What lies beneath the Gulf Stream?

Probabilistic machine learning of ocean currents from satellite altimetry

Six-month Master's research internship | Physical oceanography and machine learning

Host institution: Laboratoire d'Océanographie Physique et Spatiale, Plouzané | Expected start: April 2027
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Context

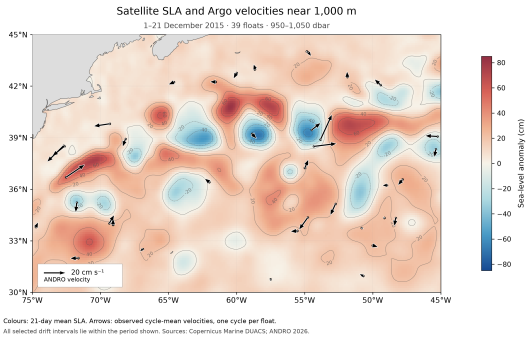
The Gulf Stream transports warm water from the subtropics towards the North Atlantic and contributes to the upper branch of the Atlantic meridional overturning circulation (AMOC), which plays an important role in the climate of the surrounding continents. Climate projections assessed by the IPCC indicate that the AMOC will very likely weaken during the 21st century [1]. However, evaluating the ocean models used for these projections remains challenging, particularly at depth, where direct current measurements are sparse.

Satellite altimetry has provided a nearly continuous record of sea level since 1993, while Argo floats have drifted at depths of around 1000 m since the early 2000s; their displacements, compiled in the ANDRO atlas [2], give estimates of the deep currents. Together, these observations offer an opportunity to investigate the relationship between surface and deep circulation. Previous studies have combined float trajectories with satellite altimetry [3], but observations in the Gulf Stream region suggest that surface and deep variability are not always strongly correlated [4]. Similar surface conditions may therefore correspond to different deep-current states.

Quantifying this relationship, and the uncertainty associated with it, would help establish what can be learned about deep circulation from the long satellite record. The central question is therefore: **to what extent can surface observations constrain deep-ocean currents, and how reliably can their uncertainty be estimated?**

Research objective

Rather than predicting a single velocity, the project will learn a joint probability distribution for the two horizontal velocity components. For each Argo drift, typically around ten days long, the model will predict how the observed average current differs from the average current normally expected at that location. The inputs are daily satellite maps of sea level and of the surface currents derived from them, collocated with each drift. The model will give both the expected deep current and its uncertainty, which varies between the jet, its eddies and the calmer regions around it.



Satellite sea-level anomaly and measured ANDRO currents, 1–21 December 2015.

Method

Building on an existing Gaussian prediction framework, the student will investigate conditional Gaussian mixture models (mixture density networks; [5]). These models account for correlations in prediction uncertainty and allow multiple plausible current directions under similar surface conditions.

The results will then be interpreted in the context of Gulf Stream dynamics, examining how deep currents respond to jet meanders and detached rings, and how bathymetry along the continental slope influences the relationship between surface and deep circulation. An additional challenge arises from the nature of Argo float observations: each float drifts for about ten days between two surfacings, so it measures a current averaged along its trajectory, rather than at a fixed location. The study will assess how this sampling affects the information that can be inferred about deep currents.

Timeline

Months 1–2	Prepare the float and altimetry data, including virtual floats simulated in an ocean model [6]; first relations between surface and deep currents.
Months 3–4	Build the probabilistic model; take into account the drift of the float during each measurement.
Months 5–6	Physical interpretation and writing of the internship report.

Profile

Master's student (M2) in physical oceanography, physics, applied mathematics or data science. Programming in Python. Experience with machine learning is welcome but not required.

References

1 Fox-Kemper, B. et al. (2021), Ocean, Cryosphere and Sea Level Change, in *Climate Change 2021: The Physical Science Basis*, IPCC AR6 WGI, Cambridge University Press. doi:10.1017/9781009157896.011.

2 Ollitrault, M. and Rannou, J.-P. (2013), *Journal of Atmospheric and Oceanic Technology*, 30, 759–788. doi:10.1175/JTECH-D-12-00073.1. ANDRO atlas, SEANOE: doi:10.17882/47077.

3 Willis, J. K. and Fu, L.-L. (2008), *Journal of Geophysical Research*, 113, C12017. doi:10.1029/2007JC004690.

4 Meinen, C. S. and Luther, D. S. (2016), *Deep-Sea Research I*, 112, 137–154. doi:10.1016/j.dsr.2016.03.002.

5 Brolly, M. T. (2023), *Journal of Advances in Modeling Earth Systems*, 15, e2023MS003718. doi:10.1029/2023MS003718.

6 Hochet, A. (2026), A virtual ANDRO atlas: deep (∼1000 m) velocities from Argo floats simulated in the GLORYS12 ocean reanalysis, SEANOE. doi:10.17882/117697.