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2022
ACTIVITY REPORT

Project-Team
ODYSSEY

Ocean DYnamicS obSErvation analYsis

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

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Project-Team ODYSSEY

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1 Team members, visitors, external collaborators

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- Etienne Mémin [Team leader, INRIA, Senior Researcher, HDR]
- Bertrand Chapron [IFREMER, Researcher, from Mar 2022]
- Clément De Boyer Montégut [IFREMER, Researcher, from Mar 2022]
- Evgunei Dinvay [Inria, Starting Research Position, until Aug 2022]
- Jocelyne Erhel [INRIA, Emeritus, HDR]
- Quentin Jamet [Inria, Starting Research Position, from Apr 2022]
- Noé Lahaye [INRIA, Researcher]
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- Claire Ménesguen [IFREMER, Researcher, from Mar 2022]
- Frédéric Nouguier [IFREMER, Researcher, from Mar 2022]
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- Jonathan Gula [UBO, Associate Professor, from Mar 2022]
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- Zoe Caspar-Cohen [Inria, from Dec 2022, Relais thèse]
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- Jean-François Piolle [IFREMER, Engineer, from Mar 2022]

Interns and Apprentices

- Thomas Gauvain [Inria, Intern, from May 2022 until Jun 2022]
- Antoine Moneyron [Inria, Intern, from Oct 2022]

Administrative Assistant

- Caroline Tanguy [INRIA]

2 Overall objectives

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

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

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

Ocean observations analysis This axis aims at exploiting novel multi-modal high-resolution 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 develop 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.

IA 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 manifold. 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 more dedicated more directly to the development, the implementation and the validation of simplified models of th 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 IA 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

The main highlight of the year is that the team was finally launched in April, after a long and tedious process that entailed solving numerous administrative and institutional puzzles.

7 New software and platforms

- Most softwares implementing machine learning methods are available at CIA-Oceanix
- MLD dataset published on SEANOE : this constitutes an update of the monthly climatology of the oceanic Mixed Layer Depth (MLD) from *in situ* observations and following the method developed in Boyer Montégut et al (2004 JGR). de Boyer Montégut Clément (2022). *Mixed layer depth climatology computed with a density threshold criterion of 0.03kg/m3 from 10 m depth value* SEANOE.

8 New results

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

Convective rolls in the marine atmospheric boundary layer

Participants: Carlos Granero Belinchon, Bertrand Chapron, Alexis Mouche, Pierre Tandeo.

The imprint of marine atmospheric boundary layer (MABL) dynamical structures on sea surface roughness, as seen from Sentinel-1 Synthetic Aperture Radar (SAR) acquisitions, is investigated. We propose a multiscale analysis with structure functions which allow an easy generalization to analyse high-order statistics and so to finely describe the shape of the rolls. The two main results are 1) second-order structure function characterizes the wavelength and direction of rolls just like correlation or power spectrum do, 2) high-order statistics can be studied with skewness and flatness which characterize the asymmetry and intermittency of rolls, respectively. This is the first time that the asymmetry and intermittency of rolls are shown from radar images of the ocean surface. Then we focus on February 13th, 2020, a case study of the EUREC4A (Elucidating the role of clouds-circulation coupling in climate) field campaign. A discretization of the SAR wide swath into $25 \times 25\,\mathrm{km}^2$ tiles then allows us to capture the spatial variability of the turbulence organization varying from rolls to cells.

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

Participants: Zoé Caspar-Cohen, Margot Demol, Noé Lahaye, Aurélien Ponte.

We have pursued our efforts around the characterization of oceanic high frequency variability, internal tides in particular. These efforts are motivated by the expected necessity to identify and filter out these motions in future SWOT altimetric data. We investigated with idealized and realistic high resolution numerical simulations to what extent surface drifter (such as those of the Global Drifter Program) could improve our knowledge of internal tides (coherence, temporal scales). These efforts were carried by Zoe Caspar-Cohen who concluded her PhD in December 2022 (advisors: Aurélien Ponte, Noé Lahaye). A first outcome of this effort is Caspar-Cohen et al. 2022, another publication is in preparation.

In preparation for the SWOT mission, Margot Demol (LOPS/Ifremer) performed a M2 internship about reconstructions of the ocean upper dynamics from altimetry and surface drifters. This will improve our understanding of the upper ocean variability and dynamics, in particular the role of high frequencies in modulating the accuracy of surface current estimates via the altimetry and the geostrophic assumption. As a reminder, this approach is a cornerstone of today's surface ocean circulation estimates. Margot started a PhD about the same topic in October 2022 (advisor: Aurélien Ponte).

Substantial efforts were dedicated to the preparation of SWOT experimental campaigns. Aurélien Ponte is involved in the development of CSWOT 2023 campaign which will take place in the Mediterranean Sea and ensured the acquisition of surface drifting buoys along with the location of the DriX unmanned surface vehicle. Aurélien is also involved in the development of an experimental campaign that will take place over the North Western Australian shelf break. These efforts will lead to further actions in 2023.

Effects of smooth divergence-free flows on tracer gradients and spectra: Eulerian prognosis description

Participants: Bertrand Chapron, Étienne Mémin.

To predict the tracer deformations by ocean eddies and the evolution of their 2nd-order statistics, an efficient proxy has been proposed in collaboration with Valentin Resseguier (Scalian). Applied to a single velocity snapshot, this proxy extends the Okubo-Weiss criterion. For the Lagrangian-advection-based downscaling methods, it successfully predicts the evolution of tracer spectral energy density after a finite time, and the optimal time to stop the downscaling operation. A practical estimation can then be proposed to define an effective parameterization of the horizontal eddy diffusivity. This work has been published in the J. of Phys. Oceanography.

Estimation of Koopman eigenvalues from time series autocovariance matrix

Participants: Bertrand Chapron, Étienne Mémin.

To infer eigenvalues of the infinite-dimensional Koopman operator, we study the leading eigenvalues of the autocovariance matrix associated with a given observable of a dynamical system. For any observable for which all the time-delayed autocovariance exist, we construct a related Hilbert space and a Koopman-like operator that acts on it. We prove that the leading eigenvalues of the autocovariance matrix has one-to-one correspondence with the energy of that observable; the associated eigenvectors correspond to the eigenvectors of the Koopman operator. The proof is associated to several representation theorems of isometric operators on a Hilbert space, and the weak-mixing property of the observables represented by the continuous spectrum.

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

Participants: Xavier Carton, Jonathan Gula, Quentin Jamet, Claire Ménesguen, Armand Vic.

