RESEARCH CENTRE

Inria Centre at the University of Bordeaux

IN PARTNERSHIP WITH:

Institut Polytechnique de Bordeaux

2024

ACTIVITY REPORT

Project-Team

CARDAMOM

Certified Adaptive discRete moDels for robust simulAtions of CoMplex flOws with Moving fronts

IN COLLABORATION WITH: Institut de Mathématiques de Bordeaux (IMB)

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Numerical schemes and simulations

Inria

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Project-Team CARDAMOM

Creation of the Project-Team: 2016 June 01

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2 Overall objectives

CARDAMOM is a joint team of INRIA Bordeaux - Sud-Ouest, University of Bordeaux and Bordeaux Inst. Nat. Polytechnique) and IMB (Institut de Mathématiques de Bordeaux – CNRS UMR 5251, University of Bordeaux). `CARDAMOM` has been created on January 1^{st}, 2015 (website).

The CARDAMOM project aims at providing a robust modelling strategy for engineering applications involving complex flows with moving fronts. The term front here denotes either an actual material boundary (e.g. multiple phases), a physical discontinuity (e.g. shock waves), or a transition layer between regions with completely different dominant flow behaviour (e.g. breaking waves). These fronts introduce a multi-scale behaviour. The resolution of all the scales is however not feasible in certification and optimization cycles. Moreover, the full scale behaviour is not necessary in many engineering applications, while in others it is enough to model the average effect of small scales on large ones (closure models). We plan to develop application-tailored models obtained by a tight combination of *asymptotic PDE* (Partial Differential Equations) modelling, *adaptive high order PDE discretizations*, and a *quantitative certification* step assessing the sensitivity of outputs to both model components (equations, numerical methods, etc) and random variations of the data. The goal is to improve operational models used in parametric analysis and design cycles, by increasing both accuracy and confidence in the results. This is achieved by combining improved physical and numerical modelling, and assessment of output uncertainties. This requires a research program mixing of PDE analysis, high order discretizations, Uncertainty Quantification

(UQ), and to some extend optimization and inverse modelling. These skiss need to be also combined with some specific engineering know how to tackle specific applications. Part of this scientific themes and of these activities have been part of the work of the BACCHUS and MC teams. CARDAMOM harmonizes and gives new directions to this know how.

2.1 Scientific context and challenges

The objective of CARDAMOM is to provide improved analysis and design tools for engineering applications involving fluid flows with moving fronts. In our applications *a front is either an actual material interface, a boundary of the domain, or a well identified transition region in which the flow undergoes a change in its dominant macroscopic character.* One example is the certification of wing de-anti icing systems, involving the predictions of ice formation and detachment, and of ice debris trajectories to evaluate the risk of downstream impact on aircraft components [98, 42]. Another application, relevant for space reentry, is the study of transitional regimes in high altitude gas dynamics in which extremely thin layers appear in the flow which cannot be analysed with classical continuous models (Navier-Stokes equations) used by engineers [49, 76]. A classical example relevant in coastal engineering is free surface flows. The free surface itself is a material interface, but we can identify also other fronts as e.g. the flooding line (wet/dry transition) or the transition between propagating and breaking waves, across which relevance of dissipation and vorticity changes dramatically [50]. For wave energies, as well as for aquifers, the transition between free surface and congested flows (below a solid surface) is another example [64]. Other similar examples exist in geophysics, astrophysics, aeronatic and aerospace engineering, civil engineering, energy engineering, material engineering, etc.

In all cases, computationally affordable, fast, and accurate numerical modelling is essential to allow reliable predictions in early stages of the design/analysis [101]. Such computational models are also needed for simulations over very long times, especially if changes in many variable input parameters need to be investigated.

To achieve this goal one needs to have a physically relevant Partial Differential Equation (PDE) model, which can be treated numerically efficiently and accurately, which means possibly with some adaptive numerical technique allowing to mimimize the computational effort. To this end, the dynamics of some of the fronts can be modelled by appropriate asymptotic/homogeneised PDEs, while other interfaces are explicitly described. Even in the best of circumstances in all practical applications the reliability of the numerical predictions is limited by the intrinsic uncertainty on the operational conditions (e.g. boundary/initial conditions, geometry, etc.). To this *aleatory* uncertainty we must add the structural *epistemic* uncertainty related possibly to the use of approximate PDE models. Besides the limited validity of the derivation assumptions, these models are often calibrated/validated with experimental data which is itself subject to errors and post-processing procedures (filtering, averaging, etc ..) [58, 90]. This is even worse in complex flows for which measurements are difficult or impossible to plan or perform due to the inherent exceptional character of the phenomenon (e.g. tsunami events), or technical issues and danger (e.g. high temperature reentry flows, or combustion), or impracticality due to the time scales involved (e.g. study of some new materials' micro-/meso- structure [59]). So the challenge is to construct computationally affordable models robust under variability of input paramters due to uncertainties, certification/optimization, as well as coming from modelling choices.

To face this challenge and provide new tools to accurately and robustly modelize and certify engineering devices based on fluid flows with moving fronts, we propose a program mixing scientific research in asymptotic PDE analysis, high order adaptive PDE discretizations and uncertainty quantification.

2.2 Our approach and objectives

We propose a research program mixing asymptotic PDE analysis, high order adaptive discretizations, and uncertainty quantification. In a standard approach a certification study can be described as a modelling exercise involving two black boxes. The first box is the computational model itself, composed of: PDE system, mesh generation/adaptation, and discretization of the PDE (numerical scheme). The second box is the main robust certification loop which contains separate boxes involving the evaluation of the physical model, the post-processing of the output, and the exploration of the spaces of physical and stochastic parameters (uncertainties). Many interactions exist in this process. Exploiting these interactions could allow to tap as much as possible into the potential of high order methods [79] such as e.g. h-, p-, r- adaptation in the physical model w.r.t. some parametric quantity/sensitivity non necessarily associated to the solution's smoothness.

Our objective is to provide some fundamental advances allowing to bring closer to the operational level modern high order numerical techniques and multi-fidelity certification and optimization algorithms, possibly using some clever paradigm different from the 2-black box approaches above, and involving tight interactions between all the parts of the play: PDE modelling, numerical discretization techniques, uncertainty quantification methods, mesh generation/adaptation methods, physical model validation/calibration, etc. The initial composition of the team provided a unique combination of skills covering all the necessary topics allowing to explore such an avenue. The questions that need to be tackled can be organized in the following main axes/scientific questions:

1. Continuous modelling: how to obtain the PDE description most suited for a given application, and make sure that on one hand its structure embeds sufficiently the physics sudied, and on the other the system is in a form suitable for efficient numerical discretization ?

2. Higher order adaptive discretization: what are the relations between PDE model accuracy (e.g. asymptotic error), PDE constraints (e.g. entropy inequalities, particular steady states, etc) and the scheme consistency ? how to account for additional contraints in the scheme ?

3. Parameter uncertainty and robust modelling: how to properly account when build models on one hand for the variability of physical states defining a processs in realistic environments, and on the other of data possibly available for the proces in consideration ? is it possible to couple the sampling in the space of parameters with the approximation in physical space ?

These themes are discussed in the following sections together with some challenges specific to the engineering applications considered:

- Aeronautics and aerospace engineering (de-anti icing systems, space re-entry, complex materials);
- Coastal engineering (coastal protection, hazard assessment etc.);
- Energy engineering with a focus on wave energy conversion
- Large scale models on manifolds with a focus on geophysics and recent models from applications in astrophysics and relativity.

3 Research program

3.1 Continuous and discrete asymptotic modelling

In many of the applications we consider intermediate fidelity models can be derived using an asymptotic expansion for the relevant scale resolving PDEs, possibly combined with some form of homogeneization or averaging. The resulting systems of PDEs are often very complex. One of the main challenges is to characterize the underlying structure of such systems: possible conservation laws embedded; additional constraints related to consistency with particular physical states (exact solutions), or to stability (entropy/energy dissipation); etc. A question of paramount importance in practical applications is also the formulation of the boundary conditions. The understanding of these properties is necessary for any new model. Moreover, different forms of the PDE may be better suited to enforce some of these properties at the numerical level.

Another issue when working with asymptotic approximations is that of closure. Indeed, important physical phenomena may be unaccounted for either due to some initial modelling assumptions, or because they involve scales much smaller than those modelled. A typical example is wave breaking in some depth averaged models. Another, relevant for our work, is the appropriate prediction of heat fluxes in turbulent flows.

So our main activities on this axis can be classified according to three main questions:

- what is the structure of the PDE model (exact solutions, stability and algebraic or differential constraints embedded, boundary conditions) ?
- what is the form of the model better suited to reproduce numerically certain constraints ?
- how to embed and design closure laws for relevant phenomena not modelled by the main PDE ?

3.2 High order discretizations on moving adaptive meshes

The efficient and robust discretization of complex PDEs is a classical and widespread research subject. The notion of efficiency is in general related to the combination of high order of accuracy and of some adaptation strategy based on an appropriate model of the error [92, 100].

This strategy is of course also part of our work. However, we are convinced that a more effective path to obtain effective discretizations consists in exploiting the knowledge of the PDE structure, embedding as much as possible the PDE structure in the discrete equations. This is related to the notion of enhanced consistency that goes in the direction of what is today often referred to as *constraint or property preserving* discretizations. For the type of PDE systems of our interest, the properties which are of paramount importance to be controlled are for example: the balance between flux divergence and forcing terms (so called well balanced of C-property [45, 89]) and the preservation of some specific steady states; the correct reproduction of the dispersion relation of the system, especially but not only for dispersive wave propagation; the preservation of some algebraic constraints, typically the non-negativity of some thermodynamic quantities; the respect of a discrete entropy/energy equality or inequality (for stability); the strong consistency with some asymptotic limit of the PDE (AP property); etc.

A fundamental issue is the efficient and accurate treatment of boundary and interface conditions. The idea is to have some approach which tolerates the use of non-conformal meshes, which is genuinely high order, and compatible with adaptation, and of course conformal meshing of the boundary/discontinuity. Techniques allowing the control of the geometrical error due to non-conformity is required. For discontinuities, this also requires an ad-hoc treatment of the jump condition. For wall boundaries, initial work using penalization has been done in CARDAMOM in the past [39, 84]. On Cartesian meshes several techniques exist to control the consistency order based on extrapolation/interpolation, or adaptive methods (cf e.g.[93, 83, 40, 56, 67, 60] and references therein). For discontinuities, we can learn from fitting techniques [46], and from some past work by Prof. Glimm and co-workers [53].

For efficiency, mesh adaptation plays a major role. Mesh size adaptation based on both deformation, r-adaptation, or remeshing h-adaptation, can be designed based on some error model representative. For unsteady flows, the capability to use moving meshes becomes necessary, and geometrical conservation (GCL) needs to be added to the list of constraints to be accounted for [94, 80]. In particular, one technique that provides meshes with optimal quality moving together with the unsteady flows, reduction of errors due to convective terms, GCL respected up to machine precision, and high order of accuracy, is offered by the Direct Arbitrary-Lagrangian-Eulerian (ALE) methods on moving Voronoi meshes with topology changes [69, 68] that will be further investigated.

3.3 Applications in physics and engineering

As already mentioned, our focus is on four main classes of problems:

- Aeronautics and aerospace engineering (de-anti icing systems, space re-entry, complex materials)
- Coastal engineering (coastal protection, hazard assessment etc.)
- Energy engineering with a focus on wave energy conversion
- Large scale models on manifolds with a focus on geophysics and recent models from applications in astrophysics and relativity.

There are several common aspects. One is the use of asymptotic vertically averaged approximations to produce efficient application-Taylored PDE models. Another common point is the construction of possibly high order constraint/property preserving numerical approximations. This entails the characterization of the underlying PDE models with a set of embedded properties, which go from classical conservation, to exact solutions (steady or moving), to the preservation of differential operators, to the thermodynamic adissibility (non-negativity, preservation of physical bounds). For all applications, the investigation of the parameter dependence of the results will take several forms from sensitivity analyses, to classical parametric studies to understand physical processes, to approximation in parameter space in the framework of hybrid PDE-meta-/reduced-order models.

4 Application domains

4.1 De-anti icing systems

Impact of large ice debris on downstream aerodynamic surfaces and ingestion by aft mounted engines must be considered during the aircraft certification process. It is typically the result of ice accumulation on unprotected surfaces, ice accretions downstream of ice protected areas, or ice growth on surfaces due to delayed activation of ice protection systems (IPS) or IPS failure. This raises the need for accurate ice trajectory simulation tools to support pre-design, design and certification phases while improving cost efficiency. Present ice trajectory simulation tools have limited capabilities due to the lack of appropriate experimental aerodynamic force and moment data for ice fragments and the large number of variables that can affect the trajectories of ice particles in the aircraft flow field like the shape, size, mass, initial velocity, shedding location, etc... There are generally two types of model used to track shed ice pieces. The first type of model makes the assumption that ice pieces do not significantly affect the flow. The second type of model intends to take into account ice pieces interacting with the flow. We are concerned with the second type of models, involving fully coupled time-accurate aerodynamic and flight mechanics simulations, and thus requiring the use of high efficiency adaptive tools, and possibly tools allowing to easily track moving objects in the flow. We will in particular pursue and enhance our initial work based on adaptive immerse boundary capturing of moving ice debris, whose movements are computed using basic mechanical laws.

In [43] it has been proposed to model ice shedding trajectories by an innovative paradigm that is based on CArtesian grids, PEnalization and LEvel Sets (LESCAPE code). Our objective is to use the potential of high order unstructured mesh adaptation and immersed boundary techniques to provide a geometrically flexible extension of this idea. These activities will be linked to the development of efficient mesh adaptation and time stepping techniques for time dependent flows, and their coupling with the immersed boundary methods we started developing in the FP7 EU project STORM [39, 84]. In these methods we compensate for the error at solid walls introduced by the penalization by using anisotropic mesh adaptation [62, 81, 82]. From the numerical point of view one of the major challenges is to guarantee efficiency and accuracy of the time stepping in presence of highly stretched adaptive and moving meshes. Semi-implicit, locally implicit, multi-level, and split discretizations will be explored to this end.

