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2024
ACTIVITY REPORT

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

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

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Creation of the Project-Team: 2022 March 01

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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 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 manage 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 scheme 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 aims 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 investigate 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 extremes (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

6.1 Awards

The team has nothing special to report. We had quite a few new project funded, and pursued our efforts in the context of previously-launched projects. The new-generation wide-swath altimeter mission SWOT has been succesfully launched in December 2022, and provided a first round data that over-perform the expectations, opening very exciting and promising perspectives for the team.

7 New software, 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 resolve 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 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.

Multiscale and Anisotropic Characterization of Images Based on Complexity

Participants: Carlos Granero Belinchon.

We present multiscale, non-linear and directional statistical characterizations of images based on high order statistics and information theory. These characterizations allow us to characterize the multiscale properties directionally and to explore their anisotropy. We use this framework to study different turbulent flows from homogeneous and isotropic to inhomogeneous and anisotropic flows.

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

Participants: Zoé Caspar-Cohen, 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. In particular, we aim to quantify the contribution of complementary data sources (drifting buoys, satellite temperature or optical imagery) to resolving these various challenges. Following Zoé Caspar-Cohen's PhD thesis, we have analysed a realistic numerical simulation (LLC4320) and proposed a convesion metrics to infereulerian internal tide energy from drifting buoys measurements. An article (entitled "Combining surface drifters and high resolution global simulations enables the mapping of internal tide surface energy") has been submitted to Scientific Report and is currently under major revision.

We also pursued the combined analyses of altimetry and in situ observations (drifting buoys) as a part of Margot Demol's thesis. An article is under second review at JGR (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 is in progress. We have also actively contributed to the creation, harmonisation, and smoothing of an inter-campaigns drifter dataset that gathered all drifters deployed in the Mediterranean Sea during the C-SWOT, BioSWOT-Med, and FaSt-SWOT campaigns (A Drifter Dataset for the Western Mediterranean Sea collected during the SWOT mission calibration and validation phase. SEANOE. doi)

Towards a stochastic generalized Ekman model with application to uncertainty quantification

Participants: Long Li, 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.

Impact of oceanic meso- and submeso-scale eddies in the ocean

Participants: Xavier Carton, Jonathan Gula.

In the context of mesoscale/submesoscale variability of the surface and shallow subsurface ocean, two geographical sites have been more particularly studied: the region north of Brazil and the Straits of Gibraltar. Both have been sampled experimentally, but have also been the loci of process studies. 1) In the former (article by Subirade et al), we have characterized the number, structure, trajectory, and lifetime of NBC rings using satellite altimetry and the in-situ measurements of the EUREC4A experiment. We have shown that altimetry in the pre-SWOT era yields weaker currents than sampled in situ. Also, it appeared that 4 to 5 NBC rings were spawn each year. These rings interact with the Amazon plume, and form fronts, with a seasonal variability, as shown by Marin Menard's M.Sc. work. Below the NBC rings, submesoscale vortices are generated in the Demerara Bay and later interact vertically with the NBC rings. The vertical interaction of eddies has been studied more theoretically in the paper by Reinaud and Carton. We have also conducted a study on the definition of the boundaries of an oceanic eddy. Using both theory and in situ data, we have shown that it is characterized by a maximum of horizontal to vertical components of Ertel PV (paper by Barabinot et al., 2024). Several criteria have been derived for the value of this ratio, in particular the limitation of existence of a stable boundary by symmetric instability, or the observation of an inflexion point of the isopycnals at this place. 2) In the latter, at very fine scale (article by Roustan et al.), 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. The dynamics of ISWs and the quantification of mixing are the subject of forthcoming papers (PhD thesis by Jean Baptiste Roustan). Finally, as a whole, the PhD thesis by Ashwita Chouksey has covered the whole Atlantic Ocean with a focus on Mediterranean water eddies.. She has statistically characterized subsurface, submesoscale eddies (including meddies). She has discovered new deep eddies and she has described their interactions. Finally, she has shown that bottom eddies west of the Mid Atlantic Ridge were shielded and achieved very slow motion and interactions.

Observations of Western boundary currents

Participants: Jonathan Gula, Quentin Jamet, Claire Menesguen.

Observations of Western boundary currents: Western boundary currents are complex systems connecting the open and coastal oceans, requiring integrated monitoring platforms and simulations for accurate observation. A recent dialogue series examined six mature monitoring systems, sharing strategies to enhance sustained observing activities and global partnerships. In the Agulhas Current region, our study shows that the “eddy graveyard” paradigm, based on sea surface height-derived EKE flux divergence and Rossby wave approximations, fails, as eddy pressure work is dominated by topographic and geostrophic-ageostrophic fluxes rather than Rossby waves, making the assumptions behind this paradigm invalid for the region. This study is associated to a publication in Oceanography (2024), and a publication in J. Geophys. Res. Oceans (2024).

Toward a Stochastic Parameterization for Oceanic Deep Convection

Participants: Quentin Jamet, Étienne Mémin.

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. Preliminary results are encouraging, and support future efforts in the direction of enriching coarse resolution, hydrostatic ocean and climate models with a stochastic representation of non-hydrostatic physics.

Climate scale and regional scale climate variability

Participants: Florian Sévellec.

We focused on understanding the role of the mesoscale ocean on the stability, variability and mean state of the large-scale ocean and climate. This was done in terms of observations and modelling. Several other areas of research have been identified and will be at the heart of the research over the next few years: Self-adapting observation systems to limit the growth of climate error (better predictability), identification of the source and sink mechanisms of interannual ocean and climate predictability (using tools derived from dynamical systems theory: adjoint method, nonlinear iterative optimisation, energy transfers) and the development of an operational climate forecasting system (using AI-related tools). Particular attention will be paid to the precursors of climate variations with the start of the ANR-PRC "PORC-ÉPIC" project, for which Florian Sévellec is the PI.

In particular, we have focused on understanding the role of climate variability in observation of climate changes. This was first with Antoine Hochet (Hochet et al., 2023a) done is estimating if the length of satellite records (30 years) is long enough to detect the effect of anthropogenically forced climate change on wave height trends? Using a statistical model to derive H_s from sea level pressure field and exploiting ERA-5 reanalysis data as well as 80 members of the Community Earth System Model v2 large ensemble, we show that, over the North Atlantic (NA), altimetry-based trends are mostly caused by internal variability. This suggests that changes computed over the satellite era are not yet controlled by anthropogenic climate change. Starting from 1993, the date of emergence, defined as the date when the forced signal becomes dominant over the internal variability, is later than 2050 for H_s in the NA. Then we have focused with Antoine Hochet (Hochet et al., 2023b) on understanding the mechanisms of regional steric sea level variability in the context of regional sea level variability. We have developed a novel method based on steric sea level variance budget that allows to detect the sources and sinks of the variability. Using ECCO state estimate, we show that interannual steric sea level variability is mainly sustained by interannual fluctuating winds via Ekman transport almost everywhere. The damping of the variability is made by both the interannual fluctuating net heat flux from the atmosphere, that largely dominates the atmospheric freshwater fluxes, and the parametrized effect of eddies. It is also found that the parametrized effect of diffusion on the variability is weak in most regions and that, although globally weak, the fluctuations of atmospheric freshwater fluxes are a source of variance close to the Equator in the Pacific Ocean.

Characterization of internal tide dynamics in high-resolution realistic simulations

Participants: Adrien Bella, Noé Lahaye, Aurélien Ponte, Gilles Tissot.

