Rentrée 2021

PROPOSITION DE SUJET DE THESE

Formulaire demande de financement : ARED - ISblue - ETABLISSEMENTS - …

pour dépôt sur le serveur https://theses.u-bretagneloire.fr/sml au format PDF

NB : ce dossier ne vous dispense pas de déposer en parallèle votre dossier à la Région

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Identification du projet

Acronyme du projet *(8 caractères maximum)* **: MIRABEAU**

Intitulé du projet *en langue française* : Impact des fines échelles sur les transformations des masses d'eaux dans l'océan profond

Intitulé du projet en langue anglaise : MIxing and RestrAtification in the Bottom mixed-layEr: impActs of sUbmesoscale instabilities

Présentation de l'établissement porteur (bénéficiaire de l'aide régionale)

Établissement porteur du projet : Université de Bretagne Occidentale (UBO)

Ecole Doctorale : EDSML ☒ SPI ou MATHSTIC pour les projets ISblue ☐

Identification du responsable du projet (futur directeur de thèse)

Nom du laboratoire d'accueil : LOPS – Laboratoire d'Oceanographie Physique et Spatiale
Code du laboratoire (U/UMR/USR/EA/JE/…) : UMR 6523
Directeur[1] du Laboratoire : Jérome Paillet
Nom de l'équipe de recherche : OSI (Ocean Scales Interactions)

Nombre HDR dans le laboratoire : 20 Nombre de thèses en cours : 26 Nombre de post-docs en cours : 16

Nom et prénom du directeur* de thèse (HDR), porteur du projet : Gula Jonathan
- website : jgula.fr
- e-mail : gula@univ-bres.fr
- Téléphone : + 33 (0)2.90.91.55.39
- Publications récentes du directeur de thèse *(nb total et 5 références max au cours des 5 dernières années)* **:**

- Lahaye, N.J., J. Gula & G. Roullet, 2020 : Internal tide cycle and topographic scattering over the North Mid-Atlantic Ridge, *J. Geophys. Res. Ocean.*

- Buckingham, C., J. Gula, & X. Carton, 2020 : The role of curvature in modifying frontal instabilities : Part 1, *J. Phys. Oceanogr.*

- Le Corre, M., J. Gula & A.-M. Tréguier, 2020 : Barotropic vorticity balance of the North-Atlantic subpolar gyre in an eddy-resolving model, *Ocean Sci.*, https ://doi.org/10.5194/os-2019-114.

[1] Ce formulaire est rédigé en style épicène

- De Marez, C., N. Lahaye & J. Gula, 2020 : Interaction of the Gulf Stream with small scale topography : a focus on lee waves, *Scientific Reports*, 10, 2332.

- Tedesco, P., J. Gula, C. Menesguen, P. Penven & M. Krug, 2019 : Generation of submesoscale frontal eddies in the Agulhas Current, *J. Geophys. Res. Ocean*, 124. https ://doi.org/10.1029/2019JC015229

- Expériences d'encadrement et co-encadrement de doctorants (passées et en cours)
(nom des doctorants dirigés et en cours et antérieurement, sur les 6 années passées : sujet, financement, date de soutenance, et situation professionnelle actuelle si connue)

- M. Le Corre, 2016 - 2020 (90% co-direction with A.-M. Tréguier), PhD defended June 2020: Impact of the topography and mesoscale turbulence activity on the dynamics of the North-Atlantic subpolar gyre. Funding Labex Mer / UBO. CDD Ingénieur de recherche LEGOS.
- P. Tedesco, 2017 - 2021 (40% co-direction with P. Penven and C. Menesguen), PhD to be defended Feb. 2021: Mesoscale eddy energy dissipation. Funding Labex Mer / Ifremer.

