



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

**Université Pierre et Marie Curie
(Paris 6)**

Activity Report 2015

Project-Team ANGE

Numerical Analysis, Geophysics and Ecology

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

RESEARCH CENTER
Paris - Rocquencourt

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

Keywords:

Computer Science and Digital Science:

- 6. - Modeling, simulation and control
 - 6.1. - Mathematical Modeling
 - 6.1.1. - Continuous Modeling (PDE, ODE)
 - 6.1.4. - Multiscale modeling
 - 6.1.5. - Multiphysics modeling
 - 6.2. - Scientific Computing, Numerical Analysis & Optimization
 - 6.2.1. - Numerical analysis of PDE and ODE
 - 6.2.6. - Optimization
 - 6.3. - Computation-data interaction
 - 6.3.2. - Data assimilation

Other Research Topics and Application Domains:

- 3. - Environment and planet
 - 3.3. - Geosciences
 - 3.3.2. - Water: sea & ocean, lake & river
 - 3.3.3. - Littoral
 - 3.4. - Risks
 - 3.4.1. - Natural risks
 - 3.4.3. - Pollution
- 4. - Energy
 - 4.2. - Renewable energy production
 - 4.2.1. - Biofuels
 - 4.2.2. - Hydro-energy

1. Members

Research Scientists

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Marie-Odile Bristeau [Senior Researcher, retired]

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Hugo Martin [Inria, Intern, from Mar 2015 to Aug 2015]
Sebastian Reyes-Riffo [Inria, Intern, from May 2015 to Nov 2015]
Fabien Wahl [Univ. Pierre et Marie Curie, from Mar 2015 to Aug 2015]
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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. Last but not least, efficient numerical resolutions of reduced-size models requires 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.

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 sense of the models (uniqueness, conservativity, entropy dissipation, ...) and propose effective numerical methods to estimate their solution in complex configurations (multi-dimensional, unstructured meshes, well-balanced, ...).

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 discretization 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, so-called shallow water assumptions, namely

- the horizontal 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 must rely on a special analysis.

3.2.1. Multilayer approach

As for the first shallow water assumption, *multi-layer* systems were proposed describing the flow as a superposition of Saint-Venant type systems [39], [43], [45]. Even if this approach has provided interesting results, layers are considered separate and non-miscible fluids, which imply strong limitation. That is why we proposed a slightly different approach [40], [41] based on Galerkin type decomposition along the vertical axis of all variables and leading, both for the model and its discretization, to more accurate results.

A kinetic representation of our multilayer model allows to derive robust numerical schemes endowed with 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 enable to guess the optimal number of layers.
- The introduction of several source terms due for instance to Coriolis forces 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 proved and conversely the possible loss of hyperbolicity cannot be characterized. 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.

When 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 integrating the 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 zone 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 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 system Euler/Poisson, 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 such as threshold laws.
- Interaction between flows and floating structures is the challenge at the scale of the shallow water equations. This study needs 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 scheme. 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.

3.3. 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 has to 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*

The hydrodynamic models comprise advection and sources terms. The conservation of the balance between the source terms, typically viscosity and friction, has a significant impact since the overall flow is generally a perturbation around one 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 potential waves and the physical velocity makes classical numerical schemes not efficient: 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 potential 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. Data assimilation

Data assimilation consists in a coupling between a model and observation measurements. Developing robust data assimilation methods for hyperbolic-type conservation laws is a challenging subject. These PDEs indeed show no dissipation effects and the input of additional information in the model equations may introduce errors that propagate and create shocks. We have recently proposed a new approach based on the kinetic description of the conservation law. Hence, data assimilation is carried out at the kinetic level, using a Luenberger observer. Assimilation then resumes to the handling of a BGK type equation. The advantage of this framework is that we deal with a single “linear” equation instead of a nonlinear system and it is easy to recover the macroscopic variables. We are able to prove the convergence of the model towards the data in case of complete observations in space and time.

This work is done in collaboration with the M3DISIM Inria project-team. M. Doumic and B. Perthame (MAMBA) also participate.

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, biogeochemistry of oceans, resilience of society w.r.t. hazardous flows, ...

