IN PARTNERSHIP WITH:
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Centre d'expertise des risques, de l'environnement, des mobilités et de l'aménagement

Sorbonne Université (UPMC)

Activity Report 2019

Project-Team ANGE

Numerical Analysis, Geophysics and Environment

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions (LJLL)

RESEARCH CENTER
Paris

THEME
Earth, Environmental and Energy Sciences

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Project-Team ANGE

Creation of the Team: 2012 November 01, updated into Project-Team: 2014 January 01

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1. Team, Visitors, External Collaborators

Research Scientists

Jacques Sainte-Marie [Team leader, Inria, Senior Researcher, HDR]
Vivien Mallet [Inria, Researcher]
Martin Parisot [Inria, Researcher, until Aug 2019]
Yohan Penel [Inria, Advanced Research Position]
Julien Salomon [Inria, Senior Researcher]

Faculty Members

Nina Aguillon [Sorbonne Université, Associate Professor]
Edwige Godlewski [Sorbonne Université, Professor, HDR]
Cindy Guichard [Sorbonne Université, Associate Professor]
Boris Haspot [Univ de Dauphine, Associate Professor, until Aug 2019]

Anne Mangeney [IPGP, Professor, until Aug 2019, HDR]

Post-Doctoral Fellow

Janelle Hammond [Inria, Post-Doctoral Fellow]

PhD Students

Frederic Allaire [Inria, PhD Student]
Léa Boittin [Inria, PhD Student, until Feb 2019]
Nelly Boulos Al Makary [Univ Paris-Nord, PhD Student]
Virgile Dubos [Sorbonne Université, PhD Student]
Ngoc Le [IRSN, PhD Student, until Oct 2019]
Antoine Lesieur [Inria, PhD Student]
Liudi Lu [Sorbonne Université, PhD Student]
Hugo Martin [Sorbonne Université, PhD Student, until Apr 2019]
Mathieu Rigal [Sorbonne Université, PhD Student, from Oct 2019]

Technical staff

Cédric Doucet [Inria, Engineer, until Mar 2019]
Apolline El Baz [Inria, Engineer, from Dec 2019]
Jérémy Ledoux [Univ de Dauphine, Engineer, until Sep 2019]
Guillaume Chérel [Inria, from Feb 2019]
Fabien Souillé [EDF, until Aug 2019]

Interns and Apprentices

Chourouk El Hassanieh [Inria, from May 2019 until Jul 2019]
Antonin Leprevost [Inria, until Jan 2019]
Sibylle Techene [CNRS, from Apr 2019 until Sep 2019]

Administrative Assistants

Laurence Bourcier [Inria, Administrative Assistant]
Maryse Desnous [Inria, Administrative Assistant, until Apr 2019]
Julien Guieu [Inria, Administrative Assistant, from Apr 2019]

Visiting Scientist

Marie-Odile Bristeau [retired]

External Collaborators

Emmanuel Audusse [Univ Paris-Nord]
Bernard Di Martino [Univ. de Corse, HDR]

2. Overall Objectives

2.1. Presentation

Among all aspects of geosciences, we mainly focus on gravity driven flows arising in many situations such as

- hazardous flows (flooding, rogue waves, landslides...),
- sustainable energies (hydrodynamics-biology coupling, biofuel production, marine energies...),
- risk management and land-use planning (morphodynamic evolutions, early warning systems...)

There exists a strong demand from scientists and engineers in fluid mechanics for models and numerical tools able to simulate not only the water depth and the velocity field but also the distribution and evolution of external quantities such as pollutants or biological species and the interaction between flows and structures (seashores, erosion processes...). The key point of the researches carried out within ANGE is to answer this demand by the development of efficient, robust and validated models and numerical tools.

2.2. Scientific challenges

Due to the variety of applications with a wide range of spatial scales, reduced-size models like the shallow water equations are generally required. From the modelling point of view, the main issue is to describe the behaviour of the flow with a reduced-size model taking into account several physical processes such as non-hydrostatic terms, biological species evolution, topography and structure interactions within the flow. The mathematical analysis of the resulting model do not enter the field of hyperbolic equations anymore and new strategies have to be proposed. Moreover, efficient numerical resolutions of reduced-size models require particular attention due to the different time scales of the processes and in order to recover physical properties such as positivity, conservativity, entropy dissipation and equilibria.

The models can remain subject to uncertainties that originate from incomplete description of the physical processes and from uncertain parameters. Further development of the models may rely on the assimilation of observational data and the uncertainty quantification of the resulting analyses or forecasts.

3. Research Program

3.1. Overview

The research activities carried out within the ANGE team strongly couple the development of methodological tools with applications to real–life problems and the transfer of numerical codes. The main purpose is to obtain new models adapted to the physical phenomena at stake, identify the main properties that reflect the physical meaning of the models (uniqueness, conservativity, entropy dissipation, ...), propose effective numerical methods to approximate their solution in complex configurations (multi-dimensional, unstructured meshes, well-balanced, ...) and to assess the results with data in the purpose of potentially correcting the models.

The difficulties arising in gravity driven flow studies are threefold.

- Models and equations encountered in fluid mechanics (typically the free surface Navier-Stokes equations) are complex to analyze and solve.
- The underlying phenomena often take place over large domains with very heterogeneous length scales (size of the domain, mean depth, wave length, ...) and distinct time scales, *e.g.* coastal erosion, propagation of a tsunami, ...
- These problems are multi-physics with strong couplings and nonlinearities.

3.2. Modelling and analysis

Hazardous flows are complex physical phenomena that can hardly be represented by shallow water type systems of partial differential equations (PDEs). In this domain, the research program is devoted to the derivation and analysis of reduced complexity models compared to the Navier-Stokes equations, but relaxing the shallow water assumptions. The main purpose is then to obtain models well-adapted to the physical phenomena at stake.

Even if the resulting models do not strictly belong to the family of hyperbolic systems, they exhibit hyperbolic features: the analysis and discretisation techniques we intend to develop have connections with those used for hyperbolic conservation laws. It is worth noticing that the need for robust and efficient numerical procedures is reinforced by the smallness of dissipative effects in geophysical models which therefore generate singular solutions and instabilities.

On the one hand, the derivation of the Saint-Venant system from the Navier-Stokes equations is based on two approximations (the so-called shallow water assumptions), namely

- the horisontal fluid velocity is well approximated by its mean value along the vertical direction,
- the pressure is hydrostatic or equivalently the vertical acceleration of the fluid can be neglected compared to the gravitational effects.

As a consequence the objective is to get rid of these two assumptions, one after the other, in order to obtain models accurately approximating the incompressible Euler or Navier-Stokes equations.

On the other hand, many applications require the coupling with non-hydrodynamic equations, as in the case of micro-algae production or erosion processes. These new equations comprise non-hyperbolic features and a special analysis is needed.

3.2.1. Multilayer approach

As for the first shallow water assumption, *multi-layer* systems were proposed to describe the flow as a superposition of Saint-Venant type systems [26], [29], [30]. Even if this approach has provided interesting results, layers are considered separate and non-miscible fluids, which implies strong limitations. That is why we proposed a slightly different approach [27], [28] based on a Galerkin type decomposition along the vertical axis of all variables and leading, both for the model and its discretisation, to more accurate results.

A kinetic representation of our multilayer model allows to derive robust numerical schemes endowed with crucial properties such as: consistency, conservativity, positivity, preservation of equilibria, ... It is one of the major achievements of the team but it needs to be analyzed and extended in several directions namely:

- The convergence of the multilayer system towards the hydrostatic Euler system as the number of layers goes to infinity is a critical point. It is not fully satisfactory to have only formal estimates of the convergence and sharp estimates would provide an optimal number of layers.
- The introduction of several source terms due for instance to the Coriolis force or extra terms from changes of coordinates seems necessary. Their inclusion should lead to substantial modifications of the numerical scheme.
- Its hyperbolicity has not yet been proven and conversely the possible loss of hyperbolicity cannot be characterised. Similarly, the hyperbolic feature is essential in the propagation and generation of waves.

3.2.2. Non-hydrostatic models

The hydrostatic assumption consists in neglecting the vertical acceleration of the fluid. It is considered valid for a large class of geophysical flows but is restrictive in various situations where the dispersive effects (like wave propagation) cannot be neglected. For instance, when a wave reaches the coast, bathymetry variations give a vertical acceleration to the fluid that strongly modifies the wave characteristics and especially its height.

Processing an asymptotic expansion (w.r.t. the aspect ratio for shallow water flows) into the Navier-Stokes equations, we obtain at the leading order the Saint-Venant system. Going one step further leads to a vertically averaged version of the Euler/Navier-Stokes equations involving some non-hydrostatic terms. This model has several advantages:

- it admits an energy balance law (that is not the case for most dispersive models available in the literature),
- it reduces to the Saint-Venant system when the non-hydrostatic pressure term vanishes,
- it consists in a set of conservation laws with source terms,
- it does not contain high order derivatives.

