RESEARCH CENTRE

Inria Paris Center at Sorbonne University

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2022

ACTIVITY REPORT

Project-Team ANGE

Numerical Analysis, Geophysics and Environment

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

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

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Project-Team ANGE

Creation of the Project-Team: 2014 January 01

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1 Team members, visitors, external collaborators

Research Scientist

- Julien Salomon [Team leader, INRIA, Senior Researcher, HDR]

Faculty Members

- Nina Aguillon [SORBONNE UNIVERSITE, Associate Professor]
- Bernard Di Martino [UNIV CORSE, Associate Professor, HDR]
- Cindy Guichard [SORBONNE UNIVERSITE, Associate Professor]
- Julien Guillod [SORBONNE UNIVERSITE, Associate Professor]

Post-Doctoral Fellow

- Liudi Lu [UNIV GENEVE]

PhD Students

- Nelly Boulos Al Makary [UNIV PARIS XIII]
- Juliette Dubois [INRIA]
- Chourouk El Hassanieh [UNIV LIBANAISE]
- Léon Migus [SORBONNE UNIVERSITE]
- Luca Perrin [INRIA]
- Djahou Norbert Tognon [INRIA]

Technical Staff

- Sibylle Techene [CNRS, Engineer]

Interns and Apprentices

- Mael Karembe [INRIA, from Jun 2022]
- Dylan Machado [INRIA, from Jun 2022]

Administrative Assistants

- Laurence Bourcier [INRIA]
- Julien Guieu [INRIA]

Visiting Scientists

- Gabriele Ciaramella [ECOLE POLYT. MILAN, from Feb 2022]
- Marco Gambarini [ECOLE POLYT. MILAN, from Feb 2022]
- John Ringwood [UNIV MAYNOOTH, from May 2022 until Jun 2022]

External Collaborators

- Marie-Odile Bristeau [Retired]
- Anne Mangeney [IPGP, 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.

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 [20, 24, 25]. 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 [21, 22] 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.

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.

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.

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

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.

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).

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.

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.

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 Social and environmental responsibility

5.1 Footprint of research activities

Only few travels were done last year (including one flight) as a consequence of a will of the team to avoid this type of transportation.

5.2 Impact of research results

Part of ANGE activity is devoted to research on renewable energy. In this way, the team took part to the organization of the EMRSim 22 conference, which devoted to Marine Energy Techniques and Simulation.

6 New software and platforms

One on-going work in collaboration with geographers (ISTEP Sorbonne Université) and statisticians (LPSM Sorbonne Université) consists of the study of tsunamigenic landslides. We are interested in the effects on the Morocco coast of a tsunami in the Alboran Sea caused by a landslide. A numerical procedure has been developed to couple Freshkiss3d (used for the wave propagation [26] see web page) with Shaltop [23] to model the landslide with a complex rheology of Bingham type [19].

6.1 New software

6.1.1 Freshkiss

Name: 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.

Contact: Jacques Sainte Marie

Participants: Fabien Souillé, Emmanuel Audusse, Jacques Sainte Marie, Marie-Odile Bristeau

Partners: UPMC, CEREMA

6.1.2 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.

URL: http://tsunamath.paris.inria.fr/

Contact: Jacques Sainte Marie

Participants: Emmanuel Audusse, Jacques Sainte Marie, Raouf Hamouda

6.1.3 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.

URL: http://verdandi.gforge.inria.fr/

Contact: Vivien Mallet

Participants: Dominique Chapelle, Gautier Bureau, Nicolas Claude, Philippe Moireau, Vivien Mallet

6.1.4 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.

URL: http://cerea.enpc.fr/polyphemus/

Contact: Vivien Mallet

Participants: Sylvain Doré, Vivien Mallet

6.1.5 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, Guillaume Chérel

Contact: Vivien Mallet

6.1.6 Freshkiss3D

Keywords: Python, Cython, Navier-Stokes

Functional Description: Tool for the numerical solution of free surface Navier-Stokes equations

Publication: hal-01393147

Contact: Jacques Sainte Marie

Participants: Cedric Doucet, Apolline El Baz, Jacques Sainte Marie

Partner: UPMC

7 New results

7.1 Numerical methods

7.1.1 Optimal periodic resource allocation in reactive dynamical systems: Application to microalgal production.

Participants: Liu-Di Lu, Julien Salomon.

Coll. with Olivier Bernard In [8], we focus on a periodic resource allocation problem applied to a dynamical system which comes from a biological system. More precisely, we consider a system with N resources and N activities, each activity use the allocated resource to evolve up to a given time $T > 0$ where a control (represented by a given permutation) will be applied on the system to reallocate the resources. The goal is to find the optimal control strategies which optimize the cost or the benefit of the system. This problem can be illustrated by an industrial biological application, namely, the optimization of a mixing strategy to enhance the growth rate in a microalgal raceway system. A mixing device, such as a paddle wheel, is considered to control the rearrangement of the depth of the algae cultures, hence the light perceived at each lap. We prove that if the dynamics of the system is periodic, then the period corresponds to one reallocation whatever the order of the involved permutation matrix is. A nonlinear optimization problem for one reallocation process is then introduced. Since $N!$ permutations need to be tested in the general case, it can be numerically solved only for a limited number of N. To overcome this difficulty, we introduce a second optimization problem which provides a suboptimal solution of the initial problem, but whose solution can be determined explicitly. A sufficient condition to characterize cases where the two problems have the same solution is given. Some numerical experiments are performed to assess the benefit of optimal strategies in various settings.

7.2 Modelling

7.2.1 Optimal optical conditions for Microalgal production in photobioreactors.

Participants: Liu-Di Lu.