Besides the numerical aspects, we will deal with modelling challenges. One source of complexity is the initial conditions which are essential to compute ice shedding trajectories. It is thus extremely important to understand the mechanisms of ice release. With the development of next generations of engines and aircraft, there is a crucial need to better assess and predict icing aspects early in design phases and identify breakthrough technologies for ice protection systems compatible with future architectures. When a thermal ice protection system is activated, it melts a part of the ice in contact with the surface, creating a liquid water film and therefore lowering ability of the ice block to adhere to the surface. The aerodynamic forces are then able to detach the ice block from the surface [44]. In order to assess the performance of such a system, it is essential to understand the mechanisms by which the aerodynamic forces manage to detach the ice. The current state of the art in icing codes is an empirical criterion. However such an empirical criterion is unsatisfactory. Following the early work of [48, 42] we will develop appropriate asymptotic PDE approximations to describe the water runoff on the wing surface, also accounting for phase change, thus allowing to describe the ice formation and possibly rupture and detachment. These models will constitute closures for aerodynamics/RANS and URANS simulations in the form of PDE wall models, or modified boundary conditions.

In addition to this, several sources of uncertainties are associated to the ice geometry, size, orientation and the shedding location. In very few papers [86], some sensitivity analysis based on Monte Carlo method have been conducted to take into account the uncertainties of the initial conditions and the chaotic nature of the ice particle motion. We aim to propose some systematic approach to handle every source of uncertainty in an efficient way relying on some state-of-art techniques developed in the Team. In particular, we will perform an uncertainty propagation of some uncertainties on the initial conditions (position, orientation, velocity,...) through a low-fidelity model in order to get statistics of a multitude of particle tracks. This study will be done in collaboration with ETS (Ecole de Technologies Supérieure, Canada). The longterm objective is to produce footprint maps and to analyse the sensitivity of the models developed.

4.2 Modeling of wave energy converters

Wave energy conversion is an emerging sector in energy engineering. The design of new and efficient Wave Energy Converters (WECs) is thus a crucial activity. As pointed out by Weber [101], it is more economical to raise the technology performance level (TPL) of a wave energy converter concept at low technology readiness level (TRL). Such a development path puts a greater demand on the numerical methods used.

Our previous work [64][47] has shown the potential of depth-averaged models for simulating wave energy devices. The approach followed so far relies on an explicit coupling of the different domains involving the flow under the structure and the free surface region. This approach has the advantage to need efficient solvers of well-known system of equations (compressible and incompressible flow). However, the transmission condition between this two regimes is now always well understood, depending on the underlying PDE models. Moreover, several sources of numerical instabilities exist because of the different nature of the regions involved (compressible/incompressible). A different approach is proposed in [73, 72], and will be pursued in the comping years. The idea is to solve a unique model in the whole computational domain, with the effect of the structure being accounted for by means of an appropriate pressure variable playing the role of a Lagrange multiplier. Out numerical developments will be performed withing the parallel platform `GeoFun`, based on the `Aerosol` library. In order to simulate the dynamic of the floating structures, we will consider the coupling with the open source code `tChrono`[1], an external code specialized in the resolution of the rigid body dynamics. The coupling is still under development. In parallel, we will add closure for other complex physical effects as e.g. the modeling of air pocket trapped under the structures. Several industrial processes (SeaTurns, Hace...) are based on chamber compressing air inside by the movement of the water surface. This strategy has the advantage of taking the turbines for energy production out of the water. The strategy is based on a polytropic modeling of the gas dynamics taking into account merging and splitting of the pockets, without a major impact on the efficiency of the simulation (robustness and numerical cost). This works benefits of the associated team LARME with RISE (C. Eskilson).

4.3 Materials engineering

Because of their high strength and low weight, ceramic-matrix composite materials (CMCs) are the focus of active research for aerospace and energy applications involving high temperatures, either military or civil. Self-healing (SH) CMCs are composed of a complex three-dimensional topology of woven fabrics containing fibre bundles immersed in a matrix coating of different phases. The oxide seal protects the fibres which are sensitive to oxidation, thus delaying failure. The obtained lifetimes reach hundreds of thousands of hours [88].

The behaviour of a fibre bundle is actually extremely variable, as the oxidation reactions generating the self-healing mechanism have kinetics strongly dependent on temperature and composition. In particular, the lifetime of SH-CMCs depends on: (i) temperature and composition of the surrounding atmosphere; (ii) composition and topology of the matrix layers; (iii) the competition of the multidimensional diffusion/oxidation/volatilization processes; (iv) the multidimensional flow of the oxide in the crack; (v) the inner topology of fibre bundles; (vi) the distribution of critical defects in the fibres. Unfortunately, experimental investigations on the full materials are too long (they can last years) and their output too qualitative (the coupled effects can only be observed a-posteriori on a broken sample). Modelling is thus essential to study and to design SH-CMCs.

[1] Project Chrono: An Open Source Multi-physics Simulation Engine

In collaboration wit the LCTS laboratory (a joint CNRS-CEA-SAFRAN-Bordeaux University lab devoted to the study of thermo-structural materials in Bordeaux), we are developing a multi-scale model in which a structural mechanics solver is coupled with a closure model for the crack physico chemistry. This model is obtained as a multi-dimensional asymptotic crack averaged approximation fo the transport equations (Fick's laws) with chemical reactions sources, plus a potential model for the flow of oxide [59, 63, 87]. We have demonstrated the potential of this model in showing the importance of taking into account the multi-dimensional topology of a fibre bundle (distribution of fibres) in the rupture mechanism. This means that the 0-dimensional model used in most of the studies (see e.g. [57]) will underestimate appreciably the lifetime of the material. Based on these recent advances, we will further pursue the development of multi-scale multi-dimensional asymptotic closure models for the parametric design of self healing CMCs. Our objectives are to provide: (i) new, non-linear multi-dimensional mathematical model of CMCs, in which the physico-chemistry of the self-healing process is more strongly coupled to the two-phase (liquid gas) hydro-dynamics of the healing oxide ; (ii) a model to represent and couple crack networks ; (iii) a robust and efficient coupling with the structural mechanics code ; (iv) validate this platform with experimental data obtained at the LCTS laboratory. The final objective is to set up a multi-scale platform for the robust prediction of lifetime of SH-CMCs, which will be a helpful tool for the tailoring of the next generation of these materials.

4.4 Coastal and civil engineering

Our objective is to bridge the gap between the development of high order adaptive methods, which has mainly been performed in the industrial context and environmental applications, with particular attention to coastal and hydraulic engineering. We want to provide tools for adaptive non-linear modelling at large and intermediate scales (near shore, estuarine and river hydrodynamics). We will develop multi-scale adaptive models for free surface hydrodynamics. Beside the models and codes themselves, based on the most advanced numerics we will develop during this project, we want to provide sufficient know how to control, adapt and optimize these tools.

We will focus our effort in the understanding of the interactions between asymptotic approximation and numerical approximation. This is extremely important in several ways. An example is the capability of a numerical model to handle highly dispersive wave propagation. This is usually done by high accuracy asymptotic PDE expansions of by means of multilayer models. In the first case, there is an issue with the constraints on the numerical approximation. Investigations of approriated error models for adaptivity in the horizontal may permit to alleviate some of these constraints, allowing a reasonable use of lower order discretizations. Concerning multi-layer models, we plan can use results concerning the relations between vertical asymptotic expansions and truncation/approximation error to improve the models by some adaptive approach.

Another important aspect which is not understood well enough at the moment is the role of dissipation in the evolution of the free surface dynamics, and of course in wave breaking regions. There are several examples of breaking closure, going from algebraic and PDE-based eddy viscosity methods [78, 91, 85, 61], to hybrid methods coupling dispersive PDEs with hyperbolic ones, and trying to mimic wave breaking with travelling bores [97, 96, 95, 77, 66]. In both cases, numerical dissipation plays an important role and the activation or not of the breaking closure, as well as on the establishement of stationary travelling profiles, or on the appearance of solitary waves. These aspects are related to the notion of numnerical dissipation, and to its impact on the resulting numerical solutions. These elements must be clarified to allow full control of adaptive techniques for the models used in this type of applications.

A fundamental issue that needs to be adressed is the proper discrete formulation of the boundary conditions for dispersive wave approximations. These conditions play of course a critical role in applications and remain an open problem for most Boussinesq models.

4.5 Geophysics and astrophysics

This is work is related to large scale simulations requiring the solution of PDEs on manifolds. Examples are tsunami simulations, as those performed in the past in the TANDEM project led by CEA [75], as well as some applications considered in the ANR LAGOON for climate change. The MSCA project SuPerMan proposes applciations in astrophysics which also involve similar issues. The idea is to consider both coordinate changes related to mesh movement, and in ALE formulations, as well as genuinely space-time manifolds as in hyperbolic reformulations of relativity [70], and combinations of both when for example considered mesh movement and adaptation in curvilinear coordinates [41]. Challenges are related to the appropriate PDE formulation, and the respect of continuous constraints at the discrete level.

The objective here is to devise the most appropriate manifold representation, and formulate the PDE system in the appropriate way allowing to embed as many continuous constraints as possible (well balancing, energy conservation, positivity preservation, etc). Embedding the ALE mapping will be necessary to envisage adaptive strategies, improving on [41] and [71].

Geophysical applications are of interest for BRGM. Some initial applications in astrophysics are performed in the context of the MSCA project SuPerMan and ERC Alchymia.

5 Highlights of the year

- Martin Parisot defended his HDR entitled, "Some Modeling and Computational Aspects of Water Waves Action" in November 2024 [28].
- Maria Kazolea defended her HDR entitled, "Advanced Numerical Methods for Nonlinear Water Wave dynamics and Breaking in Boussinesq-type models" in October 2024 [27].
- Organization of the HONOM2024 conference (8-13 of September 2024 in KAM Conference Center Chania, Crete Island, Greece) with E. Gaburro and M. Kazolea as co-chairs.
- Restart of the MMG consortium. After a period of inactivity, the consortium supporting the maintenance and development of the MMG software library has started to work again. It is hosted by Inria and led by N. Barral.

6 New software, platforms, open data

6.1 New software

6.1.1 SLOWS

Name: Shallow-water fLOWS

Keywords: Simulation, Free surface flows, Unstructured meshes

Scientific Description: Three different approaches are available, based on conditionally depth-positivity preserving implicit schemes, or on conditionally depth-positivity preserving genuinely explicit discretizations, or on an unconditionally depth-positivity preserving space-time approach. Newton and frozen Newton loops are used to solve the implicit nonlinear equations. The linear algebraic systems arising in the discretization can be solved either with the MUMPS library or with the MKL Intel library. Implicit and explicit (extrapolated) multistep higher order time integration methods are available, and a mesh adaptation technique based on simple mesh deformation are also included. This year a new higher order reconstruction for the FV scheme has been added.

Functional Description: SLOWS is a C-platform allowing the simulation of free surface shallow water flows with friction. It can be used to simulate near shore hydrodynamics, wave transformations processes, etc.

URL: `https://team.inria.fr/cardamom/slows-shallow-water-flows/`

Contact: Mario Ricchiuto

Participants: Maria Kazolea, Mario Ricchiuto

6.1.2 GeoFun

Keywords: Geophysical flows, Unified models, Finite volume methods

Scientific Description: GeoFun focuses on applications where different models in different regions in space are needed, with interfaces between these regions that depend on the solution. To deal with this complex boundary problem, the code aims at exploiting unified models available everywhere in the computational domain, and at using asymptotic preserving numerical schemes to recover specific regime flows without an a priori detection of the interfaces.

Functional Description: The GeoFun library is developed as a module on top of the kernel provided by AeroSol. Its objective is to simulate geophysical flows, free surface and underground, at large time and space scales. For this reason, unified vertically integrated (shallow water type) models are considered.

Contact: Martin Parisot

Participants: Martin Parisot, Marco Lorini

6.1.3 UHAINA

Keywords: Simulation, Ocean waves, Unstructured meshes, Finite element modelling

Scientific Description: Operational platform for near shore coastal application based on the following main elements:

- Fully-nonlinear wave propagation.

- Wave breaking handled by some mechanism allowing to mimic the energy dissipation in breakers.

- A high order finite element discretization combined with mesh and polynomial order adaptation for optimal efficiency.

- An efficient parallel object oriented implementation based on a hierarchical view of all the data management aspects cared for by middle-ware libraries developed at Inria within the finite element platform Aerosol.

- A modular wrapping allowing for application tailored processing of all input/output data (including mesh generation, and high order visualization).

- Spherical coordinates based on a local projection on a real 3D spherical map (as of 2021)

- Compilation with GUIX available (as of 2022)

- Homogenization and standardization of code outputs and hazard quatification (as of 2022)

- Correction of the management of dry/wet fronts in the presence of structures represented by a single high point (as of 2022)

- Use of FES for the calculation of the tide directly in UHAINA through an API. New compilation option for activation (as of 2022)

- Boundary conditions accounting tides from FES and corrected with the effect of the inverse barometer, for the simulation of the tidal propagation and the surge on domains at the regional scale (as of 2022)

- Hydraulic connections (e.g. sewers) in the simulation of urban flooding (as of 2022)

- Mass source term, for the injection of the volume of water overtopping structures not accounted in the elevation model during flooding episodes by sea surges (as of 2022)

Functional Description: Waves simulation

Contact: Mario Ricchiuto

Participants: Mario Ricchiuto, Philippe Bonneton, David Lannes, Fabien Marche

Partners: EPOC, IMAG, IMB

6.1.4 AleVoronoi

Name: Direct Arbitrary Lagrangian Eulerian Finite Volume and Discontinous Galerkin schemes on VORONOI moving meshes with topology changes

Keywords: Finite volume methods, Discontinuous Galerkin, High order methods, Centroidal Voronoi tessellation, ALE, Fortran, OpenMP

Scientific Description: We would like to remark that the implementation of AleVoronoi started in April 2018 as a collaboration between E. Gaburro, M. Dumbser (University of Trento, Italy) and W. Boscheri (University of Trento, then University of Ferrara, and now CNRS France). E. Gaburro was the main contributor in particular for what concerns the novelties, however, many parts of the code have been taken from existing codes of the other coauthors. Starting from July 2019, S. Chiocchetti (University of Trento, University of Stuttgart and now University of Cologne) joined the project, becoming a fundamental contributor to it. The work has continued during the years and have been moved to a git account in 2021. The main developers from 2021 up to now have been E. Gaburro and S. Chiocchetti. However, small contributions were introduced also by W. Boscheri and M. Ricchiuto. In addition, M. Dumbser has always participated int the scientific discussion concerning the development line of AleVoronoi.

