FINAL REPORT PROGRAM LEFE

Program LEFE/ GMMC-IMAGO	Project Title: North-Atlantic Ocean Subtropical Gyre: Mechanisms of Observed and projected low-frequency VARiability (SOMOVAR)	Years 2017 – 2019

PI name, email and lab:	Contribution to
Guillaume Maze (gmaze@ifremer.fr), LOPS, UMR6523	*ARGO, CLIVAR*
Participating Laboratories :	Other funding sources :
CERFACS, Lab-STICC	UBO/Ifremer (PhD student)

Context (2-3 lignes)

The North Atlantic subtropical gyre holds the largest volume of warm water (say, temperature warmer than 10°C) in the world's ocean mid-latitudes. It plays an important role for climate at the global and regional scales through its participation in the meridional overturning circulation, meridional heat transport, air-sea fluxes and heat storage. It is thus crucial to know how the North Atlantic subtropical gyre (NATSG) has and will change in the face of climate change.

Objectives / scientific questions (2-3 lignes)

The overall objective of SOMOVAR was to diagnose and to investigate the mechanisms of variability of the North Atlantic Subtropical Gyre system at interannual-to-decadal time scales for the understanding of changes in observed oceanic heat content.

Main results (y compris les relevés de conclusions des réunions de coordination si c'est l'objet du financement LEFE)

Observed variability of the NASTG. Using Argo based recent ocean analysis and historical datasets going back to the 1960s, we diagnosed the low-frequency variability of the North-Atlantic Ocean Subtropical Gyre stratification key components: the Eighteen Degree Water (EDW), the permanent pycnocline and the Gulf Stream Extension. We have found a 2005-2015 quasi-decadal trend of reduced EDW heat content due to a combined reduction of its volume and temperature (**see left Figure below**). These changes are explained by modified EDW formation region properties and wind-driven reduced overturning circulation (Stevens et al, 2020; Desbruyeres et al, 2019). We also successfully extended our objective diagnostic methods of the subtropical stratification (Objective Algorithm for the Characterization of the Permanent Pycnocline (OACP) and Profile Classification Model (PCM)) to the global ocean (Rosso et al, 2020; Feucher et al, 2019).

Mechanism of NASTG variability. PhD student Li Ke has developed an observation-based ocean heat budget of the upper 800 m in the western subtropical North Atlantic. On interannual time scale, the variability of geostrophic advection, mostly driven by the Gulf stream, is the most dominant factor to that of the ocean heat content (OHC) variability, 2.5 times as large as that of Ekman advection and almost four times as large as that of surface heat loss (which dominates at the seasonal cycle only). However, the annually ventilated EDW exhibits extreme values in 2008, 2013, and 2015 that correspond to opposite OHC anomalies. Li Ke has shown that Ekman advection is the best indicator and driving mechanism explaining these extreme occurrences (Ke et al, 2022). He further showed that such extreme extreme Ekman advection patterns can be linked to large scale atmospheric weather storms and that both storm intensity and duration have an impact on the extremity of EDW ventilation and North Atlantic heat content (**see right Figure below**).

A new perspective on WBC observed variability. The very innovative approach explored in SOMOVAR and based on recent development in machine learning and pattern recognition methods has led to 2 studies funded by H2020 project EARISE. One study led by Research Engineer Andrea Garcia Juan has shown that automatic pattern recognition can be used to improve the selection of appropriate and relevant reference profiles to validate Argo data in WBC regions (see project deliverable here). The other study, led by Postdoc Etienne Pauthenet has shown

that machine learning can be used to combine satellite with in situ data to reconstruct the ocean stratification in 4D accurately enough to study the Western Boundary Current (WBC) turbulent variability (Pauthenet et al, sub 2022 and new dataset: https://doi.org/10.5281/zenodo.6011144)

