RÉPUBLIQUE
FRANÇAISE
*Liberté*
*Égalité*
*Fraternité*

Inria

# 2025 *Activity Report*

RESEARCH CENTRE: **Inria Centre at Rennes University**

IN PARTNERSHIP WITH: **Université de Bretagne Occidentale, Ecole Nationale Supérieure Mines-Télécom Atlantique Bretagne Pays de la Loire, Institut Français de Recherche pour l'Exploitation de la Mer, CNRS, Université de Rennes**

**Project-Team**

# ODYSSEY

**Ocean DYnamicS obSERvation analYsis**

*In collaboration with* Institut de recherche mathématique de Rennes (IRMAR), Laboratoire des sciences et techniques de l'information, de la communication et de la connaissance, Laboratoire d'océanographie physique et spatiale

# Project-Team ODYSSEY

*Creation of the Project-Team: 2022 March 01*

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

# Keywords


## Computer sciences and digital sciences

A3.1. – Data

A3.1.1. – Modeling, representation

A3.2.3. – Inference

A3.4. – Machine learning and statistics

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.2. – Stochastic Modeling

A6.1.4. – Multiscale modeling

A6.2. – Scientific computing, Numerical Analysis & Optimization

A6.2.1. – Numerical analysis of PDE and ODE

A6.2.3. – Probabilistic methods

A6.2.4. – Statistical methods

A6.3. – Computation-data interaction

A6.3.1. – Inverse problems

A6.3.2. – Data assimilation

A6.3.3. – Data processing

A6.3.4. – Model reduction

A6.3.5. – Uncertainty Quantification

A6.4.1. – Deterministic control

A6.4.2. – Stochastic control

A6.5.2. – Fluid mechanics

A6.5.3. – Transport

A6.5.4. – Waves

A9.2.5. – Bayesian methods

A9.2.6. – Neural networks

A9.2.7. – Kernel methods

A9.2.8. – Deep learning

A9.3. – Signal processing

## Other research topics and application domains

B3.2. – Climate and meteorology

B3.3.2. – Water: sea & ocean, lake & river

B3.3.3. – Nearshore

B3.3.4. – Atmosphere

# Contents

**Project-Team ODYSSEY** 1

**1 Team members, visitors, external collaborators** 4

**2 Overall objectives** 5

**3 Research program** 6
- 3.1 Ocean observations analysis: upper-ocean dynamics, ocean-atmosphere interaction, waves and extreme events. 7
- 3.2 Development and analysis of numerical and mathematical models of geophysical flows 7
- 3.3 Data/Models interactions and reduced order modelling 8
- 3.4 AI models and methods for ocean data analysis 8

**4 Application domains** 9

**5 Social and environmental responsibility** 9

**6 Highlights of the year** 9

**7 Latest software developments, platforms, open data** 9
- 7.1 New platforms 9

**8 New results** 9
- 8.1 Ocean observations analysis: upper-ocean dynamics, ocean-atmosphere interaction, waves and extreme events. 9
- 8.2 Development and analysis of numerical and mathematical models of geophysical flows 12
- 8.3 Data/Models interactions and reduced order modelling 16
- 8.4 AI models and methods for ocean data analysis 18

**9 Bilateral contracts and grants with industry** 20
- 9.1 Bilateral Grants with Industry 20

**10 Partnerships and cooperations** 21
- 10.1 International initiatives 21
  - 10.1.1 Participation in other International Programs 21
- 10.2 International research visitors 21
  - 10.2.1 Visits of international scientists 21
  - 10.2.2 Visits to international teams 21
- 10.3 National initiatives 22
- 10.4 Regional initiatives 25

**11 Dissemination** 25
- 11.1 Promoting scientific activities 25
  - 11.1.1 Scientific events: organisation 25
  - 11.1.2 Journal 25
  - 11.1.3 Invited talks 26
  - 11.1.4 Scientific expertise 26
  - 11.1.5 Research administration 26
- 11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach 26
  - 11.2.1 Supervision 27
  - 11.2.2 Juries 29
  - 11.2.3 Educational and pedagogical outreach 29

**12 Scientific production** 29
- 12.1 Publications of the year 29

# 1 Team members, visitors, external collaborators

## Research Scientists

- Etienne Memin [Team leader, INRIA, Senior Researcher, HDR]
- Bertrand Chapron [Ifremer, HDR]
- Clement De Boyer Montégut [IFREMER, Researcher]
- Quentin Febvre [IFREMER, from Apr 2025]
- Noe Lahaye [INRIA, Researcher]
- Claire Menesguen [IFREMER, Researcher]
- Alexis Mouche [IFREMER]
- Frederic Nouguier [IFREMER, Researcher]
- Jean-Francois Piolle [IFREMER]
- Aurelien Ponte [IFREMER, Researcher]
- Nicolas Reul [IFREMER, Researcher]
- Gilles Tissot [INRIA, Researcher]

## Faculty Members

- Xavier Carton [UBO, Professor]
- Lucas Drumetz [IMT ATLANTIQUE, Associate Professor]
- Ronan Fablet [IMT ATLANTIQUE, Professor]
- Carlos Granero Belinchon [IMT ATLANTIQUE, Professor]
- Jonathan Gula [UBO, Associate Professor]
- Roger Lewandowski [UNIV RENNES, Professor, HDR]
- Said Ouala [IMT ATLANTIQUE, Associate Professor]
- Guillaume Roullet [UBO, Professor]
- Pierre Tandeo [IMT ATLANTIQUE, Associate Professor]

## Post-Doctoral Fellows

- William Antolin [INRAE Rennes]
- Ariane Barlet [INRIA, Post-Doctoral Fellow]
- Perrine Bauchot [IMT Atlantique]
- Simon Benaichouche [INRIA, Post-Doctoral Fellow]
- Eugenio Cutolo [IMT Atlantique]
- Solène Dealbera [IMT Atlantique & SHOM]
- Erwan Le Roux [IMT Atlantique]
- Sophie Mauran [INRIA, Post-Doctoral Fellow, from Sep 2025]
- Paul Platzer [IMT Atlantique]
- Ezra Rozier [INRIA, Post-Doctoral Fellow]

### PhD Students

- Adrien Acchiardi [INRIA, from Oct 2025]
- Daria Botvynko [IMT Atlantique]
- Daria Botvynko [IMT Atlantique & ENIB]
- Margot Demol [Ifremer]
- Ewen Frogé [IMT Atlantique]
- Emilio Gonzales [IMT Atlantique]
- Mael Jaouen [INRIA]
- Clément Lacrouts [Ifremer]
- Vincent Mokuenko [UBO]
- Antoine Moneyron [INRIA]
- Sebastien Moskowitz [INRIA]
- Matteo Nex [INRIA]
- Théo Picard [UBO]
- Tom Protin [Ifremer]
- Raphael Ravasse [UBO]
- Gaetan Rigaut [INRIA]
- Gwendal Saliou [IMT Atlantique]

### Technical Staff

- Francesco Tucciarone [INRIA, Engineer]

### Administrative Assistant

- Caroline Tanguy [INRIA]

## 2 Overall objectives

Covering more than 70% of the Earth's surface, the oceans play key roles on the Earth climate regulation as well as for human societies. Yet, from wave breaking events to the movement of weather systems, the predictive capabilities of models notoriously quickly diminish with increasing lead times, even with the assistance of the world's largest supercomputers. Despite ever-increasing developments to simulate and observe the coupled ocean-atmosphere system, our ability to understand, reconstruct and forecast the ocean dynamics remains fairly limited for numerous applications.

Our motivations are to help break this apparent logjam, and more specifically to bridge model driven and observation-driven paradigms to develop and learn novel stochastic representations of the coupled ocean-atmosphere dynamics. To address these challenges, Odyssey gathers a unique transdisciplinary expertise in Numerical Methods, Applied Statistics, Data Science, Satellite and Physical Oceanography. Methodological developments are primarily implemented and demonstrated through three main objectives: (i) the analysis of mesoscale/submesoscale processes and internal waves, (ii) the monitoring of extremes ocean-atmosphere events and routes to rapid intensifications; (iii) the derivation of forefront deep-learning stochastic data assimilation techniques. The name Odyssey is a short-cut that stands for "Ocean DYnamicS obSErvation analYsis' – the keyword "Analysis" has to be understood in terms of physical understanding, mathematical analysis and data analysis.

The objectives and research actions of the team can be separated in four methodological axes:

**Ocean observations analysis** This axis aims at exploiting novel multi-modal high-resolution observations of the ocean – mostly at the surface – through new methods of mathematical analysis, numerical simulations, stochastic analysis and machine learning to create new capabilities. The main scientific target, besides the upper ocean variability, addresses the air-sea exchanges and the rapid intensification of extreme events.

**Development and analysis of numerical and mathematical models of geophysical flows** The context of this research axis is the modelling and analysis issues of geophysical fluid dynamics. A major research effort concerns the development of stochastic modelling and its implementation in numerical models in order to address uncertainty quantification. More generally, the analysis of mathematical models on the one hand, and of data from high-resolution numerical models, on the other hand; together with the improvement of numerical schemes and the development of parameterizations (of unresolved processes) for numerical models forms the corpus of objectives in this axis.

**Data/Models interactions and reduced order modelling** Several data assimilation models are being developed with a wide range of applications, from near surface high-frequency submesoscale motions estimation to extreme event hindcast and up to basin-scale dynamics reconstruction. At the base of this work is the design and validation of simplified models based on physics and data-driven reduced order models that allows for an optimal coupling with observations. At the same time, new uncertainty-handling data assimilation strategies are being developed.

**AI models and methods for ocean data analysis** We aim to bridge the physical paradigm underlying ocean and atmosphere science and AI paradigms with a view to developing and identifying physically relevant representations of geophysical dynamics accounting for the specificities and complexities of the processes involved. To this end, we propose to jointly explore three main complementary data-driven frameworks (including their possible couplings): analog schemes, kernel approaches (especially RKHS – Reproducing kernel Hilbert space) and deep neural network (NN) representations.

# 3 Research program

A primary focus of the team intends to better characterize poorly known mechanisms of energy redistribution operating at different scales, through the interactions of different physical mechanisms such as hydrodynamical instabilities, internal or wind waves, turbulence and ocean atmosphere feedback exchanges. Our first credo is that an improved physical understanding cannot be achieved uniquely on the basis of sparse-in-time observations alone or from intrinsically imperfect models: data without models are uninformative and models built without data are useless, as models are generally too far from real-world situations of interest. Today, data and models shall thus be combined to tackle uncertainty quantification and probabilistic ensemble forecasting issues, as advanced data-driven representation of ocean dynamics requires; to that end we need to drift from a purely deterministic physics toward stochastic representations. This is the second credo. Many aspects of the models or of the data-model coupling functional still need to be specified or parameterized through dynamically-adapted basis functions, evolving parameters or covariance matrices. Our third credo is that the improved physical understanding of the multi-scale interactions encoded in such parametrizations can be learned or estimated from data.

The research objectives of our group naturally distribute in several challenges, exploring multimodal (differing space-time resolutions, differing passive and active microwave instruments, ...) observations, air-sea exchanges and upper ocean dynamics, bottom boundary turbulent processes, stochastic flow representations, data assimilation and machine learning procedures. All these challenges take place or rely on principles and/or tools of the four methodological contexts introduced above.

## 3.1 Ocean observations analysis: upper-ocean dynamics, ocean-atmosphere interaction, waves and extreme events.

Global Earth Observation (GEO) systems, in situ and satellite platforms, have significantly improved our understanding and capability to study the Earth's environment. Key products today include, among others, merged global ocean surface topography using the different available altimeter missions, global and daily high-resolution sea surface temperature and ocean colour using multi-sensor and platform measurements. One may also cite the mapping of high sea winds from combined radiometer/scatterometer, including very-high resolution synthetic aperture radar observations, and more recently, the fusion of sea state data (largely improved with the recently launched CFOSAT mission, combined with Copernicus Sentinel-1 and 2 measurements). Pushing to higher spatial resolution (about 10 m to 1 km), signatures of tracer variations from imaging instruments can further provide quantitative information, especially for characterizing internal and surface waves in interactions with the ambient underlying upper ocean flow. Note, modern satellite sensor capabilities, sustained under the Copernicus programme, will soon include the new wide-swath Surface Water & Ocean Topography (SWOT) altimeter, to more precisely characterize ocean sea surface height variability. An essential goal is thus to incorporate and combine these high resolution global observations of air-sea exchanges and upper ocean dynamics into our applications of new methods of mathematical analysis, numerical simulations, stochastic analysis and machine learning to create new capabilities. We aim to combine multi-sensor data algorithm developments with advances in mining and learning from multi-modal observations, i.e. satellite and in-situ measurements, including numerical outputs. The scientific targets of this axis are to fully unveil (1) upper ocean mesoscale variability and its associated lateral exchange processes, known as "eddy fluxes", (2) sub-mesoscale variability and associated upper-ocean vertical exchange processes, known as "vertical exchange", and finally (3) internal gravity wave variability (induced by winds, tides, and interactions of low-frequency currents with topography). Another central scientific objective is to explore and develop data-model-driven techniques in the context of extreme marine-atmosphere events, to provide new insights for air-sea exchanges processes and adapted parameterization under extreme conditions.