Thèses en cours au 01/10/2021 :

- L. Wang, 2019 - 2022 (30% co-direction with L. Memery), PhD to be defended June 2022: Impact of the meso and submesoscale dynamics on the fate of exported particles in the deep ocean. Funding ISblue.
- A. Chouksey, 2019 - 2022 (90% co-direction with X. Carton), PhD to be defended Dec. 2022: Submesoscale coherent vortices in the Atlantic and their impact on the large scale circulation. Funding CNRS / Région Bretagne.
- A. Vic, 2020 - 2023 (30%, co-direction with X. Carton) : The dynamics of oceanic VOrtices Coupled with the Atmosphere at the Mesoscale and submesoscale. Funding ENS
- C. Lemaréchal, 2020 - 2023 (30% co-direction with G. Roullet) : Deep Hydrodynamic Processes near Hydrothermal vents. Funding H2020 / UBO

Et/ou co-encadrant-e scientifique : Jacob Wenegrat

Laboratoire de recherche : Department of Atmospheric and Oceanic Science, University of Maryland
- website : https://wenegrat.github.io/
- e-mail : wenegrat@umd.edu
- Téléphone : 301-405-5391
- Expériences d'encadrement et co-encadrement de doctorants (passées et en cours)

Thèses en cours au 01/10/2021 : Victoria Whitley, 2021 – 2024.

Et/ou co-encadrant-e scientifique : Clément Vic

Laboratoire de recherche co-encadrant : LOPS – UMR 6523
- e-mail : cvic@univ-brest.fr
- Téléphone :
- Expériences d'encadrement et co-encadrement de doctorants (passées et en cours)
(nom des doctorants dirigés et en cours et antérieurement, sur les 6 années passées : sujet, financement, date de soutenance, et situation professionnelle actuelle si connue)
Pas d'encadrement de these.

Le cas échéant, autres collaborations (co-encadrant et laboratoire concerné) :
Encadrements de stages M2:
- Noémie Schifano, 2020 : dispersion of a tracer in the deep ocean
- Ivane Salaün, 2018 : numerical modelling of internal tides

Encadrements de stages M1:
- Florent Aguesse, 2017 : The Asymmetry of Greenland Currents' Eddy Fields
- Edmund Derby, 2017 : Regional modelling of internal tides over the Mid-Atlantic Ridge

Financement du projet de thèse

En cas de financement à 50 %, le cofinancement est-il déjà identifié *(oui/non)* **: oui**

Si oui, préciser la nature du cofinancement (*ANR, partenaire privé, Ademe, etc.*) : ANR DEEPER (anr-19-ce01-0002)

Si le cofinancement n'est pas encore confirmé, date prévue de réponse du cofinanceur :

En cas de non-obtention du cofinancement demandé, une autre source de cofinancement est-elle identifiée *(oui/non)* **:**

Si oui, laquelle :

Sollicitez-vous un co-financement Is-Blue (y compris ARED Is-Blue) *(oui/non)* **? oui**

Important : Veillez à bien compléter les différents co financements sollicités sur le serveur Thèses en Bretagne Loire lors du dépôt de votre dossier.

Projet de thèse en cotutelle internationale

S'agit-il d'un projet de thèse en cotutelle internationale dans le cadre d'une convention *(oui/non)* **: non**

Si oui, préciser l'établissement pressenti (*et le pays de rattachement*) :

Ce projet de thèse fera-t-il l'objet d'un cofinancement international *(oui/non)* **: non**

(Rémunération du doctorant par l'établissement implanté sur le territoire régional (18 mois sur 36 mois), et l'établissement étranger, qui s'engage également à rémunérer le doctorant dans le cadre de son séjour à l'étranger, soit durant 18 mois -a minima-)

En cas de cofinancement international, préciser -*si vous en avez connaissance*- **l'organisation du calendrier des périodes de séjour :**

Préciser quel est le stade du projet international (joindre une lettre d'engagement du partenaire)

Présentation du projet (en langue française ou anglaise, 2 à 3 pages)

merci de respecter ce format maxi compatible avec extranet région

Résumé du projet *(4000 caractères maxi espaces compris) :*

The meridional overturning circulation controls the fluxes of heat and carbon in the ocean on climatic time scales. At high latitudes, dense waters sink from the surface to the abyss, and are upwelled back to the surface on their equatorward journey to close the oceanic mass budget and circulation. While the formation of dense waters is well mapped and quantified, their upwelling from the seafloor to intermediate depths and up to the surface still suffers from large uncertainties. The classic view is that the upwelling of abyssal waters is driven by widespread and rather evenly distributed diffusion processes in the ocean interior. Over the recent years, an alternative view has emerged, with an intense upwelling occurring in a thin layer of well-mixed waters (bottom boundary layer, BBL) close to the seafloor topography, and a downwelling occurring in a thicker layer lying on top on the BBL (stratified mixing layer, SML).