Using outputs from the realistic high-resolution ($dx \approx 2$ km) numerical simulation of the North Atlantic Ocean "eNATL60", we have analysed the lifecycle of the internal tide field based on a vertical mode decomposition of the dynamics. We analysed and quantified the impact of several processes affecting the propagation of internal tides, such as topographic scattering and interaction with the mesoscale dynamics, and show that their implications is very contrasted depending of the region considered. A paper has been published in the journal JGR: Oceans. In continuation to this work, we have analysed the loss of coherence of the internal tides by interaction, by diagnosing 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 Geophysical Research Letter, and another paper is in preparation for submission in Ocean Science.

Near-surface ocean dynamics

Participants: Claire Ménesguen.

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.

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

Towards a stochastic generalized Ekman model with application to uncertainty quantification

Participants: Long Li, Étienne Mémin, Bertrand Chapron.

We consider 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 randomparameter definitions. Numerical simulations are used to assess uncertainties in the Ekman layer, focusing on statistical moment responses and sensitivity analyses of random parameters. Comparizons with real data has been performed. This model is currently extended to a coupled Ocean-Atmosphere model.

Geometry-preserving Lie group integrators for differential equations on the manifold of symmetric positive definite matrices

Participants: Lucas Drumetz.

We have developed new methods – Geometry-preserving lie group integrators –, for numerical integration of differential equations, that rely on covariance matrices, [Drumetz et al 2023, International Conference on Geometric Science of Information]. In addition, in the context of C. Bonnet PhD thesis (UBS), we have constructed efficient methods for probability distributions based on covariant matrices and optimal transport (published in International Conference on Machine Learning). Finally, in the context of G. Morel postdoc, we improved generative AI models using optimal transport and variational penalization of Euler equations in large dimension (published in Transactions on Machine Learning Research).

Turbulence Models and Boundary Layer Analysis

Participants: Francois Legeais, Roger Lewandowski.

This report synthesizes findings from three research studies focused on the mathematical modeling of turbulent flows and boundary layers. The studies investigate scalar elliptic equations, Reynolds-Averaged Navier-Stokes (RANS) models, and simplified equations for turbulent kinetic energy, each contributing to a deeper understanding of turbulence and its boundary conditions.

In a first paper ("Continuous boundary condition at the interface for two coupled fluids"), we consider two laminar incompressible flows coupled by the continuous law at a fixed interface Γ_I. We approach the system by one that satisfies a friction Navier law at Γ_I, and we show that when the friction coefficient goes to ∞, the solutions converges to a solution of the initial system. We then write a numerical Schwarz-like coupling algorithm and run 2D-simulations, that yields same convergence result. In a second paper, ("Surface boundary layers through a scalar equation with an eddy viscosity vanishing at the ground"), we introduce a scalar elliptic equation defined on a boundary layer given by $\Pi_2 \times [0, z_{top}]$, where Π_2 is a two dimensional torus, with an eddy vertical eddy viscosity of order z^α, $\alpha \in [0,1]$, an homogeneous boundary condition at $z = 0$, and a Robin condition at $z = z_{top}$. We show the existence of weak solutions to this boundary problem, distinguishing the cases $0 \leq \alpha < 1$ and $\alpha = 1$. Then we carry out several numerical simulations, showing the ability of our model to accurately reproduce profiles close to those predicted by the Monin-Oboukhov theory, by calculating stabilizing functions.

Another study addresses a steady-state turbulent RANS one-equation model that couples velocity-pressure mean field equations with the turbulent kinetic energy equation. Eddy viscosities in this model vanish near the boundary. The critical values are identified as thresholds beyond which weak solutions to the system exist. These solutions are obtained as limits of viscous regularizations. This approach ensures the stability and convergence of the model, enabling analysis of flow behavior near the boundary.

A third study focuses on a simplified equation governing turbulent kinetic energy in a bounded domain. The eddy diffusion is modeled, where the Prandtl mixing length scales with the distance to the boundary. Estimates are derived, and convergence to the formal limit equation is established in the sense of distributions. This result provides theoretical support for the validity of the model in the context of vanishing diffusion.

These studies contribute theoretical and numerical insights into turbulence modeling. The scalar elliptic equation framework reveals how boundary conditions and eddy viscosities influence the existence and uniqueness of solutions. The RANS model elucidates critical thresholds for the existence of weak solutions in turbulent flow systems, while the analysis of the simplified kinetic energy equation establishes convergence properties under diminishing eddy diffusion. Collectively, these contributions offer methodologies for predicting and understanding turbulent flows in boundary layer contexts.

Very-high numerical simulations of the ocean dynamics

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

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.

One of the recently published results using these simulations concerns the kinetic energy cascade at the ocean surface and the ability to estimate it from observations [Schubert et al., 2023]. We have shown that the total geostrophic inverse scale kinetic energy flux is linearly related to quantities that can be computed from along-track altimetry, and have presented for the first time its regional distribution and seasonal cycle on scales of 40 to 150 km for large parts of the global ocean based on observations.

Finally, we have also proposed a new form of potential vorticity (PV), rescaled using the rearranged Lorenz density profile, the novelty being that we consider its time evolution. We argue that this rescaled PV is more representative of the dynamics, in particular for assessing the respective effects of mixing and friction on the generation of the geostrophic circulation. The effect of mixing at the global scale, which only modifies the global stratification at rest, is taken into account in the evolution equation of this "objective" definition of PV, in the sense that it scales the PV changes with respect to their effect on the circulation [Morel et al, 2023].

We are studying 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 study was the subject of an M1 internship (Simon Moine, - April 29-July 19, 2024: Study of fine scales based on observations between a Mozambique ring and a cyclonic eddy). 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.

These simulations have also been used for physical analyses of several flow features:

Fronts We have studied submesoscale fronts in the northern Bay of Bengal (BoB) and the northern Atlantic using high-resolution simulations. In the BoB, we highlight the dominance of salinity-driven, compensated fronts, particularly at subsurface levels, where they drive temperature inversions and maintain the barrier layer. In the northern Atlantic, submesoscale fronts show strong seasonal variations in their contribution to tracer transport, accounting for up to 40% of the vertical advective export below the mixed layer in winter, despite occupying only 5% of the domain. These results highlight the critical role of submesoscale fronts in vertical transport and regional ocean dynamics.

Bottom We investigated the critical role of ocean topography, including seamounts and steep slopes, in driving deep ocean mixing and upwelling, processes essential for the global overturning circulation. Around seamounts, enhanced mixing occurs through lee waves and layered wake eddies, with scaling relationships linking mixing rates to topographic and hydrographic properties, suggesting a significant global contribution to deep-ocean upwelling. On steep slopes, simulations reveal prograde mean flows and complex boundary layer dynamics, where buoyancy mixing and bottom drag induce diapycnal downwelling near the slope and upwelling in the upper boundary layer, highlighting the dominant influence of abyssal slopes and seamounts on deep-ocean circulation pathways.

Vortices We have studied the dynamics of coupled baroclinic flows and vortex interactions using theoretical and numerical models. We studied the instability and evolution of coupled baroclinic flows, showing that thermal and mechanical couplings can dampen instability at the mesoscale and extend the short-wave cut-off. We also studied vertical coupling between surface and subsurface eddies in the North Brazil Current (NBC) rings, showing that coupling increases the longevity and distance of eddies, with implications for their role in the Atlantic Meridional Overturning Circulation.

These leads 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-terms 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. We study in particular the influence.

Wave solution of stochastic geophysical models

Participants: Bertrand Chapron, Noé Lahaye, Long Li, Étienne Mémin.

In this work we investigated the wave solutions of a stochastic rotating shallow water model. This approximate model provides an interesting simple description of the interplay between waves and random forcing ensuing either from the wind or coming as the feedback of the ocean on the atmosphere and leading in a very fast way to the selection of some wavelength. This interwoven, yet simple, mechanism explains the emergence of typical wavelength associated to near inertial waves. Waves that are not in phase with the random forcing are damped at a rate that depends on the random forcing variance. Geostrophic adjustment is also interpreted as a statistical homogeneization process in which, in order to conserve potential vorticity, the small-scale component tends to align to the velocity fields to form a statistically homogeneous random field. We are pursuing this study to devise a stochastic model of wave-current interaction. Another axis of study focus on the derivation of wave action principle in the stochastic setting. For vanishing noise, the classical wave action model is recovered while in the general case additional terms arise due to non-zero vorticity of the noise term.