We have run and analyzed several high-resolution numerical studies to investigate the role of (sub)mesoscale motions in the ocean. In a first axis of research, detailed energy but analyses were conducted. In the Aguhlas region, the transfers of energy between the vertical scale of mesoscale motions were analyzed, and a net input of eddy kinetic energy has been exhibited through interaction with the coastal topography [Tedesco et al 2022]. In the Gulf-Stream region, we investigated how eddies can trigger a remote eddy-to-mean kinetic energy transfer, with important implication for potential parametrization for coarse-resolution simulations [Jamet et al 2022].

In the context of EUREC4A-OA, an experiment designed to determine the impact of oceanic meso scale and submeso scale on the ocean/atmosphere exchanges, we analyse surface and sub-surface vortices in data and in a high-resolution numerical simulation of the Atlantic ocean. Besides, we are conducting studies of oceanic processes and ocean-atmosphere coupling in an idealised or analytical model – in particular on the instability of baroclinic vortices [Vic et al 2022]. In parallel of the data validation of EUREC4A-OA experimental campaign, we are analysing the considered oceanic region: in 2021, we had studied the plume of the Amazone and began to identify and to caracterise the sub-meso scales of the region. This year, we keep analysing these small vortices are studying their stability. The impact of the ocean-atmosphere coupling on these vortices will be the follow-up of our studies.

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 ($dx \sim 2$ km) numerical simulation of the North Atlantic Ocean “eNATL60”, we are analyzing the lifecycle of the internal tide field based on a vertical mode decomposition of the dynamics. We analyse and quantify 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. Overall, all these mechanisms seems to participate to a transfer of energy towards smaller scale, hence ultimately favouring the dissipation of energy. A paper for the 2022 STUOD proceedings is in preparation.

In parallel, we focus on the surface signature of the internal tide and the incoherence (lack of regularity in time). We show that the typical time of decorrelation varies between 1 month and 1 day, with shorter time associated with regions of strong mesoscale activity and internal tide with the shortest horizontal scale (i.e., high vertical mode number). A paper for GRL is in preparation.

Coherent vortices in Rotating Magneto-Hydrodynamics

Participants: Noé Lahaye.

We used a 1-layer magnetic rotating shallow water model and its quasi-geostrophic (fast background rotation), which is a model valid for solar (and similar stellar) tachocline. We showed the existence of robust dipolar solutions in these models and investigate there stability using numerical simulations. Our results show that stable solution exists for moderate magnetic field anomalies associated to the dipole, and/or in a moderate ambient magnetic field. They consist of two paired vorticies with opposite signed and co-propagating through their mutual interaction. Stronger magnetic field triggers an instability associated with small scales and leading to a complete destruction of the initial structures.

Estimations of upper ocean characteristics from *in situ* observations

Participants: Clément de Boyer Montégut, Nicolas Reul.

This CNES PhD is part of the program ESA CCI SSS, supervised by Clément de Boyer Montégut et Nicolas Reul. The goal is to study the feasibility of estimating SSS in C/X band, which is usually performed in L band (*e.g.* SMOS). We focus on the Bengal bay, which shows optimal conditions for this task. A restitution method has been set up in this zone and allows us to reconstruct monthly fields of SSS during 9 additional years (2003-2011) with an acceptable feasibility regarding inter-annual variability. This work opens ways to go further and improve this first product (Montero et al 2023, submitted). In a second step, we study the respective role of intrinsic oceanic variability (vortices), and forced by atmosphere in this region. This is performed using ensemble of oceanic runs (project CNES TOSCA IMHOTEP, PI: W, Llovel and T. Penduff).

Besides, a collaboration with Guillaume Sérazin (P.doc LOPS), in the project PPR MEDLEY (conducted by Anne-Marie Tréguier, LOPS) is in progress. We have set up a computation method of the stratification below the MLD, also called “ Upper Ocean Pycnocline ”, from *in situ* observations. A dataset of this stratification (amplitude, depth, vertical extension) has been produced an published on SEANOE. Sérazin, G., A.-M. Tréguier and C. de Boyer Montégut, *A seasonal climatology of the upper ocean pycnocline*, submitted to Frontiers in Marine Research Sérazin Guillaume, Tréguier Anne Marie, de Boyer Montégut Clement (2022). Monthly climatology of the upper ocean pycnocline. SEANOE.

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

Mathematical models for the interface of two coupled fluids and surface boundary layers

Participants: Francois Legeais, Roger Lewandowski.

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 $0 \le \alpha < 1$ 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.

Very-high numerical simulations of the ocean dynamics

Participants: Jonathan Gula, Claire Ménesguen.

Simulations with a resolution of 500 m vertically and 360 levels vertically have been carried out in the Mozambique Channel to support studies of sub-mesoscale processes that have been studied in two oceanographic campaigns (RESILIENCE 2022 and SOUSACOU 2021). A backup strategy has been devised to record every 30 minutes over restricted geographical regions and every 2 days over the entire domain, enabling the study of slow and rapid ocean movements. The Mozambique Channel is a particularly suitable region for studying the interactions between internal waves and eddies. Indeed, on the one hand, the eddy field is one of the most energetic on the globe and on the other hand, the internal tide has a strong signal there. This study is led by C. Ménesguen and as part of a LEFE-IMAGO project (2020-2023).

In the context of the ANR DEEPER, led by J. Gula, we have designed a configuration covering the full Atlantic ocean with the model CROCO at meso and submesoscale permitting resolutions (6 km, 3 km and 1 km) with realistic topography, high-frequency surface forcings and tidal forcings. These state-of-the-art simulations, called GIGATL, are used in numbers of numbers of present and forthcoming studies in the team. Different aspects of the simulations have been evaluated by comparing metrics at the surface, in the interior and at the bottom of the ocean to satellite and in-situ observations from global datasets and available observations from regional experiments). The increase in horizontal and vertical resolution contributes to a more realistic structure for currents (in particular western boundary currents) with a more realistic eastward and downward extension. More detailed analysis are underway and will be the subject of a dedicated article describing the different simulations. Data from GIGATL have been used in the SWOT Adopt-A-Xover ocean model intercomparison study [Uchida et al 2022].

Geophysical flows modeling 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 Navier-Stokes equations.

Participants: Arnaud Debussche, Berenger Hug, Étienne Mémin.

We construct martingale solutions for the stochastic Navier-Stokes equations in the framework of the modelling under location uncertainty (LU). These solutions are pathwise and unique when the spatial dimension is 2D. We then prove that if the noise intensity goes to zero, these solutions converge, up to a subsequence in dimension 3, to a solution of the deterministic Navier-Stokes equation. This warrants that the LU Navier-Stokes equations can be interpreted as a large-scale model of the deterministic Navier-Stokes equation. This work has been published in the STUOD proceeding. An extended version has recently been accepted in a journal.