## 3.2 Development and analysis of numerical and mathematical models of geophysical flows

The core of this theme of research addresses modelling and analysis issues in geophysical fluid dynamics. Within this context, we mainly focus on the study of the dynamics of the upper oceanic circulation. One overall objective is to devise random models representing the effects of the computationally unresolvable scales of fluid motion on the resolved scales. Such models are used for ensemble forecasting, uncertainty quantification and data assimilation. The representation of the fine-scale effects on the coarser scales of motion depends on the level of geophysical fluid approximation pertinent to the data resolution and to the scale of the other physical processes involved. An important research effort of the team in this context is to pursue the development of a recently established class of models of stochastic transport in fluid dynamics at the most fundamental level. This class of models, referred to as *model under Location Uncertainty* (LU), has the advantage to be derived from physical conservation laws expressed through the stochastic transport of fluid parcels. As such, they are easily extendable to classical approximations of geophysical dynamics. and the stochastic partial differential equations have nearly the same shape as the corresponding deterministic ones. As for the ocean models, a known hierarchy of approximate stochastic models can be built from the Navier-Stokes equations almost exactly in the same way as in the deterministic setting. One of their strong assets is to lead to proper energy conservation and provide new approaches to subgrid parameterization, expressed both in terms of fluctuation distributions, and spatial/temporal correlations.

Research activities in the ODYSSEY team on this subject are many. First, the mathematical properties of the involved stochastic partial differential equations are poorly known and need to be explored. The overall objective of the challenge is to explore to what extent the known properties of deterministic flow dynamics models are conserved in the stochastic framework. This concerns for instance local well-posedness of the Navier- Stokes equation or of its oceanic representatives. Another issue concerns the physical analysis of such systems. Do the stochastic systems with general noise models still admit some wave solutions (Rossby wave, Gravity waves, internal waves, etc.)? The characterization of the statistical moments associated with those wave solutions are of primal interest from a physical perspective but also to define proper shape functions for the random terms involved. All these issues are currently being studied within the STUOD project. Finally, the ODYSSEY team also addresses the development and validation of new numerical schemes for both deterministic and stochastic models of geophysical flows. In the stochastic case, the numerical approximation of the SPDEs requires the discretization of both the space and time domains. For the spatial discretization classical schemes can be used, however special care must be taken for the temporal schemes. The consistency of several splitting schemes is studied and numerically implemented.

## 3.3 Data/Models interactions and reduced order modelling

A first research effort in this theme is dedicated to the development of ensemble data assimilation techniques for geophysical problems (in this context, models and observations from e.g. satellites), addressing the issue of linearity and gaussianity hypotheses, which are major limitations of these approaches. Following recent results on the application of particle filters to address these issues on high-dimension problems, we further develop new schemes relying on multiscale dynamical paradigms. Particle filters comprise a class of numerical methods that produce asymptotically consistent approximations of posterior distributions of partially observed systems. We study hierarchical ensemble data assimilation filters, able to handle multiscale interaction in a nested hierarchy of models (from coarse to fine scale). This multiscale capability (not available today even in a simple coarse form) is expected to provide an important analysis tool to study ocean/atmosphere interactions at different scales. The hierarchy of ocean dynamics models rely on the nested capability provided by the stochastic derivation framework described in the second methodological context.

A second axis of work is dedicated more directly to the development, the implementation and the validation of simplified models of the ocean dynamics, with the main target to couple these models to the observation via data assimilation techniques. These models aim at covering a wide range of motions in the ocean. The mesoscale eddying dynamics (with typical horizontal scales greater than 100 km), such as multi-layer QG models with the inclusion of active temperature tracer (Thermal QG or coupled Surface QG / QG models) and/or surface mixed layer, allowing to couple the dynamics to sea surface temperature data. Higher frequency motions, such as internal waves and internal tides, are addressed using a hierarchy of models based on the rotating shallow water equations (possibly with some linearization). The development of these models mirrors the evolving nature and growing quantity of data available, with recent and new missions such as SWOT or CFOSAT.

## 3.4 AI models and methods for ocean data analysis

This research axis is focused on the exploration and development of data-driven and learning-based schemes and their interactions with model-based approaches, which constitute the state-of-the-art in ocean and atmosphere science. The general goal is to improve the understanding, modeling, forecasting and reconstruction of air-sea exchanges and upper ocean dynamics, as well as bottom turbulent processes, from the in-depth exploration of the existing observation and simulation data. We jointly explore three main complementary data-driven frameworks, including their possible couplings: analog schemes, kernel approaches, especially RKHS (Reproducing kernel Hilbert space), and deep neural network (NN) representations. RKHS and NN naturally arise as they may directly link to model-driven representations (e.g., NN regarded as discrete numerical solvers for ODE/PDE). Analog methods provide simple yet efficient sampling schemes for complex dynamics. Our recent contributions emphasize the relevance of these data-driven frameworks for the modelling, forecasting and assimilation of upper ocean dynamics on toy models. Ongoing studies aim at extending such methodologies for the learning of subgrid processes in full models. Besides, our recent developments illustrated on simplified systems, including for instance the identification of Neural ODE representations for partially-observed systems as well as the identification of stochastic latent dynamics, provide the methodological and numerical basis for the considered challenges.

This research axis specifically investigates the following issues: (i) embedding explicit or implicit physics-informed priors (e.g., stability, conservation laws, stochasticity, chaos...) into data-driven and hybrid representations, (ii) learning latent representations for oceanic flows and air-sea exchanges accounting for flow stochasticity, including extreme events (iii) learning schemes when dealing with partially-observed, irregularly-sampled and noisy dynamics, (iv) the joint learning of data-driven representation and associated data assimilation schemes, possibly directly from observation data.

# 4 Application domains

The application domain is mainly geophysical environmental flows, related to ocean dynamics. By designing new approaches for observation analysis, data-model coupling and stochastic representation of fluid flows, the Odyssey group contributes to several application domains of great interest for the community and in which the analysis of complex turbulent flow is key.

# 5 Social and environmental responsibility

Ocean circulations play a major role in the climate and in the biodiversity of ecosystems. These aspects are crucial for the sustainability of the resources of human societies. Understanding and providing tools to predict ocean dynamics is a brick to apprehend our environment and to help making decisions.

# 6 Highlights of the year

The team is being evaluated this year and is currently waiting for the reviews from the experts.

# 7 Latest software developments, platforms, open data

## 7.1 New platforms

**Participants:** Ronan Fablet, Pierre Tandeo.

Machine learning for ocean dynamics tools, available under free-license (licence Ceccil-C) on the GIT repository (link).
Python library for Kalman filtering and smoothing in dynamical systems Python library with augmented state (link).

# 8 New results

## 8.1 Ocean observations analysis: upper-ocean dynamics, ocean-atmosphere interaction, waves and extreme events.

**Tropical cyclone characterization from observations**

**Participants:** Alexis Mouche, Nicolas Reul, Frédéric Nouguier, Bertrand Chapron.

Recalling that our current paradigm is that process understanding derived from measurements shall foster improved models (theoretical, numerical) for improved both short-term predictions and long-term projections, important efforts have been dedicated on targeting marine-atmosphere extreme events. Indeed, NWP re-analysis (e.g. ERA-5) generally poorly resolves extreme marine-atmosphere events and their surrounding environment. Such spatio-temporal inconsistencies and unreliability of global historical re-analyses can thus hamper more accurate simulation and the projection of future changes in the main characteristics (size, intensity, locations, translation speed) of extreme events. In particular for intense vortex systems (tropical cyclones, polar lows), near-core surface wind structural properties are today still not precisely recorded and re-analyzed. Present-day available model-data cubes must thus be more systematically combined with direct observations (satellite, in situ). In particular, some theoretical and observational evidences have been accumulated and tested to monitor the integrated kinetic energy. Two characteristic scales have been identified and uniquely estimated using high-resolution ocean surface winds from all-weather spaceborne synthetic aperture radar: the radius of significant upward motions in the inflow layer, controlled by the surface wind decay, and the radius of vanishing azimuthal velocity in the outflow layer, associated with the maximum surface winds. By juxtaposing the high-resolution measurements with best-track intensity and size time derivative estimates, the instantaneous knowledge of the two characteristic scales has then been shown to inform on the steadiness of the integrated kinetic energy. The resulting criterion of steadiness depends on a multiplicative constant characterizing the system's thermodynamics. Part of this investigation is in the context of Arthur Avenas PhD work.

**Building databases of marine-atmosphere extreme event**

**Participants:** Alexis Mouche, Nicolas Reul, Jean-François Piollé.

Within the Marine-Atmosphere eXtreme Sensor Synergy (MAXSS) project, the team builds an advanced and unique workbench to more precisely study these ocean-atmosphere extreme events, from their generation to their impacts. Specifically, efforts have been dedicated to generate new 10-year-long databases:

- Intercalibrated satellite surface winds in extreme conditions.
- A global 10-year multi-mission surface wind (MMW) derived from the merging of these inter-calibrated sensor wind estimates.
- A storm atlas of all-available Earth Observation (EO) data collected around tropical cyclones (TCs), extra-tropical storms (ETC), and polar lows (PLs).
- An atlas of pre-storm upper ocean conditions, atmospheric forcing during the storms, and induced post-storm upper ocean impacts in the storm wakes.
- A new database of high resolution TC vortex, inner and outer core wind structural distribution.
- A new database of ocean swell characteristics (energy, wavelength, direction) generated by different all available sensors (satellite, in situ) and model outputs.

**Characterization of oceanic high frequency variability from altimeter and surface drifting buoys**

**Participants:** Margot Demol, Noé Lahaye, Aurélien Ponte.

We address several challenges that are expected to arise when analyzing future SWOT data: the separation of wave and eddy dynamics, and spatio-temporal sampling issues. Following Zoé Caspar-Cohen's PhD thesis, we have analysed a realistic numerical simulation (LLC4320) and proposed a conversion metrics to infer eulerian internal tide energy from drifting buoys measurements. Two articles have been published in Scientific Report this year (Caspar-Cohen et al. 2025 entitled "Combining surface drifters and high resolution global simulations enables the mapping of internal tide surface energy" and Rayson et al. 2025 entitled "Characteristic Velocity and Timescales of Nonphase-Locked Internal Tides in a Mesoscale Eddy Field"). We also pursued the combined analyses of altimetry and in situ observations (drifting buoys) as a part of Margot Demol's thesis, who defended this year. An article has been published in JGR this year (Demol et al. "Diagnosis of Ocean Near-Surface Horizontal Momentum Balance from pre-SWOT altimetric data, drifter trajectories, and wind reanalysis"). The corresponding analysis of SWOT altimetry and drifter trajectories in the Mediterranean Sea has also been submitted to GRL this year.

**Towards a stochastic generalized Ekman model with application to uncertainty quantification**

**Participants:** Long Li, Matteo Nex, Étienne Mémin, Bertrand Chapron.

We introduce a stochastic approach to model the ocean surface Ekman boundary layer. This model incorporates wind, surface waves, and turbulent mixing effects. A steady version as well as a time dependent version of this generalized Ekman model has been developed. They both consider the vertical mixing effect of Stokes drift in addition to traditional Ekman-Stokes terms. The stochastic approach aligns with traditional parameterizations through random parameter definitions. Numerical simulations are used to assess uncertainties in the Ekman layer, focusing on statistical moment responses and sensitivity analyses of random parameters. Several vertical diffusion schemes have been included and compared. The model has been recently extended to include an evolving buoyancy profile.

**Characterization of linear and nonlinear internal tide dynamics**

**Participants:** Xavier Carton, Noé Lahaye, Aurélien Ponte, Gilles Tissot.

We have finalized the previous work from Adrien Bella PhD thesis on the characterization of the loss of coherence in the North Atlantic ocean based on realistic high-resolution numerical simulations. We have diagnosed the terms accounting for interactions between the internal tide and the mesoscale currents, extended the previous theoretical framework to include a decomposition of the signal in a coherent and an incoherent part. A paper has been published in Ocean Science.

On a different axis of research, we have analysed the Sea Level Anomaly data from the SWOT mission to characterize the non-linear internal solitary wave activity in the Maluku Sea. To this aim, we have developed a method to identify the nonlinear wave packet and individual peaks and analyze their shape (width and amplitude), as well as their propagation velocity. We are currently processing these data to compare the observations with expectations from theory (e.g. based on the Korteweg-De-Vries equation for a stratified fluid).

