GENCI

# Rapport d'activité pour l'allocation A11 (2021-2022)

# HIRESTOPO

**Projet :** A0130112051

**Responsable :** ROULLET, Guillaume
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**Allocation**
Irene SKL : 1,800,000
Irene KNL : 100,000
Irene ROME: 1,800,000

**Consommation** Au 8 septembre 2022
Irene SKL : 1,013,000
Irene KNL : 19,000
Irene ROME: 1,333,000

**Résultats scientifiques**

The breakdown of our consumption during this A11 call is as follows

**Plume dynamics at Lucky Strike** (CROCO model)
Rome: 150 kh, Skylake: 105 kh

**LES simulations at the vent scale** (Basilisk model)
Rome: 8 kh, Skylake: 65 kh

**GIGATL project** (CROCO model post-processing)
Rome: 1,175 kh, Skylake: 890 kh, KNL: 19 kh

- **A/ Plume dynamics near Lucky Strike**

### A.1/ Plume dynamics at LuckyStrike

*This part of the project is led by Greace Crystle (PhD student supervised by G. Roullet and M. J. Molemaker).*

The goal of the PhD is to study how the chemical and biological species, released by the hydrothermal sources; are transported away in the deep ocean. The work focuses on relatively small-scales processes (from a few 10's meters in the horizontal) developing near the Lucky Strike site. The plume is driven by an about 1 GW heat flux coming from the Lucky Strike volcano. Most of the simulations have been done on Irene (SKL and recently ROME).

Our work have focused in producing and analyzing a series of dx=50m resolutions simulations at LuckyStrike, a hydrothermal source southwest of the Azores located with the MAR (Medio-Atlantic Ridge). To track the faith of the plume a passive tracer is seeded at the location of the heat source. The major result is that the plume dispersion is dominated by the submesoscale turbulence (Fig.1) that is ubiquitous at the plume depth, which is around 1,500m deep. At this depth, the MAR looks like a series of interconnected small basins, distributed along the main axis, and connected to the open ocean a by a few passes. The submesoscale turbulence, in the form of intense vortices, is generated by the interactions of the meso-scale circulation with the bottom topography (Fig.1). The result is a very non-uniform distribution of tracer concentration, that evolves on short time scales. We do not retrieve the trapping effect that exists in the idealized simulations, in which the tracer is being trapped into strong small anticyclones generated by the plume. The reason might be because the turbulent shear destroys these vortices or because the horizontal resolution is not good enough to avoid numerical dissipation or a combination of the two reasons. Our last finding is that the plume appears to have a dynamical signature on the temperature up to 1200m. This is not a direct transport of mass, the mechanism is dynamical and involves the salinity.

### A.2/ The plume dynamics as the scale of the edifice

*This part of the project is led by C. Lemaréchal (PhD student at LOPS under the supervision of J. Gula and G. Roullet). Contribution to the H2020 IAtlantic project.*

The goal of this work is to understand the hydrodynamics of the thermal plume during its ascent from the source at the bottom to its neutral level, about 200 m above for Lucky Strike. The simulations we are targeting are

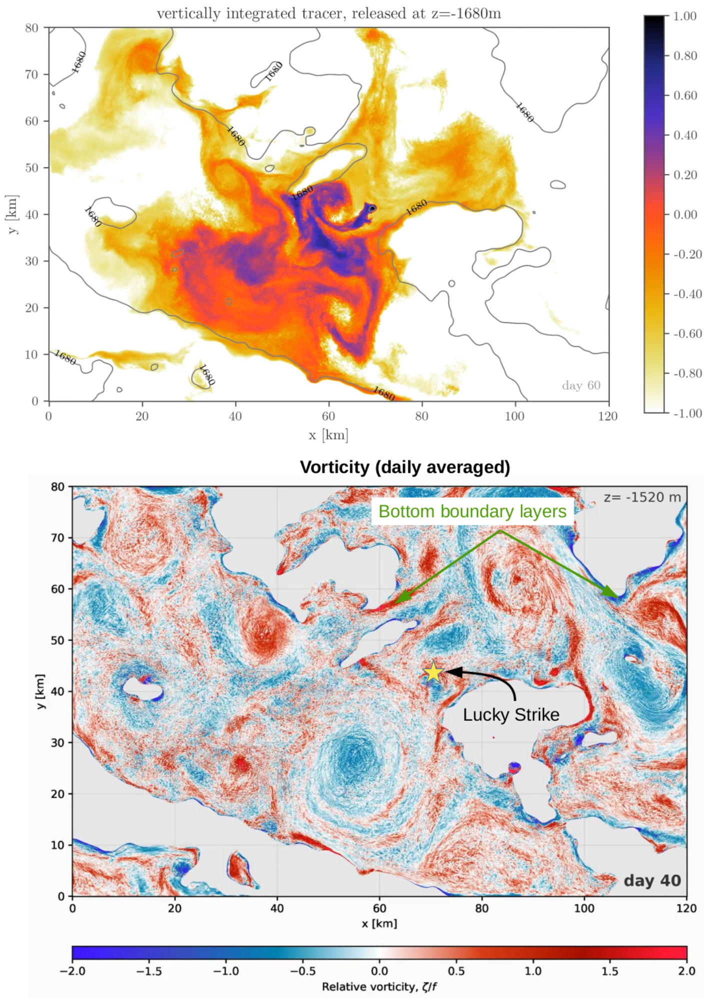


Figure 1: Snapshot of tracer concentration (top) and daily mean vorticity field (bottom) at the plume depth (1500m)

fundamentally LES. For that purpose we are using Basilisk, the octree LES model developed by S. Popinet et al. To benefit from the efforts made in learning how to use it and how to analyse the results, we will use Basilisk for all our LES studies. Three sets of scales are relevant: the plume from an isolated spring (Fig.2) ; the plume at the scale of an edifice that results from the coalescence of several sources and also diffusive sources ; the plume at the scale of the site, that results from multiple edifices. For the physical oceanography, the Lucky Strike plume is often seen as resulting from a single source. In details, this is not the case at all. A single spring, with diameters of the order of a few centimeters, is unable to produce the Lucky Strike plume, it is really the collections of many that can. How all the small plumes coallece to form a single large one is an open question.

During this allocation we have studied the sensitivity of the plume behavior on the temperature at the spring (of the order of 300°C) and the outflow velocity. Our goal is to span enough the range of possible plumes to be able to retrieve relevant geophysical informations, such as the heat flux, from an image or a video of a source.

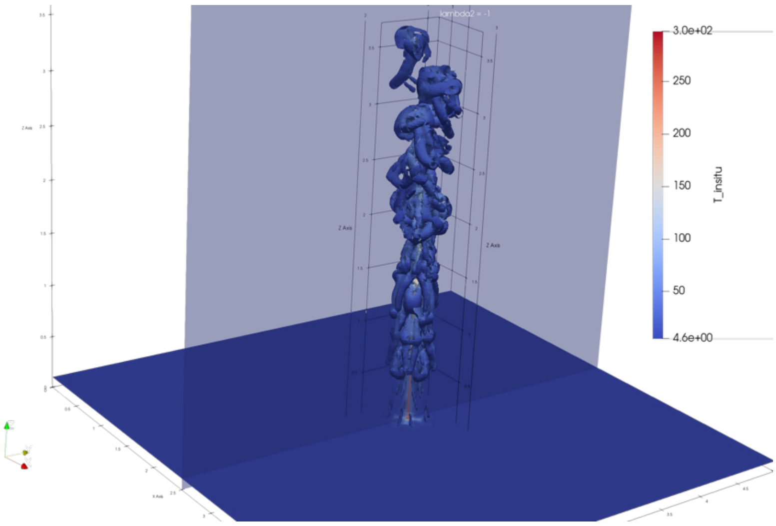


Figure 2: Snapshot of the $\lambda_2$ criterion for an isolated spring.

