

Wind and Current Couplings at Low and High Winds

Ernesto Rodriguez, Alex Wineteer and Hector Torres
Jet Propulsion Laboratory, Caltech

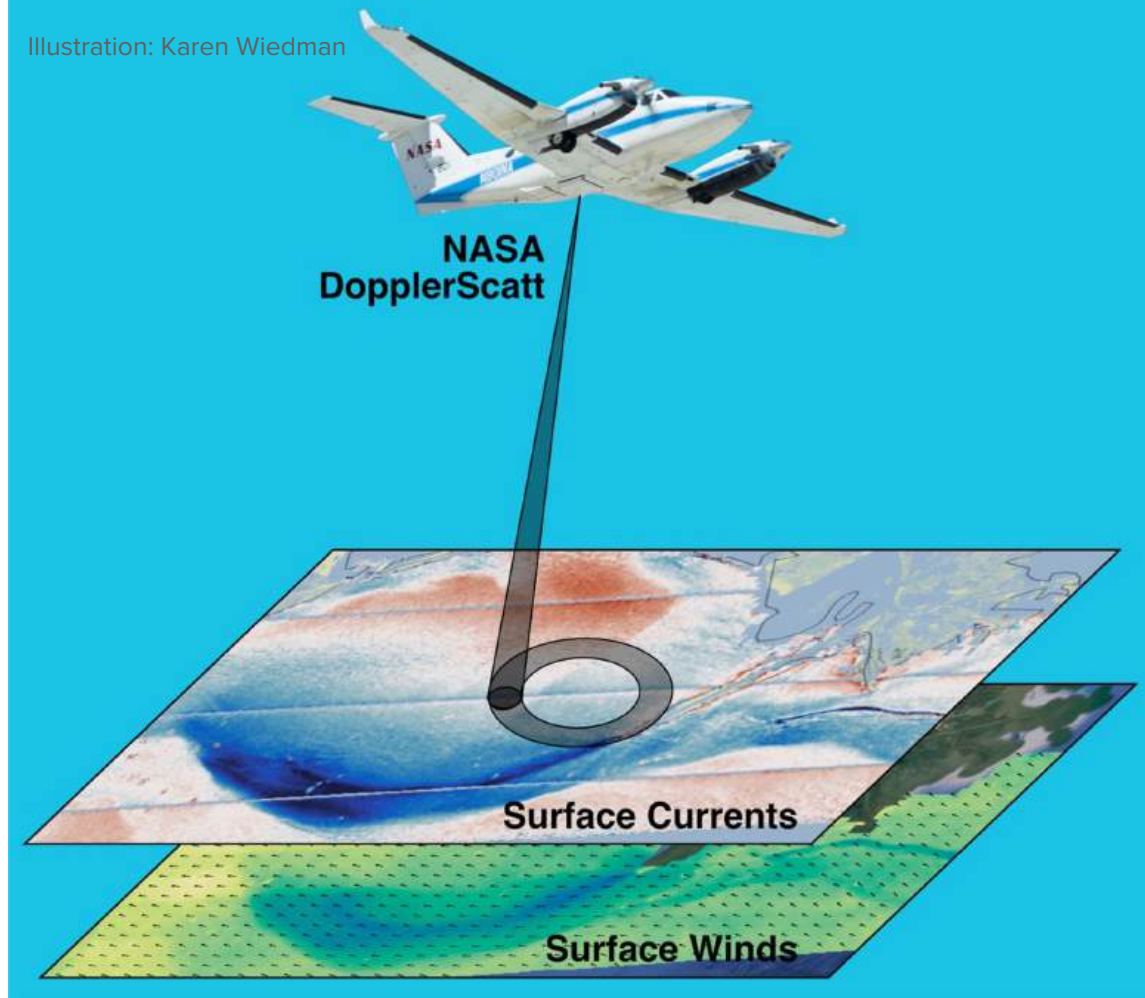
Ka-band Doppler scatterometer to measure **neutral** winds and currents simultaneously $O(300\text{m})$ resolution

Neutral winds \sim wind stress

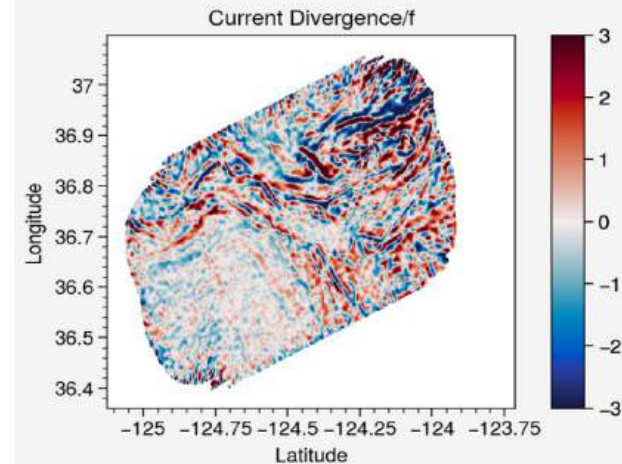
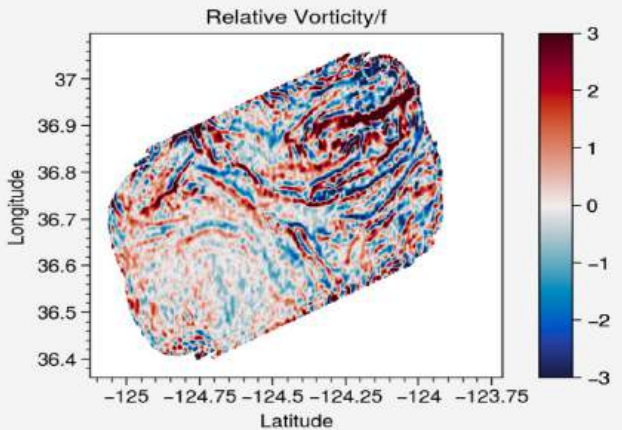
Nearly 2 months of data acquired during NASA EVS-3 S-MODE. Near daily $100\text{km} \times 40\text{km}$ synoptic maps.

