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Using SWOT Sea Surface Height to Study Coastal Eddy Dynamics

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GEOSTROPHIC AND CYCLOGEOSTROPHIC VELOCITY FROM SWOT VS. HFR

Background

Satellite altimetry **sea surface height** (**SSH**) η is related to geostrophic current $\mathbf{u}_g$ via the simple relation:

$$u_g = -\frac{g}{f}\frac{\partial\eta}{\partial y} \qquad v_g = \frac{g}{f}\frac{\partial\eta}{\partial x}$$

Additionally, the non-linear terms in the momentum equations (ignored in geostrophy) result in a higher order cyclogeostrophic balance that can improve current estimates for Ro = O(1) flows, e.g. mesoscale eddies, meandering jets (Tranchant et al., 2025). In the context of SWOT, the accuracy of velocity estimates from SSH are of central interest.

- To what extent do the geostrophic and cyclogeostrophic balances correspond to observed surface currents?
- Conversely, how reliable are current observations for validation?
- At what spatial scales can SWOT reasonably estimate currents?

Observations

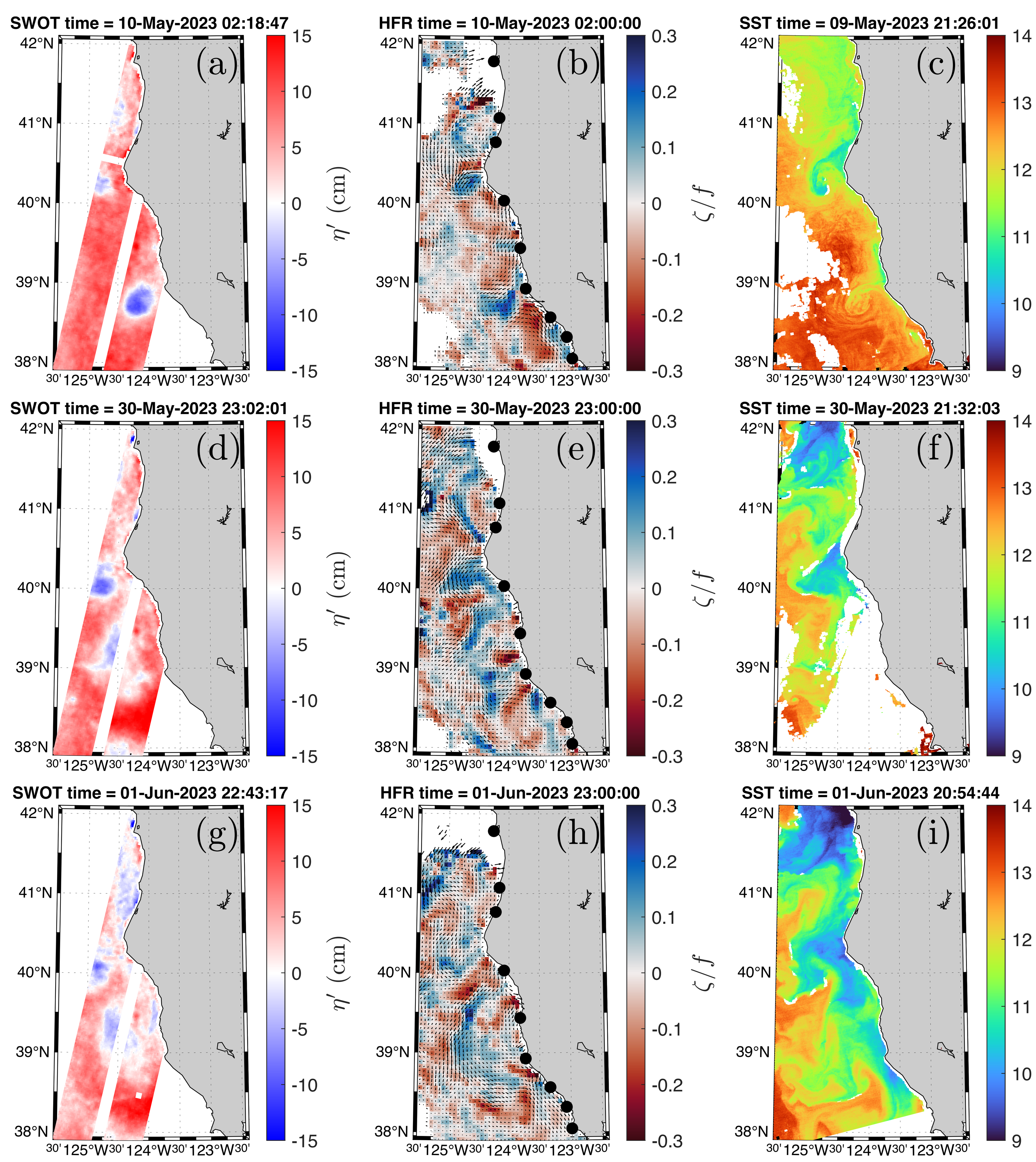
	SWOT L2 product	High-frequency radar	Suomi NPP - VIIRS
Variable	Sea surface height anomaly (SSHA, η′)	Radial and gridded surface velocity (u_r, u, v)	Sea surface temperature (SST, T)
Spatial resolution	2 km grid	Radial: scattered points Gridded: 6 km grid	1.6 km grid
Temporal resolution	Daily (cal/val orbit)	Hourly	Varies due to cloud cover, typically a few good passes per month
Purpose in this study	Estimate currents from SSH	Validation of currents	Examine/compare small scale structure