Coll. with Olivier Bernard The potential of industrial applications for microalgae has motivated their recent fast development. Their growth dynamics depends on different factors that must be optimized. Since they get their energy from photosynthesis, light is a key factor that strongly influences their productivity. Light is absorbed and scattered in the liquid medium, and irradiance exponentially decreases towards the darkest part of the photobioreactor at a rate non-linearly depending on the biomass concentration. Maximizing productivity is then a tricky problem, especially when the growth rate is inhibited by an excess of light. Productivity optimization turns out to be highly dependent on how light is distributed along the reactor, and is therefore related to the extinction rate and the background turbidity. We propose in [7] a theoretical analysis of this problem, by introducing the concept of optical depth productivity for systems where background turbidity must be accounted for. A global optimum maximizing productivity is proposed, extending the concept of the compensation condition, consisting in compensating the algal growth rate at the bottom of the reactor by the respiration. This condition can drive the optimization of the surface biomass productivity depending on the minimum reachable depth. We develop a nonlinear controller and prove the global asymptotic stability of the biomass concentration towards the desired optimal value.

7.2.2 Low-Mach type approximation of the Navier-Stokes system with temperature and salinity for free surface flows.

Participants: Léa Boittin, Marie-Odile Bristeau, Anne Mangeney, Jacques Sainte-Marie, Fabien Souillé.

Coll. with François Bouchut In [9], we are interested in free surface flows where density variations coming e.g. from temperature or salinity differences play a significant role in the hydrody-namic regime. In water, acoustic waves travel much faster than gravity and internal waves, hence the study of models arising from 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" regime using the low-Mach scaling, hence filtering the acoustic waves, neglecting the density dependency on the fluid pressure but keeping its variations in terms of temperature and salinity. A slightly modified low-Mach asymptotics is proposed to obtain a model with thermo-mechanical compatibility. The case when the density depends only on the temperature is studied first. Then the variations of the fluid density with respect to temperature and salinity are considered, and it seems to be the first time that salinity dependency is considered in this low Mach limit. 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. Several stability properties of the layer-averaged Navier-Stokes-Fourier system are proved.

7.2.3 A bed pressure correction of the friction term for depth-averaged granular flow models.

Participants: Anne Mangeney.

Coll. with François Bouchut, Juan Manuel Delgado-Sánchez, Enrique Domingo Fernández-Nieto, Gladys Narbona-Reina Depth-averaged models, such as the Savage-Hutter model with Coulomb or Pouliquen friction laws, do not in some cases preserve the physical threshold of motion. In particular, the simulated granular mass can start to flow (or stay at rest) even if the slope angle of its free surface is lower (or higher) than the repose angle of the granular material involved. The problem is related to the hydrostatic pressure assumption, associated with the direction of integration, which is orthogonal to a reference plane or a reference bottom. We propose in [10] an initial method to correct this misleading behavior. Firstly, we define a correction of the friction term that accounts for the Jacobian of a change of coordinates, making it possible to reproduce the physical threshold of motion and thus the solutions at rest. Secondly, we observe that the 3D model presented in [F. Bouchut, I. Ionescu, and A. Mangeney. An analytic approach for the evolution of the static-flowing interface in viscoplastic granular flows. Commun, Math. Sci., 14(8):2101–2126, 2016] verifies the physical thresholds of motion because it is based on a second order correction of the pressure valid for slow granular flows. The correction proposed here ensures that the model preserves, up to the second order, the physical threshold of motion defined by the repose angle of the material. Several numerical tests are presented to illustrate certain problems related to classical depth averaged models and the remedial effect of the proposed correction, in particular through comparisons with experimental data. We finally show that this correction is not exact far from the starting and stopping phases of the granular avalanche and should be improved by adding other second order terms in the pressure approximation.

7.2.4 Existence and Uniqueness for Plane Stationary Navier–Stokes Flows with Compactly Supported Force.

Participants: Julien Guillod.

Coll. with Mikhail Korobkov, Xiao Ren In [11], we study the stationary Navier–Stokes equations in the whole plane with a compactly supported force term and with a prescribed constant spatial limit. Prior to this work, existence of solutions to this problem was only known under special symmetry and smallness assumptions. In the paper we solve the key difficulties in applying Leray's invading domains method and, as a consequence, prove the existence of D-solutions in the whole plane for arbitrary compactly supported force. The boundary condition at infinity are verified in two different scenarios: (I) the limiting velocity is sufficiently large with respect to the external force, (II) both the total integral of force and the limiting velocity vanish. Hence, our method produces large class of new solutions with prescribed spatial limits. Moreover, we show the uniqueness of D-solutions to this problem in a perturbative regime. The main tools here are two new estimates for general Navier–Stokes solutions, which have rather simple forms. They control the difference between mean values of the velocity over two concentric circles in terms of the Dirichlet integral in the annulus between them.

7.2.5 Well-posedness of the Stokes-transport system in bounded domains and in the infinite strip.

Participants: Antoine Leblond.

In [12], we consider the Stokes-transport system, a model for the evolution of an incompressible viscous fluid with inhomogeneous density. This equation was already known to be globally well-posed for any initial density with finite first moment in . We show that similar results hold on different domain types. We prove that the system is globally well-posed for initial data in bounded domains of and as well as in the infinite strip . These results contrast with the ill-posedness of a similar problem, the incompressible porous medium equation, for which uniqueness is known to fail for such a density regularity.

7.3 Assessments of models by means of experimental data and assimilation

7.3.1 Simulation-based high resolution fire danger mapping using deep learning.

Participants: Frédéric Allaire, Vivien Mallet.

Coll. with Jean-Baptiste Filippi, Florence Vaysse Wildfire occurrence and behavior are difficult to predict very locally for the next day. In [6], we use an artificial neural network emulator called DeepFire, trained on the basis of simulated fire sizes, and study its application to fire danger mapping using actual weather fore-1 casts. Experimental analysis is based on DeepFire forecasts for 13 relatively big fires that occurred in Corsica and corresponding forecasts based on a fire danger index used in operational conditions. A comparative analysis of both indices is presented, highlighting the differences in terms of precision and expected results of such predictions. Forcing weather forecasts used as input have high spatial resolution and high frequency, which also applies to the fire danger predictions. Additionally, input uncertainty is propagated through DeepFire, resulting in ensembles of emulated fire size. Eventually, several approaches are proposed to analyze the results and help in investing assessment of next-day fire danger using this new simulation-based prediction system.