Wave solution of stochastic geophysical models

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

In a first work we studied a Hamiltonian stochastic formulation of the water wave problem in the setting of the modelling under location uncertainty. Starting from reduction of the stochastic fluid motion equations to the free surface, we have shown how one can naturally deduce Hamiltonian structure under a small noise assumption. Moreover, as in the classical water wave theory, the non-local Dirichlet-Neumann operator appears explicitly in the energy functional. This, in particular, allows us to conduct in a natural way the systematic approximation of the Dirichlet-Neumann operator and to devise different simplified wave models including noise. This study has been published in the Proc. of the Royal Soc.

In another 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 .

Parameterization for coarse-resolution ocean modeling

Participants: Louis Thiry, Long Li, Étienne Mémin.

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.

Higher order temporal numerical schemes in time for dynamics under location uncertainty

Participants: Pierre-Marie Boulvard, Camilla Fiorini, Long Li, Étienne Mémin.

In this work we consider the surface quasi-geostrophic (SQG) system under location uncertainty (LU) and propose a Milstein-type scheme for these equations, which is then used in a multi-step method. The SQG system considered here consists of one stochastic partial differential equation, which models the stochastic transport of the buoyancy, and a linear operator linking the velocity and the buoyancy. In the LU setting, the Euler-Maruyama scheme converges with weak order 1 and strong order 0.5. Our aim is to develop higher order schemes in time, based on a Milstein-type scheme in a multi-step framework. First we compared different kinds of Milstein schemes. The scheme with the best performance is then included in the two-step scheme. Finally, we show how our two-step scheme decreases the error in comparison to other multi-step schemes.

Stochastic compressible fluid dynamics

Participants: Étienne Mémin, Gilles Tissot.

We are currently working on the extension of the stochastic formulation under location uncertainty to compressible flows. The interest is to extend the formulation on the one hand to compressible fluids (for instability mechanisms involved in areoacoustics for instance, or for thermal effects in mixing layers) and on the other hand to geophysical flows where the Boussinesq equation is not valid anymore (density variations due to temperature or salinity gradients). A theoretical study has been performed that opens the door to numerical validations. In particular a baropycnal work term has been identified that could have major effects when resolved pressure gradient aligns with corrective drift velocity.

Stochastic hydrodynamic stability under location uncertainty

Participants: Étienne Mémin, Gilles Tissot.

In order to predict instability waves propagating within turbulent flows, eigenmodes of the linearised operator is not well suited since it neglects the effect of turbulent fluctuations on the wave dynamics. To cope this difficulty, resolvent analysis has become popular since it represents the response of the linearised operator to any forcing representing the generalised stress tensors. The absence of information on the non-linearity is a strong limitation of the method. In order to refine these models, we propose to consider a stochastic model under location uncertainty expressed in the Fourier domain, to linearise it around the corrected mean-flow and to study its response to a stochastic transport. The stochastic part represents the effect of the turbulent field onto the instability wave. It allows to specify a structure of the noise and then to improve existing models. Improvements compared to the resolvent analysis have been found for turbulent channel flow data at $Re_\tau = 180$, $Re_\tau = 550$ and $Re_\tau = 1000$. We have focused this year in accounting for non-linear interactions between coherent structures. A paper is currently in revision in Physcal Revew Fluids. This work is in collaboration with André Cavalieri (Instituto Tecnologico de Aeronautica, SP, Brésil).

8.3 Data/Models interactions and reduced order modelling

Analog data assimilation for the selection of suitable general circulation models

Participants: Pierre Tandeo.

Data assimilation is a relevant framework to merge a dynamical model with noisy observations. When various models are in competition, the question is to find the model that best matches the observations. This matching can be measured by using the model evidence, defined by the likelihood of the observations given the model. This study explores the performance of model selection based on model evidence computed using data-driven data assimilation, where dynamical models are emulated using machine learning methods. In this work, the methodology is tested with the three-variable Lorenz model and with an intermediate complexity atmospheric general circulation model (a.k.a. the SPEEDY model). Numerical experiments show that the data-driven implementation of the model selection algorithm performs as well as the one that uses the dynamical model. The technique is able to select the best model among a set of possible models and also to characterize the spatiotemporal variability of the model sensitivity. Moreover, the technique is able to detect differences among models in terms of local dynamics in both time and space which are not reflected in the first two moments of the climatological probability distribution. This suggests the implementation of this technique using available long-term observations and model simulations. This study has been the object of the publication Ruiz *et al.* (2022) in Geoscientific Model Development.

Evaluation of machine learning techniques for forecast uncertainty quantification

Participants: Pierre Tandeo.

Ensemble forecasting is, so far, the most successful approach to produce relevant forecasts with an estimation of their uncertainty. The main limitations of ensemble forecasting are the high computational cost and the difficulty to capture and quantify different sources of uncertainty, particularly those associated with model errors. In this article we perform toy-model and state-of-the-art model experiments to analyze to what extent artificial neural networks (ANNs) are able to model the different sources of uncertainty present in a forecast. In particular, those associated with the accuracy of the initial conditions and those introduced by the model error. We also compare different training strategies: one based on a direct training using the mean and spread of an ensemble forecast as target, and the other ones rely on an indirect training strategy using an analyzed state as target in which the uncertainty is implicitly learned from the data. Experiments using the Lorenz'96 model show that the ANNs are able to emulate some of the properties of ensemble forecasts like the filtering of the most unpredictable modes and a state-dependent quantification of the forecast uncertainty. Moreover, ANNs provide a reliable estimation of the forecast uncertainty in the presence of model error. Preliminary experiments conducted with a state-of-the-art forecasting system also confirm the ability of ANNs to produce a reliable quantification of the forecast uncertainty. This study has been the object of the publication Sacco *et al.* (2022) in Quarterly Journal of the Royal Meteorological Society.

Comparison of Simulation-Based Algorithms for Parameter Estimation and State Reconstruction in Nonlinear State-Space Models

Participants: Pierre Tandeo.