In the Gibraltar region (context of J. B. Roustan former PhD work), we have shown that the barotropic tide coupled with the Atlantic inflow/Med outflow exchange, leads to hydraulic jumps on Camarinal Sill and to the formation of internal bores. These bores degenerate into internal waves and particularly into solitary waves (ISW), which propagate eastward and to a lesser degree, westward, southward and northward (by reflection on the Moroccan shelf). Bore and wave breaking lead to an intense diapycnal mixing which is well characterized at the interface between the inflow and the outflow. Vertical recirculation and strong turbulent mixing is observed in the bottom (frictional) layer. These results have been published in Scientific Report.

**Mesoscale eddies and near-surface ocean dynamics**

**Participants:** Xavier Carton, Claire Ménesguen, Guillaume Roullet.

We address the dynamics of the near-surface. A collaboration with Hereon has launched us on the analysis of a dataset from two campaigns in the Agulhas Current region, where the Diurnal Warm Layer signal is predominant, and in which microstructure measurements have been made. Analysis of near-surface mixing processes is the subject of an article in preparation and a chapter in Mariana Lage's thesis.

Furthermore, in the context of mesoscale/submesoscale variability of the surface and shallow subsurface ocean, we have conducted several studies investigating the dynamics of vortices in the Quasi-Geostrophic equations, and how they can merge over a bathymetry (Reinaud, Lacasce & Carton 2025) and in the Thermal Quasi-Geostrophic model (Carton, Barabinot & Roullet 2025), in rather idealised configurations. In much more realistic configurations and based on observations, we have developed and applied a PV framework to diagnose the dynamics of mesoscale eddies (Barabinot, Speich & Carton 2025). Finally, several studies have addressed the identification and characterisation of mesoscale eddies based on In Situ and remote observations and investigation of their dynamics in the ocean (papers resulting from Y. Barabinot PhD work).

**Modern statistical methods applied to historical data and satellite observations**

**Participants:** Pierre Tandeo, Florian Sevellec.

ODYSSEY researchers use and develop methods to study global climate change to fill critical gaps in ocean and cryosphere observations. By applying modern statistical frameworks, researchers are now able to transform sparse historical data and complex satellite observations into clear, actionable trends.

## 8.2 Development and analysis of numerical and mathematical models of geophysical flows

#### Very-high resolution numerical simulations of the ocean dynamics

**Participants:** Jonathan Gula, Claire Ménesguen, Xavier Carton, Guillaume Roullet.

We have studied the Mozambique Channel region. High-resolution, particularly in the ocean interior, simulations has enabled us to highlight regions propitious to internal mixing, particularly at the edge of the Mozambique Channel rings, which have very strong dynamics. The simulations also highlighted a spurious numerical instability: BICK (Baroclinic Instability of the Computational Kind). Studying BICK, we produced recommendations for the choice of horizontal and vertical resolutions of numerical models using Lorenz discretization on the vertical (publication in JAMES)

Over the past year we have continued to analyse our numerical solutions GIGATL Gula et al. 2021, which are simulations of the Atlantic Ocean using the CROCO model at meso- and submesoscale resolutions (6 km, 3 km and 1 km) with realistic topography, high-frequency surface forcing and tidal forcing. An example animation showing the surface dynamics (eddies and waves) and the richness of the deep circulation, in particular the coherent eddies, is shown here. These simulations have also been used for physical analyses of several flow features:

**Fronts** Dauhajre et al. (2025) showed how small-scale turbulent vertical mixing controlled the sharpening or weakening of upper-ocean fronts, thereby modulating frontal heat transport. Simulations identified a measurable parameter that predicted frontal evolution and provided a new framework for improving front parameterization in climate models.

**Bottom circulation** Schubert et al. (2025) demonstrated a systematic downslope near-bottom flow with compensating upward recirculation above the seafloor, revealing a fundamental structure of abyssal circulation. Santos et al. (2025) showed that contraction of Antarctic Bottom Water drove abyssal warming in the Argentine Basin, highlighting large-scale changes in bottom water circulation.

**Mesoscale / topography interactions** De Marez et al. (2025) quantified mesoscale-induced vertical fluxes over the Iceland–Faroe Ridge, using high-resolution observations from the SWOT mission and from the GIGATL model.

**Hydrothermal sources** Lemaréchal et al. (2025) characterized near-field hydrothermal plume dynamics using large-eddy simulations and observations, advancing understanding of mixing and dispersion from hydrothermal sources.

These results led to publications in J. Geophys. Res. Oceans (Duan et al 2024, Picard et al 2024, Vic et al 2024, Napolitano et al 2024), Journal of Physical Oceanography (Capo 2024), Proc. Natl. Acad. Sci. U.S.A. (Mashayek et al 2024) and Geophysical & Astrophysical Fluid Dynamics (Carton et al 2024).

#### Geophysical flows modelling under location uncertainty

**Participants:** Noé Lahaye, Long Li, Étienne Mémin, Gilles Tissot, Francesco Tucciarone.

In this research axis we have devised a principle to derive representation of flow dynamics under location uncertainty. Such an uncertainty is formalized through the introduction of a random term that enables taking into account large-scale approximations or truncation effects performed within the dynamics analytical constitution steps. Rigorously derived from a stochastic version of the Reynolds transport theorem, this framework, referred to as modeling under location uncertainty (LU), encompasses several meaningful mechanisms for turbulence modeling. It indeed introduces without any supplementary assumption the following pertinent mechanisms: (i) a dissipative operator related to the mixing effect of the large-scale components by the small-scale velocity;(ii) a multiplicative noise representing small-scale energy backscattering; and (iii) a modified advection term related to the so-called turbophoresis phenomena, attached to the migration of inertial particles in regions of lower turbulent diffusivity. In a succession of works we have shown how the LU modelling can be applied to provide stochastic representations of a variety of classical geophysical flows dynamics. Numerical simulations and uncertainty quantification have been performed on Quasi Geostrophic approximation (QG) of oceanic models. It has been shown that LU leads to remarkable estimation of the unresolved errors opposite to classical eddy viscosity based models. The noise brings also an additional degree of freedom in the modeling step and pertinent diagnostic relations and variations of the model can be obtained with different scaling assumptions of the turbulent kinetic energy (i.e. of the noise amplitude). For a wind forced QG model in a square box, which is an idealized model of north-Atlantic circulation, we have shown that for different versions of the noise the QG LU model leads to improve long-term statistics when compared to classical large-eddies simulation strategies. For a QG model we have demonstrated that the LU model allows conserving the global energy. We have also shown numerically that Rossby waves were conserved and that inhomogeneity of the random component triggers secondary circulations. This feature enabled us to draw a formal bridge between a classical system describing the interactions between the mean current and the surface waves and the LU model in which the turbophoresis advection term plays the role of the classical Stokes drift. A study of a stochastic version of the primitive equations model is currently investigated within the PhD of Francesco Tucciarone. Preliminary results have been published in the STUOD proceedings.

In another study we explored the calibration of the noise term through dynamic mode decomposition (DMD). This technique is performed on high-resolution data to learn a basis of the unresolved velocity field, on which the stochastic transport velocity is expressed. Time-harmonic property of DMD modes allowed us to perform a clean separation between time-differentiable and time-decorrelated components. Such random scheme is assessed on a quasi-geostrophic (QG) model and has been published in the STUOD proceedings.

**Analysis of stochastic representation of the primitive equations.**

**Participants:** Arnaud Debussche, Étienne Mémin, Antoine Moneyron.

We investigate how weakening the classical hydrostatic balance hypothesis impacts theoretical properties of the LU primitive equation, such as its well-posedness. The models we consider are intermediate between the incompressible 3D LU Navier–Stokes equations and the LU primitive equations with standard hydrostatic balance. Also, they are expected to be numerically tractable, while accounting well for nonhydrostatic phenomena. Our main result is the well-posedness of a certain stochastic interpretation of the LU primitive equations: we proposed a weak filtered hydrostatic hypothesis, meaning the system we consider accounts for the influence of the transport noise of the vertical velocity component, of which higher frequencies are cut off. This well-posedness result holds with rigid-lid type boundary conditions, and when the horizontal component of noise is independent of depth. However, the vertical component of the noise can remain general. In fact, this assumption can be related to the physical validity domain of the primitive equations. Moreover, we present and study two non-filtered models, in which the transport noise of the vertical component is regularised using eddy-(hyper)viscosity terms. In the second axis of study we investigate the limit of the stochastic Navier-Stokes equation toward a stochastic version of the primitive equation.

**Wave solution of stochastic geophysical models**

**Participants:** Bertrand Chapron, Étienne Mémin.

A new stochastic representation of the ocean surface wave formulation is derived, building on the location uncertainty framework, where the Lagrangian velocity is decomposed into a temporally smooth component and a decorrelated stochastic component. Expressing the momentum velocity in Eulerian terms, the transport operator is modified to involve correlated contributions leading to: (i) a large-scale diffusion term; (ii) a correction to the large-scale advection, interpretable either as the Stokes drift correction for correlated advection, as in standard wave motion, or as a turbophoresis term arising from additional decorrelated forcing, such as that induced by wave breaking; (iii) a small-scale random advection. We first examine the implications of time correlations in the small-scale velocity, leading to the emergence of a classical Stokes drift component or a turbophoresis velocity. We then explore a consistent derivation of the wave action conservation principle for stochastic flows. Beyond providing a proper stochastic wave action principle, this study highlights a stochastic form of the wavefront Hamilton-Jacobi equation. The stochastic framework follows the modeling under location uncertainty paradigm. Within this framework, the usual slow component of the underlying current and the fast wavy component are accordingly decomposed in terms of smooth in time resolved component and unresolved highly oscillating random field. The slow current is expressed as a two-dimensional evolution equation, potentially incorporating strong noise. The fast wavy components are associated with the random current but include their own noise contributions as well.

#### Derivation of stochastic models for coastal waves

**Participants:** Arnaud Debussche, Étienne Mémin, Antoine Moneyron.

In this study, we consider a stochastic nonlinear formulation of classical coastal waves models under location uncertainty (LU). In the formal setting investigated here, stochastic versions of the Serre–Green–Nagdi, Boussinesq and classical shallow water wave models are obtained through an asymptotic expansion, which is similar to the one operated in the deterministic setting. However, modified advection terms emerge, together with advection noise terms. These terms are well-known features arising from the LU formalism, based on momentum conservation principle.

#### Variational principles for fully coupled stochastic fluid dynamics across scales

**Participants:** Antoine Barlet, Arnaud Debussche, Étienne Mémin, Sebastien Moskowitz.

This study investigates variational frameworks for modeling stochastic dynamics in incompressible fluids, focusing on large-scale fluid behavior alongside small-scale stochastic processes. The authors aim to develop a coupled system of equations that captures both scales, using a variational principle formulated with Lagrangians defined on the full flow, and incorporating stochastic transport constraints. The approach smooths the noise term along time, leading to stochastic dynamics as a regularization parameter approaches zero. Initially, fixed noise terms are considered, resulting in a generalized stochastic Euler equation, which becomes problematic as the regularization parameter diminishes. The study then examines connections with existing stochastic frameworks and proposes a new variational principle that couples noise dynamics with large-scale fluid motion. This comprehensive framework provides a stochastic representation of large-scale dynamics while accounting for fine-scale components. The evolution of the small-scale velocity component is governed by a linear Euler equation with random coefficients, influenced by large-scale transport, stretching, and pressure forcing. Within the PhD work of Sebastien Moskowitz we will conduct a mathematical analysis of this stochastic coupled models. The post-doc will aim at developing a similar strategy for the primitive equations.

**Toward a Stochastic Parameterization for Oceanic Deep Convection**

**Participants:** Quentin Jamet, Étienne Mémin, Gilles Tissot.

Current climate models are known to systematically overestimate the rate of deep water formation at high latitudes in response to too deep and too frequent deep convection events. We propose in this study to investigate a misrepresentation of deep convection in Hydrostatic Primitive Equation (HPE) ocean and climate models due to the lack of constraints on vertical dynamics. We discuss the potential of the Location Uncertainty (LU) stochastic representation of geophysical flow dynamics to help in the process of re-introducing some degree of non-hydrostatic physics in HPE models through a pressure correction method. We then test our ideas with idealized Large Eddy Simulations (LES) of buoyancy driven free convection with the CROCO modeling platform. This stochastic parametrization relies on a compressible extension of the location uncertainty modelling. We tested these ideas in a free convection LES simulation, and highlighted the potential of stochastic pressure terms to explain part of turbulent vertical temperature fluxes. This work has been presented at the CROCO user meeting (Marseille, September 2025) and at 'Journées Scientifiques LEFE/MANU' (Brest, October 2025)" Good results have been obtained, and support future efforts in the direction of enriching coarse resolution, hydrostatic ocean and climate models with a stochastic representation of non-hydrostatic physics.