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.

Parameterization for coarse-resolution ocean modeling

Participants: Louis Thiry, Long Li, Étienne Mémin, Guillaume Roullet.

We work on simple parameterization for coarse-resolution oceanic models to replace computationally expensive high-resolution ocean models. We focus on the eddy-permitting scale (grid step Rossby radius) and computationally cheap parameterization. We are currently investigating the modification of the diffusion (friction) operator to reproduce the mean velocity observed via measurements or a high-resolution reference solution. To test this new parameterization on a double-gyre quasi-geostrophic model, we are implementing a fast and portable python implementation of the multilayer quasi-geostrophic model. This study has been published in the STUOD proceedings. In another study we have explored a new discretization of the multi-layer quasi-geostrophic (QG) model that models implicitly the sub-grid-scale effects. This new discrete scheme is based on several numerical choices that first ensure an exact material conservation of the potential vorticity. The advection is performed with a weighted essentially non-oscillatory interpolation whose implicit dissipation replaces the usual explicit (bi-)harmonic dissipation. We finally proposed a new method for solving the elliptic equation that warrants reversibility which on a staggered discretization. The method has the advantage to not requiring the tuning of any additional parameter, e.g. additional hyper-viscosity. This work has been recently submitted and we released a very short, concise, and efficient PyTorch implementation of our method to facilitate future data assimilation or machine-learning developments upon this new discretization.

We also have developed a unified QG and the RSW models, exploring the effect of higher order numerics, exploring the potential of WENO interpolation, developing alternative way of describing interfacial stress (bottom, surface, lateral), diagnosing the numerical implicit dissipation, using discrete differential geometry as a framework for discretization, testing Pytorch and Julia as alternatives languages to Fortran, inventing new code architectures. This work is under review in Geoscientific Model Development (EGU journals).

Diagnostic of the Lévy area for geophysical flow models in view of defining high order stochastic discrete-time schemes

Participants: Pierre-Marie Boulvard, Étienne Mémin.

In this paper we characterize numerically through two criteria the Lévy area related to unresolved fluctuation velocities associated to a stochas tic coarse-scale representation of geophysical fluid flow dynamics. We study in particular whether or not the process associated to the random unresolved velocity components exhibits a Lévy area corresponding to a Wiener process, and if the law of this process can reasonably be approached by a centered Dirac measure. This exploration enables us to answer positively to a conjecture made for the constitution of high-order discrete time evolution schemes for stochastic representation defined from stochastic transport.

Discrete numerical schemes for stochastic shallow water models under location uncertainty

Participants: Pierre-Marie Boulvard, Étienne Mémin, Jacques Sainte Marie.

In this work we focus on the derivation of efficient discrete schemes, for a stochastic version of the shallow water model derived and analyzed in previous works of the team. We in particular pay attention to the devise of ”second order” like methods. This scheme that takes the form of an iterated double advection of the noise allow us to have an implicit, implementation of the noise associated diffusion, bringing a natural equilibrium, at the discrete level between the energy dissipation by the noise and its energy intake. The corresponding scheme corresponding to an extension of entropy conserving schemes proposed in the discrete setting by the Ange Inria team is fully justified in this study.

Stochastic compressible fluid dynamics

Participants: Quentin Jamet, Étienne Mémin, Gilles Tissot.

The aim of this study is to provide a stochastic version under location uncertainty of the compressible Navier-Stokes equations. The modelling under location uncertainty setting is used here to derive a physically consistent stochastic dynamical system for compressible flows. It relies on an extended stochastic version of the Reynolds transport theorem involving stochastic source terms. In a similar way as in the deterministic case, this conservation theorem is applied to density, momentum and total energy in order to obtain a transport equation of the primitive variables, i.e. density, velocity and temperature. For the modelling of ocean dynamics, the transport of mass fraction of species, such as salinity, is also considered. We show that performing low Mach and Boussinesq approximations to this more general set of equations allows us to recover previous versions of incompressible stochastic Navier-Stokes equations and the stochastic Boussinesq equations, respectively. Finally, we provide some research directions on the use of this general set of equations in the perspective of relaxing the Boussinesq and hydrostatic approximation for ocean modelling.

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. The results obtained are encouraging, and support future efforts in the direction of enriching coarse resolution, hydrostatic ocean and climate models with a stochastic representation of non-hydrostatic physics. Deep convection has been investigated as a particular application of compressible non-hydrostatic stochastic flow dynamics.

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 developped 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. Predincting 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).

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 CO_2 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).

Selecting and weighting dynamical models using data-driven approaches

Participants: Pierre Tandéo, Florian Sévellec.

In geosciences, multi-model ensembles are helpful to explore the robustness of a range of results. To obtain a synthetic and improved representation of the studied dynamic system, the models are usually weighted. The simplest method, namely the model democracy, gives equal weights to all models, while more advanced approaches base weights on agreement with available observations. Here, we focus on determining weights for various versions of an idealized model of the Atlantic Meridional Overturning Circulation. This is done by assessing their performance against synthetic observations (generated from one of the model versions) within a data assimilation framework using the ensemble Kalman filter (EnKF). In contrast to traditional data assimilation, we implement data-driven forecasts using the analog method based on catalogs of short-term trajectories. This approach allows us to efficiently emulate the model's dynamics while keeping computational costs low. For each model version, we compute a local performance metric, known as the contextual model evidence, to compare observations and model forecasts. This metric, based on the innovation likelihood, is sensitive to differences in model dynamics and considers forecast and observation uncertainties. Finally, the weights are calculated using both model performance and model co-dependency and then evaluated on averages of long-term simulations. Results show good performance in identifying numerical simulations that best replicate observed short-term variations. Additionally, it outperforms benchmark approaches such as strategies based on model democracy or climatology when reconstructing missing distributions. These findings encourage the application of the proposed methodology to more complex datasets in the future, like climate simulations. This work has been published in Nonlinear Processes in Geophysics.

8.3 Data/Models interactions and reduced order modelling

Data-driven methods for partially observed systems

Participants: Pierre Tandeo, Florian Sévellec.

In collaboration with Pierre Ailliot [Tandeo et al, 2023] and within a data-driven context, we have demonstrated our ability to obtain accurate and reliable predictions of a partially observed Lorenz-63 system, where only the second and third components are observed and access to the equations is not allowed. This was done by a combination of machine learning and data assimilation techniques. The key aspects were the following: the introduction of latent variables, a linear approximation of the dynamics and a database that is updated iteratively, maximizing the likelihood. Interestingly, we found that the latent variables inferred by the procedure are related to the successive derivatives of the observed components of the dynamical system. The method is also able to reconstruct accurately the local dynamics of the partially observed system. Overall, the proposed methodology is simple, is easy to code and gives promising results, even in the case of small numbers of observations.

The state of the atmosphere, or of the ocean, cannot be exhaustively observed. Crucial parts might remain out of reach of proper monitoring. Also, defining the exact set of equations driving the atmosphere and ocean is virtually impossible because of their complexity. The goal of this study is to obtain predictions of a partially observed dynamical system without knowing the model equations. In this data-driven context, we focus on the Lorenz-63 system, where only the second and third components are observed and access to the equations is not allowed. To account for those strong constraints, a combination of machine learning and data assimilation techniques is proposed. The key aspects are the following: the introduction of latent variables, a linear approximation of the dynamics and a database that is updated iteratively, maximizing the likelihood. We find that the latent variables inferred by the procedure are related to the successive derivatives of the observed components of the dynamical system. The method is also able to reconstruct accurately the local dynamics of the partially observed system. Overall, the proposed methodology is simple, is easy to code and gives promising results, even in the case of small numbers of observations.

