemistry module and parallelization.

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Authors: Caroline De Dieuleveult, Jocelyne Erhel, Souhila Sabit, Nadir Soualem

Contact: Jocelyne Erhel

Participants: Caroline De Dieuleveult, Édouard Canot, Jocelyne Erhel, Nadir Soualem, Souhila Sabit

Partner: ANDRA

6 New results

6.1 Fluid motion estimation

6.1.1 Monocular 3D reconstruction for image-based velocity estimation

Participants Etienne Mémin.

This work proposes a monocular geometric 3D reconstruction framework to be applied to image-based river velocimetry. The proposed modeling framework is based on an orthogonality assumption between the planar river surface and a plane located on any of the banks, and visible in the images. The reconstruction is then scaled to the correct physical scale if the height of the camera with respect to the river surface is known. Applications of this new method are presented and discussed both in controlled lab environment and in the field. Under simple assumptions, raw amateur videos can be processed without ever going to the site. This study in collaboration with Irstea Lyon has been published in [36].

6.1.2 Development of an image-based measurement method for large-scale characterization of indoor airflows

Participants Dominique Heitz, Etienne Mémin, Romain Schuster.

The goal is to design a new image-based flow measurement method for large-scale industrial applications. From this point of view, providing in situ measurement technique requires: (i) the development of precise models relating the large-scale flow observations to the velocity; (ii) appropriate large-scale regularization strategies; and (iii) adapted seeding and lighting systems, like Hellium Filled Soap Bubles (HFSB) and led ramp lighting. This work conducted within the PhD of Romain Schuster in collaboration with the compagny ITGA has started in february 2016. The first step has been to evaluate the performances of a stochastic uncertainty motion estimator when using large scale scalar images, like those obtained when seeding a flow with smoke. The PIV characterization of flows on large fields of view requires an adaptation of the motion estimation method from image sequences. The backward shift of the camera coupled to a dense scalar seeding involves a large scale observation of the flow, thereby producing uncertainty about the observed phenomena. By introducing a stochastic term related to this uncertainty into the observation term, we obtained a significant improvement of the estimated velocity field accuracy. The technique was validated on a mixing layer in a wind tunnel for HFSB and smoke tracers and applied on a laboratory fume-hood [30].

6.1.3 3D flows reconstruction from image data

Participants Dominique Heitz, Etienne Mémin.

Our work focuses on the design of new tools for the estimation of 3D turbulent flow motion in the experimental setup of Tomo-PIV. This task includes both the study of physically-sound models on the observations and the fluid motion, and the design of low-complexity and accurate estimation algorithms. We have proposed a novel method for volumetric velocity reconstruction exploring the locality of 3D object space. Under this formulation the velocity of local patch was sought to match the projection of the particles within the local patch in image space to the image recorded by camera. The core algorithm to solve the matching problem is an instance-based estimation scheme that can overcome the difficulties of optimization originated from the nonlinear relationship between the image intensity residual and the volumetric velocity. The proposed method labeled as Lagrangian Particle Image Velocimetry (LaPIV) is quantitatively evaluated with synthetic particle image data. The promising results that have been obtained indicates the potential application of LaPIV to a large variety of volumetric velocity reconstruction problems .

6.2 Tracking, Data assimilation and model-data coupling

6.2.1 Optimal control techniques for the coupling of large scale dynamical systems and image data

Participants Mohamed Yacine Ben Ali, Pranav Chandramouli, Dominique Heitz, Etienne Mémin, Gilles Tissot.

In this axis of work, we explore the use of optimal control techniques for the coupling of Large Eddies Simulation (LES) techniques and 2D image data. The objective is to reconstruct a 3D flow from a set of simultaneous time resolved 2D image sequences visualizing the flow on a set of 2D planes enlightened with laser sheets. Within this study we have explored techniques to enrich large-scale dynamical models by the introduction of uncertainty terms or through the definition of subgrid models from the image data. This research theme is related to the issue of turbulence characterization from image sequences. Instead of predefined turbulence models, a tuning driven by the data is instead considered. A 4DVar assimilation technique based on the numerical code Incompact3D has been implemented for that purpose to control the inlet and initial conditions in order to reconstruct a turbulent wake flow behind an unknown obstacle. This study has been published in [24].

In another axis of research, in collaboration with the CSTB Nantes centre and within the PhD of Yacine Ben Ali we will explore the definition of efficient data assimilation schemes for wind engineering. The goal is here to couple Reynolds average model to pressure data at the surface of buildings. Several techniques have been proposed to that end. We show in particular that optimisation conducted in Sobolev space is highly beneficial as it brings natural smoothing to the sought solutions and avoid the use of regularization penalty. The techniques proposed consists in correcting the equations related to turbulent kinetic energy and dissipation [43].

6.2.2 Ensemble data assimilation of large-scale dynamics with uncertainty

Participants Benjamin Dufée, Etienne Mémin.

Estimating the parameters of geophysical dynamic models is an important task in Data Assimilation (DA) technique used for forecast initialization and reanalysis. In the past, most parameter estimation strategies were derived by state augmentation, yielding algorithms that are easy to implement but may exhibit convergence difficulties. The Expectation-Maximization (EM) algorithm is considered advantageous because it employs two iterative steps to estimate the model state and the model parameter separately. In this work, we propose a novel ensemble formulation of the Maximization step in EM that allows a direct optimal estimation of physical parameters using iterative methods for linear systems. This departs from current EM formulations that are only capable of dealing with additive model error structures. This contribution shows how the EM technique can be used for dynamics identification problem with a model error parameterized as arbitrary complex form. The proposed technique is used for the identification of stochastic subgrid terms that account for processes unresolved by a geophysical fluid model. This method, along with the augmented state technique, has been evaluated to estimate such subgrid terms through high resolution data. Compared to the augmented state technique, our method is shown to yield considerably more accurate parameters. In addition, in terms of prediction capacity, it leads to smaller generalization error as caused by the overfitting of the trained model on presented data and eventually better forecasts.

6.2.3 Reduced-order models for flows representation from image data

Participants Dominique Heitz, Etienne Mémin, Gilles Tissot.

During the PhD thesis of Valentin Resseguier we have proposed a new decomposition of the fluid velocity in terms of a large-scale continuous component with respect to time and a small-scale non continuous random component. Within this general framework, an uncertainty based representation of the Reynolds transport theorem and Navier-Stokes equations can be derived [9], based on physical conservation laws. This physically relevant stochastic model has been applied in the context of POD-Galerkin methods. This uncertainty modeling methodology provides a theoretically grounded technique to define an appropriate subgrid tensor as well as drift correction terms. The pertinence of this stochastic reduced order model has been successfully assessed on several wake flows at different Reynold number. It has been shown to be much more stable than the usual reduced order model construction techniques. Beyond the definition of a stable reduced order model, the modeling under location uncertainty paradigm offers a unique way to analyse from the data of a turbulent flow the action of the small-scale velocity components on the large-scale flow. Regions of prominent turbulent kinetic energy, direction of preferential diffusion, as well as the small-scale induced drift can be identified and analyzed to decipher key players involved in the flow. This study has been published in the Journal of Fluid Mechanics. Note that these reduced order models can be extended to a full system of stochastic differential equations driving all the temporal modes of the reduced system (and not only the small-scale modes). This full stochastic system has been evaluated on wake flow at moderate Reynolds number. For this flow the system has shown to provide very good uncertainty quantification properties as well as meaningful physical behavior with respect to the simulation of the neutral modes of the dynamics. This study is pursued within a strong collaboration with the industrial partner: SCALIAN [40, 46, 47].