Data available in NASA PODAAC

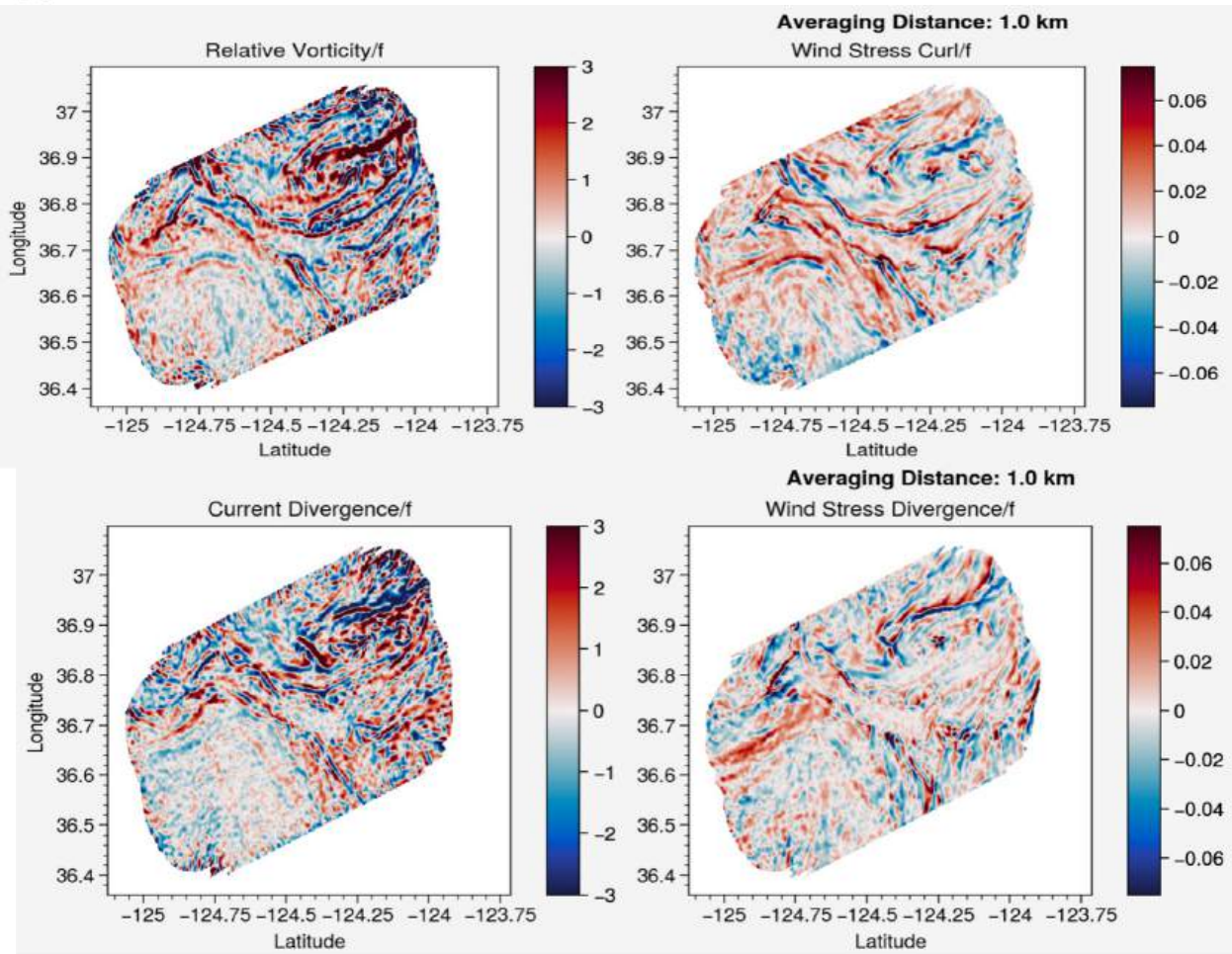
Illustration: Karen Wiedman



Filaments (low winds), wind stress derivatives



Filaments (low winds), wind stress derivatives

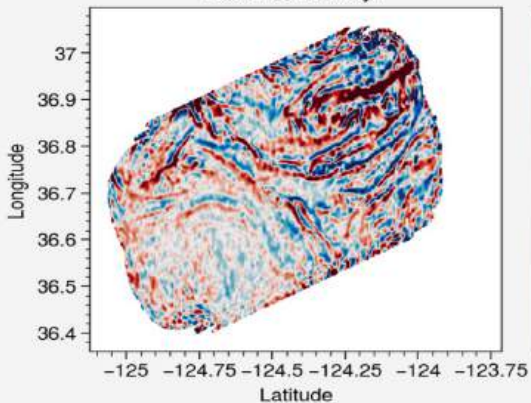


Filaments (low winds), wind stress derivatives

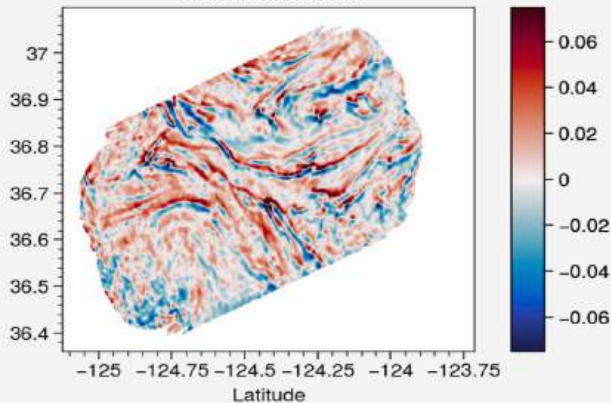


Averaging Distance: 1.0 km

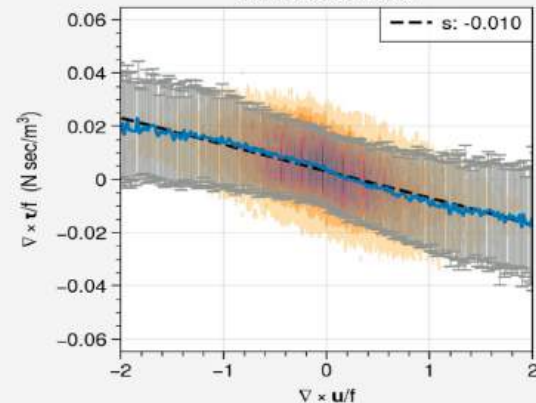
Relative Vorticity/ f



Wind Stress Curl/ f

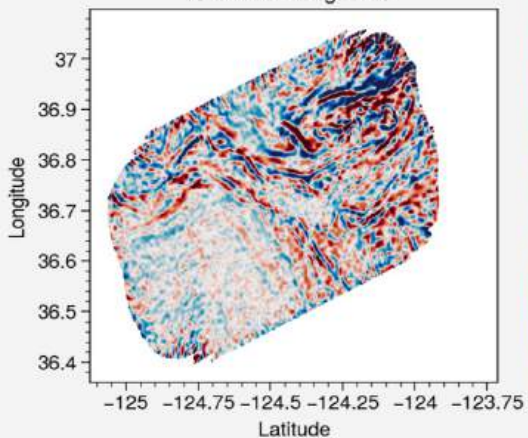


Correlation: -0.55

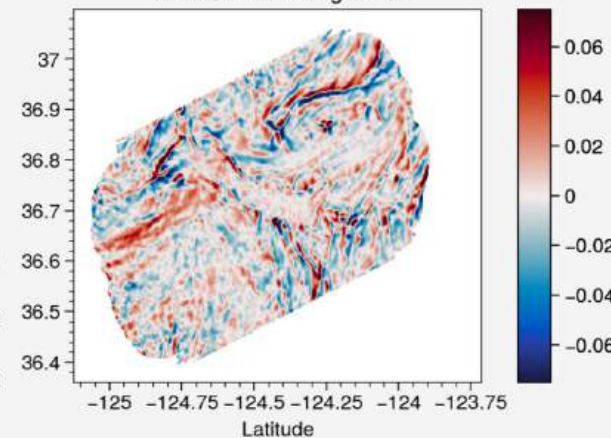


Averaging Distance: 1.0 km

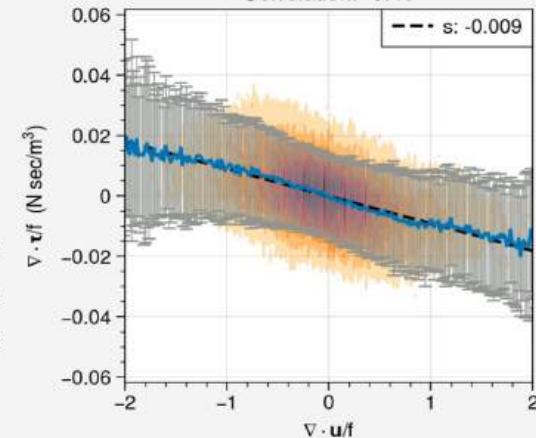
Current Divergence/ f



Wind Stress Divergence/ f

