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Submesoscale coherent vortices in the Atlantic and their impact on the large scale circulation

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Summary:
Ocean eddies contribute significantly to global fluxes of heat, salt, carbon and biogeochemical tracers. Surface intensified mesoscale eddies, with radii larger than the Rossby deformation radius (30-200 km), have been studied extensively using altimetric observations. However, we know much less about the contribution of subsurface eddies, particularly submesoscale (1-30 km) subsurface eddies due to the sparsity of in situ observations. Observations and high resolution models provide glimpses of the ocean interior richness and suggest that it is populated by a large number of deep submesoscale coherent vortices (SCVs). SCVs are long-lived energetic eddies, which can generate long-range anomalous transport of water properties and biogeochemical tracers. However, a global census of the SCVs and their impact on the global circulation is still lacking. Furthermore, climate-scale ocean models do not resolve submesoscale motions, understanding and parameterizing these phenomena within models is critical for a better prediction of climate.

The aim of this project is to provide the first census of SCVs in the Atlantic Ocean and quantify their impact on the large scale circulation using in situ observations from moorings, gliders and Argo floats, and a new realistic submesoscale resolving simulation of the full Atlantic ocean. In addition, the project will investigate the processes responsible for the generation and destruction of the SCVs, and for their propagation. Finally, it will also tackle a long standing question in oceanography: why are there more submesoscale anticyclones than cyclones in the interior ocean?

Introduction:
Submesoscale oceanic currents arise in the form of density fronts and filaments, coherent vortices, and topographic wakes (McWilliams, 2016). They are found at spatial scales below the first Rossby deformation radius (0.1-30 km). A particular type of submesoscale structures are submesoscale coherent vortices (SCVs, see example Fig. 1). They are long-lived energetic eddies with a structure localized in the vertical and an interior velocity maximum (McWilliams, 1985).

SCVs can be very long-lived (> 1 year) and travel far away from their origin, being primarily advected by mesoscale and mean currents. As SCVs retain much of their core water mass during their life, they can generate long-range anomalous transport of water properties. The cumulative effect of SCVs can potentially affect the large scale transport and distribution of heat, nutrients and other materials.

Figure 1: Generation of an anticyclonic SCV in the lee of the Charleston Bump observed in a glider section. The SCV is visible as a lens of well-
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SCVs have been observed in most regions of the global ocean and in particular in the Atlantic ocean. One of the most well-known type of SCVs are the Meddies formed at the exit of the Mediterranean Sea (Bashmachnikov et al., 2015), which spreads salty Mediterranean waters in the subtropical Atlantic ocean. SCVs also form in eastern boundary regions where poleward undercurrent flows along the slope, like the West African upwelling (Pietri & Karstensen, 2018). These SCVs are essential to redistribute properties from the eastern boundary upwelling regions into the open ocean, and in particular spread the oxygen-poor and nutrient-rich waters into the interior of gyres (Frenger et al., 2018). More generally SCVs can be generated by interaction of boundary currents with topography. Such SCVs have been sampled at the exit of the Labrador Sea (Bower et al., 2013). SCV are also generated in the deep ocean, where the geostrophic currents interact with the Mid-Atlantic ridge, and play a role for the dispersion of biogeochemical materials (Vic et al., 2018).

Historical observations of SCVs provide glimpses of the ocean interior richness, and suggest that it is populated by a large number of deep submesoscale structures, but the ocean is still largely undersampled and observational data remains limited. Furthermore, global or basin-scale models do not usually have a resolution sufficient to resolve submesoscale processes. Thus, we still do not have a quantitative assessment of the numbers and impact of SCVs for the ocean circulation.

Furthermore, observations show a larger number of anticyclonic SCVs than cyclonic SCVs, but the reason why anticyclones dominate over cyclones is still an unresolved issue (McWilliams, 16). We do not know if it is related to an asymmetry of the generation processes or to different stability properties of the SCVs after their formation. Quasi-geostrophic theory does not predict any asymmetry between cyclones and anticyclones related to the generation process, nor their stability. The generation of vortices in the lee of topography is also symmetric and does not explain the dominance of anticyclones (Fig.2).

Objectives:
The aim of this project is to provide the first census of the SCVs in the Atlantic Ocean using in situ observations from moorings and Argo floats, and a new realistic very high-resolution simulation of the full Atlantic ocean. More precisely, the objectives are to identify the processes responsible for the generation and destruction of the SCVs, quantify their impact on the large scale circulation, and answer more fundamental questions such as: why are there more submesoscale anticyclones than cyclones in the interior ocean?