On-line machine-learning forecast uncertainty estimation for sequential data assimilation

Participants: Pierre Tandeo.

Quantifying forecast uncertainty is a key aspect of state-of-the-art numerical weather prediction and data assimilation systems. Ensemble-based data assimilation systems incorporate state-dependent uncertainty quantification based on multiple model integrations. However, this approach is demanding in terms of computations and development. In this work, a machine-learning method is presented based on convolutional neural networks that estimates the state-dependent forecast uncertainty represented by the forecast error covariance matrix using a single dynamical model integration. This is achieved by the use of a loss function that takes into account the fact that the forecast errors are heteroscedastic. The performance of this approach is examined within a hybrid data assimilation method that combines a Kalman-like analysis update and the machine-learning-based estimation of a state-dependent forecast error covariance matrix. Observing system simulation experiments are conducted using the Lorenz'96 model as a proof-of-concept. The promising results show that the machine-learning method is able to predict precise values of the forecast covariance matrix in relatively high-dimensional states. Moreover, the hybrid data assimilation method shows similar performance to the ensemble Kalman filter, outperforming it when the ensembles are relatively small.oThis work has been published in Quarterly Journal of the Royal Meteorological Society.

Ensemble data assimilation of large-scale dynamics with uncertainty

Participants: Benjamin Dufé, Étienne Mémin.

We investigated the application of a physically relevant stochastic dynamical model in ensemble Kalman filter methods. Ensemble Kalman filters are very popular in data assimilation because of their ability to handle the filtering of high-dimensional systems with reasonably small ensembles (especially when they are accompanied with so called localization techniques). The stochastic framework used in this study relies on Location Uncertainty (LU) principles which model the effects of the model errors on the large-scale flow components. The experiments carried out on the Surface Quasi Geostrophic (SQG) model with the localized square root filter demonstrate two significant improvements compared to the deterministic framework. Firstly, as the uncertainty is a priori built into the model through the stochastic parametrization, there is no need for ad-hoc variance inflation or perturbation of the initial condition. Secondly, it yields better MSE results than the deterministic ones. This work has been published in QJRMS.

In another study, we investigated the calibration of the stochastic noise in order to guide the realizations towards the observational data used for the assimilation. This is done in the context of the stochastic parametrization under Location Uncertainty (LU) and data assimilation. The new methodology is rigorously justified by the use of the Girsanov theorem, and yields significant improvements in the experiments carried out on the Surface Quasi Geostrophic (SQG) model, when applied to Ensemble Kalman filters. The particular test case studied here shows improvements of the peak MSE from 85% to 93%.

Reduced Order Modelling for internal waves

Participants: Dyhia Elhaddad, Noé Lahaye, Élise Lelièvre, Igor Maingonnat, Ezra Rozier, Gilles Tissot.

In the context of Igor Maingonnat's PhD thesis, we have continued our work 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. The proposed methods, based on broadband Proper Orthogonal Decomposition on the one hand and extended POD on the other, exploit the inherent correlation between the scattered wave field and the mesoscale field. The corresponding algorithm shows good performance in idealised configurations, and we expect that the approach could be useful for the analysis of SWOT imagery, provided some additional work is done to adapt the algorithm to more realistic results. A paper is under review in Ocean Science. We have also proposed a localized version of the algorithm (Dyhia Elhaddad M1 internship), which enables improving the statistical convergence of the decomposition basis (a paper is in preparation for the Journal of Computational Physics). As a second step, we have proposed a model-driven approach using resolvent analysis, and made some links between this approach and the statistical decomposition methods developed earlier. Another line of work consists in developing reduced-order strategies for the modelisation of internal tides. As part of Elise Lelièvre M1 internship, we have work on the extension of a vertical mode Galerkin decomposition of the 2D $(x-z)$ equations for the propagation of internal waves, to include the impact of unresolved scales of the bathymetry. In the context of Ezra Rozier's postdoc, we are starting to develop 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.

Reconstruction of surface and sub-surface dynamics

Participants: Noé Lahaye, Étienne Mémin, Gaétan Rigaut.

In the context of Gaétan Rigaut's PhD, which started as an M2 intership in our team, we are exploring 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. To this end, several strategies are being investigated: we are now focusing on proposing a smoothed co-linear bottom current via a reduced set of co-linearity coefficients to be inverted by a minimisation procedure. Further developments will include a stochastic treatment of the lower layer flow, and the addition of other observed fields (e.g. temperature) and/or coupling with other simplified dynamical models.

8.4 AI models and methods for ocean data analysis

Neural network based generation of 1-dimensional stochastic fields with turbulent velocity statistics

Participants: Carlos Granero Belinchon.

We define generative neural network architectures to model stochastic 1-dimensional fields with turbulent velocity statistics. The main ideas are 1) to use architectures mimicking the structure of classical stochastic models such as random wavelet cascades and 2) to introduce Kolmogorov and Obukhov laws in both the training and validation of the models. Two approaches are used: an unsupervised one which does not require turbulent data and only needs the desired statistics to be imposed, and one based on GANs which requires turbulent data.

Learning-based prediction of the particles catchment area of deep ocean sediment traps

Participants: Jonathan Gula, Ronan Fablet.

We developed a machine learning tool to predict the surface origin of particles trapped by deep-ocean sediment traps, using numerical Lagrangian experiments in the North Atlantic. The tool outperforms traditional methods by predicting approximately 50% of the source region, compared to just 25% with conventional static box approaches. The improved predictions, based on surface data like chlorophyll concentrations, highlight the role of mesoscale eddies and local deep dynamics, providing a better link between satellite observations and deep-ocean measurements to refine our understanding of carbon export mechanisms. This lead to an article in Ocean Sciences (Picard et al 2024) and a preprint (Picard et al 2024).

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 the 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. This study has been published in the journal Physica D: nonlinear phenomena. During the PhD of Maël Jaouen we extend the numerical experimentation to a wind-forced three-layers QG model.

Learning of representations for geophysical dynamics

Participants: Maxime Beauchamp, Lucas Drumetz, Ronan Fablet, Said Ouala.

We focused our efforts on learning closure terms for the representation of subgrid-scale processes, and more broadly on learning corrections to a reference model in simulations of geophysical flows.We have applied an “a-posteriori” learning method introduced in (Frezat et al., 2022) to non-differentiable direct simulation codes. Our contributions explore both emulator-based methods (Frezat et al., 2023) and Euler-type approximations for computing the gradient of the a posteriori learning cost (Ouala et al., 2023).

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).

This work applies to several topics, and in particular the short- and mid-term prediction of sea level anomaly from real data (in the Gulf Stream area – H. Goeogenthum PhD thesis) and the prediction of multispectral image reflectance dynamics (A.Frion PhD thesis). We also proposed a CNN model with "attention mechanism" for the prediction of chlorophyll concentration from atmospheric and oceanic physical drivers, for the long term reconstruction of past chlorophyll time series at global scale (J. Rousillon PhD thesis). Finally, in the context of P. Aimé PhD work and in collaboration with S. Sharma (postdoc), we studied different evaluation metrics as well as various AI methods for merging multi-spectral and panchromatic data.