### B/ The Atlantic ocean at submesoscale-permitting resolution (GIGATL)

*This part of the project is led by J. Gula and G. Roullet, involves LOPS engineers G. Cambon and S. Theethen, and multiple national and international collaborations.*

This multi-year project is related to the ANR JCJC DEEPER (http://stockage.univ-brest.fr/~gula/Work/deeper.pdf). One goal of the project was to quantify the impacts of deep submesoscale processes and internal waves on mixing and water mass transformations. To this end, we needed a realistic simulation with high enough resolution to resolve (at least partially) submesoscale dynamics and internal waves, and with a large enough domain to fully contain the basin scale circulation. We have thus designed a configuration covering the full Atlantic ocean with the model CROCO at meso and submesoscale permitting resolutions (6 km, 3 km and 1 km) with realistic topography, high-frequency surface forcings and tidal forcings. The simulations are designed as GIGATL6, GIGATL3, and GIGATL1, respectively in the rest of the document. More information about the simulations can be found here: https://github.com/Mesharou/GIGATL.

Furthermore, to disentangle the role of internal waves versus submesoscale processes, and study the interactions between the two, we use additional experiments where sources of internal waves are switched off alternatively.

The bulk of the simulations has been run with past GENCI allocations and 3 companion projects: a PRACE proposal (20 million core hours on Joliot Curie – SKL active from April, 2019 to March 2020), a Grand-Challenge (40 million core hours on Rome, active from Dec., 2019 to July, 2020), and a special session in 2021. These included fully realistic versions of the Atlantic simulations with or without the tidal forcings.

### B.1/ Extending simulations and sensitivity runs

Part of the current GENCI allocation has been used to extend the runs and to generate a few months of a new simulation without high-frequency wind forcings, and thus with a low level of near-inertial waves. This sensitivity run is actually running and will use the remaining allocation on Irene ROME. It will then be useful to understand the impact of the near-inertial waves on the energy budget and the large-scale circulation.

We are also currently running additional sensitivity studies at low and intermediate resolution (6-km and 3-km) to better understand the impact of different numerical choices, including the vertical mixing parameterization (KPP versus $k - \epsilon$), on the large scale circulation. These simulations will use the remaining allocation on Irene SKL.

### B.2/ Evaluating the realism of the simulations

Different aspects of the simulations have been evaluated by comparing metrics at the surface, in the interior and at the bottom of the ocean (stratification, structure of the mean currents, mesoscale variability, internal waves energy levels, levels of mixing, etc.) to satellite and in-situ observations from global datasets (Argo, drifters and mooring databases) and available observations from regional experiments (OSNAP, RREX, MOMAR, etc.). Most of them are included in the related projects described in the dedicated subsections. An example comparison for frequency spectra agains observations (also including other models) at 2 moorings (Lucky Strike and OSMOSIS) is shown in Fig. 3.

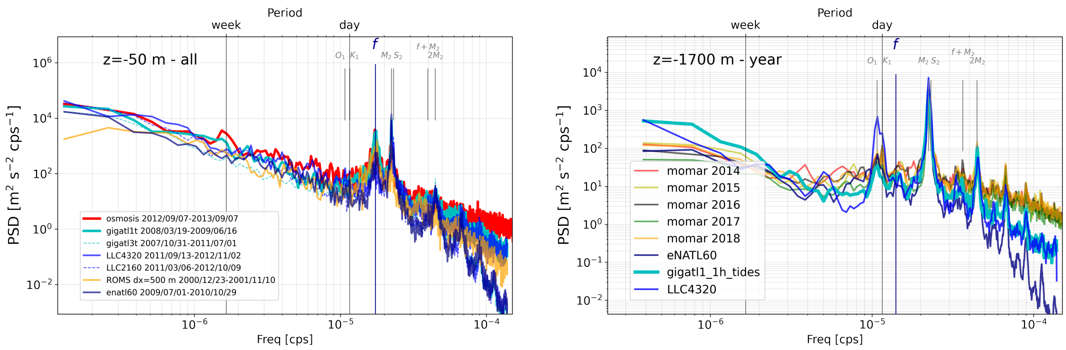


Figure 3: **examples of GIGATL - moorings comparisons**. Annual Frequency spectra of kinetic energy (left) at the Osmosis site, in the Northeast Atlantic, and (right) at the Lucky Strike site, over the Mid-Atlantic Ridge, from mooring observations (in red) and various numerical models, including GIGATL1 (in grey).

Another preliminary example showing eddy kinetic energy from observations (Altimetry and floats) and our Atlantic simulations at different resolutions (with or without tidal forcings) are shown in Fig. 4. The increase in horizontal and vertical resolution contributes to a more realistic structure for currents (in particular western boundary currents) with a more realistic eastward and downward extension. More detailed analysis are underway and will be the subject of a dedicated article describing the different simulations.

### B.3/ Intercomparing with other existing simulations

Data from GIGATL have been used in the **SWOT Adopt-A-Xover ocean model intercomparison study**, led by T. Uchida (IGE). This project included data from eight basin- to global-scale, submesoscale-permitting models to serve as a baseline for the upcoming SWOT observations during the fast-sampling phase. Several diagnostics have been performed (sea-surface height variability, submesoscale vertical buoyancy fluxes, and comparison to predictions from the mixed-layer instability parametrisation) for the different models, highlighting the large spread of results in the different models (Fig. 5). The project showcased the benefits of a cloud-based analysis framework to tackle such distribution and analysis challenges. A paper has been published in **Geoscientifc Model Development** in July 2022 (Uchida et al,

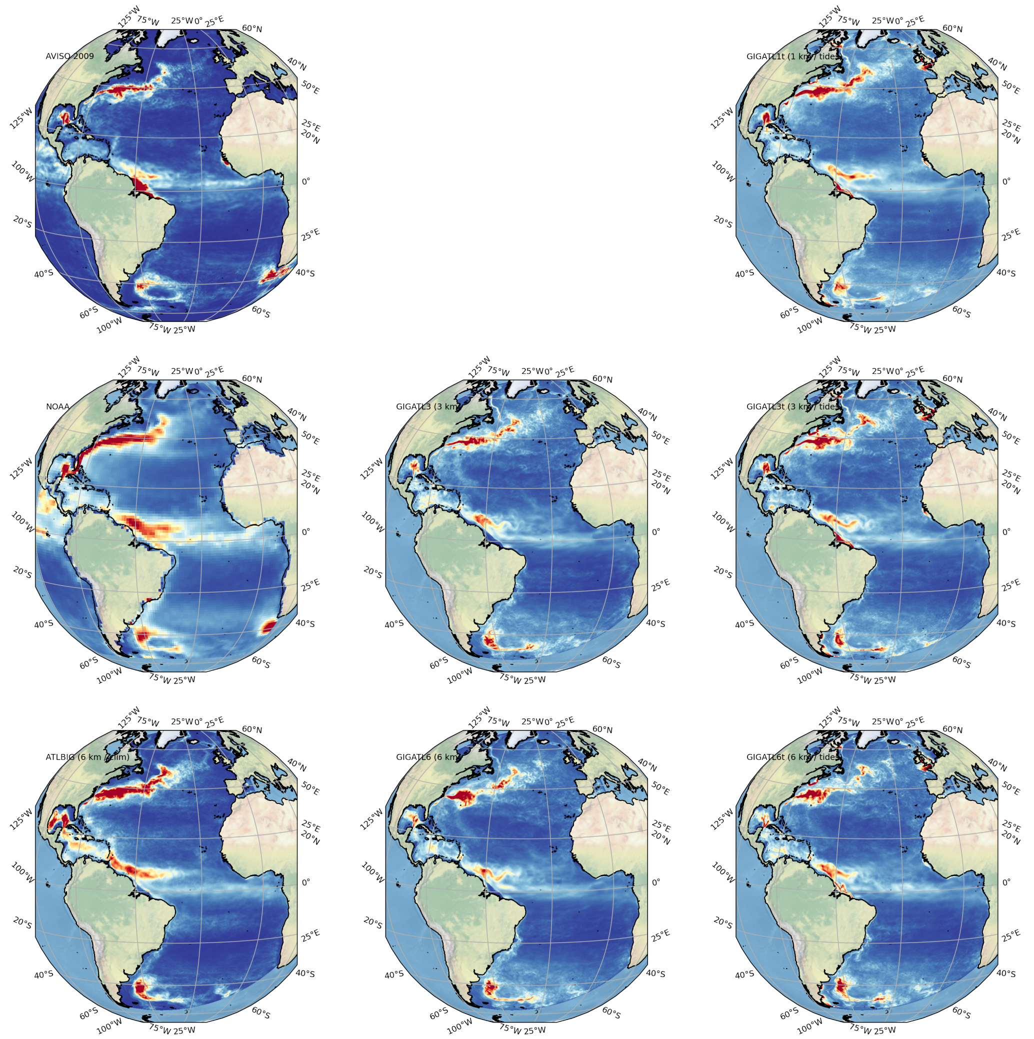


Figure 4: Eddy kinetic energy from altimetry (AVISO) in 2009, a climatology of surface floats (NOAA), and a variety of Atlantic runs at 6 km, 3 km and 1 km resolutions, with or without tides, for the year 2009.