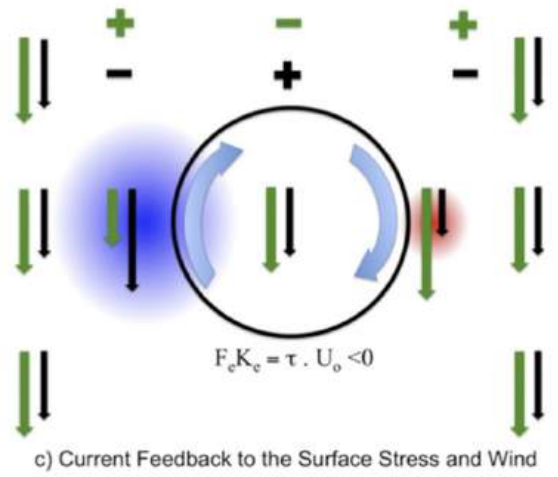
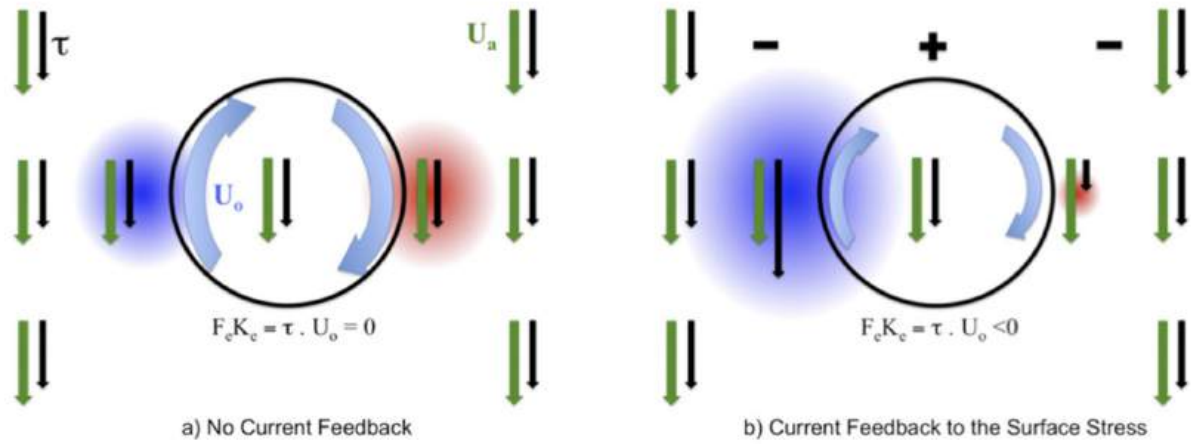


Correlation: -0.46



Wind modulation by the ocean

- The modulation of winds by SST fronts has been known since Chelton et al (2004), with many subsequent contributions.
- Renault et al (2016 and subsequent publications) showed that the impact of surface currents on winds/wind stress (and vice versa) could not be ignored
 - Impact through the surface current dependence of wind stress
 - Also secondary impacts on atmospheric winds (not stress)
 - Experimental studies using scatterometer winds and geostrophic currents
 - Modeling studies using models at different resolutions.