3.2.3. Multi-physics modelling

The coupling of hydrodynamic equations with other equations in order to model interactions between complex systems represents an important part of the team research. More precisely, three multi-physics systems are investigated. More details about the industrial impact of these studies are presented in the following section.

- To estimate the risk for infrastructures in coastal zones or close to a river, the resolution of the shallow water equations with moving bathymetry is necessary. The first step consisted in the study of an additional equation largely used in engineering science: The Exner equation. The analysis enabled to exhibit drawbacks of the coupled model such as the lack of energy conservation or the strong variations of the solution from small perturbations. A new formulation is proposed to avoid these drawbacks. The new model consists in a coupling between conservation laws and an elliptic equation, like the Euler/Poisson system, suggesting to use well-known strategies for the analysis and the numerical resolution. In addition, the new formulation is derived from classical complex rheology models and allowed physical phenomena like threshold laws.

- Interaction between flows and floating structures is the challenge at the scale of the shallow water equations. This study requires a better understanding of the energy exchanges between the flow and the structure. The mathematical model of floating structures is very hard to solve numerically due to the non-penetration condition at the interface between the flow and the structure. It leads to infinite potential wave speeds that could not be solved with classical free surface numerical schemes. A relaxation model was derived to overcome this difficulty. It represents the interaction with the floating structure with a free surface model-type.
- If the interactions between hydrodynamics and biology phenomena are known through laboratory experiments, it is more difficult to predict the evolution, especially for the biological quantities, in a real and heterogeneous system. The objective is to model and reproduce the hydrodynamics modifications due to forcing term variations (in time and space). We are typically interested in phenomena such as eutrophication, development of harmful bacteria (cyanobacteria) and upwelling phenomena.

3.2.4. Data assimilation and inverse modelling

In environmental applications, the most accurate numerical models remain subject to uncertainties that originate from their parameters and shortcomings in their physical formulations. It is often desirable to quantify the resulting uncertainties in a model forecast. The propagation of the uncertainties may require the generation of ensembles of simulations that ideally sample from the probability density function of the forecast variables. Classical approaches rely on multiple models and on Monte Carlo simulations. The applied perturbations need to be calibrated for the ensemble of simulations to properly sample the uncertainties. Calibrations involve ensemble scores that compare the consistency between the ensemble simulations and the observational data. The computational requirements are so high that designing fast surrogate models or metamodels is often required.

In order to reduce the uncertainties, the fixed or mobile observations of various origins and accuracies can be merged with the simulation results. The uncertainties in the observations and their representativeness also need to be quantified in the process. The assimilation strategy can be formulated in terms of state estimation or parameter estimation (also called inverse modelling). Different algorithms are employed for static and dynamic models, for analyses and forecasts. A challenging question lies in the optimization of the observational network for the assimilation to be the most efficient at a given observational cost.

3.3. Numerical analysis

3.3.1. Non-hydrostatic scheme

The main challenge in the study of the non-hydrostatic model is to design a robust and efficient numerical scheme endowed with properties such as: positivity, wet/dry interfaces treatment, consistency. It must be noticed that even if the non-hydrostatic model looks like an extension of the Saint-Venant system, most of the known techniques used in the hydrostatic case are not efficient as we recover strong difficulties encountered in incompressible fluid mechanics due to the extra pressure term. These difficulties are reinforced by the absence of viscous/dissipative terms.

3.3.2. Space decomposition and adaptive scheme

In the quest for a better balance between accuracy and efficiency, a strategy consists in the adaptation of models. Indeed, the systems of partial differential equations we consider result from a hierarchy of simplifying assumptions. However, some of these hypotheses may turn out to be irrelevant locally. The adaptation of models thus consists in determining areas where a simplified model (*e.g.* shallow water type) is valid and where it is not. In the latter case, we may go back to the “parent” model (*e.g.* Euler) in the corresponding area.

This implies to know how to handle the coupling between the aforementioned models from both theoretical and numerical points of view. In particular, the numerical treatment of transmission conditions is a key point. It requires the estimation of characteristic values (Riemann invariant) which have to be determined according to the regime (torrential or fluvial).

3.3.3. Asymptotic-Preserving scheme for source terms

Hydrodynamic models comprise advection and sources terms. The conservation of the balance between source terms, typically viscosity and friction, has a significant impact since the overall flow is generally a perturbation around an equilibrium. The design of numerical schemes able to preserve such balances is a challenge from both theoretical and industrial points of view. The concept of Asymptotic-Preserving (AP) methods is of great interest in order to overcome these issues.

Another difficulty occurs when a term, typically related to the pressure, becomes very large compared to the order of magnitude of the velocity. At this regime, namely the so-called *low Froude* (shallow water) or *low Mach* (Euler) regimes, the difference between the speed of the gravity waves and the physical velocity makes classical numerical schemes inefficient: firstly because of the error of truncation which is inversely proportional to the small parameters, secondly because of the time step governed by the largest speed of the gravity wave. AP methods made a breakthrough in the numerical resolution of asymptotic perturbations of partial-differential equations concerning the first point. The second one can be fixed using partially implicit scheme.

3.3.4. Multi-physics models

Coupling problems also arise within the fluid when it contains pollutants, density variations or biological species. For most situations, the interactions are small enough to use a splitting strategy and the classical numerical scheme for each sub-model, whether it be hydrodynamic or non-hydrodynamic.

The sediment transport raises interesting issues from a numerical aspect. This is an example of coupling between the flow and another phenomenon, namely the deformation of the bottom of the basin that can be carried out either by bed load where the sediment has its own velocity or suspended load in which the particles are mostly driven by the flow. This phenomenon involves different time scales and nonlinear retroactions; hence the need for accurate mechanical models and very robust numerical methods. In collaboration with industrial partners (EDF–LNHE), the team already works on the improvement of numerical methods for existing (mostly empirical) models but our aim is also to propose new (quite) simple models that contain important features and satisfy some basic mechanical requirements. The extension of our 3D models to the transport of weighted particles can also be here of great interest.

3.3.5. Optimisation

Numerical simulations are a very useful tool for the design of new processes, for instance in renewable energy or water decontamination. The optimisation of the process according to a well-defined objective such as the production of energy or the evaluation of a pollutant concentration is the logical upcoming challenge in order to propose competitive solutions in industrial context. First of all, the set of parameters that have a significant impact on the result and on which we can act in practice is identified. Then the optimal parameters can be obtained using the numerical codes produced by the team to estimate the performance for a given set of parameters with an additional loop such as gradient descent or Monte Carlo method. The optimisation is used in practice to determine the best profile for turbine pales, the best location for water turbine implantation, in particular for a farm.

4. Application Domains

4.1. Overview

Sustainable development and environment preservation have a growing importance and scientists have to address difficult issues such as: management of water resources, renewable energy production, bio/geo-chemistry of oceans, resilience of society w.r.t. hazardous flows, urban pollutions, ...

As mentioned above, the main issue is to propose models of reduced complexity, suitable for scientific computing and endowed with stability properties (continuous and/or discrete). In addition, models and their numerical approximations have to be confronted with experimental data, as analytical solutions are hardly accessible for these problems/models. A. Mangeney (IPGP) and N. Goutal (EDF) may provide useful data.

4.2. Geophysical flows

Reduced models like the shallow water equations are particularly well-adapted to the modelling of geophysical flows since there are characterized by large time or/and space scales. For long time simulations, the preservation of equilibria is essential as global solutions are a perturbation around them. The analysis and the numerical preservation of non-trivial equilibria, more precisely when the velocity does not vanish, are still a challenge. In the fields of oceanography and meteorology, the numerical preservation of the so-called geostrophic state, which is the balance between the gravity field and the Coriolis force, can significantly improve the forecasts. In addition, data assimilation is required to improve the simulations and correct the dissipative effect of the numerical scheme.

The sediment transport modelling is of major interest in terms of applications, in particular to estimate the sustainability of facilities with silt or scour, such as canals and bridges. Dredging or filling-up operations are expensive and generally not efficient in the long term. The objective is to determine a configuration almost stable for the facilities. In addition, it is also important to determine the impact of major events like emptying dam which is aimed at evacuating the sediments in the dam reservoir and requires a large discharge. However, the downstream impact should be measured in terms of turbidity, river morphology and flood.