2022, https://gmd.copernicus.org/articles/15/5829/2022/).

- **C/Bottom currents, energetics and processes.**

*This part of the project is led by R. Schubert (postdoc in the ANR DEEPER project) in collaboration with J. Gula, G. Roullet, C. Vic, X. Ruan, and J. Wenegrat.*

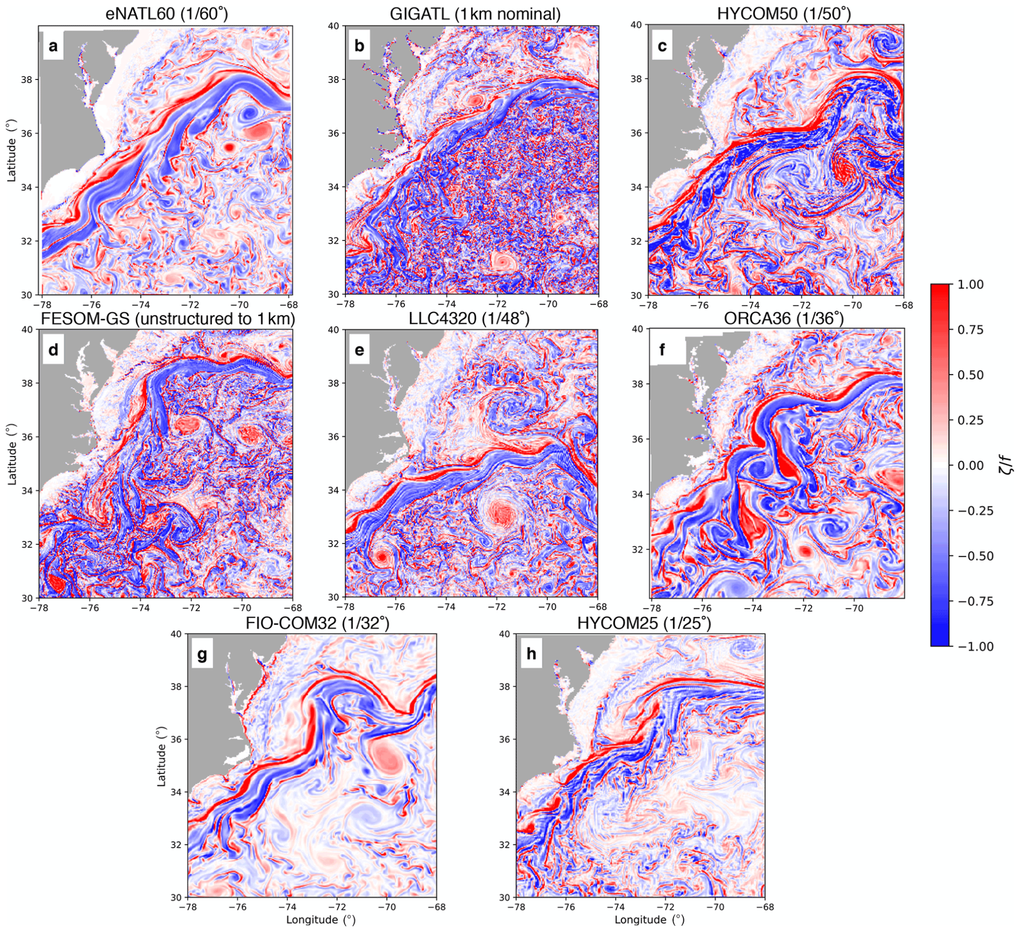


Figure 5: A snapshot of surface relative vorticity normalized by the local Coriolis parameter on 1 February at 00:00 from different models used in Uchida et al (2022)

Oceanic flows just above the sea-floor are important for the dissipation of oceanic kinetic energy, for driving the upwelling branch of the oceanic meridional overturning circulation, as well as for the transport of sediments, litter, heat, chemicals, and organisms. In particular, rare and strong near-bottom flows, referred to as benthic storms, lead to strong dissipation and transports. Not much is known about the role of near-bottom (sub-)kilometerscale flows for the bottom dissipation and the formation of benthic storms. The aim of this project was to use GIGATL data to resolve near-bottom (sub-)kilometerscale processes in the whole Atlantic, to disentangle their sources and formation mechanisms, to investigate their interactions with internal waves, deep mesoscale eddies and the large-scale circulation and to reveal their role for bottom dissipation.

A first study focused on bottom drag dissipation and the velocity structure near the bottom in the GIGATL3 simulation. It has highlighted that the combination of sloping topography and stratification can reduce the mean flow magnitude near the bottom (a process known as Ekman buoyancy arrest) and lead to an overestimation of bottom drag dissipation when considering (model or mooring) data that do not resolve this velocity structure. A paper has been published in Geophysical Research Letters in September 2021 (Ruan et al, 2021, `https://www.jgula.fr/Articles/RuanWenegratGula21.pdf`).

We are now focusing on quantifying the variability of bottom currents and disentangling the different sources of energy (internal tides, lee waves, deep-reaching mesoscale currents, submesoscale instabilities, topographic waves, etc.) in different parts of the Atlantic. We have compared model data from GIGATL3 to observations from moorings (Fig. 6) to perform a first validation and are currently applying it to GIGATL1.

- **D/Dispersal of hydrothermal iron dispersion over the Mid-Atlantic Ridge**

*This part of the project is led by C. Vic in collaboration with J. Gula, R. Williams (U. Liverpool), and A. Tagliabue (U. Liverpool).*

Iron is an essential micronutrient that governs the oceanic biological activity. In recent years, several research cruises unveiled the important role of hydrothermal vents as underwater iron sources. The FRIDGE UK-led project (PI: A. Tagliabue, `https://ga13fridge.wordpress.com`) aims at exploring the mechanisms that shape the ocean iron distribution and in particular the role of hydrothermal inputs from distinct vent sites along the ridge. Despite the extensive measurements carried out, surveyed areas are small compared to the gyre scale and uncertainties remain on the fate of iron. To complement the local view of iron spreading based on in situ observations, we ran numerical experiments of particle dispersion using the 3-D velocity outputs of GIGATL3. Particles were seeded in key sites that have been extensively sampled, Lucky Strike and TAG. Figure 7 shows the spreading of particles released at TAG after 8 months of advection by the currents. Particles mostly spread in the rift valley along the ridge and westward.