6.2.4 Learning of the dynamics of large scale geophysical systems using semi-group theory for data assimilation

Participants Berenger Hug, Etienne Mémin, Gilles Tissot.

The goal of this study is to propose new ensemble data assimilation methodologies to estimate oceanic and turbulent flows. In classical methods, from a distribution of initial conditions, an ensemble of simulations are computed and used for estimation. Ideally, from this solution, a new ensemble has to be generated to refine the estimation. However, due to large numerical costs and operational constraints, this iterative procedure is in practice intractable. In order to improve actual performances, we propose to take these limitations into account and to develop new methodologies able to better take advantage of the information contained in the ensemble and in the dynamical model. More precisely, we propose to learn the non-linear dynamical features of the system and to be able to reproduce it without having to run a new simulation. The formalism is based on two concepts: i) the reproducing kernel Hilbert spaces (RKHS) that are a basis of smooth functions in the phase space giving interpolatory properties ii) the Koopman operator, that is an infinite-dimensional operator able to propagate in time any observable of the phase space. These two elements allow to define a rigorous framework in which hypothesis classically done in ensemble methods appear naturally. Thus, classical methods enter in a special case of this new formalism, that allows us to generalise them in a way to improve the learning of the non-linear dynamical system. Numerical tests are performed with a quasi-geostrophic flow model.

6.2.5 Estimation and control of amplifier flows

Participants Gilles Tissot.

Estimation and control of fluid systems is an extremely hard problem. The use of models in combination with data is central to take advantage of all information we have on the system. Unfortunately all flows do not present the same physical and mathematical behaviour, thus using models and methodologies specialised to the flow physics is necessary to reach high performances.

A class of flows, denoted "oscillator flows", are characterised by unstable modes of the linearised operator. A consequence is the dominance of relatively regular oscillations associated with a nonlinear saturation. Despite the non-linear behaviour, associated structures and dynamical evolution are relatively easy to predict. Canonical configurations are the cylinder wake flow or the flow over an open cavity.

By opposition to that, "amplifier flows" are linearly stable with regard to the linearised operator. However, due to their convective nature, a wide range of perturbations are amplified in time and convected away such that it vanishes at long time. The consequence is the high sensitivity to perturbations and the broad band response that forbid a low rank representation. Jets and mixing layers show this behaviour and a wide range of industrial applications are affected by these broad band perturbations. It constitutes then a class of problems that are worth to treat separately since it is one of the scientific locks that render hard the transfer of methodologies existing in flow control and estimation to industrial applications.

There exists a type of models, that we will denote as "parabolised", that are able to efficiently represent amplifier flows. These models, such as parabolised stability equations and one-way Navier-Stokes propagate, in the frequency domain, hydrodynamic instability waves over a given turbulent mean flow. We can note that these models, by their structure, give access to a natural experimental implementation. They are an ingredient adapted to represent the system, but have a mathematical structure strongly different from the dynamical models classically used in control and data assimilation. It is then important to develop new methodologies of control, estimation and data assimilation with these models to reach our objectives. Moreover, inventing new models by introducing the modelling under location uncertainties in these parabolised models will be perfectly adapted to represent the evolution and the variability of an instability propagating within a turbulent flow.

6.3 Analysis and modeling of turbulent flows and geophysical flows

6.3.1 Ocean internal tide dynamics and modelling

Participants Noé Lahaye, Gilles Tissot, Etienne Mémin.

This reseach effort addresses the dynamics of internal tides in the ocean, which are high-frequency internal waves that propagate in the oceans. These internal waves are a driver of small-scale mixing and energy dissipation in the ocean, and are key for the accuracy of ocean climate models that cannot resolve it explicitly. Some work, based on analysis of high-resolution idealized and realistic numerical simulations, has been undertaken to understand how internal tides are affected by the background currents in the ocean. A method based on linearization around the background-flow and vertical mode decomposition is implemented to study the dynamics and derive a reduced-complexity, reduced-dimension models of the propagation of the internal tides [25]. Forthcoming work will extend the model through explicit dealing of uncertainties by means of stochastic calculus. We will then use this model to construct an ensemble-based data assimilation system using satellite altimeter observations and surface drifter trajectories. This aims at radically improving the estimates of the distribution of the internal tide in the ocean, which is poorly constrained to date.

6.3.2 Reduced dynamical models for geophysical flows

Participants Noé Lahaye.

In this task, the dynamics of coherent structures in a reduced model of the ocean mixed layer was addressed. This model, the thermal rotating shallow water (TRSW) equations, is a vertically averaged model of the hydrostatic navier-stokes equations under the Boussinesq approximation and with Coriolis term, and retains the horizontal variations of density (or temperature). In the strong rotation regime, a low Rossby number asymptotic model can be derived : the Thermal Quasi-Geostrohic model. This work, in collaboration with V. Zeitlin and T. Dubos (LMD, Paris), investigated the dynamics of the coherent dipolar analytical solution in this model and the parent TRSW model. It exhibited a surprising small sale instability, leading to mixing of the thermal anomaly carried by the dipole [26]. This research activity is pursued to better understand the dynamics of these models, in connexion with the STUOD project, which involve such models.

6.3.3 Geophysical flows modeling under location uncertainty

Participants Werner Bauer, Pranav Chandramouli, Noe Lahaye, Long Li, Etienne Mémin, Gilles Tissot, Francesco Tucciarone.

In this research axis we have devised a principle to derive representation of flow dynamics under location uncertainty [9]. Such an uncertainty is formalized through the introduction of a random term that enables taking into account large-scale approximations or truncation effects performed within the dynamics analytical constitution steps. Rigorously derived from a stochastic version of the Reynolds transport theorem, this framework, referred to as modeling under location uncertainty (LU), encompasses several meaningful mechanisms for turbulence modeling. It indeed introduces without any supplementary assumption the following pertinent mechanisms for turbulence modeling: (i) a dissipative operator related to the mixing effect of the large-scale components by the small-scale velocity;(ii) a multiplicative noise representing small-scale energy backscattering; and (iii) a modified advection term related to the so-called *turbophoresis* phenomena, attached to the migration of inertial particles in regions of lower turbulent diffusivity.

In a series of papers [19, 18, 34, 35, 29] we have shown how LU modeling can be applied to provide stochastic representations of a variety of classical geophysical flows dynamics. Numerical simulations and uncertainty quantification have been performed on Quasi Geostophic approximation (QG) of oceanic models. It has been shown that LU leads to remarkable estimation of the unresolved errors opposite to classical eddy viscosity based models. The noise brings also an additional degree of freedom in the modeling step and pertinent diagnostic relations and variations of the model can be obtained with different scaling assumptions of the turbulent kinetic energy (i.e. of the noise amplitude). For a wind forced QG model in a square box, which is an idealized model of north-Atlantic circulation, we have shown that for different versions of the noise the QG LU model leads to improve long-terms statistics when compared to classical large-eddies simulation strategies. For a QG model we have demonstrated that the LU model allows conserving the global energy. We have also shown numerically that Rosby waves were conserved and that inhomogeneity of the random component triggers secondary circulations. This feature enabled us to draw a formal bridge between a classical system describing the interactions between the mean current and the surface waves and the LU model in which the turbophoresis advection term plays the role of the classical Stokes drift.