Most of the energy fueling mixing in the BBL and in the SML is tidally sourced: tidal currents over uneven seafloor topography generate internal waves at tidal frequencies, or internal tides, which propagate in the interior and ultimately break. The breaking of internal tides triggers mixing of waters with different properties. The life cycle of internal tides is fairly well known under the assumption of a quiescent deep ocean featuring a steady stratification, i.e., not influenced by meso- (10-100 km) to submesoscale (0.1-10 km) processes. In the past decade, theoretical and process studies have shed light on submesoscale processes in the BBL, but we still miss a clear picture of their phenomenology and impact on the large-scale circulation. **The goal of this project is to quantify the impacts of deep-ocean submesoscale processes on mixing and water mass transformation**. The PhD candidate will investigate the deep-ocean submesoscale processes and their interaction with the internal wave field using cutting-edge **realistic modelling with the CROCO model**.

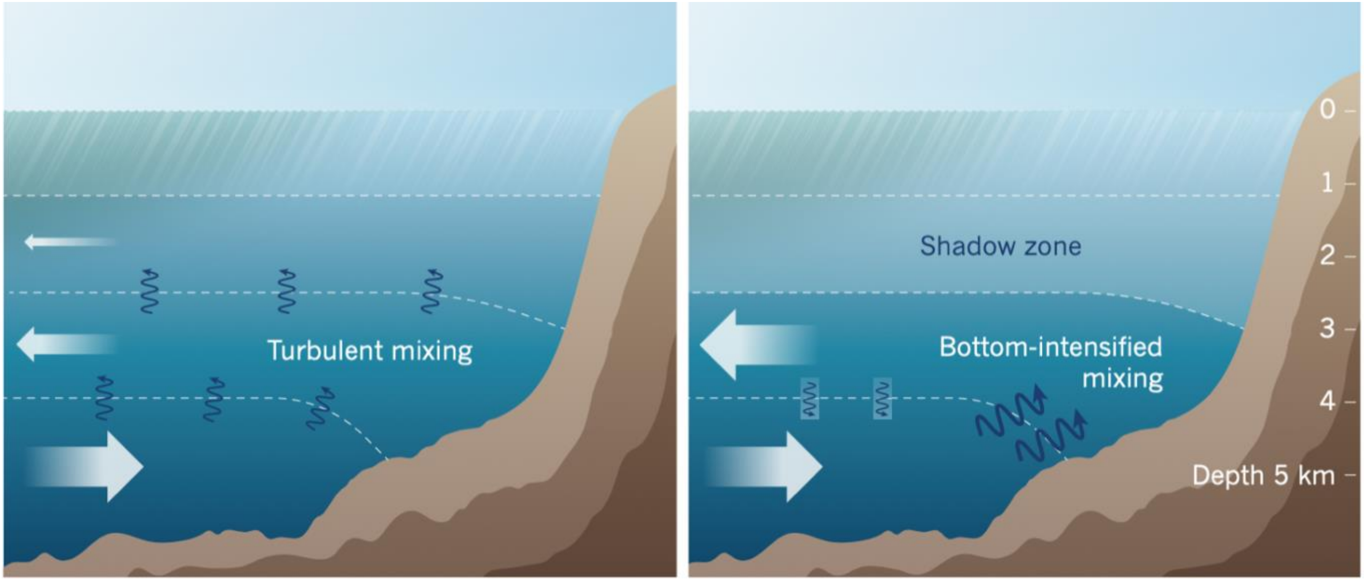
First, the PhD candidate will **map the different types of submesoscale instabilities** in the BBL of the Atlantic Ocean. This mapping will be based on quantitative diagnostics of key dynamical parameters. To this end, the candidate will use available outputs from a new numerical simulation of the Atlantic Ocean (GIGATL, dx < 1 km, 100 vertical levels, hydrostatic model), which is able to resolve some of the submesoscale processes in a fully realistic environment, i.e., including tides and high-frequency winds. This work will lead to a **first-of-the-kind assessment of the geography of submesoscale processes basin-wide.**