Our numerical results have been combined with in situ data to pro-

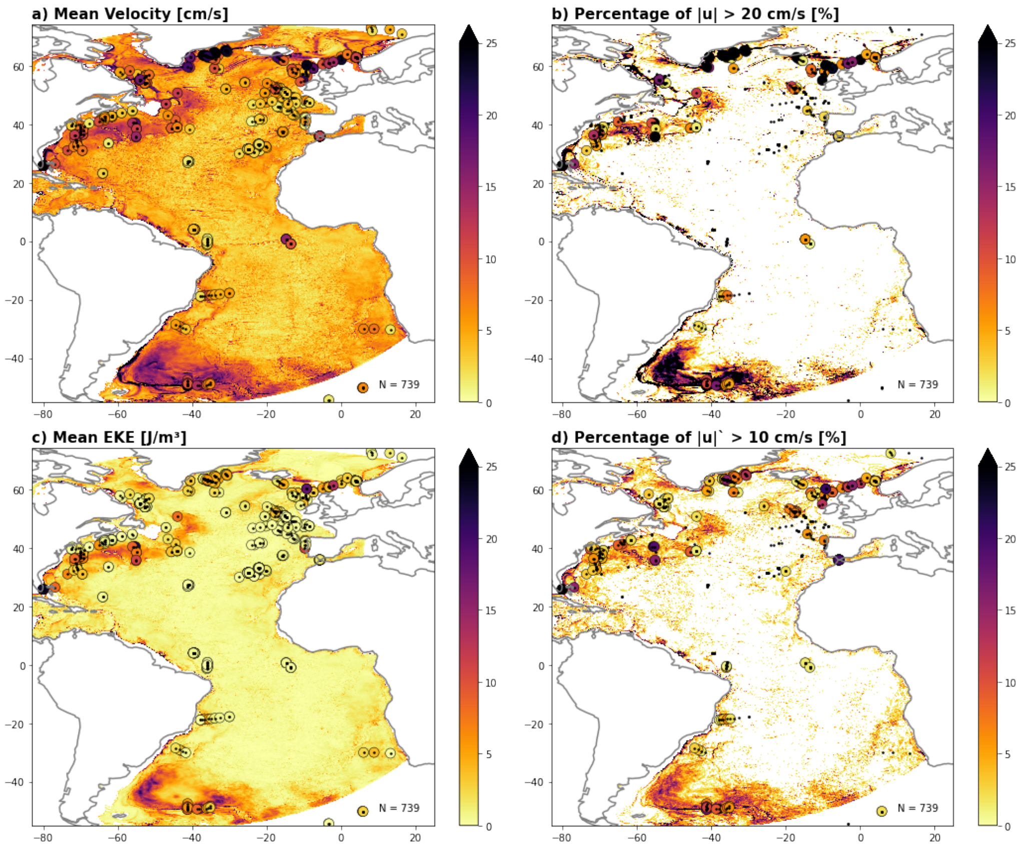


Figure 6: Time mean (a) bottom velocity and (c) bottom EKE from the GIGATL3 model (contours) and from the Global Multi-Archive Current Meter Database (colored circles). (b) and (d) show the probability for currents to reach thresholds of 10 and 20 cm/s (considered as strong bottom currents).

vide some large-scale dynamical context. The paper describing these results has now been submitted to JGR: *Mechanisms driving the dispersal of hydrothermal iron from the northern Mid Atlantic Ridge* by A. Tagliabue, A. Lough, C. Vic, V. Roussenov, J. Gula, M. Lohan, J. Resing, & R. Williams (`https://www.jgula.fr/Articles/Tagliabueetal22.pdf`).

- **E/ Mixing in the deep ocean**

### E.1/ Mixing and restratification in the bottom boundary layer

*This part of the project is led by G. Zerbini, PhD student supported by an PhD grant from the ANR project DEEPER (PI: J. Gula). She is supervised*

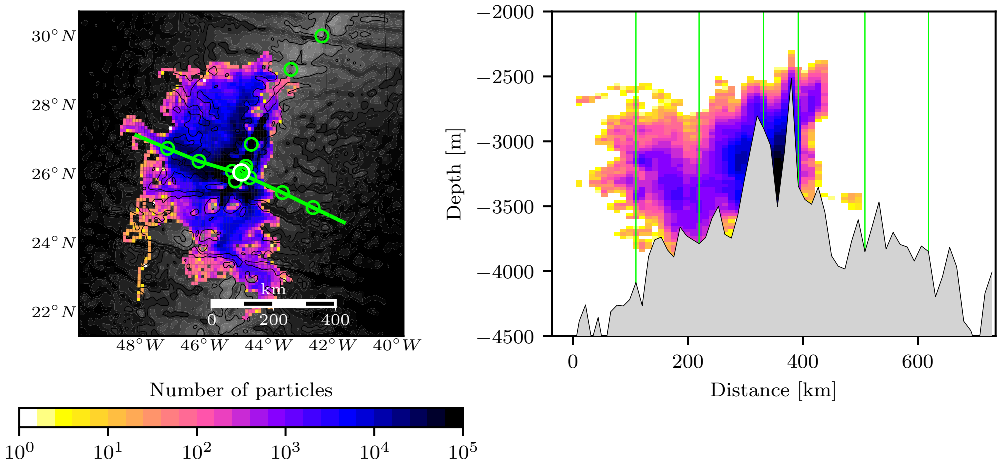


Figure 7: (left) Horizontal distributions of particles after 8 months of spreading from TAG hydrothermal vent site (white circle). Green circles represent the location of in situ data collected by the FRIDGE project. (right) Vertical section through of particle distribution along the green line in left panel.

*by J. Gula and C. Vic.*

The bottom boundary layer (BBL) of the ocean hosts a rich yet sparsely documented phenomenology of turbulent processes arising from the interaction of currents with the seafloor topography. While internal wave breaking drives cross-density mixing, submesoscale instabilities can both drive mixing and restratification, as well as cross-isobath exchanges. The coexistence and interactions of these processes are thought to shape the BBL with important consequences on the spreading pathways and lifecycles of tracers. However, the dynamics of the BBL are still poorly understood and investigations are needed to clarify their role, in order to further parametrise their effects in climate-scale models, which are not aiming to resolve them in a near future. In this work, we aimed at characterising the BBL dynamics throughout the Atlantic Ocean using GIGATL simulations and nests. As a first step, we conducted a systematic comparison of the model BBL with CTD-derived BBL through repeat hydrographic sections (see an example along the OVIDE section in Fig. 8). This will allow us to map the different dynamical regions where the model satisfactorily reproduces the BBL vs where unmodelled processes are missing to accurately represent the BBL. We will then try to characterise dynamical regimes and diagnose mixing and dissipation in the BBL in the different regions of the Atlantic.

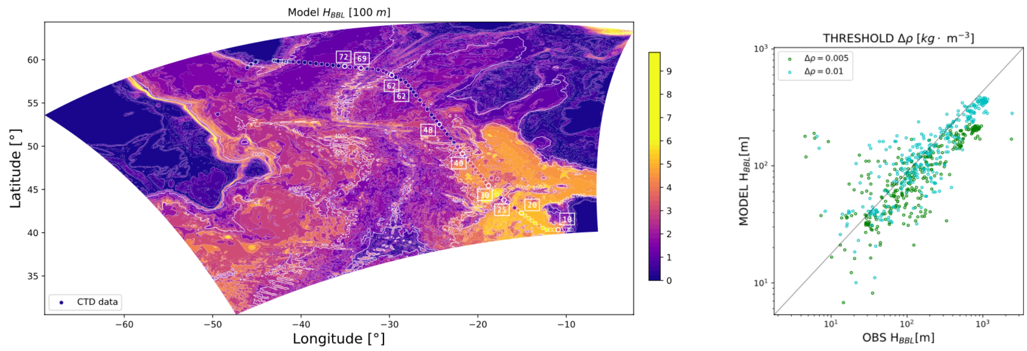


Figure 8: (left) Bottom boundary layer depth ($H_{BBL}$) computed using a density threshold method from GIGATL 3 (contours) and from CTD sections (colored circles). (right) Scatterplot for modelled and observed $H_{BBL}$.

### E.1/ Spreading and mixing of tracers in the deep ocean

*This part of the project is led by Noémie Schifano, PhD student supported by a PhD grant from the École Normale Supérieure. She is supervised by J. Gula and C. Vic.*

This part of the project specifically addresses the physical and numerical aspects of tracer dispersion and mixing in the deep ocean. Small-scale turbulence in the ocean impacts the pathways and spreading patterns of tracers. Notably, turbulence leads to irreversible mixing through density surfaces, called diapycnal mixing. Diapycnal mixing intensity is often parametrised through the diffusivity coefficient $\kappa$. Direct estimates — such as Tracer Release Experiments (TREs) and microstructure measurements of oceanic variables — and indirect estimates of diapycnal mixing have revealed different regimes of turbulence associated with a wide range of $\kappa$, from 1e-6 $m^2/s$ in the quiescent interior to 1e-3 $m^2/s$ near turbulent boundaries. Although the global mapping of $\kappa$ has significantly progressed, the representation of diapycnal mixing in numerical models remains arduous. Indeed, while diapycnal mixing is parametrised through dedicated schemes ("physical mixing"), numerical errors also lead to unphysical mixing ("numerical mixing").

Here, we set up numerical TREs in a submesoscale-resolving realistic simulation over the Reykjanes Ridge using a primitive-equation model (CROCO) to investigate the impact of the numerics on the diapycnal diffusivity experienced by a passive tracer released in the thermocline. Specifically, we have tested the sensitivity of the tracer spreading to the number of vertical levels, and to different horizontal and vertical advection schemes (3rd and 5th order upstream biased and weighted essentially non-oscillatory), see Fig. 9. We found that employing 100 vertical levels with a 3rd order horizontal advection scheme, as typically used in regional simulations, leads to spurious diapycnal mixing in places of large tracer gradients. Increasing the number of levels to 200 efficiently reduces spurious mixing at a modest computational cost. We further combined different schemes with different vertical grids to find an optimal set up featuring the lowest numerical diffusion.