4.3. Hydrological disasters

It is a violent, sudden and destructive flow. Between 1996 and 2005, nearly 80% of natural disasters in the world have meteorological or hydrological origines. The main interest of their study is to predict the areas in which they may occur most probably and to prevent damages by means of suitable amenities. In France, floods are the most recurring natural disasters and produce the worst damages. For example, it can be a cause or a consequence of a dam break. The large surface they cover and the long period they can last require the use of reduced models like the shallow water equations. In urban areas, the flow can be largely impacted by the debris, in particular cars, and this requires fluid/structure interactions be well understood. Moreover, underground flows, in particular in sewers, can accelerate and amplify the flow. To take them into account, the model and the numerical resolution should be able to treat the transition between free surface and underground flows.

Tsunamis are another hydrological disaster largely studied. Even if the propagation of the wave is globally well described by the shallow water model in oceans, it is no longer the case close to the epicenter and in the coastal zone where the bathymetry leads to vertical accretions and produces substantial dispersive effects. The non-hydrostatic terms have to be considered and an efficient numerical resolution should be induced.

While viscous effects can often be neglected in water flows, they have to be taken into account in situations such as avalanches, debris flows, pyroclastic flows, erosion processes, ...*i.e.* when the fluid rheology becomes more complex. Gravity driven granular flows consist of solid particles commonly mixed with an interstitial lighter fluid (liquid or gas) that may interact with the grains and decrease the intensity of their contacts, thus reducing energy dissipation and favoring propagation. Examples include subaerial or subaqueous rock avalanches (e.g. landslides).

4.4. Biodiversity and culture

Nowadays, simulations of the hydrodynamic regime of a river, a lake or an estuary, are not restricted to the determination of the water depth and the fluid velocity. They have to predict the distribution and evolution of external quantities such as pollutants, biological species or sediment concentration.

The potential of micro-algae as a source of biofuel and as a technological solution for CO2 fixation is the subject of intense academic and industrial research. Large-scale production of micro-algae has potential for biofuel applications owing to the high productivity that can be attained in high-rate raceway ponds. One of the key challenges in the production of micro-algae is to maximize algae growth with respect to the exogenous energy that must be used (paddlewheel, pumps, ...). There is a large number of parameters that need to be optimized (characteristics of the biological species, raceway shape, stirring provided by the paddlewheel). Consequently our strategy is to develop efficient models and numerical tools to reproduce the flow induced by the paddlewheel and the evolution of the biological species within this flow. Here, mathematical models can greatly help us reduce experimental costs. Owing to the high heterogeneity of raceways due to gradients of temperature, light intensity and nutrient availability through water height, we cannot use depth-averaged models. We adopt instead more accurate multilayer models that have recently been proposed. However, it is clear that many complex physical phenomena have to be added to our model, such as the effect of sunlight on water temperature and density, evaporation and external forcing.

Many problems previously mentioned also arise in larger scale systems like lakes. Hydrodynamics of lakes is mainly governed by geophysical forcing terms: wind, temperature variations, ...

4.5. Sustainable energy

One of the booming lines of business is the field of renewable and decarbonated energies. In particular in the marine realm, several processes have been proposed in order to produce electricity thanks to the recovering of wave, tidal and current energies. We may mention water-turbines, buoys turning variations of the water height into electricity or turbines motioned by currents. Although these processes produce an amount of energy which is less substantial than in thermal or nuclear power plants, they have smaller dimensions and can be set up more easily.

The fluid energy has kinetic and potential parts. The buoys use the potential energy whereas the water-turbines are activated by currents. To become economically relevant, these systems need to be optimized in order to improve their productivity. While for the construction of a harbour, the goal is to minimize swell, in our framework we intend to maximize the wave energy.

This is a complex and original issue which requires a fine model of energy exchanges and efficient numerical tools. In a second step, the optimisation of parameters that can be changed in real-life, such as bottom bathymetry and buoy shape, must be studied. Eventually, physical experiments will be necessary for the validation.

4.6. Urban environment

The urban environment is essentially studied for air and noise pollutions. Air pollution levels and noise pollution levels vary a lot from one street to next. The simulations are therefore carried out at street resolution and take into account the city geometry. The associated numerical models are subject to large uncertainties. Their input parameters, e.g. pollution emissions from road traffic, are also uncertain. Quantifying the simulation uncertainties is challenging because of the high computational costs of the numerical models. An appealing approach in this context is the use of metamodels, from which ensembles of simulations can be generated for uncertainty quantification.

The simulation uncertainties can be reduced by the assimilation of fixed and mobile sensors. High-quality fixed monitoring sensors are deployed in cities, and an increasing number of mobile sensors are added to the observational networks. Even smartphones can be used as noise sensors and dramatically increase the spatial coverage of the observations. The processing and assimilation of the observations raises many questions regarding the quality of the measurements and the design of the network of sensors.

4.7. SmartCity

There is a growing interest for environmental problems at city scale, where a large part of the population is concentrated and where major pollutions can occur. Numerical simulation is well established to study the urban environment, *e.g.* for road traffic modelling. As part of the smartcity movement, an increasing number of sensors collect measurements, at traditional fixed observation stations, but also on mobile devices, like smartphones. They must properly be taken into account given their number but also their potential low quality.

Pratical applications include air pollution and noise pollution. These directly relate to road traffic. Data assimilation and uncertainty propagation are key topics in these applications.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Human ressources

Martin Parisot left the team in september 2019 to join the team Cardamom (Inria-Bordeaux). Apoline El Baz joined the team on an ADT position to developp Fresh Kiss 3D. Julien Guieu is the new assistant of the team (May). Mathieu Rigal and Chourouk El Hassanieh started a PhD. (September).

5.1.2. Travel policy

The team started to limit flies for professional activities. A deeper reflexion on the environmental impact of scientific activities has been initiated in the team. C. Guichard and Y. Penel are members of the CLDD of Inria Paris.

5.1.3. Awards and new grants

- J. Sainte-Marie was promoted Adjoint au Directeur Scientifique, in charge of the topic "Sciences de la planète, de l'environnement et de l'énergie". (July)
- M. Parisot was invited for a long term stay at Aachen University (Sept.-Nov.)
- The ANR project ALLOWAP supported by J. Salomon (with L. Halpern, F. Kwok and B. Delourme) was accepted for a start in Jan. 2020.
- M. Parisot and E. Audusse organized the CEMRACS project "Land Slide Tsunami" at CIRM (July-Aug.).
- Y. Penel organized the CEMRACS project "SGN-Num" at CIRM (July-Aug.).
- E. Audusse and Y. Penel organized the CEMRACS project "SW-Cor".

6. New Software and Platforms

6.1. Freshkiss

FREe Surface Hydrodynamics using KInetic SchemeS

KEYWORDS: Finite volume methods - Hydrostatic Navier-Stokes equations - Free surface flows

FUNCTIONAL DESCRIPTION: Freshkiss3D is a numerical code solving the 3D hydrostatic and incompressible Navier-Stokes equations with variable density.

- Participants: Fabien Souillé, Emmanuel Audusse, Jacques Sainte Marie and Marie-Odile Bristeau
- Partners: UPMC - CEREMA
- Contact: Jacques Sainte Marie

6.2. TSUNAMATHS

KEYWORDS: Modeling - Tsunamis

FUNCTIONAL DESCRIPTION: Tsunamaths is an educational platform aiming at simulating historical tsunamis. Real data and mathematical explanations are provided to enable people to better understand the overall process of tsunamis.

- Participants: Emmanuel Audusse, Jacques Sainte Marie and Raouf Hamouda
- Contact: Jacques Sainte Marie
- URL: http://tsunamath.paris.inria.fr/

6.3. Verdandi

KEYWORDS: HPC - Model - Software Components - Partial differential equation

FUNCTIONAL DESCRIPTION: Verdandi is a free and open-source (LGPL) library for data assimilation. It includes various such methods for coupling one or several numerical models and observational data. Mainly targeted at large systems arising from the discretization of partial differential equations, the library is devised as generic, which allows for applications in a wide range of problems (biology and medicine, environment, image processing, etc.). Verdandi also includes tools to ease the application of data assimilation, in particular in the management of observations or for a priori uncertainty quantification. Implemented in C++, the library may be used with models implemented in Fortran, C, C++ or Python.

- Participants: Dominique Chapelle, Gautier Bureau, Nicolas Claude, Philippe Moireau and Vivien Mallet
- Contact: Vivien Mallet
- URL: http://verdandi.gforge.inria.fr/

6.4. Polyphemus

KEYWORD: Simulation

FUNCTIONAL DESCRIPTION: Polyphemus is a modeling system for air quality. As such, it is designed to yield up-to-date simulations in a reliable framework: data assimilation, ensemble forecast and daily forecasts. Its completeness makes it suitable for use in many applications: photochemistry, aerosols, radionuclides, etc. It is able to handle simulations from local to continental scales, with several physical models. It is divided into three main parts:

libraries that gather data processing tools (SeldonData), physical parameterizations (AtmoData) and post-processing abilities (AtmoPy),

programs for physical pre-processing and chemistry-transport models (Polair3D, Castor, two Gaussian models, a Lagrangian model),

model drivers and observation modules for model coupling, ensemble forecasting and data assimilation.