Functional Description: Explicit, arbitrary high order accurate, one step (ADER), Finite Volume and Discontinuous Galerkin schemes on 2D moving Voronoi meshes for the solution of general first-order hyperbolic PDEs. Main peculiarity: the Voronoi mesh is moved according to the fluid flow using a direct Arbitrary-Lagrangian-Eulerian (ALE) method achieving high quality of the moving mesh for long simulation times. The high quality of the mesh is maintained thanks to a) mesh optimization techniques and b) the additional freedom of allowing topology changes. The high quality of the results is obtained thanks to the high order ADER schemes. The main novelty is the capability of using high-order schemes on moving Voronoi meshes with topology changes.

The code is written in Fortran + OpenMP.

Publications: hal-03850200, hal-03865596, hal-03850195, hal-02411272

Contact: Elena Gaburro

6.1.5 HOTHYPE

Name: High Order shock Tracking for HYPerbolic Equations

Keywords: Finite volume methods, Discontinuous Galerkin, Partial differential equation, Delaunay triangulation

Scientific Description: We would like to remark that this code born in December 2020, but it was quickly created because many of its part were taken from AleVoronoi and simplified/adapted to the purpose of this code. The code was created and mainly developed by E. Gaburro. However, all the original contributors of AleVoronoi should be acknowledged for their contributions to HOTHYPE: S. Chiocchetti, W. Boscheri, M. Dumbser. During the years, the code was mainly maintained and developed by E Gaburro. Another important contributor has been S. Chiocchetti. Minor parts of this code have been implemented by M. Ciallella under the supervision of M. Ricchiuto.

Functional Description: High order ADER-type Finite Volume and Discontinuous Galerkin schemes on 2D triangular meshes for the solution of hyperbolic partial differential equations.

Publications: hal-03850196, hal-04341999, hal-03865587

Contact: Elena Gaburro

6.1.6 AeroSol

Keywords: High order finite elements, Parallel computing

Functional Description: The AeroSol software is a high order finite element library written in C++. The code has been designed so as to allow for efficient computations, with continuous and discontinuous finite elements methods on hybrid and possibly curvilinear meshes. The work of the team CARDAMOM (previously Bacchus) is focused on continuous finite elements methods, while the team Cagire is focused on discontinuous Galerkin methods. However, everything is done for sharing the largest part of code we can. More precisely, classes concerning IO, finite elements, quadrature, geometry, time iteration, linear solver, models and interface with PaMPA are used by both of the teams. This modularity is achieved by mean of template abstraction for keeping good performances. The distribution of the unknowns is made with the software PaMPA , developed within the team TADAAM (and previously in Bacchus) and the team Castor.

News of the Year: Highlights for the year 2024 concern:

1. *Functional tests*: reference metrics were added for several tests, allowing to check the convergence order and the execution time (M. Haefele, V. Perrier). 2. Handling of *spherical manifolds* has been merged into the master branch, allowing to support Uhaina on the Lagoon branch from the AeroSol master branch (M. Haefele, V. Perrier). 3. *Tags* have been defined for relevant historical versions of the code. 4. Complete and time-consistent *Guix channels* have been specified to avoid reproducibility issues (L. Cirrottola). 5. Guix packages and channels for legacy compilation of the Uhaina master branch with a legacy AeroSol branch (L. Cirrottola). 6. New test cases for the *curl-/divergence-preserving schemes* (J. Jung, V. Perrier). 7. Several bug fixes (CI, tests). 8. Wiki improvement.

Contribution statistics: About 300 commits this year, organized in 11 merge requests that were opened and merged into the master branch this year.

URL: https://team.inria.fr/cardamom/aerosol/

Contact: Vincent Perrier

Participants: Mario Ricchiuto, Vincent Perrier, Héloïse Beaugendre, Christopher Poette, Marco Lorini, Jonathan Jung, Anthony Bosco, Luca Cirrottola, Romaric Simo Tamou, Ibtissem Lannabi, Matthieu Haefele

6.1.7 DM2

Name: Distributed Mesh and Data Manager

Keywords: HPC, Data parallelism, High order finite elements, Unstructured meshes, Hybrid meshes

Functional Description: DM2 is a C++ library for managing mesh and data on mesh in a MPI parallel environment. It is conceived to provide parallel mesh and data management in high order finite element solvers for continuum mechanics.

The user should provide a mesh file which is read by the library. Then DM2 is able to:

- Read the mesh, and read the data provided in the mesh file, possibly in parallel

- Redistribute the mesh in order to distribute the data on a given set of processors. This redistribution is made through a graph partitioner such as PARMETIS or PT-SCOTCH.

- Allocate the memory in parallel if a number of unknown by entity type is provided by the user.

- Centralize the data.

- Compute the halo required for a numerical method. The halo is adapted for each of the possible discretization.

- Renumber mesh elements for making a difference between mesh elements that need or need not communication.

- Aggregate a mesh based on a metric for developing a multigrid method.

Release Contributions: This version introduces overlap regions ("halos") among distributed mesh partitions. These halos are specialized for discontinuous or continuous schemes, but generic with respect to the (geometric) degree of the mesh cells. These halos allow to synchronize numerical data defined on a set of entities of the distributed mesh. Numerical data is again generic with respect to the degree of their polynomial approximation, the number and combinations of scalar/vector fields, and the size of the vector spaces.

News of the Year: Highlights for the 2024 years:

- Refactoring of *mesh iterators*: dealing with constness, views on specified entity types, generalization of normal (uniform) and non-normal (non-uniform) iterators, handling an entity as a generalized reference. - Refactoring of methods for MPI communication into *generic communication algorithms*. - Refactoring of halo creation methods: no shallow entities, better object-oriented creation. - Passage to the C++14 *standard*. - Development of *generic algorithms for graph permutations*. - Specific *mesh graph composition* for DG or CG schemes. - Towards a consistent handling of 1D meshes: better role distinction between faces and points, remove hard-coded constants, template some methods on the mesh dimension. - Boundary handling: assign boundary faces if not found in the mesh file. - Development of input/output in Vtu format. - Development of input/output in NetCDF. - Full specification of Guix channels for avoiding environment reproducibility issues. - Integration of a two-dimensional finite volume test. - Test references for ParaGMSH objects. - Clean repository paths. - Several bug fixes. - Several small refactorings. - Several small contributions: introducing chronometers, storing the MPI communicator in a variable.

Contributions statistics: about 1800 commits, organized in 32 merge requests that were opened and merged into the master branch during the last year.

Contact: Vincent Perrier

Participants: Abderrahman Ben Khalifa, Matthieu Haefele, Vincent Perrier, Luca Cirrottola

7 New results

7.1 Structure preserving numerical methods for evolutionary PDEs

Participants: Elena Gaburro, Maria Kazolea, Martin Parisot, Mario Ricchiuto.

- Corresponding member: Mario Ricchiuto

7.1.1 High order well balanced discretizations

Global flux based schemes.

In the context of preserving stationary states we continued and extended the work initiated in [55] and [14]. This work is based on a notion, referred to as global flux or global flux quadrature, in which source terms are replaced by the derivative of some effective flux term to be determined in some way. While in [55] this notion has been applied directly by computing, in one dimensions, primitive of the source term, in [14] we have shown that some more interesting choices are possible. First of all, in the finite element case the method can be written in a fully local fashion. Secondly, by choosing appropriately the quadrature formula defining the source integral, one can enforce full consistency with some ODE integrator. This adds freetom to the accuracy obtained at steady state, and allows an extremely fast generation of well prepared initial data. This preperty is retained without the need to apply the ODE integrator explicitly to solve the local Cauchy problem at each time step and in each cell, as in previous work e.g. by [74].

A first extension of these ideas has been performed in the context of WENO finite difference methods. In this case, a nondimensionalapproximation of a primitive of the source can be readily written using high-order multi-step ODE methods on the finite difference grid. Then a standard WENO strategy is employed to reconstruct the global (nodal) flux. By construction, the steady discrete solutions of the proposed schemes are those of the underlying ODE integrator. We tested WENO reconstructions of varying orders (from 3 to 7), combined with multi-step ODE methods of up to order 8. We have verified that the steady-state solution is determined solely by the ODE method. Numerical experiments using scalar balance laws and shallow water equations confirm that the methods achieve optimal convergence for time-dependent solutions and significant error reduction for steady-state solutions. This work has been performed in collaboration with the U. fo Malaga (C. Parés), and presented at the 9th European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS 2024, Jun 2024, in Lisbon, Portugal [18].The full article [31] has been submitted to *Computers* & *Fluids*.

We also extended the same approach to stabilized continuous finite elements. To this end we reformulated several stabilization methods, including SUPG, and continuous interior penalty, in terms of cell value and symmetric face jump integrals of full residuals. In this setting we can naturally include the source, using a formulation similar to the one used in [14]. The schemes are specifically designed to guarantee the exact preservation of the lake at rest steady state, on the other hand, some of them make use of general structures to tackle the preservation of general steady states, whose explicit analytical expression is not known. Several basis functions have been considered in the numerical experiments and, in all cases, the numerical results confirm the high order accuracy and the ability of the novel stabilizations to exactly preserve the lake at rest steady state and to capture small perturbations of such equilibrium. Moreover, some of them, based on the notions of space residual and global flux, have shown very good performances and superconvergences in the context of general steady solutions not known in closed-form. Work performed in collaboration with the University of Zurich, and discussed in detail in [15].

We have done initial steps to extend these ideas to the multidimensional case. As a first step we looked at lienar equations. In particular, as an example we focused on the linear acoustics system (in first order hyperbolic form). Already in the homogenous case, steady states are characterized by a solenoidal constraint on the velocity, which is non-trivial to reproduce discretely. Besides this, numerical methods for hyperbolic PDEs require stabilization. For linear acoustics, divergence-free vector fields should remain stationary, but classical Finite Difference methods add incompatible diffusion that dramatically restricts the set of discrete stationary states of the numerical method. Compatible diffusion should vanish on stationary states, e.g. should be a gradient of the divergence. Some Finite Element methods allow to naturally embed this grad-div structure, e.g. the SUPG method or OSS. We prove here that the particular discretization associated to them still fails to be constraint preserving. We then introduce a new framework on Cartesian grids based on surface (volume in 3D) integrated operators inspired by Global Flux quadrature and related to mimetic approaches. We are able to construct constraint-compatible stabilization operators (e.g. of SUPG-type) and show that the resulting methods are vorticity-preserving. We show that the Global Flux approach is even super-convergent on stationary states, we characterize the kernels of the discrete operators and we provide projections onto them. The full paper [29] has been accepted on *Numerical Methods for PDEs*. The inclusion of artibrary source terms has been also studied with very similar enhancements. This last part of work has been presented to several conferences including the Oberwolfach workshop "Hyperbolic Balance Laws: interplay between scales and randomness", held in February 2024. A full manuscript is in preparation. Work performed in collaboration with the math department in Bordeaux (W. Barsukow), and U. of Roma-La Sapienza (D. Torlo).

Astrophysics. We develop a new well-balanced discontinuous Galerkin (DG) finite element scheme with subcell finite volume (FV) limiter for the numerical solution of the Einstein-Euler equations of general relativity based on a first order hyperbolic reformulation of the Z4 formalism. The first order Z4 system, which is composed of 59 equations, is analysed and proven to be strongly hyperbolic for a general metric. The well-balancing is achieved for arbitrary but a priori known equilibria by subtracting a discrete version of the equilibrium solution from the discretized time-dependent PDE system. Special care has also been taken in the design of the numerical viscosity so that the well-balancing property is achieved. As for the treatment of low density matter, e.g. when simulating massive compact objects like neutron stars surrounded by vacuum, we have introduced a new filter in the conversion from the conserved to the primitive variables, preventing superluminal velocities when the density drops below a certain threshold, and being potentially also very useful for the numerical investigation of highly rarefied relativistic astrophysical flows. Thanks to these improvements, all standard tests of numerical relativity are successfully reproduced, reaching three achievements: (i) we are able to obtain stable long term simulations of stationary black holes, including Kerr black holes with extreme spin, which after an initial perturbation return perfectly back to the equilibrium solution up to machine precision; (ii) a (standard) TOV star under perturbation is evolved in pure vacuum ($\rho = p = 0$) up to $t = 1000$ with no need to introduce any artificial atmosphere around the star; and, (iii) we solve the head on collision of two punctures black holes, that was previously considered un-tractable within the Z4 formalism. Due to the above features, we consider that our new algorithm can be particularly beneficial for the numerical study of quasi normal modes of oscillations, both of black holes and of neutron stars [10].

Shallow water equations on manifolds. Last but not least we continued our work on well balanced schemes for shallow water type models had major enhancements. We proposed a novel hyperbolic re-formulation of the shallow water model written in covariant coordinates, i.e. metric independent, and for this system we derived a cheap well balanced method able to maintain at machine precision water at rest equilibria for general metrics and complex-shaped domains. This work has been presented in ICNAAM 2022 - 20th International Conference of Numerical Analysis and Applied Mathematics [23].

7.1.2 Schemes embedding additional discrete conservation constraints

A posteriori sub-cell conservative correction of nonconservative schemes. We proposed a novel quasi-conservative high order discontinuous Galerkin (DG) method able to capture contact discontinuities avoiding any spurious numerical artifacts, thanks to the PDE evolution in *primitive variables*, while at the same time being strongly conservative on shocks, thanks to a conservative *a posteriori* subcell finite volume (FV) limiter. In particular, we have verified the improved reliability of our scheme on the *multi-fluid Euler system* on examples like the interaction of a shock with a helium bubble. The obtained results have been presented at several international conferences, and fully discussed in the *CMAME* article [12]. Currently similar ideas are being explored in collaboration with the U. fo Malaga (C. Parés, E. Pimentel-Garcia), using the discontinuous-reconstruction path conservative method.

Structure-preserving approximations of the Serre-Green-Naghdi equations in standard and hyperbolic form In collaboration with H. Ranocha (U. of Mainz), we have constructed numerical approxiamtion of the Serre-Green-Naghdi equations which conserve (to machine accuracy) mass, energy, and, when relevant, momentum. Several forms of the equations have beed studied, both involving a hyperbolic balance law reformulation, and more classical ones requiring the explicit inversion of an elliptic operator. The framework introduced is very general and exploits two main building blocks: the use of so-called summation by parts operators (SBP - which satisfy a fully discrete analog of integration by parts); the use of an appropriate split form, a combination of the conservative and non-conservative form of the PDE terms. The approach can be used with any discretization whcih has the SBP property (finite difference/element/volume). Schemes up to order 6 have been tested on complex problems. The enhancements brought by energy conservation when considerng long time propagation are undeniable. The full manuscript [34] has been submitted to *Numerical Methods for PDEs*.