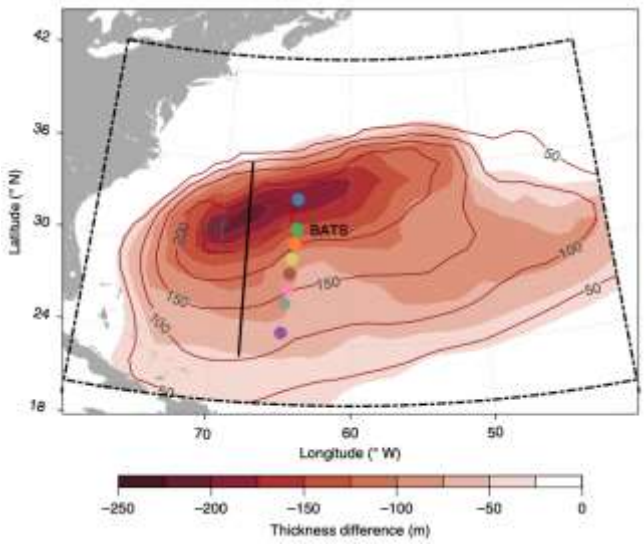

Figure 5. The difference map denotes the Subtropical Mode Water (STMW) thickness difference between 2014–2018 and 1955–2013, inclusive (derived from the EN4g10 dataset; negative values indicate STMW loss in 2014–2018). The overlaid contour lines show the mean STMW thickness (in m) before 2014. The black dotted–dashed line encloses the model region. The straight black line denotes the 68° W meridional transect. Bermuda Atlantic Time Series Study (BATS) Validation stations are depicted by coloured points.

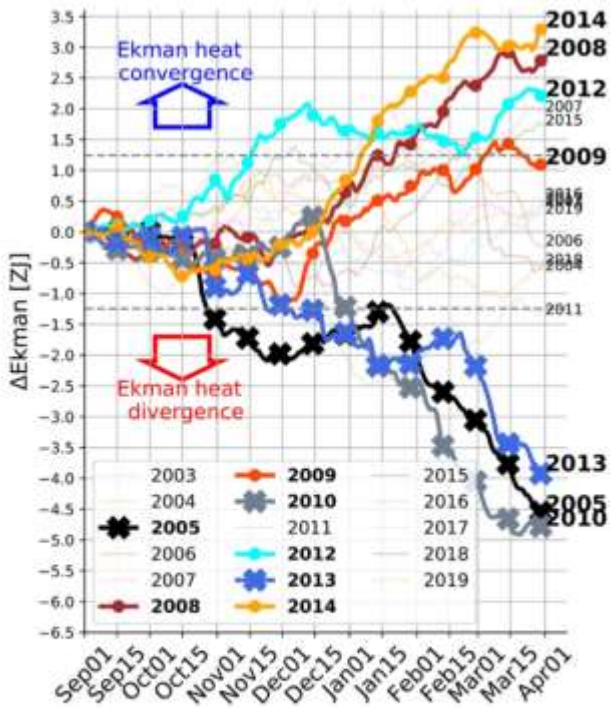

Figure 7. The 2003–2019 September–March, daily accumulated "no-smoothing" anomalies of the heat convergence due to Ekman advection. Similar to Figure 6b, except this plot is in daily time resolution. The dashed gray lines indicate the standard deviation $\sigma = 1.24$ ZJ.

Left figure: From Stevens et al (2020). EDW thickness reduction over 2014/18 compared to the 1955-2013 climatology. This illustrates the unprecedented and dramatic reduction of EDW volume and subtropical gyre stratification increase observed recently and revealed by SOMOVAR.
Right figure: From Li et al (2022). This illustrates extreme Ekman driven heat fluxes impact on the NASTG stratification, the role of storms in driving interannual signals and ultimately build a clear bridge between weather and climatic low-frequency signals.

Future of the project :

This final report is late compared to the real end of the project, which happened in 2019. At this time, work carried in SOMOVAR had led to:

- a participation in the H2020 EARISE proposal and overall funding of one research engineer for 18 months (Andrea Garcia Juan) who worked on the pattern recognition PCM method in WBC and one postdoc position (Etienne Pauthenet) who still currently work on using deep neural network to reconstruct an accurate 4D state of the ocean stratification in the Gulf Stream Extension region (one article submitted, one dataset published).