 - Bai et al (2023) and Conejero et al. (2024) looked at model coupling for both SST and Currents
- Questions addressed here:
 - How does the coupling depend on spatial scale for real data?
 - How does the coupling depend of atmospheric stability conditions?
 - Do curls and divergences couple in the same way?
- **Not addressed here** (but in the works): experimental SST-current coupling at high spatial resolution

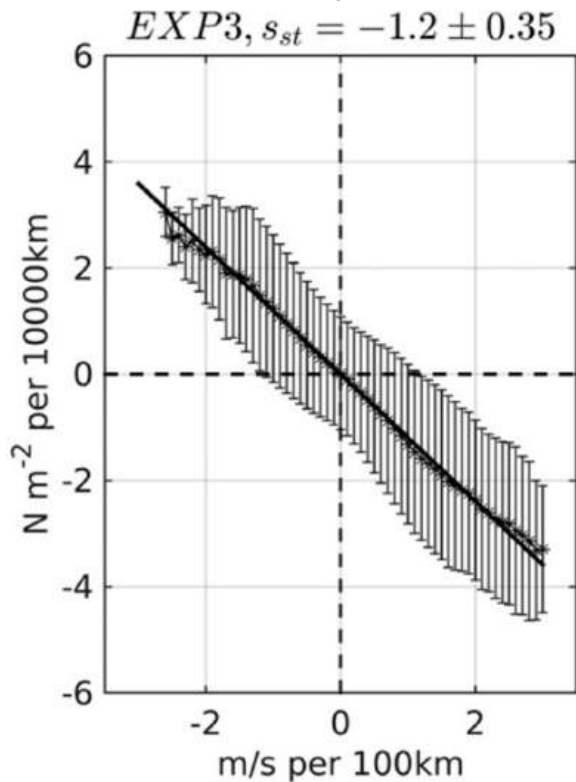


Renault, L., Molemaker, J. M., Gula, J., Masson, S., & McWilliams, J. C. (2016). Control and Stabilization of the Gulf Stream by Oceanic Current Interaction with the Atmosphere. *Journal of Physical Oceanography*. <https://doi.org/10.1175/jpo-d-16-0115.1>