7.1.3 Efficient discretizations for free surface flows

IMEX schemes in low Froude regimes We developed and analysed a second order numerical method tailored for shallow water flows in regimes characterized by low Froude numbers. The focus is on modeling oceanic and coastal dynamics across different scales, with particular attention on the variation of the Froude number from 1 near the shoreline to significantly lower values offshore. Classical hyperbolic schemes, such as Riemann solvers, become inefficient in these deep water conditions. To address this challenge, a hybrid numerical approach is proposed where part of the system is treated implicitly, resulting in an ImEx (Implicit-Explicit) scheme. To minimize the computational cost associated with solving linear systems, a fully segregated approach is used. In this method, the water height and hybrid mass fluxes are handled implicitly, while velocities are treated explicitly, thus avoiding large linear system resolutions. While various Runge-Kutta schemes are available for a second-order time integration, we chose here a Crank-Nicolson scheme to reduce the number of linear systems required. Spatial discretization is performed using a second-order MUSCL reconstruction. The novel scheme is demonstrated to be

Asymptotic Preserving (AP), ensuring that a consistent discretization of the limit model, known as the "lake equations" is obtained as the Froude number approaches zero. Through a series of one- and two-dimensional test cases, the method is shown to achieve second-order accuracy for different Froude numbers. Additionally, the computational efficiency of the proposed method is compared with that of a fully explicit scheme, demonstrating significant time savings with the ImEx approach, particularly in scenarios governed by low Froude numbers. This work has been presented in HONOM2024 conference [24] and in CEDYA 2024 [38]. A paper has also been submitted [32]

Operational discontinuous Galerkin for coastal flood assessment As a result of a long term collaboration with many partners (BRGM, EPOC, UPPA, CNRS, U. Motpellier) we proposed a free surace model - named UHAINA, Basque for wave - built upon the finite element library AeroSol (mainly developed by the Inria team CAGIRE), and based on some ad hoc developments of the DG discretization : (i) a pragmatic treatment of the solution in partially dry cells which guarantees efficiently well-balancedness, positivity and mass conservation at any polynomial order; (ii) an artificial viscosity method based on the physical dissipation of the system of equations providing nonlinear stability for non-smooth solutions. A set of numerical validations on academic benchmarks is performed to highlight the efficiency of these approaches. Finally, UHAINA is applied on a real operational case of study, demonstrating very satisfactory results. Work published in [11].

7.2 Numerical modelling of free surface flows

Participants: Maria Kazolea, Martin Parisot, Mario Ricchiuto.

- Corresponding member: Maria Kazolea

Coupling dispersive and non-dispersive models. This year we complited our work on the coupling of coastal phase-resolving water wave models, commonly employed in the study of nearshore wave propagation. Despite numerous models and the existing coupling examples, there has been a significant lack of consensus concerning the artifacts and issues induced by these strategies, as well as a vague understanding of how to analyze and compare them. To tackle this problem, this research adopts a domain decomposition approach, anchored in the principle that 3D water wave models (e.g., Euler or Navier-Stokes) serve as the ideal reference solution. Structured in two parts, the thesis first proposes new models and evaluates them through numerical experiments, identifying specific hypotheses about their accuracy and limitations. Subsequently, a theoretical framework is developed to prove these hypotheses mathematically, utilizing the one-way coupled model as an intermediate reference to distinguish between expected and unexpected effects and categorize errors relative to the 3D solution. The total error is split in three parts—coupling error, Cauchy-model error, and half-line-model error—and these concepts are applied to the linear coupling of Saint-Venant (SV) and Boussinesq (B) models using the so called 'hybrid' model. The analysis confirms that the coupling error accounts for wave reflections at the interfaces, and varies with the direction of propagation. Moreover, thanks to the choice of the one-way model as the intermediate reference solution, this analysis proves several important properties such as the well-posedness and the asymptotic size of the reflections. Additionally, the thesis also addresses the weak well-posedness of the Cauchy problem for the B model and its implications for mesh -dependent solutions that have been reported. As a byproduct, a new result for the half-line problem of the linear B model is obtained for a more general class of boundary data, including a description of the dispersive boundary layer, which had not been addressed in the literature yet. The proposed pragmatic definition of coupling error aligns with and extends existing notions from the literature. It can be readily applied to other Boussinesq type models, discrete equations, linear and nonlinear cases (at least numerically), as well as other coupling techniques, all of which are discussed in the perspective work. This work has been presented in the 27th International Conference on Domain Decomposition Methods in Science and Engineering [21] and is a part of Jose Galaz PhD thesis see[36] and [26].

On the same subject, we propose a strategy based on a thick interface coupling technique, which has already proved its relevance in the context of hyperbolic equations. The initial step involves introducing a comprehensive framework based on a projection structure and applicable to various dispersive models, demonstrating that classical weakly dispersive models are encompassed within this framework. Next, a thick interface coupling technique, well-established in hyperbolic framework, is applied. This technique enables the formulation of unified models across different subdomains, each corresponding to a specific dispersive model. The unified model preserves the conservation of mechanical energy, provided it holds for each initial dispersive model. We propose a numerical scheme that preserve the projection structure at the discrete level and as a consequence is entropy-satisfying when the continuous model conserve the mechanical energy. We perform a deep numerical analysis of the waves reflected by the interface. Finally, we illustrate the usefulness of the method with two applications known to pose problems for dispersive models, namely the imposition of a time signal as a boundary condition or the imposition of a transparent boundary condition, and wave propagation over a discontinuous bathymetry. This paper is already published in ESAIM: M2AN [16].

Modelling undular bores in channels and estuaries. We have furhter pursued the work initiated in [52]. The last work has shown the existence of two families of undular bores. One is a well known class of waves known as Favre waves (from the well known experiments reported in [65]) associated to dispersive processes related to vertical velocity profiles. The second type of waves has a different nature and is generated by kinematics along the transversal direction. These waves are thus fully hydrostatic, despite of their strongly dispersive behaviour. They are refferred to as geometrically dispersiev waves, or dispersive-like waves. One of the issues left open in the last work is the derivation of a genuinely nonlinear one-dimensional model confirming this, and allowing to predict the waves in question. This has been done in [30]. In the last work we proposed an fully nonlinear dispersive PDE model, obtained as an asymptotic transvers average approximate of the hyperbolic shallow water equations. The model has many interesting theoretical properties and can be used to simulated the waves observed e.g. in [99] for low Froude numbers.

A second question arising from our previous work is the transition from one type wave to another, observed in the latter experimets. Hoping to obtain a one dimensional model capable to simulate both family of waves, we considered the use of a section averaged dispersive model proposed by Winckler and Liu [102], and derived in a very general setting a priori allowing to incorporate all hydrodynamic effects. This work has been performed in collaboration with EDF, who aims at developing a simulation model for rivers or cooling water channel systems for nuclear plants, using networks of one dimensional solvers. The work done in the PhD of B. Jouy has provided very usefull understasnting of several modelling and numerical issues. In this study, we propose an improved version of section-averaged Boussinesq equations of Winckler-Liu. Removing some modelling hypotheses the model is reformulated in conservative variables, allowing exact mass conservation. Using the approach introduced in [66] we proposed a hybrid finite volume and finite element discretisation which has been verified using new travelling wave analytical solutions we derived. We then investigated the impact of numerical dissiaption of the long time propagation, emphasising the need for great precaution in the application of classical dissipative schemes on coarse meshes to evaluate quantities of engineering interest such as maximum wave amplitudes, even in presence of physical dissipation (e.g. friction). This is in line with the resuts obtained in the study of exactly energy conservative schemes for the Serre-Green-Naghdi equations [34] (cf. above). More surprisingly, theoretical and numerical investigations have shown that the Winckler-Liu model can only predict geometrically dispersive waves. So, depsite currenlty begin the most general Boussinesq approximation available, this model has essentially predictive capabilities similar to those of the model we derived in [30] starting from the shallow water equations. This leaves open the question of proposing a 1D model allowing to predice th transition from dispersive-like to Favre waves, which is currently ongiong work. The results obtained with EDF are published in [13, 25].

7.3 Modelling of icing and de-icing of aircrafts

Participants: Héloïse Beaugendre.

- Participants: Héloïse Beaugendre, Martin Parisot, Andres Benoit

- Corresponding member: Héloïse Beaugendre

In-flight icing is a major source of incidents and accidents. The effects of atmospheric icing can be anticipated by Computational Fluid Dynamics (CFD).

The modification of the shallow water icing model to handle de-icing phenomenon is the main focus of the study proposed in [19]. As stated in the original SWIM model, the runback water is modeled utilizing a lubrication assumption for the water film velocity profile. A constant film temperature $Tf(t,x)$ is then calculated under the thin-film hypothesis. Unlike the simplified icing model, the temperature field within the ice layer $Tice(t,x,z)$ is no longer assumed to be constant. Instead, a temperature profile is utilized, enabling the generation of a static film on the wall when a heat conduction source term from a resistance is present. A Temperature profile $Ts(t,x,z)$ is also used in the static film layer if the model predicts the occurrence of this state. In the energy equation for both the solid ice and liquid portion of the static water film, transverse transfers are not considered, a 1D heat equation is then resolved. An integral approach and proper boundary conditions are used to close the problem. The validity of the integral method deteriorates as the thickness over which vertical integration is performed increases. To avoid this problem, a multi-layer approach is proposed. The thickness of the ice block is then divided into three layers of identical thickness. The purpose of this study is to offer a straightforward and robust method suitable for conducting industrial test cases. The model will first be introduced, followed by a description of the numerical approach. Subsequently, validation test cases will be conducted. Realistic de-icing scenarios will then be designed to evaluate the model. Additionally, nonuniform roughness effects will be examined.

In clouds and under cold weather, water droplets impact and freeze on aircraft structures. The Eulerian model for the droplet flow predicts the impinging water mass. The model equations are close to the Euler equations but without the pressure term, known as pressureless Euler model. Consequently, the resulting system is only weakly hyperbolic and standard Riemann solvers strongly relying on the eigenstructure of the system cannot solve the Eulerian model. To circumvent this problem, the model is supplemented with an extra-term mimicking the divergence of a particle pressure. The main purpose of this work is to implement a multidimensional aware Riemann solver for a Finite Volume simulation code for the modified formulation of the Eulerian droplet model, [5]. The numerical method should preserve physical properties such as the positivity of the liquid water content, and must produce accurate results without sacrificing the general robustness. The flow around a cylinder assess the numerical method in 2D on radial meshes.

7.4 High order embedded and immersed boundary methods

Participants: Héloïse Beaugendre, Benjamin Constant, Elena Gaburro, Florent Nauleau, Mario Ricchiuto.

- Corresponding member: Héloïse Beaugendre

We have continued exploring new ideas allowing to improve the accuracy of immersed and embedded boundary methods, both on a fundamental level and in applications.

Immersed boundaries for turbulent flows. Realistic applications to external aerodynamics are being pursued in collaboration with ONERA and CEA-Cesta.

Within the PhD of Benjamin Constant (ONERA) we have proposed an improved Immersed Boundary Method based on volume penalization for turbulent flow simulations on Cartesian grids. The proposed approach enables to remove spurious oscillations on the wall on skin pressure and friction coefficients. Results are compared to a body-fitted simulations using the same wall function, showing that the stair-step immersed boundary provides a smooth solution compared to the body-fitted one. The IBM has been modified to adapt the location of forced and forcing points involved in the immersed boundary reconstruction to the Reynolds number. New adaptive methods are investigated for the near-field reconstruction of aerodynamic forces in an immersed boundary context.

The paper [9] presents further improvements to the immersed boundary method introduced previously. The proposed developments take place during the pre- and post-processing stages of the simulation workflow and aim to further increase the accuracy of the approach for steady-state simulations of high Reynolds number turbulent flows around aerodynamic geometries facing strong incidence. To this end, the location of the forcing points is further optimized prior to simulation, with an adaptive and local modeling height that accounts for the evolution of the turbulent boundary layer thickness, especially at the leading edge. In addition, the direct extrapolation of the pressure solution at the wall is replaced by first- and second-order reconstructions using the normal pressure gradients interpolated at a new set of image points. This second approach is used only in post-processing, after the simulation, and prevents the degradation of the wall pressure in the presence of strong curvatures or thin boundary layers. These developments have been validated by simulating subsonic turbulent flows around the NACA0012 profile, 2D multi-element airfoil (2DMEA), and HL-CRM half-plane at significant angles of attack. Smooth and accurate skin pressure and friction coefficients are observed, in excellent agreement with body fitted wallresolved solutions, even for coarser Cartesian meshes. Better drag and lift coefficients calculated by direct near-field integrations are obtained, along with accurate predictions of the near-wall flow physics throughout the turbulent boundary layer.

This work continues with the thesis of Michele Romanelli. Michele presents a data-based methodology to build Reynolds-Averaged Navier–Stokes (RANS) wall models for aerodynamic simulations at low Mach numbers. Like classical approaches, the model is based on nondimensional local quantities derived from the wall friction velocity, the wall viscosity, and the wall density. A fully-connected neural network approximates the relation. We consider reference data (obtained with RANS simulations based on fine meshes up to the wall) of attached turbulent flows at various Reynolds numbers over different geometries of bumps, covering a range of wall pressure gradients. After training the neural networks on a subset of the reference data, the paper assesses their ability to accurately recover data for unseen conditions on meshes that have been trimmed from the wall up to an interface height where the learned wall law is applied. The network's interpolation and extrapolation capabilities are quantified and carefully examined. Overall, when tested within its interpolation and extrapolation capabilities, the neural network model shows good robustness and accuracy. The global error on the skin friction coefficient is a few percent and behaves consistently over all the considered test cases.

Enancing the accuracy of emmedded boundary methods. We have further pursued the study of order enhanced embedded methods. Two appraches have been investigated.