Supported by funding from Inria-Mitacs Globalink, we hosted Ruediger Brecht, PhD student at Memorial University of Newfoundland, Canada, for a period of 3 months (May to August) in the Fluminance group. During his stay, Ruediger Brecht worked on the incorporation of a stochastic representation of the small-scale velocity component of a fluid flow in a variational integrator for the rotating shallow-water equations on the sphere, already developed within the first part of its PhD work. This work published as a preprint [44] has been recently submitted to a journal paper.

6.3.4 Large eddies simulation models under location uncertainty

Participants Pranav Chandramouli, Dominique Heitz, Etienne Mémin, Gilles Tissot.

The models under location uncertainty recently introduced by Mémin (2014) [9] provide a new outlook on LES modeling for turbulence studies. These models are derived from a stochastic transport principle. The associated stochastic conservation equations are similar to the filtered Navier- Stokes equation wherein we observe a sub-grid scale dissipation term. However, in the stochastic version, an extra term appears, termed as "velocity bias", which can be treated as a biasing/modification of the large-scale advection by the small scales. This velocity bias, introduced artificially in the literature, appears here automatically through a decorrelation assumption of the small scales at the resolved scale. All sub-grid contributions for the stochastic models are defined by the small-scale velocity auto-correlation tensor. This large scale modeling has been assed and compared to several classical large-scale models on a flow over a circular cylinder at Re 3900 and wall-bounded flows. For all these flows the modeling under uncertainty has provided better results than classicallarge eddies simulation models.

6.3.5 Variational principles for structure-preserving discretizations in stochastic fluid dynamics

Participants Werner Bauer, Long Li, Etienne Mémin.

The overarching goal of this interdisciplinary project is to use variational principles to derive deterministic and stochastic models and corresponding accurate and efficient structure preserving discretizations and to use these schemes to obtain a deeper understanding of the conservation laws of the stochastic fluid dynamics investigated. The newly developed systematic discretization framework is based on discrete variational principles whose highly structured procedures shall be exploited to develop a general software framework that applies automatic code generation. This project will first provide new stochastic fluid models and suitable approximations, with potential future applications in climate science using the developed methods to perform accurate long term simulations while quantifying the solutions uncertainties [44, 33].

6.3.6 Stochastic compressible fluid dynamics

Participants Etienne Mémin, Gilles Tissot.

We are currently working on the extension of the stochastic formulation under location uncertainty to compressible flows. The interest is to extend the formulation on the one hand to compressible fluids (for instability mechanisms involved in areoacoustics for instance, or for thermal effects in mixing layers) and on the other hand to geophysical flows where the Boussinesq equation is not valid anymore (density variations due to temperature or salinity gradients). A theoretical study has been performed that opens the door to numerical validations. In particular a baroclinic torque term has been identified that could have major effects in some situations.

6.3.7 Stochastic hydrodynamic stability under location uncertainty

Participants Etienne Mémin, Gilles Tissot.

In order to predict instability waves propagating within turbulent flows, eigenmodes of the linearised operator is not well suited since it neglects the effect of turbulent fluctuations on the wave dynamics. To cope this difficulty, resolvent analysis has become popular since it represents the response of the linearised operator to any forcing representing the generalised stress tensors. The absence of information on the non-linearity is a strong limitation of the method. In order to refine these models, we propose to consider a stochastic model under location uncertainty expressed in the Fourier domain, to linearise it around the corrected mean-flow and to study resulting eigenmodes. The stochastic part represents the effect of the turbulent field onto the instability wave. It allows to specify a structure of the noise and then to improve existing models. Improvements compared to the resolvent analysis have been found for turbulent channel flow data at $R\tau = 180$ and $R\tau = 550$. A paper has been accepted in Journal of fluid Mechanics [32]. This work is in collaboration with André Cavalieri (Instituto Tecnologico de Aeronautica, SP, Brésil).

6.3.8 Singular and regular solutions to the Navier-Stokes equations (NSE) and relative turbulent models

Participants Roger Lewandowski, Etienne Mémin, Ding Duong Nguyen, Benoit Pinier.

The common thread of this work is the problem set by J. Leray in 1934 : does a regular solution of the Navier- Stokes equations (NSE) with a smooth initial data develop a singularity in finite time, what is the precise structure of a global weak solution to the Navier-Stokes equations, and are we able to prove any uniqueness result of such a solution. This is a very hard problem for which there is for the moment no answer. Nevertheless, this question leads us to reconsider the theory of Leray for the study of the Navier-Stokes equations in the whole space with an additional eddy viscosity term that models the Reynolds stress in the context of large- scale flow modelling. It appears that Leray's theory cannot be generalized turnkey for this problem, so that things must be reconsidered from the beginning. This problem is approached by a regularization process using mollifiers, and particular attention must be paid to the eddy viscosity term. For this regularized problem and when the eddy viscosity has enough regularity, we have been able to prove the existence of a global unique solution that is of class C1 in time and space and that satisfies the energy balance. Moreover, when the eddy viscosity is of compact support in space, uniformly in time, we recently shown that this solution converges to a turbulent solution to the corresponding Navier-Stokes equations carried when the regularizing parameter goes to 0. These results are described in a paper published in JMAA

In the framework of the collaboration with the University of Pisa (Italy), namely with Luigi Berselli collaboration, we considered the three dimensional incompressible Navier-Stokes equations with non stationary source terms chosen in a suitable space. We proved the existence of Leray-Hopf weak solutions and that it is possible to characterize (up to sub-sequences) their long-time averages, which satisfy the Reynolds averaged equations, involving a Reynolds stress. Moreover, we showed that the turbulent dissipation is bounded by the sum of the Reynolds stress work and of the external turbulent fluxes, without any additional assumption, than that of dealing with Leray-Hopf weak solutions. This is a very nice generalisation to non stationnary source terms of a famous results by Foais. In the same work, we also considered ensemble averages of solutions, associated with a set of different forces and we proved that the fluctuations continue to have a dissipative effect on the mean flow. These results have been published in Nonlinearity. These results have been extended in the framework of POD for reduced models [21]. We have studied in [20] the rate of convergence of the weak solutions uα of α-regularization models to the weak solution u of the Navier-Stokes equations in the two-dimensional periodic case, as the regularization parameter α goes to zero. More specifically, we have considered the Leray-α, the simplified Bardina, and the modified Leray-α models. We have improved known results in terms of convergence rates and also to show estimates valid over long-time intervals. The results also hold in the case of bounded domain with homogeneous Dirichlet boundary conditions

In another paper [27] we have shown the existence of a solution to a 1D Reynolds Averaged Navier-Stokes vertical model suitable in the atmospheric boundary layer, under suyitable assumption on the data.