- Participants: Sylvain Doré and Vivien Mallet
- Contact: Vivien Mallet
- URL: http://cerea.enpc.fr/polyphemus/

6.5. Urban noise analysis

KEYWORD: Environment perception

FUNCTIONAL DESCRIPTION: This software processes mobile observations collected by the application Ambiciti (previously known as SoundCity). It can merge simulated noise maps with the mobile observations.

- Authors: Raphaël Ventura, Vivien Mallet and Guillaume Chérel
- Contact: Vivien Mallet

6.6. Freshkiss3D

KEYWORDS: Python - Cython - Navier-Stokes

FUNCTIONAL DESCRIPTION: Tool for the numerical solution of free surface Navier-Stokes equations

- Participants: Cédric Doucet, Apolline El Baz and Jacques Sainte Marie
- Partner: UPMC
- Contact: Jacques Sainte Marie
- Publication: Numerical approximation of the 3d hydrostatic Navier-Stokes system with free surface

7. New Results

7.1. Numerical methods for fluid flows

7.1.1. PARAOPT: A parareal algorithm for optimality systems

Member: J. Salomon,
Coll.: Martin Gander, Felix Kwok

The time parallel solution of optimality systems arising in PDE constraint optimization could be achieved by simply applying any time parallel algorithm, such as Parareal, to solve the forward and backward evolution problems arising in the optimization loop. We propose in [21] a different strategy by devising directly a new time parallel algorithm, which we call ParaOpt, for the coupled forward and backward non-linear partial differential equations. ParaOpt is inspired by the Parareal algorithm for evolution equations, and thus is automatically a two-level method. We provide a detailed convergence analysis for the case of linear parabolic PDE constraints. We illustrate the performance of ParaOpt with numerical experiments both for linear and nonlinear optimality systems.

7.1.2. Dynamical Behavior of a Nondiffusive Scheme for the Advection Equation

Member: N. Aguillon,
Coll.: Pierre-Antoine Guihéneuf

In [16], we study the long time behaviour of a dynamical system strongly linked to the anti-diffusive scheme of Després and Lagoutiere for the 1-dimensional transport equation. This scheme is overcompressive when the Courant–Friedrichs–Levy number is 1/2: when the initial data is nondecreasing, the approximate solution becomes a Heaviside function. In a special case, we also understand how plateaus are formed in the solution and their stability, a distinctive feature of the Després and Lagoutiere scheme.

7.1.3. Convergence of numerical schemes for a conservation equation with convection and degenerate diffusion

Member: C. Guichard,
Coll.: Robert Eymard, Xavier Lhébrard

In [20], the approximation of problems with linear convection and degenerate nonlinear diffusion, which arise in the framework of the transport of energy in porous media with thermodynamic transitions, is done using a θ-scheme based on the centered gradient discretisation method. The convergence of the numerical scheme is proved, although the test functions which can be chosen are restricted by the weak regularity hypotheses on the convection field, owing to the application of a discrete Gronwall lemma and a general result for the time translate in the gradient discretisation setting. Some numerical examples, using both the Control Volume Finite Element method and the Vertex Approximate Gradient scheme, show the role of θ for stabilising the scheme.

7.1.4. Gradient-based optimization of a rotating algal biofilm process

Members: N. Aguillon, J. Sainte-Marie,
Coll.: Pierre-Olivier Lamare, Jérôme Grenier, Hubert Bonnefond, Olivier Bernard

Microalgae are microorganisms that have only very recently been used for bio-technological applications and more specifically for the production of bio-fuel. In the report [15] we focus on the shape optimization and optimal control of an innovative process where microalgae are fixed on a support. They are successively exposed to light and darkness. The resulting growth rate can be represented by a dynamic system describing the denaturation of key proteins due to excess light. A Partial Derivative Equation (PDE) model for the Rotary Algae Biofilm (RAB) is proposed. It represents the local growth of microalgae subjected to time-varying light. A gradient method based on the calculation of the model adjoint is proposed to identify the optimal (constant) folding of the process and the (time-varying) speed of the biofilm. Once this method is used in a realistic case, the optimization results in a configuration that significantly improves productivity compared to the case where the biofilm is fixed.

7.2. Modelling

7.2.1. Accurate steam-water equation of state for two-phase flow LMNC model with phase transition

Member: Y. Penel,
Coll.: Stéphane Dellacherie, Bérénice Grec, Gloria Faccanoni

The paper [9] is dedicated to the design of incomplete equations of state for a two-phase flow with phase transition that are specific to the low Mach number regime. It makes use of the fact that the thermodynamic pressure has small variations in this regime. These equations of state supplement the 2D LMNC model introduced in previous works. This innovative strategy relies on tabulated values and is proven to satisfy crucial thermodynamic requirements such as positivity, monotonicity, continuity. In particular, saturation values are exact. This procedure is assessed by means of analytical steady solutions and comparisons with standard analytical equations of state, and shows a great improvement in accuracy.

7.2.2. Numerical simulations of Serre - Green-Naghdi type models for dispersive free surface flows

Members: Y. Penel, J. Sainte-Marie
Coll.: Enrique D. Fernandez-Nieto, Tomas Morales de Luna, Cipriano Escalante Sanchez

The Serre - Green-Nagdhi equations are simulated under their non-hydrostatic formulation by means of a projection-correction method. This is then extended to the layerwise discretisation of the Euler equations with a special care to the computational cost. An original alternating direction method is used and relies on the tools designed for the monolayer case.

7.2.3. Entropy-satisfying scheme for a hierarchy of dispersive reduced models of free surface flow

Member: M. Parisot

The work [12] is devoted to the numerical resolution in the multidimensional framework of a hierarchy of reduced models of the water wave equations, such as the Serre-Green-Naghdi model. A particular attention is paid to the dissipation of mechanical energy at the discrete level, that act as a stability argument of the scheme, even with source terms such space and time variation of the bathymetry. In addition, the analysis leads to a natural way to deal with dry areas without leakage of energy. To illustrate the accuracy and the robustness of the strategy, several numerical experiments are carried out. In particular, the strategy is capable of treating dry areas without special treatment.

7.2.4. Congested shallow water model: on floating body

Members: E. Godlewski, M. Parisot, J. Sainte-Marie, F. Wahl

In [22], we are interested in the numerical modeling of body floating freely on the water such as icebergs or wave energy converters. The fluid-solid interaction is formulated using a congested shallow water model for the fluid and Newton's second law of motion for the solid. We make a particular focus on the energy transfer between the solid and the water since it is of major interest for energy production. A numerical approximation based on the coupling of a nite volume scheme for the fluid and a Newmark scheme for the solid is presented. An entropy correction based on an adapted choice of discretization for the coupling terms is made in order to ensure a dissipation law at the discrete level. Simulations are presented to verify the method and to show the feasibility of extending it to more complex cases.

7.2.5. Pseudo-compressibility, dispersive model and acoustic waves in shallow water flows

Members: E. Godlewski, M-O. Bristeau, J. Sainte-Marie

In this paper we study a dispersive shallow water type model derived from the compressible Navier-Stokes system. The compressible effects allow to capture the acoustic waves propagation and can be seen as a relaxation of an underlying incompressible model. Hence, the pseudo-compressibility terms circumvent the resolution of an elliptic equation for the non-hydrostatic part of the pressure. For the numerical approximation of shallow water type models, the hy- perbolic part, often approximated using explicit time schemes, is constrained by a CFL condition. Since the approximation of the dispersive terms – im- plicit in time – generally requires the numerical resolution of an elliptic equation, it is very costly. In this paper, we show that when considering the pseudo-compressibility terms a fully explicit in time scheme can be derived. This drastically reduces the cost of the numerical resolution of dispersive models especially in 2d and 3d.

7.2.6. Some quasi-analytical solutions for propagative waves in free surface Euler equations

Members: B. Di Martino, M-O. Bristeau, J. Sainte-Marie, A. Mangeney, F. Souillé

This note describes some quasi-analytical solutions for wave propagation in free surface Euler equations and linearized Euler equations. The obtained solutions vary from a sinusoidal form to a form with singularities. They allow a numerical validation of the free-surface Euler codes.

