AAPG2019	DEEPER		JCJC
Coordinated by:	Jonathan GULA	48 months	256 k€
CES01 - Sciences de l'environnement - Terre fluide et solide			

Impacts of DEep submEsoscale Processes on the ocEan ciRculation

Summary: The meridional overturning circulation controls the fluxes of heat and carbon in the ocean. It is shaped by the turbulent processes that generate mixing at the bottom of the ocean and drive upwelling of water masses along topographic slopes. These small-scale turbulent processes are not well understood nor parameterized, which limits the accuracy of ocean models and the predictive skills of climate models.

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, in particular by applying *deep learning to the deep ocean*.

A hierarchy of numerical simulations will be built to be able to characterise submesoscale processes and their interaction with the internal wave field in the deep ocean using cutting-edge realistic modelling with the ROMS/CROCO model. It requires simulations that resolve submesoscale processes (1-30 km), and a large enough domain to generate realistic levels of internal waves and allow to evaluate impacts on the large scale circulation. This will be the first time a terrain-following model — particularly advantageous to study flow-topography interactions — will be used at sub-kilometer resolution over a domain as large as the full Atlantic Ocean.

Summary table of persons involved in the project:

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month)
LOPS	*GULA*	*Jonathan*	*Assistant Professor*	*Principal investigator, all WPs*	*32*
LOPS	*CAMBON*	*Gildas*	*Research engineer*	*WP1*	*16*
LOPS	*THEETTEN*	*Sébastien*	*Research engineer*	*WP1*	*12*
LOPS			*Postdoctoral Student*	*WP3*	*24*
LOPS			*PhD Student*	*WP4*	*36*
LOPS			*Master Student*	*WP3*	*6*
LOPS	*TEDESCO*	*Pauline*	*PhD Student*	*WP2, task 2a*	*12*
LOPS	*PENVEN*	*Pierrick*	*Researcher (DR)*	*WP2, task 2a*	*4*
LOPS	*MENESGUEN*	*Claire*	*Researcher*	*WP2, task 2a*	*4*
LEGOS	*MOREL*	*Yves*	*Researcher (DR)*	*WP2, task 2d*	*4*
LOPS	*CARTON*	*Xavier*	*Professor*	*Expert, WP2, task 2a*	*0*
Uni. Of Tel Aviv	*BARKAN*	*Roy*	*Professor*	*Expert, WP2, task 2b*	*0*
UCLA	*MOLEMAKER*	*M. Jeroen*	*Researcher*	*Expert, WP2, task 2b*	*0*
UCLA	*McWILLIAMS*	*James C.*	*Professor*	*Expert, WP2, task 2b*	*0*
LOCEAN	*DE LAVERGNE*	*Casimir*	*Researcher (CR)*	*Expert, WP2, task 2c*	*0*
Imperial College London	*MASHAYEK*	*Ali*	*Professor*	*Expert, WP2, task 2c*	*0*
LOPS	*MAZE*	*Guillaume*	*Researcher*	*Expert, WP2, task 2d*	*0*
LEGI	*WIRTH*	*Achim*	*Researcher (DR)*	*Expert, WP2, task 2d*	*0*
Caltech	*CALLIES*	*Joern*	*Professor*	*Expert, WP3, task 3a*	*0*
U. of Stanford	*THOMAS*	*Leif*	*Professor*	*Expert, WP3, task 3b*	*0*
U. of Stanford	*WENEGRAT*	*Jacob*	*Researcher*	*Expert, WP3, task 3b*	*0*
LOCEAN	*CAPET*	*Xavier*	*Researcher (DR)*	*Expert, WP3, task 3c*	*0*
IMT Atlantique	*TANDEO*	*Pierre*	*Professor*	*Expert, WP4, task 4a*	*0*
IMT Atlantique	*FABLET*	*Ronan*	*Professor*	*Expert, WP4, task 4a*	*0*
LOPS	*ROULLET*	*Guillaume*	*Professor*	*Expert, WP4, task 4a*	*0*
IGE	*LESOMMER*	*Julien*	*Researcher (DR)*	*Expert, WP4, task 4b*	*0*
IGE/FSU	*DEWAR*	*William K.*	*Professor*	*Expert, WP4, task 4b*	*0*

Any changes that have been made in the full proposal compared to the pre-proposal

Minor adjustments have been made to the budget.

I. Proposal's context, positioning and objective(s)

a. Objectives and research hypothesis

The ocean is at the heart of the climate system. It stores most of the heat of the climate system, and has the ability to impact climate over long periods. There are however major knowledge gaps on the small scale processes, especially those driving water-mass transformations in the deep ocean, that limit the accuracy of ocean models and the predictive skills of climate models [Tatebe et al, 18].

The global overturning circulation is instrumental for storing and regulating heat and carbon fluxes. The dense waters that sink to the abyss at high latitudes need to be uplifted to come back to the surface and close the circulation. Following Munk [1966], it was first assumed that breaking internal waves in the interior would be responsible for the widespread mixing of dense waters with lighter ones. This picture was later refined by taking into account the role of winds in driving upwelling of water in the Southern Ocean [Marshall & Speer, 12]. However, in-situ observations pointed out that mixing was too weak in the interior to sustain the required upwelling, and intensified mixing was observed only in localised regions over rough topography [Polzin et al, 97, Waterhouse et al., 14].

Our understanding of the water-mass transformations has evolved over the last few years to reconcile these observations with a new paradigm for the overturning circulation: in the context of the deep branches of the overturning circulation, the interior is instead a place of downwelling, and the required upwelling is happening only in localised regions over sloping topography [Ferrari et al., 16; de Lavergne et al., 16; McDougall and Ferrari, 17; Wunsch and Ferrari, 18], with major implications for the structure of the deep branch of the overturning circulation [de Lavergne et al, 17]. **Thus, the turbulent processes that cause bottom-intensified mixing are key drivers of the upwelling patterns of water masses.**

A large part of the mixing can be attributed to breaking internal waves, either in the form of internal tides, near-inertial waves (NIW) or lee waves [MacKinnon et al, 17]. These mixing patterns are also strongly influenced by the mesoscale turbulence [Walhen et al., 2018]. Close to the topography, additional mixing can be generated due to hydraulically controlled flows [Polzin et al, 97]. Furthermore, geothermal heat fluxes from the solid Earth into the ocean plays a non-negligible role for mixing abyssal waters [Mashayek et al., 13, Downes et al. 19].

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 (Fig. 1) [Molemaker et al., 15, Dewar et al. 15, Gula et al, 16]. This mechanism implies the generation of vorticity in the sheared bottom layer over a slope, detachment from the boundary, and intense submesoscale instabilities that lead to energy dissipation, mixing, and formation of submesoscale vortices [Gula et al, 15, Vic et al, 18]. Observations have confirmed that **submesoscale processes can generate strong near-bottom mixing and cross-density upwelling**, where intense bottom currents interact with sloping topography [Ruan et al, 17].

Furthermore, to sustain efficient water-mass transformations, **the 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, 18]. Submesoscale baroclinic instability of the bottom boundary layer is one strong candidate [Wenegrat et al, 18]. Mechanisms such as deep frontogenesis might also play a role.

Unfortunately, these processes are not resolved for climate-scale ocean models, which have to rely heavily on parameterisations. The current generation of climate models does not have sufficient resolution to represent submesoscale processes in the deep ocean, and exhibits large biases in the representation of mixing and water-masses transformations. In the ongoing CMIP6 exercise, ocean models will typically have a ¼ degree resolution, allowing for mesoscales but not totally resolving them [Griffies et al, 16]. One can expect that truly mesoscale-resolving ocean models will be a standard for climate studies a decade from now. However, effects of submesoscale processes and internal waves will still have to be parameterized. Such parameterisations exist to account for wave-driven mixing [MacKinnon et al, 17], but **no parameterization currently accounts for deep submesoscale turbulence and its effects**.