Second, based on the mapping described above, the candidate will **focus on key regions for submesoscale processes and water mass transformation**. In order to fully resolve submesoscale processes in the BBL, one needs to reach a sub-kilometer effective resolution. We will thus select one or two regions of interest to set up **very-high resolution simulations (< 100 m, 300 vertical levels) nested into GIGATL1**. This downscaling will allow us to investigate the sensitivity of the modeled processes to the model resolution, the numerical setup and the validity of the hydrostatic assumption. This work will lead to an **unprecedentedly thorough description of the phenomenology of the instabilities, their co-existence with tidal processes and their impact on mixing and water mass transformation.**

Présentation détaillée du projet :

1 - Hypothèse et questions posées, état de l'art, identification des points de blocages scientifiques (4000 caractères maxi espaces compris)

The ocean is a major reservoir of heat of the climate system, yet major uncertainties remain on its storing capacity at large depths (>2000 m, Desbruyeres et al, 2016). Reasons for those uncertainties are twofold. First and foremost, the lack of sustained observations below 2000 m (standard Argo profiling depth) prevents the community from inferring robust estimates. Second, **qualitative and quantitative unknowns remain on the role of small-scale and high-frequency physical processes arising in the deep layers of the ocean**. Yet, their effect on mixing and subsequent water mass transformation and export has been shown to be very efficient (Ruan et al, 2017; Naveira Garabato et al, 2019). Those small-scale processes will not be resolved in global-scale models in a near future, and their effects need to be considered through sub-grid-scale parameterisations (Fox-Kemper et al, 2019, Levin et al, 2019).



Traditional view of the circulation. Historically, the ocean's densest, Antarctic-sourced waters were thought to rise towards the surface throughout the ocean interior, becoming less dense through turbulent mixing with overlying waters . The dashed lines join points of constant density, the arrows indicate the flow of water and the size of the white arrows represents the volume of transported water.

Revised view of the circulation. de Lavergne et al. (2017) account for intensification of turbulent mixing near the ocean bottom, which implies that the densest waters rise close to the sea floor. They show that the sea floor's shape strongly favours waters undergoing changes in density at a depth of about 4 kilometres.

Figure 1: edited from Stewart 2017, summarizing the main findings of de Lavergne et al 2017.

The global overturning circulation regulates heat and carbon fluxes on climatic time scales. The dense waters that sink to the abyss at high latitudes need to come back to the surface to close the circulation. Munk (1966) first assumed that turbulent mixing in the interior was driving a diapycnal (i.e., through density surfaces) upwelling of dense waters to the surface. However, in-situ observations pointed out that mixing was too weak in the interior to sustain the required diapycnal upwelling, and intensified mixing was observed only in localized regions over rough topography (Waterhouse et al, 2014). Our understanding of water mass transformation has evolved over the last few years to reconcile these observations with a **new paradigm for the overturning circulation: the interior is instead a place of downwelling, and the required upwelling is happening only in localized regions over sloping topography** (Ferrari et al., 2016; de Lavergne et al., 2016; McDougall and Ferrari, 2017), with major implications for the structure of the deep branch of the overturning circulation (de Lavergne et al, 2017 and Figure 1).

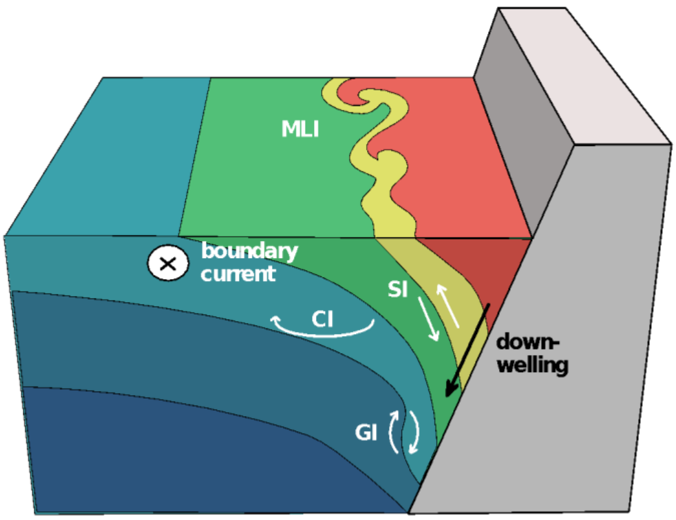


Figure 2: Idealized depiction of various submesoscale processes in the bottom boundary layer. After loss of potential vorticity due to friction and diapycnal mixing at the bottom, the front can be unstable to gravitational instability (GI), symmetric instability (SI), or centrifugal instability (CI). Submesoscale eddies develop through baroclinic instability of the bottom mixed-layer (MLI). From Gula et al (2020).

