RESEARCH CENTRE

Inria Centre at Université Côte d'Azur

IN PARTNERSHIP WITH:

CNRS

2024

ACTIVITY REPORT

Project-Team

CALISTO

Stochastic Approaches for Complex Flows and Environment

IN COLLABORATION WITH: Centre de Mise en Forme des Matériaux (CEMEF)

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Stochastic approaches

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Creation of the Project-Team: 2020 November 01

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1 Team members, visitors, external collaborators

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2 Overall objectives

Particles transported by turbulent flows can interact with each other, form aggregates which can fragment later on, and deposit on filters or solid walls. In turn, this deposition phenomenon includes many aspects, from the formation of monolayer deposits to heavy fouling that can clog flow passage sections. Such potential complexity is at play in numerous industrial processes involving circulating fluids that contain inclusions (bubbles, droplets, debris, micro-swimmers or other kinds of materials). Active particles, seen as artificial micro-swimmers can be used as vehicles for the transport of therapeutics or as tools for limited invasive surgery. Driving such micro-swimmers requires monitoring the evolution of their characteristics, and their effects on the fluid with a high level of accuracy. On the other hand, sustainable power systems require to integrate climate and meteorological variability into operational processes, as well as into medium/long term planning processes. Moreover, turbulence amplifies the variability of wind/water flows and makes it even more complex to simulate the flow around wind/hydro farms.

These challenges represent critical technological locks. To address them, industrial design increasingly relies on macroscopic numerical models, broadly known as "Computational Fluid Dynamics" (CFD). However, such large-scale approaches are only well deployed on crude particle descriptions (monodisperse sizes, spherical shapes, rigid bodies), with oversimplified small-scale physics. They often rely on statistical closures for single-time, single-particle probability distributions. Yet, these mean-field simplifications do not accurately reproduce complex features of the involved physics, which require more advanced approaches to reproduce higher-order correlations.

Through a unique synergy between team members originating from various disciplines, CALISTO aims at developing/extending state-of-the-art models to these complex situations and thus improve their applicability, fidelity, and performance. Our ambition is to meet the following goals:

- produce original answers (methodological and numerical) for challenging environmental simulation models, with applications to renewable energy, filtration/deposition technology in industry (cooling of thermal or nuclear power plants), climate and meteorological prediction, and dispersion of materials or active agents (such as biological organisms, micro-robots);
- design new mathematical tools to analyze the fundamental physics of turbulence;
- develop numerical methods to analyze, control and optimize the displacement of micro-swimmers in fluids of various natures, ranging from water to non-Newtonian mucus;
- develop stochastic modeling approaches and approximation methods, in the rich context of particle-particle and fluid-particle interactions in complex flows;
- contribute to the field of numerical probability, with new simulation methods for complex stochastic differential equations (SDEs) arising from multi-scale Lagrangian modeling for the dynamics of material/fluid particle dynamics with interactions.

3 Research program

CALISTO is structuring its research according to five interacting axes.

AXIS A Complex flows: from fundamental science to applied models.

AXIS B Particles and flows near boundaries: specific Lagrangian approaches for large-scale simulations.

AXIS C Active agents in a fluid flow.

AXIS D Mathematical and numerical analysis of stochastic systems.

AXIS E Variability and uncertainty in flows and environment.

3.1 AXIS A- Complex flows: from fundamental science to applied models

This research axis focuses on complex particles transported by turbulent flows. In practical applications suspended particles often have inertia (such as droplets in clouds or dust in gaseous circumstellar disks), might be non-spherical (like cellulose fibers in paper industry or soot and sand aerosols) and even deformable in some cases (as organic matter in rivers or phytoplankton in the oceans). This brings out a number of questions about the small-scale physical phenomena at play in the turbulent dynamics of such particles, such as their local concentration fluctuations, their relative motion, the effect of spatial and temporal correlations, their aggregation and fragmentation, and how they affect large-scale evolutions (such as mean densities, average rotation, size distributions).

Despite strong interlinks, microscopic phenomena and macroscopic models are most of the time addressed separately in current studies of complex particles in turbulence. From a microscopic viewpoint, fine-scale investigations can rely on particle-resolved direct numerical simulations (PR-DNS) [44], allowing one to track detailed particle-flow couplings (such as fluid-structure interactions). Yet, such approaches quickly become very expensive and point-particle approximations (PP-DNS) are much better adapted to study many-particle systems and particles smaller than the Kolmogorov dissipative scale. From a macroscopic viewpoint, models rely on reduced descriptions of the turbulent flow and particle dynamics. They are implemented either in Euler-Euler frameworks (like two-fluid models [24]) or in hybrid Euler-Lagrange approaches.

The project-team CALISTO has a unique positioning since it combines the expertise of its members across various levels of description (including PP-DNS and hybrid Euler-Lagrange methods) and cross-disciplinary points of view (physicists, mathematicians and engineers). This synergy gives the means to tackle both aspects at once and validate models.

This research axis is currently investigating the following distinct topics

- Models for polydisperse, complex-shaped, deformable particles;
- Particle interactions and size evolution;
- Transfers between the dispersed phase and its environment.

3.2 AXIS B- Particles and flows near boundaries: specific Lagrangian approaches for large scale simulations

This research direction aims to develop Lagrangian macroscopic models for the simulation of turbulent flows in single-phase and particle-laden conditions.

In many practical applications, suspended particles are indeed moving close to surfaces (like sand / dust / pollen in the atmospheric boundary layer) or even on surfaces (like sediments and gravels in rivers). It is therefore both a great need and a challenge to take into account both the flow and the particles dynamics near boundaries.

The additional difficulties that arise are two-fold: first, the highly anisotropic flow near boundaries induces a much more rich and complex dynamics of particles; second, the physico-chemical interactions between particles and surfaces result in intricate phenomena like resuspension (where particles get detached from the surface and re-entrained by the flow).

As for AXIS A, such phenomena are usually addressed either with a microscopic or a macroscopic viewpoint. This axis further draws from the unique cross-disciplinary skills of each member to tackle this highly multidisciplinary issue (comprising small-scale dynamics, turbulence, chemical engineering and statistical modeling). An additional objective is to come up with a new stochastic Lagrange-Lagrange approach for large-scale simulations, where both the fluid and the particles are described in a coherent and consistent way (by tracking the motion of individual elements thanks to stochastic equations for their dynamics).

This research axis is currently investigating the following distinct topics.

3.2.1 Stand-alone Lagrangian simulations in atmospheric boundary layer (ABL)

The turbulent nature of the atmospheric boundary layer (ABL) contributes to the uncertainty of the wind energy estimation. This has to be taken into account in the modeling approach when assessing the wind power production. The purpose of the Stochastic Downscaling Model (SDM) is to compute the wind at a refined scale in the ABL, from a coarse wind computation obtained with a mesoscale meteorological solver. The main features of SDM reside in the choice of a fully Lagrangian viewpoint for the turbulent flow modeling. This is allowed by stochastic Lagrangian modeling approaches that adopt the viewpoint of a fluid-particle dynamics in a flow. Such particle methods have more flexible numerical convergence constraints, allowing a freer choice of time step size relative to the grid in space, in contrast to the limits imposed (as the Courant-Friedrichs-Lewy condition) on the convergence of many explicit time-marching numerical methods. This makes SDM advantageous in terms of computational cost when finer spatial resolutions are required.

Special emphasis is given to enhancing stand-alone Lagrangian numerical models within the Atmospheric Boundary Layer (ABL), including additional buoyancy models and canopy models. Furthermore, the coupling of fluid particle modeling with phase particle models opens up new modeling tools for some of some of the applications we are considering.

3.2.2 Advanced stochastic models for discrete particle dispersion and resuspension

As a particle nears a surface, deposition can occur depending on the interactions between the two objects. Deposits formed on a surface can then be resuspended, i.e. detached from the surface and brought back in the bulk of the fluid. Resuspension results from a subtle coupling between forces acting to move a particle (including hydrodynamic forces) and forces preventing its motion (such as adhesive forces, gravity). In the last decades, significant progresses have been achieved in the understanding and modeling of these processes within the multiphase flow community. Despite these recent progresses, particle resuspension is still often studied in a specific context and cross-sectoral or cross-disciplinary exchange are scarce. Indeed, resuspension depends on a number of processes making it very difficult to come up with a general formulation that takes all these processes into account.

Our goal here is to improve deposition law and resuspension law for more complex deposits in turbulent flows, especially towards multilayered deposits. For that purpose, we are improving existing Lagrangian stochastic models while resorting to meta-modeling to develop tailored resuspension law from experimental measurements and fine-scale numerical simulations. We are targeting practical applications such as pollutants in the atmosphere and plastic in marine systems.

3.2.3 Coherent descriptions for fluid and particle phases

Simulations of two-phase flows require the coupling of solvers for the fluid and particle phases. Numerical Weather Prediction (NWP) software usually rely on an Eulerian solver to solve Navier-Stokes equations. Solid particles are often treated using a Lagrangian point of view, i.e. their motion is explicitly tracked by solving Newton's equation of motion, the key difficulty being then to couple these intrinsically different approaches together. In line with the models and numerical methods developed in Sections 3.2.1 and 3.2.2, as an alternative to Eulerian-Lagragian approaches, CALISTO is developing a *new Lagrange-Lagrange formulation* that remains tractable to perform simulations for two-phase turbulent flows. We are particularly interested in *Lagrange-Lagrange models for interactions with surfaces*, as turbulence and collisions with surfaces can significantly affect the concentration of particles in the near-wall region.

3.2.4 Active particles near boundary

Surface effects can lead to the trapping of micro-swimmers near boundaries, as the presence of a boundary breaks both the symmetry of the fluid (leading to strong anisotropy) and the symmetry of the fluid-swimmer system. The better understanding of fluid-particle interactions near boundaries are expected here to help in the design of new control actuation for driving artificial swimmers in confined environments (developed in AXIS C).