8 Bilateral contracts and grants with industry

Participants: Yohan Penel.

Yohan Penel supervises the PhD thesis of Giuseppe Parasiliti about the Physical, mathematical and numerical modelling of a gas flow for the transportation of liquified natural gas. This work is the result of a close collaboration with the corporation GTT, which has already collaborated with ANGE in the last years, through the Carnot institute SMILE.

Participants: Jacques Sainte-Marie.

Jacques Sainte-Marie has a contract with Eaux de Paris about Hydraulic modeling, calibration and diagnosis. (2020-2023, with S. Labbé, Laboratoire D'Alembert and LPSM)

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

OCEANIA

- Title: Intelligence Artificielle, Données et Modèles pour Comprendre les Océans et le Changement Climatique
- Partner Institution(s):
  - ANGE, BIOCORE, TAU Inria teams, France
  - Universidad de Chile (Center of Mathematical Modeling), Chile
  - Pontificia Universidad Catól ica de Chile, Chile
  - Fondation TARA Océan, France,
  - GO-SEE CNRS Federation, France
  - Université de Nantes (ComBi team), France
- Date/Duration: 11.2020–10.2024
- Additionnal info/keywords: Artificial Intelligence and Modeling for Understanding Oceans and Climate Change

There is strong scientific evidence of the negative effects of climate change on the ocean. These changes will have a drastic impact on nearly all life forms in the ocean, as well as additional consequences for food security and ecosystems in coastal communities as well as inland. Despite these impacts, scientific data and infrastructure are still lacking to better understand and quantify the consequences of these disturbances on the marine ecosystem. There is a need not only to collect more data, but also to develop and apply state-of-the-art mechanisms capable of transforming this data into real knowledge, policy, and action. This is where artificial intelligence, machine learning and modeling tools are needed. OceanIA, this ambitious interdisciplinary Inria Challenge, aims to develop new artificial intelligence and mathematical modeling tools to contribute to the understanding of the structure, functioning, and underlying mechanisms and dynamics of the Ocean and its role in regulating and sustaining the biosphere and fighting climate change. OceanIA is also an opportunity to structure Inria's contributions around a global scientific challenge in the convergence of artificial intelligence, biodiversity and climate change.

9.2 International research visitors

- 6-9 June 2022: visit of F. Kwok (Université Laval, Canada). Work on time parallelization of assimilation techniques.
- 6-13 Feb. 2022: visit of G. Ciaramella and M. Gambarini (MOX, Polytechnico de Milano). Work about optimization of wave energy converters.
- G. Barennechea (U. Strathclyde, Scotland) has been invited (1 month) for a work about Free Surface Navier-Stokes equations.

9.3 National initiatives

Projet Emergence ALARM (2018-2022)

Participants: Jacques Sainte-Marie, Apolline El-Baz.

- Project acronym: ALARM
- Project title: Alboran sea submarine landslides
- Coordinator: Sara Lafuerza (ISTeP - UMR 7193 Institut des Sciences de la Terre de Paris)
- Funding: 55 00 euros.

Simulation et étude de glissements de terrain et tsunami dans la mer d'Alboran

équipe junior ISCD (2019-2022)

Participants: Jacques Sainte-Marie, Nina Aguillon, Sybille Téchène, Julien Guillod.

- Project acronym: Andiamo
- Project title: Andiamo
- Coordinator: N. Aguillon, S. Téchène, J. Deshayes (SU)
- Funding: 70 000 euros.

The ANDIAMO project brings together mathematicians and oceanographers from SU around long term global ocean models. The main challenge is that the mesh size and time step are large, yielding non-negligible truncation errors and schemes dominated by numerical diffusion. Importantly, solutions for regional simulations do not transfer to our needs, as small errors in water mass characteristics have large impact on long term simulations. Thus “non-converged” methods and numerical analysis on coarse mesh are needed.

Another important part of the project is to establish a dialogue and to build further collaborations between mathematicians and oceanographers, around questions arising in climatology that require new numerical methods (interactions with continental ice, quantification of uncertainties. . .).

Projet Emergence (2021-2023)

Participants: Julien Guillod.

- Project acronym: Emergence
- Project title: Etudes numériques d’équations fluides
- Coordinator: Julien Guillod (SU)
- Funding: 28 000 euros.

ANR ALLOWAPP (2019-2023)

Participants: Julien Salomon.

- Project acronym: ALLOWAPP
- Project title: Algorithmes pour l’optimisation à grande échelle de problèmes de propagation d’ondes
- Coordinator: Laurence Halpern (Université Paris-Nord)
- Funding: 317 891 euros.

The goal of the ALLOWAPP project is the design of space-time parallel algorithms for large-scale optimization problems associated with wave propagation phenomena. Such problems appear in seismology, geophysics, but also in various applications from data assimilation. The large amount of data and the volume of computations required for the accurate numerical solution of wave propagation problems, within an optimization loop, requires the use of massively parallel computers. Time-parallel methods have experienced a great development in the last ten years, and for parabolic problems an almost perfect efficiency for a large number of processors has been achieved (scalability). It is quite different for wave propagation problems. In this project, we propose to develop robust, efficient and scalable methods for space-time parallelization of these optimization problems.

ANR GeoFun (2020-2024)

Participants: Nina Aguillon.

- Project acronym: GeoFun
- Project title: Ecoulements géophysiques avec des modèles unifiés

- Coordinator: Martin Parisot (INRIA Bordeaux Sud-Ouest)
- Funding: 524 880 euros.