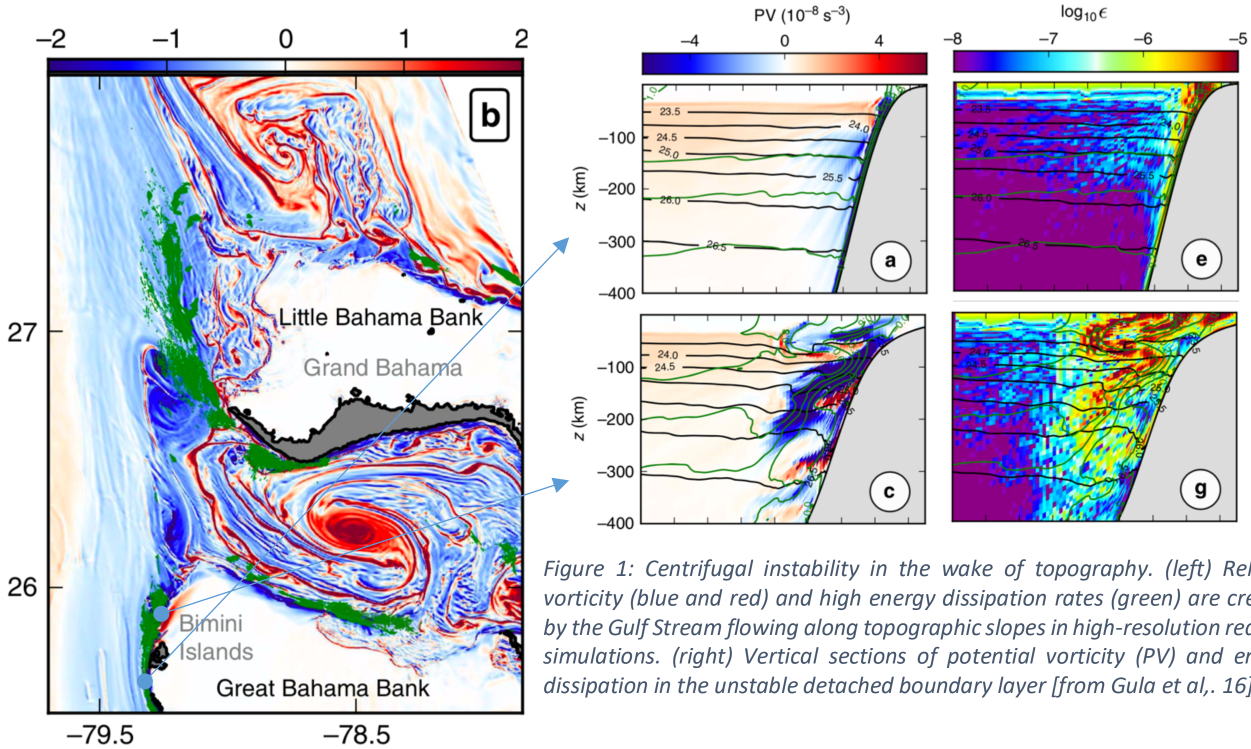

Figure 1: Centrifugal instability in the wake of topography. (left) Relative vorticity (blue and red) and high energy dissipation rates (green) are created by the Gulf Stream flowing along topographic slopes in high-resolution realistic simulations. (right) Vertical sections of potential vorticity (PV) and energy dissipation in the unstable detached boundary layer [from Gula et al,. 16]

OBJECTIVES: The goals of **DEEPER** are (1) to quantify for the first time the impacts of deep submesoscale processes on mixing and turbulent fluxes of buoyancy in the Atlantic Ocean; (2) to explore ways of parameterizing them for climate-scale ocean models that are unlikely to resolve submesoscale motions in the near future.

The project is organized around 5 different work packages, which have been designed 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.
- **H3**: Taking into account bottom submesoscale processes will modify the deep circulation, the large-scale distribution of water masses, and the meridional overturning circulation.

EXPECTED RESULTS: DEEPER will improve our knowledge on the role of deep submesoscale processes in determining the ocean energy budget, 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.

DEEPER will develop and test parameterizations of deep submesoscale processes using machine learning methods, that could be used for coarser ocean models as typically used in CMIP6 exercise.

DEEPER will participate in the development of ocean models, in particular the model CROCO, based on ROMS, which is a community ocean model widely used in regional oceanography. DEEPER will also foster collaborations between experts from two different ocean communities: the GDR-CROCO and the NEMO consortium, by using results from both models to develop and test the parameterizations for deep-ocean turbulence.

Finally, the numerical simulations produced in the context of DEEPER will be made available to the scientific community and serve in a number of projects for physical oceanography research or applications in biogeochemistry.

b. Position of the project as it relates to the state of the art

POSITIONING: 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. Observations have confirmed that intense bottom currents interacting with sloping topography could generate submesoscale processes with important implications for mixing and cross-density upwellings [Ruan et al, 17]. But these effects cannot be resolved in climate-scale ocean models, and no parameterization currently accounts for their effects.

Building on previous works by the PI, which aimed at characterising deep submesoscale processes in realistic set-ups, this project will move up a gear and tackle effects of these processes on an **unprecedented scale using cutting-edge realistic modelling with the CROCO model**. This will be the first time a **terrain-following model** will be used at sub-kilometer resolution over the full Atlantic Ocean. Such model is particularly advantageous to study flow-topography interactions as it permits very high vertical resolution in the bottom boundary layer everywhere in the domain, and because it uses a cleaner formulation of the bottom boundary condition. A hierarchy of simulations will be built to be able to characterise all processes driving deep ocean mixing and will constitute **a unique set of simulations** to test theory related to submesoscale processes and quantify their effects on the large scales.

ROMS/CROCO is widely used throughout the international oceanographic community and its numerical performances on supercomputers and stability constraints are well-known. It has been instrumental in revealing the importance of the submesoscale currents in the surface layer [Capet et al, 08]. Pioneer results on the deep submesoscale turbulence have also been obtained with ROMS/CROCO [Molemaker et al., 15, Gula et al, 16]. It is perfectly suited to investigate deep-ocean dynamics in regimes where submesoscale turbulence, internal tides and current-topography are important. A regional version of this model has been able to reproduce realistic levels of mixing and, for the first time, mean currents and variability matching observations over the Mid-Atlantic ridge [Vic et al, 2018, Lahaye et al, 19] when both meso/submesoscale processes and tidal forcings were included (Fig.2). In particular, the model was able to reproduce a realistic abyssal circulation over the Mid-Atlantic ridge with a persistent up-valley current, fed by internal tides and vortex turbulence, and an associated density gradient in the rift valley, comparable to in-situ observations.

There are 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*

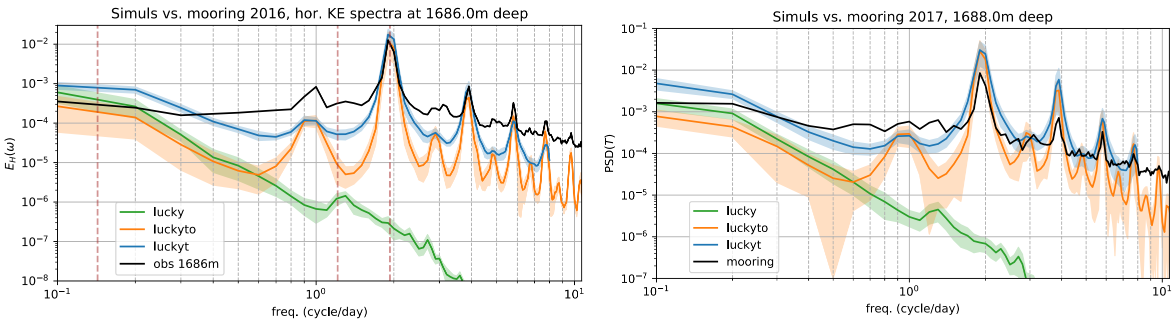

Figure 2: Power spectra of horizontal velocity (left) and Temperature (right) at 1700 m depth over the Mid-Atlantic ridge (37.29N, 32.27W). Observations from a mooring are shown in black. Simulations have been run with CROCO at 750 m resolution with 80 vertical levels in a regional domain centered on the Mid-Atlantic ridge. The simulation "lucky" includes meso/submesoscale, but no tides. The simulation "luckyto" is a simulation with flat stratification forced by tides only. The simulation "luckyt" includes meso/submesoscale and tides [Lahaye et al, 19].

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. DEEPER will have strong interactions with the community involved in this project and complement it on the modelling side. DEEPER 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.

c. Methodology and risk management

The project is decomposed into 5 work packages (WP). There is one technical WP (WP1), which involves the realization of a new set of simulations, and 3 scientific work packages (WP2 – 4). WP2 aims at quantifying the impacts of the deep submesoscale processes on the large scale energy, buoyancy, and PV budgets. WP3 is oriented toward process studies and aim at understanding how submesoscale processes impact the mixing and restratification at the bottom. Finally, WP4 aims at parameterizing these processes in coarser models. The project is supported by one WP on Management and coordination (WP0). A Gantt chart is provided in Figure 3.

The package WP1 is instrumental to the realization of WP2 – 4, which all require simulations developed in WP1. That is why an extensive preparatory work has already been performed to assess the feasibility of WP1, as detailed below.