This study aims at comparing simulation-based approaches for estimating both the state and unknown parameters in nonlinear state-space models. Numerical results on different toy models show that the combination of a Conditional Particle Filter (CPF) with Backward Simulation (BS) smoother and a Stochastic Expectation-Maximization (SEM) algorithm is a promising approach. The CPFBS smoother run with a small number of particles allows to explore efficiently the state-space and simulate relevant trajectories of the state conditionally to the observations. When combined with the SEM algorithm, this algorithm provides accurate estimates of the state and the parameters in nonlinear models, where the application of EM algorithms combined with a standard particle smoother or an ensemble Kalman smoother is limited. This study has been the object of the publication Chau *et al.* (2022) in Discrete & Continuous Dynamical Systems – Series S

Optimal control techniques for the coupling of large scale dynamical systems and image data

Participants: Mohamed Yacine Ben Ali, Étienne Mémin, Gilles Tissot.

In collaboration with the CSTB Nantes centre and within the PhD of Yacine Ben Ali we explored the definition of efficient data assimilation schemes for wind engineering. The goal is here to couple Reynolds average model to pressure data at the surface of buildings. Several techniques have been proposed to that end. We show in particular that optimisation conducted in a Sobolev space is highly beneficial as it brings natural smoothing to the sought solutions and avoids the use of regularization penalty. The techniques proposed consists in correcting the equations related to turbulent kinetic energy and dissipation. This work is thoroughly detailed in the PhD manuscript of Yacine Ben Ali. One journal article has been recently published on this study in Journal of Wind Engineering and Industrial Applications.

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: Noé Lahaye, Igor Maingonnat, Gilles Tissot.

Using an idealized configuration in a 1-layer rotating shallow water model, we study the evolution of an inertia-gravity wave interacting with a turbulent mesoscale jet. The resulting incoherent inertia-gravity wave field is then analyzed using several methods: spectral POD, extended spectral POD and resolvent analysis. The goal of this study is twofold: 1) better understand and characterize the loss-of coherence of the inertia-gravity wave when interacting with the turbulent background flow and 2) extract the relevant modes of variability to formulate a reduced order model that is able to capture and predict the inertia-gravity wave, given some knowledge of the mesoscale flow contribution. The latter is oriented towards the devise of data-assimilation models for incoherent internal wave fields in the ocean. A paper summarizing the results is in preparation for the STUOD proceedings.

8.4 IA models and methods for ocean data analysis

Learning of the dynamics of large scale geophysical systems using semi-group theory for data assimilation

Participants: Benjamin Dufé, Berenger Hug, 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 manifold of reproducible kernel Hilbert spaces with kernel functions driven by the dynamics. This manifold is nicknamed Wonderland for its appealing properties. In Wonderland the Koopman and Perron-Frobenius operator (also referred to in the literature as the composition and transfer operators, respectively) are unitary and uniformly continuous. They can be safely expressed in exponential series of diagonalizable bounded infinitesimal generators. Access to Lyapunov exponents and to exact ensemble based expressions of the tangent linear dynamics are directly available as well. Wonderland 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. Numerical proofs of concept for data assimilation and trajectory recovery have been performed with a quasi-geostrophic flow model.

Learning of representations for geophysical dynamics

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

We have continued our work on the identification of augmented representations for partially observed systems [Ouala et al., 2020]. In particular, we have highlighted the advantage of ensuring explicit energy conservation constraints to guarantee the stability of the identified systems [Ouala et al., 2023]. The proposed generic framework also provides a generalization of (E)DMD type approaches for the approximation of the Koopman operator. In a related way, we have also obtained new results around closure term learning strategies for LES simulations. In particular, we have illustrated the relevance of a posteriori criteria to improve the stability of neural closures, including via surrogate techniques in the case of non-differentiable direct simulation codes [Frezat et al., 2022].

End-to-end learning for data assimilation

Participants: Maxime Beauchamp, Simon Bennaïchouche, Bertrand Chapron, Lucas Drumetz, Ronan Fablet, Etienne Mémin, Said Ouala, Pierre Tandeo.

We are 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]. In particular, we have clarified the relations between our 4DVarNet method and the optimal interpolation framework, proposed extensions for the assimilation of multimodal data and introduced probabilistic extensions of the 4DVarNet variational framework to take into account uncertainty notions. The performances obtained for applications on simulated and real data representative of ocean surface dynamics (e.g., surface currents, turbidity, sea surface height) suggest operational applications with significant potential improvements of the state of the art [Beauchamp et al., 2022; Fablet et al., 2022].

Machine learning for trajectory data

Participants: Carlos Graneo Belinchon, Amédée Roy, 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., 2022] or the exploitation of ship trajectory data for the estimation of marine currents [Benaichouche et al., 2022].

Besides, we propose an extension/development of techniques proposed in the team to dynamical temporal series of multispectral images (Anthony Frion thesis). We develop some representations of stochastic processes based on the dynamics of the moments of order 1 and 2, requiring time-integration schemes respecting the geometry of the order 2 moments (covariance).

Synthetic generation of surface wind time series

Participants: Carlos Graneo Belinchon.

We define and study a fully-convolutional neural network stochastic model, NN-Turb, which generates 1-dimensional fields with turbulent velocity statistics. Thus, the generated process satisfies the Kolmogorov 2/3 law for second order structure function. It also presents negative skewness across scales (i.e. Kolmogorov 4/5 law) and exhibits intermittency. Furthermore, our model is never in contact with turbulent data and only needs the desired statistical of the structure functions across scales for training.

9 Bilateral contracts and grants with industry

9.1 Bilateral Grants with Industry

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

- projet R&D CMEMS with Mercator Ocean et e-odyn.
- M. Zambra PhD thesis with NavalGroup
- CMEMS project 4DVarNET-OFDA,
- projet R&D CMEMS with Mercator Ocean et e-odyn. A. Colin PhD thesis with CLS
- CMEMS project 4DVarNET-OFDA,
- projet R&D CMEMS with Mercator Ocean et e-odyn. P. Tripathi PhD thesis with OceanDataLab
- S. Benaïchouche PhD thesis with Eodyn
- H2020 project EditoModelLab, Ocean Intl

10 Partnerships and cooperations

10.1 International initiatives

SWOT Science Team

Participants: Clément De Boyer Montégut, Bertrand Chapron, Ronan Fablet, Jonathan Gula, Noé Lahaye, Alexis Mouche, Frédéric Nouguier, Aurélien Ponte, Nicolas Reul.

10.2 International research visitors

10.2.1 Visits to international teams

Sabbatical programme

Jonathan Gula

Visited institution: University of California, Los Angeles

Country: USA

Dates: mid-2022 – mid-2023

Context of the visit: collaboration in the group of James C. McWilliams

Mobility program/type of mobility: sabbatical

Research stays abroad

Gilles Tissot

Visited institution: California Institute of Techology.

Country: California, USA.