3.3 AXIS C- Active agents in a fluid flow

This research axis deals with the study of self-propelled particles, which have the ability to convert internal or ambient free energy into dynamical motion. Such active agents can be microorganisms, such as bacteria or plankton, as well as artificial devices used for micro-manufacturing, toxic waste disposal, targeted drug delivery or localized medical diagnostics. Many questions remain open on how to control the displacement of these micro-swimmers, in particular for complex flows comprising inhomogeneities, fluctuations, obstacles, walls, or having a non-Newtonian rheology. There is also a need to study the impact of additional stochastic effects in driving a swarm of such micro-swimmers.

Studying and optimizing the displacement of these swimmers is generally done in two successive steps. The first is to find a *locomotion strategy* by choosing the composition, shape, and deformation for an efficient swimming. The second is to define a *navigation strategy* aimed at minimizing the energy needed to reach a target in a given environment. CALISTO's interdisciplinary expertise encompasses optimal control of viscous flows, small-scale fluid-structure interactions, statistical modeling and large-scale turbulent transport. This is a unique opportunity to address locomotion and navigation simultaneously.

Modeling approach

The equations of motion of the swimmer derive from its hydrodynamical interactions with the fluid through Newton laws. At a high level of description, this can be described by coupling the Navier-Stokes equations with the hyper-elastic equations describing the swimmer's deformation (in the case of elastic bodies). In the case of artificial magnetic swimmers, additional contribution representing the action of an external magnetic field on the swimmer needs to be added in the equations of motion. Solving the resulting system of PDEs is a challenging task, since it combines a set of equations deemed to be numerically difficult to solve even when they are decoupled. To overcome these difficulties, CALISTO considers various types of models, ranging from simpler but rough models to more realistic but complex models.

Control and optimal control for swimmers displacement

CALISTO investigates the controllability issues and the optimal control problems related in particular to two situations: the displacement of *(i)* real self-propelled swimmer by assuming that the control is the deformation of its body *(ii)* artificial bio-inspired swimmers that are able to swim using an external magnetic field.

Reinforcement learning

Another line of research concerns optimal path planning in turbulent flow. As a microswimmer swims towards a target in a dynamically evolving turbulent fluid, it is buffeted by the flow or it gets trapped in whirlpools. The general question we want to address is whether such a microswimmer can develop an optimal strategy that reduces the average time or energy it needs to reach a target at a fixed distance. In this context, the use of methods borrowed from artificial intelligence has been mainly used for navigation problems in which locomotion mechanisms are oversimplified. Based on recent smart-swimming approach developed in CALISTO, [19] [25], we plan to extend this work to more realistic cases, including for instance other control parameters for the swimmers, the presence of boundaries, of a feedback of the swimmers on the fluid flow, or interactions between swimmers.

3.4 AXIS D- Mathematics and numerical analysis of stochastic systems

Stochastic analysis, and related numerical analysis, together with improved statistical descriptions of highly-nonlinear dynamics are central topics in CALISTO. This research axis encompasses activities aiming, either (a) at strengthening our understanding on the origin and nature of fluctuations that are inherent to turbulent flows, or (b) at providing a coherent framework in response to the various mathematical challenges raised by the development of novel models in other research axes. Addressing these two fundamental aspects concomitantly to more practical and applied objectives is again a hallmark of the team.

Fundamental aspects of turbulence and turbulence transport

This research line has the scope of providing a unified description of turbulent flows in the limit of large Reynolds numbers and thus will be applicable to a large range of physical applications. It is conjectured since Kolmogorov and Onsager that the flow develops a sufficiently singular structure to provide a finite dissipation of kinetic energy when the viscosity vanishes. This dissipative anomaly gives a consistent framework to select physically acceptable solutions of the limiting inviscid dynamics. However, recent mathematical constructions of weak dissipative solutions face the problem of non-uniqueness, raising new questions on the relevance to turbulence and on the notion of physical admissibility.

On the one hand, the conservation of kinetic energy is actually not the only symmetry that is broken by turbulence. Various experimental and numerical measurements show significant deviations from simple scaling, time-irreversible fluctuations along fluid elements trajectories, and possibly other broken inviscid symmetries, such as circulation. Still, these anomalies may have a universal nature and, as such, provide new constraints for the design of physically admissible solutions. On the other hand, non-uniqueness could be an intrinsic feature of turbulence. Singular solutions to non-linear problems have an explosive sensitivity leading to spontaneously stochastic behaviors, thus questioning the pertinence of uniqueness and providing a framework to interpret solutions at a probabilistic level. To address such issues and provide unified appreciation, we simultaneously develop three strongly interrelated viewpoints: a) numerical approach, exploiting relevant and efficient fully-resolved simulations; b) new theoretical approaches based on the statistical physics of turbulent flow; c) mathematical construction of "very weak" flows, such as measure-valued solutions to the Euler equations.

Stochastic dynamics : analysis and numerics

Interacting Stochastic Systems and nonlinear SDEs. CALISTO explores examples of *particle* systems in interaction, possibly under mean field interaction, with the overall goal of analyzing the effect of stochasticity in such system. In particular, our goal is to identify and analyze conditions conducive to the emergence of collective behaviors, including but not limited to collective motions, synchronization, and organization, whether or not involving the concept of leaders.

An important example of complex interacting system is given by collisioning particle system under Langevin dynamics. If the case of collisioning systems in the context of gas dynamics –where particles experiment free path between two collision events– and in the context of overdamped Brownian dynamics have been largely studied, until now, situation of a finite number of particles collisioning under a Langevin dynamics is poorly addressed. This last case, describing particles in turbulent flow, is of great interest for CALISTO from both numerical and theoretical view points.

(Numerical) analysis for complex SDEs. This topic stands as a long-term commitment for Calisto. We draw and motivate our objects of study directly from observations and analyses of physical phenomena developed within the team. This approach adds significant value in terms of originality and has the potential for a substantial impact on the addressed problem.

In tandem with modeling activities across all other axes, there is a continuous need to enhance our mathematical toolbox and expertise in dealing with nonlinear Stochastic Differential Equations (SDEs) driven by complex noises, particularly non-Markovian ones. Our objective is to analyze the solutions, explore their asymptotic behavior, and delve into approximation techniques, with a particular emphasis on numerical methods.

3.5 AXIS E- Variability and uncertainty in flows and environment

Uncertainty analysis has evolved as a crucial research topic, especially in predictive systems grappling with an ever-expanding array of parameters.

This analysis effort is particularly pronounced in Computational Fluid Dynamics (CFD), especially in the context of particle-laden turbulent flows. The significance of addressing uncertainty amplifies in environmental applications, prominently in climate-related studies. Our position on these subjects is based on the stochastic modeling of the variability of the phenomena under study.

Integrating uncertainty analysis with solution formulations that already incorporate a statistical approach offers substantial flexibility, both in modeling the sources of uncertainty and in the numerical implementation. Although still in the early stages of development within the team, this line of research enables us to enhance our expertise in essential tools for evaluating our models.

Variability in wind/hydro simulation at small scale: application to wind/hydro energy

The turbulent nature of the atmospheric boundary layer (ABL) contributes to the uncertainty of the wind energy estimation. This has to be taken into account in the modeling approach when assessing the wind power production. The stochastic nature of the SDM approach developed in Axis B offers some rich perspectives to assess variability and uncertainty quantification issues in the particular context of environmental flows and power extraction evaluation. In particular, as a PDF method, SDM delivers a probability distribution field of the computed entities. Merging such numerical strategy with Sensitivity Analysis (SA)/Uncertainty Quantification (UQ) are potentially fruitful in terms of computational efficiency.

Metamodeling and uncertainty

While building and using computational fluid dynamics (CFD) simulation models, sensitivity analysis and uncertainty quantification methods allow to study how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input. UQ approaches allow to model verification and factor prioritization. It is a precious aid in the validation of a computer code, guidance research efforts, and in terms of system design safety in dedicated application. As CFD code users, we aim at applying UQ tools in our dedicated modeling and workflow simulation. As Stochastic Lagrangian CFD developers, we aim at developing dedicated SA and UQ tools as Stochastic solvers have the ability to support cross Monte Carlo strategy at the basis of SA methodology.

Another goal is to address some control and optimization problems associated with the displacement of swimmers through metamodeling, such as Gaussian process regression model, proved to be efficient for solving optimization of PDEs systems in other contexts.

4 Application domains

Environmental challenges: predictive tools for particle transport and dispersion

Particles are omnipresent in the environment:

- formation of clouds and rain results from the coalescence of tiny droplets in suspension in the atmosphere;
- fog corresponds to the presence of droplets in the vicinity of the Earth's surface, reducing the visibility to below 1 km [29];
- pollution corresponds to the presence of particulate matter in the air. Due to their impact on human health [37], the dispersion of fine particulate matter is of primary concern: PM1, PM2.5 and PM10 (particles smaller than 1, 2.5 or 10 μm) and Ultra Fine Particles (UFP, smaller than 0.1 μm) are particularly harmful for human respiratory systems while pollen can trigger severe allergies;
- the dispersion of radioactive particles following their release in nuclear incidents has drawn a great deal of attention to deepen our understanding and ability to model these phenomena [43];
- plastic contamination in oceans impacts marine habitats and human health [31];
- suspension of real micro-swimmers [20] such as sperm cell, bacteria, and in environmental issues with animal flocks attracted intrinsic biological interest[33];
- accretion of dusts is responsible for the formation of planetesimals in astrophysics [32].

These selected examples show that the presence of particles affects a wide range of situations and has implications in public, industrial and academic sectors.