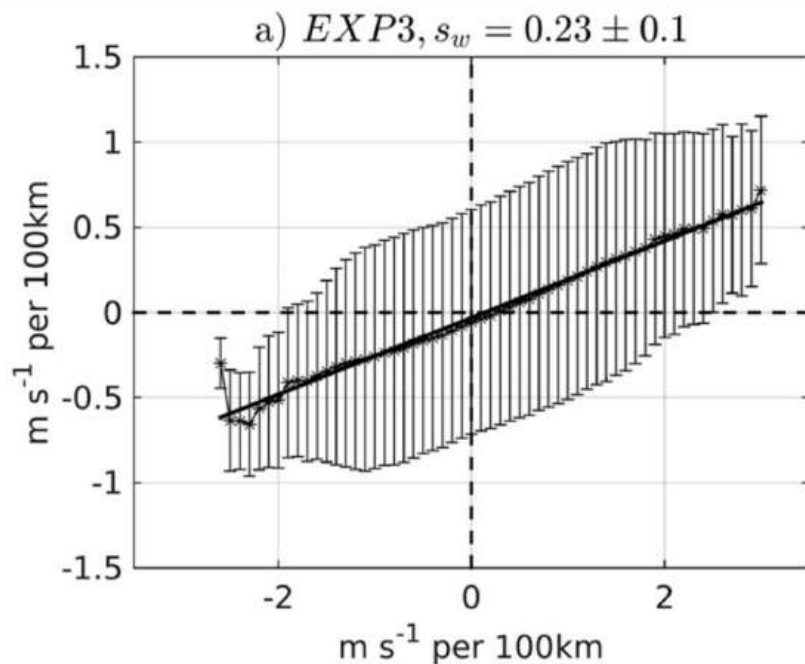
Renault et al. (2019) results

Renault, L., Molemaker, M. J., McWilliams, J. C., Shchepetkin, A. F., Lemarié, F., Chelton, D., et al. (2016) Modulation of Wind Work by Oceanic Current Interaction with the Atmosphere. *Journal of Physical Oceanography*, 46(6), 1685–1704. <https://doi.org/10.1175/jpo-d-15-0232.1>

Relative Vorticity - Wind stress curl

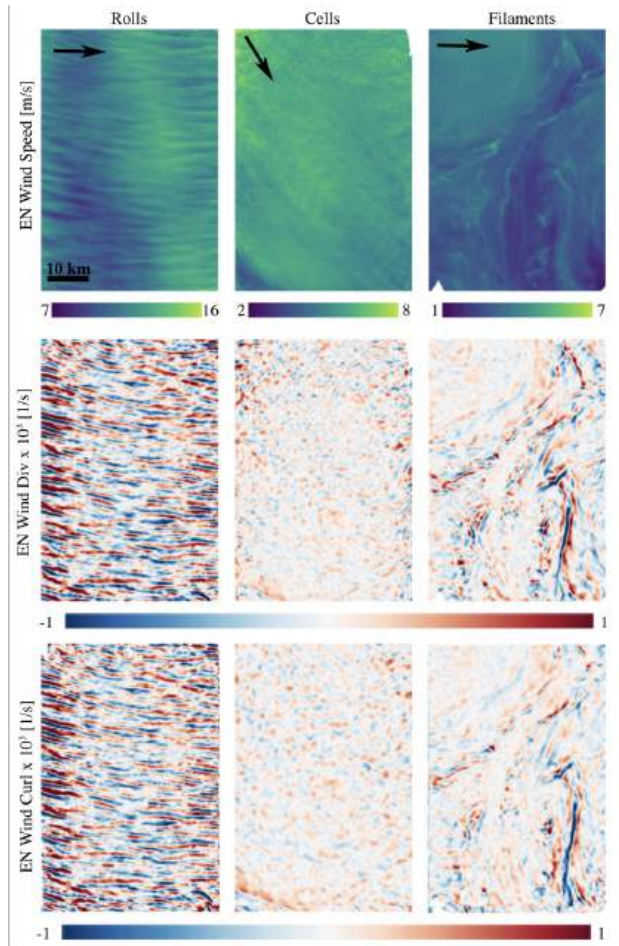


Relative Vorticity - curl atmospheric wind



Binned scatterplot of the full time series of 1-month running means of surface stress curl and surface current vorticity over the domain 30° to 45°N and $(150 < d < 500 \text{ km})$. The bars indicate plus and minus one the standard deviation about the average drawn by stars. The linear regression is indicated by a black line, and the slope s is indicated in the title

Stability conditions from wind texture



- Wind “texture” has been used to estimate surface layer stratification/Richardson number (Stopa et al. 2022) and Obukhov length (O’Driscoll et al. 2023).
- To examine the dependence of air-sea coupling on atmospheric conditions, we classify (by eye) the wind field different textures observed during the S-MODE deployments.
- Question: does the nature of the air sea coupling depend on the stability conditions?

Stopa, J. E., Wang, C., Vandemark, D., Foster, R., Mouche, A., & Chapron, B. (2022). Automated Global Classification of Surface Layer Stratification Using High-Resolution Sea Surface Roughness Measurements by Satellite Synthetic Aperture Radar. *Geophysical Research Letters*, 49(12). <https://doi.org/10.1029/2022gl098686>