In collaboration with DTU Compute (A.P. Engsig-Karup, J. Visbech) we preshave proposed a new high-order accurate spectral element solution to the two-dimensional scalar Poisson equation subject to a general Robin boundary condition. The solution is based on a simplified version of the shifted boundary method using the underlying finite element bases rather than Taylor expansions at quadrature points for the extrapolation from the approximate to the ture domain, as initially proposed in [54]. Dirichlet, Neumann, as well as a new general Robin boundary formulation are enforced weakly through: i) a generalized Nitsche's method and ii) a generalized Aubin's method. An asymptotic preserving formulation of the embedded Robin formulations is presented. We performed several numerical experiments and analysis of the algorithmic properties of the different weak formulations. With this, we include convergence studies under polynomial, p, increase of the basis functions, mesh, h, refinement, and matrix conditioning to highlight the spectral and algebraic convergence features, respectively. This allowed to assess the influence of variational formulations, polynomial order, mesh size, and mappings between the true and surrogate boundaries. Accuracy and stability enhancements are observed, for orders beyond 5, when using interpolation rather than extrapolation (true boundary within the computational domain). Work discussed in detail in [17], and preliminary applications to wave-body interaction discussed in [22].

The work discussed in [54] on the use of the shifted boundary method for yperbolic systems, while very promising, showed one limitation, namely that for higher orders the approach can only be used on nodally conformal lienar meshes to correct for the geometrical error of potentially curved boundaries. To this end we have explored the use of aother embedded approach, referred to as Reconstruction for Off-site data (ROD) in [56]. In this method the extrapolation is based on a polynomial reconstruction that embeds the considered boundary treatment thanks to the implementation of a constrained minimization problem which uses the data given on the true boundary. In collaboration with the University of Coimbra (S. Clain) we proposed a novel approach based on a genuine space-time reformulation of reproduce coupled with explicit ADER time integration. This space-time setting is used to avoid a new reconstruction (linear system inversion) at each sub-time node and retrieve a single space-time polynomial that embeds the considered boundary conditions for the entire space-time element. Several numerical experiments are presented proving the consistency of the new approach for all kinds of boundary conditions, for curved boundaries and fully non-conformal meshes. Computations involving the interaction of shocks with embedded curved boundaries are made possible through an a posteriori limiting technique. Work discussed in detail in [8].

7.5 Adaptation techniques

Participants: Nicolas Barral, Héloïse Beaugendre, Sourabh Bhat, Luca Cirrottola, Mario Ricchiuto, Ishak Tifouti.

- Corresponding member: Nicolas Barral

MMG Consortium the anisotropic meshing library MMG is supported by a consortium of industrial and academic partners. It had been inactive for a little while, but it started to work again in 2024, Nicolas Barral taking the lead of the consortium. A new engineer, Corentin Prigent, was hired in October 2024, who started to work on the roadmap designed by the consortium. Extensive meetings with the partners were also carried out.

Mesh adpatation for sea ice modelling. The collaboration with Institut des Géosciences de l'Environnement, Grenoble, is now fully operational with the begining of Fabien Salmon's postdoc in February 2024. The 2D version of MMG was parallelized with MPI, following recent developments with the 3D version. It was coupled with the state-of-the-art sea-ice model NeXtSIM, in which new developments are carried out to remove the existing sequential remeshing mechanism.

Coupling mesh adaptation with model reduction.

In [6], we explore coupling linear model order reduction and mesh adaptation, with a hierachical clustering technique. The resolution and accuracy of numerical partial differential equation solvers are governed by the mesh density and the order of accuracy of the solver. Anisotropic mesh adaptation combined with a posteriori error estimation is known to be a powerful tool to enhance the efficiency of the solvers. However, in engineering applications involving multiple complex configurations, optimization or uncertainty quantification, generating a single adapted mesh to efficiently capture features of the solutions for all possible choices of the problem parameters (geometry, boundary conditions, etc.) is not feasible. This is particularly true when the solution is very sensitive to the problem parameters and changes in the topology of the solution features (e.g. one vs two shocks) occur for small changes in the computational setting. This paper presents a novel algorithm coupling partitioning the parameter space for efficient parameter clustering and local model order reduction and anisotropic mesh adaptation. The hierarchical partitioning is performed by sampling the parameter space using a full-order model on a relatively coarse mesh. The variance of the physical solutions is reconstructed in the parameter space using proper orthogonal decomposition and Taylor's series to guide each partition's size and shape. Subsequently, the solutions are sampled within the optimal partitions to compute the locally adapted mesh and optimal reduced-order model for each partition. The efficacy of the new algorithm is demonstrated by solving heat conduction with material discontinuity and compressible flow problems.

In [4], we propose an automated nonlinear model reduction and mesh adaptation framework for rapid and reliable solution of parameterized advection-dominated problems, with emphasis on compressible flows. The key features of our approach are threefold: (i) a metric-based mesh adaptation technique to generate an accurate mesh for a range of parameters, (ii) a general (i.e., independent of the underlying equations) registration procedure for the computation of a mapping Φ that tracks moving features of the solution field, and (iii) an hyper-reduced least-square Petrov-Galerkin reduced-order model for the rapid and reliable estimation of the mapped solution. We discuss a general paradigm — which mimics the refinement loop considered in mesh adaptation — to simultaneously construct the high-fidelity and the reduced-order approximations, and we discuss actionable strategies to accelerate the offline phase. We present extensive numerical investigations for a quasi-1D nozzle problem and for a two-dimensional inviscid flow past a Gaussian bump to display the many features of the methodology and to assess the performance for problems with discontinuous solutions.

Finally, we build upon the two previous works. We propose a localized automated nonlinear model reduction framework for rapid and reliable solution of parameterized shock-dominated flows. Our formulation exploits the adaptive procedure of [Barral et al, JCP, 2024] and a clustering technique to devise a piecewise Lagrangian approximation of the solution to the parametric problem: the application of clustering is designed to cope with parameter-induced shock-topology changes that hinder the effectiveness of standard (monolithic) Lagrangian approximations. We rely on (i) metric-based mesh adaptation to generate an accurate mesh for a range of parameters, (ii) parametric registration for the computation of a bijection Φ that tracks moving features of the solution field, and (iii) projection-based model reduction to rapidly and reliably estimate the mapped solution; finally, we develop (iv) a clustering technique to partition the parameter domain in subregions where the shock topology does not change. We present numerical investigations for a two-dimensional supersonic inviscid flow past a Gaussian bump to illustrate the many features of the methodology: in more detail, we display the performance of three clustering techniques, and we compare our approach with monolithic Lagrangian approximations.

7.6 Modeling of flows in aquifers

Participants: Manon Carreau, Martin Parisot.

- Corresponding member: Martin Parisot

The objective of this project is to propose a numerical tool (software GeoFun) for the simulation of flows in aquifers based on unified models. Different types of flows can appear in an aquifer: free surface flows (hyperbolic equations) for lakes and rivers, and porous flows (elliptic equations) for ground water. The variation in time of the domain where each type of flow must be solved makes the simulation of flows in aquifers a scientific challenge. Our strategy consists of writing a model that can be solved in the whole domain, i.e. without domain decomposition.

For the beginning of the project we start by considering only the saturated areas. In [51], we propose and study a unified model between shallow water and Dupuit-Forchheimer models, which are both classical models in each areas. A numerical scheme has been proposed and analysed. It satisfies a discrete entropy dissipation which ensure a strong stability.

In [33], we propose a formal derivation of a hierarchic of asymp- totic models that approximate the groundwater wave problem within the Dupuit- Forchheimer regime, over a regular, non-planar substratum. The derivation methodology employed bears resemblance to the techniques utilized in hierarchic of asymptotic models for approximating the water waves problem in the shallow water regime. Mathematically speaking, the asymptotic models manifest as nonlinear, non-local diffusion equations. We identify an energy dissipation law inherent to these models, thereby bolstering the physical validity and confidence in the proposed framework. A numerical strategy is proposed that preserved at the discrete level the energy dissipation. Several simulations are conducted to discuss and validate the dynamic behavior of the solution.

8 Bilateral contracts and grants with industry

8.1 Bilateral Contracts

CEA-CESTA

Participants: Héloïse Beaugendre.

- Title: Development of models and numerical methods for the degradation of a pyrolysable material

- Type: contrat d'accompagnement for Alexis Cas's PhD.
- Duration: 36 months
- Starting date : 1st October 2023
- Coordinator: Heloise Beaugendre Celine Baranger and Simon Peluchon(CEA)
- Summary: During re-entry into the atmosphere, a spacecraft is subjected to considerable mechanical stress and heat flows. These heat flows, applied to the vehicle's wall, cause the heat shield to heat up significantly. The heat shield is made up of materials that chemically degrade under the effect of heat to limit the temperature rise inside the vehicle. These reactions are known as pyrolysis. Similarly, on the surface, these materials undergo physical degradation known as ablation. Understanding these two phenomena is essential for the design of heat shields. The design of such a shield requires precise numerical simulations of the airflow that is created around the vehicle throughout its trajectory. This airflow must be coupled with ablation and pyrolysis phenomena.

EDF

Participants: Bastien Jouy, Mario Ricchiuto.

- Title: Numerical modelling of Favre waves and undular bores in channels with banks
- Duration: 36 months
- Starting date : 08 November 2021
- Coordinator: Mario Ricchiuto
- Summary: The collaboration with EDF (Eleectricité de France) focuses on the improvement of their in house code TELEMAC-Mascaret, initially for the advection of passive scalars (pollutant transport), and more recently for the simulation of hydrostatic and dispersive (undular) bore dynamics in networks of channels (application to abrupt closing/opening of valves). The past work on advection schemes has been done with J.M. Hervouet (retired) and R. Ata (riadh.ata@edf.fr - currently at FLOW-3D) was an informal collaboration. The ongoing collaboration on bore dynamics is with D. Violeau (damien.violeau@edf.fr) is object of a CIFRE contract. This work aims at increasing the capabilities of EDF's code to simulate the undulating bores studied in [52].

Airbus

Participants: Nicolas Barral, Clarisse Chabaud, Mario Ricchiuto.

- Title: Curvilinear Mesh Adaptation for Aircraft Design
- Duration: 36 months
- Starting date : 1st October 2024
- Coordinator: Nicolas Barral
- Summary: The aim of this thesis work is to develop a mesh adaptation strategy compatible with the high-order numerical methods in Airbus' code CODA. Of particular interest will be the consideration of complex curved geometric shapes found in aeronautics. The success of this work will be measured by the ability of the chosen strategy to control the numerical error near curved boundaries. To this end, a curvilinear mesh generation tool for the automatic mesh adaptation process by metric specification will be developed in the Flowsimulator environment. A method for correcting

the geometric error during spatial integration at wall level will also be developed in the CODA tool. On the basis of these two main technologies, a high-order mesh adaptation process will then be developed, enabling reliable control of the numerical error. The range of applications targeted will be the simulation of highly loaded supercritical wings and hyper-supported configurations in icing conditions.

IFPEN

Participants: Martin Parisot, Sebastien Erdocio.

- Title: Monarc
- Duration: 36 months
- Starting date : 1st November 2024
- Coordinator: Martin Parisot
- Summary: This project is a collaboration with Benoit Chauveau, Leo Argelas and Arnaud Pujol, from IFPEN, to supervised the PdH of Sebastien Erdocio. The objective is to propose a model for the dynamics of unsaturated (Vadose area) and saturated (water table) groundwater. To avoid costly 3D simulations, the strategy is based on a 2D-horizontal Dupuit-Forchheimer model for the dynamics of the water table and several (one by horizontal mesh cell) 1D-vertical infiltration equation. The main issue of the project is the coupling between the water dynamics preserving the physical conservation, i.e. mass and energy conservation. In a second phase, perched water, confined water and exchanges with the surface will be considerated.

9 Partnerships and cooperations

9.1 International research visitors

9.1.1 Visits of international scientists

Other international visits to the team

Carlos Pares Madronal

Status Professor

Institution of origin: University of Malaga

Country: Spain

Dates: 13-19 October 2024

Context of the visit: Prof. Carlos Pares visited the team to work on several topocs. With M. Ricchiuto and M. Kazolea he contributed to the development approximate well-ballanced WENO finite difference schemesusing a global-flux quadrature method with multi-step ODE integrator weights. Also with M. Ricchiuto Prof. Pares is working on the extension of the discontinuous-reconstruction path conservative method to mult-material flows.

Mobility program/type of mobility: research stay

Laura Del Rio Martin

Status Post doctoral student

Institution of origin: University of Trento

Country: Italy

Dates: 19-25 September 2024

Context of the visit: collaboration with M. Ricchiuto on innovative multi-material models involveing dispersive regularizations. Laura del Rio Martin also delivered a seminar in the group Séminaire de Calcul Scientifique et Modélisation.

Mobility program/type of mobility: research stay and lecture.

Joel Perez Villarino

Status: Doctoral student

Institution of origin: University of Corogne

Country: Spain

Dates: 1st October 2024 -31 January 2025

Context of the visit: work with M. Ricchiuto on the investigation of multi-resolution and multigrid methods in the approximation of dispersive equations.

Mobility program/type of mobility: research stay.

Victor Gonzalez Tabernero

Status: Doctoral student

Institution of origin: University of Corogne

Country: Spain

Dates: 1st October 2024 -31 January 2025

Context of the visit: work with M. Ricchiuto on approximate fully well balanced methods based on local optimization and global fluxes.

Mobility program/type of mobility: research stay.

Michael Dumbser

Status Professor

Institution of origin: University of Trento

Country: Italy

Dates: 25 November - 1st December 2024

Context of the visit: collaboration with E. Gaburro and M. Ricchiuto on the construction of finite volume method using multidimensional point fluxes. A journal manuscript is in finalization for submission to the special issue of Comuters & Fluids dedicated to the HONOM2024 conference. Prof. Dumbser also contributed as reviwer to the HDR committe of M. Parisot.

Mobility program/type of mobility: research stay and HDR committee.

Hedrik Ranocha

Status Professor

Institution of origin: Johannes Gutenberg University Mainz

Country: Germany

Dates: 2 - 16 February 2024

Context of the visit: collaboration with M. Ricchiuto on the construction of energy conservative approximation of nonlienar dispersive equations. The work resulted in the submission of the paper [34] to Numerical Methods for PDEs. Prof. Ranocha also delivered a seminar in the group Séminaire de Calcul Scientifique et Modélisation.

Mobility program/type of mobility: research stay and lecture.

Davide Torlo

Status: Research scientist

Institution of origin: Sissa Trieste

Country: Italy

Dates: 24 - 28 June 2024

Context of the visit: Davide Torlo visited M. Ricchiuto to work on stracture preserving methods via Global Flux quadrature. They sumbitted a paper in Numerical Methods for PDEs [29], which is now accepted. Davide Torlo also gave a seminar in the group Séminaire de Calcul Scientifique et Modélisation.

Mobility program/type of mobility: research stay and lecture.