**Stochastic hydrodynamic stability under location uncertainty**

**Participants:** Étienne Mémin, Gilles Tissot.

Stochastic linear modeling (SLM) proposed in Tissot, Mémin, and Cavalieri [J. Fluid Mech. 912, A51 (2021), PRF 8, 033904 (2023)] is based on classical conservation laws subject to a stochastic transport. Once linearized around the mean flow and expressed in the Fourier domain, the model has proven its efficiency to predict the structure of the streaks of streamwise velocity in turbulent channel flows. It has been in particular demonstrated that the stochastic transport by unresolved incoherent turbulence allows us to better reproduce the streaks through lift-up mechanism. In the present work, we have developed SLM to predict the evolution of Kelvin-Helmholtz instability within turbulent jets. We have shown that such a model is able to predict two-point coherence statistics, which is classically misrepresented by resolvent analysis. Predicting these two-point statistics is a key ingredient for obtaining relevant acoustic wave propagation, which is still today a challenge in subsonic jets. This work is the subject of a conference proceeding and a paper in preparation. This work is in collaboration with A.V.G Cavalieri (ITA, Brasil), P. Jordan (PPRIME) and T. Colonius (Caltech).

**Acoustic scattering by a turbulent mixing layer using stochastic modelling**

**Participants:** Gilles Tissot.

The objective of this work is to apply the location uncertainty framework for acoustic propagation within aerodynamic turbulence described by the compressible Euler equations under homentropic flow assumption. We propose a model defined in the frequency domain, where the non-linear interactions between turbulent fluctuations — modelled as a stochastic noise carrying Kelvin-Helmholtz coherent structures — and the incident acoustic wave is explicitly computed through a convolution operation. The goal is to provide a computationally efficient model able to predict the lobes in the spectra produced by acoustic scattering by a turbulent mixing layer. This work is in collaboration with Gwénaël Gabard (LAUM).

**Surface wave modelling**

**Participants:** Bertrand Chapron.

Not only for extreme events, ocean surface waves have been demonstrated to be an important component of coupled earth system models. They affect atmosphere-ocean momentum transfer, break ice floes, alter CO2 fluxes, and impact mixed-layer depth through Langmuir turbulence. In contrast to the goals of third-generation spectral models, the wave information needed for mixing, air-sea, and wave-ice-coupling is much less than a full directional wave spectrum. All present parameterizations – for wave-induced mixing, surface drag, floe fracture, or sea spray – use primarily the wave spectrum's dominant frequency, direction, and energy or quantities that can be estimated from these such as Stokes drift and bending moments. Modest errors in sea state do not strongly affect the impacts of these parameterizations. This minimal data and accuracy need starkly contrasts with the computational costs of spectral wave models as a component of next-generation Earth System Models (ESM). In that context, an alternative, cost-efficient wave modeling framework for air-sea interaction to enable the routine use of sea state-dependent air-sea flux parameterization in ESMs. In contrast to spectral models, the Particle-in-Cell for Efficient Swell Wave Model (PiCLES) is under developments targeting coupled atmosphere-ocean-sea ice modeling. Combining Lagrangian wave growth solutions with the Particle-In-Cell method leads to a periodically meshing wave model on an arbitrary grid that scales in an embarrassingly parallel manner. The set of equations solves for the growth and propagation of a parametric wave spectrum's peak wavenumber and total wave energy, which reduces the state vector size by a factor of 50-200 compared to spectral models. Ideally, PiCLES will only require a fraction of the cost of established wave models with sufficient accuracy for ESMs–rivaling that of spectral models in the open ocean. We will evaluate PiCLES against WaveWatchIII in efficiency and accuracy and discuss planned extensions of its capability. This work is in collaboration with M. Hell, B. Fox-Kemper and T. Protin (PhD).

## 8.3 Data/Models interactions and reduced order modelling

**The advantages of data assimilation in parametric space rather than classic grid space**

**Participants:** Carlos Granero Belinchon, , Solène Dealbera, , Pierre Tandeo.

Data assimilation (DA) is an important tool in the field of geosciences. However, in the presence of geophysical structures such as cyclones or ocean eddies, classic DA schemes in gridded space fail to properly estimate the structure properties, for example, their position and intensity. In this work, we propose a new DA scheme, in a reduced parametric space, which assimilates only the relevant parameters to describe the structures, with an application to a one-dimensional ocean eddy. Comparison of DA performed in the classic gridded field and in the parametric space is made through a series of experiments with perturbed eddy parameters. Results show that DA in the parametric space can account for the nonlinearity of the eddy parameters and preserve eddy properties. This is not the case for classic DA in the gridded space. Moreover, DA in the parametric space considerably reduces the computational cost.

**Identification of system states and reconstruction of missing data**

**Participants:** Pierre Tandeo.

Several studies of the team focus on refining how we identify system states and reconstruct missing data. By evolving traditional analog methods, researchers have developed algorithms that jointly optimize feature selection and distance metrics, allowing for accurate forecasting even with limited datasets. This is complemented by the integration of deep learning with variational data assimilation, where neural networks are used to learn the underlying physics (priors) of a system. By embedding stochastic differential equations into these neural schemes, scientists can now reconstruct complex fields like sea surface height with greater speed and interpretability than traditional linear methods. ODYSSEY also addresses the critical challenges of uncertainty and regime shifts in climate dynamics. To combat the limitations of standard filters in non-Gaussian systems, a hybrid Particle Filter-EnKF approach has been proposed; this method allows for the simultaneous estimation of physical states and the hidden stochastic parameters (like inflation and localization) that often degrade model performance. Finally, the introduction of topological tools, that maps the pathways of flow in a system's phase space, provide a new framework for identifying tipping points. By analyzing these topological structures, researchers can better predict when a system, such as the Atlantic Meridional Overturning Circulation, is likely to transition between distinct climate regimes.

**Reduced Order Modelling for internal waves**

**Participants:** Adrien Acchiardi, Virgile Le Gallois, Noé Lahaye, Ezra Rozier, Gilles Tissot.

We have finalized the work corresponding to the PhD of Igor Maingonnat (defended December 2024) on the development of statistical modal decomposition methods for the extraction of internal waves scattered by a turbulent mesoscale field and the construction of an estimation algorithm from snapshot observations of the sea surface height. A paper has been published in Ocean Science this year, and we have also proposed a localized version of the algorithm (Dyhia Elhaddad M1 internship in 2024), which enables improving the statistical convergence of the decomposition basis (a paper has been published in Theoretical and Computational Fluid dynamics). In continuation of this work, Adrien Acchiardi has begun his PhD in October and is currently investigating a model-driven method based on the resolvent analysis, applied to the coupled eddy / internal tide system, using the Rotating Shallow Water model.

Another line of work consists in developing reduced-order strategies for the modelisation of internal tides. As part of Virgille Le Gallois M1 internship, we have worked on the extension of a vertical mode Galerkin decomposition of the 2D ($x - z$) equations for the propagation of internal wave based on a piecewise linear discretization of the bottom topography and a set of exact 2D solutions on a sloping bottom. A paper is under preparation. In the context of Ezra Rozier's postdoc, we have developed a numerical model for the generation and propagation of internal tides in the ocean, based on a discontinuous Galerkin method using plane-wave reconstruction. The main goal of this model, which describes the horizontal + time evolution of the vertically projected modes of internal tides, is the data assimilation of internal tides from altimetry data, where we expect this method to be very efficient in providing an accurate solution at very coarse resolution. At this stage, the model handles the generation and propagation of a single vertical mode, including interaction with a time-varying background flow, and shows promising results in term of convergence of the solution and numerical cost. A paper is under preparation for the Journal of Computational Physics.

**Reconstruction of surface and sub-surface dynamics**

**Participants:** Noé Lahaye, Étienne Mémin, Gaétan Rigaut.

In the context of Gaétan Rigaut's PhD, we have been pursuing to explore modelling strategies to extend the standard quasi geostrophic equations (a model describing the advection of vertical vorticity at lower order of the Rossby number, i.e. in a regime where the Earth rotation is dominant) as a dynamical model to describe ocean dynamics, and in particular to invert observations – e.g. from altimetry. The problem at hand is to parameterise a bottom current – which is not observed – in order to take into account its influence on the evolution of the observed surface dynamics. The employed strategy is based on the formulation of the sub-surface streamfunction using a reduced order basis of smooth functions, regularized based on a conservation principle of the quasi-geostrophic potential vorticity. The model exhibits good performances compared with state-of-the-art models (1-layer QG with reduced-order error term) in an idealized configuration, and further work will include the application of the developed method to realistic configurations using realistic high-resolution numerical simulations.

## 8.4 AI models and methods for ocean data analysis

### Analog-based ensembles to characterize turbulent dynamics from observed data

**Participants:** Carlos Granero Belinchon.

We study the predictability of turbulent velocity signals using probabilistic analog-forecasting. Here, predictability is defined by the accuracy of forecasts and the associated uncertainties. We study the Gledzer-Ohkitani-Yamada (GOY) shell model of turbulence as well as experimental measurements from a fully developed turbulent flow. In both cases, we identify the extreme values of velocity at small scales as localized unpredictable events that lead to a loss of predictability: worse predictions and increase of their uncertainties. The GOY model, with its explicit scale separation, allows to evaluate the prediction performance at individual scales, and so to better relate the intensity of extreme events and the loss of forecast performance. Results show that predictability decreases systematically from large to small scales. These findings establish a statistical connection between predictability loss across scales and intermittency in turbulent flows.

Furthermore, we use analogs for the study of the dispersion of trajectories of stochastic processes in reconstructed phase spaces from observed data. The methodology allows to find ensembles of analog states, i.e. states that are close in the phase space. Once these states are found, we focus on the characterization of their dispersion in function of 1) the time and 2) their initial separation. We study an experimental turbulent velocity measurement and two scale-invariant stochastic processes: a regularized fractional Brownian motion and a regularized multifractal random walk. Both stochastic processes are synthesized to have the same covariance structure as the experimental turbulent velocity, but only the regularized multifractal random walk mimics the intermittency of turbulent velocity. We illustrate that while the covariance structure of the processes governs the time dependence of the dispersion of the analog states, the intermittency phenomenon is responsible of the impact of the initial separation of the analogs on their dispersion.

### Simulation-informed deep learning for enhanced swot observations of fine-scale ocean dynamics

**Participants:** Carlos Granero Belinchon, Eugenio Cutolo, Ronan Fablet.

Oceanic processes at fine scales are crucial yet difficult to observe accurately due to limitations in satellite and in-situ measurements. The Surface Water and Ocean Topography (SWOT) mission provides high-resolution Sea Surface Height (SSH) data, though noise patterns often obscure fine scale structures. Current methods struggle with noisy data or require extensive supervised training, limiting their effectiveness on real-world observations. We introduce SIMPGEN (Simulation-Informed Metric and Prior for Generative Ensemble Networks), an unsupervised adversarial learning framework combining real SWOT observations with simulated reference data. SIMPGEN leverages wavelet-informed neural metrics to distinguish noisy from clean fields, guiding realistic SSH reconstructions. Applied to SWOT data, SIMPGEN effectively removes noise, preserving fine-scale features better than existing neural methods. This robust, unsupervised approach not only improves SWOT SSH data interpretation but also demonstrates strong potential for broader oceanographic applications, including data assimilation and super-resolution.

### Machine learning for the monitoring and modelling of ocean Bio-Geo-Chemistry dynamics

**Participants:** Jonathan Gula, Ronan Fablet, Saïd Ouala.

We explore machine learning for the modelling, reconstruction and emulation of ocean BGC dynamics. Using state-of-the-art deep learning architectures, such as Unets, the focus is on exploring how to address shortcomings of state-of-the-art model-based schemes. Our contributions are three-fold.

We first demonstrate the ability to train deep learning models to predict the origin of particles trapped by deep-ocean sediment traps (Picard et al., 2025). This work investigated how mesoscale ocean dynamics controlled the subsurface transport and deep-ocean collection of particles in the Northeast Atlantic. Using forward tracking of 51.9 million virtual particles released at 200 m depth, the study showed that purely physical processes generated strong spatial and seasonal variability in deep particle collection, with sediment trap location playing a critical role. Machine learning methods were then used to identify particle clusters and to predict the surface origin of particles collected at depth based solely on surface conditions. This approach was successfully extended to real observations using satellite data, demonstrating its potential for interpreting sediment trap measurements.

Second, we showcase on intermediate-complexity case-studies how deep learning can deal with uncertainties in physical forcings as well as partial observations to calibrate ocean BGC models, which classifies in error-prone model parameter estimates using classic data assimilation systems (Littaye et al., 2025).

Third, we also address the reconstruction of 3D+t ocean BGC processes in data-sparse context with a focus on oxygen, which is a key driver of ocean BGC dynamics, the model-based reconstruction of ocean BGC dynamics being a major challenge for operational DA systems (Ouala et al., 2025).