WP0: Coordination

People involved: J. Gula

The coordination of DEEPER will consist in organizing meetings of its consortium, in hiring DEEPER's staff (postdoctoral researcher, PhD student, master student), in organizing the work of different parties and ensuring their fruitful integration, in ensuring timely production of deliverables, and, in applying resources not covered by the present proposal (e.g. securing the required computing resources). Throughout the project, short visits and visioconferences will be organized when needed to communicate with the members of the board. A final meeting gathering all members in Brest, as well as the scientific community sharing common scientific interests, will be held three years into the project in order to discuss conclusions of the project and potential follow up proposals.

WP1: The Atlantic Ocean at submesoscale-permitting resolution

People involved: J. Gula, G. Cambon, S. Theetten

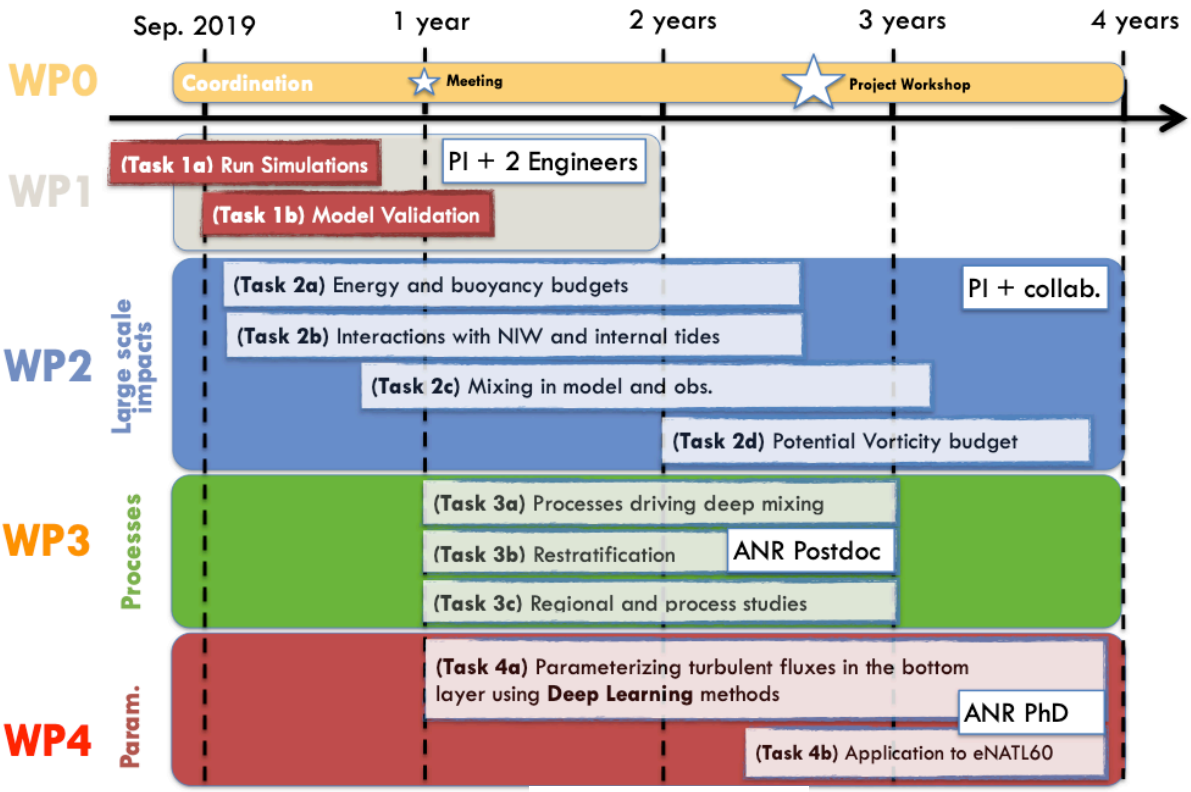

Figure 3: DEEPER timeline

Rationale and Objectives: To investigate the impacts of the submesoscale processes and internal waves on larger scales, we need a realistic simulation with high enough resolution to resolve (at least partially) submesoscale dynamics, with realistic levels of internal waves, and with a large enough domain to fully contain the basin scale circulation. A basin scale domain is especially critical to simulate realistic level of internal tides at a given location, as they can be generated remotely.

WP1 thus involves the design and run of new multi-year realistic simulations of the full Atlantic Ocean (Fig. 4) at sub-kilometer resolution, including realistic topography, surface, geothermal and tidal forcings.

Methods: The numerical model that will be employed is the Regional Oceanic Modelling System (ROMS) [Shchepetkin & McWilliams, 2005] in its Coastal and Regional Ocean COmmunity version (CROCO, https://www.croco-ocean.org/). CROCO solves either the primitive (hydrostatic) or non-hydrostatic equations for an incompressible fluid with free surface. It uses generalized terrain-following coordinates (i.e., a sigma model); the Boussinesq approximation using a realistic Equation of State (EOS) for seawater; general orthogonal curvilinear coordinates in horizontal directions; and a set of physical parameterizations for the Planetary Boundary Layer (PBL), as well as small-scale, subgrid mixing processes. Numerous diagnostic packages and utilities have been implemented. The code is parallelized in horizontal directions based on MPI directives.

CROCO is discretized in coastline- and terrain-following curvilinear coordinates using high-order numerical methods. it is a split-explicit, free-surface ocean model, where short time steps are used to advance the surface elevation and barotropic momentum, with a much larger time step used for temperature, salinity, and baroclinic momentum. The model has a 2-way time-averaging procedure for the barotropic mode, which satisfies the 3D continuity equation. The specially designed 3rd order predictor-corrector time step algorithm allows a substantial increase in the permissible time-step size. The complete time stepping algorithm is described in Shchepetkin & McWilliams [2005]. Associated with the 3rd order time-stepping, a 5th-order, upstream-biased advection scheme allows the generation of steep gradients, enhancing the effective resolution of the solution for a given grid size. Because of the implicit diffusion in the upstream-biased advection scheme, explicit lateral viscosity is not needed in CROCO, except in sponge layers near the open boundaries where it increases smoothly close to the lateral open boundaries.

As an alternative to default CROCO output libraries, outputs will be performed here via the XIOS module, which provides a great ease of use for data outputs on top of I/O optimization with in particular asynchronous data writing. It already performs well in other ocean circulation models (e.g. NEMO).

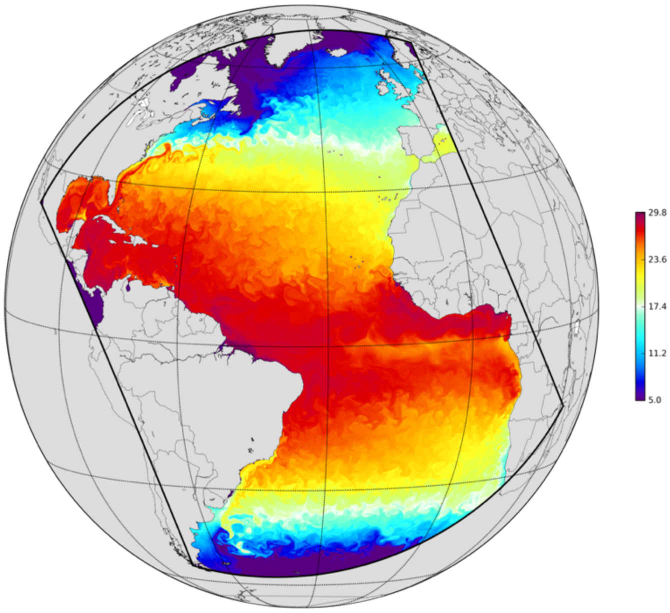

Figure 4: Snapshot of SST for the Atlantic simulation domain from a 6 km CROCO simulation.

The simulations will be forced at the surface using a bulk formula and daily or hourly atmospheric fields from Climate Forecast System Reanalysis (CFSR), and data from the SODA ocean reanalysis at the boundaries. They will be forced at the bottom using geothermal heat fluxes data from Davies & Davies [2010]. They will use an UP5 scheme for advection of momentum, a RSUP5 scheme rotated along geopotentials for advection of tracers, and the k-ε vertical mixing closure. The two parameters controlling the bottom and surface refinement of the grid are 2 and 5, respectively. The effect of bottom friction will be parameterized through a logarithmic law of the wall with a roughness length Z0 = 0.01 m. Bathymetry will be constructed from the SRTM30_PLUS dataset. A Gaussian smoothing kernel with a width of 4 times the topographic grid spacing will be used to avoid aliasing whenever the topographic data are available at higher resolution than the computational grid.

