SWOT reveals fine-scale balanced motions and particle dispersion in the Antarctic Circumpolar Current

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The new **SWOT** (Surface Water and Ocean Topography) satellite provides a new view of ocean dynamics, at scales down to a 15 km wavelength [1]. This has motivated an international validation effort with in-situ campaigns in key dynamic regions, including FOCUS (Fine-scale Observations of the Antarctic Circumpolar Current Under SWOT), conducted in an **energetic meander of the Antarctic Circumpolar Current (ACC).**

Using drifter pairs deployed during the FOCUS voyage, we assess the **validity of SWOT SSH to derive surface currents** in the region, we test the **geostrophic and cyclogeostrophic balances** and we **compare dispersion properties** derived from both SWOT velocities and in-situ drifter pairs.

SWOT SSH remain predominantly balanced and valid to infer surface velocities at small scales in the ACC

We introduce a method to fit velocities to SWOT 2D SSH fields through a moving kernel [3]. To determine the spatial scale at which SWOT SSH remain valid to infer surface velocities through momentum balance, we compare low-passed (> 1 day) velocities from drifter with SWOT velocities derived at different length scale (by adjusting the kernel size).

RMSD is reduced when increasing the fitting lengthscale to 18 km
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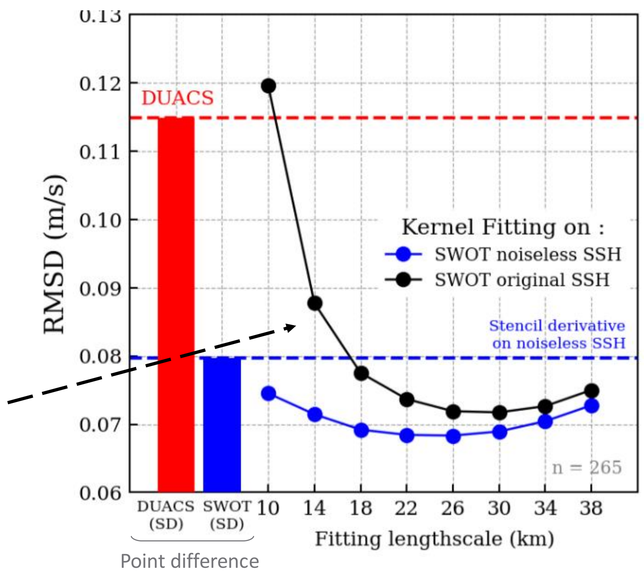
Suppression of noise and unbalanced signal

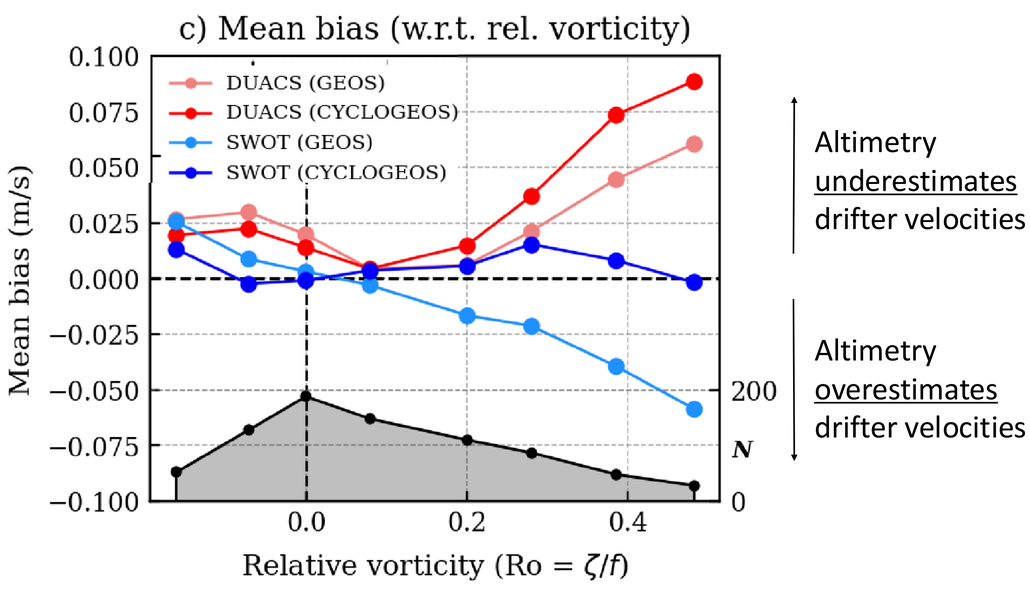


- ✓ Velocity estimates from SWOT are in excellent and unprecedented agreement with low-passed (> 1 day) observations from drifters
- ✓ **SWOT SSH remains predominantly balanced and valid to infer surface velocities at scales at least larger than 18 km**