Variable `ssha_karin_2` displayed:

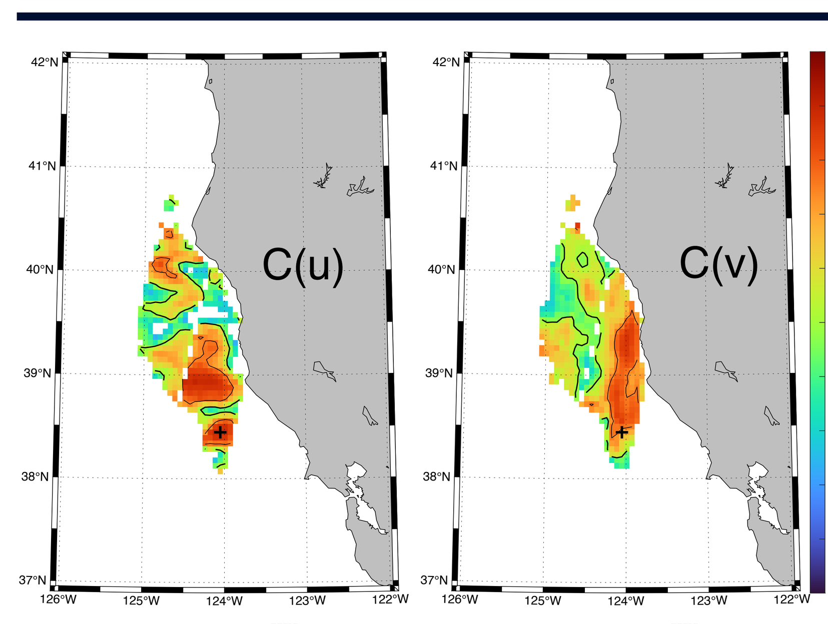
```
ssh_karin_2
- mean_sea_surface_cnescls
- solid_earth_tide - ocean_tide_fes
- internal_tide_hret - pole_tide
- dac - height_cor_xover
```

- Near-real time vector surface currents
- Bragg scattering, radar frequencies of 5-40 MHz
- Radial obs. gridded to 6 km
- Matched to within 1 hour of SWOT flyover time

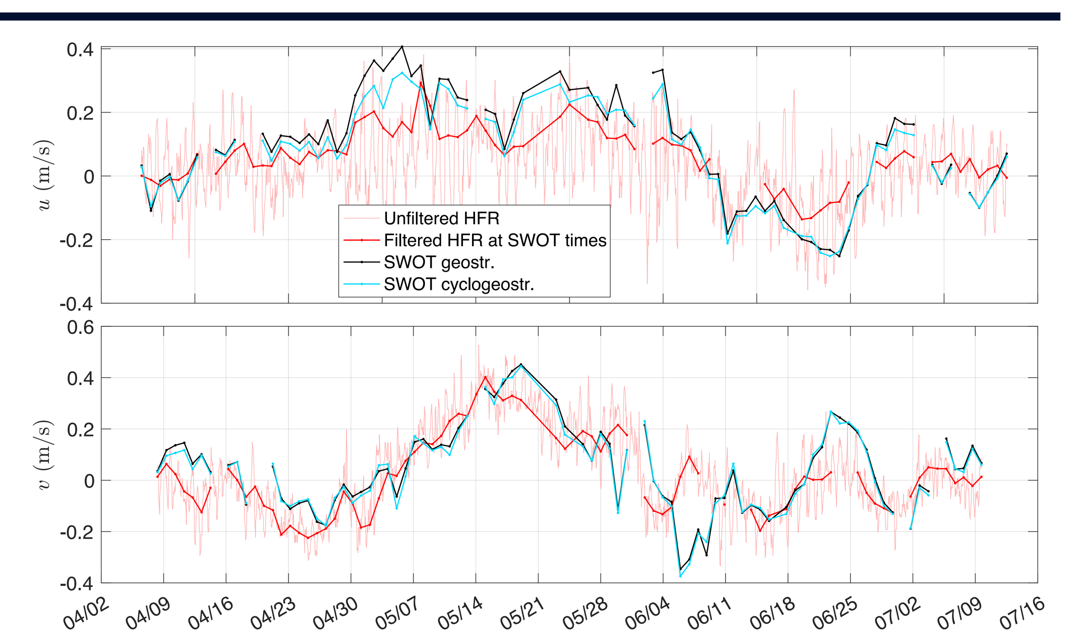
- Sun-synchronous, polar orbiting
- 16 day repeat but very wide (3000 km) swath
- Measures at wavelengths of 3.7 µm (band M12), 10.76 µm (M15) and 12.01 µm (M16)