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 they 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 quasi-steady 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 costly and generally not efficient in long term. The objective is to determine a configuration almost stable with 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 origins. 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 the 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.

5. Highlights of the Year

5.1. Highlights of the Year

Contracts and cooperations

- ANR project Hyflo-Eflu accepted
- Industrial contract with SAUR/Agence de l'eau Loire-Bretagne concerning the Vilaine River
- IPL Algae In Silico

Involvement of the team in a large popularisation process

In 2015, members of the team got involved in many popularisation events on behalf of Inria to emphasize the scope of research for the advantages of citizens, whether they be average people, entrepreneurs, decision-makers or students.

6. New Software and Platforms

6.1. Freshkiss3D (FREe Surface Hydrodynamics using KInetic SchemeS)

FUNCTIONAL DESCRIPTION

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

- Participants: Jacques Sainte-Marie, Emmanuel Audusse, Marie-Odile Bristeau, Raouf Hamouda, David Froger and Anne-Céline Boulanger
- Partners: UPMC - CEREMA
- Contact: Jacques Sainte-Marie

For a list of recent developments, refer to §7.5.1.

6.2. TSUNAMATHS

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: Jacques Sainte-Marie, Emmanuel Audusse and Raouf Hamouda
- Contact: Jacques Sainte-Marie
- URL: http://ange.raoufhamouda.com/tsunami/en_motivation.htm

7. New Results

7.1. Modelling of complex flows

7.1.1. *Non-hydrostatic models*

Participant: Martin Parisot.

A new shallow water type model involving non-hydrostatic effects is derived in [37]. Under the assumption that the horizontal velocity is close to its vertical mean value, the model enables to recover the energy from the Euler system before integration. Link with the non-hydrostatic published in [18] is identified. Compared to the aforementioned models, the new system consists of more equations (6). However, the numerical strategy presented in the paper does not induce extra computational time.

7.1.2. *Seismic activities: energy radiated by elastic waves*

Participants: Anne Mangeney, Jacques Sainte-Marie.

Estimating the energy loss in elastic waves during an impact is an important problem in seismology and in industry. Three complementary methods to estimate the elastic energy radiated by bead impacts on thin plates and thick blocks from the generated vibration are proposed in [30]. The first two methods are based on the direct wave front and are shown to be equivalent. The third method makes use of the diffuse regime. These methods are shown to be relevant to establish the energy budget of an impact. The radiated elastic energy estimated with the presented methods is quantitatively validated by Hertz's model of elastic impact.

7.1.3. *Layer-averaged Euler and Navier-Stokes systems*

Participants: Marie-Odile Bristeau, Bernard Di Martino, Cindy Guichard, Jacques Sainte-Marie.

In [25] we propose a strategy to approximate incompressible free surface Euler and Navier-Stokes models. The main advantage of the proposed models is that the water depth is a dynamical variable of the system and hence the model is formulated over a fixed domain.

The proposed strategy extends previous works approximating the Euler and Navier-Stokes systems using a multilayer description. Here, the needed closure relations are obtained using an energy-based optimality criterion instead of an asymptotic expansion. Moreover, the layer-averaged description is successfully applied to the Navier-Stokes system with a general form of the Cauchy stress tensor.

7.2. Applications to marine energies

7.2.1. *Partially free surface flow*

Participants: Martin Parisot, Fabien Wahl.

In view of taking into account interactions with buoys, a new formulation of the shallow water model is derived with a constraint corresponding to a static roof. A relaxation approach is considered to adapt the standard numerical schemes. A particular attention is paid to the energy law whether it be for the original model with constraint or the relaxed version.

7.2.2. *Swell energy*

Participants: Sebastian Reyes-Riffo, Julien Salomon.

The internship consisted in designing an optimisation algorithm to determine advantageous topographies in view of producing energy from swell. This approach corresponds to the coupling between a shallow water type model with iterative updates of the topography. Stability of the numerical scheme is a critical point and requires the tuning of parameters.

7.3. Analysis of models in Fluid Mechanics

7.3.1. *Weak solutions of multilayer models*

Participants: Bernard Di Martino, Ethem Nayir, Yohan Penel.