We are also developing original end-to-end approaches for learning neural data assimilation methods based on both variational formulations (Fablet et al., 2021) and Kalman filtering methods (Ouala et al., 2022). Our contributions over the past year concern in particular the quantification of uncertainties in the 4DVarNet scheme, for example by exploiting Bayesian variational inference-type formulations (Lafon et al., 2023) and stochastic PDE-type representations of the underlying dynamics. We are developing various simulated and real case studies to demonstrate these approaches (e.g. surface currents, turbidity, sea surface height) (Febvre et al., 2023; Fablet et al., 2023). This line of work is in the context of the PhD thesis (at IMT) of Quentin Febvre, Hugo Georgenthum and Simon Bennaïchouche, and in collaboration with Said Ouala (postdoc IMT) and Maxime Beauchamp (postdoc IMT).

Machine learning for trajectory data

Participants: Carlos Graneo Belinchon, Ronan Fablet.

Simulation and analysis of trajectometric data are specific issues for ocean observation (e.g., ocean surface drift, ship trajectories, marine animal movements...). We are exploring learning methods for the simulation and analysis of these different types of trajectory data. This includes both new GAN methods for the simulation of bird trajectories [Roy et al., 2022], conditional simulation of drift trajectories [Botvinko et al., 2022], short-term prediction of ship trajectories [Nguyen et al., 2024] or the exploitation of ship trajectory data for the estimation of marine currents [Benaichouche et al., 2022].

Reconstructing the Ocean State Using Argo Data and a Data-Driven Method

Participants: Pierre Tandeo, Florian Sévellec.

Over the past two decades, Argo profiles have provided unprecedented insight into the global patterns of space and time variability of ocean temperature and salinity, significantly reducing associated uncertainties. However, analyzing such assessments during the pre-Argo period remains challenging due to the scarcity of observations in many regions. From the Argo period, a set of dominant three-dimensional patterns can be estimated using empirical orthogonal function (EOF) analysis, which helps to fill in observational gaps. From the associated principal components, temporal fluctuations can be observed, aiming to build a catalog of possible ocean state trajectories. To map pre-Argo observations, EOFs are used in a data assimilation framework that uses this catalog to feed an analog prediction and provide reanalysis. In this study, a new data-driven interpolation method called Reduced-Space Analog Data Assimilation (RedAnDA) was tested in the tropical Pacific Ocean. RedAnDA was first validated through an observing system simulation experiment (OSSE) approach, using synthetic observations extracted from a model simulation. It was subsequently applied to a real historical dataset and compared with other available reanalysis products. Overall, the reconstructed temperature field showed variability consistent with the OSSE true field and other reanalysis products in the real data application. Further improvements are needed to optimally estimate uncertainty, but RedAnDA already combines valuable information about state predictability, observational sampling, and unresolved scale issues. This work has been published in Journal of Atmospheric and Oceanic Technology.

Intermittency and predictability in turbulence

Participants: Carlos Graneo Belinchon.

We evaluate the performance of analog-based methodologies to predict, in a statistical way, the longitudinal velocity in a turbulent flow. We compared different methods and explored the impact of varying the number of analogs and their sizes on prediction accuracy. We illustrate that the innovation, defined as the difference between the true velocity value and the prediction value, and its uncertainty highlight particularly unpredictable events that we directly link with extreme events of the velocity gradients and so to intermittency. A statistical study of the innovation indicates that while the estimator effectively seizes linear correlations, it fails to fully capture higher-order dependencies. The innovation underscores the presence of intermittency, revealing the limitations of current predictive models and suggesting directions for future improvements in turbulence forecasting.

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.

10 Partnerships and cooperations

10.1 International initiatives

- **EUREC4A-OA**: Improving the representation of small-scale nonlinear ocean-atmosphere interactions in Climate Models by innovative joint observing and modelling approaches. JPl-Ocean project, 2020-2024. Jonathan Gula: LOPS coordinator and Xavier Carton.
- **ARCHANGE**: MOGBPA chair on climate change in Arctic (PI: A.V. Fedorov – Yale University & LOCEAN-IPSL). 2020-2024. Florian Sévellec: contributor.

10.2 International research visitors

10.2.1 Visits to international teams

Research stays abroad

Etienne Mémin

Visited institution: Imperial College, London

Country: UK

Dates: November – December 2024

Context of the visit: collaboration with D. Crisan and D. Holm

Mobility program/type of mobility: CNRS/Imperial Fellowship UMI Abraham De Moivre, Visiting professor

Florian Sévellec

Visited institution: University of Southampton

Country: UK

Context of the visit: visiting scientist.

Pierre Tandeo

Visited institution: RIKEN Center for Computational Science

Country : Kobe, Japan

dates : 2 months

Context of the visit: Research stay.

Eugenio Cutolo (Post-Doc)

Visited institution: IMEDEA

Country : Mallorque, Spain

dates : 1 jan. – 30 Apr. 2024

Context of the visit: Research stay during post-doc.

10.3 European initiatives

10.3.1 Horizon Europe

EERIE – European Eddy Rich Earth System Models

Participants: Florian Sévellec.

Delivrable DA3.4 of HORIZON-CL5-2022-D1-02-02. PIs: Thomas Jung (Alfred Wegner Intitute, Université de Bremen, Allemagne) and Malcolm Roberts (MetOffice, UK). F. Sévellec is co-investigator.

10.3.2 H2020 projects

EDITO Model Lab

Participants: Ronan Fablet.

H2020 project 2023–2025 with MercatorOceanIntl (D. Botvinko PhD thesis). Collaboration with J. Le Sommer (IGE), J. Staneva (Hereon, Germany), L. Meszaros, F. Dols (Deltares, Neetherlands).

AI4PEX

Participants: Ronan Fablet.

2024–2026. Collaboration with R. Seferian (CNRM).

AI4COSPEC

Participants: Ronan Fablet.

2024–2027.

10.3.3 Other european programs/initiatives

ERC Synergy Grant: STUOD

Participants: Bertrand Chapron, Étienne Mémin.

Stochastic transport of upper ocean dynamics. (Ifremer, Imperial College, Inria).

ERC Consolidator Grant: COSSMoSS

Participants: Jonathan Gula.

Capturing Oceanic Submesoscales, Stirring and Mixing with Sound and Simulations. 2023-2028. UCLA, Univ. of Exeter, UKRI Future Leaders fellowship.

10.4 National initiatives

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 developping 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 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).

ANR JCJC SCALES

Participants: Carlos Granero Belinchon.

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

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-IMAGO: ARVOR

Participants: Florian Sévellec.

"Assessing the Role of forced and internal Variability for the Ocean and climate Response in a changing climate" (PI: F. Sévellec), 2022–2024.

LEFE-GMMC: OASIS

Participants: Florian Sévellec.

"Ocean state Analog in-SItu analyses System" (PI: N. Kolodziejczyk – CNAP, LOPS), 2022–2024.

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. This project was the support of Master 2 internship of Mattéo Nex.

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. This project was the support of the Master 1 internships of Dyhia Elhaddad and Élise Lelièvre.

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.

IMHOTEP PI: T. Penduff (IGE, CNRS) & W. Llovel (CNRS, LOPS). Participants: F. Sévellec.

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).

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.

10.5 Regional initiatives

ARED AMMSDO

Participants: Étienne Mémin, Antoine Moneyron.

The Britany ARED project "Analyse Mathématique de Modèles Stochastiques réalistes de la Dynamique Océanique" in collaboration with Arnaud Debussche (ENS/MINGUS) funds 50 percent of the PhD thesis of Antoine Moneyron.

SAD AMIGAS

Participants: Pierre Tandeo, Florian Sévellec.

"Analog Methods to Identify Global Atmospheric Simulations" (PI: P. Tandeo).

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

Member of the organizing committees

- Étienne Mémin, Claire Menesguen, organization atelier LEFE (MANU/CLIMAGO) "Représentation des fines échelles océaniques dans les simulations numériques", Ifremer 9-11th october 2024.
- Bertrand Chapron, Étienne Mémin, 4th STUOD workshop, 23-26th September Rennes.
- Claire Menesguen Organization workshop: atelier fines échelles, à Brest. Octobre 2024 (link). Around 50 people on-site.