Eitan Tadmor

Status Professor

Institution of origin: University of Maryland

Country: Italy

Dates: 25 November - 1st December 2024

Context of the visit: visit to the applied mathematics department of Bordeaux, during which he delivered a lecture on Swarm-Based Gradient Descent Method for Non-Convex Optimization.

Mobility program/type of mobility: lecture.

Yongle Liu

Status post-doc

Institution of origin: University of Zurich

Country: Italy

Dates: 5 June - 15 June 2024

Context of the visit: Collaboration with M. Ricchiuto on well balanced discretization using a combination of Active and Global flux methods.

Mobility program/type of mobility: research stay.

9.2 European initiatives

9.2.1 Horizon Europe

SuPerMan

Participants: Elena Gaburro.

SuPerMan project on cordis.europa.eu

Title: Structure Preserving schemes for Conservation Laws on Space Time Manifolds

Duration: From April 19, 2024 to December 31, 2024

Inria contact: Elena Gaburro

Coordinator:

Summary: Solving hyperbolic conservation laws in computational astrophysics: Nonlinear systems of hyperbolic partial differential equations are characterised by invariants, whose preservation also on the discrete level plays a fundamental role in reducing the computational complexity of their numerical simulations. Furthermore, the conservation of mass and angular momentum, the conservation of stationary and moving equilibria, and the identification of asymptotic limits are challenging issues. These are especially relevant in astrophysical applications, such as turbulent flows around black holes, oscillations of neutron stars and generation and propagation of gravitational waves. Funded by the Marie Skłodowska-Curie Actions programme, the SuPerMan project will develop smart structure preserving methods independent of the coordinate system and with high order of accuracy, to effectively study the evolution of spacetime in general relativity.

ALcHyMiA

Participants: Elena Gaburro.

ALcHyMiA project on cordis.europa.eu

Title: Advanced Structure Preserving Lagrangian schemes for novel first order Hyperbolic Models: towards General Relativistic Astrophysics

Duration: From April 1, 2024 to March 31, 2029

Partners:

- UNIVERSITA DEGLI STUDI DI VERONA (UNIVR), Italy

Inria contact: Elena Gaburro

Coordinator: Elena Gaburro

Summary: ALcHyMiA will make substantial progress in applied mathematics, targeting long-time stable and self-consistent simulations in general relativity and high energy density problems, via the development of new and effective structure preserving numerical methods with provable mathematical properties. We will devise innovative schemes for hyperbolic partial differential equations (PDE) which at the discrete level exactly preserve all the invariants of the continuous problem, such as equilibria, involutions and asymptotic limits. Next to fluids and magnetohydrodynamics, key for benchmarks and valuable applications on Earth, we target a new class of first order hyperbolic systems that unifies fluid and solid mechanics and gravity theory. This allows to study gravitational waves, binary neutron stars and accretion disks around black holes that require the coupled evolution of matter and spacetime. Here, high resolution and minimal dissipation at shocks and moving interfaces are crucial and will be achieved by groundbreaking direct Arbitrary-Lagrangian-Eulerian (ALE) methods on moving Voronoi meshes with changing topology. These are necessary to maintain optimal grid quality even when following rotating compact objects, complex shear flows or metric torsion. They also ensure rotational invariance, entropy stability and Galilean invariance in the Newtonian limit. The breakthrough of our new Finite Volume and Discontinuous Galerkin ALE schemes lies in the geometrical understanding and high order PDE integration over 4D spacetime manifolds. The high-risk high-gain challenge is the design of smart DG schemes with virtual, bound-preserving, genuinely nonlinear data-dependent function spaces, taking advantage of the Voronoi properties. Finally, it is an explicit mission of ALcHyMiA to grow a solid scientific community, sharing know-how by tailored dissemination activities from top-level schools to carefully organized international events revolving around personalized interactions.

RESCUER

Participants: Maria Kazolea, Alessandro Del Piero.

RESCUER project on cordis.europa.eu

Title: Resilient Solutions for Coastal, Urban, Estuarine and Riverine Environments

Duration: From February 1, 2024 to January 31, 2028

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- COMUNE DI SENIGALLIA (COMUNE), Italy
- UNIVERSIDAD DE ZARAGOZA (UNIVERSIDAD DE ZARAGOZA), Spain
- STATENS VEGVESEN (STATENS VEGVESEN VEGDIREKTORATET), Norway
- Águas da Figueira, S.A. (Águas da Figueira, S.A.), Portugal
- UNIVERSITE DE PAU ET DES PAYS DE L'ADOUR, France
- Hydronia Europe SL (Hydronia Europe SL), Spain
- UNIVERSITA DEGLI STUDI ROMA TRE (UNIROMA3), Italy
- TRUSTEES OF COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK, United States
- UNIVERSIDADE DE COIMBRA (UNIVERSIDADE DE COIMBRA), Portugal
- COWI AS (KAMPSAX GEODAN GEOPLUS KAMPSAX DATA GEOPLAN GEOMASTERS GEODATAAGRINOVA INTERNATIONAL KAMPSAX INTERNATIONAL KAMPSAX TEKNIK), Denmark
- KARLSRUHER INSTITUT FUER TECHNOLOGIE (KIT), Germany
- UNIVERSITE DE BORDEAUX (UBx), France
- FUNDACION AZTI - AZTI FUNDAZIOA (AZTI), Spain
- UNIVERSITA POLITECNICA DELLE MARCHE (UNIVPM), Italy
- AALBORG UNIVERSITET (AAU), Denmark
- UNIVERSITETET I BERGEN (UiB), Norway
- SUEZ EAU FRANCE, France

Inria contact: Maria Kazolea

Coordinator: Prof. Henrik Kalisch

Summary: The Doctoral Network (DN) “RESCUER“ (Resilient Solutions for Coastal, Urban, Estuarine and Riverine Environments) will focus on the training of young researchers (Fellows) in the general area of coastal oceanography, hydraulic and coastal engineering, applied mathematics, and scientific computation. The network will leverage advances in the numerical treatment of hydrodynamic equations in the past decade to create multi-physics models able to address pressing needs in practical modeling of various phenomena in the coastal zone with the goal of improving overall safety of coastal areas.

Ensuring the safety of property and commercial developments onshore and offshore requires an integrated approach, including phase-resolving wave modeling, tracking and mitigation of morphological changes, potential flooding in urban areas and monitoring of water quality. While protective structures and emergency plans for catastrophic storm waves and storm surges are well established, the confluence of global warming and sea level rise with other known natural risk factors and increasing human activity create a new set of hazards and requires new thinking in coastal modeling and the planning of mitigation strategies.

To address the challenges outlined above, we will rely on numerical techniques which are in each case tested against existing models and validated with experiments and field measurements. In our work with consulting companies and government agencies, we have identified a trend towards coupled models instead of traditionally used stand-alone models and a need for operational capabilities. These needs will be answered using new multi-physics models, state-of-the-art numerical methods, image recognition algorithms and innovative programming techniques such as GPU programming. The synergistic interplay of physical modelling, numerical analysis and large-scale simulation with lab experiments and field work plays an essential role in this network. Our project goes beyond the state of the art by improving existing numerical models, employing GPU programming and super-resolution techniques and building a unified suite of solvers that will allow us to address the multi-physics problems in coastal, estuarine, riverine and urban areas.

9.2.2 H2020 projects

eFlows4HPC

Participants: Nicolas Barral, Shourab Bhat, Héloïse Beaugendre, Mario Ricchiuto.

eFlows4HPC project on cordis.europa.eu

Title: Enabling dynamic and Intelligent workflows in the future EuroHPCecosystem

Duration: From January 1, 2021 to February 29, 2024

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- DTOK LAB SRL, Italy
- FORSCHUNGSZENTRUM JULICH GMBH (FZJ), Germany
- SCUOLA INTERNAZIONALE SUPERIORE DI STUDI AVANZATI DI TRIESTE (SISSA), Italy
- INSTYTUT CHEMII BIOORGANICZNEJ POLSKIEJ AKADEMII NAUK, Poland
- ALFRED-WEGENER-INSTITUT HELMHOLTZ-ZENTRUM FUR POLAR- UND MEERESFORSCHUNG (AWI), Germany
- EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH (ETH Zürich), Switzerland
- INSTITUT POLYTECHNIQUE DE BORDEAUX (Bordeaux INP), France
- STIFTELSEN NORGES GEOTEKNISKE INSTITUTT (NGI), Norway
- BULL SAS (BULL), France

- CENTRE INTERNACIONAL DE METODES NUMERICS EN ENGINYERIA (CIMNE-CERCA), Spain
- UNIVERSIDAD DE MALAGA (UMA), Spain
- UNIVERSITAT POLITECNICA DE VALENCIA (UPV), Spain
- ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA, Italy
- FONDAZIONE CENTRO EURO-MEDITERRANEOSUI CAMBIAMENTI CLIMATICI (FONDAZIONE CMCC), Italy
- SIEMENS AKTIENGESELLSCHAFT, Germany
- BARCELONA SUPERCOMPUTING CENTER CENTRO NACIONAL DE SUPERCOMPUTACION (BSC CNS), Spain

Inria contact: Mario RICCHIUTO

Coordinator: Rosa Badia (BSC, Spain)

Summary: Today, developers lack tools that enable the development of complex workflows involving HPC simulation and modelling with data analytics (DA) and machine learning (ML). TheFlows4HPC aims to deliver a workflow software stack and an additional set of services to enable the integration of HPC simulation and modelling with big data analytics and machine learning in scientific and industrial applications. The software stack will allow to develop innovative adaptive workflows that efficiently use the computing resources and also considering innovative storage solutions.

To widen the access to HPC to newcomers, the project will provide HPC Workflows as a Service (HPCWaaS), an environment for sharing, reusing, deploying and executing existing workflows on HPC systems. The workflow technologies, associated machine learning and big data libraries used in the project leverages previous open source European initiatives. Specific optimization tasks for the use of accelerators (FPGAs, GPUs) and the EPI will be performed in the project use cases.

To demonstrate the workflow software stack, use cases from three thematic pillars have been selected. Pillar I focuses on the construction of DigitalTwins for the prototyping of complex manufactured objects integrating state-of-the-art adaptive solvers with machine learning and data-mining, contributing to the Industry 4.0 vision. Pillar II develops innovative adaptive workflows for climate and for the study of Tropical Cyclones (TC) in the context of the CMIP6 experiment, including in-situ analytics. Pillar III explores the modelling of natural catastrophes - in particular, earthquakes and their associated tsunamis- shortly after such an event is recorded. Leveraging two existing workflows, the Pillar will work of integrating them with the eFlows4HPC software stack and on producing policies for urgent access to supercomputers. The pillar results will be demonstrated in the target community CoEs to foster adoption and get feedback.

9.3 National initiatives

ANR GEOFUN

Participants: Manon Carreau, Martin Parisot.

Title: GEOphysical Flows with UNified models

Type: ANR

Duration: 48 months

Starting date : 1st Jan 2020

Coordinator: Martin Parizot

Abstract: The objective of the GeoFun project is to improve the modeling and simulation of geophysical flows involving at least two different processes. The main application we have in mind is water catchment areas, where a shallow free surface flow stands above a underground flow on porous medium. Our vision of water transport is often naive, because we first think of rivers, lakes, and flooding, but actually, 80% of water in continental areas is underground. Sometimes, the porous substrate is covered with an impermeable rock stratum, which confines the flow as in pipelines, except at certain points where springs and resurgences appear. Our long term goal is to propose a global and unified model of an aquifer. By global, we mean a complete description, including free surface flow (rivers), exchanges with the groundwater in unsaturated area, flows in caves, that might be congested or not, and might contain air pockets. By unified, we mean that we do not aim to decompose the domain and use different models for each part of the aquifer. On the contrary, we plan to propose and study models able to pick the relevant physic by themselves in a multi-physics context. The numerical approximation will be a main concern all along the way. The final contribution of the GeoFun project is the development of a scientific computing library, simulating complex flows in water catchment areas thanks to the numerical strategies analyzed in this project. Since unified models are design to be applied in the whole computational domain with no domain decomposition, the robustness of the numerical strategy at all regime are essential. Our unified numerical schemes will degenerate towards existing schemes in those regions, in order to guarantee a similar feasibility and robustness. Moreover, since the final goal is to test the library on realistic aquifers, the efficiency of the methods is of crucial importance.

ANR LAGOON

Participants: Maria Kazolea, Ralph Lteif, Martin Parisot, Vincent Pilorget, Mario Ricchiuto.

Title: Large scale global storm surge simulations

Type: ANR

Duration: 48 months

Starting date : 1st Oct 2021

Coordinator: Vincent Perrier (U.Pau et des Pays de l'Adour)

Abstract: The aim of the project is to develop an all-scale shallow water storm-surge model simulating different features of oceanic flows: from large scale linear waves in open ocean to small scale non-linear flows in coastal areas, and using high resolution by combining novel numerical approaches on unstructured grids and high performance computing.

PERPR IRIMA ROM

Participants: Nicolas Barral, Maria Kazolea, Mario Ricchiuto, Dean Yuan.

Title: Seismo-volcanic, tsunami and hydro-climatic risks in overseas France

Type: ANR

Duration: 48 months

Starting date : 1st Oct 2024

Inria Contact: Mario Ricchiuto

Coordinator: Anne Le Friant (IPGP)

Abstract: The PC Outermer project focuses on the intense and frequent telluric and hydro-meteorological hazards faced by overseas and intertropical populations, such as earthquakes, volcanic eruptions, tsunamis, gravity instabilities, flooding/submersions and coastal erosion in connection with cyclones and climate change. It is essential to take into account the geographical and societal particularities of overseas and intertropical areas (distance from the hexagone, insularity, lack of connection and size of territories, high proportion of the total population of the territory exposed to one or more hazards, diversity of cultural and historical practices, social and political tensions), which require a specific understanding of local capacities for risk prevention and management, as well as adaptation and resilience. Innovative management strategies therefore need to be developed and tested in terms of feasibility/acceptability/inclusivity, taking into account the political and social status of these territories. Knowledge of telluric and hydrometeorological hazards, and of the vulnerabilities of these territories, is essential because of the active observation conditions they offer, and above all in order to meet the challenges of risk and crisis management. However, all our scientific achievements show that there are still limits to our ability to detect changes in the phase of activity as early as possible, to the resilience of our networks, and to our capacity to develop integrated risk management models that can characterize the issues and assess their vulnerability to different hazards. The risks to which overseas populations are exposed need to be reconsidered in order to accurately qualify and model cascading phenomena and forcing processes, and the superposition of hazards and vulnerabilities on the same territories, in order to reduce the consequences of major disasters and help develop relevant risk and resilience policies.