Proving the existence of global weak solutions is a difficult problem for Navier-Stokes type equations, particularly in case of a degenerate viscosity (viscosity term can vanish if density or thickness goes to zero). In some recent works, Vasseur and Yu [46], have proved this existence for 2D shallow water equations. For the multilayer model, a collaboration with Boris Haspot (Univ. Paris-Dauphine) lead to stability results for the system with a focus on the difficulty to construct a sequence of approximate solutions that conserve all a priori estimates.

7.3.2. *Strong solutions of multilayer models*

Participants: Emmanuel Audusse, Ethem Nayir, Yohan Penel.

The existence and uniqueness of strong solutions of the multilayer model proposed in [41] was previously proven in the case of boundary conditions. We extended this result to an unbounded domain for short times, overcoming the issue of integrability often barely evoked in similar investigations. Current works deal with the long time existence by a continuation process which requires a particular care of the short time solution at the end of its existence interval.

7.3.3. *Hyperbolic problems under constraints*

Participant: Nicolas Seguin.

In [21], we study a family of linear hyperbolic systems whose solution must satisfy a constraint (e.g. a simplified model of river flows taking risk of flooding into account). We analyse relaxed models based on a penalisation. This theoretical approach could be used to derive numerical methods.

7.3.4. *Entropy-satisfying finite volume schemes*

Participant: Nicolas Seguin.

In [44], we carry out an analysis of 1st-order entropy-satisfying finite volume schemes for hyperbolic systems. More precisely, we investigate the numerical dissipation on unstructured meshes under relevant stability conditions. This results in a minimal convergence order towards smooth solutions.

7.3.5. *Global existence for Green-Naghdi type equations*

Participant: Dena Kazerani.

In [31], we consider the Cauchy problem for the Green-Naghdi equations with viscosity, for small initial data. It is well-known that adding a second order diffusion term to a hyperbolic system leads to the existence of global smooth solutions, as soon as the hyperbolic system is symmetrizable and the so-called Kawashima-Shizuta condition is satisfied. In a previous work, we have proved that the Green-Naghdi equations can be written in a symmetric form, using the associated Hamiltonian. This system being dispersive, in the sense that it involves third order derivatives, the symmetric form is based on symmetric differential operators. We use this structure for an appropriate change of variable to prove that adding viscosity effects through a second order term leads to global existence of smooth solutions, for small data. We also deduce that constant solutions are asymptotically stable.

7.4. Numerical methods for free-surface flows

7.4.1. *Godunov schemes for the low Froude regime*

Participants: Emmanuel Audusse, Do Minh Hieu, Yohan Penel.

We investigated in [29] the behaviour of collocated Godunov type finite volume schemes when applied to the 1d linear wave equation with Coriolis force in collaboration with S. Dellacherie and P. Omnes (CEA). Accuracy for short time and stability were proven for different versions of the classical Godunov schemes, including some schemes already proposed in the literature (Bouchut *et al.*, [42]). Next step will be to include linear advection and then to study the fully non linear shallow water model. Then results will be extended to 2d problems for which geometrical constraints should be taken into account.

7.4.2. Numerical method for non-hydrostatic models

Participants: Nora Aïssiouene, Marie-Odile Bristeau, Edwige Godlewski, Jacques Sainte-Marie.

In [1], a numerical method based on a prediction-correction scheme in one dimension has been developed and compared to experimental data and analytical solutions. The issue is then to extend the method in higher dimensions. We propose a variational framework for the resolution of a non-hydrostatic Saint-Venant type model with bottom topography. This model is a shallow water type approximation of the free surface incompressible Euler system and slightly differs from the Green-Naghdi model. The resolution of the incompressibility constraint leads to an elliptic problem involving the non-hydrostatic part of the pressure. This step uses a variational formulation of a shallow water version of the incompressibility condition. Several numerical experiments are performed to confirm the relevance of our approach. This work is exposed in [18].

7.4.3. Uncertainties with the topography

Participants: Emmanuel Audusse, Nicole Goutal, Philippe Ung.