11.1.2 Journal

Member of the editorial boards

- Bertrand Chapron, Étienne Mémin: Editor Stochastic transport in upper ocean dynamics, Springer collection, Mathematics of Planet Earth.
- Pierre Tandeo: Member of the editorial board in Nonlinear Processes in Geophysics (EGU journal).
- Jonathan Gula: Member of the editorial board in Ocean Modelling until July 2024.
- Ronan Fablet: Associate editor in Frontier in Marine Science (special issue on AI & Ocean Remote Sensing); Associated editor in Remote Sensing.

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 revoewed for “Physica A”, “Physical Review E”, “Nature” and “Remote Sensing”.
- Jonathan Gula is reviewer for “NSF”, “Earth and Space Science” and “JGR-Oceans”.
- Noé Lahaye has reviewed for “Journal of Physical Oceanography”, “EGU Ocean Science”, “Journal of Fluid Mechanics”, “Nature Communications”, “Journal of Geophysical Research: Ocean”.
- Etienne Mémin is reviewer for “J. Fluid Mech.”, “JAMES”, “J. Comp. Phys.”, “Physica D”, “Chaos”, “ERC advanced grant”.
- Claire Ménesguen has reviewed for “JPO”, “JAMES” and “GRL”.
- Aurélien Ponte has reviewed for “J. Phys. Oceanogr.”.
- Florian Sévellec: reviewer for “Climate Dynamics”, “Communications Earth & Environment”, “Geophysical Research Letters”, “Journal of Climate” and “Journal of Physical Oceanography”.
- Gilles Tissot has reviewed for “JFM Rapids”, “Nonlinear Dynamics”, “International Journal of Electrical Power and Energy Systems”, “American Control Conference”.

11.1.3 Invited talks

- Roger Lewandowski
  - Seventeenth International Conference, Zaragoza-Pau (Spain), on Mathematics and its Applications Jaca, 4-6 September 2024, invited speaker in the session “PDEs in fluid mechanics”.
  - Conference in honor of Chérif Amrouche, plenary speaker, 2-3 September 2024, Pau (France).
  - Seminar at Czech Acamdely of Sciences (Czech Republic), Dec 2024.
- Etienne Mémin’
  - keynote speaker, CANUM 2024
- Pierre Tandéo: keynote, 10th International Symposium on Data Assimilation, Kobe (Japan, 2024).
- Gilles Tissot: Seminar at CNAM Paris April 2024 and at LISN Saclay, June 2024.
- Ronan Fablet:
  - “End-to-end neural Data Assimilation. ISDA online event on Machine Learning in Data Assimilation”. Jan. 2024.
  - “Bridging Physics and Deep learning for ocean modeling, monitoring and forecasting. Solving inverse problems with deep learning: applications to ocean dynamics CAS”, Qingdao. Sept. 2024.
  - “Bridging End-to-end neural ocean forecasts from sparse observations. NMEFC-Moi workshop on Ocean Forecasting”, CUIT, Chengdu. Sept. 2024.
  - “Bridging End-to-end neural Data Assimilation: applications to ocean modeling, monitoring and forecasting”, Grenoble AI for Physical Sciences Workshop, Grenoble. June. 2024.
  - “Bridging Physics and Deep Learning for Ocean Modeling and Monitoring: How to deal with sparsely-sampled data?” workshop “few-shot learning”, Brest, Dec. 2024.

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 CS LEFE-MANU.
- Claire Menesguen is member of CS LEFE CLIMAGO.
- Florian Sévellec is member of panels of funding agencies DFG (Germany), Lefe GMMC et CLIMAGO (France).
- 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 panel of IRGA projets (UGA) and commitee CNES – TOSCA Océan.
- Noé Lahaye is co-organizer of the European Responsible Research and Innovation Event (ERRIE) for the Cofund Bienvenüe postdoctoral fellows (European project coordinated by the Région Bretagne).
- 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

11.2.1 Teaching

- Jonathan Gula: M2 Marine Physics (64h), IUEM, Brest: Numerical Modelling (M2); Ocean Turbulence (M2); Scientific English (M2); Fluids (M1).
- Roger Lewandowski: Course ANAM, Master CSM, course ED2, Liscence of mathematics in University of Rennes.
- Florian Sévellec: Advanced Methods in Physical Oceanography, M1 (Université de Bretagne Occidentale, France).
- 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).
- Gilles Tissot: Reduced-order modelling for fluid flows (M2 CSM U. Rennes, 20h).

11.2.2 Supervision

- PhD in progress: Margot Demol, supervised by Aurélien Ponte (started Sept. 2022).
- 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: 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: Arthur Coquereau, since 2022, “Assessing the Role of forced and internal Variability for the Ocean and climate Response in a changing climate”. Bourse région bretagne et UBO. Supervisor: Sévellec; co-supervisors: J.-M. Hirschi et T. Huck.

- PhD in progress: 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 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: Benoit Presse, since Sept. 2023, (UBO, ANR REPLICA). Pierre Tandeo: supervisor.

- PhD in progress: Ewen Frogé, since Oct. 2022 (IMT, ANR Scales). Carlos Granero Belinchon: 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: D. Botvinko, ENIB, supervisors: A. Benzinou (ENIB, Lab-STICC), S. Van Gennip (MOi), C. Granero-Belinchon (Odyssey) and R. Fablet (Odyssey).

- PhD in progress: Guillaume Leloup, IRMAR, Méthodes numériques pour le couplage de deux fluides turbulents, started in 2022. supervisor: R. Lewandowski (IRMAR).

- PhD in progress: N. Schifano, “Tracer transport and mixing in the bottom mixed-layer”, started in 2021. Supervisors: J. Gula, C. Vic.

- PhD in progress: Margot Demol (Ifremer), 2022 - 2024. "Estimating the Ocean Circulation in the SWOT era », supervisors: Aurélien Ponte, Pierre Gareau.

- PhD in progress: Mathis Grangeon (DGA/Region Bretagne), 2021 - 2023: "Acoustic geolocation and small-scale ocean variability", supervisors: Aurélien Ponte, François-Xavier Socheleau, Florent Le Courtois.

- 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: C. Lemaréchal, “Deep Hydrodynamic Processes near Hydrothermal vents”, started in 2020. Supervisors: J. Gula, G. Roullet.
- PhD in progress: Perrine Bauchot, since 2021, “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 in progress: Soumaïa Tajouri, since 2021, “Impact of freshwater flux interannual variability on regional ocean circulation and sea level changes over the altimetric period 1993-2020”. Bourse CNES and UBO. supervisor: F. Sévellec and co-supervisor: W. Llovel.
- 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: Qian Liu, started in 2024, Chinese Academy of Science, visiting student.
- PhD in progress: Duan Wei, 2023 - 2024, Hohai Univ., visiting student, Left Dec. 2024.
- 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 in progress: Domitille Coron, “Variabilité spatio-temporelle de l’oxygène et de ses flux dans la zone de minimum d’oxygène de l’Atlantique Nord”, Université de Bretagne Occidentale. Fellowship région Bretagne and UBO, started in 2024. Supervisors: F. Sévellec, E. Portela.
- PhD defended: Francesco Tucciarone, Stochastic models for high resolution oceanic models, started November 2020, supervisors: Long Li, Étienne Mémin. Defended in March 2024.
- PhD defended: Adrien Bella, Understanding interactions between internal tides and currents in the ocean using high-fidelity numerical simulations, started October 2021, supervised by Noé Lahaye, Gilles Tissot, Étienne Mémin. Defended in Nov. 2024.
- PhD defended: Igor Maingonnat, Understanding and modelling nonlinear mechanisms in the ocean: internal waves / background flow interactions. Started November 2021, supervised by Noé Lahaye, Gilles Tissot, Étienne Mémin. Defended in Dec. 2024.