Work Programme: The design of the simulations, benchmark and validation will be performed J. Gula and 2 engineers from LOPS (G. Cambon and S. Theetten).

- Task 1a - **Running the simulations**. The Atlantic configuration will be run in a framework as realistic as possible, which includes realistic sources of internal waves (hourly winds and tides) and geothermal forcings. Different versions will be run with a gradual increase in resolution from mesoscale resolving (12 km / 50 lev., 6 km / 50 lev. and 3 km / 100 lev.), to submesoscale permitting (1 km, 200 lev.). The 12 km and 6 km runs will be initialized from the SODA ocean reanalysis and run for a 20 years period (1998 -2018). The 3 km run will be initialized from the equilibrated 6 km run and run for about 6 years.
  The "most realistic" configuration will be submesoscale permitting (dx < 1 km, 200 vertical levs.) and corresponds to a 10500 x 14000 x 200 points domain. A duration of approximately 18 months is planned, starting from the equilibrated 3 km run. Such a run will require between 6 and 10 millions cpu-hours depending on the time-step used.
  Comparisons between the different runs will be useful to quantify the effects of resolving submesoscale turbulence on the large scale circulation (WP2) and to test parameterizations for submesoscale turbulence in coarser models (WP4).

Additional experiments will be run where sources of internal waves will be switched off alternatively to better quantify interactions between near-inertial waves, tides, and the meso/submesoscale turbulence (WP2). We will start by using daily winds instead of hourly in order to remove most of the near-inertial energy in the simulation. If the computing allocation allows it, we will also run a simulation without tidal forcings to better evaluate the interactions between internal tides and the sub-inertial circulation. A specific Gantt chart is provided in Figure 5 for the planned simulations.

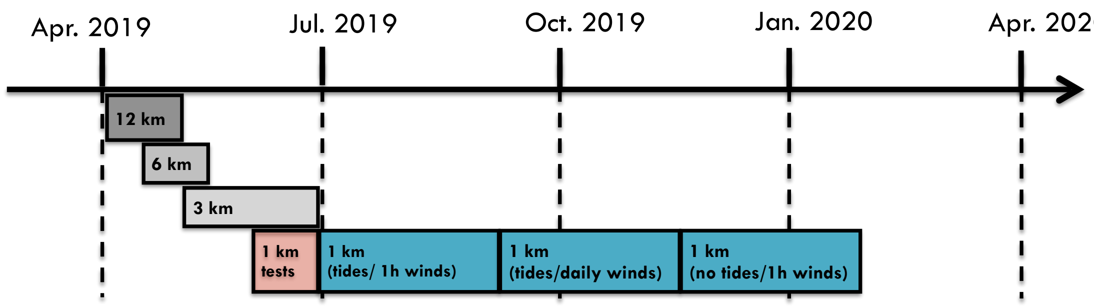

Figure 5: Timeline for the planned simulations

- Task 1b - **Validation of the mean structure and mesoscale variability.** All simulations will be carefully validated by comparing the relevant metrics (structure of the mean currents, mesoscale variability, internal waves energy levels, etc.) to available observations (satellite, drifters, gliders, moorings, Argo floats, etc.). This task is of course intertwined with Task 1a as it will influence numerical and physical choices for the configurations.
  We have already run various sensitivity tests using simulations over the Atlantic domain with resolutions of 9 km and 6 km, to find out the best choices in terms of numerical options (advective schemes, KPP versus k-ε), vertical resolution, and surface forcings (CFSR versus ERA-interim) based on a few selected metrics (realism of the mean currents, mesoscale variability, well-behavior of the separation of the Gulf Stream, mean temperature and salinity biases in the subtropical and subpolar gyres, mixed-layer depth in the regions of deep convection in the subpolar gyre, rate of formation of Meddies near the Strait of Gibraltar).

Milestones and deliverables:

- A set of realistic simulations of the Atlantic Ocean from mesoscale-resolving to submesoscale-permitting resolution, with geothermal fluxes, tidal forcings, and high-frequency wind forcings.
- The same set of simulations without high-frequency wind forcings.
- The same set of simulations without high-frequency wind forcings, nor tidal forcings.

Risk mitigation: There is a certain technical challenge associated with the implementation of realistic simulations at such high resolutions. We will build on the extensive experience of the PI in running submesoscale resolving simulations in the Atlantic Ocean and we will also beneficiate from the technical expertise of G. Cambon and S. Theetten, who are both developers of the CROCO model and specialists of high-performance computing.

The CROCO code has already been used over a lot of different sectors of the Atlantic Ocean with up to 100 m resolution [Gula et al, 14, 15, 16]. The numerics are perfectly suited to resolve internal waves and submesoscale dynamics at the targeted resolution.

Performance tests have already been carried out thanks to the GENCI project A0030107638 ('HIRESTOPO') which provided us with 2.5 million core hours on the IRENE-SKL supercomputer. A preliminary run has been performed at the highest resolution (1 km / 200 vertical levels) over a domain covering the North Atlantic Ocean (8811 x 7002 x 200 points), using 96 x 96 = 9216 processors. We have been successful in running several months of simulation using a dt = 50 s baroclinic time step. A snapshot of vorticity after 15 days of simulation is shown in Fig. 1. High-resolution images, at the true resolution of the model, are available here: http://stockage.univ- brest.fr/~gula/Megatl/. We are hopeful that the time-step can be further increased by a factor 2 after the initial equilibration of the dynamics in the model and several planned improvements in the setup of the model.

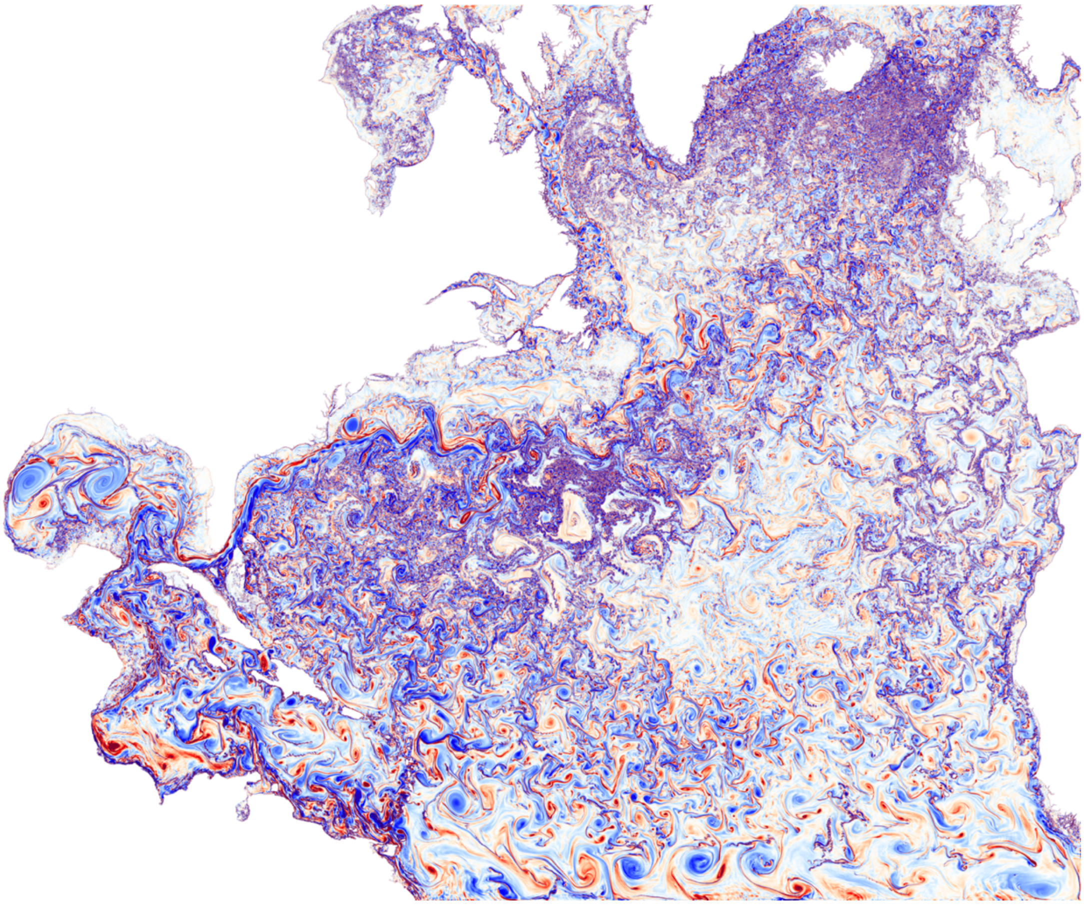

Figure 6. Preliminary result: Snapshot of surface relative vorticity (normalized by f) for the 1-km resolution simulation. Pictures at the true resolution of the model, are available here: http://stockage.univ-brest.fr/~gula/Megatl/

WP2: Quantify impacts of submesoscale turbulence on the large scale circulation

People involved: J. Gula (all tasks), P. Tedesco, P. Penven, C. Menesguen (task 2a); R. Barkan, M.J. Molemaker, J.C. McWilliams (task 2b), C. de Lavergne, A. Mashayek (task 2c); Y. Morel, G. Maze, A. Wirth, (task 2d).