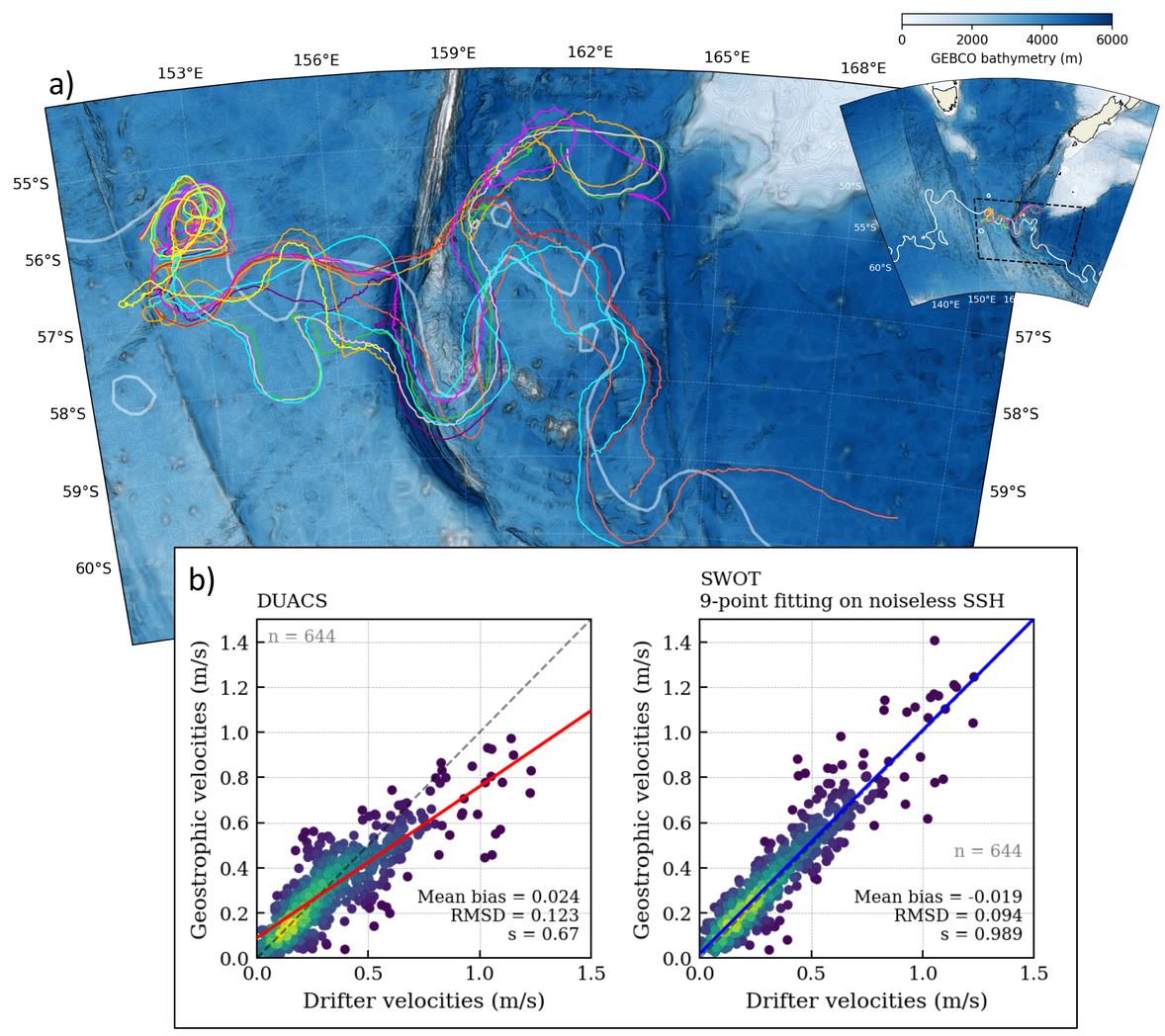
Importance of cyclogeostrophy at the scales newly resolved by SWOT

$$\underbrace{\mathbf{u}\cdot\nabla\mathbf{u}}_{\text{Cyclogeostrophy } (Ro <= 1)} + \underbrace{f\mathbf{k}\times\mathbf{u}}_{\text{Geostrophy } (Ro << 1)} = -g\nabla \mathrm{SSH}_{\mathrm{balanced}}$$

Neglecting non-linear terms in the momentum balance is expected to lead to an overestimation of velocities as Rossby number increases. To quantify the contribution of cyclostrophic effects, we compare geostrophic and cyclogeostrophic velocities from DUACS and SWOT with drifter data, and average the mean bias per relative vorticity bins (equivalent to Rossby number bins).



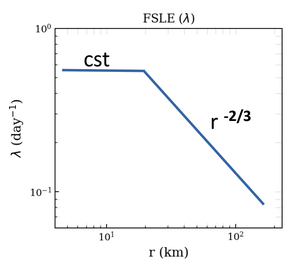
- ✓ High-resolution SWOT observations provide an unprecedented view into higher-order balance, beyond geostrophy
- ✓ **Geostrophic approximation is not sufficient at scales resolved by SWOT, with velocity bias up to 20% in cyclonic eddies**



a) Drifters deployed by pairs in the ACC meander during the FOCUS campaign (Nov-Dec 2023).
b) Comparison of drifter velocities against geostrophic velocities from **DUACS [2]** and **SWOT**

Virtual particles released on SWOT velocity fields reproduce dispersion observed in real drifter pairs

The Finite-scale Lyapunov Exponent (FSLE) quantifies the separation rates of particle pairs for a given separation distance, providing insight into the length scales of features driving particle dispersion [4].