Each of these situations (deposition, resuspension, turbulent mixing, droplet/matter agglomeration, thermal effect) involves specific models that need to be improved. Yet, one of the key difficulties lies in the fact that the relevant phenomena are highly multi-scale in space and time (from chemical reactions acting at the microscopic level to fluid motion at macroscopic scales), and that consistent and coherent models need to be developed together. This raises many issues related both to physical sciences (i.e. fluid dynamics, chemistry or material sciences) and to numerical modeling.

Next generation of predictive models for complex flows

Many processes in power production involve circulating fluids that contain inclusions, such as bubbles, droplets, debris, sediments, dust, powders, micro-swimmers or other kinds of materials. These particles can either be inherent components of the process, for instance liquid drops in sprays and soot formed by incomplete combustion, or external foul impurities, such as debris filtered at water intakes or sediments that can obstruct pipes. Active particles, seen as artificial micro-swimmers, have attracted particular attention for medical applications since they can be used as vehicles for the transport of therapeutics or as tools for limited invasive surgery. In these cases, optimization and control requires monitoring the evolution of their characteristics, their trajectories (with/without driving), and their effects on the fluid with a sufficiently high level of accuracy. These are very challenging tasks given a numerical complexity of the numerical models.

These challenges represent critical technological locks and power companies are devoting significant design efforts to deal with these issues, increasingly relying on the use of macroscopic numerical models. This framework is broadly referred to as "Computational Fluid Dynamics". However, such large-scale approaches tend to oversimplify small-scale physics, which limits their suitability and precision [21]. Particles encountered in industrial situations are generally difficult to model: they are polydisperse, not exactly spherical but of any shape, and deform; they have complex interactions, collide and can agglomerate; they usually deposit or stick to the walls and can even modify the very nature of the flow (e.g. polymeric flows). Extending present models to these complex situations is thus key to improve their applicability, fidelity, and performance.

Models operating in industry generally incorporate rather minimalist descriptions of suspended inclusions. They rely on statistical closures for single-time, single-particle probability distributions, as is the case for the particle-tracking module in the open-source CFD software CODE_SATURNE developed and exploited by EDF R&D. The underlying mean-field simplifications do not accurately reproduce complex features of the involved physics that require higher-order correlation descriptions and modeling. Indeed, predicting the orientation and deformation of particles requires suitable models of the fluid velocity gradient along their trajectories [45] while concentration fluctuations and clustering depend on relative particle dispersion [39, 30]. Estimates of collision and aggregation rates should also be fed by two-particle dynamics [38], while wall deposition is highly affected by local flow structures [40]. Improving existing approaches is thus key to obtain better prediction tools for multiphase flows.

New simulation approach for renewable energy and meteorological/climate forecast

A major challenge of sustainable power systems is to integrate climate and meteorological variability into operational processes, as well as into medium/long term planning processes [28]. Wind, solar, marine/rivers energies are of growing importance, and the demand for forecasts goes hand in hand with it [27, 36]. Numerous methods exist for different forecast horizons [22]. One of the main difficulties is to address refined spatial description. In the case of wind energy, wind production forecasts are submitted to the presence of turbulence in the near wall atmospheric boundary layer. Turbulence increases the variability of wind flows interacting with mill structures (turbine, mast, nacelle), as well as neighboring structures, terrain elevation and surface roughness. Although some computational fluid dynamics models and software are already established in this sector of activity [41] [35], the question of how to enrich and refine wind simulations (from meteorological forecast, or from larger scale information, possibly combined with local measurements) remains largely open.

Though hydro turbine farms are of a less assertive technological maturity than wind farms, simulating hydro turbines farms in rivers and sea channels submitted to tidal effect present similar features and challenges. Moreover in the marine energy context, measures are technically more difficult and more costly, and the demand in weather forecast concerns also the safety in maintenance operations.

At the time scale of climate change, the need for uncertainty evaluation of predictions used in long-term planning systems is increasing. For managers and decision makers in the field of hydrological forecasts, assessing hydropower predictions taking into account their associated uncertainties is a major research issue, as shown by the recent results of the European QUICS project [42]. The term uncertainty here refers to the overall error of the output of a generic model [34]. Translating time series of meteorological forecast into time series of run-of-river hydropower generation necessitates to capture the complex relationship between the availability of water and the generation of electricity. The water flow is itself a nonlinear function of the physical characteristics of the river basins and of the weather variables whose impact on the river flow may occur with a delay.

5 Highlights of the year

5.1 Awards

Jéremie Bec was awarded the Prize ONERA Académie Des Sciences 2024 for aeronautics and aerospace.

5.2 HDR

On September 18, 2024, Laetitia Giraldi successfully defended her Habilitation à Diriger des Recherches (HDR) before a jury composed of: François Alouges (ENS Paris Saclay), Michel Bergmann (INRIA Bordeaux), Peer Fischer (University of Heidelberg), Thierry Goudon (Université Côte d'Azur), Frédéric Jean (ENSTA Paris), Aline Lefèbvre-Lepot (ENS Paris Saclay), Christophe Prieur (Université de Grenoble). She was awarded her HDR from the Doctorate School on Fundamental and Applied Science (ED-SFA), within Université Côte d'Azur [11].

6 New software, platforms, open data

6.1 New software

6.1.1 SDM_brine

Keyword: Computational Fluid Dynamics

Scientific Description: We develop specialized numerical methods designed to model and analyze the behavior of brine discharges in three-dimensional fluid domains with complex bathymetric features. Developed in line with methodologies like those outlined in the WINDPOS project, SDM-Brine aims to incorporate computational fluid dynamics (CFD) techniques to solve the governing equations of fluid motion following a stochastic Lagrangian approach consistent with Navier-Stokes equations. The idea is to couple fluid motion equations with a fluid particle feature vector, including information on salinity, temperature, or density-driven properties.

Functional Description: A numerical method designed to model and analyze the behavior of brine discharges in three-dimensional fluid domains with complex bathymetric features.

Release Contributions: prototyping initial version

URL: https://project.inria.fr/swam/work-in-progress/stochastic-lagrangian-approach-for-brine-discharge-simulations/

Contact: Mireille Bossy

Participant: Mireille Bossy

7 New results

7.1 Axis A – Complex flows: from fundamental science to applied models

7.1.1 Book on the progress in the modeling of discrete particle dynamics in turbulent flows

Participant: Christophe Henry.

The purpose of this book is to present the statistical description of turbulent poly-disperse two-phase flows based on the probability density function (PDF) approach. Adopting the point of view of the physicist, the presentation focuses on the analysis of the physical content of stochastic formulations used to model the dynamics of discrete particles in non-fully resolved turbulent flows. We follow a step-by-step approach to introduce this multi-scale and multi-physics topic, and bring out current challenges to emphasize not only how but why PDF models are developed. By investigating state-of-the-art models, the book also invites researchers to address the open issues presented and, to that effect, new ideas are proposed. Starting with examples from daily situations and covering the basic equations as well as going through the reasons calling for a statistical treatment, this book can serve as an introduction for readers not yet familiar with the topic. Since we provide detailed accounts of the specific challenges we are faced with when considering statistical descriptions of discrete particle dynamics in random media with non-zero time and space correlations, the book is also intended for practitioners in the field. Finally, new ideas and cutting-edge formulations are developed in the hope to overcome present limitations and embolden specialists to pursue their own views.

This work is a collaboration with Jean-Pierre Minier (EDF R&D, MFEE, Chatou, France) and Martin Ferrand (EDF R&D, MFEE, Chatou and CEREA laboratory, Ponts ParisTech). It has been submitted to Springer in December 2024 for an open-source publication.

7.1.2 Review article on statistical models for the dynamics of heavy particles in turbulence

Participant: Jérémie Bec.

When very small particles are suspended in a fluid in motion, they tend to follow the flow. How such tracer particles are mixed, transported, and dispersed by turbulent flow has been successfully described by statistical models. Heavy particles, with mass densities larger than that of the carrying fluid, can detach from the flow. This results in preferential sampling, small-scale fractal clustering, and large collision velocities. To describe these effects of particle inertia, it is necessary to consider both particle positions and velocities in phase space. In recent years, statistical phase-space models have significantly contributed to our understanding of inertial-particle dynamics in turbulence. These models help to identify the key mechanisms and non-dimensional parameters governing the particle dynamics, and have made qualitative, and in some cases quantitative predictions. This article reviews statistical phase-space models for the dynamics of small, yet heavy, spherical particles in turbulence. We evaluate their effectiveness by comparing their predictions with results from numerical simulations and laboratory experiments, and summarize their successes and failures.

This review was written in collaboration with Kristian Gustavsson and Bernhard Mehlig from the University of Gothenburg (Sweden). It is now pushished in the Annual Review of Fluid Mechanics [1].

7.1.3 Turbophoresis of heavy inertial particles in statistically homogeneous flow

Participant: Jérémie Bec.

Dispersed particles suspended in turbulent flows are widely encountered in nature or industry under the form of droplets, dust, or sediments. When they are heavier than the fluid, such particles possess inertia and are ejected by centrifugal forces from the most violent vortical structures of the carrier phase. Once cumulated along particle paths, this small-scale mechanism produces an effective large-scale drift where particles leave the excited turbulent zones and converge to calmer regions to form uneven spatial distributions. This fundamental phenomenon, called turbophoresis, has been extensively used to explain why particles transported by non-homogeneous flows concentrate near the minima of the turbulent kinetic energy.

We have shown that turbophoretic effects are just as crucial in statistically homogeneous and isotropic flows. Instantaneous spatial fluctuations of the turbulent activity, despite their uniform average, trigger local fluxes that play a key role in the emergence of inertial-range inhomogeneities in the particle distribution. Direct numerical simulations have been used to thoroughly probe and depict the statistics of particle accelerations and in particular their scale-averaged properties conditioned on the local turbulent activity. They confirm the relevance of the local energy dissipation to describe instantaneous spatial fluctuations of turbulence. This analysis yields an effective coarse-grained dynamics, in which particles detachment from the fluid and their ejection from excited regions are accounted for by a space and time-dependent non-Fickian diffusion.