The GeoFun project aims to improve the modeling and simulation of geophysical flows involving at least two different processes. Numerical simulation of watersheds and estimation of water resources is the main application of the project's achievements. In this context, a free surface flow (rivers, lakes) is the upper part of a groundwater flow (water table). Our vision of river transport is often naive, because we think first of rivers, lakes and floods, but in reality, 80 % of the water of the continents is underground. Sometimes, the porous substratum is covered by an impermeable rock stratum, which confines the flow as in pipes, except for some points where springs and resurgences appear.

ANR SingFlows (2019-2023)

Participants: Julien Guillod.

- Project acronym: SingFlows
- Project title: Ecoulements avec singularités : couches limites, filaments de vortex, interaction vague-structure
- Coordinator: David Gerard-Varet (Institut de mathématiques de Jussieu - Paris Rive Gauche)
- Funding: 263 628 euros.

The objective of SingFlows is to develop mathematical and numerical tools for the analysis of three problems in fluid dynamics: the behaviour of anisotropic flows (boundary layers, shallow water flows), the dynamics of vortical structures, and the evolution of fixed or floating structures in water waves. Our will to unify these different problems is natural, because they share many mathematical features. The underlying keypoint is that they are described by singular solutions of Euler or Navier-Stokes equations. The word singular refers here: - either to a lack of smoothness: it applies for instance to vortex filaments, which are Dirac masses along curves, or to the contact line between water and the floating structure, - or to a singular dependence of the solution with respect to a parameter, typically the Reynolds number (like in boundary layers). The connection between the two points of view is usually made by viscous regularization of the non-smooth structure, or conversely by taking the vanishing limit of the parameter. More generally, the three problems considered in SingFlows involve flows with very small scales. A relevant description then requires the derivation of reduced models.

ANR Top-up (2021-2024)

Participants: Cindy Guichard.

- Project acronym: Top-up
- Project title: High-resolution topography upscaling for overland flows
- Coordinator: Konstantin Brenner (UNIVERSITE COTE D'AZUR - Laboratoire Jean-Alexandre Dieudonné)
- Funding: 248 335 euros.

The objective of the project is to design efficient DD and Ms methods adapted to multi-scale free-surface flow problems, to implement them in the form of an HPC code, and finally to validate them on a set of tests based on realistic high-resolution topographic data. The last objective will be achieved through a close collaboration with the Nice Côte d'Azur Metropolis

ANR Saphir (2022-2024)

Participants: Jacques Sainte-Marie, Bernard Di Martino.

- Project acronym: Saphir
- Project title: Sensor Augmented weather Prediction at high Resolution
- Coordinator: J-F. Muzy (Université de Toulouse Paul Sabatier)
- Funding: 296 000 euros.

ANR DEEPNUM (2022-2026)

Participants: Julien Salomon.

- Project acronym: DEEPNUM
- Project title: Algorithmes pour l'optimisation à grande échelle de problèmes de propagation d'ondes
- Coordinator: Julien Salomon
- Funding: 493 799,20 euros.

The project aims at developing the interplay between Deep Neural Networks (DNNs) and Differential Equations (DEs), with the goal of modeling complex dynamical systems arising from the observation of natural phenomena. Two application domains are targeted, environment and healthcare. We address three fundamental questions: how to adapt and apply numerical analysis theory to DNNs for analyzing them, providing theoretical guaranties and improving their robustness, how to combine simulation and data based models into hybrid systems, how could DNNs help solving DEs and complement numerical solvers. In addition, we evaluate our methods on simulation and real world data in the environment and health domains. DeepNuM gathers partners with complementary skills: DEs and Environment (INRIA-ANGE), Machine Learning and DNNs (Sorbonne – MLIA), DEs and Biophysics (INRIA-EPIONE).

GdR MathGeoPhy (2022–2027)

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

The MathGeoPhy interdisciplinary research group was created in January 2022, for five years. It is funded by the French National Center for Scientific Research (CNRS), with the mission of animating the French scientific community around the theme of mathematics in interaction with the geophysics of fluid and solid envelopes. The members of the GdR are interested in mathematical modeling, scientific computing and the development of new numerical methods applied in particular to :

- offshore and coastal ocean dynamics, gravity waves, coastal erosion problems
- micro-macro approaches, granular and complex flows
- fluvial and torrential hydrodynamics, extreme events and environmental risks, landslides, avalanches, volcanic eruptions, glaciology, etc.

GdR EOL-EMR (2021–2026)

Participants: Julien Salomon, Jacques Sainte-Marie.

OBJECTIVES : To promote the dissemination of existing knowledge and expertise within and across disciplines. The GDR EMR is a forum for the exchange of expertise and know-how within and across disciplines. To promote the implementation of collaborations, between partners of the GDR and with the industrial fabric. The GDR is an entry and orientation point. It provides a forum for the exchange of information concerning industrial needs and the skills of the academic community; and enables the bringing together of players. Valuing the national scientific community The GDR EMR gives visibility to the community, in particular through the development of a mapping of the actors and themes available on the web platform

10 Dissemination

10.1 Promoting scientific activities

We use the following acronyms : NAg (Nina Aguillon), JS (Julien Salomon), JG (Julien Guillod), BM (Bernard di Martino), JSM (Jacques Sainte-Marie), NAy (Nathalie Ayi), CG (Cindy Guichard), AL (Antoine Leblond), NT (Norbert Tognon), LP (Lucas Perrin), MR (MAthieu Rigal), EA (Emmanuel Audusse), LM (Léon Migus), JD (Juliette Dubois) etc.