We propose to study the uncertainty related to the Saint-Venant system. A perturbation is introduced in the bottom topography such that the topography deviation is characterized by two parameters: its amplitude and its smoothness. In particular, we extend the work previously done with periodic boundary conditions and suggest a treatment of the physical ones. In doing so, we are interested in the influence of the topography deviation on the hydraulic quantities, and in particular, we numerically exhibit a relationship between the spatial correlations of the topography and the water height. Furthermore, we complete the study by a comparison of the outputs between the two flow regimes – fluvial and torrential.

7.4.4. Coupled Stokes-Exner model

Participant: Nora Aïssiouene.

In the framework of the 2015 CEMRACS session (Coupling Multi-Physics Models involving Fluids), we explored an approach to model the sediment transport. In [17], we consider a coupling between the Exner equation and the Stokes system to model sediments in geophysical flow phenomena. We focus on a model without free surface and used some numerical tests to evaluate the relevance of the method. The fluid structure interaction theory and methods have been applied on the coupled system and the objective is to test the proposed method which can be extend to a free surface model. The library Feel++ and the high computing performance embedded have been used to test the solution method. Therefore, the goal of this project is to understand the impact of the sediment transport on the flow using Navier-Stokes with a free surface system coupled with the standard Exner equation. This work has been done in collaboration with Tarik Amtout, Matthieu Brachet, Emmanuel Frenod, Romain Hild, Christophe Prud'homme, Antoine Rousseau and Stéphanie Salmon.

7.5. Software developments and assessments

7.5.1. Improvements in the FRESHKISS3D code

Participants: Marie-Odile Bristeau, David Froger, Raouf Hamouda, Jacques Sainte-Marie.

Several tasks have been achieved in the FRESHKISS3D software:

- The parallelisation of FRESHKISS3D with MPI is achieved for the Eulerian description and the explicit time scheme.
- The paddle wheel vertical effect is now taken into account.
- Vertical and time dependent flow rates can be customised.
- Unit tests have been improved and functional tests have been added.
- Software dependencies are packaged in SED-Paris repository.
- Online documentation is being written.
- A prototype of the software implemented in Cython is under discussion.
- Code executing time's loop is being refactored into multiple classes.
- Various improvements (build system, continuous integrations, coding rules) have been provided.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- A research contract with SAUR (company managing water supplies) was negotiated in 2015. It deals with the modelling and the simulation of saline stratification in a dam reservoir of the Vilaine river in Brittany.
- ANGE appealed to SciWorks Technologies to transfer Freshkiss3D in a user-friendly tool for a larger diffusion to potential industrial partners. The joint development will result in an advanced easy-to-use software.

8.2. Bilateral Grants with Industry

P. Ung's PhD was funded by EDF, CNRS, AMIES (French agency for mathematics in interaction with companies and the society) and ANTEA-group and ended in late 2015. A collaboration with EDF for a new PhD grant in 2016 is currently under consideration.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. *Instabilities in Hydrodynamics (2011-2015)*

Participant: Nicolas Seguin.

The Emergence project (Ville de Paris and FSMP) "Instabilities in Hydrodynamics" is related to theoretical, applied, and numerical mathematics for the study of hydrodynamical turbulence phenomena.

9.1.2. *Plasticity of geophysical flows and seismic emissions (2013-2016)*

Participant: Anne Mangeney.

This project is funded by Sorbonne Paris Cité (80.000 euros) and is a collaboration between IPGP and Univ. Paris 13.

9.1.3. *LRC Manon (2014-2018)*

Participants: Edwige Godlewski, Yohan Penel, Nicolas Seguin.

CEA and Laboratory Jacques-Louis Lions launched a collaboration in order to carry out studies about complex fluids (modelling, numerical simulations and optimisation), in particular about compressible two-phase flows. This includes the derivation of strategies for model coupling, for instance in the case of an asymptotic hierarchy of models.

9.2. National Initiatives

9.2.1. 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).

9.2.2. ANR Hyflo-Eflu (2016-2020)

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

Appel à projets ANR : Energies marines renouvelables

Project acronym: Hyflo-Eflu

Project title: Hydroliennes flottantes et énergie fluviale

Coordinator: Julien Salomon

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. Thanks to the collaboration between a team of mathematician specialist of free surface flow and optimization and the industrial developers of the turbine. 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 horizontal 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.