Such considerations led us to cast inertial-range fluctuations in the particles distributions in terms of a local Péclet number Pe, which measures the relative importance of turbulent advection compared to turbophoresis induced by inertia. Numerical simulations confirm the relevance of this dimensionless parameter to characterize how particle concentration recovers homogeneity at large scales. This approach also explains the presence of voids with inertial-range sizes, and in particular that their volumes have a non-trivial distribution with a power-law tail whose exponent depends on the particle response time. These results are gathered in an article published in the Journal of Fluid Mechanics [3].

7.2 Axis B – Particles and flows near boundaries: specific Lagrangian approaches for large-scale simulations

7.2.1 Particle resuspension from complex multilayer deposits by laminar flows: statistical analysis and modeling

Participants: Mireille Bossy, Christophe Henry.

Particle resuspension refers to the physical process by which solid particles deposited on a surface are, first, detached and, then, entrained away by the action of a fluid flow.

In this study, we explore the dynamics of large and heavy spherical particles forming a complex sediment bed which is exposed to a laminar shear flow. For that purpose, we rely on fine-scale simulations based on a fully-resolved flow field around individual particles whose motion is explicitly tracked. Using statistical tools, we characterize several features: (a) the overall bed dynamics (e.g. the average particle velocity as a function of the elevation), (b) the evolution of the top surface of the sediment bed (e.g. distribution of the surface elevation or of the surface slope) and (c) the dynamics of individual particles as they detach from or re-attach to the sediment bed (including the frequency of these events, and the velocity difference/surface angle for each event). These results show that particles detach more frequently around the peaks in the top surface of the sediment bed and that, once detached, they undergo short hops as particles quickly sediment towards the sediment bed. A simple model based on the surface characteristics (including its slope and elevation) is proposed to reproduce the detachment ratio.

This is a collaborative work with researchers from the Technical University of Dresden in Germany (especially Bernhard Vowinckel who provided the fine-scale simulations) as well as from the University of Bayreuth in Germany (Hao Liu, who did his master internship within CALISTO in 2023 to develop analysis tools). These results are published in International Journal of Multiphase Flow [6].

7.2.2 Enhanced transport of flexible fibers by pole vaulting in turbulent wall-bounded flow

Participants: Jérémie Bec, Christophe Henry.

Long, flexible fibers transported by a turbulent channel flow sample non-linear variations of the fluid velocity along their length. One of the challenges of the dynamics of flexible fibers in confined flows is related to their interactions with boundaries, which can lead to a range of behavior. In this work, we explore how such fibers tumble and collide with the boundaries and the resulting effect on their near-wall dynamics. Using fine microscopic simulations (based on a Direct Numerical Simulations of the turbulent flow coupled to an explicit tracking of inertialess flexible fibers described with the slender-body theory), we show that as fibers bounce off surfaces, an impulse propels them toward the center of the flow, similar to pole vaulting. As a result, the fibers migrate away from the walls, leading to depleted regions near the boundaries and more concentrated regions in the bulk. These higher concentrations in the center of the channel result in a greater net flux of fibers than what was initially imposed by the fluid. This effect becomes more pronounced as fiber length increases, especially when it approaches the channel height.

This is a collaborative work with Christophe Brouzet (Institut de Physique de Nice). An article has been published this year in Physical Review Fluids [2]. This topic was presented By Christophe Brouzet (Institut de Physique de Nice) in the 2024 edition of Complex Days, Nice [10].

7.3 Axis C – Active agents in a fluid flow

This research axis deals with the study of self-propelled particles, which have the ability to convert internal or ambient free energy into dynamical motion. Such active agents can be microorganisms, such as bacteria or plankton, as well as artificial devices used for micro-manufacturing, toxic waste disposal, targeted drug delivery or localized medical diagnostics. Many questions remain open on how to control the displacement of these micro-swimmers, in particular for complex flows comprising inhomogeneities, fluctuations, obstacles, walls, or having a non-Newtonian rheology. Studying and optimizing the displacement of these swimmers is generally done in two successive steps. The first is to find a locomotion strategy by choosing the composition, shape, and deformation for an efficient swimming. The second is to define a navigation strategy aimed at minimizing the energy needed to reach a target in a given environment. CALISTO works rely on cross-disciplinary skills, comprising the optimal control of viscous flows, small-scale fluid-structure interactions, statistical modeling, and large-scale turbulent transport to tackle both aspects, locomotion and navigation, at once.

7.3.1 Mathematical and computation framework for moving and colliding rigid bodies in a Newtonian fluid

Participants: Jérémie Bec, Chiara Calascibetta, Zakarya El Khiyati, Laetitia Giraldi.

The self-organization of active particles on a two-dimensional single-occupancy lattice is investigated, with an emphasis on the effects of boundary confinement and the influence of an external mean fluid flow. The study examines collective behaviors, particularly the transition from a disordered phase to the formation of orientationally ordered patterns, and their impact on particle transport and flux. In the absence of fluid flow, confinement causes particles to accumulate near the walls, leading to clogs or obstructions that hinder movement, or to the formation of bands aligned with the channel. Although these bands limit the particles' ability to freely self-propel, they still result in a net flux along the channel. The introduction of an external Poiseuille fluid flow induces vorticity, shifts the phase transition to higher alignment sensitivities, and promotes particle clustering at the channel center, significantly enhancing overall flux.

This is a collaborative work with Zakarya El khiyati. An article has been accepted to Physical Review E [4].

7.3.2 Mathematical and computation framework for moving and colliding rigid bodies in a Newtonian fluid

Participant: Laetitia Giraldi.

This work is done in collaboration, with Celine Van-Landeghem (IRMA, Université de Strasbourg), PhD student co-advised by Laetitia Giraldi.

We studied numerically the dynamics of colliding rigid bodies in a Newtonian fluid. The finite element method is used to solve the fluid-body interaction and the fluid motion is described in the Arbitrary-Lagrangian-Eulerian framework. To model the interactions between bodies, we consider a repulsive collision-avoidance model, defined by R. Glowinski. The main emphasis in this work is the generalization of this collision model to multiple rigid bodies of arbitrary shape. Our model first uses a narrow-band fast marching method to detect the set of colliding bodies. Then, collision forces and torques are computed for these bodies via a general expression, which does not depend on their shape. Numerical experiments examining the performance of the narrow-band fast marching method and the parallel execution of the collision algorithm are discussed. We validate our model with literature results and show various applications of colliding bodies in two and three dimensions. In these applications, the bodies either move due to gravity, a flow, or can actuate themselves. Finally, we present a tool to create arbitrary shaped bodies in discretized fluid domains, enabling conforming body-fluid interface and allowing to perform simulations of fluid-body interactions with collision treatment in these realistic environments. All simulations are conducted with the Feel++ open source library.

This is collaborative work with Christophe Prud'Homme, Luca Berti, Yannick Hoarau, Vincent Chabannes and Agathe Chouippe. The paper [9] is published in Annals of Mathematical Sciences and Applications.

7.3.3 Necessary conditions for local controllability of a particular class of systems with two scalar controls

Participant: Laetitia Giraldi.

In this paper [5], in collaboration with Pierre Lissy (Ceremade, Paris), Jean-Baptiste Pomet (Inria, McTAO) and Clement Moreau (LS2N, University of Nantes), we consider control-affine systems with two scalar controls, such that one control vector field vanishes at an equilibrium state. We state two necessary conditions for local controllability around this equilibrium, involving the iterated Lie brackets of the system vector fields, with controls that are either bounded, small in L^∞ or small in $W^{1,\infty}$. These results are illustrated with several examples. This paper was now published in ESAIM: Control, Optimisation and Calculus of Variations (ESAIM:COCV).

7.3.4 Towards a computational framework using finite element methods with Arbitrary Lagrangian-Eulerian approach for swimmers with contact

Participant: Laetitia Giraldi.

Swimming involves a body's capability to navigate through a fluid by undergoing self-deformations. Typically, fluid dynamics are described by the Navier-Stokes equations, and when integrated with a swimming body, it results in a highly intricate model. This paper introduces a computational framework for simulating the movement of multiple swimmers with various geometries immersed in a Navier-Stokes fluid. The approach relies on the finite element method with an Arbitrary Lagrangian-Eulerian (ALE) framework to handle swimmer displacements. Numerous numerical experiments demonstrate the adaptability of the computational framework across various cases. The implementations are made using the Feel++ finite element library.

This is collaborative work with Luca Berti Laetitia Giraldi, Christophe Prud'Homme, and Celine Van-Landeghem (IRMA, University of Strasbourg). The paper [12] is published in SEMA SIMAI Springer Series.

7.3.5 Parametric Shape Optimization of Flagellated Micro-Swimmers Using Bayesian Techniques

Participants: Lucas Palazzolo, Laetitia Giraldi.

Understanding and optimizing the design of helical micro-swimmers is crucial for advancing their application in various fields. This study presents an innovative approach combining Free-Form Deformation with Bayesian Optimization to enhance the shape of these swimmers. Our method facilitates the computation of generic swimmer shapes that achieve optimal average speed and efficiency. Applied to both monoflagellated and biflagellated swimmers, our optimization framework has led to the identification of new optimal shapes. These shapes are compared with biological counterparts, highlighting a diverse range of swimmers, including both pushers and pullers.

It is part of the research conducted by Lucas Palazzolo under the supervision of Laetitia Giraldi, funded by her ANR JCJC Nemo. This work was also carried out in collaboration with Mickael Binois and Luca Berti [16]. It has been submitted to Physical Journals of Fluids.