- PhD defended: Berenger Hug, analysis of stochastic models under location uncertainty, started November 2020, supervisors: Étienne Mémin, Arnaud Debussche. Defended in Dec. 2024.
- PhD defended: François Legeais, Couplage et turbulence à l'interface océan/atmosphère, started in 2021. Supervisor: R. Lewandowski. Defended the 2 July 2024.
- PhD defended: Erwan Oulhen, "Ocean state Analog in-SItu analyzes System", UBO. Bourse ARED (région Bretagne) and UBO. Supervisors: B. Blanke , N. Kolodziejczyk, P. Tandeo, F. Sévellec, defended Dec. 2024.
- PhD defended: Arthur Avenas, IMT Atlantique. Supervisors: A. Mouche (Odyssey), P. Tandeo (Odyssey), J. Knaf (NOAA) and R. Fablet (Odyssey), defended in 2024.
- PhD defended: T. Picard, "Data-driven Modeling and sampling to monitor particle origins in deep sediment traps (Biological Carbon Pump), started in 2021. Supervisors: J. Gula, R. Fablet, L. Mémery. Defended in Dec. 2024.
- PhD defended: Armand Vic, The dynamics of oceanic Vortices Coupled with the Atmosphere at the Mesoscale and submesoscale, started 2020. Supervisors: J. Gula and X. Carton. Defended in Dec. 2024.
- PhD defended: L. Wang, Impact of the meso and submesoscale dynamics on the fate of exported particles in the deep ocean. Supervisors: J. Gula (50%) and L. Mémery. Defended in May 2024.
- PhD defended: Pierre Le Bras, since 2020, "Méthodes analogues pour l'identification de simulations océanographiques globales, Université de Bretagne Occidentale. Bourse ARED-ISblue (région Bretagne) et UBO. Supervisors: F. Sévellec; co-supervisors: P. Tandeo et J. Riuz.

11.2.3 Juries

- Jonathan Gula:

  PhD defense D. Cortes-Morales, LOCEAN, 2024.

  PhD defense R. Torres, CNRM, 2024.

  PhD defense J.-B. Roustan, LOPS, 2024.

- Ronan Fablet:

  PhD defense T. Picard, UBO, Dec. 15 2024 (Supervisor).

  PhD defense P. Bernabé, Univ. Bourgogne, Dec. 10, 2024 (Rapporteur).

  PhD defense A. Ciocarlan, Univ. Paris-Saclay. Dec. 10, 2024 (Rapporteur).

  PhD defense B. Rousse, Univ. Paris Cité. Nov. 21, 2024 (President).

  PhD defense A. Lovo, ENS Lyon. Oct. 15, 2024 (Rapporteur).

  PhD defense M. Peyron, Univ. Toulouse. Oct. 8, 2024 (Examinateur).

  PhD defense Jannik Kuehn, Univ. Pau, Sept. 18, 2024 (Rapporteur).

  PhD defense R. Marcille, IMT Atlantique, Sept 14, 2024 (Supervisor).

  PhD defense J. Jenkins, Univ. Toulon. July 3, 2024 (Rapporteur).

  PhD defense N. Decaux, IMT Atlantique, June 6, 2026 (President).

  PhD defense Q. Malartic, ENPC. May 13, 2024 (Examinateur).

  PhD defense S. Chali, Univ. Paris-Saclay. March 28, 2024 (Rapporteur).

  PhD defense A. Avenas, UBO, March 28, 2024 (Supervisor).

  PhD defense Nicolas Lafon, UVSQ, Feb. 15. (Supervisor).

  PhD defense R. Lumet, Univ. Toulouse. Jan. 12, 2024 (Examinateur).

PhD defense M. Zambra, IMT Atlantique, Jan. 19, 2024 (Supervisor).

- Roger Lewandowski:

  PhD defense Adrien Bella, Inria Rennes, Nov.2024 (President).

- Étienne Mémin:

  PhD defense Anthony Frion, December 2024, IMT Atlantique.

  PhD defense Igor Maingonnat, December 2024, U. Rennes.

  PhD defense Adrien Bella, December 2024, U. Rennes.

  PhD defense Berenger Hug, December 2024, U. Rennes.

  PhD defense Francesco Tucciaronne, March 2024, U. Rennes.

  PhD defense Marius Duvillard, École Polytechnique, January 2025 (Rapporteur).

- Claire Menesguen:

  PhD defense Pierre-Antoine Dumont - 1 oct. 2024 - Université Toulouse 3 Paul Sabatier: Modélisation océanographique compressible: dynamique océanique et propagation acoustique, supervised by Francis Auclair and Frank Dumas.

- Auréien Ponte:

  PhD defense Gaspard Geoffroy, Stockholm University, Faculty of Science, Department of Meteorology (supervised by Jonas Nycander), 22 April (opponent).

- Pierre Tandeo:

  PhD defense Javier Martinez-Amaya, Univ. Valencia, Spain.

11.3 Popularization

11.3.1 Specific official responsibilities in science outreach structures

- Jocelyne Ehrel: editorial responsabilities in Interstices.

11.3.2 Productions (articles, videos, podcasts, serious games, ...)

- Jocelyne Ehrel: two articles in Interstices and popularization video: link.

11.3.3 Participation in Live events

- Jocelyne Ehrel: Interview in Inria Alumni.

11.3.4 Others science outreach relevant activities

- Pierre Tandeo: “L’océan et le climat”, fête de la science, Qwartz, Brest.
- Pierre Tandeo: “L’eau douce dans le Finistère”, public conference for the association “Vivre dans les monts d’Arrée”, Botmeur, France.

12 Scientific production

12.1 Major publications

[1] W. Bauer, P. Chandramouli, B. Chapron, L. Li and E. Mémin. 'Deciphering the role of small-scale inhomogeneity on geophysical flow structuration: a stochastic approach'. In: *Journal of Physical Oceanography* 50.4 (Apr. 2020), pp. 983–1003. DOI: 10.1175/JPO-D-19-0164.1. URL: https://hal.inria.fr/hal-02398521.

[2] Z. Caspar-Cohen, A. Ponte, N. Lahaye, X. Carton, X. Yu and S. Le Gentil. 'Characterization of internal tide incoherence : Eulerian versus Lagrangian perspectives'. In: *Journal of Physical Oceanography* 52.6 (2022), pp. 1245–1259. DOI: 10.1175/JPO-D-21-0088.1. URL: https://hal.archives-ouvertes.fr/hal-03514215.

[3] R. Fablet, B. Chapron, L. Drumetz, E. Mémin, O. Pannekoucke and F. Rousseau. 'Learning Variational Data Assimilation Models and Solvers'. In: *Journal of Advances in Modeling Earth Systems* 13.10 (Oct. 2021), article n° e2021MS002572. DOI: 10.1029/2021MS002572. URL: https://imt-atlantique.hal.science/hal-02906798.

[4] H. Frezat, J. Le Sommer, R. Fablet, G. Balarac and R. Lguensat. 'A posteriori learning for quasi-geostrophic turbulence parametrization'. In: *Journal of Advances in Modeling Earth Systems* (2022), pp. 1–35. DOI: 10.1029/2022MS003124. URL: https://imt-atlantique.hal.science/hal-03808230.

[5] N. Lahaye, J. Gula and G. Roullet. 'Internal tide cycle and topographic scattering over the North Mid-Atlantic Ridge'. In: *Journal of Geophysical Research. Oceans* 125.12 (12th Nov. 2020). DOI: 10.1029/2020JC016376. URL: https://hal.archives-ouvertes.fr/hal-03015814.