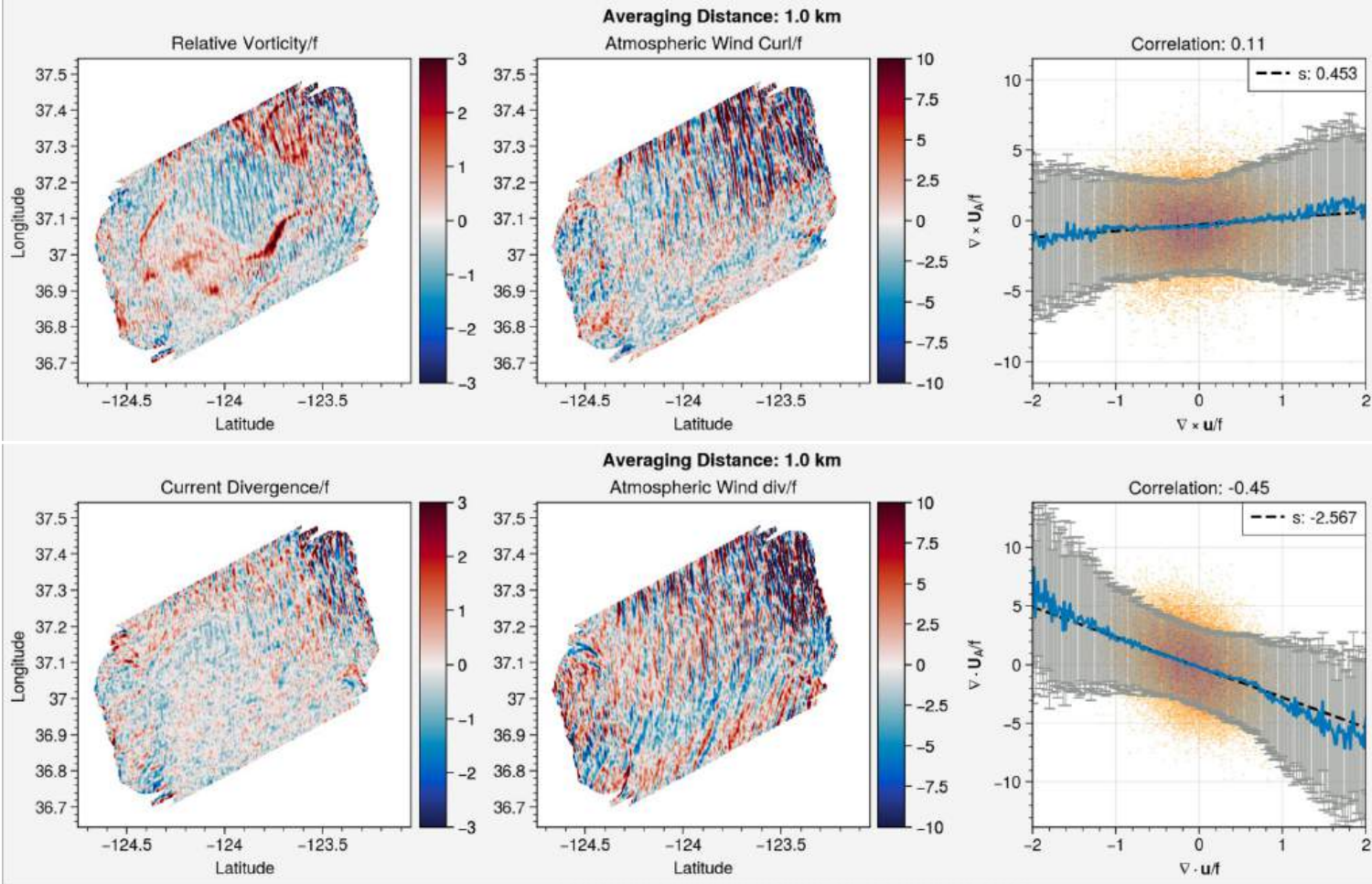
O’Driscoll, O., Mouche, A., Chapron, B., Kleinherenbrink, M., & López-Dekker, P. (2023). Obukhov Length Estimation From Spaceborne Radars. *Geophysical Research Letters*, 50(15). <https://doi.org/10.1029/2023gl104228>

Approximating the atmospheric wind from DopplerScatt data

$$\mathbf{U}_{Neutral} \approx \mathbf{U}_{Atmosphere} - \mathbf{U}_{Ocean}$$

I.e., the atmospheric wind is approximated as the measured neutral wind after adding back the surface current. This is the neutral wind when no currents are present, but it is not quite the atmospheric wind, since the ocean stability conditions can make a difference between the neutral wind (no currents) and the true atmospheric wind.

Wind Rolls (high winds), wind derivatives



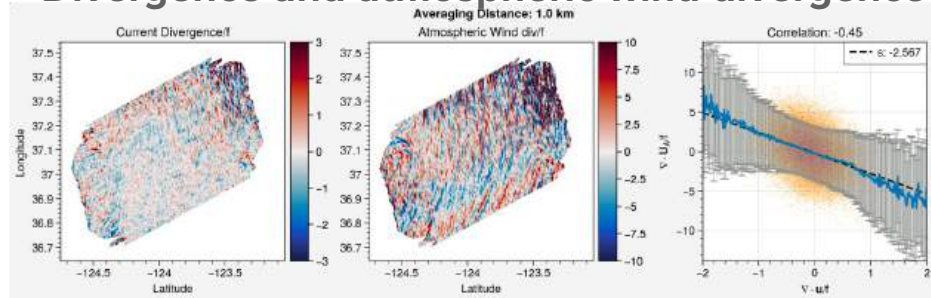
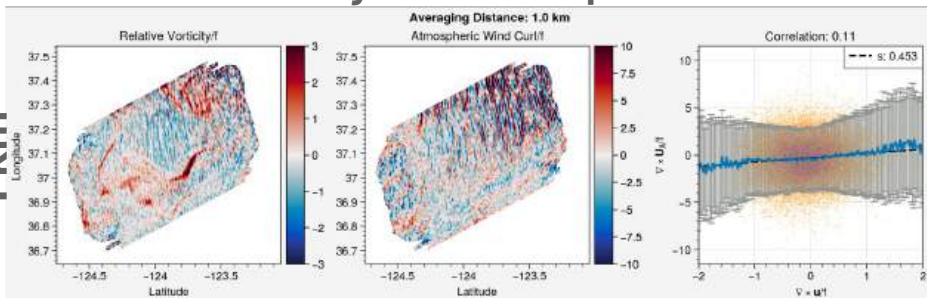
Atmospheric rolls: Coupling scale dependence