10.1.1 Scientific events: organisation

Member of the organizing committees

- JS took part of the organization of the conference EMRSim 22 at Roscoff,
- JG took part of the organization of the conference FoCM 2023 at Paris,
- JS co-organizes the bi-monthly seminar "Rencontres INRIA-JLL en analyse numérique et calcul scientifique"
- JG co-organizes the monthly seminar "Analyse non-linéaire et EDP"
- JG co-organizes the monthly seminar "InfoMath"
- NAg co-organizes the yearly "Journée interne du Laboratoire J-L. Lions"
- BM co-organized the "Journées du GDR Analyse Fonctionnelle, Harmonique et Probabilité 2022"

10.1.2 Journal

Member of the editorial boards JS is editor in chief of MATAPLI (national journal of the applied maths community). EA is responsible for its section "Du côté des écoles d'ingénieurs".

Reviewer - reviewing activities The team members were referee for the following journals

- JS: SIAM SISC, AIMS Maths, JSSC
- JG: Philosophical Transactions of the Royal Society A, European Physical Journal Plus, Zeitschrift für Angewandte Mathematik und Mechanik, Journal of Differential Equations
- BM: Journal of Fluid Mechanics, Scientific Reports
- CG: Zeitschrift fuer Angewandte Mathematik und Mechanik (ZAMM)
- Nay: Journal of Differential Equations EA Computer & Fluids, Calcolo, CMS

10.1.3 Invited talks

- JS: PinT 2022: 11th Conference on Parallel-in-Time Integration CIRM Marseille 11-15.07.22
- JS: Jean-Morlet Chair 2022: Research School - Domain Decomposition for Optimal Control Problems CIRM Marseille 5-9.09.22
- JS: 27-th International Conference on Domain Decomposition Methods. Prague 11-15.07.22
- JG: Séminaire du Laboratoire de Mathématiques de Versailles Versaille, Paris 24/03
- JG: Conference in honor of J.-P. Eckmann Genève 07-10.06.2022
- JG: Workshop On Fluid Structure Interaction Problems Bruxelles 10-12.10.2022
- JG: Journée interne du LJLL Paris 8/11
- JG: Infomath: construre un site web Paris 01/12
- JSM: Digital Tech Conference Rennes 06/12
- JSM: Green Tech Forum Paris 01/12
- LM: ICLR Workshop on Geometrical and Topological Representation Learning A distance 29/04/22
- LM: GDR ISIS Apprentissage et modélisation physique Paris 14/06/22
- LM: SCAI PhD Workshop on Artificial Intelligence Paris 10/10/22
- LP: emrsim2022 : Simulation et Optimisation pour les Énergies Marines Renouvelables Roscoff 30.05-2.06.2022
- LP: 45ème congrès d'Analyse Numérique (CANUM 2020) Evian-Les-Bains 13-17.06.2022
- NT: 45ème congrès d'Analyse Numérique (CANUM 2020) Evian-Les-Bains 13-17.06.2022
- NT: 27-th International Conference on Domain Decomposition Methods. Prague 25-29.07.2022
- NAy: Conférence de clôture de l'ANR MoHyCon Pornichet 10/03/22
- NAy: Working group of QuAMProcs ANR Inria Paris 08/03/22
- NAy: Frontiers in the interplay between probability and kinetic theory Edimburgh (online) 04/04/22
- NAy: GDR ANGE Paris 19/05/22
- NAy: 45ème congrès d'Analyse Numérique (CANUM 2020) Evian-Les-Bains 13-17.06.2022
- NAy: Round Meanfield : crowd-opinion-cells Rome 29/09/22
- NAy: Se‘minaire du LMAC UTC Compiègne 04/10/22
- NAy: Kinetic and hydrodynamic descriptions in collective behavior Grenade (Espagne) 08/11/22
- NAy: Séminaire Bourbaki du Vendredi IHP, Paris 18/11/22
- JD: GDR ANGE Inria Paris 29/03/22
- JD: Séminaire des doctorants de l'UMA ENSTA Paris 04/11/22
- NAg: séminaire de mathématiques appliqués du laboratoire Jean Leray Nantes 22/11/22
- NAg: Séminaire ÉDP, Modélisation et Calcul Scientifique de Lyon-Saint Etienne Lyon 24/05/22
- NAg: Séminaire EDP Strasbourg 12/05/22

- NAg: GDR ANGE Inria Paris 10/10/22
- NAg: Semaine pour le Climat Inria Paris 29/09/22
- MR: CANUM 2022 Evian-les-bains 15/06/22
- MR: Séminaire d'analyse appliquée A3 (laboratoire LAMFA) Amiens 10/10/22
- EA: Séminaire ASCIOM Montpellier 22/03/22
- EA: Séminaire INRIA-LJLL Paris 16/05/22
- EA: Séminaire LAMFA Amiens 04/04/22
- EA: Journée Modélisation en hydrodynamique Toulon 27/04/22
- EA: Séminaire Calcul Scientifique et Modélisation Bordeaux 24/11/22
- EA: Séminaire LJLL Paris 9/12/22
- AL: Conférence Singflows Bordeaux Bordeaux 12/04/22
- AL: CIRM Conférences écoulements Luminy 09/05/22
- AL: EMSRIM 2022 Roscoff 30/05/22
- AL: Séminaire des doctorant-es de l'IRMAR Rennes 13/06/22
- AL: Summer School fluids Lyon 27/06/22
- AL: Mathflows CIRM Luminy 04/12/22

10.1.4 Leadership within the scientific community

- EA is adjoint director of GDR MathGeoPhy (2022-)
- JS is member of the board of AMIES (2018-)

10.1.5 Research administration

- JS is Membre du CES of INRIA (2018-).
- JSM is directeur scientifique adjoint (2019-).
- JG is Member of the admin. board of IHP (2021-).
- JSM belongs to the External advisory board - ERC Synergy (2020-2024).
- JSM belongs to the board of the PEPR 'agroécologie et numérique' (2022-2028).
- JSM is responsible for the program 'Numérique et environnement' (2022-).
- NAy belongs to the council of laboratoire LJLL (2020-).
- NAy belongs to the scientific comittee of UFR 929 (2020-).
- JG belongs to the council of Licence mathématiques de Sorbonne Université (2019).
- NAy and JG is in jury of Prime RIPEC (2022-).
- EA is member of the Commission Recherche and CAC of USPN (2020-2024).
- NAg belongs to the administration council of UFR 929, SU (2022-).
- EA and JS were in the specialists comittee for the recruitment of an assistant prof. at IUT Bobigny.
- JG and NAy were in the specialists comittee for the recruitment of an assistant prof. at LJLL.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

EG is the president of commission française pour l'enseignement des mathématiques (CFEM)

Teaching activities of ANGE are summarized in the following.