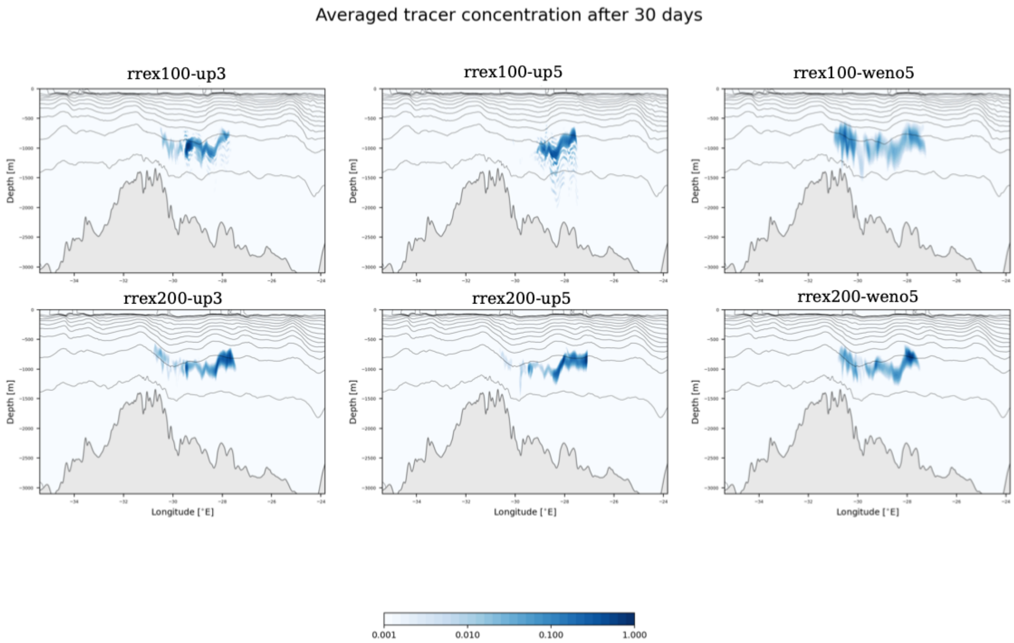


Figure 9: Averaged tracer concentration after 30 days in different sensitivity experiments using 100 or 200 vertical levels, with advective tracer schemes UP3, UP5 or WENO5

- **F/ Turbulence and mixing in the wake of seamounts**

*This work is an ongoing collaboration with A. Mashayek, L. Baker (Imperial College London), L. Cimoli (SCRIPPS), A. Naveira-Garabato (NOCS), and Jim Riley (U. of Washington).*

Ocean turbulent mixing exerts an important control on the rate and structure of the overturning circulation. Recent observational evidence suggests, however, that there is a mismatch between the observed intensity of mixing integrated over basin or global scales, and the net mixing required to sustain the overturning's deep upwelling limb. The aim of this project was to investigate the hitherto largely overlooked role of tens of thousands of seamounts in resolving this discrepancy. Dynamical theory indicates that seamounts may stir and mix deep waters by generating layered vortical motions and/or topographic lee waves, with the layered vortex regime prevailing at low latitudes. We have thus considered different case studies (in the equatorial zone, Southern Ocean and Gulf Stream) that are predicted by theory to be representative of, respectively, a layered vortex, topographic lee wave and hybrid regimes, to corroborate theoretical scalings of mixing in each case with a realistic regional ocean model. We have then applied scalings to a global seamount dataset and an ocean model climatology to show that seamount-generated mixing makes a leading-order contribution to the global upwelling of deep waters.

GIGATL3 data in particular have been used to come up with a climatology of bottom currents and stratification in the Atlantic, which has been compared with global outputs from the LLC4320 MITgcm model in the process. Then two of the regional simulations have been realized with the model CROCO using GIGATL3 outputs to provide initial and boundary data in order to create the two test cases for the Gulf Stream and the Equatorial Atlantic (Fig. 10). The Gulf Stream simulation has $dx = 500$ m with 256 vertical levels. It has further been repeated with 3 different types of vertical mixing parameterization (KPP and 2 variations of $k-\epsilon$) to ensure the robustness of the vertical mixing estimates. The equatorial simulation has $dx = 750$ m with 300 vertical levels. This second nest simulates an environment with large Rossby and Burger numbers, prone to the generation of layered vortices. Our first paper on the subject is now in revision for Nature Geoscience (Mashayek et al, 2022, `https://doi.org/10.21203/rs.3.rs-939198/v1`).

- **G/ Submesoscale coherent vortices in the Atlantic.**

*This part of the project is the PhD of A. Chouksey, 2019-2023, supervised by J. Gula and X. Carton.*

This study focuses on the detection and characterization of Submesoscale Coherent Vortices (SCVs) in the Atlantic. We aim to quantify their physical characteristics (radius, bias in polarity: cyclonic SCVs versus anticyclonic SCVs, Rossby number, etc.) in different regions of the Atlantic ocean, and

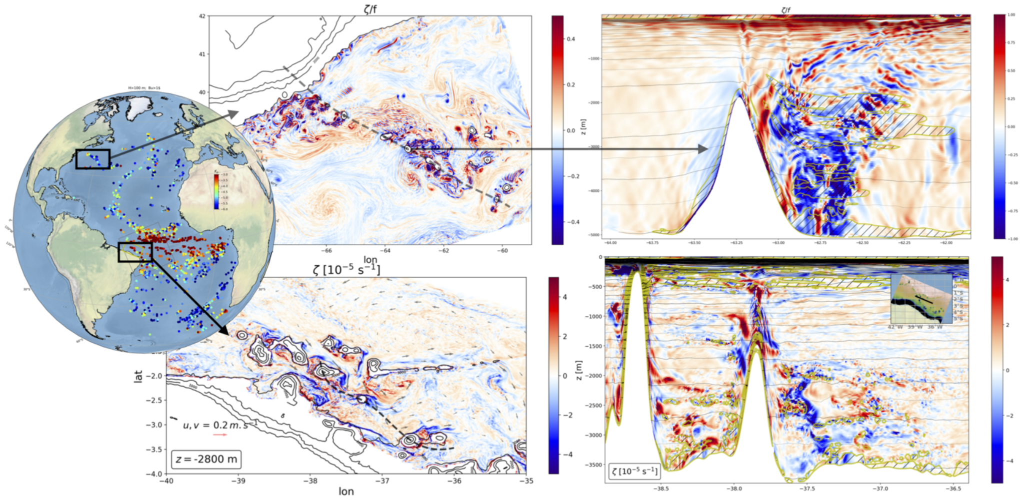


Figure 10: **Mixing induced by seamounts wakes**. Snapshots of relative vorticity at 2800 m depth (left) and along a vertical section aligned with the flow (right) for 2 submesoscale resolving CROCO simulations of the New-England seamounts (top) and of the western equatorial Atlantic (bottom). High levels of diffusivity in the model are shown as green dashed areas.

analyze the dynamics involved in the generation and destruction of the SCVs throughout their life-cycle.

We have used the GIGATL6 and GIGATL3 simulations and adapted an eddy-tracking algorithm (py-eddy-tracker) to detect and track SCVs using the Okubo-Weiss parameter along different isopycnals. There is a dominance of cyclonic SCVs when considering the short-lived structures, whereas long-lived and longer distance travelling SCVs are dominated by anticyclonic SCVs (Fig. 11). A paper is about to be submitted (Chouksey, Carton & Gula, in prep).