7.4 Axis D – Mathematics and numerical analysis of stochastic systems

Stochastic analysis, and related numerical analysis, together with improved statistical descriptions of highly-nonlinear dynamics are central topics in CALISTO. This research axis encompasses activities aiming, either (a) at strengthening our understanding on the origin and nature of fluctuations that are inherent to turbulent flows, or (b) at providing a coherent framework in response to the various mathematical challenges raised by the development of novel models in other research axes. Addressing these two fundamental aspects concomitantly to more practical and applied objectives is again a hallmark of the team.

7.4.1 Anomalous dissipation and spontaneous stochasticity in deterministic surface quasi-geostrophic flow

Participants: Jérémie Bec, Simon Thalabard, Nicolas Valade.

Surface quasi geostrophy (SQG) describes the two-dimensional active transport of a temperature field in a strongly stratified and rotating environment. Besides its relevance to geophysics, SQG bears formal resemblance with various flows of interest for turbulence studies, from passive scalar and Burgers to incompressible fluids in two and three dimensions. In the article [8], published in Annales Henri Poincaré in 2024, we substantiated this analogy by considering the turbulent SQG regime emerging from deterministic and smooth initial data prescribed by the superposition of a few Fourier modes. While still unsettled in the inviscid case, the initial value problem is known to be mathematically well-posed when regularized by a small viscosity. In practice, our numerics revealed that in the presence of viscosity, a turbulent regime appears in finite time, which features three of the distinctive anomalies usually observed in three-dimensional developed turbulence: (i) dissipative anomaly, (ii) multifractal scaling, and (iii) super-diffusive separation of fluid particles, both backward and forward in time. These three anomalies point towards three spontaneously broken symmetries in the vanishing viscosity limit: scale invariance, time reversal and uniqueness of the Lagrangian flow, a fascinating phenomenon dubbed spontaneous stochasticity. In the light of previous work on the passive scalar problem, we argued that spontaneous stochasticity and irreversibility are intertwined in SQG, and provided numerical evidence for this connection. Our numerics, though, revealed that the deterministic SQG setting only features a tempered version of spontaneous stochasticity, characterized in particular by non-universal statistics.

7.4.2 Numerical analysis of stochastic system

Strong rate of convergence of approximation scheme for SDEs with superlinear coefficients.

Participants: Mireille Bossy, Kerlyns Martínez Rodríguez.

In collaboration with Kerlyns Martínez (University of Valparaíso), we address the problem of approximating the solution of a one-dimensional stochastic differential equation (SDE) with a piecewise locally Lipschitz drift and a continuous diffusion coefficient exhibiting polynomial growth. Based on the previously proposed (semi-explicit) exponential-Euler scheme [26], we analyze its convergence by studying its strong approximation error.

In the paper [13], we explore the discrete-time approximation of the solution of a one-dimensional SDE with a piecewise locally Lipschitz drift and continuous diffusion coefficient with polynomial growth. We investigate the strong convergence of the (semi-explicit) exponential-Euler scheme introduced in [26]. Specifically, we demonstrate the standard $\frac{1}{2}$ rate of convergence for the exponential-Euler scheme when the drift is continuous. However, in cases where the drift is discontinuous, the convergence rate is penalized by a factor ε, which decreases with the time-step size.

We also analyze the case where the diffusion coefficient vanishes at zero, which introduces additional challenges such as a positivity preservation condition. The convergence analysis in this scenario leverages the use of negative moments and exponential moments, employing a time-change technique as introduced in [23]. Our analysis is complemented by a study of the asymptotic behavior and theoretical stability of the exponential-Euler scheme, as well as numerical experiments that support our theoretical findings.

Rather than a priori control of the schema by a tamed/truncated strategy, we aim to identify a robust a posteriori threshold for the approximated process, defining a value range for the scheme that ensures its convergence. By obtaining a threshold that expands as we refine the time-step, we pave the way for exploring natural and explicit strategies for adaptive time-step schemes handling increasingly explosive cases of SDEs. With Bernhard Eisvogel (CALISTO intern), we investigated the behavior of the scheme near the limit of the Feller zone of the exact process, (the set of coefficients parameters that insures non explosion of solution in finite time with probability one), and the ability of the scheme to capture explosive parameter zone. A second paper on that topic is in preparation.

On the ε–Euler-Maruyama scheme for time inhomogeneous jump-driven SDEs

Participants: Mireille Bossy, Paul Maurer.

In [15], we consider a class of general SDEs with a jump integral term driven by a time-inhomogeneous random Poisson measure. We propose a two-parameters Euler-type scheme for this SDE class and prove an optimal rate for the strong convergence with respect to the $L^p(\Omega)$-norm and for the weak convergence. One of the primary issues to address in this context is the approximation of the noise structure when it can no longer be expressed as the increment of random variables. We extend the Asmussen-Rosinski approach to the case of a fully dependent jump coefficient and time-dependent Poisson compensation, handling contribution of jumps smaller than ε with an appropriate Gaussian substitute and exact simulation for the large jumps contribution. For any $p \geq 2$, under hypotheses required to control the L^p-moments of the process, we obtain a strong convergence rate of order $1/p$. Under standard regularity hypotheses on the coefficients, we obtain a weak convergence rate of $1/n + \epsilon^{3-\beta}$, where β is the Blumenthal-Getoor index of the underlying Lévy measure. We compare this scheme with the Rubenthaler's approach where the jumps smaller than ε are neglected, providing strong and weak rates of convergence in that case too. The theoretical rates are confirmed by numerical experiments afterwards.

This study is mainly motivated by the simulation of stochastic models, with a focus on investigating Lévy processes, and particularly α-stable processes, arising as the limit distribution of the generalised Central Limit Theorem for independent random variables with infinite variance. We apply this model class for some anomalous diffusion model related to the dynamics of rigid fibres in turbulence studied in [18].

Weak rough kernel comparison via PPDEs for integrated Volterra processes.

Participants: Mireille Bossy, Paul Maurer, Kerlyns Martínez Rodríguez.

Motivated by applications in physics, in paricular with the causal modeling of turbulence intermittency via the Lagrangian dissipation (also with rough volatility models in financial mathematics), we analyze a family of integrated stochastic Volterra processes characterized by a small Hurst parameter $H < \frac{1}{2}$. We investigate the impact of kernel approximation on the integrated process by examining the resulting weak error. Our findings quantify this error in terms of the L^1 norm of the difference between the two kernels, as well as the L^1 norm of the difference of the squares of these kernels. Our analysis is based on a path-dependent Feynman-Kac formula and the associated partial differential equation (PPDE), providing a robust and extendible framework for our analysis. A first paper is now submitted [14]. A second one, specifically on Markovian approach for a reduced model of turbulence intermittency is in preparation.

7.4.3 Finite-time Lyapunov exponents of deep neural networks

Participant: Jérémie Bec.

For deep neural networks trained on different classification problems, we explored geometrical structures of finite-time Lyapunov exponents (FTLE) in input space. In fluid mechanics, such Lagrangian coherent structures appear as ridges of large exponents, and they are used with great success to organize the phase space of complex spatiotemporal flow patterns. The same is true for deep neural networks: FTLE ridges partition input space into different regions associated with different classes. Our analysis showed how the network exploits its exponential expressivity to form the ridges. Their sharpness determines how quickly classification errors and prediction uncertainty decreases as one moves away from the ridge. As the width of the network increases, the contrast between ridge and background disappears, leading to a different learning mechanism, random embedding, with qualitative differences regarding classification errors and predictive uncertainties. The transition to this lazy-learning regime occurs for very wide networks. The transition may explain why wider networks are more robust against adversarial attacks: the less important the ridges are for representing the relevant data structures, the harder it is to realize adversarial attacks. The geometrical method presented in our work may extend to other network architectures, such as resnets or transformers, and could help to visualize and understand the mechanisms that allow such neural networks to learn. This study is the subject of a collaboration with Kristian Gustavsson, Hampus Linander, Bernhard Mehlig, and Ludvig Storm (University of Gothenburg) and is published in Physical Review Letters [7].

7.5 Axis E – Variability and uncertainty in flows and environment

7.5.1 Short term predictive models with times-serie based on Lagrangian stochastic approach in CFD and application to wind gust risk

Participants: Mireille Bossy, Kerlyns Martínez Rodríguez, Diego Ruiz Ramirez.

The need for statistical information on wind at a specific location over long time periods is of critical importance for many applications. These include the structural safety of large construction projects and the economic viability of wind farms, whether related to investment decisions, operational management, or repowering efforts.

Obtaining detailed insights into wind gusts is particularly essential for evaluating wind-induced damage and safety risks. Even short-term prevention of gust-related risks is crucial for ensuring safety in various human activities. A wind gust is defined as a sudden and temporary increase in wind speed, resulting in a brief surge in instantaneous wind speed above its average value at that time. Unlike deviations in mean wind speed, a gust is characterized by its persistence over a minimum period of time to qualify as such.

Building on the work presented in [17] in collaboration with Kerlyns Martínez (University of Valparaíso), our current research focuses on modeling wind gust occurrences at specific locations using time series data from recorded wind measurements. In partnership with Diego Ruiz (Inria Chile intern), we analyzed high-frequency wind data, which confirmed the need for models incorporating varying degrees of long-term memory. These stochastic models are derived from a family of Lagrangian dissipation representations, with the mathematical approximations detailed in Section 7.4.2.

8 Partnerships and cooperations

8.1 International initiatives

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

Participants: Jérémie Bec, Mireille Bossy, Christophe Henry, Paul Maurer.