7.2.7. Challenges and prospects for dynamical cores of oceanic models across all scales

Members: E. Audusse, J. Sainte-Marie
Review paper, more than 30 co-authors

The paper [11] provides an overview of the recent evolution and future challenges of oceanic models dynamical cores used for applications ranging from global paleoclimate scales to short-term prediction in estuaries and shallow coastal areas. The dynamical core is responsible for the discrete approximation in space and time of the resolved processes, as opposed to the physical parameterizations which represent unresolved or under-resolved processes. The paper reviews the challenges and prospects outlined by the modeling groups that participated to the Community for the Numerical Modeling of the Global, Regional, and Coastal Ocean (COMMODORE) workshop. The topics discussed in the paper originate from the experience acquired during the development of 16 dynamical cores representative of the variety of numerical methods implemented in models used for realistic ocean simulations. The topics of interest include the choice of model grid and variables arrangement, vertical coordinate, temporal discretization, and more practical aspects about the evolution of code architecture and development practices.

7.2.8. The Navier-Stokes system with temperature and salinity for free surface flows Part I: Low-Mach approximation & layer-averaged formulation

Members: M-O. Bristeau, L. Boittin, A. Mangeney, J. Sainte-Marie, F. Bouchut

In this paper, we are interested in free surface flows where density variations coming e.g. from temperature or salinity differences play a significant role in the hydrodynamic regime. In water, acoustic waves travel much faster than gravity and internal waves, hence the study of models arising in compressible fluid mechanics often requires a decoupling between these waves. Starting from the compressible Navier-Stokes system, we derive the so-called Navier-Stokes-Fourier system in an incompressible context (the density does not depend on the fluid pressure) using the low-Mach scaling. Notice that a modified low-Mach scaling is necessary to obtain a model with a thermo-mechanical compatibility. The case where the density depends only on the temperature is studied first. Then the variations of the fluid density with respect to the temperature and the salinity are considered. We give a layer-averaged formulation of the obtained models in an hydrostatic context. Allowing to derive numerical schemes endowed with strong stability properties – that are presented in a companion paper – the layer-averaged formulation is very useful for the numerical analysis and the numerical simulations of the models. Several stability properties of the layer-averaged Navier-Stokes-Fourier system are proved.

7.2.9. The Navier-Stokes system with temperature and salinity for free surface flows - Part II: Numerical scheme and validation

Members: M-O. Bristeau, L. Boittin, A. Mangeney, J. Sainte-Marie, F. Bouchut

In this paper, we propose a numerical scheme for the layer-averaged Euler with variable density and the Navier-Stokes-Fourier systems presented in part I.These systems model hydrostatic free surface flows with density variations. We show that the finite volume scheme presented is well balanced with regards to the steady state of the lake at rest and preserves the positivity of the water height. A maximum principle on the density is also proved as well as a discrete entropy inequality in the case of the Euler system with variable density. Some numerical validations are finally shown with comparisons to 3D analytical solutions and experiments.

7.3. Functional analysis of PDE models in Fluid Mechanics

7.3.1. On the rigid-lid approximation of shallow water Bingham model

Member: J. Sainte-Marie
Coll.: Bilal Al Taki, Khawla Msheik

The paper [17] discusses the well posedness of an initial value problem describing the motion of a Bingham fluid in a basin with a degenerate bottom topography. A physical interpretation of such motion is discussed. The system governing such motion is obtained from the Shallow Water-Bingham models in the regime where the Froude number degenerates, i.e taking the limit of such equations as the Froude number tends to zero. Since we are considering equations with degenerate coefficients, then we shall work with weighted Sobolev spaces in order to establish the existence of a weak solution. In order to overcome the difficulty of the discontinuity in Bingham's constitutive law, we follow a similar approach to that introduced in [G. Duvaut and J.-L. Lions, Springer-Verlag, 1976]. We study also the behavior of this solution when the yield limit vanishes. Finally, a numerical scheme for the system in 1D is furnished.

7.3.2. Global bmo-1($\mathbb{R}^N$) radially symmetric solution for compressible Navier-Stokes equations with initial density in $\mathbb{L}^\infty(\mathbb{R}^N)$

Member: B. Haspot

In [24], we investigate the question of the existence of global weak solutionfor the compressible Navier Stokes equations provided that the initial momentum belongs to bmo-1($\mathbb{R}^N$) with $N = 2, 3$ and is radially symmetric. We prove then a equivalent of the so-called Koch-Tataru theorem for the compressible Navier-Stokes equations. In addition we assume that the initial density is only bounded in $\mathbb{L}^\infty(\mathbb{R}^N)$, it allows us in particular to consider initial density admitting shocks. Furthermore we show that if the coupling between the density and the velocity is sufficiently strong,then the initial density which admits initially shocks is instantaneously regularizinginasmuch as the density becomes Lipschitz. To finish we prove the global existence of strong solution for large initial data pro-vided that the initial data are radially symmetric and sufficiently regular in dimension $N = 2, 3$ for $\gamma-$law pressure.

7.3.3. New effective pressure and existence of global strong solution for compressible Navier-Stokes equations with general viscosity coefficient in one dimension

Member: Boris Haspot
Coll.: Cosmin Burtea

In this paper we prove the existence of global strong solution for the Navier-Stokesequations with general degenerate viscosity coefficients. The cornerstone of the proofis the introduction of a new effective pressure which allows to obtain an Oleinik-typeestimate for the so called effective velocity. In our proof we make use of additionalregularizing effects on the velocity which requires to extend the technics developedby Hoff for the constant viscosity case.

7.4. Assessments of models by means of experimental data and assimilation

7.4.1. Metamodeling corrected by observational data

Members: V. Mallet, J. Hammond

An air quality model at urban scale computes the air pollutant concentrations at street resolution based on various emissions, meteorology, imported pollution and city geometry. Because of the computational cost of such model, we previously designed a metamodel using dimension reduction and statistical emulation, and then corrected this metamodel with observational data. Novel work was dedicated to the error modeling for a more balanced integration of the observations. The work was also applied to air quality simulation over Paris using several months of data.

7.4.2. Metamodeling of a complete air quality simulation chain

Members: A. Lesieur, V. Mallet
Coll.: Ruiwei Chen

With the objective of uncertainty quantification, we worked on the generation of a metamodel for the simulation of urban air quality, using a complete simulation chain including dynamic traffic assignment, the computation of air pollutant emissions and the dispersion of the pollutant in a city. The traffic model and the dispersion model are computationally costly and operate in high dimension. We employed dimension reduction, and coupled it with Kriging in order to build a metamodel for the complete simulation chain.

7.4.3. Artificial neural networks for the modeling of air pollution

Member: V. Mallet

Air quality simulations at national, continental or global scales are subject to large uncertainties which are typically mitigated by data assimilation techniques. Another approach to improve the forecasts is to design an error model, learning from historical discrepancies between simulations and observations. Such a model was built using an artificial neural network trained with many meteorological and geographical data. Further studies showed that the technique could successfully generate not only an error model (to improve pre-existing simulations), but also a complete model (without the need for pre-existing simulations) whose forecasts are more accurate than those of traditional models.

7.4.4. Uncertainty quantification in atmospheric dispersion of radionuclides

Members: V. Mallet,
Coll.: Irène Korsakissok

In collaboration with IRSN (Institute of Radiation Protection and Nuclear Safety), we investigated the uncertainties of the atmospheric-dispersion forecasts that are used during an accidental release of radionuclides such as the Fukushima disaster. These forecasts are subject to considerable uncertainties which originate from inaccurate weather forecasts, poorly known source term and modeling shortcomings. In order to quantify the uncertainties, we designed a metamodel and carried out the calibration of the metamodel input distributions using Markov chain Monte Carlo.

7.4.5. *Meta-modeling for urban noise mapping*

Members: A. Lesieur, V. Mallet
Coll.: Pierre Aumond, Arnaud Can

Noise computing software can require several hours to produce a map over an urban center for a given set of input data. This computational cost makes the models unsuitable for applications like uncertainty quantification or data assimilation where thousands of simulations, or more, can be required. One solution is to replace the physical model with a meta-model which is very fast and yet fairly reproduces the results of the physical model. The strategy is first to reduce the dimension of both inputs and outputs of the physical model, which leads to a reduced model. This reduced model is then replaced by a statistical emulator. The emulator is trained with calls to the reduced model for a set of chosen inputs. The emulator relies on the interpolation between the training output values.

7.4.6. *Data assimilation for urban noise maps generated with a meta-model*

Members: A. Lesieur, V. Mallet
Coll.: Pierre Aumond, Arnaud Can

In an urban area, it is increasingly common to have access to both a simulated noise map and a sensor network. A data assimilation algorithm is developed to combine data from both a noise map simulator and a network of acoustic sensors. One-hour noise maps are generated with a meta-model fed with hourly traffic and weather data. The data assimilation algorithm merges the simulated map with the sound level measurements into an improved noise map. The performance of this method relies on the accuracy of the meta-model, the input parameters selection and the model of the error covariance that describes how the errors of the simulated sound levels are correlated in space. The performance of the data assimilation is obtained with a leave-one-out cross-validation method.