- Julien Salomon
  - Méthodes numériques pour des modèles incluants des EDP, 45,M2,Université d'Abomey-Calavi, Bénin, CM
  - Méthodes numériques pour des modèles incluants des EDP, 45H, M2, Univ. Paris-Dauphine, CM
- Cindy Guichard
  - Analyse numérique 48H, L3, Sorbonne Université TD+TP
  - Méthodes numériques 31H, M2, Sorbonne Université CM+TD
  - Co responsable de la majeure Ingénierie Mathématiques pour l'Entreprise M2 Sorbonne Université
- Jacques Sainte-Marie
  - Modélisation des écoulements gravitaires, 40 H, M1, Univ. Paris-Diderot et IPGP
  - Méthodes numériques en géosciences, 50 H, M2, Univ. Paris-Diderot et IPGP,
  - Hyperbolic models for complex flows, 25 H, M2, Sorbonne Université
- Nelly Boulos Al Makary
  - Analyse2, 36 H, L1, Université Sorbonne Paris Nord, TD
  - Mathématiques pour les études scientifiques, 36H, L1, Sorbonne Université
- Nathalie Ayi
  - Probabilités, 38H, L3, Sorbonne Université, TD
  - Approximation des EDPs, 36H, M1, Sorbonne Université CM
  - Algèbre linéaire, 60H, L2, Sorbonne Université CM-TD
- Bernard Di Martino
  - Outils Mathématiques, 45H, L1, Université de Corse
  - Pratique d'analyse, 18H, L2, Université de Corse TP
  - Pratique d'algèbre, 18H, L2, Université de Corse TP
- Emmanuel Audusse
  - EDO, 30H, ING1, USPN, TD-TP
  - Optimisation, 30H, ING2, USPN,TD-TP
  - Optimisation, 45H, M1, USPN,TD-TP
  - Calcul scientifique, 30H, L2, USPN, CM-TD-TP
  - analyse numérique avec Matlab, 30H, L3, USPN, TP
- Léon Migus
  - Informatique 2 (fortran), 40H, M1, Polytech Sorbonne, TP
- Julien Guillod

  - Méthodes numériques pour les EDP instationnaires 18H, M2 Sorbonne Université TD/TP
  - Programmation Python pour les mathématiques 45H, L2 Sorbonne Université TP/TD

- Nina Aguillon
  - Directrice des études de L2 mathématiques, 64H, L2, Sorbonne Université
  - Mathématiques pour les études scientifiques 2, 42H, L1, Sorbonne Université CM-TD
  - Topologie et calcul différentiel 1, 36H, L2, Sorbonne Université TD
  - Modèles hyperboliques d'écoulements complexes dans le domaine de l'environnement, 10H, M2, Sorbonne Université, CM
- Mathieu Rigal
  - Topologie, analyse hilbertienne et intégration, 36H, L3, (ING1) Polytech Sorbonne
  - TP d'introduction à Matlab 4, 4H, L1, Polytech Sorbonne
- Chourouk El Hassanieh
  - Mathématiques pour les études scientifiques 1 & 2, 46 + 102H, L1, Sorbonne Université
- Antoine Leblond
  - Analyse numérique, 72H, L3, Sorbonne Université, TP, TD+TP
- Juliette Dubois
  - Analyse mathématique, 16H, L3, Polytech Sorbonne, TP
- Lucas Perrin
  - Méthodesng the second a numériques : algèbre matricielle et fonctions d'une variable réelle, 40H, L2, Univ. Paris-Dauphine, TP+TD
  - Analyse de Fourier, 28H, L3, Polytech Sorbonne, TD

10.2.2 Supervision

- JS, PhD, Lucas Perrin, SU, 2021-2024
  Parallélisation en temps et assimilation de données.
- JS, PhD, Léon Migus, SU, 2020-2023
  Deep Neural Networks and Differential Equations.
- NA, EA, Martin Parisot, PhD, Nelly BOULOS, Paris 13, 2018-2022
  Modélisation et simulation numérique de la dynamique d'un acquifère érodable.
- NA, JSM, NAy, PhD, Mathieu Rigal, UPMC, 2019-2022
  Low Froude regime and dispersive effects in kinetic formulations.
- BDM, JSM, JG, EG, Samer Israwi (Libanese university), PhD, Chourouk El Hassanieh, Inria, 2019-2023
  Mathematical and numerical analysis of some dispersive models in fluids mechanics
- JSM, Sébastien Impériale, PhD, Juliette Dubois, Inria 2020-2023,
  Modélisation et approximation numérique de la propagation des ondes acoustique et des ondes de gravité dans les fluides à surface libre
- YP, Nora Aissiouene, Pierre-Yves Lagrée, PhD, Giuseppe Parasiliti, SU, 2020-2023
  Physical, mathematical and numerical modelling of a gas flow for the transportation of liquified natural gas

- JS, PhD, Norbert Tognon, SU, 2022-2025,
  Analyse de l'algorithme ParaOpt.

- JS, Intern M1, Dylan Machado, INRIA, 03.2022-07.22,
  Etude de stratégies de mélanges pour la production d'algues?