Objectives: The objectives of this WP are to quantify how submesoscale processes and internal waves modify the large-scale budgets of energy and buoyancy **(H1-H2)**, how they impact mixing and water-mass transformations **(H1)**, and finally use a PV-framework to characterize the impact of boundary PV fluxes related to diabatic processes on the large-scale mean PV budget and associated circulation **(H3)**.

Methods: This WP will use the sequence of simulations produced in WP1. Complete budgets of momentum, energy, tracers (T, S, b) and potential vorticity, including horizontal and vertical turbulent fluxes of all quantities will be computed for the simulations at different resolutions, from mesoscale resolving (12 km / 50 lev., 6 km / 50 lev. and 3 km / 100 lev.) to submesoscale permitting (1 km, 200 levs.), and for the different setups, with or without NIW and tides. Online diagnostics have already been implemented in CROCO by the PI over the last few years to output exact budgets of mean/eddy kinetic and potential energy [Gula et al, 16], mean/eddy fluxes of tracers and buoyancy, barotropic vorticity [Schoonover et al., 16], and potential vorticity [Wenegrat et al., 2018], such that these diagnostics will be readily available at the end of WP1.

We will also use available datasets for microstructure measurements [Waterhouse et al., 14, https://microstructure.ucsd.edu/#/], including recently acquired data from "The Reykjanes Ridge Experiment" (RREX) or data that will be acquired over the mid-Atlantic ridge around the Lucky Strike hydrothermal site during the MoMARSAT19 cruise, with the help of C. Vic and B. Ferron (LOPS).

- Task 2a - **Energy and buoyancy budgets:** To characterize the presence and impact of submesoscale processes, we will first quantify the potential and kinetic energy for the time-mean flow and the eddies, traditionally known as the Lorenz energy cycle [Chen et al, 14]. We will also quantify how the different terms, in particular terms involving eddy-mean flow interactions, change with the resolution of the model and subsequently how energy dissipation is impacted. We will also investigate how the submesoscale dynamics play a role in fluxing energy across scales using methods such as coarse-graining [Capet et al., 16, Aluie et al, 17]. We will similarly compute the buoyancy budget over the Atlantic Ocean, and compare eddy buoyancy fluxes in the different simulations.

- Task 2b - **Impact of the internal waves:** To disentangle the role of internal waves versus submesoscale processes, and study the interactions between the two, we will use the additional experiments where sources of internal waves are switched off alternatively. We will be able to get a more global picture of the impact of NIW and tides on the energy budget. We will quantify the energy directly extracted from the geostrophic currents by the waves, and see if it can lead to a "stimulated imbalance" [Barkan et al., 17], which catalyzes a forward energy cascade from mesoscale down to dissipative processes. Furthermore, we will be able to evaluate the vertical decay scale of near-inertial energy [Jochum et al., 12], which can have strong implications for bottom mixing [Clément & Thurnherr, 18].

- Task 2c - **Mixing and water-mass transformations:** We will evaluate the intensity and localisation of energy dissipation and mixing in the different simulations and compare them to bulk estimates and observations from microstructure measurements [Waterhouse et al., 14]. The thickness of the bottom boundary layer is another diagnostic that will be used to compare the simulations to observations [Banyte et al., 18]. We will finally compute water-mass transformations in the simulation and evaluate the differences depending on the resolution and forcings used **(H1-H3)**.

- Task 2d - **Potential vorticity budget**: Another central quantity in oceanography, which can give insights to the gyres dynamics, is the Potential Vorticity (PV). PV is only modified by diabatic processes. For instance, it has been shown that PV fluxes are modified by submesoscale turbulence at the surface, with potentially strong impacts for the rate of formation of the 18 degree mode water [Wenegrat et al., 2018].
  In the present context, mixing and friction near the bottom boundary can create PV anomalies that can then lead to baroclinic instability and generation of eddies, spreading water mass properties within the ocean interior. There exists strong constraints on the evolution of the net PV in diabatic evolution and specific methodologies to calculate PV so as to verify these constraints [Morel et al, 19]. We will use these diagnostics to calculate and interpret PV budgets, focusing on the production and spreading of the Mode Water. The emergence of submesoscale vortices from baroclinic instability and their impact on the generation of Mode Water and subsequently on modification of the large scale gyre dynamics, will be investigated in terms of the bottom PV fluxes **(H3)**.

Milestones and deliverables:

- Detailed energy and buoyancy budgets of the Atlantic Ocean in a submesoscale-permitting regime.

- Evaluation of the effect of the near-inertial waves and internal tides on the energy and buoyancy budgets.
- A map of mixing rates and water-mass transformations in a fully realistic submesoscale-permitting simulation and a comparison with in-situ observations.
- A link between PV fluxes at the bottom and the large-scale PV budget and circulation in the presence of submesoscale and internal waves.

Risk and mitigation: The principal risk of this WP is failure to demonstrate qualitatively and quantitatively comparable results from observations and model simulations.

The members of the project have an extensive experience of running the CROCO model in this region, and have already performed and validated a large number of simulations against available observations in several publications [Gula et al, 15a, 15b, 16, Vic et al. 18, Lahaye et al, 19].

Simulations of the Atlantic region at 6 km resolution using the CROCO model (without tides nor high frequency forcing) are robustly able to produce realistic structures for the mean currents in the subtropical gyre, including a well simulated separation of the Gulf Stream [Renault et al, 16]. They also produce realistic levels of mesoscale turbulence at the surface and in the interior, as seen from comparisons of eddy kinetic energy with observations from AVISO satellite and drifters, and comparisons of eddy available potential energy (EAPE) with observations from Argo floats down to 2000 m [Vic et al. 18]. Simulations in the subpolar gyre at resolutions 6 km and 2 km with the CROCO model have also been validated by comparison with satellite (AVISO) and in-situ data (Argo floats, OVIDE and RREX cruise data). We see an improved representation of the mean currents and their variability (Fig.7) compared to previous simulations with coarser resolution.

Regional simulations in the region of the Gulf Stream, with resolutions equivalent to the highest targeted resolutions in this project, have also been validated in several papers published by the PI over the last few years [Gula et al, 15a, 15b,16, Callies et al, 15]. They have shown that the circulation was getting more and more realistic with increasing resolution and that submesoscale turbulence was well resolved in the model. Submesoscale statistics in the model have been directly compared to in-situ observations during the LatMix campaign [Shcherbina et al, 2015].

Finally, regional simulations using an equivalent set-up, including tidal forcings, have been able to generate realistic levels of energy, tracer variability and mixing in the deep ocean over the Mid-Atlantic ridge [Vic et al, 18, Lahaye et al, 19].

Should the model produce results significantly different from observations in regions of the Atlantic Ocean. We will investigate the possible reasons for disagreement in these regions. This could be due to large differences in the background stratification or circulation, or to the wrong representation of some local dynamical processes. In the latter case, we will specifically target some of these regions for the higher-resolution simulations planned in WP3.

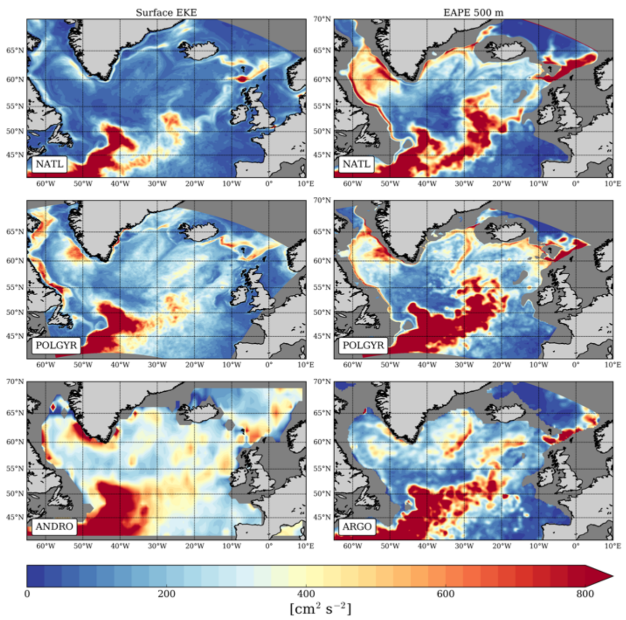

Figure 7: (left) surface EKE, and (right) EAPE at 1000 m depth, computed from (top) a CROCO simulation at 6 km resolution, (middle) a CROCO simulation at 2 km resolution, and (bottom) Argo floats.