SWAM

Title: Sea, Waves, And ecosysteMs: Stochastic models for perturbed marine environments

Duration: 2024 ->

Coordinator: Kerlyns Martínez Rodríguez

Partners:
- Universidad de Valparaiso (UV) (Chile)

Inria contact: Mireille Bossy

Summary: This associated team project brings together a multidisciplinary team of experts in areas such as stochastic analysis, numerical probabilities, fluid mechanics, ocean engineering, and ecology. The primary objective is to address current challenges related to the installation of desalination plants and their potential impacts on ocean dynamics, thereby affecting the composition and distribution of species in surrounding aquatic ecosystems. The two issues at hand involve different time and space scales.

On the one hand, a large-time scale stochastic model analysis will be conducted to study species potentially at risk in certain coastal areas. On the other hand, desalination plants interact with the marine environment through seawater intake points and brine discharge points into the sea. This discharge process occurs on a much shorter time scale. Nevertheless, it is essential to understand how the brine generated during the internal plant process is dispersed and/or accumulated, and how it may potentially disrupt the current. For this aspect, we intend to develop CFD simulation tools to analyze response variabilities and sensitivity, based on Lagrangian stochastic approach and the code SDM developed at CALISTO.

During 2024, the project held several online meetings (administratives and research) and an online seminar (in collaboration with the LabOceano UV). The aim of this seminar was to build bridges across the different expertise of the team members. The project's team also organized the first SWAM Workshop in collaboration with the ANID Exploration Project 13220168. In this workshop, 3 permanents members and 1 PhD candidate from CALISTO were able to visit Chile to refine the objectives of the project and modeling methodologies thanks to discussions held in various laboratories, representatives of the disciplines involved.

This year we worked on three connected approaches:

(a) 2D model for species response to pollution. The length of the outfall from the coast at the desalination plant to be installed in Quintero Bay will be approximately 700 meters from the coast. As a first approach in the study of the species response to pollutant injected into the ocean, we propose to couple advection-diffusion models for the dynamics of the concentration of a pollutant and the density presence of a typical marine species. The pollutant is released from a source point that mimics the discharge of an outfall from a desalination plant. The pollutant particles are transported by a non-stationary sinusoidal velocity field, representing periodic currents generated by tides and waves. The larvae are transported by the velocity field and are affected by the pollutant concentration, which causes local biomass losses. The interaction with the coast is captured by appropriate boundary conditions.

(b) SDM_brine, a Lagrangian stochastic solver for large scale simulations. Regarding 3D fluid domain, we started to develop specialized numerical methods designed to model and analyze the behavior of brine discharges with complex bathymetric features and current forcing. Developed on the basis of SDM-WINDPOS solver project, SDM_brine incorporate computational fluid dynamics (CFD) techniques to solve the governing equations of fluid motion following a stochastic Lagrangian approach consistent with Navier-Stokes equations. The main idea is to couple transport equations with a fluid particle feature vector, including information on salinity, temperature, or any density-driven properties of scalar transport. This framework is particularly well-suited for studying mesoscale phenomena, where bathymetry plays a critical role in shaping and trapping brine plume dispersion. A first implementation of SDM_brine is now in the phase of its validation against experimental data. Once calibrated, we believe this salinity Lagrangian transport will be very efficient for farfield transport model purpose in particular, if we couple it with transport of active matter (larvea, fishes) or passive particles (kelp seeds). We also plan to evaluate the Euler coupling (dedicated coastal dynamics code) and the Lagrangian coupling (active & passive transport).

(c) Statistical analysis on larvae motility and brine effect. Building on a FONDEF project led by Patricio Winckler (Universidad de Valparaiso), we conducted a statistical analysis of larval motility in environments with varying salinity concentrations. The dataset, collected by LabOceano, was obtained through a tracking procedure applied to 324 videos. This will enable the definition of observables to assess the impact of salinity changes on the mobility of sea urchin (Loxechinus albus) and loco (Concholepas concholepas) larvae. It will also support the implementation of classification algorithms to distinguish movement under baseline and altered salinity conditions, as well as the development of a mobility model combined with a semi-supervised learning approach to estimate the disturbances caused by salinity changes.

8.1.2 CEFIPRA project "Polymers in turbulent flows"

Participants: Jérémie Bec.

This bilateral project aims at studying the dynamics of polymers in turbulent flows, with the idea to use Lagrangian approaches to find links between microscopic scales and the rheology of polymer suspensions and macroscopic continuum models. The french PI is Dario Vincenzi (CNRS-Laboratoire Jean Alexandre Dieudonné) and the Indian PI is Jason Picardo (IIT Mumbai). The CALISTO team is a partner of the project and received funding to support bilateral visits.

8.2 International research visitors

8.2.1 Visits of international scientists

Other international visits to the team

Kerlyns Martínez Rodríguez

Status Associate Professor

Institution of origin: Universidad de Valparaíso

Country: Chile

Dates: from 01/15/2023 to 02/15/2023 and from 12/07/2023 to 02/07/2024

Mobility program: research stay

8.2.2 Visits to international teams

Research stays abroad

Jérémie Bec

Visited institution: IMPA

Country: Brazil

Dates: from February 11 to March 1, 2024.

Context of the visit: Collaboration with Alexei Mailybaev, Instituto de Matematica Pura e Aplicada (IMPA) on spontaneous stochasticity in turbulence.

Mobility program/type of mobility: research stay

Nicolas Valade

Visited institution: IMPA

Country: Brazil

Dates: from Dcember 31, 2023 to February 29, 2024.

Context of the visit: Winter school

Mobility program/type of mobility: research stay

Jéremie Bec, Mireille Bossy, Christophe Henry, Paul Maurer

Visited institution: Universitad de Valparaiso, ECIM, Universitad de Concepción

Country: Chile

Dates: October 12 to October 27, 2024.

Context of the visit: SWAM

Mobility program/type of mobility: research stay

8.3 National initiatives

8.3.1 ANR PRC TILT

Participants: Jérémie Bec.

The ANR PRC project TILT (Time Irreversibility in Lagrangian Turbulence) started on January 1st, 2021. It is devoted to the study and modeling of the fine structure of fluid turbulence, as it is observed in experiments and numerical simulations. In particular, recall that the finite amount of dissipation of kinetic energy in turbulent fluid, where viscosity seemingly plays a vanishing role, is one of the main properties of turbulence, known as the dissipative anomaly. This property rests on the singular nature and deep irreversibility of turbulent flows, and is the source of difficulties in applying concepts developed in equilibrium statistical mechanics. The TILT project aims at exploring the influence of irreversibility on the motion of tracers transported by the flow. The consortium consists of 3 groups with complementary numerical and theoretical expertise, in statistical mechanics and fluid turbulence. They are located in Saclay, at CEA (Bérengère Dubrulle), in Lyon, at ENSL (Laurent Chevillard, Alain Pumir), and in Sophia Antipolis (Jérémie Bec). Within TILT, a postdoc joined CALISTO in January 2023 until early 2025.

8.3.2 ANR JCJC NEMO

Participant: Laetitia Giraldi.

The JCJC project NEMO (controlliNg a magnEtic Micro-swimmer in cOnfined and complex environments) was selected by ANR in 2021, and started on Jan. 1, 2022 for four years. NEMO team is composed of Laetitia Giraldi, Mickael Binois and Laurent Monasse (Inria, ACUMES).

NEMO aims at developing numerical methods to control a micro-robot swimmer in the arteries of the human body. These robots could deliver drugs specifically to cancer cells before they form new tumors, thus avoiding metastasis and the traditional chemotherapy side effects.

NEMO will focus on micro-robots, called Magnetozoons, composed of a magnetic head and an elastic tail immersed into a laminar fluid possibly non-Newtonian. These robots imitate the propulsion of spermatozoa by propagating a wave along their tail. Their movement is controlled by an external magnetic field that produces a torque on the head of the robot, producing a deformation of the tail. The tail then pushes the surrounding fluid and the robot moves forward. The advantage of such a deformable swimmer is its aptness to carry out a large set of swimming strategies, which could be selected according to the geometry or the rheology of the biological media where the swimmer evolves (blood, eye retina, or other body tissues).

Although the control of such micro-robots has mostly focused on simple unconfined environments, the main challenge is today to design external magnetic fields that allow them to navigate efficiently in complex realistic environments.

NEMO aims at elaborating efficient controls, which will be designed by tuning the external magnetic field, through a combination of Bayesian optimization and accurate simulations of the swimmer's dynamics with Newtonian or non-Newtonian fluids. Then, the resulting magnetic fields will be validated experimentally in a range of confined environments. In such an intricate situation, where the surrounding fluid is bounded laminar and possibly non-Newtonian, optimization of a strongly nonlinear, and possibly chaotic, high-dimensional dynamical system will lead to new paradigms.

8.3.3 ANR PRC NETFLEX

Participants: Jérémie Bec, Mireille Bossy, Laetitia Giraldi, Christophe Henry, Paul Maurer.

The ANR PRC project NEFFLEX (*Tangles, knots, and breakups of flexible fibers in turbulent fluids*) started on January 1, 2022. NETFLEX is a four-years project that aims at advancing our knowledge on the dynamics of long, flexible, macroscopic fibres in turbulent flows, and to understand and model the processes of fibre fragmentation and aggregation. NETFLEX brings together Université Côte d'Azur (Institut de Physique de Nice, Laboratoire Jean Alexandre Dieudonné), Inria (CALISTO) and Aix-Marseille University (IRPHE). NETFLEX approach combines three levels of description (micro, meso, and macroscopic) and relies on a synergy between mathematical modeling, numerical simulations, and laboratory experiments. It relies on the development of newly designed experiments and a substantial improvement of the mathematical and numerical tools currently used in the study of fibre dynamics. An overall aim is to develop a new framework able to cope with such intricate effects of turbulence and to reproduce the significant observable features in a macroscopic approach.

Improved modeling of turbulent fluctuations and effective transport models for aggregates are among the key issues to be addressed in order to extend the macroscopic models.

Starting in October 2022, Paul Maurer's thesis work on analysis and simulation for temporal intermittency and long-range correlation models is part of this project, and will be applied to the dynamics of flexible particles.