7.4.7. *Uncertainty quantification in wildland fire propagation*

Members: F. Allaire, V. Mallet
Coll.: Jean-Baptiste Filippi

We worked further on the Monte Carlo simulation of wildland fires. We calibrated the input distributions that represent the uncertainties in the inputs of our fire spread predictions by using the observations of the final contours for a number of fire cases. We used a new metric to measure the dissimilarity between two burned sufaces that relies on the Wasserstein distance. We designed a metamodel and carried out the calibration of the model input distributions using Markov chain Monte Carlo.

7.4.8. *A non-intrusive reduced order data assimilation method applied to the monitoring of urban flows*

Member: J. Hammond
Coll.: R. Chakir

In [13], we investigate a variational data assimilation method to rapidly estimate urban pollutant concentration around an area of interest using measurement data and CFD based models in a non-intrusive and computationally efficient manner. In case studies presented here, we used a sample of solutions from a dispersion model with varying meteorological conditions and pollution emissions to build a Reduced Basis approximation space and combine it with concentration observations. The method allows to correct for unmodeled physics, while significantly reducing online computational time.

7.5. Software Devlopments

Members: C., A. El Baz, J. Sainte-Marie

Several improvements of FreshKiss3D software have been made:

1. the code can now be used on RPM-based systems (Fedora, Redhat) thanks to a user contribution (Julien Jerphanion);
2. the conda-based installation steps are now automatically tested by means of a continuous integration process performed on Linux and Mac virtual machines provided by the Inria platform https://ci.inria.fr/;
3. third-party libraries have been updated so as to benefit from their very latest features;
4. software quality is now monitored by static analysis via the Inria SonarQube platform (https://sonarqube.inria.fr/);
5. code optimization including parallelization with MPI is currently under development.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- A contract between Institut Carnot SMILES and the corporation GTT involving (Jacques Sainte-Marie, Cindy Guichard, Yohan Penel and Julien Salomon) of 78 k€ has been approved. The aim is to improve the numerical modelling tool to simulate gas flows in the insulation spaces of LNG tankers. A Ph. D. thesis should start next year on that topic.

8.2. Bilateral Grants with Industry

- The ANR project Hyflo-Eflu relies on a collaboration with the company "HydroTube Energie", that ended in December has given rise to deep collaboration with Hydotube Energy.
- The ANR project Firecaster supports the Ph. D. Thesis of F. Allaire on the developpment of a fire decision support system at the national scale to estimate upcoming fire risk. The collaborations are CERFACS and CNRM (recherche de Météo-France).
- The ANR project Cense supports the Ph. D. Thesis of A. Lesieur on the developpment of a new methodology for the production of more realistic noise maps. The industrial collaborations include:
  - Bouygues Énergies & Services
  - Wi6Labs
  - Bruitparif (association)

  We refer to

  https://cense.ifsttar.fr/partenaires/entreprises-privees/

  https://cense.ifsttar.fr/partenaires/associations/

  for more details.

8.3. Other collaborations with Industry

- On the public operational side, ANGE team works with IRSN and its Modelling Bureau environmental transfers for the study of consequences of accidents (BMCA). This collaboration led to Bao Le's thesis. For more details, we refer to

  https://www.irsn.fr/FR/Larecherche/Organisation/equipes/radioprotection-homme/BMCA/Pages/bureau-modelisation-transferts-environnement-etude-consequences-accidents.aspx
- On the corporate side, ANGE collaborates with NUMTECH for pollution modelling. We mention also the long term collaboration with Ambiciti- co-founded by V. Mallet. In particular, the newspaper Ouest-France uses Ambiciti's air quality forecasts since the summer, so with the algorithms that come from ANGE.

  https://www.ouest-france.fr/meteo/

- Y. Penel obtained a partial support from EDF for the organisation of the project SGN-Num at CEMRACS 2019.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR MFG (2016-2021)

Participant: Julien Salomon.

Project acronym: MFG

Project title: Mean Field Games

Coordinator: Sébastien Boyaval (LHSV/ENPC)

Funding: 299 160 euros.

Mean field game theory (MFG) is a new and active field of mathematics, which analyses the dynamics of a very large number of agents. Introduced about ten years ago, MFG models have been used in different fields: economics, finance, social sciences, engineering,... MFG theory is at the intersection of mean field theory, mathematical game theory, optimal control, stochastic analysis, variation calculation, partial differential equations and scientific calculation. Drawing on an internationally recognized French team on the subject, the project seeks to obtain major contributions in 4 main directions: the "medium field" aspect (i.e., how to obtain macroscopic models from microscopic models); the analysis of new MFG systems; their numerical analysis; the development of new applications. In this period of rapid expansion of MFG models, the project seeks to foster French leadership in the field and attract new researchers from related fields.

9.1.2. ANR INFAMIE (2015-2019)

Participant: Boris Haspot.

Program: ANR Défi de tous les savoirs (DS10) 2015

Project acronym: INFAMIE

Project title: INhomogeneous Flows : Asymptotic Models and Interfaces Evolution

Coordinator: Raphaël Danchin (Univ. Paris-Est)

Funding: 232 960 euros.

Our project aims at a better mathematical understanding of several models for the evolution of inhomogeneous flows. Through three main lines of research (see below), we will pursue a twofold final objective. First, we want to develop the current theory of regular solutions for several equations for the evolution of fluids, proposing a new approach and developing tools that are likely to be efficient in various areas of PDEs. Second, for a few selected concrete systems that describe flows in the earth environment or in astrophysics, we wish to use this general approach to extract as much information as possible concerning the qualitative behavior of the solutions.

9.1.3. ANR SEDIFLO (2015-2019)

Participants: Emmanuel Audusse, Martin Parisot.

Program: ANR Défi 1 “Gestion sobre des ressources et adaptation au changement climatique” (JCJC)

Project acronym: SEDIFLO

Project title: Modelling and simulation of solid transport in rivers

Coordinator: Sébastien Boyaval (LHSV/ENPC)

Based on recent theoretical and experimental results, this project is aimed at modelling transport of sediments within rivers. It will rely on innovations from the point of view of rheology as well as advanced mathematical tools (asymptotic model reduction, PDE discretisation).

9.1.4. ANR Hyflo-Eflu (2016-2019)

Participants: Jérémy Ledoux, Martin Parisot, Jacques Sainte-Marie, Julien Salomon.

ANR project call: Energies marines renouvelables

Project acronym: Hyflo-Eflu

Project title: Hydroliennes flottantes et énergie fluviale

Coordinator: Julien Salomon

The project is a collaboration between the Inria-team ANGE, specialist of free surface flow and optimisation, and the industrial developers of the turbine, HydroTube Energie. The objective of the project HyFlo-EFlu is to deliver a numerical software able to simulate the dynamic of a floating water turbine in real context. For the academic partner, the main challenge is in the simulation of the floating structure at the scale of the river, and the modelling of the vertical and horisontal axis turbine. For the industrial partner, the objective is the validation of the stability of the structure and the performance in term of energy production.

9.1.5. ANR CHARMS (2016-2020)

Participant: Cindy Guichard.

ANR project call: Transformations et inter-conversions énergétiques

Project acronym: CHARMS

Project title: Modèles de réservoirs quantitatifs pour les systèmes hydrothermaux complexes

Coordinator: Simon Lopez (BRGM)

Funding: 73k euros for LJLL (in 767k euros for the whole project)

CHARMS ANR project is focused on the mathematical methods and software tools dedicated to the simulation of the physical models issued from geothermal engineering. The final objective is the achievement of a highly parallel code, validated on realistic cases.

9.1.6. GdR EGRIN (2017–2021)

Participants: Emmanuel Audusse, Bernard Di Martino, Nicole Goutal, Cindy Guichard, Anne Mangeney, Martin Parisot, Jacques Sainte-Marie.

EGRIN stands for Gravity-driven flows and natural hazards. J. Sainte-Marie is the head of the scientific committee of this CNRS research group and A. Mangeney is a member of the committee. Other members of the team involved in the project are local correspondents. The scientific goals of this project are the modelling, analysis and simulation of complex fluids by means of reduced-complexity models in the framework of geophysical flows.

9.1.7. ANR FireCaster (2017-2020)

Participants: Frédéric Allaire, Vivien Mallet.

ANR project call: DS0104

Project acronym: FireCaster

Project title: Plateforme de prévision incendie et de réponse d'urgence

Coordinator: Jean-Baptiste Filippi (Univ. Corse)

Funding: 442k euros

The goal of the FireCaster project is to prototype a fire decision support system at the national scale to estimate upcoming fire risk (H+24 to H+48) and in case of crisis, to predict fire front position and local pollution (H+1 to H+12).