We also have introduced a turbulence model including a backscatter term, which has the same structure as the Voigt model. The additional term is derived in certain specific regimes of the flow, such as the convergence to stable statistical states. We get estimates for the velocity v in $L^\infty_t H^1_x \cap W^{1,2}_t H^{1/2}_x$, that allow us to prove the existence and uniqueness of a regular-weak solutions (v, p) to the resulting system, for a given fixed eddy viscosity. We then prove a structural compactness result that highlights the robustness of the model. This allows us to pass to the limit in the quadratic source term in the equation for the turbulent kinetic energy k, which yields the existence of a weak solution to the corresponding Reynolds Averaged Navier-Stokes system satisfied by (v, p, k). These results are published in [17]. We have derived in [22] from the laws of the turbulence and Leray's energy inequality for weak solutions of the Navier-Stokes equations, a back-scatter rotational Large Eddy Simulation model, which is the extension of the Baldwin and Lomax model to non-equilibrium problems. The model is particularly designed to mathematically describe a fluid filling a domain with solid walls and consequently the differential operators appearing in the smoothing terms are degenerate at the boundary. After the derivation of the model, we have prove some of the mathematical properties coming from the weighted energy estimates and which allow to prove existence and uniqueness of a class of regular weak solutions.

Another study in collaboration with B. Pinier, P. Chandramouli and E. Memin has been undertaken. This work takes place within the context of the PhD work of B. Pinier. We have tested the performances of an incompressible turbulence Reynolds-Averaged Navier-Stokes one-closure equation model in a boundary layer, which requires the determination of the mixing length l. A series of direct numerical simulation have been performed, with flat and non trivial topographies, to obtain by interpolation a generic formula $l = l(Re\delta, z)$, $Re\delta$ being the frictional Reynolds number, and z the distance to the wall. Numerical simulations have been carried out at high Reynolds numbers with this turbulence model, in order to discuss its ability to properly reproduce the standard profiles observed in neutral boundary layers, and to assess its advantages, its disadvantages and its limits. We also proceeded to a mathematical analysis of the model. The study has been published [28]

6.3.9 Stochastic flow model to predict the mean velocity in wall bounded flows

Participants Roger Lewandowski, Etienne Mémin, Benoit Pinier.

To date no satisfying model exists to explain the mean velocity profile within the whole turbulent layer of canonical wall bounded flows. We propose a modification of the velocity profile expression that ensues from the stochastic representation of fluid flows dynamics proposed recently in the group and referred to as "modeling under location uncertainty" [9]. This framework introduces in a rigorous way a subgrid term generalizing the eddy-viscosity assumption and an eddy-induced advection term resulting from turbulence inhomogeneity. This latter term gives rise to a theoretically well-grounded model for the transitional zone between the viscous sublayer and the turbulent sublayer. An expression of the small-scale velocity component is also provided in the viscous zone. Numerical assessment of the results have been performed for turbulent boundary layer flows, pipe flows and channel flows at various Reynolds numbers.

6.3.10 Numerical and experimental image and flow database

Participants Pranav Chandramouli, Dominique Heitz.

The goal was to design a database for the evaluation of the different techniques developed in the Fluminance group. The first challenge was to enlarge a database mainly based on two-dimensional flows, with three-dimensional turbulent flows. Synthetic image sequences based on homogeneous isotropic turbulence and on circular cylinder wake have been provided. These images have been completed with time resolved Particle Image Velocimetry measurements in wake and mixing layers flows. This database provides different realistic conditions to analyse the performance of the methods: time steps between images, level of noise, Reynolds number, large-scale images. The second challenge was to carry out orthogonal dual plane time resolved stereoscopic PIV measurements in turbulent flows. The diagnostic employed two orthogonal and synchronized stereoscopic PIV measurements to provide the three velocity components in planes perpendicular and parallel to the streamwise flow direction. These temporally resolved planar slices observations have been be used within a 4DVar assimilation technique, to reconstruct three-dimensional turbulent flows from data. The third challenge was to carry out a time resolved tomoPIV experiments in a turbulent wake flow. This work has been pblished in the Journal of Computational Physics [24].

6.3.11 Fast 3D flow reconstruction from 2D cross-plane observations

Participants Pranav Chandramouli, Dominique Heitz, Etienne Mémin.

We proposed a computationally efficient flow reconstruction technique, exploiting homogeneity in a given direction, to recreate three dimensional instantaneous turbulent velocity fields from snapshots of two dimension planar fields. This methodology, termed as "snapshot optimisation" or SO, enables to provide 3D data-sets for studies which are currently restricted by the limitations of experimental measurement techniques. The SO method aims at optimising the error between an inlet plane with a homogeneous direction and snap-shots, obtained over a sufficient period of time, on the observation plane. The observations are carried out on a plane perpendicular to the inlet plane with a shared edge normal to the homogeneity direction. The method is applicable to all flows which display a direction of homogeneity such as cylinder wake flows, channel flow, mixing layer, and jet (axi-symmetric). The ability of the method is assessed with two synthetic data-sets, and three experimental PIV data-sets. A good reconstruction of the large-scale structures are observed for all cases. This study has been published in the journal "Experiments in Fluids".

6.3.12 Dissipation mechanisms in perforated liners with grazing flow

Participants Gilles Tissot.

Perforated liners are a technology implanted in the nacelles of aircraft engines, in order to absorb noise coming from the fan and the combustion chamber. It is constituted by honeycomb cavities covered by a perforated plate. The cavities produce resonance, thus inducing a flow through the perforations where viscous dissipation occurs, necessary for sound absorption. These perforations cause drag in the air intake, which can be reduced by considering micro perforates. However, existing models are not able to predict correctly the impedance of such plates. Understanding the dissipation mechanisms and improving the impedance predictions for microperforated plates is the objective of the thesis of Robin Billard, in collaboration with Gwénaël Gabard (LAUM – laboratoire d'acoustique de l'université du Mans) and Safran Nacelles. The challenge is to account for non-linear effects and grazing flow in the developed models. Resolvent analysis has been explored to identify relevant non-linearities that impact the impedance, with and without flow. A numerical study without flow has been published in Journal of the Acoustical Society of America [23]. Modelling with non-linear effects has been presented in forum Acusticum 2020 [37]. Besides, shape optimisation strategies have been considered to enhance absorption at low frequency [31].

6.4 Visual servoing approach for fluid flow control

6.4.1 A state space representation for the closed-loop control of shear flows

Participants Johan Carlier, Christophe Collewet.

The goal of this study is to develop a generic state representation for the closed-loop control of shear flows. We assume that the actuator acts at the boundaries. Our approach is based on a linearization of the Navier-Stokes equations around the desired state. Particular care was paid to the discrete approximation of the linear model to design a well-conditioned and accurate state matrix describing time evolution of disturbances evolving in parallel shear flow as long as these disturbances remain sufficiently small. A state matrix representation is obtained for the periodic channel flow and the spatially developing mixing layer flow. This approach has been validated through the representativity of our model in terms of linear stability. This work has been presented to the French Mechanics Congress CFM.

6.4.2 Closed-loop control of a spatially developing shear layer

Participants Christophe Collewet, Johan Carlier.