9.2.3. ANR MIMOSA (2014–2017)

Participants: Nora Aïssiouene, Marie-Odile Bristeau, Anne Mangeney, Bernard Di Martino, Jacques Sainte-Marie.

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

Project acronym: MIMOSA

Project title: MIMOSA: MICOseism MOdeling and Seismic Applications

Coordinator: Eleonore Stutzmann (IPGP)

Seismic noise is recorded by broadband seismometers in the absence of earthquakes. It is generated by the atmosphere-ocean system with different mechanisms in the different frequency bands. Even though some mechanisms have been known for decades, an integrated understanding of the noise in the broadband period band 1-300sec is still missing. Using novel theoretical, numerical and signal processing methods, this project will provide a unified understanding of the noise sources and quantitative models for broadband noise. Conversely, we will be able to interpret seismic noise in terms of ocean wave properties. This first analysis step will lead to the identification and characterization of source events, which we will use to improve noise tomography, and seismic monitoring.

9.2.4. ANR LANDQUAKES (2012–2016)

Program: ANR Blanc “Mathématiques et interactions”

Project acronym: LANDQUAKES

Project title: Modélisation des glissements de terrain et des ondes sismiques générées pour détecter et comprendre les instabilités gravitaires

Coordinator: Anne Mangeney

Within the ANR domain “Mathematics and Interfaces”, this ANR project (between Univ. Paris-Est – LAMA, Univ. Denis Diderot Paris 7 – IPGP, Univ. Nantes – LPGN, Univ. Strasbourg EOST, 180.000 euros) deals with the mathematical and numerical modelling of landslides and generated seismic waves.

A. Mangeney is also involved in the CARIB ANR program (2014–2017) entitled “Comprendre les processus de construction et de destruction des volcans de l’Arc des Petites Antilles”.

9.2.5. GdR EGRIN (2013–2017)

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.

9.2.6. Inria Project Lab “Algae in Silico” (2015-2018)

Participants: Nora Aïssiouene, Marie-Odile Bristeau, David Froger, Raouf Hamouda, Jacques Sainte-Marie.

In the framework of the ADT Inlgae (2013–2015), we developed in collaboration with the BIOCORE Inria project-team a simulation tool for microalgae culture. An Inria Project Lab “Algae in Silico” has started in collaboration with several Inria teams, many BIOCORE and DYLISS. It concerns microalgae culture for biofuel production and the aim is to provide an integrated platform for numerical simulation “from genes to industrial processes”.

9.2.7. ANR project HJnet (2013–2015)

Participant: Edwige Godlewski.

This research project consists in studying Hamilton-Jacobi equations on networks, and more generally on heterogeneous structures. This theoretical problem has several potential applications, in particular to traffic flow theory.

9.2.8. Hydraulics for environment and sustainable development (HED²)

The scientific group (GIS in French), which includes Inria and the ANGE team, brings together scientists and engineers involved in hydraulics, risk management and sustainable development. It results in a continuum between fundamental research, applied research and engineering. On the one hand, the ANGE team can be provided with experimental measurements (erosion, long waves, fluid structure interactions,...) thanks to this collaboration; on the other hand, the GIS can favor the transfer of numerical tools and scientific results.

9.3. European Initiatives

9.3.1. ERC Consolidator Grant (2013-2018)

Participant: Anne Mangeney.

The project SLIDEQUAKES is about detection and understanding of landslides by observing and modelling gravitational flows and generated earthquakes and is funded by the European Research Council (2 million euros). More precisely, it deals with the mathematical, numerical and experimental modelling of gravitational flows and generated seismic waves coupled with field measurements to better understand and predict these natural hazards and their link with volcanic, seismic and climatic activities.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Spanish collaborators – Enrique Fernández-Nieto (Univ. Sevilla) and Tomás Morales de Luna (Univ. Córdoba) – spent one week in Paris (UPMC and Inria) in September.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific events organisation

10.1.1.1. Member of the organizing committees

Y. Penel was involved in the organising committee of the day workshop “Low velocity flows – application to low Mach and low Froude regimes” that took place in University Paris Descartes on November 5-6 and that gathered 105 researchers.

E. Audusse and Y. Penel organised the welcome session for newly recruited researchers in mathematics on behalf of national research institutions (CNRS, Inra, Inria, SFdS, SMAI, SMF) on January 19.