- **H/ The submesoscale kinetic energy cascade.**

*This part of the project is led by R. Schubert (postdoc in the ANR DEEPER project) in collaboration with J. Gula, G. Roullet, C. Vic, and Jim McWilliams group (UCLA).*

In this project, we investigate how the (sub)mesoscale dynamics play a role in fluxing energy across scales using spectral and coarse-graining methods. We have recently used these methods to characterize kinetic energy cas-

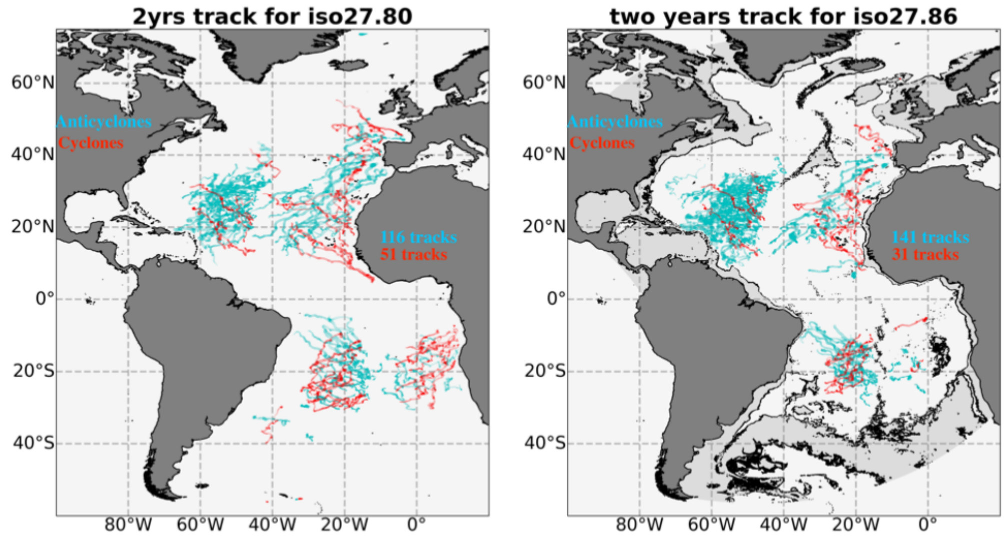


Figure 11: Trajectories of long-lived (> 2 years) deep SCVs on isopycnals 27.8 and 27.86, which lie in the depth range of 1200-3000 m, and 1800-4000 m respectivel, from 5 years of GIGATL3. See also https://vimeo.com/416610450 for animations.

cade in the Agulhas Current (Schubert et al, 2020) and highlighted the role played by submesoscale structures. In particular the submesoscale mixed-layer eddies generated in winter induce an upscale flux of energy contributing to a significant energization of the mesoscale eddies later in the year, while a strong direct cascade toward dissipation occurs in the frontogenetic regions. However, intensity of the cascades and the spatial scales at which they switch direction highly depends on the region and season.

On the basis of AVISO and GIGATL, we have shown that the total geostrophic inverse scale kinetic energy flux is linearly related to quantities that are computable from along-track altimetry. This linear relationship can now be used to estimate for the first time the submesoscale inverse kinetic energy cascade, as well as its regional distribution and seasonal cycle for large parts of the global ocean (Fig. 12). An article is in preparation.

We have also studied the role of internal waves (internal tides and near-inertial waves) on the kinetic energy cascade. Using simulations with or without sources of internal waves, we have found that solutions including waves have 25% less mesoscale KE compared with solutions without waves. We have applied a coarse-graining method to quantify the KE fluxes across

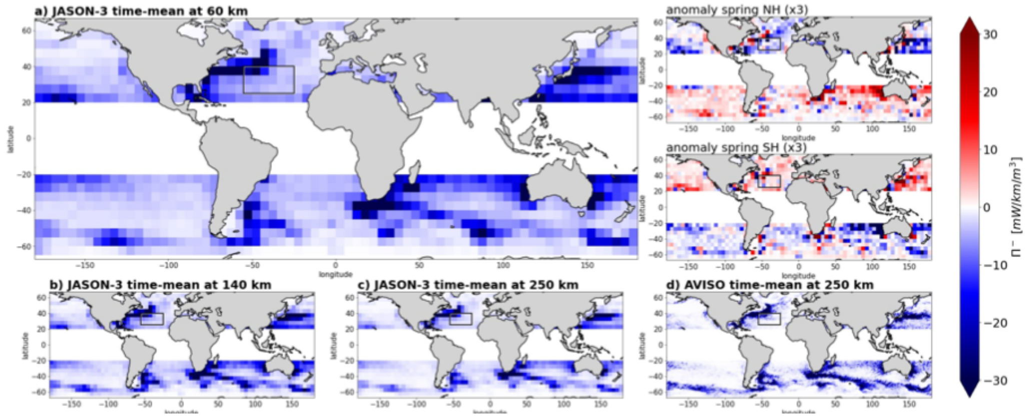


Figure 12: Amplitude of the inverse energy cascade computed as the coarse-grained surface geostrophic scale kinetic energy flux through a particular scale (60, 140, or 250 km), estimated from along-track altimetry data or from gridded altimetry data.

time scales and demonstrated that the decrease in mesoscale KE is associated with an internal wave-induced reduction of the inverse energy cascade and an enhancement of the forward energy cascade from sub-to super-inertial frequencies. The integrated KE forward transfer rate in the upper ocean is equivalent to half and a quarter of the regionally averaged near-inertial wind work in winter and summer, respectively, with the strongest fluxes localized at surface submesoscale fronts and filaments. A paper has been published in Geophysical Research Letters in September 2021 (Barkan et al, 2021, https://www.jgula.fr/Articles/Barkanetal21.pdf).

- **I/ Meso and submesoscale dynamics in the Northwest Tropical Atlantic.**

*This part of the project is included in the project EUREC4A-OA (Improving the representation of small-scale nonlinear ocean-atmosphere interactions in Climate Models by innovative joint observing and modelling approaches, PI: S. Speich), funded by JPI-Oceans. A new Masters Student has been involved in the project in 2022, a postdoctoral student (Dante Napolitano) has been hired in August 2022.*

Air-sea exchange of heat, freshwater and constituents is controlled by a multitude of physical, biogeochemical and biological processes that vary in importance by region but also in time. The EUREC4A-OA project seeks to advance our understanding of ocean-atmosphere exchanges and fluxes between the surface and the interior of the ocean at small-scale by two complementary approaches: 1) by compiling an unprecedented set of observations of, in parallel, the ocean, the atmosphere and their exchanges at the ocean small-scale and 2) by combining the observations with a large hierarchy of ocean and ocean- atmosphere coupled models for exploring the nature of air-sea interactions and ocean dynamics at these scales. The EUREC4A field campaign took place in Feb 2020 over the Northwest Tropical Atlantic, near Barbados (www.eurec4a.eu).

We have been using GIGATL outputs (at 6 km, 3 km, and 1 km) to tackle different aspects of the meso- and submesoscale dynamics and their interaction with Near-Inertial Waves (NIW) and the Amazon river plume in this region in the context of several Masters internships. The M2 internship of L. Eisenring in 2021 (*Eddy analyses in the EUREC4A-OA region using HR simulations, with emphasis on submesoscale structures in Demerara Bay*) has led to the writing of a paper on the formation of deep submesocale coherent vortices, which is currently in preparation. A new internship by J. Lambert (M2) focused on the analysis of the North Brazil Current rings and their interactions with the topography using GIGATL1 outputs and Lagrangian studies (Fig. 13).

**• J/ Impacts of meso- and submesoscale currents on the distribution of floating macro- and microplastics**

*This part of the project is a collaboration between J. Gula, C. Vic, T. Huck, and C. Maes (LOPS), and was the subject of the M2 internship of S. Hascoet in 2021*

Submesoscale motions (0.1 to 10 kilometres) are associated with sharp gradients in flow properties such as currents and density, corresponding to marked convergence and divergence zones. As a result, they are believed to play an important role in the transport of tracer. In this project we investigated, thanks to 1-km and 6-km simulations of the Atlantic Ocean, the role of meso- and submesoscale structures in the repartition of plastic floating debris, modelled as buoyant tracers following the surface flow.