A large part of mixing in the interior can be attributed to breaking internal waves, either in the form of internal tides, near-inertial waves or lee waves (Whalen et al, 2020). Recently, high resolution numerical models have highlighted a new efficient mechanism for energy dissipation and mixing — **topographic generation of submesoscale turbulence** — due to the interaction of geostrophic currents with topography (Molemaker et al., 2015, Gula et al, 2016), see Fig. 2.

Theoretical and process studies are now just beginning to highlight the role played by the different types of submesoscale processes in the bottom layer (Wenegrat et al., 2018; Wenegrat and Thomas 2020, Fig. 2). Observations have confirmed that **submesoscale processes can generate strong near-bottom mixing and cross-density upwelling** (Ruan et al, 2017 Naveira Garabato et al., 2019).

Furthermore, to sustain efficient water-mass transformations, **mixing needs to be accompanied by other processes driving restratification at the bottom of the ocean** and exporting buoyancy outside of the bottom mixed layer (Callies 2018). Submesoscale baroclinic instability of the bottom boundary layer is one strong candidate (Wenegrat et al, 2018). Mechanisms such as deep frontogenesis might also play a role.

The goals of this project are to quantify, for the first time, the impacts of deep submesoscale processes on mixing and turbulent fluxes of buoyancy. In particular the objective will be to test the following hypotheses:

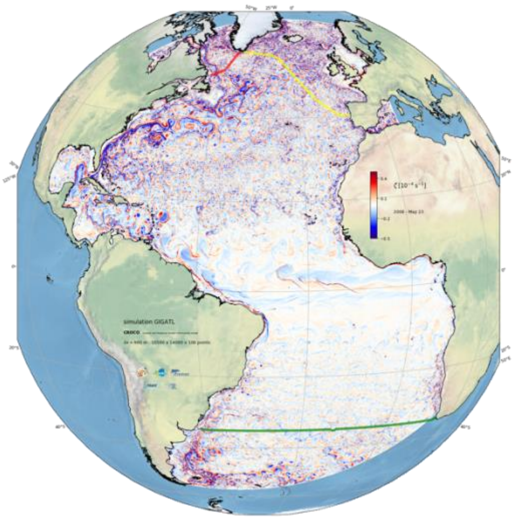
• **H1**: Submesoscale turbulence generated over sloping topography is a significant source of diapycnal mixing, and can drive intense localized upwelling of deep waters.

• **H2**: Submesoscale baroclinic instability and deep frontogenesis drive the restratification of the bottom boundary layer and help sustain water mass transformations.

2 - Approche méthodologique et techniques envisagées : (4000 caractères maxi espaces compris)

First, the candidate will map the different kind of submesoscale instabilities occurring in the bottom boundary layer of the Atlantic Ocean (Fig. 2) based on the computation of several dynamical parameters (Wenegrat et al, 2020). To this end, we will use **the numerical simulations suite GIGATL** (Fig. 3) which has been run in 2020 in the context of the ANR project DEEPER and a corresponding PRACE allocation. This is a set of realistic simulations covering the full Atlantic using the CROCO model, with different resolutions ranging from 27 km to 1 km. The highest resolution simulation has submesoscale-permitting resolution (dx < 1 km). It includes tides and high-frequency atmospheric forcing in order to generate realistic levels of internal waves.

Figure 3 : Snapshot of surface relative vorticity in the GIGATL simulation



Based on these results, we will identify some critical regions, where mixing and buoyancy fluxes are expected to be particularly strong, and study them in more detail by setting-up **regional simulations at higher resolution**. Using outputs from the GIGATL at 1-km resolution to generate boundary forcing, we will set up a suite of simulations with increasing resolution from 1 km to 100 m. For the highest resolution nests, we will take advantage of the recently developed non-hydrostatic version of CROCO (Roullet et al, 2017) to relax the hydrostatic approximation and evaluate a possible impact on the dynamics. The modeling strategy is well established (Gula et al., 2014, 2015a, 2015b, 2016) and all the tools are available. One important challenge will be to quantify **how sensitive the processes are to the horizontal and vertical resolution** of the model, to the resolution of the bathymetry, and to **choices for the numerical schemes**.