8.4 Regional initiatives

8.4.1 Thematic Semester POPULATE

Participants: Mireille Bossy, Laetitia Giraldi, Christophe Henry.

The thematic semester POPULATE (*Population dynamics: from fundamental to applied science*) started on June 1st, 2024. POPULATE is an 18-month project that aims to consolidate ongoing research initiatives at Université Côte d'Azur, encompassing various aspects of biology, physics (including astrophysics and fluid dynamics), mathematics and life sciences (plants, insects and crowd dynamics), from experimental and applied methods to numerical modeling. For that purpose, three main events are planned between March 2025 and October 2025: two one-week international conferences and one two-week summer school.

The project is coordinated by Christophe Henry and the committee is composed of researchers from various laboratories in Nice (more details on the website).

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

General chair, scientific chair

- Mireille Bossy co-chaired the 2024 edition of the Mascot-Num Annual Conference, held in the Giens Peninsula, Hyères, France, alongside Mickael Binois (ACUMES).

Member of the organizing committees

- Workshop on Numerical Analysis, Control, and Optimization for Physics

  Laetitia Giraldi, in collaboration with Laurent Monasse, organized the "Numerical Analysis, Control, and Optimization for Physics" workshop (link to the webpage of the event). This event, held at INRIA Université Côte d'Azur on September 18-19, following her HDR defense, involved a significant part of her jury members.

  This symposium focuses on the areas of numerical analysis, control, and optimization for physics, with particular attention paid to active particles. Our goal is to bring together diverse scientific communities, including experimentalists, theorists from various disciplines (mathematics, control engineering, physics, and biology), and representatives from innovation-driven startups. This initiative aims to catalyze interdisciplinary dialogue and foster an enriched sharing of knowledge and experiences on these innovative topics.

Scientific seminars of the Team. Christophe Henry is organizing the monthly Seminar of Team CALISTO. In 2024, the following researchers were invited to give a presentation: Jérémy Zurcher (Lille University), Juliane Klamser (Montpellier University), Łukasz Mądry (Cerema, Paris), Jessie Levillain (CMAP, Palaiseau), Siddhartha Mukherjee (LJAD, Nice), Rémi Catellier (LJAD, Nice), Alexis Anagnostakis (Grenobles Alpes University), Thomas Rey (LJAD, Nice), Long Li (Inria, Rennes), Tony Jin (Centrale Méditerranée, Nice), Radomyra Shevchenko (Centrale Méditerranée, Nice).

9.1.2 Scientific events: selection

Member of the conference program committees

- Mireille Bossy is member of the scientific comittee for "EHF 2025 – The XXI edition of the Jacques-Louis Lions Hispano-French School on Numerical Simulation in Physics and Engineering", which will be held in Ciudad Real, Spain, in June 2025.

- Mireille Bossy is member of the scientific comittee for the International Workshop "Milstein's method: 50 years on", which will be held at the School of Mathematics, University of Nottingham, from June 30th to July 3rd, 2025.
- Laetitia Giraldi is member of the scientific committee for Active Matter: the synergy between Maths and Physics, Paris in June 2025.
- Laetitia Giraldi is member of the scientific committee for the Summer school: Population Balance: From Fundamental to Applied Science, which will be held in Grasse in June 2025.
- Christophe Henry is member of the scientific committee for the Summer school: Population Balance: From Fundamental to Applied Science, which will be held in Grasse in June 2025.
- Christophe Henry is member of the scientific committee for the Spring Conference: Population Balance: From Data to Models, which will be held in Sophia Antipolis in March 2025.

Reviewer

- Christophe Henry is member of the reviewing committee of the Spring Conference: Population Balance: From Data to Models, which will be held in Sophia Antipolis in March 2025.

9.1.3 Journal

Reviewer - reviewing activities: In 2024, CALISTO scientific staff have been acting as reviewers for various international journals, listed in the following according to each team member:

- Jérémie Bec reviewed for *Journal of Fluid Mechanics, Journal of Statistical Physics, Physical Review Fluids, Physical Review Letters.*
- Mireille Bossy acted as reviewer for *Stochastic Processes and their Applications*, *Journal of Computational Physics*, *Journal of Applied Mathematics and Physics* (ZAMP), *Stochastics and Partial Differential Equations: Analysis and Computations Journal.*
- Laetitia Giraldi serves as a reviewer for several prestigious journals, including Computational and Applied Mathematics, Journal of Optimization Theory and Applications (JOTA), Interface Focus (Royal Society), and Journal of Fluids.
- Christophe Henry acted as reviewer for Journal of Hazardous Materials, Journal of Aerosol Science, Nuclear Engineering and Design, NPJ Climate and Atmospheric Science.

9.1.4 Invited talks

- Jérémie Bec was invited to give a keynote lecture at the conference "Turbulence on the banks of the Arno", in Pisa, Italy.
- Mireille Bossy was invited to the workshop *Boundaries, Multiscale dynamics, and Stochastic* in Rennes (May 2024), and to the STUOD Group at ICL (Online Sandbox Session, November 2024).
- Christophe Henry was invited to give a seminar in the Physics Report Seminar Series on November 7th, 2024 (link to the webinar).

9.1.5 Leadership within the scientific community

- Jérémie Bec is in charge of the Academy of excellence "Complex Systems" of the IDEX Université Côte d'Azur (Decision-making role for funding; Coordination and animation of federative actions); Jérémie Bec is also member of the Laboratory Council at the Institut de Physique de Nice and is a member of the laboratory executive board as coordinator of the "Soft Matter" axis.
- Mireille Bossy is Chairing of the Scientific Council of the Academy of excellence "Complex Systems" of the IDEX Université Côte d'Azur.

- Since July 2024, Mireille Bossy is member of the Scientific Committee of the "Maison de la simulation et des interactions" of Université Côte d'Azur.

CALISTO team members are involved in the scientific/steering committees of several national research networks. This includes the following GdR (CNRS Research network):

- RT-UQ : Research network on Uncertainty Quantification (former GdR Mascot-NUM).
- GdR Défis théoriques pour les sciences du climat on theoretical aspects for climate science.
- GDR Calcul that promotes communication and exchange within the computing community in France.

CALISTO team members are also involved as partners in other networks including: GdR Navier-Stokes 2.0 on turbulence, and Euromech (European Mechanics Society).

9.1.6 Scientific expertise

- Jérémie Bec participated in a tenure evaluation committee for the Okinawa Institute of Science and Technology, Japan.
- Mireille Bossy was vice-chair of the hiring committee PR 26 at LaMME, Université d'Evry Val d'Essonne, and member of the hiring committee PR 26 at Université d'Orleans.
- Mireille Bossy reviewed project propositions from the generic ANR AAP 2024.

9.1.7 Research administration

- Jérémie Bec and Laetitia Giraldi are members of the Comité Nice for Inria Center at Université Côte d'Azur.
- Christophe Henry is acting as the local correspondent for the yearly activity reports of all Teams within Inria Center at Université Côte d'Azur.
- Mireille Bossy s a member of the Project-team Committee's Bureau of the Inria research center at Université Côte d'Azur.

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

CALISTO scientific staff have been involved in the following teaching activities:

- Assignments (Khôlles) in preparatory schools MPSI, MP* (Laetitia Giraldi, 2h weekly, Centre International de Valbonne).
- Advanced models for hydrology (Christophe Henry): master students in their final (fifth) year within the program "Génie de l'eau" (47h) at the engineering school Polytech'Nice.

9.2.2 Supervision

- PhD Defense: Zakarya El-Khiyati defended his PhD on December 13 2024, under the supervision of Jérémie Bec and Laetitia Giraldi
- PhD Defense: Fabiola Gerosa defended her PhD on September 27 2024: "Turbulent fluid-particles coupling and applications to planet formation" started in October 2021, supervised by Jérémie Bec and Héloïse Méheut (Lagrange, Observatoire de la Côte d'Azur).
- PhD in progress: Paul Maurer, "Stochastic models for deformable particle dynamics in turbulence: mathematical analysis and simulation for temporal intermittency and long-range correlation models" started in October 2022; supervised by Mireille Bossy.

- PhD in progress: Nicolas Valade, “Spontaneous stochasticity of quasi-geostrophic surface turbulence” started in October 2022; supervised by Jérémie Bec and Simon Thalabard (Institut de Physique de Nice, Université Côte d’Azur).
- PhD in progress: Lucas Palazzolo is pursuing his PhD under the supervision of Laetitia Giraldi. His work focuses on the control and optimization of micro-swimmers as part of the NEMO ANR project.
- PhD in progress: Celine Van-Landeghem is pursuing her PhD at IRMA, Université de Strasbourg, under the co-supervision of Laetitia Giraldi. Her research focuses on the numerical framework for micro-swimmers, as part of collaborative projects involving Christophe Prud’Homme (IRMA, Université de Strasbourg).
- M2 internship: Yanis Meziani (Sorbonne Université) supervised by Mireille Bossy and Christophe Henry.
- Inria Chile Internship: Diego Ruiz (Universitad de Chile) supervised by Mireille Bossy.
- M1 internship: Bernhard Eisvogel (Sorbonne Université) supervised by Mireille Bossy.