#### Ensemble forecasts in reproducing kernel Hilbert space family

**Participants:** Maël Jaouen, Étienne Mémin, Gilles Tissot.

A methodological framework for ensemble-based estimation and simulation of high dimensional dynamical systems such as the oceanic or atmospheric flows is proposed. To that end, the dynamical system is embedded in a family of reproducing kernel Hilbert spaces (RKHS) with kernel functions driven by the dynamics. In the RKHS family, the Koopman and Perron Frobenius operators are unitary and uniformly continuous. This property warrants they can be expressed in exponential series of diagonalizable bounded evolution operators defined from their infinitesimal generators. Access to Lyapunov exponents and to exact ensemble based expressions of the tangent linear dynamics are directly available as well. The RKHS family enables us to devise of strikingly simple ensemble data assimilation methods for trajectory reconstructions in terms of constant-in-time linear combinations of trajectory samples. Such an embarrassingly simple strategy is made possible through a fully justified superposition principle ensuing from several fundamental theorems. We recently extended the numerical experimentation to a wind-forced three-layers QG model. Localization procedure have been also introduced in the proposed scheme as well as a cheap forward-backward numerical forecast strategy. Very good results have been obtained on realistic configurations.

#### Hybrid approaches for learning of representations for geophysical dynamics

**Participants:** Bertrand Chapron, Ronan Fablet, Said Ouala.

We focused our efforts on developing hybrid numerical models that couple physical models with machine learning components. The ML component aims to correct the physical model in reproducing a target field through bias correction, learning improved parameterizations, or tuning parameters of physical parameterizations. Training the ML model can be framed as an optimal control problem (Frezat et al., 2022), and we developed new methods to solve this optimization on non-differentiable numerical codes. In this context, our contributions explore both emulator-based methods (Frezat et al 2023) and Euler-type approximations (Ouala et al 2024) for computing the gradient of the cost function. Current work on hybrid modeling focuses on scaling these developments to large-scale ocean models (Meunier et al 2025) used in both global and regional ocean simulations.

#### Data-driven methods and End-to-end learning for data assimilation

**Participants:** Bertrand Chapron, Lucas Drumetz, Ronan Fablet, Etienne Mémin, Pierre Tandeo.

We developed several data-driven variational data assimilation methods, addressing various methodological challenges tackled, namely:

- learning from partial data (incomplete in space and time, in collaboration with A. Frion)
- parameterization of generative/stochastic models enabling the prediction of time series and the resolution of inverse problems with uncertainties (A. Frion, N. El Bekri).

We dedicate a significant research to developing data-driven approaches for data assimilation problems, especially end-to-end neural data assimilation. We distinguish three main directions: methodological developments to bridge model-based data assimilation schemes (e.g., Kalman approaches, Optimal Interpolation, 4DVar schemes) and end-to-end learning schemes (e.g., le Minh, et al., 2025; Fablet et al, in prep), embedding uncertainty quantification in neural DA schemes (e.g., Beauchamp et al., 2025; Fablet et al., in prep.) as well as developing at-scale demonstrations of end-to-end neural DA schemes for real-world ocean reconstruction and forecasting problems. Regarding the latter, we currently focus on global-scale sea surface dynamics as experimental testtbed.

**Neural Prediction of Lagrangian Drift Trajectories on the Sea Surface**

**Participants:** Carlos Graneo Belinchon, Daria Botvynko, Ronan Fablet.

We propose a new deep learning approach for the simulation of Lagrangian drift at the sea surface with the objective to overcome the current limitations of the existing model-based and learning-based methods. The proposed framework, called DriftNet, is inspired by the Eulerian Fokker–Planck representation of Lagrangian drift. DriftNet can simulate the Lagrangian trajectory of a fluid parcel given the corresponding Eulerian sea surface currents and the spatially explicit encoding of the parcel's initial position.

**Conditional distribution learning for ensemble data assimilation**

**Participants:** Simon Benaichouche, Étienne Mémin.

Ensemble forecasting has become critically important for managing the uncertainty in future states associated with chaotic numerical weather models. This method relies on forecasting perturbed initial conditions using a dynamical system. While many studies have explored the use of deep learning in geosciences to improve various components of the operational forecasting pipeline—such as data assimilation and the accuracy of numerical models—they often depend on synthetic data. In this work, we introduce a framework that enables the learning of initial perturbations directly from partial observations and physical models. We formulate the problem as a conditional distribution learning task, where the target distribution is explicitly derived as a Gibbs energy associated with a variational cost involving future observations and the dynamic model. Importantly, this formulation allows for learning from non-differentiable models, such as those written in Fortran, thus extending the applicability of deep learning beyond differentiable model contexts. This approach is not limited to assimilation tasks but offers a broader framework for leveraging physical models in various geoscientific applications. Once trained, the model can sample perturbations via Langevin dynamics, enabling robust uncertainty quantification and prediction.

# 9 Bilateral contracts and grants with industry

## 9.1 Bilateral Grants with Industry

**Participants:** Carlos Granero Belinchon, Ronan Fablet, Pierre Tandeo.

- ADIOS project with SHOM.
- M. Zambra PhD thesis with NavalGroup.
- CMEMS project 4DVarNET-OFDA with CLS, OceanDataLab (P. Tripathi PhD thesis).
- H2020 project EditoModelLab with MercatorOceanIntl (D. Botvinko PhD thesis).
- Grants with OceanDataLab, SHOM, CNES, NavalGroup, Eodyn.
- contract with FEM (25 k€), Tessa Chevalier PhD thesis

# 10 Partnerships and cooperations

## 10.1 International initiatives

### 10.1.1 Participation in other International Programs

- Collaboration with Univ. of Exeter and UCLA, in the context of the UKRI Future Leaders fellowship COSSMoSS (Jonathan Gula)

## 10.2 International research visitors

### 10.2.1 Visits of international scientists

**Other international visits to the team**

**Magdalena Lucini** from Univ. Corrientes (Argentina), visit to IMT Atlantique Jan-Feb 2025, collab with Pierre Tandeo

**Manuel Pulido** from Univ. Corrientes (Argentina), visit to IMT Atlantique Jan-Feb 2025, collab with Pierre Tandeo

**Takemasa Miyoshi** from RIKEN (Japan), visit to IMT Atlantique May-June 2025, collab. with Pierre Tandeo.

### 10.2.2 Visits to international teams

**Research stays abroad**

**Etienne Mémin**

**Visited institution:** Imperial College, London

**Country:** UK

**Dates:** march - April, May - June 2025

**Context of the visit:** colaboration with D. Crisan and D. Holm

**Mobility program/type of mobility:** CNRS/Imperial Fellowship UMI Abraham de Moivre, visiting professor

## 10.3 National initiatives

**PPR Maths-Vives**

**Participants:** Etienne Mémin.

Project CLIMATH on the elaboration of fundamental tools for uncertainty forecasting.

**PPR CLIMArcTIC**

**Participants:** Pierre Tandeo, Ronan Fablet, Lucas Drumetz, Florian Sévellec.

The CLIMARCTIC project (“From regional to global impacts of climate change in the Arctic : an interdisciplinary perspective”) is a PPR “Océan et Climat” project (Océan 2030; PI: C. Lique, LOPS Ifremer) that aims at improving our understanding of climate change in the arctic, both at regional and global scales. F. Sévellec is in charge of WP1, Pierre Tandeo is co-PI with C. Lique (Ifremer, LOPS) and R. Fablet and L. Drumetz participate to WP1.

**PPR MEDIATION**

**Participants:** Etienne Mémin, Carlos Granero Belinchon, Pierre Tandeo.

The MEDIATION project aims at improving and developing better numerical code of the ocean dynamics. E. Mémin is co-PI of WP2 “parametrisation stochastique et quantification d’incertitude” and participate to WP3 “Modèles sous maille”. P. Tandeo and C. Granero Belinchon participate to WP4 “IA pour les codes océaniques”.

**ANR Chair: OceaniX**

**Participants:** Ronan Fablet, Florian Sévellec.

“Physics-Informed AI for Observation- driven Ocean AnalytiX” (PI: R. Fablet). Collaboration with L. Memery (CNRS, LEMAR).

**ANR PRC : PORC-EPIC**

**Participants:** Florian Sévellec, Pierre Tandeo.

Project during the period 2024-2028. PI: F. Sévellec, 450.000€, including 150.000€ for IMT Atlantique.

**ANR PRC : MOTIONS**

**Participants:** Jonathan Gula, Noé Lahaye.

Simulations océaniques multi-échelles basées sur une stratégie de raffinement de maillage avec adaptation locale de la dynamique et de la physique. PI: Florian Lemarié.

**ANR Melody**

**Participants:** Ronan Fablet.

"Bridging geophysics and MachinE Learning for the modeling, simulation and reconstruction of Ocean DYnamics". (PI: R. Fablet). Collaboration with P. Naveau (LSCE), J. Le Sommer (IGE), F. Rousseau (IMT Atlantique), L. Debreu (INRIA GRA).

**ANR SCALP**

**Participants:** Carlos Granero Belinchon.

With LadHyx, LISN and INRIA Saclay.

**ANR Dream**

**Participants:** Ronan Fablet.

Collaboration with E. Martinez (LOPS) and M. Lengaigne (MARBEC).

**ANR HERCULES**

**Participants:** Xavier Carton.

PI: Maria Eletta Negretti, 2022-2025

**ANR JCJC ModITO**

**Participants:** Noé Lahaye.

"Modelling the Internal Tide in the Ocean" project aims at developing a data assimilation model for the ocean internal tide field, in the context of the SWOT mission. (PI: N. Lahaye, fin en 2026).

**ANR JCJC SCALES**

**Participants:** Carlos Granero Belinchon.

"Statistical ChAracterization of multi-scaLE complex Systems with information theory" (PI: C. Granero Belinchon, fin en 2025).

**ANR JCJC DEEPER**

**Participants:** Jonathan Gula.

"Impacts of DEep submEsoscale Processes on the ocEan ciRculation" (PI: J. Gula), 2020 – 2025. The goals of the DEEPER project are to quantify the impacts of deep submesoscale processes and internal waves on mixing and water mass transformations. In addition, the DEEPER project will explore ways of parameterizing these impacts using the latest advances in machine learning.

#### LEFE-MANU: SNOEMI

**Participants:** Quentin Jamet, Étienne Mémin.

"A Stochastic description of Non-lOcal Eddy-Mean flow Interactions", 2024–2026. The aim of this project is to providing first steps in the direction of accounting for non-local processes in the development of sub-grid scale parameterizations for Ocean General Circulation models through stochastic modelling.

#### LEFE-MANU: ADVECT

**Participants:** Noé Lahaye, Gilles Tissot.

"Assimilation de Données Variationnelle et d'Ensemble par modèles d'ordre réduit des interactions entre ondes internes et CouranTs", 2024–2026.

#### LEFE-GMMC: OxUMAS

**Participants:** Xavier Carton.

Oxygen minimum zone & Upwelling measured at Mesoscale in the Arabian Sea. 2025-2026

#### ESA CROSCIM

**Participants:** Ronan Fablet.

2024–2026. Collaboration with M. Beauchamp (DMI, Danemark).

#### CMEMS SE Oceanbench-STOF

**Participants:** Ronan Fablet.

2024–2026. Collaboration with L. Gautier (OceanDataLab).

#### TOSCA CNES projects

**DIEGOB** (SWOT science team). Participants: A. Ponte (PI), J. Gula, N. Lahaye, P. Tandeo, R. Fablet, C. Menesguen.

**THEIA** PI: C. Granero Belinchon.

**CNES OSTST DUACS HR** Ronan Fablet, 2024–2028. Collaboration with L. Renaud (IRD, LEGOS).

**SWOT ST DIEGO** Ronan Fablet, 2024–2028. Collaboration with A. Pascual (IMEDEA, spain).

#### Project WHIRLS

**Participants:** Xavier Carton.

FMAC and GMMC Coriolis support. 2025-2027

**Inrae-Inria Funding**

**Participants:** Etienne Mémin.

PhD thesis of Merveille Talla, on the development of diffusion generative models applied to turbulent flows. Collaboration with Dominique Heitz and Valentin Resseguier (ACTA Inrae Rennes team).

**Action exploratoire "KoopduMonde"**

**Participants:** Gilles Tissot, Étienne Mémin.

This project ("Koopman operator modelling of non-linear dynamical systems for ensemble methods") consists in expressing the Koopman operator associated with a high-dimensional geophysical dynamical system in a family of reproducing kernel Hilbert spaces. The interest is to learn the non-linear dynamics, locally in the phase space, in order to solve efficiently ensemble data assimilation problems. Multi-layer quasi-geostrophic models representative of the Gulf stream area is considered in this work.