One suspected region of interest – to be confirmed by the diagnostics led by the candidate – is the Brazil Basin, which includes a deep abyssal plain and a ridge. It is a region with strong bottom mixing and known impacts on the consumption of Antarctic Bottom Water (AABW). Submesoscale baroclinic instability is suspected to be an important mechanism there to export buoyancy outside of the bottom mixed layer and contribute to water-mass transformations (Ruan and Callies, 2019). Furthermore, there is a historical interest and observational context that will be useful to analyze the realism of the simulation.

Another region of potential interest is along the North American continental slope, where the large topographic slopes and strong currents should lead to higher impacts of symmetric and centrifugal instabilities (Gula et al, 2016). Such submesoscale processes may impact transformations of the North Atlantic Deep Water, flowing southward along the slope. This region, in particular the continental slope off Newfoundland is currently a target of observational efforts (project CROSSROAD, P.I.: D. Desbruyeres) that will be complementary to the modelling effort.

For these regions, we will evaluate carefully the **intensity and localisation of mixing** and compare them to available observations from microstructure measurements (Waterhouse et al 2014, Vic et al 2019). We will then quantify the **contribution of the different processes to deep ocean mixing**, to determine where it is predominantly associated with internal waves breaking and where submesoscale turbulence contributes significantly. We will also investigate **processes driving the restratification of the bottom boundary layer**. This will be accomplished by using 3d maps of turbulent vertical buoyancy fluxes and compare them to predictions for the growth-rate of **baroclinic instability in the bottom boundary layer**. Another process that can potentially generate turbulent buoyancy fluxes in the deep part of the ocean is **deep frontogenesis**, following the same mechanism as in the surface layer. We will compute frontogenetic tendencies and check the possible impact of the secondary circulation associated with deep fronts and filaments**.**

3 - Positionnement et environnement scientifique dans le contexte régional, national et international :

There is a worldwide effort in simulating the global ocean, in a climate change context, at increasing resolution to obtain better scenarios of climate evolution. In this context, it has been shown that the mesoscale and submesoscale structures play an essential role.

Submesoscale processes in the surface layer of the ocean have received a great deal of attention over the past 15 years [McWilliams, 16], and it has led to important discoveries that have changed our vision of the ocean. In particular we have come to realise the essential role they play in modifying momentum, buoyancy and gas exchange between the ocean and atmosphere [Su et al, 2018], and in generating the strong vertical velocities that drive exchanges of nutrient or carbon between the surface layer and the ocean's interior [Mahadevan, 16, Balwada et al, 18].

Theoretical and process studies are now just beginning to also highlight the role played by submesoscale processes in the bottom layer. But we still miss a clear picture of their phenomenology, we do not know how they are affected by the internal wave field and we have not quantified their impacts on the large scale circulation. In particular, there is a dynamic link between deep small-scale turbulence and large-scale overturning circulation. That is, changes in dense water will necessarily have an impact on overturning circulation and, ultimately, climate.

The aim of this project will be to improve our knowledge on the role of deep submesoscale processes in driving water masses transformations in the deep ocean and impacting the large scale circulation. It will allow to disentangle the different processes at play in the different parts of the ocean and highlight the most important ones that should be considered and parameterized in global models.

4 - Contexte scientifique et partenarial : éléments généraux (ERC, CPER, FEDER, Breizhcop …) (4000 caractères maxi espaces compris)

This PhD project is a part of the ANR JCJC project DEEPER (Impacts of DEep submEsoscale Processes on the ocEan ciRculation, PI: J. Gula), which has been funded for the period 2020-2024. The full proposal is available here: http://stockage.univ-brest.fr/~gula/Work/deeper.pdf. It will benefit from the strong collaborative environment between all the groups linked to the project (LOPS, LOCEAN, LEGOS, Caltech, U. Of Maryland, UCLA, Stanford, Imperial College London, U. of Tel Aviv).

There are also several international initiatives aiming at acquiring observations of bottom boundary layer turbulence such as the NERC/NSF funded project BLT Recipes (Bottom Boundary Layer Turbulence and Abyssal Recipes, 2018-2022), which will study diapycnal upwelling along sloping boundaries in the Rockall Trough in the Northeast Atlantic by means of turbulence-measuring moored instruments and tracer release. This project will have strong interactions with the community involved in this project and complement it on the modelling side.