This project aims to: 1/ identify new observables for the study of natural hazards and their anthropogenic impact on large spatio-temporal scales, 2/ develop holistic and integrated models of complex processes, taking into account the uncertainties associated with climate change projections and the integration of coupled predictive models, 3/ to develop integrated risk management strategies adapted to overseas and intertropical areas, and capable of dealing with the consequences of extreme and cascading events that induce multiple risks (eruptions, instabilities, tsunamis, floods). Inria is participating in WP2 which is devoded in on estimating the damage and socio-economic impact of tsunami hazards, applying our methodologies to Mayotte in the Indian Ocean.

Inria Action Exploratoire: AM^{2}OR

Participants: Nicolas Barral.

Title: AM^{2}OR: Adaptive meshes for Model Order Reduction

Type: Inria Action Exploratoire

Duration: 48 months

Starting date : 1st October 2022

Coordinator: Nicolas Barral

Partner: Tommaso Taddei (Inria MEMPHIS)

Abstract: Mesh adaptation and Model Order Reduction both aim at reducing significantly the computational cost of numerical simulations by taking advantage of the solution's features. Reduced Order Modelling is a method that builds lighter surrogate models of a system's response over a range of parameters, which is particularly useful in the solution of design and optimization inverse problems. Reduced-order models rely on a high-fidelity (e.g., finite element) approximation that should be sufficiently accurate over the whole range of parameters considered: in presence of structures such as shocks and boundary layers, standard mesh refinement techniques would lead to high-fidelity models of intractable size. In this project, we propose a novel adaptive procedure to simultaneously construct a high-fidelity mesh (and associated discretisation) and a reduced-order model for a range of parameters, with particular emphasis on inverse problems in computational fluid dynamics.

9.4 Regional initiatives

RNA PSGAR CORALI

Participants: Maria Kazolea, Martin Parisot, Mario Ricchiuto.

Title: COnnaissances inteRdisciplinaires pour meilleure Adaptation face aux risques LIttoraux

Duration: 48 months

Starting Date: December 2024

Inria Contact: Mario Ricchiuto

Coordinator: Prof. Aldo Sottolichio

Abstract: The aim of PSGAR CORALI is to provide the multidisciplinary scientific knowledge needed to better forecast coastal changes and developments, and to better anticipate societal adaptations to the natural risks of erosion and submersion at the land-sea interface. The research proposed will be fundamental and international in scope, with direct application to regional sites in New Aquitaine. To achieve this, the PSGAR will implement a series of research and expert assessments (observation, modeling, analysis and decision support) to accelerate the transition towards a society capable of adapting to and becoming more resilient and sustainable in the face of current and future changes in open and semi-enclosed coastlines. To meet this challenge, heightened by climate change, interdisciplinary research will be encouraged and stimulated. This holistic, integrative approach to knowledge brings together the geosciences, environmental sciences, human and social sciences, and engineering. These disciplines, although involved in these issues, still too often work without direct interaction with society. The PSGAR proposes to integrate them more fully and to encourage the co-construction and transfer of knowledge to public and private coastal stakeholders. The PSGAR CORALI is built around a consortium federating the major universities of New Aquitaine and leading research organizations in the field of natural and environmental risks, already grouped around the regional research network (R3) RIVAGES, dedicated to the specific theme of coastal risks.

IMPT 2023

Participants: Nicolas Barral, Fabien Salmon.

Title: Parallel mesh adaptation for sea ice dynamic

Duration: 24 months

Starting Date: 1st September 2023

Coordinator: Nicolas Barral

Abstract: In this project we work with the sea ice model neXtSIM, developed at Nansen Environmental and Remote Sensing Center (Bergen, Norway) and Institute of Environmental Geosciences (Grenoble, France). This new model aims at modelling complex sea ice dynamics accross scales, in order to be used for both local short-term predictions and global climate prediction simulations. The specificity of neXtSIM is the use of a purely Lagrangian advection formalism on fully unstructured meshes, coupled with a novel rheological framework, that has given promising results. Such a Lagrangian approach results in strongly deformed meshes over time, in particular in the vicinity of cracks in the ice resulting from the mechanical forces coming from winds and currents, and where large drift of the ice can occur. A remeshing step is thus necessary to locally replace stretched or invalid mesh elements and restore the quality of the mesh. However, unlike the rest of the code that was parallelised recently for distributed memory architectures using MPI, the remeshing stage remains sequential, thus strongly impacting the performance of the code. Besides, the current remeshing does not yet take advantage of modern anisotropic mesh adaptation techniques that aim at optimising the size and orientation of the mesh elements to minimise a certain numerical error estimate and makes it possible to reduce the computationnal cost while increasing the accuracy. The goal of the collaboration is to leverage these methods to accelerate simulations, and thus be able to perform ensembles of large-scale high-resolution (kilometric) simulations of the sea ice, and to study ice trajectories from a statistical perspective.

IMPT 2024

Participants: Martin Parisot, Tony Bonnet.

Title:

Duration: 36 months

Starting Date: 1st octobre 2024

Coordinator: Martin Parisot

Abstract: This project is a collaboration with Mathieu Coquerelle, from I2M, to supervised the PdH of Tony Bonnet. The objective of this project is to propose a numerical tools for the analysis of the exchange between surface water and ground water. A 3D modeling is considerate based on the VANS (Volume Averaged Navier–Stokes) model. The scientific lock lies on the boundary condition that depends on the the direction of the flows (from surface to ground or the opposite), making simulations usually not robust. In a second time, we propose to analyse the evolution of the physical parameters of the ground media (porosity and permeability), recovering experimental data and ensuring the conservation of mass and energy.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

General chair, scientific chair

The team organized the HONOM 2024 (High-Order NOnlinear numerical Methods for evolutionary PDEs: theory and applications) conference, that held on 8-13 of September 2024 in KAM Conference Center Chania, Crete Island, Greece. Conference Chairs were E. Gaburro and M. Kazolea (co-chair).

10.1.2 Journal

Member of the editorial boards

- Elena Gaburro: Associate editor of Applied Mathematics and Computations, Elsevier journal;
- Maria Kazolea: Guest editor of Computers and Fluids (Elsevier) for the Special Issue HONOM 2024;
- Martin Parisot: managing editor of J.Comput.Math. (Smai);

- Mario Ricchiuto is member of the editorial board of J.Comput.Physics (Elsevier), Computers and Fluids (Elsevier), Numerical Methods for Partial Differential Equations (Whiley), Water Waves (Springer). He is guest editor for the special issue of Communications on Applied Mathematics and Computation in Honor of Prof. R. Abrall (CAMC Volume 6, issue 3, 2024, see editorial [7]).

Reviewer - reviewing activities

- Maria Kazolea served as a reviewer in: J.Comput.Physics (Elsevier), Computers and Fluids (Elsevier), Journal of Fluid mechanics (Cambridge University Press), Ocean engineering (Elsevier), Computer Physics Communications (Elsevier), EGU Open access peer-reviewed journals
- Martin Parisot served as a reviewer for the Isaac Newton Institute, Journal of Computational Physics (Elsevier) (twice), Journal of Scientific Computing (Springer), ESAIM-M2AN (EDP sciences), Mathematical Modelling of Natural Phenomena (EDP sciences).
- Nicolas Barral was a referee for Journal of Computational Physics and International Journal of Computational Fluid Dynamics.

10.1.3 Invited talks

- M. Ricchiuto has delilvered invited talks to the following events
  - Oberwolfach workshop “Hyperbolic Balance Laws: interplay between scales and randomness”, 21 February-01 March 2024, Oberwolfach (Germany);
  - Gold shark-FV - Sharing high order reserach know-how on Finite-Volume, May 26-31 2024, Minho (Portugal);
  - 2024 International Conference on Water Waves and Bores, Sptember 13-18, Ningbo University (China);
- M. Parisot has delilvered invited talks to the following events
  - Bourgeons ANR, January 2024, Paris;
  - Canum, June 2024, Ile de Ré;
  - Journées de Modélisation des Surfaces Continentales: JMSC24, Strasbourg.

10.1.4 Leadership within the scientific community

Member of scientific committees

- Mario Ricchiuto is member of the scientific committee of the ICCFD series (last edition in Kobe Japan in 2024), and of the “Réseau Thématique 2166 du CNRS Mathématiques: Terre et Énergies”.

10.1.5 Research administration

M. Ricchiuto has been deputy head of science of the Inria center at University of Bordeaux until Arpil 2024.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Licence: Nicolas Barral, Calcul Scientifique en Fortran 90, 22h, L3, ENSEIRB-MATMÉCA, France
- Licence : Nicolas Barral, TP Fortran 90, 44h, L3, ENSEIRB-MATMÉCA, France
- Licence : Nicolas Barral, TP C++, 48h, M1, ENSEIRB-MATMÉCA, France
- Master : Nicolas Barral, Calcul Haute Performance (OpenMP-MPI), 45h, M1, ENSEIRB-MATMÉCA et Université de Bordeaux, France

- Master : Nicolas Barral, Meshing for computational science, 24h, M2, ENSEIRB-MATMÉCA et Université de Bordeaux, France
- Master : Nicolas Barral : projet professionnel et suivi de stages, 14 h, ENSEIRB-MATMÉCA, France
- Master : Nicolas Barral : responsable des stages 2A, 20 h, ENSEIRB-MATMÉCA, France
- Héloïse Beaugendre has been the Director of Research, Innovation, and Transfer at ENSEIRB-MATMECA since September 2024. 96 h.
- Licence: Héloïse Beaugendre, Encadrement de projets sur la modélisation du biomimétisme ou le chaos, 20h, L3, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Calcul Haute Performance (OpenMP-MPI), 45h, M1, ENSEIRB-MATMÉCA et Université de Bordeaux, France
- Master : Héloïse Beaugendre, Responsable de filière de 3ème année, 20h, M2, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Calcul parallèle (MPI), 39h, M2, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Encadrement de projets de la filière Calcul Haute Performance, 10h, M2, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Modélisation des écoulements turbulents, 36h, M2, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Encadrement de projets sur la quantification d'incertitudes et la sensibilté au maillage, 20h, M1, ENSEIRB-MATMÉCA, France
- Master : Héloïse Beaugendre, Projet fin d'études, 4h, M2, ENSEIRB-MATMÉCA, France
- License: Martin Parisot, TP Fortran, 21h, M1, ENSEIRB-MATMÉCA, France
- Master : Martin Parisot, GeoPhysics course, 26h cours magistrale, M2, ENSEIRB-MATMÉCA, France
- Master and PhD: Elena Gaburro, Advanced Numerical Methods for the solution of Hyperbolic Equations, 12h (University of Verona, Italy)

10.2.2 Supervision

- PhD (defended in June 2024): J. Galaz Mora, Coupling of free surface coastal models, started in February 2021, co-supervised by M. Kazolea and A. Rousseau.
- PhD (up to April 2024): M. Carreau, Modeling, analysis and scientific computing for the simulation of geophysical flows with unified models, started in November 2020, co-supervised by M. Parisot and R. Masson.
- PhD (defended in December 2024): M. Romanelli, Deep Wall Models for Aerodynamic Simulations, started in october 2021, co-supervised by H. Beaugendre and M. Bergmann (MEMPHIS).
- PhD (defended in October 2024): B. Jouy, Simulation of Favre waves in channels with variable section, started in November 2021, co-supervised by M. Ricchiuto and D. Violeau (EDF).
- PhD in progress: V. Pilorget, High order DG modelling of global storm surges for very long term inundation simulations, started in January 2022, co-supervised by A.-G. Filippini (BRGM) and M. Ricchiuto.
- PhD in progress: A. Cas, Development of models and numerical methods for the degradation of a pyrolysable material , started in October 2023, co-supervised by C. Baranger and S. Peluchon (CEA) and H. Beaugendre.

- PhD in progress: F. Forte Tenreiro,On the design of an improved Boussinesq model for real applications: equilibrium between accuracy and performance, started in April 2024, co-supervised by A.-G. Filippini (BRGM) and M. Kazolea.
- PhD in progress: A. Del Piero, Advanced Discontinuous Galerkin Framework for Urban Flood Simulation: Sub-Cell Modeling and Integration with Real-World Dynamics, started in October 2024, co-supervised by A.-G. Filippini (BRGM) and M. Kazolea.
- PhD in progress: I. Tifouti, Mesh adaptation with model order reduction, started in October 2022, co-supervised by N. Barral and T. Taddei (Inria MEMPHIS).
- PhD in progress: T. Bonnet, started in October 2024, co-supervised by Martin Parisot and Mathieu Coquerelle (I2M).
- PhD in progress: S. Erdocio, started in November 2024, co-supervised by Martin Parisot and Benoit Chauveau (IFPEN).
- PhD in progress: C. Chabaud, Curvilinear Mesh Adaptation for Aircraft Design, co-supervised by N. Barral, M. Ricchiuto, and R. Laraufie (Airbus).
- PhD in progress: M. Janin, Numerical modelling of tsunami propagation with short crested waves, started in November 2024, co-supervised by P. Heinrich (CEA) and M. Ricchiuto.

10.2.3 Juries

- Heloise Beaugendre's participation in the selection committee for the MCF position in Rennes.
- Heloise Beaugendre's participation in the selection committee for the PR position in Poitiers.
- H. Beaugendre, On October 1, 2024, participation in Claire Roche's thesis defense. Thesis examiner. CEA Paris Saclay.
- H. Beaugendre, On November 29, participation in Benoit Cossart's thesis defense. Bordeaux University.
- H. Beaugendre, On December 10, participation in Alexis Dorange's thesis defense. ONERA Châtillon.
- H. Beaugendre, On December 12, participation in Michele Romanelli's thesis defense. PhD Supervisor. Bordeaux University.
- H. Beaugendre, On December 13, participation in Lucas Ménez's thesis defense. Thesis examiner. Poitiers ENSMA.
- H. Beaugendre, On December 17, participation in Ludovic Taguema's thesis defense. Thesis examiner. ONERA Toulouse.
- H. Beaugendre, On December 19, participation in Thomas Vigier's thesis defense. Bordeaux University.
- M. Ricchiuto has been member of the following juries:
  - PhD defense of C. Brutto, University of Trento, on June 18th, 2024. As thesis reviewer;
  - PhD defense of M. Nunez, Universitat Politècnica de Catalunya, on July 4th, 2024. As thesis reviewer;
  - PhD defense of M. Salihoglu, Sorbonne Université, on November 20th 2024. As thesis reviewer.