We have performed numerous Lagrangian particles experiments and used an eddy tracking algorithm to study the impact of mesoscale structures on the concentration of floating particles (Fig. 14). We have found that cyclonic

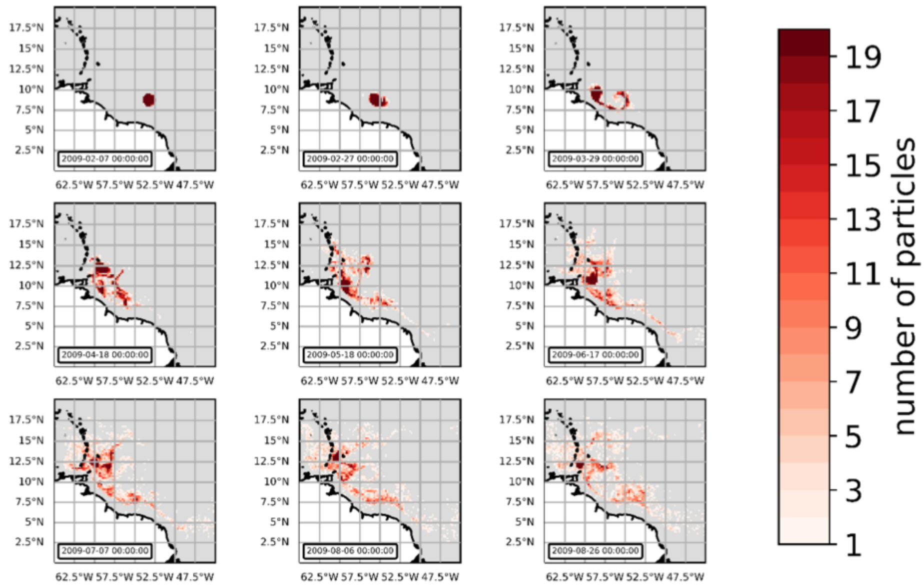


Figure 13: Density of Lagrangian particles released in the core of a NBC ring in the GIGATL1 simulation.

eddies tend to concentrate more particles than anticyclonic ones (around 20% more), and this difference in concentration exists since the first detection of eddy contours. Experiments have been performed on the scale of the Atlantic with outputs from the GIGATL6 simulation. An article has been published in Geophysical Research Letters (Vic et al, 2022, https://www.jgula.fr/Articles/VicHascoetGulaHuckMaes22.pdf).

## • K/ Impact of the meso and submesoscale dynamics on Carbon export

### K.1/ Impact of the mesoscale dynamics on the fate of exported particles in the deep ocean

*This part of the project is a continuing work related to the PhD project of Lu Wang, supervised by L. Memery (LEMAR) and J. Gula (LOPS), from 2019 to 2023*

The aim of the project is to study the impact of the fine scale ocean dynamics on the export flux and the fate of carbon throughout the water

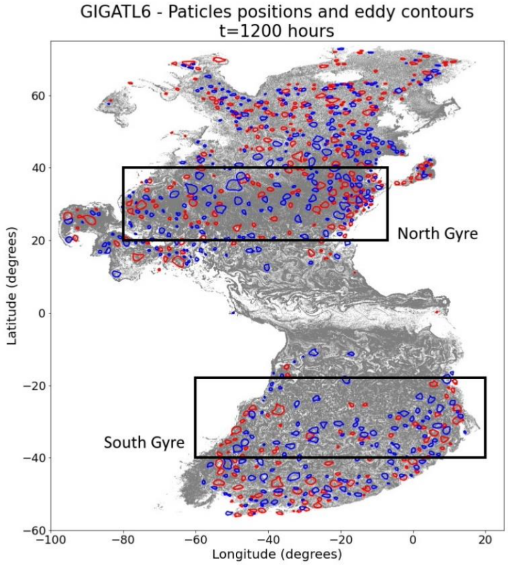


Figure 14: Particles positions and eddy contours at t=1200 hours (50 days) after the beginning of a 2 months Lagrangian experiment starting on 23 May 2008. Particles positions are shown as grey dots. Cyclonic eddy contours are blue contours while anticyclonic eddy contours are red contours. In this figure, eddy contours were detected using SSH. We can see the Equator region emptying due to the effect of the Ekman divergence, and particles accumulation begin in the North Gyre mainly.

column by connecting the downward flux of gravitationally sinking particles sampled by deep-ocean sediment traps with the surface particle sources. This work is also a preparation for the APERO (Assessing marine biogenic matter Production, Export and Remineralisation : from the surface to the dark Ocean) campaign that is planned to happen in the Porcupine Plain in 2023, as it is used to evaluate the sampling strategy that will be put in place during the campaign.

The first part of this work has focused on the role of mesoscale dynamics in the source area and subsurface transport of particles in the eddy field. The meso- and submesoscale currents play an important role as they not only create a very strong heterogeneity on the particle production at the surface, but they also drive horizontal and vertical velocities that impact exchanges between the surface layer and the ocean interior. Backward Lagrangian simulations have been used to construct the source funnels of particles sampled in traps (Fig 15). Also, diagnostics of physical parameters computed along particle trajectories have been performed to relate particle transport with specific dynamical features (fronts/filaments, cyclones, anticyclones). An article has been published in Journal of Geophysical Research (Wang et al, 2022, https://www.jgula.fr/Articles/WangGulaCollinMemery22.pdf). The production of higher-resolution (up to dx = 200 m) in the Osmosis region will be realized in late 2022 as planned in last years's proposal.

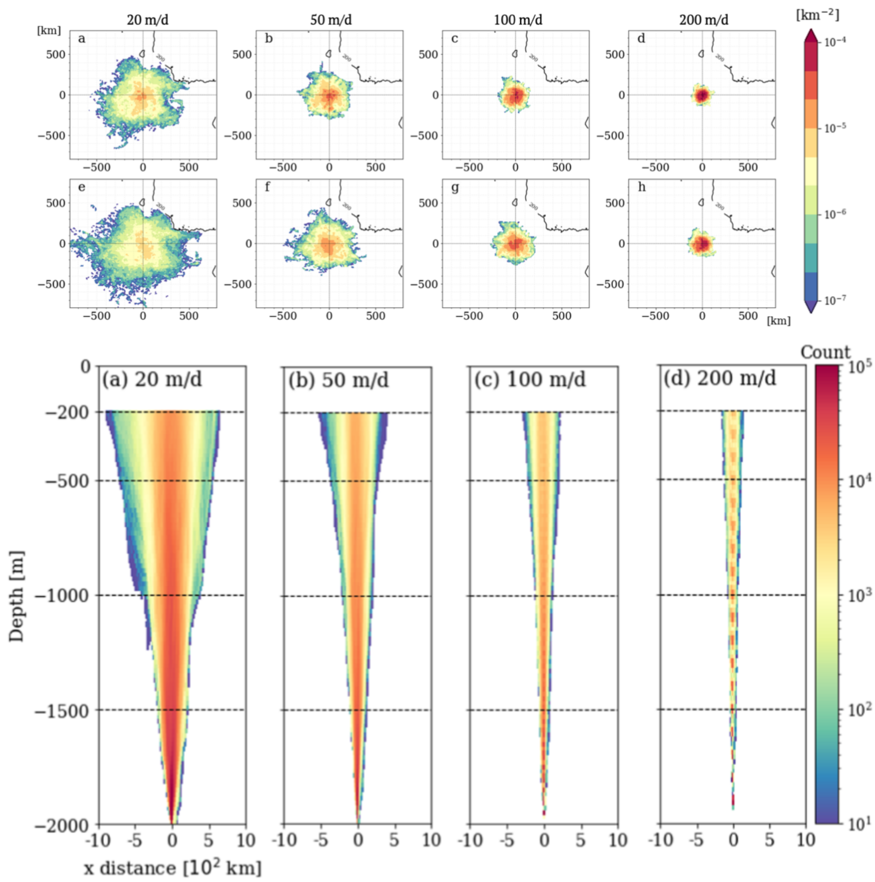


Figure 15: (top) Probability density of particles collected by the moored sediment traps over the period of seven years (2002 - 2008), for different sinking velocity and two trap depths (a-d, 1000m; e-h, 2000 m). Particles are backtracked until they reach above 200 m. (bottom) Integrated trajectories of particles released from 2000 m, projected on the zonal section.

### K.2/ Impacts of submesoscale fronts on Carbon Export

*This part of the project was the topic of a M2 internship by Théo Picard* *supervised by C. Vic and J. Gula (LOPS) in 2021.*

The aim of this project was to quantify the impact of meso- and submesoscale currents on generating vertical tracer fluxes between the mixed-layer and the interior of the ocean. We have used again GIGATL3 to force a new nest at 800-m resolution with 200 vertical levels (including versions with and without tides) covering the region of the Reykjanes Ridge and Iceland Basin. We have released passive tracers at different depths (at the surface and just below the mixed-layer) to study the vertical dispersion of the tracer and used online tracer budgets to evaluate the role of mixing and advection. Preliminary results are highlighting the importance of submesoscale frontogenetic regions with positive vorticity and high strain, in driving intense negative fluxes of tracer (Fig. 16). A detailled budget of tracer has been performed this year. A paper is currently in preparation (Picard et al, "Seasonal tracer subduction in the Subpolar North Atlantic driven by submesoscales", in prep.).