WP3: Identify and characterise processes responsible for water-mass transformations

People involved: J. Gula, Postdoctoral researcher (all tasks), J. Callies (task 3a), L. Thomas, J. Wenegrat (task 3b), X. Capet (task 3c).

Objectives: This WP aims at identifying and better understanding the processes generating mixing and driving water-mass transformations **(H1-H2)**. Building on quantitative budgets in WP2, we will identify critical locations, with intense bottom mixing and turbulent fluxes, and investigate the processes at play by means of high-resolution regional simulations and idealized process studies. We will also evaluate the limitations of the numerical simulations of WP1.

Methods: **Nested simulations** with the CROCO model will be used to study specific regions at higher resolution and check how sensitive the processes are to the horizontal and vertical resolution, choices for the numerical schemes and the hydrostatic approximation. The modeling strategy is well established [Gula et al., 2014, 2015a, 2015b, 2016]. Using outputs from the Atlantic simulations at 1-km resolution to generate boundary forcings, we can set-up a suite of simulations with increasing resolution from 1-km to 10s of meters. For the highest resolution nests, we will take advantage of the recently developed **non-hydrostatic version of CROCO** [Roullet et al, 17] to relax the hydrostatic approximation and evaluate a possible impact on the dynamics.

Work Programme: The postdoctoral researcher will be in charge of the work conducted in WP2, under the supervision of J. Gula, and working closely with experts involved in this WP: X. Capet (LOCEAN), J. Callies (Caltech), L. Thomas and J. Wenegrat (Uni. of Stanford)

- Task 3a: We will first quantify the **contribution of the different processes to deep ocean mixing**, to determine where it is predominantly associated with internal waves breaking (internal tides, near-inertial waves, lee waves, or the formation of hydraulic jumps) and where submesoscale turbulence contributes significantly. We will compute criteria for typical processes such as gravitational, centrifugal or symmetrical instabilities over the full domain **(H1)**.

- Task 3b: We will 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**, and compare them to other processes that can potentially generate turbulent buoyancy fluxes in the deep part of the ocean. One possible candidate is **deep frontogenesis**, following the same mechanism than in the surface layer. We will compute frontogenetic tendencies and check the possible impact of the secondary circulation associated to deep fronts and filaments **(H2)**.

- Task 3c: We will identify some critical regions, where mixing and buoyancy fluxes are particularly strong, and study them in more detail by setting-up regional simulations at higher resolution. One important challenge will be to quantify **how sensitive the processes are to the horizontal and vertical resolution** of the model, and to the resolution of the bathymetry. We will further check on selected cases the validity of the hydrostatic approximation.
  Identified processes will be further studied by designing **idealized simulations**. If possible, we will try to use **theory** to develop some scaling-laws for the impact of the processes for mixing and buoyancy fluxes.

Milestones and deliverables:

- Quantification of the relative importance of the different processes in driving ocean mixing.
- Evaluation of the importance of submesoscale baroclinic instability as a restratification mean in the bottom boundary layer.
- Identification of other possible mechanisms driving restratification.

Risk mitigation: The risk is the same than for WP2. The realism of the solution always has limits, especially when it comes to water mass properties in the deep-ocean. However, we will run here relatively short simulations (compared to the equilibration time for tracers in the ocean) that do not have time to drift away too far from their initial state. Furthermore, the processes studies planned in this WP are not too sensitive to the overall degree of realism of the model and can be performed independently in a more or less idealized setup.

WP4: Parameterise impacts of deep submesoscale turbulence using machine learning

People involved: J. Gula (all tasks), P. Tandeo, R. Fablet, G. Roullet (task 4a), J. Le Sommer, W.K. Dewar (task 4b).

Rationale and Objectives: The sub-grid scale turbulence is taken into account in ocean models through the **Reynolds stress terms in the momentum and tracer equations** ("eddy" momentum and tracer fluxes). These terms can be computed using different types of closures, based on different physical principles, which provide a relation between the Reynolds fluxes and the resolved model variables. Some parameterizations are already used in ocean models to incorporate effects of some specific unresolved processes, such as the effect of internal waves [MacKinnon et al., 17] or the effects of submesoscale mixed-layer instability [Fox Kemper et al., 2007], and symmetrical instability [Bachman et al., 2017]. However, no parameterizations are currently able to incorporate effects of deep submesoscale processes in mesoscale resolving models. Designing a parameterization based on physical principles for a specific dynamical process is a long and uncertain task. But it is now possible to use empirical data-driven methods, based on machine learning algorithms, that allows to extract the information without knowing all underlying physical principles.

The objective of this WP is thus to take advantage of the latest advances in machine learning to **parameterise the effects of deep submesoscale turbulence and internal waves** for a coarser (here mesoscale-resolving) simulation **(H3)**.

Methods: One way to predict Reynolds stresses without knowing a priori all underlying physical principles is to use machine learning methods, and in particular, **a deep neural network (DNN).** The DNN transforms input data through multiple layers of nonlinear interactions. The DNN has proved very efficient to find intricate structures in high-dimensional data [LeCun et al., 2015] and it has gained a lot of attention in the last few years for its ability to be successful in different domains such as playing the game of Go [Silver et al., 2016]. The concepts behind deep learning are not that recent, but can now take advantage of the growing computational power and the large amount of data available to train the DNN. Such methods have been successfully applied to parameterize Reynolds stresses for Reynolds-averaged Navier-Stokes (RANS) models [Ling et al., 16] or large eddy simulations (LES) [Vollant et al, 17]. More recently, DNN have been able to successfully replicate the spatiotemporal variability of the Reynolds stresses for momentum in an idealized quasi-geostrophic ocean model [Bolton and Zanna, 18]. We are planning to apply a DNN along the same lines but in a more realistic context. The objective will be to predict Reynolds stress corrections to the momentum and tracer equations for a mesoscale resolving (12 km) simulation using the DNN. The DNN will be built in Python using Keras and TensorFlow.

- Task 4a: The DNN will be trained to relate coarse-grained turbulent Reynolds stresses to coarse-grained horizontal velocities and tracers computed from the highest resolution simulation (1 km) including tides and high-frequency winds from WP1. The coarse-grained variables will correspond to the best solution we could achieve with a mesoscale model and an optimal subgrid-scale parameterization. The parameterization then consists in calling the neural network to compute the Reynolds stresses from the mesoscale variables when running the mesoscale simulation, which will not explicitly resolve submesoscale processes. The same procedure will be applied for the

mesoscale simulations with or without tides and high-frequency winds. Somehow, we want to encapsulate the knowledge we can acquire from the submesoscale simulations into a deep neural network and then benefit from this knowledge to run lower resolution simulations **(H3)**.
The North Atlantic Ocean offers various dynamical regimes and a wide range of dynamical processes. It will be interesting to see if the DNN trained in the Atlantic can be applied in other regions as well. The DNN will be tested over other regions where sets of simulations with the same characteristics will be available such as the Weddell Sea, where nested simulations with CROCO are being run in the context of the Marie Curie project CIOP *"Centrifugal instability in the Orkney Passage"* of C. Buckingham and J. Gula, in collaboration with A. Naveira Garabato (NOCS), S. Griffies, and S. Legg (NOAA/GFDL).

- Task 4b: We will then apply the DNN to another simulation: eNATL60, a North Atlantic NEMO simulation with different vertical coordinates (z-coordinates) and numerical schemes. The goal will be to evaluate the sensitivity of the approach to numerics and model discretisation. This task will imply to design a common framework of tools for both models that are able to deal with very large datasets. We will rely on the Pangeo software ecosystem (https://pangeo.io/) for this purpose.
If the test with the NEMO model is successful, we will envision implementing the DNN based parameterisation in a coarser-resolution global ocean model. A collaboration and a multi-week stay at the NOAA/GFDL are already planned in the context of the Marie Curie project CIOP involving C. Buckingham, J. Gula and S. Griffies (NOAA/GFDL). As a part of CIOP, model data from the ocean component of a coupled climate model (CM2.6) run at 0.1-degree resolution will be used to infer vertical energy and buoyancy fluxes due to centrifugal instability in the global ocean based on theoretical scaling-laws. We will then build on this collaboration in the context of DEEPER to implement and test the parameterization in a global climate model, which will allow a true verification of **H3** and the impacts for the meridional overturning circulation over long time scales.