This study aims at controling one of the prototypical flow configurations encountered in fluid mechanics: the spatially developing turbulent shear layer occuring between two parallel incident streams with different velocities. Our goal is to maintain the shear-layer in a desired state and thus to reject upstream perturbations. In our conference IFAC paper (`https://hal.inria.fr/hal-01514361`) we focused on perturbations belonging to the same space that the actuators, concretely that means that we were only able to face perturbations of the actuator itself, like failures of the actuator. This year we enlarged this result to purely exogenous perturbations, in term of magnitude as well as in term of spatial dispersion. An optimal control law has been derived to minimize the influence of the perturbation on the flow. To do that, an on-line estimation of the perturbation (magnitude and spatial dispersion) has been developed to lead to an adaptive control law. Simple conditions to ensure the local asymptotic stability of the whole scheme have been derived. This work has been also presented to the French Mechanics Congress CFM.

6.4.3 Design of a DBD plasma actuator for closed-loop control

Participants Johan Carlier, Christophe Collewet.

The goal of this study is to design a DBD plasma actuator for closed-loop control. This kind of actuator is widely used in the flow control community however, it is more appropriate to force a flow than to control it. Indeed, to control a flow under a closed-loop fashion, the action must be proportional to the control signal provided by the control law. It is unfortunately not the case with these actuators. We have modified the classical DBD plasma actuator so that the action is almost a linear fonction of the control signal. Our approach has been first experiments.

6.5 Coupled models in hydrogeology

6.5.1 Reactive transport in multiphase flow

Participants Jocelyne Erhel.

Groundwater resources are essential for life and society, and should be preserved from contamination. Pollutants are transported through the porous medium and a plume can propagate. Reactive transport models aims at simulating this dynamic contamination by coupling advection dispersion equations with chemistry equations. If chemistry is at thermodynamic equilibrium, then the system is a set of partial differential and algebraic equations (PDAE). Space discretization leads to a semi-discrete DAE system which should be discretized in time. An explicit time scheme allows an easy decoupling of transport and chemistry, but very small timesteps should be taken, leading to a very large CPU time. Therefore, an implicit time scheme is preferred, coupling transport and chemistry in a nonlinear system. The special structure of linearized systems can be used in preconditioned Newton-Krylov methods in order to improve efficiency. Some experiments illustrate the methodology and show also the need for an adaptive timestep and a control of convergence in Newton's iterations.

This work was presented at a workshop.

6.5.2 Characterizations of Solutions in Geochemistry at equilibrium

Participants Jocelyne Erhel.

Geochemistry at thermodynamic equilibrium involves aqueous reactions and mineral precipitation or dissolution. Quantities of solute species are assumed to be strictly positive, whereas those of minerals can vanish. The mathematical model is expressed as the minimization of Gibbs energy subject to positivity of mineral quantities and conservation of mass. Optimality conditions lead to a complementarity problem. We show that, in the case of a dilute solution, this problem can also be considered as optimality conditions of another minimization problem, subject to inequality constraints. This new problem is easier to handle, both from a theoretical and a practical point of view. Then we define a partition of the total quantities in the mass conservation equation. This partition builds a precipitation diagram such that a mineral is either precipitated or dissolved in each subset. We propose a symbolic algorithm to compute this diagram. Simple numerical examples illustrate our methodology.

This work was published in the journal Computational Geosciences and presented at an international conference.

6.5.3 Mathematical models of kinetic reactions in geochemistry

Participants Jocelyne Erhel, Bastien Hamlat.

In geochemistry, kinetic reactions can lead to the appearance or disappearance of minerals or gas. We defined two mathematical models based first on a differential inclusion system and second on a projected dynamical system. We proposed a regularization process for the first model and a projection algorithm for the second one.

This work, supported by IFPEN, was presented at a conference and a workshop.

6.6 Sparse Linear solvers

6.6.1 Parallel GMRES

Participants Jocelyne Erhel.

Sparse linear systems $Ax = b$ arise very often in computational science and engineering. Krylov methods are very efficient iterative methods, and restarted GMRES is a reference algorithm for non-symmetric systems. A first issue is to ensure a fast convergence, by preconditioning the system with a matrix M. Preconditioning must reduce the number of iterations, and be easy to solve. A second issue is to achieve high performance computing. The most time-consuming part in GMRES is to build an orthonormal basis V. With the Arnoldi process, many scalar products involve global communications. In order to avoid them, s-step methods have been designed to find a tradeoff between parallel performance and stability. Also, solving a system with the matrix M and for multiplying a vector by the matrix A should be efficient. A domain decomposition approach involves mainly local communications and is frequently used. A coarse grid correction, based on deflation for example, improves convergence. These techniques can be combined to provide fast convergence and fast parallel algorithms. Numerical results illustrate various issues and achievements.

This work was presented at an international conference (invited talk).

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Contract ITGA

Participants Dominique Heitz, Etienne Mémin.

duration 36 months. This partnership between Inria, Irstea and ITGA funds the PhD of Romain Schuster. The goal of this PhD is to design new image-based flow measurement methods for the study of industrial fluid flows. Those techniques will be used in particular to calibrate industrial fume hood.

Contract CSTB

Participants Mohamed Yacine Ben Ali, , Dominique Heitz, Etienne Mémin.

duration 36 months. This partnership between Inria, Irstea and CSTB funds the PhD of Yacine Ben Ali. This PhD aims to design new data assimilation scheme for Reynolds Average Simulation (RANS) of flows involved in wind engineering and buildings construction. The goal pursued here consists to couple RANS models and surface pressure data in order to define data driven models with accurate turbulent parameterization.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Participation in other international programs

Noé Lahaye and Etienne Mémin are part of the SWOT Science Team. They participate to the DIEGO project (CNES-NASA) headed by Aurélien Ponté (Ifremer). Noé Lahaye is leader of WP4: Internal tide mapping and predictability.

8.2 International research visitors

8.2.1 Visits to international teams

Research stays abroad Etienne Mémin is visiting professor at the Mathematics department of Imperial College London.

8.3 European initiatives

8.3.1 FP7 & H2020 Projects

ERC Synergy Grant STUOD

Title: Stochastic Transport in Upper Ocean Dynamics

Duration: *01/03/2020 - 01/03/2026*

Coordinator: *E. Mémin*

Partners:

- *Mathematics department*, IMPERIAL COLLEGE London (*(UK)*)

Inria contact: *(E. Mémin)*

Summary: *71 percent of Earth is covered by ocean. The ocean has absorbed 93 percent of the heat trapped by human's greenhouse gas emissions. The ocean's future responses to continued warming are uncertain. Our project will deliver new capabilities for assessing variability and uncertainty in upper ocean dynamics. It will provide decision makers a means of quantifying the effects of local patterns of sea level rise, heat uptake, carbon storage and change of oxygen content and pH in the ocean. Its multimodal monitoring will enhance the scientific understanding of marine debris transport, tracking of oil spills and accumulation of plastic in the sea. Our approach accounts for transport on scales that are currently unresolvable in computer simulations, yet are observable by satellites, drifters and floats. Four scientific capabilities will be engaged: (i) observations at high resolution of upper ocean properties such as temperature, salinity, topography, wind, waves and velocity; (ii) large scale numerical simulations; (iii) data-based stochastic equations for upper ocean dynamics that quantify simulation error; and (iv) stochastic data assimilation to reduce uncertainty. These four scientific capabilities will tackle a network of joint tasks achieved through cooperation of three world-calibre institutions: IFREMER (ocean observations, reanalysis); INRIA (computational science); and Imperial College (mathematics, data assimilation). Our complementary skill sets comprise a single systemic effort: (1) Coordinate and interpret high-resolution satellite and in situ upper ocean observations (2) Extract correlations from data needed for the mathematical model (3) Perform an ensemble of computer simulations using our new stochastic partial differential equations (SPDE) which are derived by matching the observed statistical properties (4) Apply advanced data assimilation and computer simulations to reduce model uncertainty The key to achieving these goals will be synergy in our combined expertise.*