Theoretical expectations

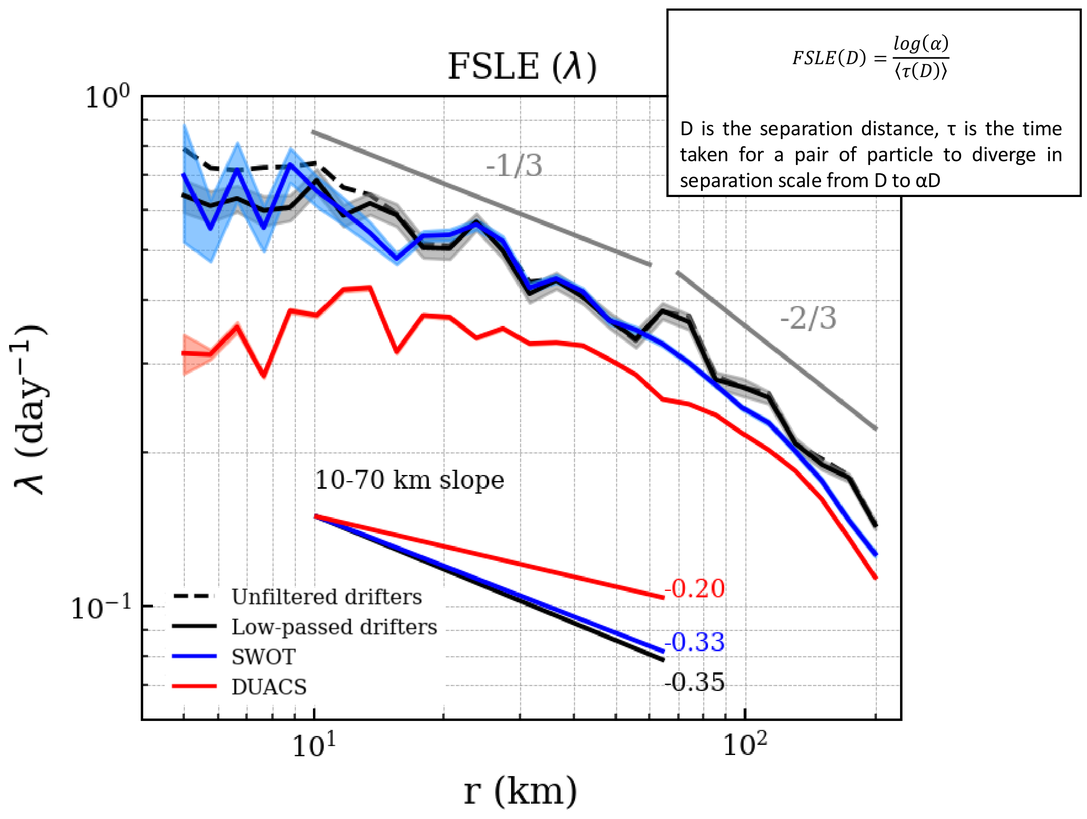
Cst : Non-local regime, dispersion driven by larger scale features (mesoscale stirring)

$r^{-2/3}$: Local regime, where dispersion is driven by features of same size as the particle separation

To evaluate the influence of the new scales resolved by SWOT on particle dispersion, we seed virtual particles in **DUACS** and **SWOT** velocity fields using the Ocean Parcels python package [5], and compute and compare FSLE from real drifter pairs and virtual particles.

$$FSLE(D) = \frac{log(\alpha)}{\langle \tau(D) \rangle}$$

D is the separation distance, τ is the time taken for a pair of particle to diverge in separation scale from D to αD



- ✓ **Virtual particles released in SWOT velocities effectively reproduce dispersion of drifter pairs over the 10–200 km range**

This study constitutes a first SWOT validation effort tailored to this ACC region, showing its ability to retrieve accurate surface velocities and dispersion properties in the 10-100 km range (Tranchant et al., 2025).

- **The velocity fitting method may be adapted spatially by scaling the kernel size on local Rossby deformation radius**
- **Drifter velocities are filtered at a 1-day timescale, which may remove fast, yet balanced motions**

References
[1] Morrow, R. et al. (2019). Global Observations of Fine-Scale Ocean Surface Topography With the Surface Water and Ocean Topography (SWOT) Mission. Frontiers in Marine Science, 6, 433647.
[2] Near Real Time (NRT) Data Unification and Altimeter Combination System (DUACS) "SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046"
[3] Tranchant, Y.-T. et al., (2025). SWOT reveals fine-scale balanced motions driving near-surface currents and dispersion in the Antarctic Circumpolar Current. *ESS*, 12, e2025EA004248
[4] Meunier, T.; LaCasce, J.H. (2021) The Finite Size Lyapunov Exponent and the Finite Amplitude Growth Rate. Fluids 2021, 6, 348.
[5] Parcels (Probably A Really Computationally Efficient Lagrangian Simulator) https://oceanparcels.org/index.html