Milestones and deliverables:

- A parameterization of deep submesoscale processes for mesoscale-resolving and coarser models.

Risk mitigation: This WP is the most exploratory and it is difficult to predict how much can be learned from the application of machine learning techniques to this problem. The technical aspects of setting-up and training a DNN are easy to deal with. We will benefit from the experience of R. Fablet ant P. Tandeo (IMT Atlantic), which are both experts in machine learning and will also supervise the PhD student involved in this WP.

II. Organisation and implementation of the project

a. Scientific coordinator and its consortium / its team

The PI of this project is Jonathan Gula. He is an assistant professor at Université de Brest (UBO) since September 2015, and works at the Laboratory for Ocean Physics and Satellite remote sensing (LOPS). He has published 32 peer–reviewed scientific publications in international journals since 2009, including several highly-cited papers on submesoscale ocean dynamics.

J. Gula received his PhD in 2009 from the Université Pierre et Marie Curie (Paris, France). His thesis focused on ageostrophic instabilities of fronts, mixing and generation of gravity waves in the ocean and the atmosphere, under the supervision of V. Zeitlin and R. Plougonven at the Laboratoire de Météorologie Dynamique (LMD-ENS) in Paris, France. He subsequently spent 2 years as a postdoctoral fellow at University of Toronto, working on regional climate modeling with Prof. W.R. Peltier. He studied the impact of the Great Lakes on the regional climate, using a suite of global climate models and a regional atmospheric model. In 2012, he moved to the University of California, Los Angeles

(UCLA) to work on ocean dynamics with Prof. James C. McWilliams. He focused on the dynamics of the Gulf Stream and the understanding of submesoscale (< 10 km) processes in the ocean.

His research centers on better understanding ocean dynamics at meso- and submesoscale and their connection to global ocean circulation and climate. He uses numerical models, theory and observations to get dynamical insights on submesoscale processes. He has become expert in realistic high-resolution modelling using an innovative approach of progressively nesting smaller-domain, high-resolution models within coarse-resolution models, achieving numerically consistent and balanced energetics. He has used these methods to study ocean turbulence and scale interactions in a realistic context. This has led to important results on the dynamics of surface submesoscale fronts and filaments and seasonality of the submesoscale turbulence. His most recent works have focused on the generation of submesoscale turbulence by flow-topography interactions.

J. Gula is the PI of the project TADOMA (Abyssal Turbulence on the Mid-Atlantic Ridge, SAD Région Bretagne / CG29 / Prestige, 130 k€, 2017 – 2019). He is the French coordinator of a France-Stanford Collaborative project: "Simulating Turbulent Mixing in the Abyssal Waters of the Equatorial Pacific Ocean" (15 k€, 2018 – 2019), with L. Thomas (Uni. of Stanford).

He presently supervises 2 PhD students on topics related to flow/topography interactions and submesoscale turbulence sponsored by LabexMer and Région Bretagne (M. Le Corre, 2016-2019, and P. Tedesco, 2017-2020). He also supervises a PRESTIGE Fellow (N. Lahaye: Submesoscale Turbulence at the Mid-Atlantic Ridge, 2017-2019), a MARIE-CURIE fellow (C. Buckingham, project H2020-MSCA-IF-2017 CIOP: Centrifugal Instability in the Orkney Passage, 2019-2021) and a LabexMer postdoctoral fellow (C. Vic: Investigating deep-ocean turbulence over the Reykjanes Ridge, 2020-2022).

DEEPER being a JCJC project, J. Gula plays a central role. He will coordinate the project, be involved in all the tasks, and supervise the postdoctoral researcher as well the PhD and the master students. He will dedicate most of his time to this project over the next 4 years.

The workload required in order to meet the objectives will be distributed between J. Gula (the PI), G. Cambon (research engineer at LOPS), S. Theetten (research engineer at LOPS), P. Penven (research director at LOPS), C. Menesguen (researcher at LOPS), P. Tedesco (PhD student at LOPS), Y. Morel (research director at LEGOS), and the additional staff: 1 Postdoc, 1 PhD student and 1 master student hired thanks to the ANR requested.

P. Tedesco is a PhD Student supervised by J. Gula, P. Penven, and C. Menesguen, working on "the dissipation of mesoscale eddies in the ocean". She is financed by LabexMer and Ifremer until Oct. 2020. The third year of the PhD will naturally fall in line with the analysis of the energy balance for the Atlantic simulations planned in Task 2a.

J. Gula will also gather an advisory board of international scientists, whose expertise spans all aspects of the project, from fundamental geophysical dynamics to machine learning methods. The members of the panels are both junior and senior scientists, and targeted for their interest in different aspects of the project: (Task 2a) X. Carton, LOPS; (Task 2b) R. Barkan, Uni. Of Tel Aviv, M.J. Molemaker, UCLA, J.C. McWilliams, UCLA; (Task 2c) C. de Lavergne, LOCEAN, A. Mashayek, Imperial College London; (Task 2d) G. Maze, LOPS, A. Wirth, LEGI; (Task 3a) J. Callies, Caltech; (Task 3b) L. Thomas, Uni. Of Stanford, J. Wenegrat, Uni. Of Stanford; (Task 3c) X. Capet, LOCEAN; (Task 4a) P. Tandeo, IMT, R. Fablet, IMT, G. Roullet, LOPS; (Task 4b) J. LeSommer, IGE, W.K. Dewar, IGE/FSU.

This project will be an important opportunity for the PI, who was recently hired at Université de Brest, to significantly strengthen his team and develop his approach to study deep sea, submesoscale turbulence. The postdoctoral researcher, the PhD student and the master student that will be hired thanks to DEEPER will fasten the development of the PI research and facilitate the dissemination of his team's work (paper publications, conference participations). The collaborations initiated during the project, including within the scientific panel involved in DEEPER's activities, will help the PI establish himself within the national and international communities. While the PI has extensive experience working with ocean models and studying dynamical processes, he is not a specialist of machine learning methods. The collaborations with various members of DEEPER will help him gain new expertise on this topic.

Implication of the scientific coordinator in on-going project(s)

Name of the researcher	Person.month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start - End
Jonathan GULA	1	Call: H2020-BG-2018-2020, Proposal SEP-210522255	iAtlantic (*Integrated Assessment of Atlantic Marine Ecosystems in Space and Time*)	J. Murray Roberts (Uni. Of Edinburgh)	2019-2023

b. Implemented and requested resources to reach the objectives

RESOURCES: This project requires significant computational resources that will be obtained at the local level (Datarmor, IUEM), at the national level (GENCI), and through the European PRACE infrastructure.

An allocation of 2.5 million cpu-hours has been granted on the Irene supercomputer (CEA) through GENCI for 2019. It will allow to run the 12/6/3 km simulations and set up the 1-km version. The 1-km resolution Atlantic configuration is 10500 x 14000 x 200 points and will require between 5 and 10 million cpu-hours for each 18 months-long run. **A PRACE proposal asking for 20 millions cpu-hours** on the Irene supercomputer has been submitted in October 2018. If unsuccessful, a new proposal will be resubmitted to the next call (April 2019). If we are still unable to secure computing hours from PRACE, we will have access to about 10 million cpu-hours provided by A. Mashayek on the UK National Supercomputing Service ARCHER. This allocation could then be completed by a larger request to the GENCI program (4 – 5 millions cpu-hours). In the worst-case scenario, a reduced domain covering only the North-Atlantic part of the domain can be run for 2-3 times less cpu-hours.

The DNN (WP4) will be run locally using graphics processing units (GPUs) available at LOPS.

We have dedicated a lot of efforts over the past few years to implement online diagnostics to minimize the storage needs and provide perfectly closed budgets for the various physical quantities we are interested in. We will save about 800 To of data on the Irene supercomputer, a large part of it will be dedicated to save hourly 3d velocities that are needed for Lagrangian particle experiments.

A storage of about 500 To will be available locally in Brest to download data from the supercomputer. 250 To are already available to the PI. An additional 256 To will be bought using the ANR funding. They will be used to make most of the **model data freely available to the scientific community.**

The requested resources will be attributed to the principal investigator of the project and will finance consumables, travels, publication fees, and staff salary (postdoctoral researcher, PhD, and master student) as specified below. **The total amounts to 256 932,00 €**, including 8% of marginal costs.

