Polar eddies and Antarctic cross-shelf transport: exploring the mesoscale beneath sea ice in the SWOT era

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Seeking a candidate for a pre-doctoral position (9 months) followed by a doctoral thesis

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Scientific context and motivation

The Southern Ocean plays a disproportionate role in global climate and its change: it is a major sink for anthropogenic carbon and heat, hosts intense deep water mass formation that makes it one of the principal drivers of global thermohaline circulation, and allows warm circumpolar waters to intrude onto its continental shelves, thereby destabilising the polar ice sheet. It is also changing very rapidly, as evidenced by the spectacular retreat of Antarctic sea ice in recent years. These changes raise central questions about the dynamical processes governing them, yet these questions remain largely unresolved due to the lack of suitable observations in these ice-covered regions.

Satellite observation has revolutionised our understanding of the world's oceans, but still struggles in ice-covered regions because sea ice complicates its exploitation. Over the past decade, our teams have developed unique expertise in the use of altimetric observations in ice-covered Southern Ocean regions, the fruit of a fruitful collaboration between LOCEAN, CLS, and CNES (Auger et al., 2022a,b; 2023; Mosneron Dupin et al., 2025). The present project builds on this collaboration, proposing a new step through the exploitation of observations from a new type of satellite that has been opening an unprecedented window onto the world's oceans in recent years. We propose here to turn this new perspective onto the ice-covered Southern Ocean, and thereby lift the veil on Antarctic polar eddy dynamics.

The SWOT satellite (NASA/CNES, launched in 2022) represents a technological breakthrough in sea surface height observation: through its KaRIn interferometric altimeter, it resolves for the first time from space the surface topography at scales of 15–20 km, making the full geography of mesoscale structures accessible even in coastal and ice-covered areas. Its exploitation in these environments remains an open technical challenge, which this project proposes to meet.

[Phase 1] Pre-doctoral fixed-term position at CLS: a SWOT sea level product, validated in the ice-covered Southern Ocean

The first phase of the project, lasting 9 months, will be carried out within the CLS teams in Toulouse, France. Its objective will be to characterise the potential and limitations of SWOT measurements in ice-covered polar regions, articulated around two complementary axes: validation of existing products, and methodological exploration of measurements at the ice–sea interface.

Cross-validation KaRIn / Nadir at the ice–ocean interface. Conventional nadir altimetry presents processing discontinuities at the interface between open ocean surface and ice-covered surfaces, questions that remain open in CLS's current operational procedures. The new geometry of SWOT, which simultaneously observes in nadir mode and in

wide-swath KaRIn mode, offers a unique opportunity to examine these discontinuities at fine spatial resolution. The candidate will conduct a systematic comparative analysis of KaRIn and Nadir measurements in the marginal ice zone, drawing on the SWOT archives available since 2023 and documenting the biases, discontinuities, and instrumental artefacts associated with surface transitions.

Synthesis of multi-source validation building blocks. CLS holds numerous elements for validating polar altimetric measurements (multi-mission comparisons, in situ data, comparisons with ICESat-2), currently dispersed across different teams and projects. Part of the first phase of the present project will consist of gathering, documenting, and consolidating these validation building blocks to produce an integrated assessment of SWOT L3 products in ice-covered areas. This synthesis work, conducted in interaction with the CNES scientific teams, will directly help orient R&D priorities for future product versions.

Beyond validation, this first phase of immersion in SWOT data will allow the candidate to acquire in-depth mastery of the instrument's potential and limitations before tackling the thesis questions on ocean dynamics. Handling a diverse range of satellite sources (multi-mission altimetry, ICESat-2, thermal and radiometric data) and in situ data will also provide a solid foundation for the forthcoming multi-scale analyses.

[Phase 2] PhD thesis (3 years): fine-scale dynamics in ice-covered regions

The thesis itself will be structured around two major complementary scientific questions, exploiting SWOT measurements and their contextualisation with complementary data to document fine-scale dynamics in polar regions, their controls, and their climatic implications. These questions are directly relevant to understanding the ongoing changes in Antarctica.

Question 1: Eddy–sea ice interactions: what mechanisms and what balances?

Seasonally ice-covered regions host intense ocean dynamics, dominated at the mesoscale by eddies whose interactions with sea ice remain very poorly quantified. Yet these interactions are potentially critical for the thermal and dynamical budget of sea ice. Some processes warrant particular attention:

- *Eddy generation in the marginal ice zone.* The marginal ice zone (MIZ) is a particularly favourable environment for eddy generation, driven by melt fronts, wind-induced upwelling at the ice edge, and associated instabilities. Recent studies suggest that these eddies preferentially form in dipoles: cyclones at the surface, accompanied by subsurface anticyclones that subsequently migrate into the halocline, far from their formation zone. The surface signature of this process and its intensity across the Southern Ocean remain however unknown. SWOT, through its unprecedented spatial resolution, will for the first time allow this eddy generation to be mapped and source regions to be distinguished.

- *Eddy–sea ice interactions and energy dissipation.* While sea ice drift can be affected by the presence of fronts and eddies, it also draws part of their energy and affects them in return. This coupling between sea ice and eddies will be explored, and its impact on the transfer of momentum and heat between sea ice and ocean will be quantified. More broadly, energy transfers and their impacts between ocean, sea ice,

and atmosphere are poorly documented in the Southern Ocean. By comparing eddy activity and energy spectra between open ocean, MIZ, and ice-covered zones, the way in which sea ice modulates mesoscale activity will be explored using SWOT observations.

Question 2: Slope current and eddy transport over Antarctic continental shelves

Exchanges between the open ocean and Antarctic continental shelves play a crucial role for global climate given their importance for heat transport towards the polar ice sheet and for the export of dense shelf water to the abyss. The fine-scale dynamics of the Antarctic slope current, which runs along the continental slope and controls these exchanges between shelf and deep basin, are however very poorly known. We propose here to address this theme around two sub-questions:

- *Variability and instability of the slope current.* The slope current is subject to baroclinic and barotropic instabilities that generate slope eddies. These instabilities partly control the exchange of properties (heat, salinity, oxygen) between the shelf and the open ocean. SWOT will for the first time enable the fine-scale variability of this current to be characterised over extended coastal segments, inaccessible to regular in situ observations. The candidate will analyse the spatial and temporal structure of the instabilities, the conditions favourable to their development, and the scale interactions between slope current intensity and eddy energy.

- *Cross-shelf eddy transport and implications for deep circulation.* The transport of tracers (heat, salt, carbon, nutrients) between the continental shelf and the deeper basins is partly carried out by eddies. Quantification of this cross-shelf eddy transport remains poorly constrained. By combining SWOT observations with available in situ data (moorings, floats), the candidate will produce new estimates of this transport and document its spatial and temporal variability.

Supervision and collaborators

Principal supervision: Francesco Nencioli (CLS, Toulouse), Jean-Baptiste Sallée (LOCEAN, Paris; CNRM, Toulouse), + Casimir de Lavergne (LOCEAN, Paris)?

Collaborators: Matthis Auger (LOPS, Brest), Cosme Mosneron Dupin (LOCEAN, Paris), Lia Siegelman (SCRIPPS, San Diego, USA)

Contact

If this project interests you or if you have any questions, please contact us at: jean-baptiste.sallee@locean.ipsl.fr

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Key references

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