## 10.4 Regional initiatives

- ARED PhD funding (50%), project MERMAID. Gilles Tissot, Noé Lahaye, Etienne Mémin

# 11 Dissemination

## 11.1 Promoting scientific activities

### 11.1.1 Scientific events: organisation

- Saïd Ouala and Gilles Tissot: organization of the LEFE/MANU workshop in Plouzané (7-8 Oct. 2025 – manu2025.sciencesconf.org)
- Bertrand Chapron & Etienne Mémin: members of the organizing committee of the 5th STUOD workshop, September, Edinburgh.

### 11.1.2 Journal

**Member of the editorial boards**

- Pierre Tandeo is editor for Nonlinear Processes in Geophysics (EGU)
- Jonathan Gula is associate editor for Journal of Physical Oceanography.

**Reviewer - reviewing activities**

- Pierre Tandéo is a reviewer for "Quarterly Journal of the Royal Meteorological Society".
- Roger Lewandowski has reviewed for "Journal of Mathematical Fluid Mechanics" and "Physica D, Nonlinear Analysis".
- Carlos Granero Belinchon has reviewed for "Physica A", "Physical Review E", "Physical Review Fluids" and "Physical Review Letters".
- Jonathan Gula is reviewer for ANR, Emmy Noether Programme, Bourse AID CNRS, Earth and Space Science, JGR-Oceans, Journal of Physical Oceanography, Science Advances.

- Noé Lahaye: “Journal of Physical Oceanography”, “EGU Ocean Science”, “Journal of Fluid Mechanics”, “JAMES”, “Journal of Geophysical Research: Ocean”.
- Etienne Mémin is reviewer for "J. Fluid Mech.", JAMES", "J. Comp. Phys.", "Physica D", "Chaos", Ocean Modelling, ERC advanced grant.
- Claire Ménesguen has reviewed for "J. Phys. Oceanogr.", "JAMES" and "GRL".
- Aurélien Ponte has reviewed for “J. Phys. Oceanogr.”, EGU Ocean Science.
- Gilles Tissot: Nature communications, Journal of Fluid Mechanics, JFM Rapids, Journal of Computational Physics, Theoretical and Computational Fluid Dynamics, Non-linear Dynamics, Nonlinear Processes in Geosciences, Communications engineering.

#### 11.1.3 Invited talks

- Pierre Tandeo: invited talks at the "Workshop on Uncertainty Quantification in Climate Science" (IHP Paris)
- Etienne Mémin: keynote speaker, "Modern Approaches in SPDEs & DA", Sibiu Roumania, 28 July - 2 August 2025
- Jonathan Gula: invited oral presentation, "Submesoscale turbulence in the deep ocean", CELLO Conference, Hamburg, Germany, Sep. 16, 2025
- Roger Lewandowski: main speaker at RAMA 13 congress, Tamnarasset; invited mini-course at VIASM (Hanoï)

#### 11.1.4 Scientific expertise

- Ronan Fablet is member of CS LEFE-MANU, CS GDR Omer, CST SHOM and science Board Mercator Ocean Intl. He is scientific and technical coordinator of the action IA of PPR “Océan & Climat” to setup benchmarks IA/ocean and a call for postdocs fundings (8 to 9 postdocs of 2 years).
- Étienne Mémin is member of the SMAI GAMNI (Applied and Industrial Mathematical Society Comittee – section numerical methods for engineering)
- Claire Menesguen is member of CS LEFE CLIMAGO, section 19 CNRS and GENCI CT1.
- Gilles Tissot is member of CS CLIMAT AmSud.

#### 11.1.5 Research administration

- Ronan Fablet is a member of the ANR committee for AAP ASTRID.
- Jonathan Gula is a member of the commitee CNES – TOSCA Océan.
- Roger Lewandowski: member of IRMAR head commity, CA of Rennes University, Rennes University commitee for ecological transition of l’Université de Rennes, council of the department of mathematics.
- Claire Menesguen is member of section 19 of CNRS.

### 11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

- Jonathan Gula: M2 Marine Physics (192h), IUEM, Brest: Numerical Modelling (M2); Ocean Turbulence (M2); Scientific English (M2); Coastal Dynamics (M2); Internal Waves (M2); Fluids (M1); Applied Mathematics (M1); Numerical Physics (L3)
- Noé Lahaye: Fluid Mechanics, L3 INSA Rennes.

- Roger Lewandowski: Course ANAM, Master CSM, course ED2, Licence of mathematics in University of Rennes; Mini cours at CIRM (Marseille, November)
- Pierre Tandeo: Probability and Statistics (40h/year), Machine Learning and Deep Learning (20h/year), Big Data and Cloud Computing for Climate (30h/year), Data Assimilation (30h/year). IMT Atlantique
- Gilles Tissot: Reduced-order modelling for fluid flows (M2 CSM U. Rennes, 20h).
- Carlos Granero Belinchon: Probabilité et Statistiques (IMT Atlantique, 40 h/an), Analyse et Optimisation (IMT Atlantique, 20 h/an), Traitement du signal (IMT Atlantique, 20 h/an), Physique quantique (IMT Atlantique, 10 h/an), Big data and cloud computing pour le climat (IMT Atlantique & M2 IUEM, 15 h/an), projects on recent advances in machine learning (IMT Atlantique, 20 h/an)

### 11.2.1 Supervision

- PhD in progress: Adrien Acchiardi, started in Oct. 2025, supervised by Gilles Tissot, Noé Lahaye and Etienne Mémin.
- PhD in progress: Emilio Gonzales, started in 2024 (IMT Atlantique). Pierre Tandeo: supervisor
- PhD in progress: Clément Lacrouts, started in 2024 (IFREMER). Pierre Tandeo: supervisor
- PhD in progress: Gwendal Saliou, started in 2024 (IFREMER). Pierre Tandeo: supervisor
- PhD in progress: Tessa Chevalier, started in 2024 (FEM & IMT Atlantique). Pierre Tandeo: supervisor
- PhD in progress: Gaetan Rigaut, simplified models of upper ocean dynamics in the context of satellite data of new generation, started November 2024, supervised by N. Lahaye and E. Mémin.
- PhD in progress: Sébastien Moskowitz, Stochastic modelling of oceanic flow, small-scale dynamics, started October 2024.
- PhD in progress: Matteo Nex, Stochastic methods for uncertainty modelling and quantification in coupled physical biogeochemical ocean models, started October 2024.
- PhD in progress: V. Mokuenko, started in 2024, UBO, co-supervised by X. Carton and J. Gula.
- PhD in progress: Antoine Moneyron, Mathematical analysis of stochastic ocean dynamics models, started March 2023, supervisors: Arnaud Debussche, Étienne Mémin.
- PhD in progress: Mael Jaouen, Learning of ocean dynamics models through Koopman operator and Kernel methods, started June 2023, supervisors: Étienne Mémin, Gilles Tissot.
- PhD in progress: Benoit Presse, since Sept. 2023, (UBO, ANR REPLICA). Pierre Tandeo: supervisor.
- PhD in progress: Merveille Talla, Generative diffusion methods for turbulent flows, started october 2023, supervisors: Dominique Heitz, Étienne Mémin, Valentin Resseguier.
- PhD in progress: R. Ravasse, 2023 - 2026. Structure and dynamics of submesoscale coherent vortices in the ocean. Supervisors: Xavier Carton, Jonathan Gula.
- PhD in progress: Axel Tassigny (Ecole Polytechnique=, Fine-scale dynamics in the straits of Gilbraltar from lab experiments (X. Carton, 20% co-mentoring with M. Eletta Negretti and J. Sommeria)
- PhD in progress: Anastasia Volorio-Galea (X. Carton, 20% co-mentoring with P. Rivière)
- PhD in progress: P. Aimé, IMT ATlantique, supervisors: L. Drumetz, M. Dalla Mura (Gipsa-lab), T. Bajjouk (IFREMER), R. Garello (IMT Atlantique).
- PhD in progress: Hugo Georgenthum, IMT Atlantique, supervisors: L. Drumetz (Odyssey), J. Le Sommer (CNRS/IGE), D. Greenberg (HEREON) and R. Fablet (Odyssey).
- PhD in progress: Nafoual El Bekri, UBO, supervisors: L. Drumetz and F. Vermet (UBO/EURIA).

- PhD in progress: Adrien Stella, “Dynamique du phytoplancton et processus sous-jacents dans l’océan Arctique sur la base d’observations et d’apprentissage profond”, LOPS & IMT Atlantique (Lucas Drumetz: co-supervisor).
- PhD in progress: Daria Botvynko, ENIB/Lab-STICC. Supervisors: Carlos Granero Belinchon, A. Benzinou and R. Fablet.
- PhD in progress: J. Littaye, UBO CNRS/Lab-STICC, co-supervised by L. Memery (CNRS/LEMAR) and R. Fablet.
- PhD in progress: M. Zambra, IMT Atlantique, co-encadrement avec D. Cazau (ENSTA Bretagne/IGE), N. Farrugia (IMT Atlantique/Lab-STICC), A. Gense (NavalGroup) et R. Fablet (Odyssey).
- PhD in progress: P. Beauchot, ENSTA Bretagne,. Supervisors: F. Sévellec (CNRS/LOPS), A. Drémeau (ENSTA Bretagne/Lab-STICC) and R. Fablet (Odyssey).
- PhD in progress: Margot Demol (Ifremer), 2022 - 2024. "Estimating the Ocean Circulation in the SWOT era », supervisors: Aurélien Ponte, Pierre Gareau.
- PhD in progress: Mariana Lage (Helmhotz-Zentrum Hereon - Germany), 2021-2024, « Small-scale variability of turbulence and stratification in the Surface Mixed Layer », Supervisors: Claire Menesguen, Jeff Carpenter.
- PhD in progress: Yao Meng (Exeter), 2021-2024. « Investigating Submesoscale Ocean Dynamics in the Mozambique Channel with Seismic and Simulation Datasets », supervisors: K. Sheen, K. Gunn, C. Menesguen, I. Ashton.
- PhD in progress: Théo Picard, “Data-driven MOdeling and sampling to MOnitor PARticle origins in deep sediment traps”, 2021 - 2024. Supervisors: J. Gula, L. Memery (LEMAR), R. Fablet.
- PhD in progress: Parth Tripathi, IMT Atlantique, co-supervised by B. Chapron, F. Collard.
- PhD in progress: Alice Laloue, CNES/LEGOS, co-dsupervised by L. Renault (IRD, LEGOS), S. Pujol (CLS) and R. Fablet.
- PhD in progress: Daniel Zhu, IMT Atlantique/Lab-STICC, co-supervised by J. Le Sommer (DR CNRS, IGE) et F. Rousseau (PR, IMT Atlantique, LATIM) and R. Fablet.
- PhD in progress: Tom Protin, Ifremer, co-supervised by B. Chapron, V. Resseguier and R. Fablet.
- PhD in progress: Robin Marcille, ITE FEM, co-supervised by Pierre Pinson (Prof. ICL) and Ronan Fablet.
- PhD in progress: Nicolas Lafon, CNRS/LSCE, co-supervised by Philippe Naveau (CNRS, LSCE) and Ronan Fablet.
- PhD defended: Perrine Bauchot, “Intelligence artificielle pour l’observation de l’environnement marin”, ENSTA Bretagne. Bourse ANR Chair OceaniX. Co-supervisors: F. Sévellec, A. Drémeau (MC HDR, ENSTA Bretagne), R. Fablet.
- PhD defended: Mathis Grangeon (DGA/Region Bretagne), 2021 - 2023: "Acoustic geolocation and small-scale ocean variability", supervisors: Aurélien Ponte, François-Xavier Socheleau, Florent Le Courtois.
- PhD defended: Noémie Schifano, “Tracer transport and mixing in the bottom mixed-layer”. Supervisors: J. Gula, C. Vic.
- PhD defended: Anthony Frion, “méthodes d’apprentissage de systèmes dynamiques et assimilation variationnelle basées données en utilisant l’opérateur de Koopman”, IMT Atlantique (Lucas Drumetz: supervisor).

- PhD defended: Guillaume Leloup, IRMAR, Méthodes numériques pour le couplage de deux fluides turbulents. supervisor: R. Lewandowski (IRMAR).
- PhD defended: Margot Demol, supervised by Aurélien Ponte.
- PhD defended: Ewen Frogé, (IMT, ANR Scales). Carlos Granero Belinchon: co-supervisor.
- PhD defended: C. Lemaréchal, "Deep Hydrodynamic Processes near Hydrothermal vents". Supervisors: J. Gula, G. Roullet
- PhD defended: Yan Barabinot, LMD/ENS. (co-supervised by X. Carton with S. Speich).