- JS, Intern M2, Constanza Molina, INRIA Chile, 05.2022-10.2022
  Holocene dust transport simulation using PINN

- JG, Anne-Laure Dalibard, PhD, Antoine Leblond, SU 09.2020-,
  Evolution de patches de densité dans des fluides incompressibles

- JG, Tutorat FSMP, Kala Agbo Bidi, FSMP/SU 09.2021-06.2022
  Tutorat d'un étudiant de M2 étranger lauréat d'une bourse PGSM de la FSMP

- JSM, Etienne Mémin, Post-doc, Pierre-Marie Boulvard, Inria 2021-2022,
  Location uncertainties in free surface flows models - Numerical analysis and implementation in Freshkiss3d

- EA, F. Benkhaldoun, PhD Laila Baroukh, USPN 2021-2024,
  Simulation numérique pour des écoulements partiellement congestionnés avec rhéologie complexe

- NA, EA, Stage L1, J. Baraka, SU juin 2022, Tsunamaths

10.2.3 Juries

- JS, 01.06.2022, PhD Rapporteur, Raed Blel, Cermics,
  "Analyse et le développement de méthodes de réduction de modèles dans des contextes stochastiques".

- JS, 14.09.2022, PhD Jury (président), Ibrahim Ayed CIFRE SU-Thales SIX
  "Réseaux de neurones profonds pour la modélisation de phénomènes physiques complexes incorporation de connaissances a priori".

- JSM, 12.2022, PhD, Directeur de thèse, Mathieu Rigal, Sorbonne Université,
  "Régime bas Froude et schémas cinétiques implicites pour les équations de Saint-Venant".

- NAy, 14.11.2022, PhD, Co-encadrante Mathieu Rigal, Sorbonne Université
  "Régime bas Froude et schémas cinétiques implicites pour les équations de Saint-Venant".

- NAg, 14.11.2022, PhD Co-encadrante Mathieu Rigal, Sorbonne Université
  "Régime bas Froude et schémas cinétiques implicites pour les équations de Saint-Venant".

- NAg, 13.12.2022, PhD Co-encadrante, Nelly Boulos El Makary, Sorbonne Paris Nord
  "Analyse d'un modèle hyperbolique de type Saint Venant à deux vitesses".

- NAg, 07.12.2022, PhD, Examinatrice, Alice Masset, Université de Picardie,
  "Équations de Saint-Venant avec effets rotatifs et thermiques : aspects théoriques et schémas numériques".

- EA, 13.12.2022, PhD Directeur de thèse, Nelly Boulos El Makary, Sorbonne Paris Nord,
  "Analyse d'un modèle hyperbolique de type Saint Venant à deux vitesses".

- EA 16.6.2022, PhD, Examinateur, Noémie Gaveau, Univ. Orléans,
  "Résultats numériques et théoriques sur les équations de Saint-Venant, couplées à un modèle d'érosion ou avec force de Coriolis".

10.3 Popularization

- JS, dec. 2022 Accueil de Collégiens
- NA, 2018-, co-organization de Mathematic Park (Licence Level)
- JSM, oct. 2022, Ambassadeur for "la fête de la science 2022"
- JSM, 2022, MOOC "impact environnemental du numérique"
- NAy, Sept 2022 -, Creation of the podcast "Tête-à-tête Chercheuse(s)"
- NAy, May 2022 -, Participation to the exposition "Mathématiques, Informatique ... avec elles"
- NAy, jan. 2022, Interview of Laure Saint-Raymond about her participation to ICM
- NAy, june 2022 Participation à la Master Class Lyceéennes organise'e par l'association Seéphora Berrebi Scolarships for Women in Advanced Mathematics & Computer Science
- NAy, aug. 2022, Paneliste à la confe'rence Matrix x Imaginary co-organiseée by MoMaths (New York) and Imaginary
- NAy, oct. 2022, Intervention devant des lycéennes et lycéens, lycée Louis le Grand
- NAy, dec. 2022, Conférence dans le cadre d'une journée Filles et Maths à Tours
- NAy, dec. 2022, Intervention devant des lycéens et des lycéennes, Lycée Jean Zay, Orléans
- NAy, dec. 2022, Intervention devant des lycéens et des lycéennes, Lycée Charles Péguy, Orléans
- JD, dec. 2022, Intervention devant des lycéens et lycéennes, Lycée Racine Paris
- NAg, oct. 2022, Invitée pour une intervention fête de la sciences
- NAg, april 2022, Speed meeting métier, journée "filles, maths et info, une équation lumineuse" at polytechnique
- NAg, march 2022, Speed meeting métier, journée "filles, maths et info, une équation lumineuse" at IHP + video
- NAg, oct. 2022, cycle de Conférences-métiers du Master Mathématiques de Sorbonne Université

11 Scientific production

11.1 Major publications

[1] E. Audusse, M.-O. Bristeau, M. Pelanti and 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.* 230 (2011), pp. 3453–3478. DOI: 10.1016/j.jcp.2011.01.042. URL: http://dx.doi.org/10.1016/j.jcp.2011.01.042.

[2] E. Audusse, M.-O. Bristeau, B. Perthame and J. Sainte-Marie. 'A multilayer Saint-Venant system with mass exchanges for Shallow Water flows. Derivation and numerical validation'. In: *ESAIM Math. Model. Numer. Anal.* 45 (2011), pp. 169–200. DOI: 10.1051/m2an/2010036. URL: http://dx.doi.org/10.1051/m2an/2010036.

[3] M.-O. Bristeau, A. Mangeney, J. Sainte-Marie and N. Seguin. 'An energy-consistent depth-averaged Euler system: derivation and properties'. In: *Discrete and Continuous Dynamical Systems - Series B* 20.4 (2015), p. 28.

[4] J. Ledoux, S. Riffo and J. Salomon. 'Analysis of the Blade Element Momentum Theory'. working paper or preprint. Apr. 2020. URL: https://hal.archives-ouvertes.fr/hal-02550763.