9.2.3 Juries

- Habilitation defense Referee: Mireille Bossy served as referee for the Habilitation thesis of Celine LABART (Laboratoire de mathématiques, Université Savoie Mont-Blanc) on *Some contributions to numerical schemes for backward stochastic differential equations* (June 26, 2024).
- Ph.D. defense Referee: Mireille Bossy served as referee for the Ph.D. thesis of Berenger HUG (University de Rennes) on *Analyse mathématique de modèles stochastiques de dynamique des fluides* (December 19, 2024). Jérémie Bec was referee of the thesis of Antoine BARLET (Université Paris Saclay) on *From a rough flow to experiments: a path towards probing spontaneous stochasticity* (October 11, 2024) and of Gin GE (Centrale Lille) on *Evolution of uncertainty in three-dimensional Navier-Stokes turbulence* (December 10, 2024).
- Ph.D. defense Chair: Mireille Bossy served as Jury chair for the Ph.D. theses of Elias FEKHARI (Université Côte d’Azur) *Quantification d’incertitudes en simulation multiphysique pour la gestion d’actifs éoliens*; Athanasios VASILEIADIS (Université Côte d’Azur) on *Apprentissage par renforcement à champ moyen : une perspective de contrôle optimal*; Thibaut DEVOS (Mines Paris, Université PSL) on *Flux-corrected transport strategies for continuous finite element approximations of the compressible Euler equations on unstructured meshes.* Jérémie Bec chaired the PhD defense of Selim MECANNA (Aix-Marseille University) on *A critical assessment of reinforcement learning methods for bio-inspired navigation*.
- Ph.D. defense Examiner: Mireille Bossy served as an examiner for the Ph.D. theses of Lucas JOURNEL (Sorbonne université) on *Long-time behavior of some Markov processes, and application to stochastic algorithms*, Guilhem BALVET (Marne-la-vallée, ENPC) on *Lagrangian Modelling of gas/particle pollutant dispersion for atmospheric flows within stable, neutral and unstable situations*. Laetitia Giraldi served as an examiner for the PhD defense of Jessie Levillain, which took place at École Polytechnique (Palaiseau) on September 27th, 2024.

9.3 Popularization

9.3.1 Participation in Live events

- Fête de la Science: Every year, a science festival is held across France in autumn where researchers present their activities to the public (especially for kids and young students).
  - Christophe Henry took part in the festival held in Villeneuve-Loubet (October 6th, 2024) and in Valbonne (October 5th, 2024), presenting a workshop on "Water and senses: from perception to the physical sense”.

- Terra Numerica (TN): TN is a federative project for the dissemination of digital science (initiated by CNRS, Inria and Université Côte d'Azur). CALISTO scientific staff took part in the following activities organized within TN:
  - Christophe Henry gave a 3h intervention during the educational activity "Stage Math C2+" that took place on July 1st, 2024 in front of an audience of 40 students in the first year of upper secondary education (classe de 2nde au Lycée).
  - Christophe Henry gave a 1h intervention during the educational activity "Stage 3e" that took place on December 17th, 2024 in front of an audience of 15 students in the last year of lower secondary education (classe de 3ème au collège).
  - Christophe Henry gave a 1h wide-audience presentation on "Physics and Mathematics of sand castles" that took place on June 25th, 2024 during the monthly presentation held at TN.
  - Christophe Henry took part in 3 of the practical workshops held every first Saturday of each month, from 2pm to 6pm with workshops on the "Physics of sand castles" and on "Water and senses".
- Sciences pour Tous 06 (SPT06): SPT06 is an association that organizes regular scientific conferences for the general public in the Alpes-Maritimes department.
  - Christophe Henry gave a 1h presentation on "Sandcastles: is there a recipy that does not fail?" on two occasions (in Biot on February 29th, 2024 and in Villeneuve-Loubet on September 9th, 2024).

10 Scientific production

10.1 Publications of the year

International journals

[1] J. Bec, K. Gustavsson and B. Mehlig. 'Statistical models for the dynamics of heavy particles in turbulence'. In: *Annual Review of Fluid Mechanics* 56.1 (2024), pp. 189–213. DOI: 10.1146/annurev-fluid-032822-014140. URL: https://hal.science/hal-04058674 (cit. on p. 12).

[2] J. Bec, C. Brouzet and C. Henry. 'Enhanced transport of flexible fibers by pole vaulting in turbulent wall-bounded flow'. In: *Physical Review Fluids* 9.6 (11th June 2024), p. L062501. DOI: 10.1103/PhysRevFluids.9.L062501. URL: https://hal.science/hal-04296840 (cit. on p. 14).

[3] J. Bec and R. Vallée. 'Homogeneous turbophoresis of heavy inertial particles in turbulent flow'. In: *Journal of Fluid Mechanics* 999 (5th Nov. 2024), https://doi.org/10.1017/jfm.2024.980. URL: https://hal.science/hal-04781927 (cit. on p. 13).

[4] C. Calascibetta, L. Giraldi, Z. E. Khiyati and J. Bec. 'Effects of collective patterns, confinement, and fluid flow on active particle transport'. In: *Physical Review E* 110 (2nd Dec. 2024), p. 064601. DOI: 10.1103/PhysRevE.110.064601. URL: https://hal.science/hal-04781941 (cit. on p. 14).

[5] L. Giraldi, P. Lissy, C. Moreau and J.-B. Pomet. 'Necessary conditions for local controllability of a particular class of systems with two scalar controls'. In: *ESAIM: Control, Optimisation and Calculus of Variations* 30.4 (2024). DOI: 10.1051/cocv/2023073. URL: https://hal.science/hal-02178973 (cit. on p. 15).

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[8] N. Valade, S. Thalabard and J. Bec. 'Anomalous dissipation and spontaneous stochasticity in deterministic surface quasi-geostrophic flow'. In: *Annales Henri Poincaré* 25.1 (2024), pp. 1261–1283. DOI: 10.1007/s00023-023-01284-3. URL: https://hal.science/hal-03868221 (cit. on p. 16).

[9] C. Van Landeghem, L. Berti, V. Chabannes, A. Chouippe, L. Giraldi, Y. Hoarau and C. Prud'homme. 'Mathematical and computational framework for moving and colliding rigid bodies in a Newtonian fluid'. In: *Annals of Mathematical Sciences and Applications* (2024), pp. 59–89. DOI: 10.4310/AMSA.2024.v9.n1.a2. URL: https://hal.science/hal-04101291 (cit. on p. 15).

International peer-reviewed conferences

[10] C. Brouzet, J. Bec and C. Henry. 'Pole vaulting of long fibres in a turbulent wall-bounded flow'. In: *Complex Days*. Complex Days. 4. NICE, France, Feb. 2024. URL: https://hal.science/hal-04806528 (cit. on p. 14).

Doctoral dissertations and habilitation theses

[11] L. Giraldi. 'Simulations, control and optimization for swimming'. Université Côte D'Azur, 18th Sept. 2024. URL: https://hal.science/tel-04894635 (cit. on p. 11).

Reports & preprints

[12] L. Berti, L. Giraldi, C. Prud'Homme and C. Van Landeghem. *Towards a computational framework using finite element methods with Arbitrary Lagrangian-Eulerian approach for swimmers with contact*. 2024. URL: https://hal.science/hal-04670959 (cit. on p. 15).

[13] M. Bossy and K. Martínez Rodríguez. *Strong convergence of the exponential Euler scheme for SDEs with superlinear growth coefficients and one-sided Lipschitz drift*. 1st May 2024. URL: https://inria.hal.science/hal-04692634 (cit. on p. 17).

[14] M. Bossy, K. Martínez Rodríguez and P. Maurer. *Weak rough kernel comparison via PPDEs for integrated Volterra processes*. 13th Jan. 2025. DOI: 10.48550/arXiv.2501.07509. URL: https://inria.hal.science/hal-04885861 (cit. on p. 18).

[15] M. Bossy and P. Maurer. *On the ε-Euler-Maruyama scheme for time inhomogeneous jump-driven SDEs*. 17th Jan. 2024. URL: https://inria.hal.science/hal-04404438 (cit. on p. 17).

[16] L. Palazzolo, M. Binois, L. Berti and L. Giraldi. *Parametric Shape Optimization of Flagellated Micro-Swimmers Using Bayesian Techniques*. 2024. URL: https://hal.science/hal-04699705 (cit. on p. 16).

10.2 Cited publications

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[18] L. Campana, M. Bossy and J. Bec. 'Stochastic model for the alignment and tumbling of rigid fibres in two-dimensional turbulent shear flow'. In: *Physical Review Fluids* 7.12 (2022), p. 124605. URL: https://hal.inria.fr/hal-03718232 (cit. on p. 17).

[19] J. K. Alageshan, A. K. Verma, J. Bec and R. Pandit. 'Machine learning strategies for path-planning microswimmers in turbulent flows'. In: *Physical Review E* (2020). https://arxiv.org/abs/1910.01728 - 8 pages, 10 figures. DOI: 10.1103/PhysRevE.101.043110. URL: https://hal.archives-ouvertes.fr/hal-02362934 (cit. on p. 7).

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[21] S. Balachandar and J. K. Eaton. 'Turbulent Dispersed Multiphase Flow'. In: *Annual Review of Fluid Mechanics* 42.1 (2010), pp. 111–133 (cit. on p. 10).

[22] P. Bauer, A. Thorpe and G. Brunet. 'The quiet revolution of numerical weather prediction'. In: *Nature* 525.7567 (2015), pp. 47–55 (cit. on p. 10).

[23] A. Berkaoui, M. Bossy and A. Diop. 'Euler scheme for SDEs with non-Lipschitz diffusion coefficient: strong convergence'. In: *ESAIM: Probability and Statistics* 12 (2008), pp. 1–11. DOI: 10.1051/ps:2007030 (cit. on p. 17).

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[25] L. Berti, Z. E. Khiyati, Y. Essousy, C. Prud'homme and L. Giraldi. 'Reinforcement learning with function approximation for 3-spheres swimmer'. In: *IFAC-PapersOnLine* 55.16 (2022). 18th IFAC Workshop on Control Applications of Optimization CAO 2022, pp. 1–6. DOI: https://doi.org/10.1016/j.ifacol.2022.08.072. URL: https://www.sciencedirect.com/science/article/pii/S2405896322011624 (cit. on p. 7).

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