Nearly simultaneous observations near Cape Mendocino of (a,d,g) SSHA from SWOT, (b,e,h) surface currents (arrows) and associated normalized vorticity (color) from HFR, and (c,f,i) SST from VIIRS. Time stamps are in UTC, and dots in the middle column indicate radar antenna locations.

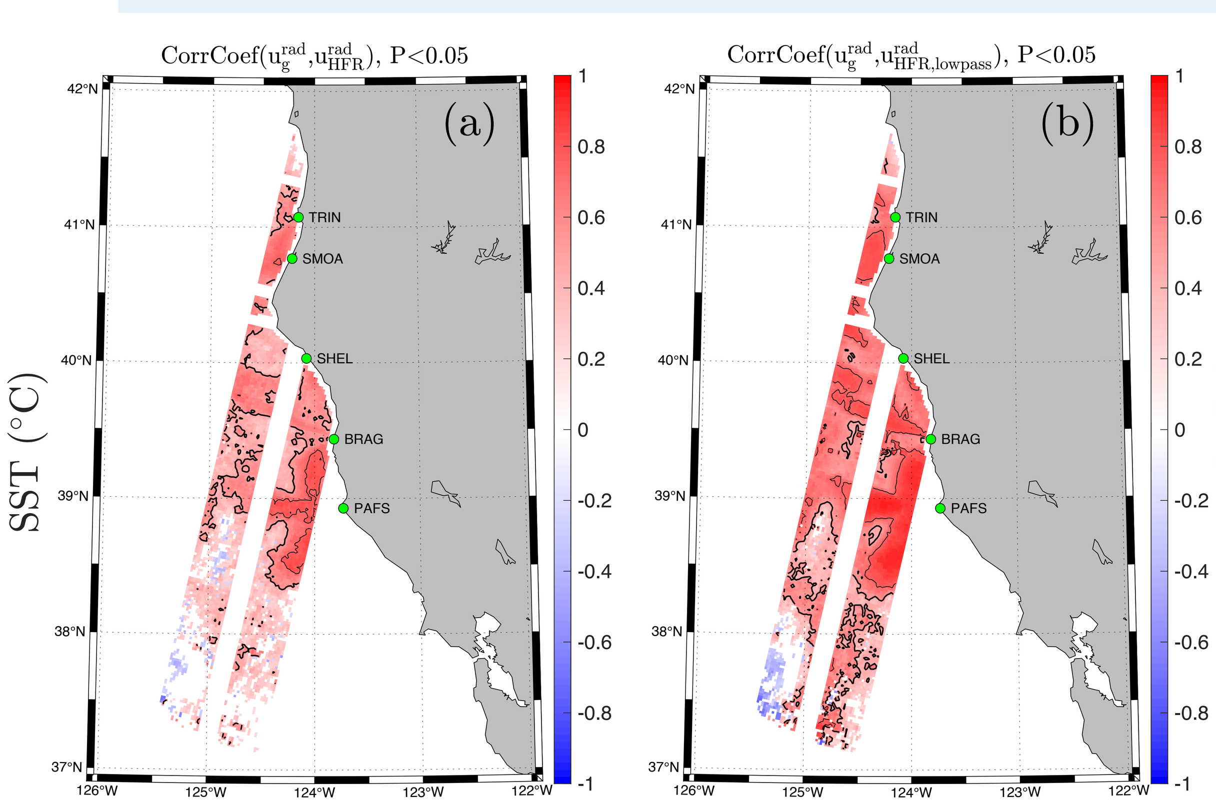


Maps of correlation coefficients of $\mathbf{u}_g$ and gridded HFR **u**. Thick lines = 0.5, thin lines = 0.75.