10.3 Popularization

10.3.1 Participation in Live events

On June 24th 2024, in the framework of the cycle ‘Unithé ou Café” of the Inria center at Unviersity of Bordeaux, M. Ricchiuto has delivered a presentation on the “Continuum : modélisation, simulation, calcul”.

On October 7, 2024, H. Beaugendre participated in the Forum Emploi Math event at La Villette, Paris. She led and moderated the roundtable discussion on Mathematics and Space.

On September 9-14, 2024, M. Kazolea participated in the HONOM2024 conference, where she presented the European Project Rescuer as part of the project’s communication and dissemination package [37].

11 Scientific production

11.1 Major publications

[1] S. Bhat, N. Barral and M. Ricchiuto. ‘Error-based efficient parameter space partitioning for mesh adaptation and local reduced order models’. In: *Computer Methods in Applied Mechanics and Engineering* 435 (Feb. 2025), p. 117649. DOI: 10.1016/j.cma.2024.117649. URL: https://inria.hal.science/hal-04851883.

[2] Y. Mantri, P. Öffner and M. Ricchiuto. ‘Fully well-balanced entropy controlled discontinuous Galerkin spectral element method for shallow water flows: global flux quadrature and cell entropy correction’. In: *Journal of Computational Physics* 498 (Feb. 2024), p. 112673. DOI: 10.1016/j.jcp.2023.112673. URL: https://inria.hal.science/hal-04334768.

[3] M. Parisot. ‘Thick interfaces coupling technique for weakly dispersive models of waves’. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.4 (27th Aug. 2024), pp. 1497–1522. DOI: 10.1051/m2an/2024048. URL: https://hal.science/hal-04452924.

11.2 Publications of the year

International journals

[4] N. Barral, T. Taddei and I. Tifouti. ‘Registration-based model reduction of parameterized PDEs with spatio-parameter adaptivity’. In: *Journal of Computational Physics* 499 (Feb. 2024), p. 112727. DOI: 10.1016/j.jcp.2023.112727. URL: https://inria.hal.science/hal-04371531 (cit. on p. 21).

[5] H. Beaugendre, A. Chan, V. Delmas, R. Loubère, P.-H. Maire, F. Morency and T. Vigier. ‘Multidimensional aware subfaced-based Finite Volume scheme for the Eulerian droplet system of equation’. In: *Computers and Fluids* 279 (July 2024), p. 106326. DOI: 10.1016/j.compfluid.2024.106326. URL: https://hal.science/hal-04671864 (cit. on p. 19).

[6] S. Bhat, N. Barral and M. Ricchiuto. ‘Error-based efficient parameter space partitioning for mesh adaptation and local reduced order models’. In: *Computer Methods in Applied Mechanics and Engineering* 435 (Feb. 2025), p. 117649. DOI: 10.1016/j.cma.2024.117649. URL: https://inria.hal.science/hal-04851883 (cit. on p. 21).

[7] W. Boscheri, F. Chinesta, R. Loubère, S. Mishra, G. Puppo, M. Ricchiuto and C.-W. Shu. ‘Preface in Honour of Prof. Rémi Abgrall on the Occasion of His 61th Birthday’. In: *Communications on Applied Mathematics and Computation* 6.3 (2nd July 2024), pp. 1519–1520. DOI: 10.1007/s42967-024-00434-6. URL: https://hal.science/hal-04671861 (cit. on p. 35).

[8] M. Ciallella, S. Clain, E. Gaburro and M. Ricchiuto. 'Very high order treatment of embedded curved boundaries in compressible flows: ADER discontinuous Galerkin with a space-time Reconstruction for Off-site data'. In: *Computers & Mathematics with Applications* 175 (12th Dec. 2024), pp. 1–18. DOI: 10.1016/j.camwa.2024.08.028. URL: https://inria.hal.science/hal-04706736 (cit. on p. 21).

[9] B. Constant, S. Péron, H. Beaugendre and C. Benoit. 'An improved immersed boundary method for turbulent flow simulations on Cartesian grids: extension of a global geometric approach for thin boundary layers and strong flow incidence'. In: *Journal of Computational Physics* 519 (2024), p. 113441. DOI: 10.1016/j.jcp.2024.113441. URL: https://hal.science/hal-04731107 (cit. on p. 20).

[10] M. Dumbser, O. Zanotti, E. Gaburro and I. Peshkov. 'A well-balanced discontinuous Galerkin method for the first–order Z4 formulation of the Einstein–Euler system'. In: *Journal of Computational Physics* 504 (May 2024), p. 112875. DOI: 10.1016/j.jcp.2024.112875. URL: https://hal.science/hal-04883714 (cit. on p. 16).

[11] A. G. Filippini, L. Arpaia, V. Perrier, R. Pedreros, P. Bonneton, D. Lannes, F. Marche, S. de Brye, S. Delmas, S. Lecacheux, F. Boulahya and M. Ricchiuto. 'An operational discontinuous Galerkin shallow water model for coastal flood assessment'. In: *Ocean Modelling* 192 (Dec. 2024), p. 102447. DOI: 10.1016/j.ocemod.2024.102447. URL: https://brgm.hal.science/hal-04761792 (cit. on p. 17).

[12] E. Gaburro, W. Boscheri, S. Chiocchetti and M. Ricchiuto. 'Discontinuous Galerkin schemes for hyperbolic systems in non-conservative variables: quasi-conservative formulation with subcell finite volume corrections'. In: *Computer Methods in Applied Mechanics and Engineering* 431 (21st June 2024), p. 117311. DOI: 10.1016/j.cma.2024.117311. URL: https://inria.hal.science/hal-04706734 (cit. on p. 16).

[13] B. Jouy, D. Violeau, M. Ricchiuto and M. H. Le. 'One dimensional modelling of Favre waves in channels'. In: *Applied Mathematical Modelling* 133 (Sept. 2024), pp. 170–194. DOI: 10.1016/j.apm.2024.05.020. URL: https://inria.hal.science/hal-04706732 (cit. on p. 18).

[14] Y. Mantri, P. Öffner and M. Ricchiuto. 'Fully well-balanced entropy controlled discontinuous Galerkin spectral element method for shallow water flows: global flux quadrature and cell entropy correction'. In: *Journal of Computational Physics* 498 (Feb. 2024), p. 112673. DOI: 10.1016/j.jcp.2023.112673. URL: https://inria.hal.science/hal-04334768 (cit. on pp. 14, 15).

[15] L. Micalizzi, M. Ricchiuto and R. Abgrall. 'Novel well-balanced continuous interior penalty stabilizations'. In: *Journal of Scientific Computing* 100.1 (27th Feb. 2024), p. 14. DOI: 10.1007/s10915-024-02563-9. URL: https://inria.hal.science/hal-04706726 (cit. on p. 15).

[16] M. Parisot. 'Thick interfaces coupling technique for weakly dispersive models of waves'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.4 (27th Aug. 2024), pp. 1497–1522. DOI: 10.1051/m2an/2024048. URL: https://hal.science/hal-04452924 (cit. on p. 18).

[17] J. Visbech, A. Engsig-Karup and M. Ricchiuto. 'A spectral element solution of the Poisson equation with shifted boundary polynomial corrections: influence of the surrogate to true boundary mapping and an asymptotically preserving Robin formulation'. In: *Journal of Scientific Computing* 102.1 (2025), p. 11. DOI: 10.1007/s10915-024-02713-z. URL: https://inria.hal.science/hal-04829220 (cit. on p. 20).

Invited conferences

[18] M. Kazolea, C. Parés-Madronal and M. Ricchiuto. 'Discrete fully well balanced WENO finite difference schemes via a global-flux quadrature method'. In: 9th European Congress on Computational Methods in Applied Sciences and Engineering. Lisbon, Portugal, 3rd June 2024. DOI: 10.1016/j.jcp.2023.112673. URL: https://inria.hal.science/hal-04883587 (cit. on p. 15).

International peer-reviewed conferences

[19] H. Beaugendre, A. Benoit, F. Morency and M. Parisot. 'A Multi-layered Integral Approach to the de-icing process'. In: *Volume Advances in Numerical Methods for Solution Of PDEs, 2024DOI: 10.23967/eccomas.2024.031*. 9th European Congress on Computational Methods in Applied Sciences and Engineering. Vol. Advances in Numerical Methods for Solution Of PDEs, 2024. Lisbon, Portugal, 23rd Oct. 2024. URL: https://inria.hal.science/hal-04868484 (cit. on p. 19).

[20] B. Constant, H. Beaugendre, S. Péron and C. Benoit. 'Amélioration des méthodes de frontières immergées pour la simulation d'écoulements turbulents sur grilles cartésiennes'. In: CANUM 2024 - 46ème Congrès National d'Analyse Numérique. Le-Bois-Plage-en-Ré, France, 27th May 2024. URL: https://inria.hal.science/hal-04868304.

[21] J. Galaz, M. Kazolea and A. Rousseau. 'Coupling Dispersive Shallow Water Models by Deriving Asymptotic Interface Operators'. In: *Domain Decomposition Methods in Science and Engineering XXVII*. 27th International Conference on Domain Decomposition Methods in Science and Engineering - DD27. Vol. 149. Lecture Notes in Computational Science and Engineering. Prague, Czech Republic: Springer Nature Switzerland, 23rd Jan. 2024, pp. 181–188. DOI: 10.1007/978-3-031-50769-4_21. URL: https://inria.hal.science/hal-03851031 (cit. on p. 17).

[22] J. Visbech, A. P. Engsig-Karup, H. B. Bingham, M. Amini-Afshar and M. Ricchiuto. 'A high-order shifted boundary method for water waves and floating bodies'. In: IWWWFB 2024 - 39th International Workshop on Water Waves and Floating Bodies. St Andrews, Scotland, United Kingdom, 14th Apr. 2024. URL: https://inria.hal.science/hal-04706771 (cit. on p. 20).

Conferences without proceedings

[23] M. G. Carlino and E. Gaburro. 'Second Order Finite Volume Scheme for Shallow Water Equations on Manifolds'. In: ICNAAM 2022 - 20th International Conference of Numerical Analysis and Applied Mathematics. Vol. 3094. 1. Heraklion (CR), Greece: AIP Conference Proceedings, 7th June 2024. DOI: 10.1063/5.0210596. URL: https://hal.science/hal-03865596 (cit. on p. 16).

[24] M. Kazolea, R. Lteif and M. Parisot. 'High order ImEx method for the shallow water model'. In: HONOM 2024 - High-Order NOnlinear numerical Methods for evolutionary PDEs: theory and applications. Chania Crete, Greece, 8th Sept. 2024. URL: https://inria.hal.science/hal-04884370 (cit. on p. 17).

Edition (books, proceedings, special issue of a journal)

[25] *Serre and Boussinesq Models for Favre Waves in Trapezoidal Cross-Sectional Channels*. Advances in Hydroinformatics—SimHydro 2023 Volume 2. Springer Water. Springer Nature Singapore, 2024, pp. 473–483. DOI: 10.1007/978-981-97-4076-5_32. URL: https://inria.hal.science/hal-04706779 (cit. on p. 18).

Doctoral dissertations and habilitation theses

[26] J. Galaz. 'Coupling methods of phase-resolving coastal wave models'. Université de montpellier, 26th June 2024. URL: https://inria.hal.science/tel-04689721 (cit. on p. 17).

[27] M. Kazolea. 'Advanced Numerical Methods for Nonlinear Water Wave dynamics and Breaking in Boussinesq-type models'. Université de Bordeaux, 3rd Oct. 2024. URL: https://hal.science/tel-04724479 (cit. on p. 10).

[28] M. Parisot. 'Some modeling and computational aspects of water waves action'. Université de Bordeaux, 29th Nov. 2024. URL: https://hal.science/tel-04814817 (cit. on p. 10).

Reports & preprints

[29] W. Barsukow, M. Ricchiuto and D. Torlo. *Structure preserving nodal continuous Finite Elements via Global Flux quadrature*. 15th July 2024. URL: https://hal.science/hal-04779510 (cit. on pp. 15, 26).

[30] S. Gavrilyuk and M. Ricchiuto. *A geometrical Green-Naghdi type system for dispersive-like waves in prismatic channels.* 17th Dec. 2024. URL: https://inria.hal.science/hal-04889204 (cit. on p. 18).

[31] M. Kazolea, C. Parés-Madronal and M. Ricchiuto. *APPROXIMATE WELL-BALANCED WENO FINITE DIFFERENCE SCHEMES USING A GLOBAL-FLUX QUADRATURE METHOD WITH MULTI-STEP ODE INTEGRATOR WEIGHTS.* 10th Jan. 2025. URL: https://inria.hal.science/hal-04890566 (cit. on p. 15).

[32] R. Lteif, M. Kazolea and M. Parisot. *An efficient second order ImEx scheme for the shallow water model in low Froude regime.* 12th Dec. 2024. URL: https://hal.science/hal-04834508 (cit. on p. 17).

[33] M. Parisot. *Derivation of weakly hydrodynamic models in the Dupuit-Forchheimer regime.* 31st Mar. 2024. URL: https://hal.science/hal-04532765 (cit. on p. 22).

[34] H. Ranocha and M. Ricchiuto. *Structure-preserving approximations of the Serre-Green-Naghdi equations in standard and hyperbolic form.* 19th Aug. 2024. URL: https://inria.hal.science/hal-04888829 (cit. on pp. 16, 18, 26).

[35] F. Salmon. *Unifying all physics with a single postulate.* 14th July 2024. URL: https://hal.science/hal-04543109.

Other scientific publications

[36] J. Galaz, M. Kazolea and A. Rousseau. 'The linear hybrid Boussinesq-SaintVenant model is well-posed and produces O(h^2/L^2) reflections: Couplin phase-resolving coastal wave models'. In: PhD day 2024. Montpellier, France, 19th Mar. 2024. URL: https://inria.hal.science/hal-04612106 (cit. on p. 17).

[37] M. Kazolea. 'Resilient Solutions for Coastal, Urban, Estuarine and Riverine Environments'. In: HONOM 2024 - High-Order NOnlinear numerical Methods for evolutionary PDEs: theory and applications. Chania, Greece, 8th Sept. 2024. URL: https://hal.science/hal-04724516 (cit. on p. 38).

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11.3 Cited publications

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