10.1.2. Journal

10.1.2.1. Reviewer - Reviewing activities

Member	Journal
E. Audusse	Ocean Modeling, Computational Geosciences, M2AN
C. Guichard	International Journal On Finite Volumes
A. Mangeney	Natural Hazards
J. Sainte-Marie	M2AN, M3AS, IJNMF, Computers & Fluids
N. Seguin	M2AN, ESAIM ProcS, SIAM Scientific Computing

10.1.3. Invited talks

Conference	Location	Month	Members involved
Avalanche and Rupture Phenomena	Inria (Nancy)	Feb.	A. Mangeney
CoToCoLa	Besancon	Feb.	J. Sainte-Marie, N. Seguin
Inria-Mexico	Mexique	June	M. Parisot
MAMERN15	Pau	June	C. Guichard
NumHyp15	Cortone (Italy)	June	N. Aïssiouene, M. Parisot, N. Seguin
AP and Multiscale methods	June	Madison (USA)	N. Seguin
CEMRACS	CIRM (Marseille)	Aug.	N. Aïssiouene, E. Audusse, Y. Penel
JAG15	Caen	Sept.	A. Mangeney
CAFFEET15	San Francisco (USA)	Sept.	J. Sainte-Marie
Algae In Silico	Sophia-Antipolis	Oct.	N. Aïssiouene
Workshop Gladys	Gard	Nov.	N. Aïssiouene
Workshop LowMach	Paris	Nov.	E. Audusse, M. Parisot
FAST	Orsay	Nov.	A. Mangeney
JILL15	LJLL (Paris)	Nov.	B. di Martino
Seminars		Date	Member
Suisse (Zürich, Davos)		19-20 Jan.	A. Mangeney
Orsay		16 Apr.	N. Seguin
Manon (LJLL)		07 May	M. Parisot
Amiens		05 Oct.	E. Audusse
Nice		12 Nov.	Y. Penel

10.1.4. Leadership within the scientific community

Organisation	People	Duty
AMIES	E. Godlewski	Member of board
CNU 26	N. Seguin	Member
EGRIN	E. Audusse	Correspondent (Paris 13)
	B. di Martino	Correspondent (Corse)
	N. Goutal	Correspondent (EDF)
	C. Guichard	Correspondent (UPMC)
	A. Mangeney	Member of board
	M. Parisot	Correspondent (ANGE)
	J. Sainte-Marie	Scientific head
SMAI	Y. Penel	Member of board

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master's degree (M2) - E. Godlewski and J. Sainte-Marie, Models and numerical methods for free surface flows, 20 hours (lectures), Univ. Pierre et Marie Curie Paris 6

Master's degree (M2) - C. Guichard, Numerical methods for nonstationary PDEs, 18 hours (example and programming classes), Univ. Pierre et Marie Curie Paris 6

Master's degree (M2) - A. Mangeney and J. Sainte-Marie, Modélisation des écoulements gravitaires et tsunamis, 40 hours (lectures and programming classes), Univ. Paris Diderot Paris 7, IPGP

Engineering school (2nd year) - E. Audusse, Hyperbolic systems, 30 hours (lectures), Univ. Paris 13

Master's degree (M1) - C. Guichard, Basis of numerical methods, 63 hours (programming classes), Univ. Pierre et Marie Curie Paris 6

Master's degree (M1) - A. Mangeney and J. Sainte-Marie, Dynamique des écoulements gravitaires et tsunamis, 40 hours (lectures and programming classes), Univ. Paris Diderot Paris 7, IPGP

Master's degree (M1) - N. Seguin, Mathematics, Numerical Analysis and Algorithmics, 72 hours (lectures, example and programming classes), Univ. Nantes

Bachelor's degree (L3) - N. Aïssiouene, Numerical methods for linear systems with Scilab, 36 hours (example classes), Univ. Pierre et Marie Curie Paris 6

Engineering school (1st year) - E. Audusse, Numerical analysis for differential equations, 30 hours (example classes), Univ. Paris 13

Bachelor's degree (L3) - C. Guichard, Numerical linear algebra, 72 hours (example and programming classes), Univ. Pierre et Marie Curie Paris 6