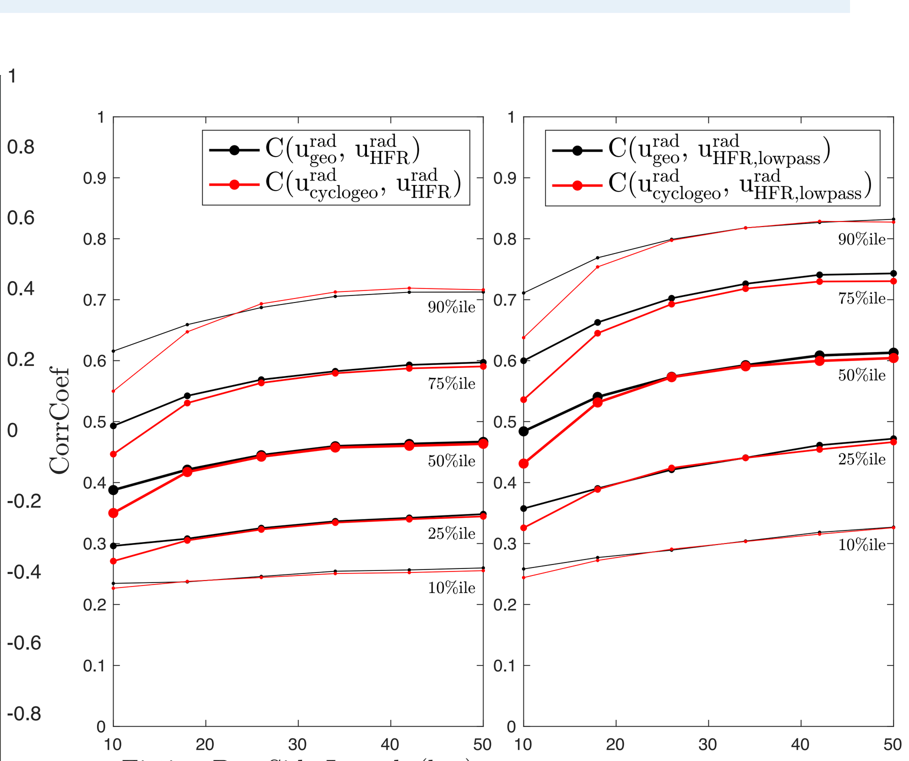


Time series of u and v at the point indicated by a "+" at left.

Though gridded HFR products are useful, gridding averages over information that SWOT appears to capture, as correlation between SWOT and radial HFR is often higher (below). Wavenumber spectra of **u** and **v** (not shown) become shallow at $k > (18\,\mathrm{km})^{-1}$, indicating limitations of the 6km gridded product.



Maps of correlation coefficients of radial velocities. Low-passed HFR has noticeably higher correlation with SWOT than unfiltered. SWOT fit to 50km x 50km box for calculating $\mathbf{u}_g$. Thick lines = 0.5, thin lines = 0.75.



Correlation as a function of fitting window for polynomial fit to SSHA. Larger windows improve agreement with HFR. Low-passing HFR further improves correlation (right) but cyclogeo. estimate does not.

Methods

$\mathbf{u}_g$ Geostrophic velocity calculated using polynomial fitting method of Tranchant et al. (2025) on η', varying the radius of fitting. This smooths η', reducing noise and unbalanced signals but also small balanced processes.

$\mathbf{u}_{cg}$ Cyclogeostrophic correction uses a single iteration of the iterative method outlined in Penven et al. (2014).

$$\mathbf{u}^{(n+1)} = \mathbf{u}_g + \frac{\hat{\mathbf{k}}}{f} \times (\mathbf{u}^{(n)} \cdot \nabla \mathbf{u}^{(n)})$$

$\mathbf{u}^{\mathrm{HFR}}$ Isolate the rotational component of HFR velocity via Helmholtz decomposition.

$\mathbf{u}^{\mathrm{HFR}}_{\mathrm{LP}}$ Low-pass HFR velocities by convolving with a 36 hr Hann window in time.

Conclusions

1. Sub-50 km features are observed in all three data sets.
2. Currents derived from SWOT are largely correlated with HFR. Some very small features are seen in SSHA and SST but not HFR velocities.
3. Cyclogeostrophy only notably improves agreement in a strong cyclonic eddy, otherwise makes little difference.
4. Larger fitting window on SWOT and low-passing HFR both improve correlation, as does use of radial HFR data.

Future Work

- Expand analysis to science orbit and regions with greater HFR coverage.
- Determine if 2 km gridded HFR avoids issues of 6 km product.
- How close to the coast and at what scales can SWOT estimate coastal circulation?

References

Penven, P., I. Halo, S. Pous, and L. Marié, **2014**: Cyclogeostrophic balance in the Mozambique Channel. *J.G.R. Oceans.*, **119**, 1054–1067, https://doi.org/10.1002/2013JC009528.

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Tranchant, Y.-T., Legresy, B., Foppert, A., Pena-Molino, B., & Phillips, H. , **2025**: SWOT Reveals Fine-Scale Balanced Motions Driving Near-Surface Currents and Dispersion in the Antarctic Circumpolar Current. *Earth and Space Sci.*, **12**, e2025EA004248, https://doi.org/10.1029/2025EA004248.

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