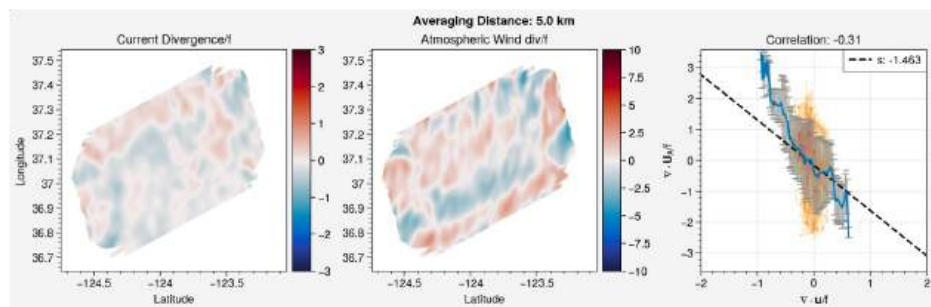
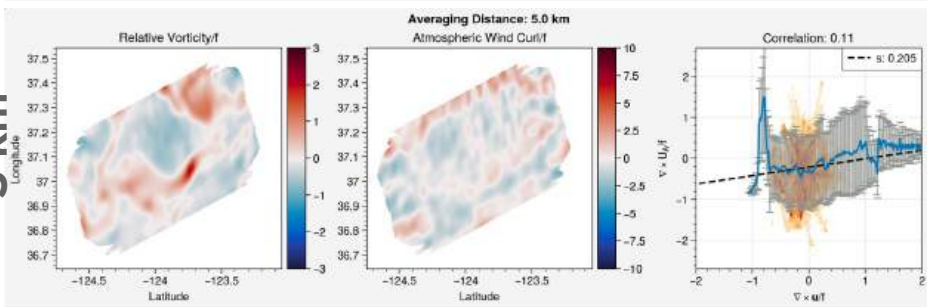
Relative vorticity and atmospheric wind curl

Divergence and atmospheric wind divergence

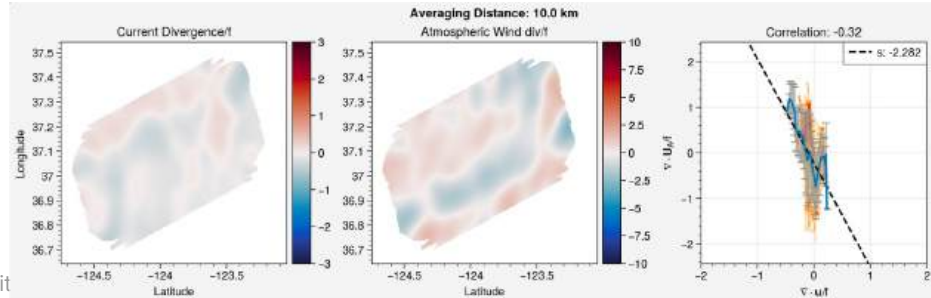
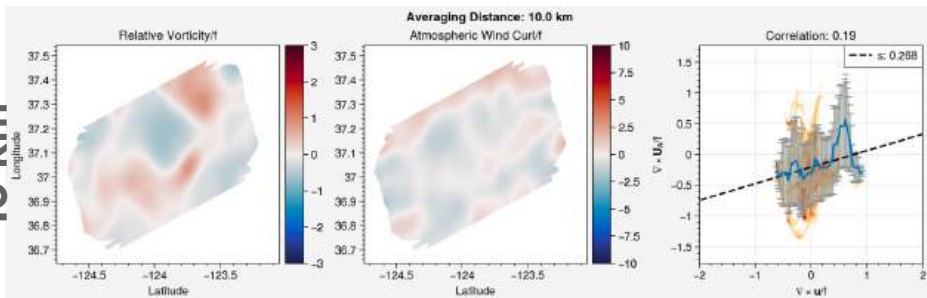
1 km