Bachelor's degree (L3) - M. Parisot, Hilbert analysis, 30 hours (lectures and example classes), Univ. Pierre et Marie Curie Paris 6

Bachelor's degree (L3) - N. Seguin, Mathematics for engineers, 37 hours (lectures and example classes), Univ. Nantes

Bachelor's degree (L2) - E. Audusse, Scientific computing, 36 hours (lectures), Univ. Paris 13

Engineering school (1st year) - Y. Penel, Partial Differential Equations, 15 hours (example classes), École Centrale Paris

Bachelor's degree (L2) - Y. Penel, Integration in 2 and 3 dimensions, 42 hours (lectures and example classes), Univ. Pierre et Marie Curie Paris 6 and Station Biologique Marine de Roscoff

Bachelor's degree (L1) - E. Nayir, Mathematics, 72 hours (example classes), Univ. Pierre et Marie Curie Paris 6

Bachelor's degree (L1) - F. Wahl, Calculus, 18 hours (example classes), Univ. Pierre et Marie Curie Paris 6

E. Godlewski is the head of the “Mathematics for Industry” M.Sc. program of Univ. Pierre et Marie Curie Paris 6. We mention that E. Audusse is the deputy director of the “Applied Mathematics and Scientific Computing” program of the SupGalilee engineering school.

10.2.2. Supervision

PostDoc in progress - Pierre-Olivier Lamarre, *Optimization of the hydrodynamic regime in a raceway and lagrangian trajectories of algae*, supervised by J. Sainte-Marie (in collaboration with O. Bernard, BIOCORE), from Nov. 2015

PostDoc in progress - Erica Schwindt, *Data assimilation for an advection/diffusion equation*, supervised by J. Sainte-Marie (in collaboration with M. Boulakia, REO), from Sept. 2015

PostDoc - Vivien Desveaux, *Méthodes d'assimilation de données dans le cadre de la surveillance des agressions biologiques et chimiques*, supervised by J. Sainte-Marie (in collaboration with M. Boulakia, REO), until Aug. 2015

PhD in progress - Nora Aïssiouene, *Derivation and analysis of a non-hydrostatic Shallow water type model*, Univ. Pierre et Marie Curie Paris 6 (Inria grant), supervised by E. Godlewski and J. Sainte-Marie, from 2013

PhD in progress - Vincent Bachelet, *Granular flows and generated acoustic waves: a laboratory investigation*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with J. De Rosny and R. Toussaint), from 2015

PhD in progress - Tim Borikov, *Physical processes at play in Martian landslides*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with D. Mège), from 2012

PhD in progress - Do Minh Hieu, *Analyse mathématique et schémas volumes finis pour la simulation des écoulements quasi-géostrophiques à bas nombre de Froude*, Univ. Paris 13, supervised by E. Audusse and Y. Penel (in collaboration with S. Dellacherie and P. Omnes), from 2014

PhD in progress - Dena Kazerani, *Simulation et modélisation de problèmes à frontière libre*, Univ. Pierre et Marie Curie Paris 6, supervised by N. Seguin (in collaboration with P. Frey and C. Audiard), from 2013

PhD in progress - Hélène Miallot, *Numerical modelling of landquakes*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with Y. Capdeville), from 2015

PhD in progress - Clément Mifsud, *Analyse et approximation des systèmes de Friedrichs : application à la modélisation de l'élastoplasticité*, Univ. Pierre et Marie Curie Paris 6, supervised by N. Seguin (in collaboration with J.-F. Babadjian and B. Després), from 2013

PhD in progress - Ethem Nayir, *Approximation multi-vitesse des équations de Navier-Stokes hydrostatiques: Analyse mathématique et simulations numériques*, Univ. Pierre et Marie Curie Paris 6, supervised by E. Audusse, Y. Penel and J. Sainte-Marie, from 2014

PhD in progress - Amandine Sergeant-Boy, *Detection and characterisation of seismic sources generated by glaciers: numerical modelling and analysis of seismic waves*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with J.-P. Montagner, E. Stutzmann and O. Castelnau), from 2013

