MIxing and RestrAtification in the Bottom mixed-layEr: impActs of sUbmesoscale instabilities

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Applicants are invited to submit a letter of motivation, their CV, and a description of the academic curriculum to J. Gula (gula@univ-brest.fr) and C. Vic (cvic@univ-brest.fr)

Summary:

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.

Detailed presentation:

1. Introduction:

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).

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...
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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).

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.

2. Objectives:

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.
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3. Data and methods:

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.

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
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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.

Candidate Profile:

Master in physical oceanography or fluid mechanics. Interest in geophysical fluid dynamics, numerical modeling, statistical methods, and experience in scientific programming (Python, Julia, Fortran etc).