[5] J. Sainte-Marie. 'Vertically averaged models for the free surface Euler system. Derivation and kinetic interpretation'. In: *Math. Models Methods Appl. Sci. (M3AS)* 21.3 (2011), pp. 459–490. DOI: 10.1142/S0218202511005118. URL: http://dx.doi.org/10.1142/S0218202511005118.

11.2 Publications of the year

International journals

[6] F. Allaire, J.-B. Filippi, V. Mallet and F. Vaysse. 'Simulation-based high resolution fire danger mapping using deep learning'. In: *International Journal of Wildland Fire* 31.4 (6th Apr. 2022), pp. 379–394. DOI: 10.1071/WF21143. URL: https://hal.inria.fr/hal-03189847.

[7] O. Bernard and L.-D. Lu. 'Optimal optical conditions for Microalgal production in photobioreactors'. In: *Journal of Process Control* 112 (2022), pp. 69–77. DOI: 10.1016/j.jprocont.2022.03.001. URL: https://hal.archives-ouvertes.fr/hal-03323094.

[8] O. Bernard, L.-D. Lu and J. Salomon. 'Optimal periodic resource allocation in reactive dynamical systems: Application to microalgal production'. In: *International Journal of Robust and Nonlinear Control* (5th May 2022). DOI: 10.1002/rnc.6171. URL: https://hal.archives-ouvertes.fr/hal-03170481.

[9] L. Boittin, M.-O. Bristeau, F. Bouchut, A. Mangeney, J. Sainte-Marie and F. Souillé. 'Low-Mach type approximation of the Navier-Stokes system with temperature and salinity for free surface flows'. In: *Communications in Mathematical Sciences* (2022). URL: https://hal.inria.fr/hal-02510711.

[10] F. Bouchut, J. M. Delgado-Sánchez, E. D. Fernández-Nieto, A. Mangeney and G. Narbona-Reina. 'A bed pressure correction of the friction term for depth-averaged granular flow models'. In: *Applied Mathematical Modelling* 106 (Feb. 2022), pp. 627–658. DOI: 10.1016/j.apm.2022.01.034. URL: https://hal.archives-ouvertes.fr/hal-03613387.

[11] J. Guillod, M. Korobkov and X. Ren. 'Existence and Uniqueness for Plane Stationary Navier–Stokes Flows with Compactly Supported Force'. In: *Communications in Mathematical Physics* (15th Nov. 2022). DOI: 10.1007/s00220-022-04504-9. URL: https://hal.archives-ouvertes.fr/hal-03865543.

[12] A. Leblond. 'Well-posedness of the Stokes-transport system in bounded domains and in the infinite strip'. In: *Journal de Mathématiques Pures et Appliquées* 158 (1st Feb. 2022). DOI: 10.1016/j.matpur.2021.10.006. URL: https://hal.archives-ouvertes.fr/hal-03184943.

Scientific books

[13] C. Fiorini, P.-M. Boulvard, L. Li and É. Mémin. *A two-step numerical scheme in time for surface quasi geostrophic equations under location uncertainty*. 2022, pp. 1–10. URL: https://hal.archives-ouvertes.fr/hal-03695944.

Doctoral dissertations and habilitation theses

[14] M. Rigal. 'Low Froude regime and implicit kinetic schemes for the Saint-Venant system'. Sorbonne Universite, 14th Nov. 2022. URL: https://hal.archives-ouvertes.fr/tel-03883170.

Reports & preprints

[15] N. Aguillon, E. Audusse, V. Desveaux and J. Salomon. *How to find a discrete entropy inequality when you don't know if it exists*. 2nd Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03881570.

[16] E. Audusse, V. Dubos, N. Gaveau and Y. Penel. *Energy stable and linearly well-balanced numerical schemes for the non-linear Shallow Water equations with Coriolis force*. 4th Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03509990.

[17] J. Dubois, S. Imperiale, A. Mangeney, F. Bouchut and J. Sainte-Marie. *Acoustic and gravity waves in the ocean: a new derivation of a linear model from the compressible Euler equation*. 1st Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03880423.

[18] S. Riffo, F. Kwok and J. Salomon. *Time-parallelization of sequential data assimilation problems*. 4th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03884022.

11.3 Cited publications

[19] B. Al Taki, K. Msheik and J. Sainte-Marie. 'On the rigid-lid approximation of shallow water bingham model'. In: *DCDS-B* 26.2 (2021), pp. 875–905. DOI: 10.3934/dcdsb.2020146. URL: https://hal.inria.fr/hal-02052055.

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[21] E. Audusse, M.-O. Bristeau, M. Pelanti and 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.* 230 (2011), pp. 3453–3478. DOI: 10.1016/j.jcp.2011.01.042. URL: http://dx.doi.org/10.1016/j.jcp.2011.01.042.

[22] E. Audusse, M.-O. Bristeau, B. Perthame and J. Sainte-Marie. 'A multilayer Saint-Venant system with mass exchanges for Shallow Water flows. Derivation and numerical validation'. In: *ESAIM Math. Model. Numer. Anal.* 45 (2011), pp. 169–200. DOI: 10.1051/m2an/2010036. URL: http://dx.doi.org/10.1051/m2an/2010036.

[23] F. Bouchut and M. Westdickenberg. 'Gravity driven shallow water models for arbitrary topography'. In: *Comm. in Math. Sci.* 2 (2004), pp. 359–389.

[24] F. Bouchut and V. Zeitlin. 'A robust well-balanced scheme for multi-layer shallow water equations'. In: *Discrete Contin. Dyn. Syst. Ser. B* 13 (2010), pp. 739–758.

[25] M. Castro, J. García-Rodríguez, J. González-Vida, J. Macías, C. Parés and M. Vázquez-Cendón. 'Numerical simulation of two-layer shallow water flows through channels with irregular geometry'. In: *J. Comput. Phys.* 195.1 (2004), pp. 202–235.

[26] Freshkiss3d. 'home page'. https://freshkiss3d.gitlabpages.inria.fr/freshkiss3d/applications.html. 2020.