8.4 National initiatives

COMINS'LAB**: SEACS : Stochastic modEl-dAta-Coupled representationS for the analysis, simulation and reconstruction of upper ocean dynamics**

Participants Etienne Mémin.

duration 48 months. The SEACS project whose acronym stands for: "Stochastic modEl-dAta-Coupled representationS for the analysis, simulation and reconstruction of upper ocean dynamics" is a Joint Research Initiative between the three Britanny clusters of excellence of the "Laboratoires d'Excellence" program: Cominlabs, Lebesgue and LabexMer centered on numerical sciences, mathematics and oceanography respectively. Within this project we aim at studying the potential of large-scale oceanic dynamics modeling under uncertainty for ensemble forecasting and satellite image data assimilation.

ANR **BECOSE : Beyond Compressive Sensing: Sparse approximation algorithms for ill-conditioned inverse problems.**

Participants Dominique Heitz.

duration 48 months. The BECOSE project aims to extend the scope of sparsity techniques much beyond the academic setting of random and well-conditioned dictionaries. In particular, one goal of the project is to step back from the popular L1-convexification of the sparse representation problem and consider more involved nonconvex formulations, both from a methodological and theoretical point of view. The algorithms will be assessed in the context of tomographic Particle Image Velocimetry (PIV), a rapidly growing imaging technique in fluid mechanics that will have strong impact in several industrial sectors including environment, automotive and aeronautical industries. The consortium gathers the Fluminance and Panama Inria research teams, the Research Center for Automatic Control of Nancy (CRAN), The Research Institute of Communication and Cybernetics of Nantes (IRCCyN), and ONERA, the French Aerospace Lab.

8.4.1 IFPEN project

Participants Jocelyne Erhel, Bastien Hamlat.

Contract with IFPEN (Institut Français du Pétrole et Energies Nouvelles) Duration: three years from October 2016. Title: Fully implicit Formulations for the Simulation of Multiphase Flow and Reactive Transport Coordination: Jocelyne Erhel. Contract with IFPEN (Institut FranÃ§ais du Pétrole et Energies Nouvelles). Duration: three years October 2016-September 2019. Title: Fully implicit Formulations for the Simulation of Multiphase Flow and Reactive Transport. Coordination: Jocelyne Erhel. Abstract: Modeling multiphase flow in porous media coupled with fluid-rock chemical reactions is essential in order to understand the origin of sub-surface natural resources and optimize their use. This project focused on chemistry models, with kinetic reactions. We developed a mathematical tool, which can be embedded into a reactive transport code.

8.4.2 LEFE MANU: MSOM

Participants Long Li, Etienne Mémin.

Title: Multiple Scale Ocean Model
Duration: From 2018 to 2021
Coordination: Bruno Deremble (CNRS LMD/ENS Paris)
Abstract: The objective of this project is to propose a numerical framework of a multiscale ocean model and to demonstrate its utility in the understanding of the interaction between the mean current and eddies.

8.4.3 LEFE MANU: ADOTSAD

Participants Gilles Tissot, Etienne Mémin.

Title: Apprentissage de la Dynamique de modèles Océaniques par des approches issues de la Théorie des Semi-groupes pour l'Assimilation de Données (ADOTSAD). Duration: From 2019 to 2021

9 Dissemination

9.1 Scientific events: selection

Jocelyne Erhel is member of

- the international advisory committee of the parallel CFD conferences (Antalya, May 2019).
- the program committee of the workshop Visualization in Environmental Sciences 2019 (co-event of EuroVis).
- the scientific Committee of the workshop "Parallel solution methods for systems arising from PDEs" (Marseille, September 2019).
- the scientific Committee of the conference SimRace (IFPEN, Rueil-Malmaison, scheduled in December 2019 and postponed in 2020).

9.2 Journal

9.2.1 Member of the editorial boards

Jocelyne Erhel

- member of the editorial board of ETNA.
- member of the editorial board of ESAIM:Proceedings and Surveys.

Etienne Mémin

- Associate editor for the Image and Vision Computing Journal (IVC)

9.2.2 Reviewer - reviewing activities

Jocelyne Erhel: Reviewer for the journals Computational Geosciences, SISC, M2AN, JCAM, PARCO
Dominique Heitz: Reviewer for Exp. in Fluids, AMI Région Auvergne Rhone Alpes
Noé Lahaye : Reviewer for Journal of Physical Oceanography, Journal of Geophysical Research:Ocean, Geophysical Research Letters, Journal of Fluid Mechanics, Physics of Fluids, Fluid Dynamics Research
Etienne Mémin: Reviewer for Tellus-A, Quat. J. of the Roy. Met. Soc., Journ. of Fluid Mech., Im. Vis. Comp., Exp. in Fluids, Journ. of Comp. Phys., Journ. of Math. Imaging and Vis.
Gilles Tissot: Reviewer for Journal of Sound and Vibration, Fluid Dynamics Research, Journ. of Fluid Mech.

9.3 Invited talks

Etienne Mémin

- Workshop Big data, data assimilation, and uncertainty quantification, IHP, Paris (France), 12-15 November 2019
- Workshop on stochastic parameterizations and their use in data assimilation 1-5 July 2019 Imperial College London
- Siam Conf. on mathematics for planet earth, august 2020, Los-Angeles, USA.
- Workshop on Conservation Principles, Data and Uncertainty in Atmosphere-Ocean Modelling, Potsdam, Germany April 2019

9.4 Leadership within the scientific community

- J. Erhel is scientific coordinator of the website Interstices (since June 2012). https://interstices.info.

9.5 Scientific expertise

- J. Erhel is a member of the scientific council of IFPEN, since April 2016.

9.6 Research administration

Jocelyne Erhel

- the Inria administrative commission (CAP) for researchers, 2016-2019.
- the maths thesis committee of IRMAR, 2017-2019.
- the selection committee for PhD grants of OSUR, 2019.