#### 11.2.2 Juries

- Pierre Tandeo: PhD defense of Victor Bertret (Univ. Rennes), Dina Rapp (DMI, Danemark), Gimena Casaretto (Univ. Buenos Aires)
- Noé Lahaye: PhD defense of Cyprien Le Maréchal (LOPS, UBO), Noémie Schifano (LOPS, UBO) and Cécile Le Dizes (IMFT, Univ Toulouse)
- Etienne Mémin: HDR defense of Lionel Mathelin (Paris Saclay, October 2025); PhD defense of Sophie Moran (IRIT Toulouse, Reviewer, Fevrier 2025); PhD defense of Marius Duvillard (Paris Saclay, Reviewer, January 2025)
- Jonathan Gula: PhD defense of M. Jakes (University of Tasmania); HDR defense of W. Llovel (LOPS)
- Xavier Carton: PPhD defense of A. Chauchat (IRPHE, Univ Aix Marseille) – referee; PhD defense of B. Pratama (LOPS, UBO) – Chairman; PhD defense of R. Bajon (LOPS, UBO) – Chairman; PhD defense of A. K. Thiam (LEGOS, UPS Toulouse) – Chairman.

#### 11.2.3 Educational and pedagogical outreach

- Roger Lewandowski: publication of a textbook (Dunod): "Mathématiques pour la modélisation", Dunod, Paris, collection Mathématiques appliquées pour le Master/SMAI, 2025. (French)

# 12 Scientific production

## 12.1 Publications of the year

**International journals**

[1] R. Ait-Bachir, C. Granero-Belinchon, A. Michel, J. Michel, X. Briottet and L. Drumetz. 'Land Surface Temperature Super-Resolution with a Scale-Invariance-Free Neural Approach: Application to MODIS'. In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 18 (2025), pp. 14480–14494. DOI: 10.1109/JSTARS.2025.3573610. URL: https://hal.science/hal-04925380.

[2] C. Amrouche, L. C. Berselli, F. Legeais, G. Leloup and R. Lewandowski. 'Singular boundary condition for a degenerated turbulent toy model'. In: *Pure and Applied Functional Analysis* 10.1 (3rd Apr. 2025), pp. 1–19. URL: https://hal.science/hal-04143082.

[3] M. Ballarotta, C. Ubelmann, V. Bellemin-Laponnaz, F. Le Guillou, G. Meda, C. Anadon, A. Laloue, A. Delepoulle, Y. Faugère, M.-I. Pujol, R. Fablet and G. Dibarboure. 'Integrating wide-swath altimetry data into Level-4 multi-mission maps'. In: *Ocean Science* 21.1 (15th Jan. 2025), pp. 63–80. DOI: 10.5194/os-21-63-2025. URL: https://hal.science/hal-04896365.

[4] P. Bauchot, A. Drémeau, F. Sévellec and R. Fablet. 'Neural Data Assimilation for Regime Shift Monitoring of an Idealized AMOC Chaotic Model'. In: *Journal of Advances in Modeling Earth Systems* 17.4 (Apr. 2025), pp. 1–21. DOI: 10.1029/2024ms004462. URL: https://hal.science/hal-05086921.

[5] M. Beauchamp, R. Fablet, S. Benaichouche, P. Tandeo, N. Desassis and B. Chapron. 'Neural Variational Data Assimilation with Uncertainty Quantification Using SPDE Priors'. In: *Artificial Intelligence for the Earth Systems* 4.3 (July 2025), pp. 1–29. DOI: 10.1175/AIES-D-24-0060.1. URL: https://hal.science/hal-05232110.

[6] A. Bella, N. Lahaye and G. Tissot. 'Internal tide loss of coherence in a realistic simulation of the North Atlantic'. In: *Ocean Science* 22.1 (5th Jan. 2026), pp. 1–15. DOI: 10.5194/os-22-1-2026. URL: https://inria.hal.science/hal-05446339.

[7] D. Botvynko, C. Granero-Belinchon, S. Van Gennip, A. Benzinou and R. Fablet. 'Neural prediction of Lagrangian drift trajectories on the sea surface'. In: *Artificial Intelligence for the Earth Systems* 4.3 (13th June 2025), pp. 1–17. DOI: 10.1175/AIES-D-24-0052.1. URL: https://hal.science/hal-04569385.

[8] Z. Caspar-cohen, A. Ponte, N. Lahaye, E. D. Zaron, B. K. Arbic, X. Yu, S. Legentil and D. Menemenlis. 'Combining surface drifters and high resolution global simulations enables the mapping of internal tide surface energy'. In: *Scientific Reports* 15.1 (28th Mar. 2025), p. 10672. DOI: 10.1038/s41598-025-92662-w. URL: https://hal.science/hal-05043518.

[9] S. Clement, E. Blayo, L. Debreu, J.-M. Brankart, P. Brasseur, L. Li and E. Mémin. 'Link between stochastic grid perturbation and location uncertainty framework'. In: *Journal of Advances in Modeling Earth Systems* 17.5 (May 2025), e2024MS004528. DOI: 10.1029/2024MS004528. URL: https://inria.hal.science/hal-04629335.

[10] A. Coquereau, F. Sévellec, T. Huck and A. V. Fedorov. 'Increase in ENSO frequency and intensity under 20th and 21st century warming: Insights from CMIP6 large ensembles'. In: *Geophysical Research Letters* 52.22 (11th Nov. 2025), e2025GL116541. DOI: 10.1029/2025GL116541. URL: https://hal.science/hal-05361770.

[11] D. Dauhajre, K. Srinivasan, M. J. Molemaker, J. Gula, D. Hypolite, J. Mcwilliams, R. Barkan and W. Young. 'Vertical Mixing Can Both Induce and Inhibit Submesoscale Frontogenesis'. In: *Journal of Physical Oceanography* (12th June 2025), pp. 1–57. DOI: 10.1175/JPO-D-24-0148.1. URL: https://hal.univ-brest.fr/hal-05196319.

[12] A. Debussche and E. Mémin. 'Variational principles for fully coupled stochastic fluid dynamics across scales'. In: *Physica D: Nonlinear Phenomena* 481 (Nov. 2025), p. 134777. DOI: 10.1016/j.physd.2025.134777. URL: https://inria.hal.science/hal-05327779.

[13] C. Dorffer, F. Jourdin, T. T. N. Nguyen, R. Devillers, D. Mouillot and R. Fablet. 'Observation-only deep learning for gappy satellite-derived ocean colour data using 4DVarNet'. In: *IEEE Transactions on Geoscience and Remote Sensing* (2025), pp. 1–1. DOI: 10.1109/tgrs.2025.3624465. URL: https://ird.hal.science/ird-05338406.

[14] D. Elhaddad, I. Maingonnat, G. Tissot and N. Lahaye. 'Localised proper orthogonal decomposition'. In: *Theoretical and Computational Fluid Dynamics* 39.5 (17th Sept. 2025), p. 40. DOI: 10.1007/s00162-025-00760-2. URL: https://inria.hal.science/hal-05268871.

[15] A. Frion, L. Drumetz, M. Dalla Mura, G. Tochon and A. Aïssa-El-Bey. 'Augmented Invertible Koopman Autoencoder for long-term time series forecasting'. In: *Transactions on Machine Learning Research Journal* (May 2025), pp. 1–28. URL: https://hal.science/hal-04989093.

[16] E. Frogé, C. Granero-Belinchon, S. G. Roux, N. B. Garnier and T. Chonavel. 'Analog-Based Forecasting of Turbulent Velocity: Relationship between Unpredictability and Intermittency'. In: *EPL - Europhysics Letters* 149 (20th Jan. 2025), p. 13001. URL: https://hal.science/hal-04694737.

[17] E. Frogé, C. Granero-Belinchon, S. G. Roux, T. Chonavel and N. B. Garnier. 'Relationship between unpredictability and intermittency in shell models of turbulence and experiments'. In: *Physics of Fluids* 37.11 (21st Nov. 2025), p. 115159. DOI: 10.1063/5.0285208. URL: https://hal.science/hal-05110160.

[18] C. Granero-Belinchon, S. G. Roux and N. B. Garnier. 'Structure functions and flatness of streamwise velocity in a turbulent channel flow'. In: *Physics of Fluids* 37.8 (21st Aug. 2025), p. 085225. DOI: 10.1063/5.0283648. URL: https://hal.science/hal-05094264.

[19] J. Guillot, P. Ailliot, E. Frénod, J. Ruiz and P. Tandeo. 'State and Stochastic Parameters Estimation with Combined Ensemble Kalman and Particle Filters'. In: *Monthly Weather Review* 153.7 (2025), pp. 1141–1154. DOI: 10.1175/MWR-D-24-0123.1. URL: https://hal.science/hal-04916479.

[20] M. Hell, B. Fox-Kemper and B. Chapron. 'A Particle-in-Cell Wave Model for Efficient Sea-State Estimates in Earth System Models-PiCLES'. In: *Journal of Advances in Modeling Earth Systems* 17.8 (Aug. 2025), pp. 1–38. DOI: 10.1029/2025MS005221. URL: https://hal.science/hal-05314421.

[21] F. Le Guillou, B. Chapron and M.-H. Rio. 'VarDyn: Dynamical Joint-Reconstructions of Sea Surface Height and Temperature From Multi-Sensor Satellite Observations'. In: *Journal of Advances in Modeling Earth Systems* 17.4 (Apr. 2025), e2024MS004689 (18p.) DOI: 10.1029/2024MS004689. URL: https://hal.science/hal-05105666.

[22] C. Lemaréchal, G. Roullet and J. Gula. 'Hydrothermal Plume Near-Field Dynamics From LES and Observations'. In: *Journal of Geophysical Research. Oceans* 130.10 (16th Oct. 2025), e2024JC022277. DOI: 10.1029/2024JC022277. URL: https://hal.science/hal-05322703.

[23] L. Li, E. Mémin and B. Chapron. 'A Generalized Stochastic Formulation of the Ekman–Stokes Model with Statistical Analyses'. In: *Journal of Physical Oceanography* 55.9 (Sept. 2025), pp. 1389–1407. DOI: 10.1175/JPO-D-24-0116.1. URL: https://inria.hal.science/hal-05327658.

[24] I. Maingonnat, G. Tissot and N. Lahaye. 'Coupled estimation of incoherent internal tides and turbulent motions via statistical modal decomposition'. In: *Ocean Science* 21.2 (17th Apr. 2025), pp. 807–827. DOI: 10.5194/egusphere-2024-1483. URL: https://inria.hal.science/hal-04866439.

[25] C. de Marez, A. Ruiz-angulo and J. Gula. 'Mesoscale Induced Vertical Fluxes Over the Iceland-Faroe Ridge'. In: *Geophysical Research Letters* 52 (5th July 2025), pp. 1–12. DOI: 10.1029/2025gl115520. URL: https://hal.univ-brest.fr/hal-05196322.

[26] C. Ménesguen, N. Ducousso, C. Vic and S. Le Gentil. 'Exploring Baroclinic Instability of the Computational Kind (BICK) in Numerical Simulations of the Ocean'. In: *Journal of Advances in Modeling Earth Systems* 17.4 (Apr. 2025), e2024MS004600 (23p.) DOI: 10.1029/2024MS004600. URL: https://hal.science/hal-05105673.

[27] C. Mosto, G. D. Charó, F. Sévellec, P. Tandeo, J. J. Ruiz and D. Sciamarella. 'A templex-based study of the Atlantic Meridional Overturning Circulation dynamics in idealized chaotic models'. In: *Chaos: An Interdisciplinary Journal of Nonlinear Science* 35.1 (6th Jan. 2025), pp. 1–17. DOI: 10.1063/5.0231713. URL: https://imt-atlantique.hal.science/hal-04872005.

[28] S. Ouala, L. Debreu, B. Chapron, F. Collard, L. Gaultier and R. Fablet. 'Enhanced Computational Complexity in Continuous-Depth Models: Neural Ordinary Differential Equations With Trainable Numerical Schemes'. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2025), pp. 1–8. DOI: 10.1109/TPAMI.2025.3599629. URL: https://hal.science/hal-05232101.

[29] E. Oulhen, N. Kolodziejczyk, P. Tandeo, B. Blanke and F. Sévellec. 'Reconstructing monthly 20th century salinity fields using a data-driven method and Argo data'. In: *Ocean Dynamics* 75.6 (15th May 2025), p. 47. DOI: 10.1007/s10236-025-01690-7. URL: https://imt-atlantique.hal.science/hal-05097260.

[30] P. Platzer, B. Chapron, L. Drumetz, A. Mouche, P. Tandeo and L. Vinour. 'Distance Learning for Analog Methods'. In: *Monthly Weather Review* (29th July 2025). DOI: 10.1175/MWR-D-24-0204.1. URL: https://imt-atlantique.hal.science/hal-05283123.

[31] P. Platzer, B. Chapron and G. Messori. 'Disentangling density and geometry in weather regime dimensions using stochastic twins'. In: *npj climate and atmospheric science* 8.1 (May 2025), pp. 1–10. DOI: 10.1038/s41612-025-01086-w. URL: https://hal.science/hal-05206198.