This project will also be connected to the H2020 project iAtlantic (Integrated Assessment of Atlantic Marine Ecosystems in Space and Time, 2019-2023) which aims at documenting the deep-sea circulation in the Atlantic and the impact for ecosystems, and in which J. Gula is also involved. This project will also involve collaborations with the new observational program that is planned along the continental slope of Newfoundland (submitted ANR project CROSSROADS by D. Desbruyeres, Ifremer/LOPS).

Vous sollicitez un financement ISblue, ou une ARED ISblue :

Précisez le lien du sujet avec les thèmes ISblue

hème ISblue	Thème principal	hème secondaire (si nécessaire)	utre (si nécessaire)
a régulation du climat par l'océan	X		
es interactions entre la Terre et l'océan			
a durabilité des systèmes côtiers			
'océan vivant et les services écosystémiques			
es systèmes d'observation à long terme			

Expliquez/précisez en quelques lignes dans quelle mesure votre demande correspond à l'un ou plusieurs des critères ISblue ci-dessous :

Ce projet va contribuer au thème **ISblue 1: Ocean and Climate regulation.** Il s'intéressera à des processus de sous-mésoéchelle dans l'océan profond et permettra de quantifier leurs impacts sur les transformations de masses d'eaux et la circulation de grande échelle. Ces travaux contribueront à l'amélioration des outils de modélisation numériques utilisés pour étudier l'impact du changement climatique et de l'activité humaine sur les milieux marins.

1- Originalité, impact potentiel du projet (4 lignes maxi)

C'est la première fois qu'un modèle « topography-following » - particulièrement avantageux pour étudier les interactions courants/topographie - est utilisé à une résolution inférieure au kilomètre sur un domaine aussi vaste. Il fournira des données uniques pour mieux comprendre les processus dynamiques profonds et aider à la conception de paramétrisations pour les modèles qui ne sont pas capables de les résoudre.

2- Positionnement international du sujet, cotutelle ou co-encadrement international (4 lignes maxi)

Le projet doctoral sera co-encadré par J. Wenegrat (U. of Maryland) et bénéficiera de fortes interactions avec J. Callies (Caltech). Un séjour (de moyenne ou longue durée) sera organisé dès que les conditions sanitaires le permettront à U. of Maryland et/ou Caltech. Le-la doctorant-e sera aussi amené à collaborer avec les autres participants du projet ANR DEEPER (UCLA, Stanford, Imperial College London, U. of Tel Aviv).

3- Effet intégrateur entre unités de recherche et / ou interdisciplinarités (4 lignes maxi)

Le projet doctoral sera au carrefour de thématiques plutôt « GFD » abordées dans l'équipe interactions d'échelles au sein du LOPS et de thématiques portant sur les transformations de masses d'eaux et la circulation grande échelle telles qu'étudiées par des collègues de l'équipe Océan-Climat et du LOCEAN (e.g. C. de Lavergne). Il permettra ainsi de mieux faire le lien entre la vision « processus dynamiques» et les impacts climatiques .

4- Potentiel d'insertion à un haut niveau dans la communauté académique ou non académique du docteur (4 lignes maxi)

Le-la doctorant-e abordera une large palette de thématiques alliant théorie, modélisation numérique et analyse de données. Il-elle travaillera sur des thématiques émergentes (dynamique de petite échelle dans l'océan profond) qui seront un très bon atout pour d'éventuels recrutement sur des postes académiques (CNRS, Ifremer, Université). De plus, l'expérience acquise par le-la doctorant-e sur le plan technique (Python, big data, etc) est très recherchée et permettra des débouchés dans l'entreprise.

Le candidat

Profil souhaité du candidat (spécialité/discipline principale, compétences scientifiques et techniques requises) :

Master 2 en océanographie physique ou mécanique des fluides. Intérêt pour la dynamique des fluides géophysiques, et la modélisation numérique. Programmation avec le langage scientifique Python. Forte motivation, capacité à travailler en équipe.

ATTENTION :

Tout dossier non déposé sur le serveur dans les délais indiqués, ne pourra être pris en compte notamment par les instances ISblue, conseil de l'EDSML.