9.1.8. ANR CENSE (2017-2020)

Participants: Antoine Lesieur, Vivien Mallet.

ANR project call: DS0601

Project acronym: CENSE

Project title: Caractérisation des environnements sonores urbains : vers une approche globale associant données libres, mesures et modélisations

Coordinator: Judicaël Picaut (IFSTTAR)

Funding: 856k euros

The CENSE project aims at proposing a new methodology for the production of more realistic noise maps, based on an assimilation of simulated and measured data through a dense network of low-cost sensors.

9.1.9. ANR RAVEX (2017-2020)

Participant: Anne Mangeney.

ANR project call: DS0106

Project acronym: RAVEX

Project title: Développement d'une approche intégrée pour la réduction des Risques Associés au Volcanisme EXplosif, de la recherche sur l'aléa aux outils de gestion de crise : le cas de la Martinique

Coordinator: Olivier Roche (IRD)

Funding: 619k euros

9.1.10. ANR CINE-PARA (2015-2019)

Participant: Julien Salomon.

ANR project call: DS0708

Project acronym: CINE-PARA

Project title: Méthodes de parallélisation pour cinétiques complexes

Coordinator: Yvon Maday (LJLL)

9.1.11. PGMO Project ORACLE (2019-2021)

Participant: Julien Salomon.

PGMO Call

Project acronym: Oracle

Project title: Optimal Resource Allocation in micro-organisms under Changing Environment

Coordinator: Térence Bayen

9.2. European Initiatives

9.2.1.

Participants: Martin Parisot, Yohan Penel, Jacques Sainte-Marie.

CNRS PICS NHML (2017-2019)

Program: CNRS PICS (projet international de collaboration scientifique)

Project acronym: NHML

Project title: non-hydrostatic multilayer models

Duration: 01/17-12/19

Coordinator: Yohan Penel (Inria)

Other partners: IMUS (Sevilla, Spain)

Other Participants: Enrique Fernández-Nieto (Sevilla), Tomas Morales de Luna (Cordoba)

Funding: 12k euros

Abstract: This collaboration aims at designing a hierarchy of multilayer models with a non-hydrostatic pressure as a discretisation along the vertical axis of the Euler equations. The hierarchy relies on the degree of approximation of the variables discretised with a Discontinuous Galerkin method for the vertical direction. These innovative models will imply a theoretical study and the development of numerical tools in dimensions 1 and 2 before the modelling of other physical phenomena (viscosity effects, ...).

9.3. International Initiatives

9.3.1. Inria International Partners

Three long-term collaborations with foreign colleagues have to be mentioned:

- **Spain** - A collaboration with spanish researchers has been initiated in 2016 to derive accurate models and effecient algorithms for free surface flows including non-hydrostatic effects.
- **Germany** A collaboration with researchers from the University of Constance is in progress about domain decomposition and identifaction algorithms (G. Ciaramella, S. Volkwein). The internship (Masterarbeit) of S. Buchwald has been co-supervised by J. Salomon.
- **Hong-Kong, Switzerland** A collaboration with F. Kwok and M. Gander on time parallelization for assimilation algorithm is in progress. A first paper has been submitted in october.

9.4. International Research Visitors

- Y. Penel made two two-week stay (March, October) at the university of Sevilla (Spain) to collaborate with E. Fernández-Nieto.
- M. Parisot spent two months (October, November) at the university of Aachen (Germany) to collaborate with S. Noelle.

9.4.1. Visits of International Scientists

- G. Ciaramella (Constance University) visited J. Salomon (20.05-23.05) to work on algorithms related to design of experiments and identification.
- F. Kwok (Baptist University, Hong-Kong) visited J. Salomon (8.07-11.07) to work on algorithms related to time parallelization for identification.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

Some members of ANGE were in the organizing committees of scientific events.

- J. Sainte-Marie took part of the organization of the 7th EGRIN summer school that took place at Le Lioran from 24th to 27th of June and that gathered 40 researchers [1].
- J. Sainte-Marie belongs to the "Groupe de travail Recherche et développement durable" at french ministry of research.
- Y. Penel and N. Aguillon organize the monthly ANGE seminar [2]. The speakers were : F. Allaire, M. Peruzzetto (IPGP), L. Boittin, S. Junca (Nice), H. Martin, A. Leprevost, M. Parisot, C. Donadello (Besançon), A. Lesieur, M. Rigal, M. Ancellin (Sorbonne Univeristé).
- J. Salomon co-organises the LJLL-Inria meetings [3] (twice a month).
- M. Parisot and J. Salomon organized the conference "EmrSim2019" [4] from 2nd to 4th July.
- Y. Penel and J. Sainte-Marie organized the session "challenges in geosciences" in the framework of Tarantola days [5] from 6 to 7 June.
- C. Guichard co-organized the "Journée d'Accueil des nouveaux recrutés en Mathématiques", at IHP [6]
- E. Godlewski is the president of the CFEM (commission française pour l'enseignement des mathématiques).
- E. Godlewski took part of the organization of the 50th birthday of the "laboratoire J-L. Lions" by giving a talk "Le rayonnement de l'école Lions. Vers une politique scientifique".

10.1.2. Journal

The summary of the reviewing activities of the team is given in the next table.

Member	Journals
JS	CRAS, SIAM SISC, JCP
CG	Computers and Mathematics with Applications, Numerische Mathematik
EG	M2AN, JCP, AIDE, JEP
MP	Journal of Hydraulic Research, DCDS, JCP, Journal of Computational Science
VM	JCP
JSM	M2AN, JCP, Applied Mathematical Modeling

10.1.3. Invited Talks

[1] https://indico.math.cnrs.fr/event/4391/
[2] https://team.inria.fr/ange/gdt-slides/
[3] https://project.inria.fr/rencontresljll/fr/
[4] https://emrsim2019.sciencesconf.org/
[5] https://ange-geophysics.sciencesconf.org/
[6] http://postes.smai.emath.fr/apres/accueil/

Member	Conference	Location	Date
JS	Colloque d'ouverture 50 ans du LJLL	Roscoff	4-8/3
NA	Séminaire Centrale Paris	Saclay	05/12
NA	journée de clôture MANON	Paris	March
NA	journée Tarantola : défis en géosciences	Paris	June
VD	CEMRACS	Marseille	13/08
VD	Congrès SMAI	Guidel	16/05
VD	EGRIN	Le Liorant	25/06
CG	journée Tarantola : défis en géosciences	Paris	June
FA	GdT ANGE	Inria Paris	23/01
YP	séminaire de l'équipe ACSIOM	Montpellier	19/02
YP	séminaire d'analyse appliquée	Amiens	14/01
YP	Congrès SMAI	Guidel	16/05
YP	Ecole EGRIN	Le Liorant	24/06
YP	ICIAM	Valencia (Spain)	16/07
MP	séminaire de l'IRMAR	Rennes	28/02
MP	Cours sur les modèles dispersif	Aachen	22-24/10
MP	Séminaire d'équipe d'analyse numérique	Aachen	31/10
VM	Nommer, modéliser, représenter le hasard dans les arts et les sciences	Arras	15/03
VM	AI for Climate	Paris	20/09
VM	Séminaire du laboratoire Jacques-Louis Lions	Paris	25/10
VM	AI, data and models for sustainable development, COP25	Madrid	3/12
JSM	"Geophysical flows - From hydrostatic to non-hydrostatic models"	Malaga	22/09

10.1.4. Research Administration

- J. Sainte-Marie is now "Adjoint au Directeur Scientifique" of Inria, in charge of the topic "Sciences de la planète, de l'environnement et de l'énergie".
- J. Salomon belongs to Inria's "Commission des emplois scientifiques".