### K/ numerical developments related to GIGATL

The GIGATL project has produced a huge amount of data, of the order of 4.5 PB (Peta bytes). It is a formidable database to study many problems in physical oceanography. But to be really capable of roaming through this database, we had to develop new tools. The offline tools that we were using so far (crocotools) were insufficient to tackle this volume of data.

In our A9 summary we end up with a better data format. During A11 we have converted most of the database into this new format. To recall, the basic format we had was tar files containing of the order 1500 netcfiles each. Each tar file, corresponding to one day of one of the 13 regions of the whole domain, was roughly 350 GB. One experiment in the database has about 5000 of these tar files (365 days times 13 regions). The new format replaces each tar file with a binary direct access file. With this data format, any single float at a given grid cell, at a given time, can be accessed via one open, one seek and one read. Furthermore, the reading can be multithreaded (12 threads seems a good number). The result is that, provided the files are on disks (and not migrated on tape), we achieve a sustained throughput of 3 GB/s between the storedir and the cpu.

As it is stored now, GIGATL is essentially a 8 dimensional database with 1 dimension for the nature of the variable (u,v,T,S etc), two dimensions for the time (day, hour), and 5 dimensions for the space (region, tile, k, j, i). The *tile* is the native computational subdomain (there are 6552 of them in

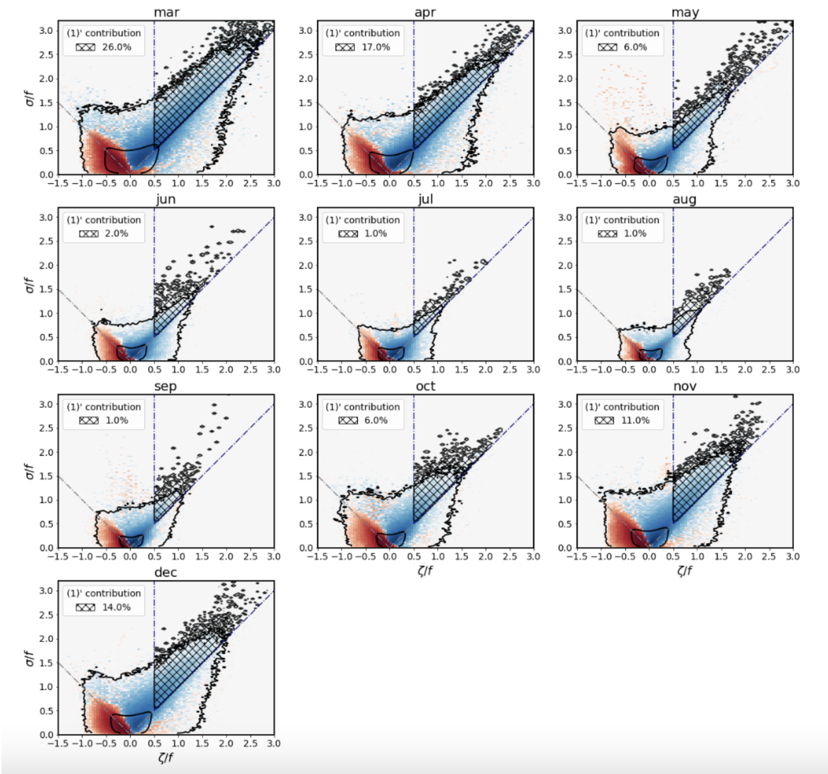


Figure 16: Monthly integrated vertical transport of tracer $wC$ at the mixed-layer base in a surface vorticity-strain space.

the whole domain). A 3D tile is a $100 \times 140 \times 104$ array. The basic read instruction is to read a whole tile of a given variable at a given time. This is a super fast operation.

During this allocation, we have also developed a set of Python tools to tackle this particular chunking of the data. They are fast and run in parallel. The main novelty, compared for instance to the Pangeo tools, is the data structure. Instead of working with large arrays obtained by gluing several tiles, we perform all computations at the scale of a tile. Therefore the ad-hoc data structure is a dictionary of tiles!

Thanks to these tools, we are now able to fully exploit the capabilities of GIGATL.

This development did not consume significant computational time. But access to Irene was absolutely decisive in developing these tools. The database is on the storedir, and because of its size, it can not be transferred elsewhere.

**Published articles**

- Barkan, R., K. Srinivasan, L. Yang, J.C. McWilliams, J. Gula & C. Vic (2021): Oceanic mesoscale eddy depletion catalyzed by internal waves, Geophys. Res. Lett., https://doi.org/10.1029/2021GL094376
- Ruan, X., J. Wenegrat & J. Gula (2021): Slippery bottom boundary layers and the loss of energy from the general circulation by the bottom drag, Geophys. Res. Lett., https://doi.org/10.1029/2021GL094434
- Roullet, G., & Gaillard, T. (2022) : A fast monotone discretization of the rotating shallow water equations. Journal of Advances in Modeling Earth Systems, 14(2), e2021MS002663.
- Uchida, T., Le Sommer, J., . . . , J. Gula, G. Roullet, R. Schubert, . . . , A. (2022) : Cloud-based framework for inter-comparing submesoscale-permitting realistic ocean models. Geoscientific Model Development, https://doi.org/10.5194/gmd-2022-27
- Vic, C., S. Hascoet, J. Gula, T. Huck & C. Maes (2022): Oceanic mesoscale cyclones cluster surface Lagrangian material, Geophys. Res. Lett., https://doi.org/10.1029/2021GL097488
- Wang, L., J. Gula, J. Collin & L. Memery (2022): Effects of mesoscale dynamics on the distribution and transport of gravitationally sinking particles to the deep ocean, J. Geophys. Res., https://doi.org/10.1029/2022JC018799

**Articles in revision / submitted**

- Mashayek, A., J. Gula, L. Baker, L. Cimoli, A. Naveira Garabato & J. Riley: Mountains to climb : on the role of seamounts in the ascent of deep ocean waters, in revision for Nature Geoscience. https://doi.org/10.1002/essoar.10512044.1
- Tagliabue, A., A. Lough, C. Vic, V. Roussenov, J. Gula, M. Lohan, J. Resing, & R. Williams, Mechanisms driving the dispersal of hydrothermal iron from the northern Mid Atlantic Ridge, submitted, https://doi.org/10.1002/essoar.10512044.1

**Conferences and posters**

- Dialogues on Boundary Systems : #5 : Gulf Stream. Oral (invited) by J. Gula, Oct. 06, 2021, GOOS Physics and Climate panel Webinar series.

- Study of Submesoscale Coherent Vortices (SCVs) in the Atlantic Ocean along different isopycnals. Oral by A Chouksey, Dec. 14, 2021, AGU Fall Meeting, San Francisco, USA.

- Spreading of a passive tracer in a numerical model: implicit versus explicit mixing, Poster by N. Schifano, June 6, 2022, Ocean Mixing Gordon Research Conference, South Hadley, MA, United States

- Validation of realistic Atlantic Ocean model with CTD data, Poster by G. Zerbini, June 6, 2022, Ocean Mixing Gordon Research Conference, South Hadley, MA, United States

- Seasonal tracer subduction driven by submesoscales, Poster by T. Picard, June 6, 2022, Ocean Mixing Gordon Research Conference, South Hadley, MA, United States

- Deep Coherent Vortices in the Atlantic Ocean. Oral by A. Chouksey, Aug. 29, 2022, FilaChange international conference, Paris France.

- Estimating the Submesoscale Inverse Kinetic Energy Cascade From Along-Track Altimetry. Poster by R. Schubert, Aug. 29, 2022, FilaChange international conference, Paris France.

- Fine-scale ocean structures in the Tropical Atlantic from observations and modeling. Poster by D. Napolitano, Aug. 29, 2022, FilaChange international conference, Paris France.

- Dépasser NetCDF pour analyser des centaines de TB sur architecture LUSTRE par G. Roullet, journées du PNTS, avril 2022