- a new PhD entitled "Analysis of an ocean GCM simulations ensemble: stochastic variability of water masses" that was funded and has started since Oct. 2020 (Olivier Narinc, PhD supervisor: Thierry Penduff and Guillaume Maze).

Nombre de publications, de communications et de thèses

The LEFE program and SOMOVAR project were acknowledged in the following:

Articles:

1. Li Ke, Maze Guillaume, Mercier Herle (2022). Ekman transport as the driver of extreme interannual formation rates of Eighteen Degree Water . *Journal Of Geophysical Research-oceans* , 127(1), e2021JC017696 (15p.) . https://doi.org/10.1029/2021JC017696
2. Stevens Samuel W., Johnson Rodney J., Maze Guillaume, Bates Nicholas R. (2020). A recent decline in North Atlantic subtropical mode water formation . *Nature Climate Change* , 10(4), 335–341 . Publisher's official version : https://doi.org/10.1038/s41558-020-0722-3 , Open Access version : https://archimer.ifremer.fr/doc/00618/72973/
3. Rosso Isabella, Mazloff Matthew R., Talley Lynne D., Purkey Sarah G., Freeman Natalie M., Maze Guillaume (2020). Water Mass and Biogeochemical Variability in the Kerguelen Sector of the Southern Ocean: A Machine Learning Approach for a Mixing Hotspot . *Journal Of Geophysical Research-oceans* , 125(3), e2019JC015877 (23p.) . Publisher's official version : https://doi.org/10.1029/2019JC015877 , Open Access version : https://archimer.ifremer.fr/doc/00613/72471/
4. Desbruyères Damien, Mercier Herle, Maze Guillaume, Daniault Nathalie (2019). Surface predictor of overturning circulation and heat content change in the subpolar North Atlantic . *Ocean Science* , 15(3), 809-817 . Publisher's official version : https://doi.org/10.5194/os-15-809-2019 , Open Access version : https://archimer.ifremer.fr/doc/00503/61443/
5. Feucher Charlene, Maze Guillaume, Mercier Herle (2019). Subtropical Mode Waters and Permanent Pycnocline properties in the World Ocean . *Journal Of Geophysical Research-oceans* , 124(2), 1139-1154 . Publisher's official version : https://doi.org/10.1029/2018JC014526 , Open Access version : https://archimer.ifremer.fr/doc/00480/59176/

Thèse, HdR:

- Ke Li. Ekman transport : a trigger of interannual extreme formation rates of eighteen degree water. Oceanography. Université de Bretagne occidentale - Brest, 2020. English. ⟨NNT : 2020BRES0085⟩. ⟨tel-03348108⟩
- Maze Guillaume (2020). Structure and variability of the subtropical gyre . HDR. https://archimer.ifremer.fr/doc/00721/83302/

Posters and talks in conferences:

- Li Ke (2019). Interannual impact of extreme wintertime weather on the North Atlantic subtropical stratification. 7th Euro-Argo Science Meeting. 22-23 October 2019, Athens. Journées Scientifiques LEFE/GMMC 2019. 12-14 juin 2019, Toulon
- Maze Guillaume, Li Ke, Mercier Herle (2019). SOMOVAR project: “Detection and understanding of the North- Atlantic Ocean Subtropical Gyre low-frequency Variability”. Focus on the 2005-2015 Eighteen Degree Water variability . 7th Euro-Argo Science Meeting. 22-23 October 2019, Athens . https://archimer.ifremer.fr/doc/00591/70278/ , Journées Scientifiques LEFE/GMMC 2019. 12-14 juin 2019, Toulon . https://archimer.ifremer.fr/doc/00524/63543/
- Maze Guillaume, Feucher Charlene, Mercier Herle, Dewar William (2018). Large-scale structure of the pycnocline stratification in subtropical gyres . 2018 Ocean Sciences Meeting. 11–16 February 2018, Portland, Oregon . https://archimer.ifremer.fr/doc/00435/54641/

Workshops:

- Maze Guillaume, Mercier Herle, Feucher Charlene (2017). ORCA025 representation of large-scale stratification features in the North-Atlantic . DRAKKAR 2017 Annual Workshop. 16-18 January 2017, Grenoble .