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[7] G. Tissot, A. V. G. Cavalieri and E. Mémin. 'Stochastic linear modes in a turbulent channel flow'. In: *Journal of Fluid Mechanics* 912 (10th Apr. 2021), pp. 1–33. DOI: 10.1017/jfm.2020.1168. URL: https://hal.inria.fr/hal-03081978.

12.2 Publications of the year

International journals

[8] C. Amrouche, G. Leloup and R. Lewandowski. 'TKE model involving the distance to the wall. Part 1: the relaxed case'. In: *Journal of Mathematical Fluid Mechanics* 26.4 (2nd Sept. 2024), pp. 1–21. DOI: 10.1007/s00021-024-00895-y. URL: https://hal.science/hal-04111072.

[9] 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.

[10] A. Bella, N. Lahaye and G. Tissot. 'Internal Tide Energy Transfers Induced by Mesoscale Circulation and Topography Across the North Atlantic'. In: *Journal of Geophysical Research. Oceans* 129.8 (25th Aug. 2024), pp. 1–54. DOI: 10.1029/2024JC020914. URL: https://hal.science/hal-04680513.

[11] L. C. Berselli, F. Legeais and R. Lewandowski. 'Surface boundary layers through a scalar equation with an eddy viscosity vanishing at the ground'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.2 (Mar. 2024), pp. 489–513. DOI: 10.1051/m2an/2024009. URL: https://hal.science/hal-04533458.

[12] P.-M. Boulvard and E. Mémin. 'Diagnostic of the Lévy area for geophysical flow models in view of defining high order stochastic discrete-time schemes'. In: *Foundations of Data Science* 6.1 (2024), pp. 1–21. DOI: 10.3934/fods.2023011. URL: https://inria.hal.science/hal-04241686.

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[14] X. Carton, J. Reinaud, A. Vic and J. Gula. 'The nonlinear evolution of two surface quasi-geostrophic vortices'. In: *Geophysical and Astrophysical Fluid Dynamics* 118.2 (5th Apr. 2024), pp. 93–119. DOI: 10.1080/03091929.2024.2330646. URL: https://inria.hal.science/hal-04841654.

[15] A. Colin, P. Tandeo, C. Peureux, R. Husson, N. Longépé and R. Fablet. 'Rain Regime Segmentation of Sentinel-1 Observation Learning From NEXRAD Collocations With Convolution Neural Networks'. In: *IEEE Transactions on Geoscience and Remote Sensing* 62 (2024), pp. 1–14. DOI: 10.1109/TGRS.2024.3353311. URL: https://imt-atlantique.hal.science/hal-04502265.

[16] E. Cutolo, A. Pascual, S. Ruiz, N. Zarokanellos and R. Fablet. 'CLOINet: ocean state reconstructions through remote-sensing, in-situ sparse observations and deep learning'. In: *Frontiers in Marine Science* 11 (2024), p. 1151868. DOI: 10.3389/fmars.2024.1151868. URL: https://hal.science/hal-04536436.

[17] W. Duan, X. Cheng, Y. Zhou and J. Gula. 'Characteristics of Submesoscale Compensated/Reinforced Fronts in the Northern Bay of Bengal'. In: *Journal of Geophysical Research. Oceans* 129.10 (4th Oct. 2024). DOI: 10.1029/2024JC021204. URL: https://inria.hal.science/hal-04841646.

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[19] R. Fablet, B. Chapron, J. Le Sommer and F. Sévellec. 'Inversion of Sea Surface Currents From Satellite-Derived SST-SSH Synergies With 4DVarNets'. In: *Journal of Advances in Modeling Earth Systems* 16.6 (June 2024), e2023MS003609 (19p.) DOI: 10.1029/2023MS003609. URL: https://hal.science/hal-04669231.

[20] Q. Febvre, J. Le Sommer, C. Ubelmann and R. Fablet. 'Training Neural Mapping Schemes for Satellite Altimetry With Simulation Data'. In: *Journal of Advances in Modeling Earth Systems* 16.7 (9th July 2024), pp. 1–13. DOI: 10.1029/2023MS003959. URL: https://imt-atlantique.hal.science/hal-04672619.

[21] Q. Febvre, C. Ubelmann, J. Le Sommer and R. Fablet. 'Scale-Aware Neural Calibration for Wide Swath Altimetry Observations'. In: *IEEE Transactions on Geoscience and Remote Sensing* 62 (2024), pp. 1–8. DOI: 10.1109/TGRS.2024.3363503. URL: https://imt-atlantique.hal.science/hal-04672614.

[22] Z. Gao, B. Chapron, C. Ma, R. Fablet, Q. Febvre, W. Zhao and G. Chen. 'A Deep Learning Approach to Extract Balanced Motions From Sea Surface Height Snapshot'. In: *Geophysical Research Letters* 51.7 (5th Apr. 2024). DOI: 10.1029/2023GL106623. URL: https://hal.science/hal-04536442.

[23] C. Granero-Belinchon and M. Cabeza Gallucci. 'A multiscale and multicriteria Generative Adversarial Network to synthesize 1-dimensional turbulent fields'. In: *Machine Learning: Science and Technology* 5.2 (7th May 2024), p. 025032. DOI: 10.1088/2632-2153/ad43b3. URL: https://hal.science/hal-04173074.

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[27] N. Lahaye, A. Ponte, J. Le Sommer and A. Albert. 'Internal Tide Surface Signature and Incoherence in the North Atlantic'. In: *Geophysical Research Letters* 51.12 (14th June 2024). DOI: 10.1029/2024GL108508. URL: https://hal.science/hal-04614612.

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[30] R. Marcille, P. Tandeo, M. Thiébaut, P. Pinson and R. Fablet. 'Convolutional encoding and normalizing flows: a deep learning approach for offshore wind speed probabilistic forecasting in the Mediterranean Sea'. In: *Artificial Intelligence for the Earth Systems* (9th July 2024), pp. 1–41. DOI: 10.1175/aies-d-23-0112.1. URL: https://imt-atlantique.hal.science/hal-04645705.

[31] É. Martinez, T. Gorgues, M. Lengaigne, R. Sauzède, C. Menkes, J. Uitz, E. Di Lorenzo and R. Fablet. 'Corrigendum: Reconstructing global chlorophyll-a variations using a non-linear statistical approach'. In: *Frontiers in Marine Science* 11 (8th May 2024). DOI: 10.3389/fmars.2024.1419611. URL: https://hal.science/hal-04650259.

[32] A. Mashayek, J. Gula, L. Baker, A. Naveira Garabato, L. Cimoli, J. Riley and C. de Lavergne. 'On the role of seamounts in upwelling deep-ocean waters through turbulent mixing'. In: *Proceedings of the National Academy of Sciences of the United States of America* 121.27 (25th June 2024), pp. 1–10. DOI: 10.1073/pnas.2322163121. URL: https://hal.science/hal-04685001.

[33] 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). DOI: 10.1063/5.0231713. URL: https://imt-atlantique.hal.science/hal-04872005.

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Invited conferences

[52] D. Botvynko, C. Granero-Belinchon, S. Van Gennip, A. Benzinou and R. Fablet. 'Deep Learning for Lagrangian Drift Simulation on Sea Surface'. In: Climate Informatics 2024. London, United Kingdom, 2024, pp. 1–3. URL: https://hal.science/hal-04569396.

International peer-reviewed conferences

[53] N. E. Bekri, L. Drumetz and F. Vermet. 'Time Changed Normalizing Flows for Accurate SDE Modeling'. In: ICASSP 2024 - 2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). Seoul, France: IEEE, 2024, pp. 6395–6399. DOI: 10.1109/ICASSP48485.2024.10446131. URL: https://imt-atlantique.hal.science/hal-04716987.

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