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

10.2.2. Supervision and Jury

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

Table 3. Teaching (1/2)

Member	Topic	Duration	Level	Institution	Type (CM,TD,TP)
JS	Méthodes numériques pour des modèles incluants des EDP	45	M2	Université d'Abomey-Calavi, Bénin	CM
JS	Méthodes numériques pour des modèles incluants des EDP	45	M2	Univ. Paris-Dauphine	CM
VD	Mathématiques appliquées	32	L3	Polytech Sorbonne	TP
VD	Traitement numérique	14+22	M1	Polytech Sorbonne	CM+TP
VD	Initiation Latex	4	L3	Polytech Sorbonne	CM
LL	Méthodes numériques pour les équations différentielles	24	L3	Sorbonne Université	TP
LL	Mathématiques pour les études scientifiques I	102	L1	Sorbonne Université	TD
LL	Mathématiques pour DU RESPE S2	12	L0	Sorbonne Université	CM+TD
LL	Mathématiques pour DU RESPE S1	10	L0	Sorbonne Université	CM+TD
NA	Topologie et calcul différentielle	111	L2	Sorbonne Université	CM+TD
NA	Projet	15	L3	Sorbonne Université	TD
CG	Fondements des méthodes numériques	58	M1	SU	TP
CG	Méthodes numériques	31	M2	SU	CM+TD
CG	Co responsable de la majeure Ingénierie Mathématiques pour l'Entreprise		M2	SU	
BDM	Analyse et TP Python Sage algèbre et analyse	72	L2	Univ. Corse	C+TD+TP
BDM	Analyse numérique matricielle	54	L3	Univ. Corse	C+TD+TP
EG	Modèles hyperboliques d'écoulements complexes dans le domaine de l'énergie	10	M2	SU	CM
NB	Analyse2	15	L1	Paris13	TD
NB	Analayse3: Intégrales et séries	30	L2	Paris13	TD

Table 4. Teaching (2/2)

Member	Topic	Duration	Level	Institution	Type (CM,TD,TP)	
JS	VM	Simulation de la dispersion atmosphérique	3	M2	ENPC	TP
VM	Assimilation de données pour la géophysique	7	M2	ENPC	TP	
JH	Méthodes numériques pour les équations différentielles	25	L3	Sorbonne Université	TP	
JH	Analyse Appliquée	40	L3	Sorbonne Université	TD	
EA	Equations différentielles	30	L3	Paris13	TD	
EA	Optimisation différentiable	30	M1	Paris13	TD	
EA	Mécanique des fluides	18	M1	Paris13	CM	
EA	Calcul scientifique	30	L2	Paris13	CM+TD	
YP	Equations différentielles	15	L2	Paris 13	CM+TD	

- J. Salomon is a member of the "Commission Mentorat" in view of introducing a mentoring procedure in Inria-Paris,
- Y. Penel and C. Guichard belong to the "Groupe de travail Developpement Durable d'Inria Paris",
- J. Sainte-Marie took part of the committe MakeSenSe, that produced the report [14].

10.3.2. Education

- Congrès MATh.en.JEANS (CentraleSupélec, Modélisation de certains écoulements),
- E. Godlewski and J. Salomon dealt with secondary-school pupils in the framework of observation training course at LJLL and Inria, respectively,
- N. Aguillon was in the organizing committe of "Mathematic Park",
- N. Aguillon was in the organizing committe of "Cycle SMAI-Musée des arts et métiers",
- J. Salomon co-organized the stand "Logiciel Libre" at the "Salon Culture et Jeux mathématiques, 2019".

10.3.3. Interventions

- J. Sainte-Marie organized a round-table discussion about "Mathématiques et environnement" at the "Forum Emploi-Math 2019" (14/11).
- J. Sainte-Marie organized a debate "la sobriété numérique" at "cité des Sciences et de l'industrie" (15/11).

11. Bibliography

Table 5. Supervision of thesis and intership (1/2)

Member	Other advisors	Type	Student	Institution	Period	Title
JS		PhD	Sebastian Reyes-Riffo	Paris-Dauphine	2016-2019	Méthodes numériques pour les énergies marines renouvelables
JS, VM		PhD	Antoine Lesieur	Inria	2017-2020	Estimation d'état et modélisation inverse appliquées à la pollution sonore en milieu urbain
JS		PhD	Nadia Jbili	Paris-Dauphine	2016-2019	Contrôle optimal pour la résonance magnétique nucléaire
JS, JSM		PhD	Liudi Lu	Inria	2018-2021	Approches Lagrangiennes pour la modélisation et l'optimisation du couplage hydrodynamique-photosynthèse
JSM, VM		PhD	Frédéric Allaire	Inria	2017-2020	Quantification du risque incendie par méta-modélisation de la propagation de feux de forêt
YP, CG, JSM		PhD	Virgile Dubos	SU	2017-2020	Numerical methods for the elliptic/parabolic parts of non-hydrostatic fluid models
NA, EA, MP		PhD	Nelly BOULOS	Paris 13	2018-2021	Modélisation et simulation numérique de la dynamique d'un acquifère érodable
VM	Isabelle Herlin	PhD	Ngoc Bao Tran Le	Inria	2016-2019	Uncertainty quantification based on model reduction for atmospheric dispersion
VM		Post Doc	Janelle Hammond	Inria	2017-2020	Uncertainty quantification, metamodeling and data assimilation applied to urban air quality
EA,MP,JSM		PhD	Léa Boittin	inria	2016-2019	Modelling, analysis and efficient numerical resolution for erosion processes

Table 6. Supervision of thesis and intership (2/2)

NA		Stage M2	Mathieu Rigal	UPMC	2019	Schéma exact sur les chocs isolés pour les équations de St Venant avec topographie
NA, JSM	Nathalie Ayi	PhD	Mathieu Rigal	UPMC	2019-2022	Low Froude regime and dispersive effects in kinetic formulations
BDM, JSM		Stage M2	Chourouk El Hassanieh	Inria	04-08/2019	Multilayer Shallow Water Equations: Derivation, Properties, and Well Posedness
BDM, JSM	Samer Israwi	PhD	Chourouk El Hassanieh	Inria	2019-2022	Mathematical and numerical analysis of some dispersive models in fluids mechanics

Major publications by the team in recent years

[1] E. Audusse, M.-O. Bristeau, M. Pelanti, J. Sainte-Marie. *Approximation of the hydrostatic Navier-Stokes system for density stratified flows by a multilayer model. Kinetic interpretation and numerical validation*, in "J. Comput. Phys.", 2011, vol. 230, pp. 3453-3478, http://dx.doi.org/10.1016/j.jcp.2011.01.042

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[4] J. Sainte-Marie. *Vertically averaged models for the free surface Euler system. Derivation and kinetic interpretation*, in "Math. Models Methods Appl. Sci. (M3AS)", 2011, vol. 21, n° 3, pp. 459-490, http://dx.doi.org/10.1142/S0218202511005118

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[5] L. Boittin. *Modeling, analysis and simulation of two geophysical flows : Sediment transport and variable density flows*, Sorbonne Université, April 2019, https://tel.archives-ouvertes.fr/tel-02126695

[6] S. Riffo. *Mathematical methods for marine energy extraction*, Paris Sciences et Lettres ; Paris IX Dauphine, November 2019, https://hal.archives-ouvertes.fr/tel-02446450

Articles in International Peer-Reviewed Journals

Table 7. Participation to committees

Initiales	Mois	Type (PhD, HdR)	Rôle (rapp., prés., mbre)	Prénom Nom candidat	Etablissement	Titre
JS	Novembre	PhD	rapporteur	Pierre-Yves Wuillaume	Ecole Centrale de Nantes	Simulation numérique des opérations d'installation pourles fermes d'éoliennes offshore
NA	juillet	PhD	examinatrice	Mostafa Kadiri	Normandie Université	Optimisation de forme et applications aux ouvrages hydrauliques
CG	mars	PhD	examinatrice	Patrik Daniel	SU et Inria	Adaptive hp-finite elements with guaranteed errorcontraction and inexact multilevel solvers
CG	septembre	PhD	examinatrice	Pierrick Quemar	Paris 13 et EDF	MODELING AND NUMERICAL ANALYSIS OF FREE SURFACE FLOWS
CG	novembre	PhD	invitée	Karine LAURENT	IFPEN et Univ. Paris Saclay	Étude de nouveaux schémas numériques pour la simulation des écoulements à rapport de mobilités défavorable dans un contexte EOR
JSM	novembre	PhD	examinateur	Sebastian Reyes Riffo	PSL	Méthodes mathématiques pour l'extraction d'énergie marine
JSM	décembre	PhD	rapporteur	H. Boukili	univ. Marseille	Schémas de simulation d'un modèle à trois phases immiscibles pour application à l'explosion vapeur
EG	novembre	thèse (PhD)	présidente	Jean-François Abadie	SU	Estimations fiables d'une fonction et de ses dérivées & Étude théorique et numérique d'un problème de "shape from shading"
YP	novembre	PhD	rapporteur	Victor Osores	Univ. Concepcion, Chile	On multilayer shallow water systems for polydisperse sedimentation

[7] F. ALLAIRE, J.-B. FILIPPI, V. MALLET. *Generation and evaluation of an ensemble of wildland fire simulations*, in "International Journal of Wildland Fire", 2020, forthcoming [*DOI :* 10.1071/WF19073], https://hal.inria.fr/hal-02447187

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[15] P.-O. LAMARE, N. AGUILLON, J. SAINTE-MARIE, J. GRENIER, H. BONNEFOND, O. BERNARD. *Gradient-based optimization of a rotating algal biofilm process*, Inria - Sophia antipolis, January 2019, n^{o} RR-9250, https://hal.inria.fr/hal-01990002

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