Staff expenses

Postdoctoral researcher (24 months = 110 000 €): The postdoctoral researcher will be in charge of the work conducted in WP3. Under the supervision of J. Gula, they will conduct the analysis laid out in Task 3a, 3b, and 3c. They will work closely with experts involved in this WP: X. Capet (LOCEAN), J. Callies (Caltech), L. Thomas and J. Wenegrat (Uni. of Stanford) through frequent conversations. A month-long visit to California (Caltech and/or Uni. of Stanford) will be organized in the course of the project for the postdoctoral researcher. They will be responsible for leading the publications resulting from the work and will also present the results at conferences.

PhD student (18 months requested out of 36 months = 55 000 €): The PhD student will work on Task 3a and Task 3b. They will be supervised by physical oceanographers (J. Gula and G. Roullet, LOPS), and specialists of applied mathematics and machine learning methods (P. Tandeo and R. Fablet, IMT Atlantique). They will apply machine learning methods to the model simulations (high-resolution and the coarse-grained versions) produced in WP1. The remainder of the budget required to fund the full PhD fellowship will be sought through applications to UBO, EUR-ISBlue, or Région Bretagne.

Master student (6 months = 3 900 €): The master student will contribute to WP3. They will analyse additional idealized experiments to explore the processes identified in Task 3c (e.g. a 2d version of deep frontogenesis on a sloping bottom). They will be supervised by J. Gula and by the postdoctoral researcher involved in WP3.

Instruments and material costs

2 computers (4000 €): laptop or desktop for the Postdoc and PhD student.

Servers and disks (35000 €): We will need to store a large amount of model output locally in Brest in order to be able to share outputs of the model and perform some of the analysis. One powerful server (e.g. Server R740xd + CPU Intel Xeon Gold 6136 3GHz + 128 Go RAM) with 2 racks containing a total of 22 x 8 To = 176 To, which amounts to a RAID6 array of about 128 To, is evaluated at 19500 €. Another less powerful server with 22 x 8 To = 176 To (128 To effective), is evaluated at 15500 €.

		LOPS
Staff expenses		168900
Instruments and material costs (including the scientific consumables)		39000
Building and ground costs		0
Outsourcing / subcontracting		5000
General and administrative costs & other operating expenses	Travel costs	25000
	Administrative management & structure costs**	19 032
Sub-total		**256 932,00**
Requested funding		**256 932,00**

Outsourcing / subcontracting

Publication fee (5 000 €) for 5 papers

General and administrative costs & other operating expenses

International meetings (8 000 €): 2 for J. Gula, 1 for postdoc, 1 for PhD student

U.S. visits for the postdoc (3000 €)

National missions (4 000 €): 2 for J. Gula, 2 for postdoc, 2 for PhD student

Short Visits (4 000 €): 2 short visits for members of the board

Organization of a meeting in Brest (**6000 €**). We will also apply for additional funding through EUR-ISBlue, IUEM, and Région Bretagne, in order to gather the international community working on the topic (~40 people).

III. Impact and benefits of the project

IMPACTS: The main scientific impact of this research will be a thorough **understanding of deep-sea submesoscale processes**. It will increase our knowledge of the processes generating mixing and driving water-masses transformations in the deep ocean. It will quantify for the first time the **impacts of deep-sea submesoscale processes on the large scale circulation**. It will help estimate the numerical requirements to be able to model these different processes and design **parameterizations for models** that are not able to resolve them.

The most important societal impact of this research will come from the **improvement of numerical models**. Long-term projections of climate change depend on a realistic representation of ocean dynamics, circulation, and deep ocean processes in climate models. The current generation of climate models does not have sufficient resolution to properly represent submesoscale processes in the deep ocean, and exhibits large biases in the representation of mixing and water-masses transformations. DEEPER will deliver a better knowledge of the deep ocean processes and provide the basis for **improvements of climate models used for IPCC projections**. Such improvements are crucially needed for a better prediction of climate.

The outputs of the simulations planned in WP1 will be **distributed to the scientific community** and will serve multiple scientific objectives not included in this project through numerous collaborations. We can already cite collaborations with C. Maes and T. Huck (LOPS, Surface Dispersion of tracers), F. Ardhuin (LOPS, SKIM project), L. Memery (LEMAR, Apero project submitted to ANR), A. Ponte (LOPS, diagnosis of surface velocities in preparation of SWOT), R. Barkan (Uni. Of Tel Aviv, NISKINE project), A. Mashayek (Imperial College London, Mixing in a western boundary current), and with the consortium of the H2020 project iAtlantic. Thus, the data generated during DEEPER will have impacts over a very wide range of topics: the dispersion of micro-plastics at the ocean surface by submesoscale currents, the impact of the meso- and submesoscale dynamics on the fate of exported particles in the deep ocean and the biological carbon pump, the future satellite estimation of small-scale variability of the ocean surface velocity, or the connectivity between deep-sea ecosystems.

DISSEMINATION: Conferences and journals are an efficient way to disseminate scientific results. The results of DEEPER will be published in peer-reviewed journals. Publication in open access will be favored. We expect a significant number of scientific publications (5-10) based on the results of this project, both in multidisciplinary and specialized journals. The results of DEEPER will be presented at international conferences. We plan to attend both generalist meetings (Ocean Sciences, EGU), as well as smaller meetings dedicated to submesoscale processes, deep-ocean mixing and the meridional overturning circulation, in order to reach the specialized community. We will actually promote the organisation of sessions about deep-ocean submesoscale processes and mixing in such meetings. A meeting will be specifically organized in Brest, three years into the project, to gather all members and experts of the project, as well as the scientific community sharing common scientific interests. Results will also be presented during seminars in the different French laboratories. In particular, we will make sure that the PhD student and postdoctoral researcher working on DEEPER have plenty of opportunities to present their work at conferences and during seminars. This is indeed an important aspect of promoting their research and raising their profile. Finally, a presentation to a wider audience could be organized at Oceanopolis, in Brest.

We will make a strong effort to make all the **model codes developed within DEEPER freely available** online. Developments related to the CROCO ocean model will be readily available on the official CROCO website (https://gitlab.inria.fr/croco-ocean), for which the PI and several members of the project are developers. Analysis tools will be made available as well on dedicated Git based repositories.

Model outputs will be made freely available to the scientific community. In a context of a global anthropogenic climate change, it is essential that we all make efforts to reduce our carbon footprints, and earth scientists have to lead by example on this aspect. Unfortunately, some of the tasks involved in oceanographic research, such as running supercomputers, organizing oceanographic campaigns, or launching satellite observations, require significant resources. So, we have a responsibility to make sure that these resources are not wasted and are made useful for the highest number.

Data stored locally at LOPS (about 500 To) will be directly accessible for local scientists (LOPS, LEMAR, etc.) and available from the outside through FTP. It will include the most commonly sough-for data such as hourly surface fields and a selection of 3d variables from the most realistic high-resolution nest. Specific subset of data or other variables will be available upon request.

Dealing with such amount of data is not an easy task and transferring them is often too cumbersome in practice. **To make our data easily accessible to a wider audience, we will enable the use of a jupyterhub server (https://jupyter.org/hub) hosted on the LOPS machines**, where one could directly interact with the data using standard python or R functions to allow for most diagnostics and visualisations. The server will use a JupyterHub spawner based on libcloud for OpenStack (https://github.com/tristanlt/jupyter-libcloudspawner), set up with the help of T. Le Toullec (CNRS engineer at LOPS).

We will also adapt another tool, developed in parallel in the context of the H2020 project iAtlantic (also involving J. Gula, G. Roullet, and T. Le Toullec) to allow **on-the-fly computation and visualization of Lagrangian particles dispersion based on the outputs of the 1-km simulation**. This will be accessible in the form of a web interface, which uses in the background a fast hybrid Python/Fortran particles code developed by the PI (Pyticles, https://github.com/Mesharou/Pyticles) for an efficient computation on high-resolution ocean simulations. This tool will be very effective to communicate about the complexity of the flows in the deep ocean and promote a wider usage of high-resolution ocean models.

The DEEPER project also has a strong educational component. First, the project will involve the **training of one postdoc, one PhD, and one graduate student**. J. Gula and several members of the project (X. Carton, G Roullet) are heavily involved in the international **Marine Sciences Master Program** at the Marine Institute of Brest University (IUEM), which include in particular specialties: *"Physics of the Ocean and Climate"* and newly created *"Ocean Data Science"*. Results from the project will naturally feed the different courses from the Masters. In particular access to the model data through the jupyterhub interface will be a very useful educational tool. Finally, J. Gula and several members of the project are involved in the **EUR-ISBlue "Interdisciplinary graduate School for the blue planet"**, both for research and education aspects.

IV. References related to the project

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