[32] X. Qiu, X. Xiong, L. Li, G. Guo, T. Gong, S. Guo, Z. Shang, X. Sun, Y. Tian, G. Xie, H. Tan, C. Fittschen, B. Fiser, M. Szőri, G. Tarczay and C. Li. 'Development of an FDM-TDLAS Sensor for Long-Term Online Monitoring of H 2 S and CO to Predict Water Wall Corrosion Trends'. In: *Analytical Chemistry* 97.26 (17th June 2025), pp. 14058–14066. DOI: 10.1021/acs.analchem.5c02691. URL: https://hal.science/hal-05392307.

[33] N. Schifano, C. Vic, J. Gula, M. J. Molemaker and J. C. Mcwilliams. 'Diapycnal Mixing and Tracer Dispersion in a Terrain-Following Coordinate Model'. In: *Journal of Advances in Modeling Earth Systems* 17 (Aug. 2025), e2024MS004768. DOI: 10.1029/2024ms004768. URL: https://hal.univ-brest.fr/hal-05244469.

[34] R. Schubert, J. Gula, E. Capó, P. Damien, M. J. Molemaker, C. Vic and J. C. Mcwilliams. 'The ocean flows downhill near the seafloor and recirculates upward above'. In: *Nature Communications* 16.1 (1st July 2025), p. 5873. DOI: 10.1038/s41467-025-61027-2. URL: https://hal.univ-brest.fr/hal-05196317.

[35] F. Sévellec, N. Kolodziejczyk, Q. Jamet and A. Colin de Verdière. 'Global Observations of Eddy–Mean Flow Interactions at the Ocean Surface and in the Deep Ocean'. In: *Journal of Physical Oceanography* 55.9 (Sept. 2025), pp. 1569–1590. DOI: 10.1175/JPO-D-24-0137.1. URL: https://hal.univ-brest.fr/hal-05404411.

[36] A. Simon, P. Tandeo, F. Sévellec and C. Lique. 'Arctic regional changes revealed by clustering of sea-ice observations'. In: *The Cryosphere* 19.12 (8th Dec. 2025), pp. 6639–6658. DOI: 10.5194/tc-19-6639-2025. URL: https://imt-atlantique.hal.science/hal-05407599.

[37] F. Tucciarone, L. Li, E. Mémin and P. Chandramouli. 'Derivation and Numerical Assessment of a Stochastic Large–Scale Hydrostatic Primitive Equations Model'. In: *Journal of Advances in Modeling Earth Systems* 17.7 (10th July 2025), pp. 1–37. DOI: 10.1029/2024MS004783. URL: https://inria.hal.science/hal-05327649.

[38] T. Uchida, Q. Jamet, A. C. Poje, N. Wienders, L. Sun and W. K. Dewar. 'Dynamics and Thermodynamics of the Boussinesq North Atlantic Eddy Kinetic Energy Spectral Budget'. In: *Journal of Advances in Modeling Earth Systems* 17.4 (21st Apr. 2025). DOI: 10.1029/2024MS004781. URL: https://hal.inrae.fr/hal-05450740.

[39] L. Wang, J. Gula, J. Collin, L. Mémery and X. Yu. 'Connecting the Deep Collection of Sinking Particles With Surface Ocean Signatures'. In: *Journal of Geophysical Research. Oceans* 130.6 (June 2025), e2024JC021777. DOI: 10.1029/2024JC021777. URL: https://hal.univ-brest.fr/hal-05133417.

[40] M. Zambra, N. Farrugia, D. Cazau, A. Gensse and R. Fablet. 'Multimodal learning–based reconstruction of high-resolution spatial wind speed fields'. In: *Environmental Data Science* 4 (7th Jan. 2025), e2. DOI: 10.1017/eds.2024.34. URL: https://hal.science/hal-04896368.


### International peer-reviewed conferences


[41] S. Close, P. Tandeo and G. Maze. 'A multi-disciplinary approach to teaching climate change and data science'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-12914. URL: https://imt-atlantique.hal.science/hal-05054149.

[42] S. Dealbera, P. Tandeo, C. Granero-Belinchon, C. Granero-Belinchon, S. Raynaud and B. Boussidi. 'Object-oriented mesoscale eddy prediction'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-4043. URL: https://imt-atlantique.hal.science/hal-05054174.

[43] E. Frogé, C. Granero-Belinchon, S. G. Roux, N. B. Garnier and T. Chonavel. 'Relationship between Unpredictability and Intermittency with analog-based forecasting: from shell models to experimental turbulence'. In: *Proceedings of STATPHYS29*. STATPHYS 2025 - 29th International Conference On Statistical Physics. Florence (IT), Italy, 2025. URL: https://hal.science/hal-05125207.

[44] T. Miyoshi, S. Otsuka, J. Liang, M. Goodliff, G. Saliou, S. Ouala and P. Tandeo. 'RIKEN's activities to integrate data assimilation and AI/ML'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-4099. URL: https://imt-atlantique.hal.science/hal-05054182.

[45] E. Oulhen, N. Kolodziejczyk, P. Tandeo, B. Blanke and F. Sévellec. 'Reconstructing historical salinity fields over the 20th century using a data-driven method and Argo data'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-10637. URL: https://imt-atlantique.hal.science/hal-05054167.

[46] B. Presse, S. Close, P. Tandeo and G. Maze. 'Estimation of the time-varying probability density function from ensemble simulations and observations using Analogs'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-6284. URL: https://imt-atlantique.hal.science/hal-05054163.

[47] A. Simon, P. Tandeo, F. Sévellec and C. Lique. 'Arctic regional changes revealed by clustering of sea-ice observations'. In: EGU 2025 - General Assembly of the European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-4117. URL: https://imt-atlantique.hal.science/hal-05054155.

### Conferences without proceedings

[48] A. El Aouni, Q. Gaudel, C. Regnier, J. L. Sommer, S. V. Gennip, R. Fablet, M. Drevillon, Y. Drillet and P.-Y. Le Traon. 'OceanBench: A Benchmark for Data-Driven Global Ocean Forecasting systems'. In: *NeurIPS 2025*. NeurIPS 2025 - Thirty-Ninth Annual Conference on Neural Information Processing Systems. 1-14. San Diego (CA), United States, 7th Dec. 2025. URL: https://hal.science/hal-05412248.

[49] C. Granero-Belinchon, S. G. Roux and N. B. Garnier. 'A multiscale characterization of turbulence based on information theory'. In: EFDC2 2025 - 2nd European Fluid Dynamics Conference. Dublin, Ireland, 2025, pp. 1–2. URL: https://hal.science/hal-05125225.

[50] E. Le Roux, P. Tandeo, C. Granero-Belinchon, M. Baklouti, J. Le Sommer, F. Sevault, S. Somot, A. Doury and M. Al Najar. 'Equation discovery for climate impact: symbolic regression to emulate climate impact indicators for unseen scenarios'. In: EGU 2025 - European Geosciences Union. Vienna, Austria, 18th Mar. 2025. DOI: 10.5194/egusphere-egu25-3836. URL: https://imt-atlantique.hal.science/hal-05054197.

[51] L. Li, E. Mémin and B. Chapron. 'Stochastic Approaches to Air-Sea Boundary Layer Dynamics'. In: STUOD 2025 - 6th Stochastic Transport in Upper Ocean Dynamics Annual Workshop. Edinbourgh (Scotland), United Kingdom, 2025. URL: https://hal.science/hal-05279728.

[52] L. Li, F. Tucciarone and E. Mémin. 'Stochastic Modeling in Geophysical Fluid Dynamics'. In: 2025 - Seminar at INRIA ANGE Team. Paris, France, 2025. URL: https://hal.science/hal-04978081.

[53] E. Meunier, S. Ouala, H. Frezat, J. L. Sommer and R. Fablet. 'Towards fully differentiable neural ocean model with Veros'. In: EurIPS 2025 - Differentiable Systems and Scientific Machine Learning - A workshop @. Copenhagen, Denmark, 21st Nov. 2025, pp. 1–8. URL: https://hal.science/hal-05410440.

[54] T. Protin, V. Resseguier, M. Hell, B. Chapron and R. Fablet. 'Sequential importance resampling of particle-in-cell for swell dynamics'. In: Stochastic Transport in Upper Ocean Dynamics IV: STUOD 2024 Workshop. Rennes, France, 2nd Sept. 2025. URL: https://hal.science/hal-05257031.

[55] M. Talla, V. Resseguier, R. Gruhlke, D. Heitz and E. Mémin. 'Multiplicative score-based generative models for fluid dynamics'. In: CSE 2025 - SIAM Computational Science and Engineering. Fort Worth, Texas, United States, 2025. URL: https://hal.science/hal-05035629.

[56] R. Tiphaigne, P. Barbet, M. Petit, T. M. Merveille C., A. Moneyron, A. Valls, F. Regnault, G. Stabile, L. Wallian, V. Resseguier and D. Heitz. 'Hyperreduction in a method coupling stochastic reduced models and data assimilation to predict turbulent flows'. In: ETMM-15 2025 - 15th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements. Dubrovnik, Croatia, 2025, pp. 1–23. URL: https://hal.science/hal-05299435.

[57] R. Tiphaigne, P. Barbet, M. Petit, T. M. Merveille C., A. Moneyron, A. Valls, F. Regnault, G. Stabile, L. Wallian, V. Resseguier and D. Heitz. 'Stochastic Reduced-Order Model of the deterministic Navier-Stokes equation for turbulent flow prediction'. In: MORTech 2025 - 7th International Workshop on Model Reduction Techniques. Zaragoza, Spain, Nov. 2025. URL: https://hal.inrae.fr/hal-05406088.

### Reports & preprints

[58] C. Bonet, E. Cazelles, L. Drumetz and N. Courty. *Busemann Functions in the Wasserstein Space: Existence, Closed-Forms, and Applications to Slicing*. 2025. DOI: 10.48550/arXiv.2510.04579. URL: https://hal.science/hal-05307431.

[59] D. Botvynko, P. Haslée, L. Gaultier, B. Chapron, C. de Boyer Montégut, A. El Aouni, J. L. Sommer and R. Fablet. *Neural ocean forecasting from sparse satellite-derived observations: a case-study for SSH dynamics and altimetry data*. 2025. URL: https://hal.science/hal-05406906.

[60] E. Cutolo, C. Granero-Belinchon, P. Thiraux, J. Wang and R. Fablet. *Simulation-informed deep learning for enhanced swot observations of fine-scale ocean dynamics*. 2025. URL: https://hal.science/hal-05004872.

[61] A. Debussche, É. Mémin and A. Moneyron. *Stochastic interpretations of the oceanic primitive equations with relaxed hydrostatic assumptions*. 20th Feb. 2025. URL: https://hal.science/hal-04958571.

[62] C. Granero-Belinchon. *Analog-based ensembles to characterize turbulent dynamics from observed data*. 2025. URL: https://hal.science/hal-05223006.

[63] M. Jaouen, B. Dufée, E. Mémin and G. Tissot. *Ensemble Filter on dynamically driven RKHS: Application to a Multilayer Quasi-Geostrophic ocean model*. 2025. URL: https://inria.hal.science/hal-04915412.

[64] G. Leloup. *Density results for smooth functions in weighted Sobolev spaces*. 11th Feb. 2025. URL: https://hal.science/hal-04916380.

[65] R. Lewandowski and G. Leloup. *Renormalized solutions for a simplified steady-state turbulent kinetic energy equation*. 2025. URL: https://hal.science/hal-04912612.

[66] L. Li, E. Memin and B. Chapron. *A Stochastic Ekman-Stokes Model for Coupled Ocean-Atmosphere-Wave Dynamics*. Apr. 2025. DOI: 10.48550/arXiv.2504.07632. URL: https://hal.science/hal-05329464.

[67] J. Littaye, R. Fablet and L. Mémery. *Learning-based calibration of ocean carbon models to tackle physical forcing uncertainties and observation sparsity*. 8th Apr. 2025. URL: https://hal.science/hal-05042751.

[68] J. Littaye, L. Memery and R. Fablet. *Solving calibration and reanalysis challenges of ocean BGC dynamics with neural schemes: a 1D NNPZD case-study*. 2025. URL: https://hal.science/hal-05430535.

### Other scientific publications

[69] C. Granero-Belinchon, S. G. Roux and N. B. Garnier. 'Quantification of non-stationarity across the scales of turbulence with information theory'. In: STATPHYS 2025 - 29th International Conference On Statistical Physics. Florence, Italy, 2025. URL: https://hal.science/hal-05125253.

[70] R. Lewandowski, S. Reich and A. Zaslavsky. *Preface: Calculus of variations, PDE and their Applications*. 1st Mar. 2025. URL: https://hal.science/hal-04985701.

### Scientific popularization

[71] N. Lahaye. 'Estimer les courants océaniques depuis l'espace'. In: *Interstices* (2025). URL: https://hal.science/hal-05111065.