Dominique Heitz

- Member of Pôle Cristal scientific council
- Member of scientific council of CSTB's Jules Verne Platform

Roger Lewandowski

- President du Comité de liaison du groupe GAMNI-SMAI
- President of the Blaise Pascal award jury
- President of GAMNI-SMAI PhD thesis award
- Corresponding person of the SMAI in Rennes
- Responsible of the group "Mathematical modeling" of IRMAR
- Member of the scientific council of IRMAR,
- Member of Mathematical teaching council of U. Rennes I
- Member of the scientific council of the Henri Lebesgue Centre

Etienne Mémin

- Member of the scientific council of LEFE-MANU action of CNRS INSU
- Member of the comity GAMNI-SMAI

9.6.1 Teaching

- Licence: Jocelyne Erhel, Optimisation, 12h, niveau L3, ENSAI Rennes
- Licence : Dominique Heitz, Mécanique des fluides, 30h, niveau L2 INSA Rennes
- Master: Jocelyne Erhel, arithmétique flottante, 4h, niveau M1, INSA Rennes
- Master : Dominique Heitz, Mécanique des fluides, 25h, niveau M1, Dep GMA INSA Rennes
- Master: Roger Lewandowski, Euler and the Navier-Stokes equations, M2, master « fondamental mathematics».
- Master : Etienne Mémin, Analyse du mouvement, Master Informatique, 15h, niveau M2, Université de Rennes 1.
- Master : Etienne Mémin, Vision par ordinateur , 15h, niveau M2, ESIR Université de Rennes 1.
- Master : Etienne Mémin, Motion analysis , 9h, Master 2 SISEA Université de Rennes 1.
- Master : Gilles Tissot, mathematics for acoustics, 20h, niveau M1, Université du Mans.

9.6.2 Supervision

- PhD in progress: Clara Le Cap, Numerical simulations and field measurements of frosty events in viticultural area protected by wind machine farm: Application to the Quincy vineyard, started April 2020, supervised by Dominique Heitz, Johan Carlier, Hervé Quénol, Emmanuel Buisson.
- PhD in progress : Corentin Cazès, Experimental study of the resuspension of microparticles in air induced by transient events, started October 2020, supervised by Dominique Heitz, Lionel Fiabane, Félicie Théron, Laurence Le Coq.
- PhD in progress : Berenger Hug, analysis of stochastic models under location uncertainty started November 2020, supervisors: Etienne Mémin, Arnaud Debussche.
- PhD in progress: Benjamin Dufée, Particle filters in high dimentional spaces, started November 2020, supervisors: Dan Crisan, Etienne Mémin
- PhD in progress: Francesco Tuccarone, Stochastic models for high resolution oceanic odels, started November 2020, Etienne Mémin
- PhD in progress: Bastien Hamlat, University of Rennes 1, October 2016, co-advisors Jocelyne Erhel and A. Michel.
- PhD in progress : Long Li, Data assimilation and stochastic transport for the upper ocean dynamics, started November 2017, supervisor: Etienne Mémin.
- PhD in progress : Yacine Ben Ali, Variational assimilation of RANS models for wind engineering, started November 2017, supervised by Dominique Heitz, Etienne Mémin, Gilles Tissot.
- PhD in progress : Robin Billard, Modelling of non-conventional perforated acoustic liners, Université du Mans, started December 2017, supervised by Gilles Tissot.
- PhD in progress : Z. Caspar-Cohen, PhD student at Ifremer, LOPS, Signatures des ondes de marée internes et des mouvements en équilibre quasi-géostrophique sur les courants de surface : perspectives eulérienne vs lagrangienne. Started 15/10/2019. Supervised by Noé Lahaye with X. Carton (UBO) and A. Ponte (Ifremer).
- PhD successfully defended : Dienh Duong Nguyen, October 1st, 2020.

9.6.3 Juries

Jocelyne Erhel

- Etienne Ahusborde, HdR, Univ. Strasbourg (rapporteur)
- Benoit Pinier, PhD, Univ. Rennes (examinatrice)
- Quentin Tournois, PhD, Univ. Rennes (examinatrice)

Etienne Mémin

- Anthony Fillion, Ecoles des Ponts, U. Paris-Est (Rapporteur)
- Alban Farchi, Ecoles des Ponts, U. Paris-Est (Examinateur)
- Arthur Pajot, Sorbonne Université, (Rapporteur)

Dominique Heitz

- Georges HALIM ATALLAH, PhD, U Gustave Eiffel (Rapporteur), 17 décembre 2020.

9.7 Popularization

Jocelyne Erhel

- was scientific coordinator of the website Interstices (June 2012 - September 2019). She is now member of the editorial board, from October 2019.

10 Scientific production

10.1 Major publications

[1] K. Burrage and J. Erhel. 'On the performance of various adaptive preconditioned GMRES'. In: *Numerical Linear Algebra with Applications* 5 (1998), pp. 101–121.

[2] J. Carrayrou, J. Hoffmann, P. Knabner, S. Kräutle, C. D. Dieuleveult, J. Erhel, J. V. der Lee, V. Lagneau, K. Mayer and K. MacQuarrie. 'Comparison of numerical methods for simulating strongly non-linear and heterogeneous reactive transport problems. The MoMaS benchmark case'. In: *Computational Geosciences* 14.3 (2010), pp. 483–502.

[3] T. Chacón-Rebollo and R. Lewandowski. *Mathematical and Numerical Foundations of Turbulence Models and Applications*. Modeling and Simulation in Science, Engineering and Technology. Birkhäuser Basel, 2014.

[4] T. Corpetti, D. Heitz, G. Arroyo, E. Mémin and A. Santa-Cruz. 'Fluid experimental flow estimation based on an optical-flow scheme'. In: *Experiments in fluids* 40 (2006), pp. 80–97.

[5] J.-R. D. Dreuzy, A. Beaudoin and J. Erhel. 'Asymptotic dispersion in 2D heterogeneous porous media determined by parallel numerical simulations'. In: *Water Resource Research* 43.W10439, doi:10.1029/2006WR005394 (2007).

[6] A. Gronskis, D. Heitz and E. Mémin. 'Inflow and initial conditions for direct numerical simulation based on adjoint data assimilation'. In: *Journal of Computational Physics* 242 (2013), pp. 480–497. DOI: 10.1016/j.jcp.2013.01.051. URL: http://www.sciencedirect.com/science/article/pii/S0021999113001290.

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[9] E. Mémin. 'Fluid flow dynamics under location uncertainty'. In: *Geophysical & Astrophysical Fluid Dynamics* 108.2 (2014), pp. 119–146. URL: http://dx.doi.org/10.1080/03091929.2013.836190.

[10] N. Nassif, J. Erhel and B. Philippe. *Introduction to computational linear Algebra*. CRC Press, 2015.

[11] N. Papadakis and E. Mémin. 'A variational technique for time consistent tracking of curves and motion'. In: *Journal of Mathematical Imaging and Vision* 31.1 (2008), pp. 81–103. URL: http://www.irisa.fr/fluminance/publi/papers/Papadakis-Memin-JMIV07.pdf.

[12] V. Resseguier, E. Mémin and B. Chapron. 'Geophysical flows under location uncertainty, Part I Random transport and general models'. In: *Geophys. & Astro. Fluid Dyn.* 111.3 (2017), pp. 149–176.

[13] V. Resseguier, E. Mémin, D. Heitz and B. Chapron. 'Stochastic modelling and diffusion modes for proper orthogonal decomposition models and small-scale flow analysis'. In: *J. Fluid Mech.* 828 (2017), p. 29.

[14] V. Resseguier, E. Mémin and B. Chapron. 'Geophysical flows under location uncertainty, Part II Quasi-geostrophy and efficient ensemble spreading'. In: *Geophysical and Astrophysical Fluid Dynamics* 111.3 (Apr. 2017), pp. 177–208. DOI: 10.1080/03091929.2017.1312101. URL: https://hal.inria.fr/hal-01391476.