Dates: 18-29 July 2022

Context of the visit: Collaboration with the team of Tim Colonius.

Mobility program/type of mobility: Research stay.

Roger Lewandowski

Visited institution: University of Pisa

Country: Italia

Dates: Fall 2022

Context of the visit: Collaboration with L. Berselli

Mobility program/type of mobility: Research stay.

Roger Lewandowski

Visited institution: University of Sevilla

Country: Spain

Dates: September 2022

Context of the visit: Collaboration with T. Chacon

Mobility program/type of mobility: Research stay.

Etienne Mémin

Visited institution: Imperial College, London.

Country: United Kingdom.

Dates: May, September 2022

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

10.3 European initiatives

ERC Synergy Grant STUOD: Stochastic Transport in Upper Ocean Dynamics

PI: Bertrand Chapron, Étienne Mémin

Duration: 01/03/2020 – 01/03/2026

Participants: Bertrand Chapron, Evgueni Dinvay, Benjamin Dufée, Camilla Fiorini, Beranger Hug, Long Li, Étienne Mémin, Louis Thiry, Francesco Tucciarone.

Partners: IFREMER, IMPERIAL COLLEGE London (UK)

Summary: 71 percent of Earth is covered by ocean. The ocean has absorbed 93 percent of the heat trapped by human's greenhouse gas emissions. The ocean's future responses to continued warming are uncertain. Our project will deliver new capabilities for assessing variability and uncertainty in upper ocean dynamics. It will provide decision makers a means of quantifying the effects of local patterns of sea level rise, heat uptake, carbon storage and change of oxygen content and pH in the ocean. Its multimodal monitoring will enhance the scientific understanding of marine debris transport, tracking of oil spills and accumulation of plastic in the sea. Our approach accounts for transport on scales that are currently unresolvable in computer simulations, yet are observable by satellites, drifters and floats. Four scientific capabilities will be engaged: (i) observations at high resolution of upper ocean properties such as temperature, salinity, topography, wind, waves and velocity; (ii) large scale numerical simulations; (iii) data-based stochastic equations for upper ocean dynamics that quantify simulation error; and (iv) stochastic data assimilation to reduce uncertainty. These four scientific capabilities will tackle a network of joint tasks achieved through cooperation of three world-calibre institutions: IFREMER (ocean observations, reanalysis); INRIA (computational science); and Imperial College (mathematics, data assimilation). Our complementary skill sets comprise a single systemic effort: (1) Coordinate and interpret high-resolution satellite and in situ upper ocean observations (2) Extract correlations from data needed for the mathematical model (3) Perform an ensemble of computer simulations using our new stochastic partial differential equations (SPDE) which are derived by matching the observed statistical properties (4) Apply advanced data assimilation and computer simulations to reduce model uncertainty The key to achieving these goals will be synergy in our combined expertise.

10.3.1 H2020 projects

R. Fablet is involved in the H2020 projects IMEDEA (H2020 Eurosea) and HEREON (H2020 Edito-ModelLab).

10.4 National initiatives

PPR "Océan et climat" CLIMARCTIC

Participants: Pierre Tandeo, Ronan Fablet, Lucas Drumetz.

The CLIMARCTIC project aims at improving our understanding of climate change in the arctic, both at regional and global scales. Pierre Tandeo is co-PI 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 Melody

Participants: Ronan Fablet.

“Bridging geophysics and MachinE Learning for the modeling, simulation and reconstruction of Ocean DYnamics”. (PI: R. Fablet)

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). 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.

ALESE

Participants: Carlos Granero Belinchon.

ALESE is a MITI CNRS project

TOSCA CNES projects The Odyssey team is involved in the science team of the SWOT mission mainly 2 projects:

DIEGO Participants: A. Ponte (PI), J. Gula, N. Lahaye, P. Tandeo, R. Fablet, C. Menesguen

THEIA PI: C. Granero Belinchon

Action exploratoire “KoopduMonde”

Participants: Gilles Tissot, Étienne Mémin.

“Koopman operator modelling of non-linear dynamical systems for ensemble methods”.

10.5 Regional initiatives

ARED COMIOE

Participants: Adrien Bela, Noé Lahaye, Gilles Tissot, Étienne Mémin.

The Britany ARED project "COmpréhension et Modélisation de mécanismes non-linéaires dans l’océan : les Interactions entre Ondes internes et Ecoulement" funds 50 percent of the PhD thesis of Adrien Bela.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Journal

Member of the editorial boards

- Pierre Tandeo: Member of the editorial board in Nonlinear Processes in Geophysics (EGU journal).
- Jocelyne Erhel: Member of the editorial board in Interstices, and review activity in this journal (10 reviews in 2022); Member of the editorial board in ETNA; Member of the editorial board in ESAIM Proceedings and Surveys.
- Jonathan Gula: Member of the editorial board in Ocean Modelling
- Ronan Fablet: Associate editor in Frontier in Marine Science (special issue on AI & Ocean Remote Sensing); Associated editor in Remote Sensing

Reviewer - reviewing activities

- Clément De Boyer Montégut is a reviewer for Deep sea research and GRL.
- Lucas Drumetz is a reviewer for Neurips, ICML, IEEE TGRS, IEEE JSTARS, IEEE ICASSP, GRETSI.
- Carlos Granero Belinchon is a reviewer for Physical Review Research, Physical Review E, Physica D, Entropy MDPY and Remote Sensing MDPI.
- Jonathan Gula is reviewer for J. Geophys. Research Ocean, Geophys. Res. Letter, JAMES, Nat. Comm., Deep-Sea Res.
- Noé Lahaye is reviewer for J. Phys. Oceanogr., J. Fluid Mech., JAMES
- Roger Lewandowski has reviewed for Physica D, Nonlinear Analysis, M2AN
- Etienne Mémin is reviewer for J. Fluid Mech., Ocean Modelling, J. Comp. Phys., Siam Review, Comp. and Fluids.
- Claire Ménesguen has reviewed for J. Geophys. Res. Ocean.
- Gilles Tissot has reviewed for AIAA Journal.

11.1.2 Invited talks

Ronan Fablet

- Formal Workshop on Machine Learning for Marine Sciences, Paris, May 2022.
- International Digital Twins of the Ocean Summit. Paris, May 2022.
- RITS Conference, Brest, April 2022.
- SERENADE Workshop, Brest, June 2022.
- Assemblé du GDR Défis Théoriques pour le Climat. Paris, June 2022.
- Workshop Mathematics and theoretical physics for climate dynamics, Sept. 2022.
- Remote Sensing ML Club, July 2022.