PhD - Maxime Farin, *Analysis of the seismic signal generated by laboratory granular flows*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with R. Toussaint and J. de Rosny), until Mar 2015

PhD - Jannes Kinscher, *Analysis of seismicity in quarries*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with P. Bernard and I. Contrucci), until Feb 2015

PhD - Philippe Ung, *Simulation, modélisation et analyse numérique pour le transport sédimentaire*, Univ. Orléans (EDF-CNRS grant), supervised by E. Audusse and Y. Penel (in collaboration with S. Cordier), until Dec 2015

M2 internship - Pauline Le Bouteiller, *Ecoute sismique et analyse statistique des éboulements sur le Piton de la Fournaise*, Ecole des Mines, supervised by A. Mangeney, Summer 2015

M2 internship - Hugo Martin, *Modélisation et simulation d'un fluide partiellement à surface libre*, Univ. Pierre et Marie Curie Paris 6, supervised by C. Guichard, M. Parisot and J. Sainte-Marie, Summer 2015

M2 internship - Jean-Luc Ralaiarisoa, *Ecoute sismique et analyse statistique des tremblements de terre liés au vâlage d'icebergs au Groenland*, IPGP, supervised by A. Mangeney, Summer 2015

M2 internship - Fabien Wahl, *Simulations de tsunamis à l'aide d'un modèle non-hydrostatique*, Univ. Pierre et Marie Curie Paris 6, supervised by A. Mangeney and J. Sainte-Marie, Summer 2015

10.2.3. Juries

Feb, PhD - A. Mangeney (referee): Noe Bernabeu (Univ. Grenoble, *Modélisation multi-physique des écoulements viscoplastiques: application aux coulées de lave volcaniques*)

Apr, PhD - J. Sainte-Marie: Xavier Lhébrard (Univ. Paris-Est, *Analyse de quelques schémas numériques pour des problèmes de shallow water*)

May, HdR - A. Mangeney (referee): Yves Le Gonidec (Institut de Physique de Rennes, *Propagation, imagerie et monitoring acoustiques : développements méthodologiques et expérimentaux pour des systèmes complexes en géosciences*)

May, PhD - J. Sainte-Marie (referee): Sébastien Barthélemy, (Univ. Toulouse, *Ensemblist data assimilation and 1D-2D hydraulic model coupling for real-time flood forecasting. Application to the "Adour maritime" hydraulic network*)

Aug, PhD - A. Mangeney (referee): Franzisca Dammeier (ETH Zurich, *Seismic characterization of rockslides using existing regional networks*)

Aug, PhD - A. Mangeney (referee): Belinda Bates (EPF Lausanne, *Basal Entrainment by Geophysical Gravity Currents: An Experimental Fluid Dynamics Approach*)

Oct, PhD - A. Mangeney (referee): Aurore Carrier (IsTerre Chambéry, *Endommagement et processus non-linéaires au sein d'un édifice volcanique pressurisé*)

Dec, HdR - E. Godlewski: C. Cancès (Univ. Pierre et Marie Curie, *Analyse mathématique et numérique d'équations aux dérivées partielles issues de la mécanique des fluides : application aux écoulements en milieux poreux*)

Dec, PhD - A. Mangeney (referee): Jordane Mathé (Univ. Blaise Pascal, Clermont-Ferrand, *Modélisation d'écoulements gravitaires fluidisés et application à la volcanologie*)

Dec, PhD - N. Seguin: Matthias Mimault (Univ. Nice–Sophia Antipolis, *Lois de conservation pour la modélisation des mouvements de foule*)

10.3. Popularization

11/06/15 - Futur en Seine (Cap Digital): B. di Martino, M. Parisot and J. Sainte-Marie were present during the numerical festival

24/09/15 - 6th Plenary Research Data Alliance (Cap Digital): N. Aïssiouene, B. di Martino, Y. Penel and J. Sainte-Marie contributed to the Inria stand

9-11/10/15 - Fête de la Science: all the members of the team run the ANGE stand to present scientific works related to water

07-10/12/15 - Solutions COP21: N. Aïssiouene, E. Nayir, M. Parisot, Y. Penel and J. Sainte-Marie participated to the exhibition at the Grand Palais to show the application of applied mathematics to climate issues

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

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