[15] V. Resseguier, E. Mémin and B. Chapron. 'Geophysical flows under location uncertainty, Part III SQG and frontal dynamics under strong turbulence conditions'. In: *Geophysical and Astrophysical Fluid Dynamics* 111.3 (Apr. 2017), pp. 209–227. DOI: 10.1080/03091929.2017.1312102. URL: https://hal.inria.fr/hal-01391484.

[16] Y. Saad, M. Yeung, J. Erhel and F. Guyomarc'h. 'A deflated version of the Conjugate Gradient Algorithm'. In: *SIAM Journal on Scientific Computing* 21.5 (2000), pp. 1909–1926.

10.2 Publications of the year

International journals

[17] C. Amrouche, L. C. Berselli, R. Lewandowski and D. Duong Nguyen. 'Turbulent flows as generalized Kelvin-Voigt materials: modeling and analysis'. In: *Nonlinear Analysis: Theory, Methods and Applications* 196 (July 2020). DOI: 10.1016/j.na.2020.111790. URL: https://hal.archives-ouvertes.fr/hal-02523938.

[18] W. Bauer, P. Chandramouli, B. Chapron, L. Li and E. Mémin. 'Deciphering the role of small-scale inhomogeneity on geophysical flow structuration: a stochastic approach'. In: *Journal of Physical Oceanography* 50.4 (2020), pp. 983–1003. DOI: 10.1175/JPO-D-19-0164.1. URL: https://hal.inria.fr/hal-02398521.

[19] W. Bauer, P. Chandramouli, L. Li and E. Mémin. 'Stochastic representation of mesoscale eddy effects in coarse-resolution barotropic models'. In: *Ocean Modelling* 151 (2020), pp. 1–50. DOI: 10.1016/j.ocemod.2020.101646. URL: https://hal.inria.fr/hal-02666147.

[20] L. C. Berselli, A. A. Dunca, R. Lewandowski and D. Duong Nguyen. 'Modeling Error of α-Models of Turbulence on a Two-Dimensional Torus'. In: *Discrete and Continuous Dynamical Systems - Series B* (2021). DOI: 10.3934/dcdsb.2020305. URL: https://hal.archives-ouvertes.fr/hal-02469048.

[21] L. C. Berselli, T. Iliescu, B. Koc and R. Lewandowski. 'Long-Time Reynolds Averaging of Reduced Order Models for Fluid Flows: Preliminary Results'. In: *Mathematics in Engineering* 2.1 (2020), pp. 1–25. DOI: 10.3934/mine.2020001. URL: https://hal.archives-ouvertes.fr/hal-01979939.

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[23] R. Billard, G. Tissot, G. Gabard and M. Versaevel. 'Numerical Simulations of Perforated Plate Liners: Analysis of the Visco-Thermal Dissipation Mechanisms'. In: *Journal of the Acoustical Society of America* 149.1 (5th Jan. 2021), pp. 16–27. DOI: 10.1121/10.0002973. URL: https://hal.inria.fr/hal-03082707.

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[25] N. Lahaye, J. Gula and G. Roullet. 'Internal tide cycle and topographic scattering over the North Mid-Atlantic Ridge'. In: *Journal of Geophysical Research. Oceans* (12th Nov. 2020). DOI: 10.1029/2020JC016376. URL: https://hal.archives-ouvertes.fr/hal-03015814.

[26] N. Lahaye, V. Zeitlin and T. Dubos. 'Coherent dipoles in a mixed layer with variable buoyancy: Theory compared to observations'. In: *Ocean Modelling* 153 (Sept. 2020), p. 101673. DOI: 10.1016/j.ocemod.2020.101673. URL: https://hal.archives-ouvertes.fr/hal-03006503.

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[31] G. Tissot, R. Billard and G. Gabard. 'Optimal cavity shape design for acoustic liners using Helmholtz equation with visco-thermal losses'. In: *Journal of Computational Physics* 402 (2020), p. 109048. DOI: 10.1016/j.jcp.2019.109048. URL: https://hal.inria.fr/hal-02335784.

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International peer-reviewed conferences

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[36] L. Pénard, K. S. Mohammad and E. Mémin. 'Monocular 3D reconstruction for image-based velocity estimation'. In: Proceedings of the 10th Conference on Fluvial Hydraulics. Delft, Netherlands, 7th July 2020. URL: https://hal.inria.fr/hal-03081977.

Conferences without proceedings

[37] R. Billard, G. Gabard, M. Versaevel and G. Tissot. 'A non-minear impedance model for micro-perforated liners'. In: e-Forum Acusticum 2020. online, France, 7th Dec. 2020. URL: https://hal.inria.fr/hal-03143278.

[38] R. Brecht, L. Li, W. Bauer and E. Mémin. 'Rotating shallow water flow under location uncertainty: Part II: some numerical results'. In: Seminar STUDO. Rennes, France, 4th Sept. 2020. URL: https://hal.archives-ouvertes.fr/hal-02946835.

[39] R. Fablet, L. Drumetz, F. Rousseau, O. Pannekoucke, B. Chapron and E. Mémin. 'Joint learning of variational data assimilation models and solvers'. In: ECMWF-ESA 2020 - Workshop on Machine Learning for Earth System Observation and Prediction. Reading, United Kingdom, 5th Oct. 2020. URL: https://hal.archives-ouvertes.fr/hal-02927356.

[40] M. Ladvig, A. M. Picard, V. Resseguier, D. Heitz, E. Mémin and B. Chapron. 'Real-time observer from stochastic reduced order model'. In: GDR Flow Separation Control. Poitiers, France, 12th Nov. 2020. URL: https://hal.archives-ouvertes.fr/hal-03013492.

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Scientific book chapters

[42] S. Kadri and E. Mémin. 'A stochastic sub-grid viscosity model and wavelet based method for images assimilation'. In: *Identification and Control : some challenges*. 2020, pp. 1–23. URL: https://hal.inria.fr/hal-02542523.

Reports & preprints

[43] M. Y. Ben Ali, G. Tissot, D. Heitz, S. Aguinaga and E. Mémin. *An adjoint approach for the analysis of RANS closure using pressure measurements on a high-rise building*. 16th Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03076369.

[44] R. Brecht, L. Li, W. Bauer and E. Mémin. *Rotating shallow water flow under location uncertainty with a structure-preserving discretization*. 4th Feb. 2021. URL: https://hal.inria.fr/hal-03131680.

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[46] A. M. Picard, M. Ladvig, V. Resseguier, D. Heitz, E. Mémin and B. Chapron. *Real-time flow estimation from reduced order models and sparse measurements*. 16th Oct. 2020. URL: https://hal.inria.fr/hal-02969086.

Other scientific publications

[47] V. Resseguier, M. Ladvig, A. M. Picard, E. Mémin and B. Chapron. *Toward real-time embedded observer of unsteady fluid flow environment*. Toulouse, France, 29th Jan. 2020. URL: https://hal.inria.fr/hal-02465508.

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[51] S. Cai, E. Mémin, P. Dérian and C. Xu. 'Motion Estimation under Location Uncertainty for Turbulent Fluid Flow'. In: *Exp. in Fluids* 59.8 (2017).

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