11.1.3 Scientific expertise

- Jocelyne Erhel is a member of the scientific council of IFPEN, since April 2016.
- Ronan Fablet has participated to the following scientific comities: LEFE-Manu, FOF, PPR "Un Océan de Solutions", CST SHOM, Science Board Mercato Ocean Intl.
- Ronan Fablet has participated to the ANR comity for the ASTRID AAP.
- Roger Lewandowski contributed to the 2022 white paper of the ANR.
- Etienne Mémin is a member of the scientific council of LEFE-MANU action of CNRS INSU.
- Etienne Méminis a member of the comity GAMNI-SMAI.
- Claire Ménesguen is a member of the Scientific Comities of LEFE-IMAGO and GENCI, and of the office for the CNRS GDR “Théorie et Climat”.
- Gilles Tissot is a member of the scientific council of CLIMAT AmSud.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Clément De Boyer Montégut: UE interdisciplinaire en sciences de la mer et du littoral : présentation générale des aspects physique du système O/A, puis focus sur la thématique de la vulnérabilité des socio-écosystèmes face au changement climatique (19h, M1 UBO).
- Carlos Granero Belinchon: Analysis, signal processing, numerical calculus, probability and statistics (L3, IMT Atlantique); Introduction to machine learning, Dynamical systems modelling, Big data and cloud computing for climate (M1 & M2, IMT Atlantique).
- Lucas Drumetz: IMT Atlantique; Master SISEA Rennes 1; Master Copernicus Digital Earth UBS; Master Ocanographie physique UBO/IMT Atlantique/ENSTA Bretagne, parcours science des données océaniques;cours doctoral AI for geophysical dynamics (PI: R. Fablet).
- Jonathan Gula: Numerical modelling (M2 Marine Sciences, UBO) and Ocean Turbulence (M2 Marine Sciences, UBO).
- Noé Lahaye: Fourier Series and Complex Analysis (L2 Physics, Université de Tours).
- Roger Lewandowski: Finite elements (M2 Mathematics, UR1).
- Pierre Tandeo: Summer school on the Atlantic salmon (27th June to 1st July).
- Gilles Tissot: Numerical methods for acoustics and vibration (M2 acoustics and mechanics université du Mans).

11.2.2 Supervision

- Phd supervision of Zoé Caspar-Cohen by Aurélien Ponte and Noé Lahaye. Defended in December 2022.
- M2 internship supervision of Margot Demol (LOPS/Ifremer) by Aurélien Ponte.
- PhD in progress: 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.
- PhD in progress: Igor Maingonnat, Understanding and modelling nonlinearmechanisms in the ocean: internal waves / background flow interactions. Started November 2021, supervised by Noé Lahaye, Gilles Tissot, Étienne Mémin.

- PhD in progress: Manolis Perrot (Inria AirSea), student at U. Grenoble Alpes, Consistent modelling of subgrid scale for ocean climate models. Started October 2021, supervised by Eric Blayo, Florian Lemarié, Étienne Mémin.

- PhD in progress : Berenger Hug (Université Rennes I), analysis of stochastic models under location uncertainty, started November 2020, supervisors: Étienne Mémin, Arnaud Debussche.

- PhD in progress: Benjamin Dufée, Particle filters in high dimentional spaces, started November 2020, supervisors: Dan Crisan, Étienne Mémin.

- PhD in progress: Francesco Tucciarone, Stochastic models for high resolution oceanic models, started November 2020, supervisors: Long Li, Étienne Mémin.

- PhD supervision of A. Chouksey (UBO-LOPS), Submesoscale coherent vortices in the Atlantic and their impact on the large scale circulation. Supervisors: J. Gula and X. Carton.

- PhD supervision of L. Wang (UBO-LOPS), Impact of the meso and submesoscale dynamics on the fate of exported particles in the deep ocean. Supervisors: J. Gula (50%) and L. Mémery.

- PhD in progress: Armand Vic (UBO-LOPS), The dynamics of oceanic Vortices Coupled with the Atmosphere at the Mesoscale and submesoscale, started 2020. Supervisors: J. Gula and X. Carton.

- PhD in progress: Cyprien Le Maréchal (UBO-LOPS), Deep Hydrodynamic Processes near Hydrothermal vents, started in 2020. Supervisors: J. Gula (20%) and G. Roullet.

- PhD in progress: Giulia Zerbini (UBO-LOPS), MIxing and RestrAtification in the Bottom mixed-layEr : impActs of sUbmesoscale instabilities, started 2021. Supervisors: J. Gula (50%) and C. Vic.

- PhD in progress: N. Schifano (UBO-LOPS), Tracer transport and mixing in the bottom mixed-layer, started in 2021. Supervisors: J. Gula (50%) and C. Vic.

- PhD in progress: T. Picard (UBO-LOPS), 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.

- PhD in progress: Guillaume Leloup (UR1 IRMAR), Méthodes numériques pour le couplage de deux fluides turbulents, started in 2022. Supervisor: R. Lewandowski.

- PhD in progress: François Legeais, Couplage et turbulence à l'interface océan/atmosphère, started in 2021. Supervisor: R. Lewandowski.

- PhD in progress: N. El Bekri, UBO, supervisors: L. Drumetz and F. Vermet (UBO/EURIA).

- 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: H. Georgenthum, IMT Atlantique, supervisors: L.Drumetz, J. Le Sommer (CNRS/IGE), D. Greenberg (HEREON), L. Drumetz (Odyssey) et R. Fablet (Odyssey).

- PhD in progress: A. Frion, IMT Atlantique, supervisors: L.Drumetz, M. Dalla Mura (Gipsa-lab), G. Tochon (EPITA), A. Aissa El Bey (IMT Atlantique).

- PhD in progress: M. Montero, IFREMER, supervisors: C. de Boyer Montégut, N. Reul (defense planned end of april 2023).

11.2.3 Juries

Pierre Tandeo

- PhD defence of Aurélien Colin (jury + supervisor).
- PhD defence of Antoine Bernigaud (jury).
- Jury for the recruitment of an assistant professor (ENSTA Bretagne).

Jocelyne Erhel

- Member of the HDR jury of Pierre Jolive, Toulouse, October 2022.

Etienne Mémin

- Emilie Duval, (Rapporteur) Univ Grenoble Alpes, 15/12/2022.
- Hugo Freza, Univ Grenoble Alpes, 09/12/2022.
- Suart Patching, (Rapporteur), Imperial College, 21/07/2022.

Jonathan Gula

- Jury for the recruitment of an assistant professor (LEGOS, Toulouse), May 2022.