Data and Methods:
To achieve the aim of this project we will use observations from moorings and Argo buoys, and high-resolution model simulations.

Moorings: We plan to analyze all publicly available mooring datasets in the Atlantic from the Global Multi-Archive Current Meter Database, including recent data provided by the OSNAP/RREX (Overturin in the Subpolar North Atlantic) mooring array (Lozier et al., 2016, Fig. 3). Time series will be analyzed to find imprints of SCVs in temperature and salinity fields and in the observed velocity data following the methodology developed by Lilly and Rhines (2002), already applied in the northwestern Mediterranean Sea (Bosse et al., 2016).

Argo: The Argo platform will provide the observational data necessary to detect SCVs and to perform statistics on their structure and distribution. To identify submesoscale eddies using Argo data we will follow the methodology applied in the northwestern Pacific ocean (Li et al., 2018) that consists in the detection of extreme temperature and salinity anomalies and potential vorticity (vertical stratification) values.

Model: Regional simulations at submesoscale permitting resolution (dx < 1 km) are available in various regions of the globe to study local impacts and generation processes. A new realistic simulation of the Atlantic with the model CROCO resolving the submesoscale (MEGATL with dx = 1 km and 200 vertical levels) will also be used in this project to provide a more general description of the distribution of SCVs and to analyze the impact on the global circulation. SCVs will be detected...
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from model outputs through an adapted version of the eddy tracker code of Mason et al. (2014) following the methodology of Frenger et al. (2018). With this aim we will identify representative density surfaces embracing subsurface eddies, then we will identify anticyclonic (cyclonic) SCVs as positive (negative) anomalies of the density layer thickness. This method will be compared with the recently developed AMEDA eddy detection and tracking algorithm (Le Vu et al., 2018) applied to the detection of eddies in the Arabian Sea by Mathieu Morvan at LOPS.

1. Basin scale statistics for SCVs
Moorings, argo data and model outputs will be used to compute basin scale statistics on the presence and structure of SCVs. After the detection of submesoscale eddies we will be able to perform statistics of eddy characteristics: hydrographic signatures at the eddy cores, vertical distribution of hydrographic anomalies, and vertical and horizontal scales; and to analyze their spatial and temporal variability.

The numerical outputs from the model will be used to track long-lived SCVs. We aim to compile statistics of the structure and propagation of these eddies: amplitude, radius, lifespan, propagation speed, propagation distance, preferred trajectories, formation and dead zones, etc. We will also look at the ratio between cyclonic and anticyclonic SCVs in the different regions, and check how it varies depending on the SCVs age and origin. In particular we will check if the ratio matches the ratio of prograde versus retrograde currents, or if it is related to a different behavior for the cyclones and anticyclones after their generation. The Argo statistics and moorings data will be used to validate these results.

2. Generation mechanisms and life-cycle of SCVs
The previous statistics will provide knowledge on the preferred eddy formation and decay regions. Then, using targeted realistic and/or idealized numerical simulations, we aim to investigate: the generation mechanisms of SCVs in the different regions; the mechanisms driving SCVs trajectories (e.g. advection by mean currents, interactions with the mesoscale eddies); the interactions between SCVs (cyclonic and/or anticyclonic) possibly leading to erosion, fusion or alignment of SCVs; the mechanisms leading to SCVs destruction (e.g. large scale current shear and strain, interactions with topography, Fig. 4); the mechanisms potentially leading to different stability properties for the cyclones and anticyclones.

Figure 4: Collision between a SCV and a Seamount at 36N, 51W
3. **Impact on the large scale circulation**

Finally, we plan to assess, for the first time, the contribution of SCVs to the transport of waters and to the budget of temperature, salinity and energy in the Atlantic ocean. This work will be a first step towards a rational representation of the SCV fluxes in coarser-resolution models where submesoscale dynamics are not resolved.

**Collaboration:**

The work will be done in collaboration with Jim McWilliams (UCLA) for the theory and interpretation, Loic Houpert (NOCS) for the analysis of the in-situ observations from moorings and gliders, and Guillaume Maze (LOPS) for the statistical analysis of the Argo floats and numerical simulations.

This project is a contribution to the LEFE/IMAGO project RADII. It is also linked to the recently funded H2020 project iAtlantic “Integrated Assessment of Atlantic Marine Ecosystems in Space and Time”. The project is a contribution to ISblue, in particular Theme 1: Ocean and Climate regulation. It will investigate how nonlinear submesoscale processes may impact the large scale circulation, biogeochemical tracer budgets, and climate.

**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).

**Bibliography:**