Claire Ménesguen

- PhD defence of Nicola Perez (Université de Lyon).
- PhD defence of Lisa Maillard (Université de Toulouse 3 Paul Sabatier).

Ronan Fablet

- PhD defence of H. Frezat, UGA, Dec. 2022.
- PhD defence of A. Roy, Univ. Montpellier, Nov. 2022.
- PhD defence of A. Colin, IMT Atlantique, Dec. 2022.
- PhD defence of J.M. Vient, UBO, Dec. 2022.
- PhD defence of A. Filoche, SU, Dec. 2022.
- PhD defence of A. Mounier, Univ. Toulouse, Dec. 2022.

11.3 Popularization

11.3.1 Articles and contents

Jocelyne Erhel

- Strong contribution to making a popularization video on mathematical modeling of the spread of epidemics. Will be online in 2023.

11.3.2 Interventions

Pierre Tandeo

- 4 public conferences on climate change, biodiversity and drinkable water.

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`.

[6] E. Mémin. 'Fluid flow dynamics under location uncertainty'. In: *Geophysical and Astrophysical Fluid Dynamics* 108.2 (28th May 2014), pp. 119–146. DOI: `10.1080/03091929.2013.836190`. URL: `https://hal.inria.fr/hal-00852874`.

[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] B. K. Arbic, S. Elipot, J. M. Brasch, D. Menemenlis, A. L. Ponte, J. F. Shriver, X. Yu, E. D. Zaron, M. H. Alford, M. C. Buijsman, R. Abernathey, D. Garcia, L. Guan, P. E. Martin and A. D. Nelson. 'Near-Surface Oceanic Kinetic Energy Distributions From Drifter Observations and Numerical Models'. In: *Journal of Geophysical Research. Oceans* 127.10 (2022), e2022JC018551. DOI: `10.1029/2022JC018551`. URL: `https://hal.archives-ouvertes.fr/hal-03898547`.

[9] M. Y. Ben Ali, G. Tissot, S. Aguinaga, D. Heitz and E. Mémin. 'Mean wind flow reconstruction of a high-rise building based on variational data assimilation using sparse pressure measurements'. In: *Journal of Wind Engineering and Industrial Aerodynamics* 231 (4th Oct. 2022), pp. 16/105204. DOI: `10.1016/j.jweia.2022.105204`. URL: `https://hal.archives-ouvertes.fr/hal-03602618`.

[10] T. T. T. Chau, P. Ailliot, V. Monbet and P. Tandeo. 'Comparison of simulation-based algorithms for parameter estimation and state reconstruction in nonlinear state-space models'. In: *Discrete and Continuous Dynamical Systems - Series S* (2022), pp. 1–24. DOI: `10.3934/dcdss.2022054`. URL: `https://hal-imt-atlantique.archives-ouvertes.fr/hal-03616079`.

[11] A. Colin, R. Fablet, P. Tandeo, R. Husson, C. Peureux, N. Longépé and A. Mouche. 'Semantic Segmentation of Metoceanic Processes Using SAR Observations and Deep Learning'. In: *Remote Sensing* 14.4 (2022), p. 851. DOI: `10.3390/rs14040851`. URL: `https://hal-imt-atlantique.archives-ouvertes.fr/hal-03616058`.

[12] E. Dinvay and E. Mémin. ‘Hamiltonian formulation of the stochastic surface wave problem’. In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* (14th Sept. 2022), pp. 1–26. DOI: `10.1098/rspa.2022.0050`. URL: `https://hal.inria.fr/hal-03777888`.

[13] 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://hal-imt-atlantique.archives-ouvertes.fr/hal-03808230`.

[14] C. Granero-Belinchon, S. G. Roux, N. B. Garnier, P. Tandeo, B. Chapron and A. Mouche. ‘Two-dimensional structure functions for characterizing convective rolls in the marine atmospheric boundary layer from Sentinel-1 SAR images’. In: *Remote Sensing Letters* 13.9 (21st Aug. 2022), pp. 946–957. DOI: `10.1080/2150704X.2022.2112107`. URL: `https://hal.archives-ouvertes.fr/hal-03576400`.

[15] M. A. Kamal, J. A. Janeš, L. Li, F. Thibaudau, A.-S. Smith and K. Sengupta. ‘Physics of Organelle Membrane Bridging via Cytosolic Tethers is Distinct From Cell Adhesion’. In: *Frontiers in Physics* 9 (12th Jan. 2022), pp. 1–12. DOI: `10.3389/fphy.2021.750539`. URL: `https://hal.archives-ouvertes.fr/hal-03867300`.

[16] F. Legeais and R. Lewandowski. ‘Continuous boundary condition at the interface for twocoupled fluids’. In: *Applied Mathematics Letters* 135 (2023), article n°108393. URL: `https://hal.archives-ouvertes.fr/hal-03694918`.

[17] C. Ménesguen, C. Lique and Z. Caspar-cohen. ‘Density Staircases Are Disappearing in the Canada Basin of the Arctic Ocean’. In: *Journal of Geophysical Research. Oceans* 127.11 (Nov. 2022), pp. 1–17. DOI: `10.1029/2022JC018877`. URL: `https://hal.archives-ouvertes.fr/hal-03910680`.

[18] E. Pauthenet, L. Bachelot, K. Balem, G. Maze, A.-M. Tréguier, F. Roquet, R. Fablet and P. Tandeo. ‘Four-dimensional temperature, salinity and mixed-layer depth in the Gulf Stream, reconstructed from remote-sensing and in situ observations with neural networks’. In: *Ocean Science* 18.4 (25th Aug. 2022), pp. 1221–1244. DOI: `10.5194/os-18-1221-2022`. URL: `https://hal-imt-atlantique.archives-ouvertes.fr/hal-03762091`.

[19] J. Ruiz, P. Ailliot, T. Tuyet Trang Chau, P. Le Bras, V. Monbet, F. Sévellec and P. Tandeo. ‘Analog data assimilation for the selection of suitable general circulation models’. In: *Geoscientific Model Development* 15 (2022), pp. 7203–7220. DOI: `10.5194/gmd-15-7203-2022`. URL: `https://hal-insu.archives-ouvertes.fr/insu-03868833`.

[20] M. Sacco, J. Ruiz, M. Pulido and P. Tandeo. ‘Evaluation of Machine Learning Techniques for Forecast Uncertainty Quantification’. In: *Quarterly Journal of the Royal Meteorological Society* (23rd Aug. 2022). DOI: `10.1002/qj.4362`. URL: `https://hal-imt-atlantique.archives-ouvertes.fr/hal-03685523`.

[21] A. Tagliabue, A. Lough, C. Vic, V. Roussenov, J. Gula, M. Lohan, J. Resing and R. Williams. ‘Mechanisms Driving the Dispersal of Hydrothermal Iron From the Northern Mid Atlantic Ridge’. In: *Geophysical Research Letters* 49.22 (28th Nov. 2022), e2022GL100615. DOI: `10.1029/2022GL100615`. URL: `https://hal-cnrs.archives-ouvertes.fr/hal-03926090`.

[22] P. Tedesco, J. Gula, P. Penven and C. Ménesguen. ‘Mesoscale Eddy Kinetic Energy Budgets and Transfers between Vertical Modes in the Agulhas Current’. In: *Journal of Physical Oceanography* 52.4 (Apr. 2022), pp. 677–704. DOI: `10.1175/JPO-D-21-0110.1`. URL: `https://hal.archives-ouvertes.fr/hal-03910686`.

[23] C. Vic, S. Hascoët, J. Gula, C. Maes and T. Huck. ‘Oceanic Mesoscale Cyclones Cluster Surface Lagrangian Material’. In: *Geophysical Research Letters* 49 (2022). DOI: `10.1029/2021GL097488`. URL: `https://hal-insu.archives-ouvertes.fr/insu-03683304`.

[24] V. Zeitlin and N. Lahaye. ‘Coherent magnetic modon solutions in quasigeostrophic shallow water magnetohydrodynamics’. In: *Journal of Fluid Mechanics* 941 (2022), A15. DOI: `10.1017/jfm.2022.289`. URL: `https://hal.archives-ouvertes.fr/hal-03651956`.

International peer-reviewed conferences

[25] L. Li, E. Mémin, B. Chapron and N. Lahaye. 'Stochastic transport in an idealized ocean-atmosphere coupled system'. In: EGU General Assembly 2022. Vienna, Austria, 23rd May 2022, pp. 1–24. URL: https://hal.inria.fr/hal-03676056.

Scientific book chapters

[26] A. Debussche, B. Hug and E. Mémin. 'Modeling Under Location Uncertainty: A Convergent Large-Scale Representation of the Navier-Stokes Equations'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 15–26. DOI: 10.1007/978-3-031-18988-3_2. URL: https://hal.archives-ouvertes.fr/hal-03910767.

[27] B. Dufée, E. Mémin and D. Crisan. 'Observation-Based Noise Calibration: An Efficient Dynamics for the Ensemble Kalman Filter'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 43–56. DOI: 10.1007/978-3-031-18988-3_4. URL: https://hal.archives-ouvertes.fr/hal-03910764.

[28] C. Fiorini, P.-M. Boulvard, L. Li and E. Mémin. 'A Two-Step Numerical Scheme in Time for Surface Quasi Geostrophic Equations Under Location Uncertainty'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 57–67. DOI: 10.1007/978-3-031-18988-3_5. URL: https://hal.archives-ouvertes.fr/hal-03910769.

[29] L. Li, E. Mémin and G. Tissot. 'Stochastic Parameterization with Dynamic Mode Decomposition'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 179–193. DOI: 10.1007/978-3-031-18988-3_11. URL: https://hal.archives-ouvertes.fr/hal-03910774.

[30] L. Thiry, L. Li and E. Mémin. 'Modified (Hyper-)Viscosity for Coarse-Resolution Ocean Models'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 273–285. DOI: 10.1007/978-3-031-18988-3_17. URL: https://hal.archives-ouvertes.fr/hal-03910773.

[31] F. Tucciarone, E. Mémin and L. Li. 'Primitive Equations Under Location Uncertainty: Analytical Description and Model Development'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 287–300. DOI: 10.1007/978-3-031-18988-3_18. URL: https://hal.archives-ouvertes.fr/hal-03910760.

[32] Y. Zhen, B. Chapron and E. Mémin. 'Bridging Koopman Operator and Time-Series Auto-Correlation Based Hilbert–Schmidt Operator'. In: *Stochastic Transport in Upper Ocean Dynamics*. Vol. 10. Mathematics of Planet Earth. Springer International Publishing, 24th Sept. 2023, pp. 301–316. DOI: 10.1007/978-3-031-18988-3_19. URL: https://hal.archives-ouvertes.fr/hal-03910777.

Reports & preprints

[33] L. C. Berselli, F. Legeais and R. Lewandowski. *Surface boundary layers through a scalar equation with an eddy viscosity vanishing at the ground*. 29th Nov. 2022. URL: https://hal.archives-ouvertes.fr/hal-03877325.

[34] A. Debussche, B. Hug and E. Mémin. *A consistent stochastic large-scale representation of the Navier-Stokes equations*. 2022. URL: https://hal.inria.fr/hal-03724396.

[35] L. Drumetz, A. Reiffers-Masson, N. El Bekri and F. Vermet. *Geometry-preserving lie group integrators for differential equations on the manifold of symmetric positive definite matrices*. 24th Oct. 2022. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-03815325.

[36] C. Granero-Belinchon. *Neural network based generation of 1-dimensional stochastic fields with turbulent velocity statistics*. 19th Nov. 2022. URL: https://hal.archives-ouvertes.fr/hal-03861273.

[37] B. Hug, E. Mémin and G. Tissot. *Ensemble forecasts in reproducing kernel Hilbert space family: dynamical systems in Wonderland*. 30th July 2022. URL: `https://hal.inria.fr/hal-03740500`.

[38] O. Lang, D. Crisan and É. Mémin. *Analytical Properties for a Stochastic Rotating Shallow Water Model under Location Uncertainty*. 27th Oct. 2022. URL: `https://hal.inria.fr/hal-03832450`.

[39] L. Li, B. Deremble, N. Lahaye and E. Mémin. *Stochastic data-driven parameterization of unresolved mesoscale eddies*. 19th July 2022. URL: `https://hal.archives-ouvertes.fr/hal-03727820`.

[40] P. Tandeo, P. Ailliot and F. Sévellec. *Data-driven Reconstruction of Partially Observed Dynamical Systems*. 29th Nov. 2022. DOI: `10.5194/egusphere-2022-1316`. URL: `https://hal.archives-ouvertes.fr/hal-03877235`.

Other scientific publications

[41] V. Resseguier, B. Chapron and E. Mémin. 'Understanding and parametrizing downscaling and mixing analyses from altimeter-derived oceanic currents'. In: LPS 2022 - Living Planet Symposium. Bonn, Germany, 23rd May 2022, p. 1. URL: `https://hal.archives-ouvertes.fr/hal-03709380`.