5 km



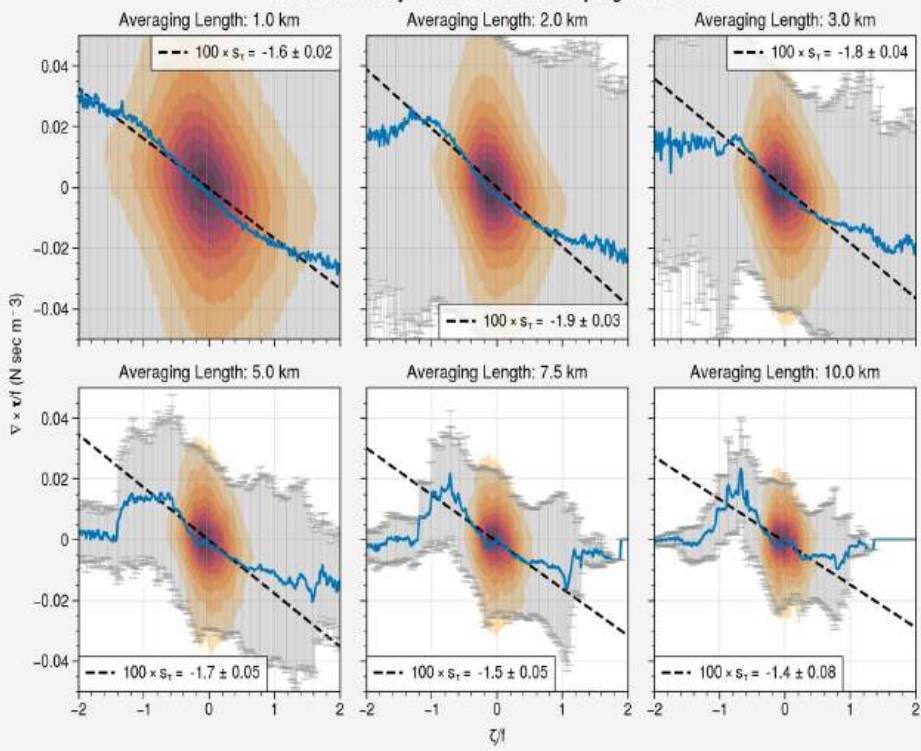
10 km



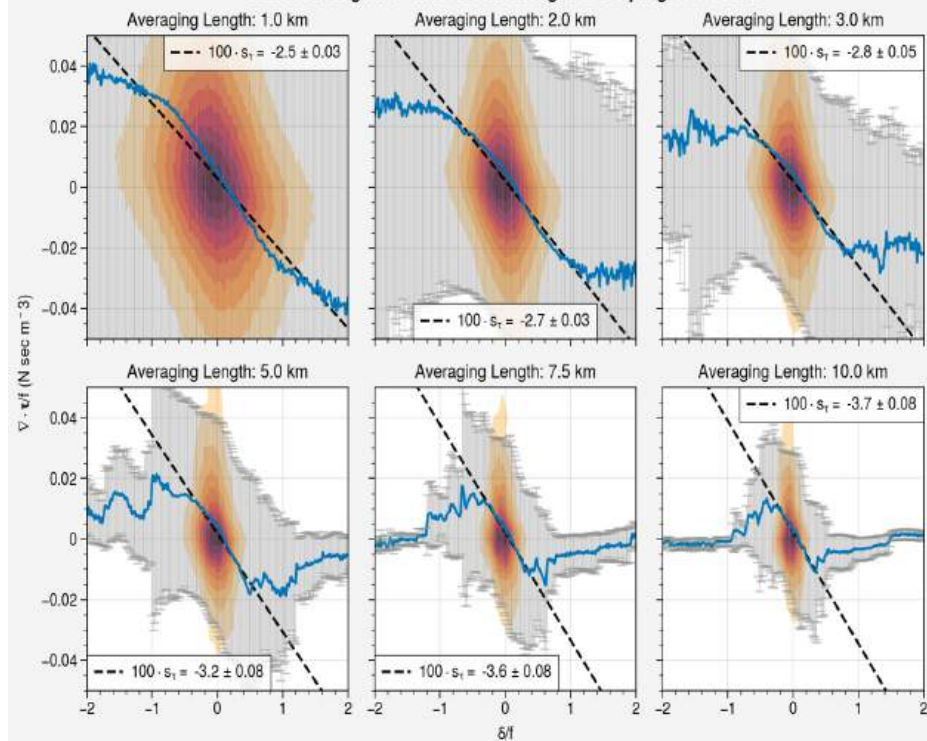
Relative vorticity and wind stress curl coupling

Divergence and wind stress divergence coupling

Relative Vorticity - Wind Stress Curl Coupling IOP1 + IOP2

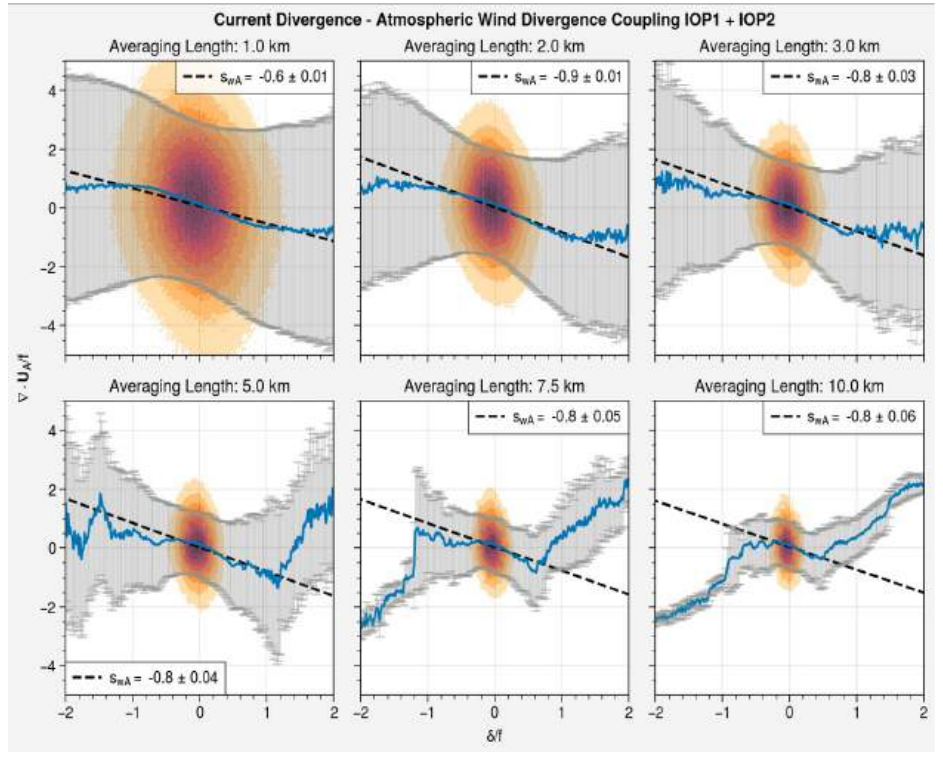
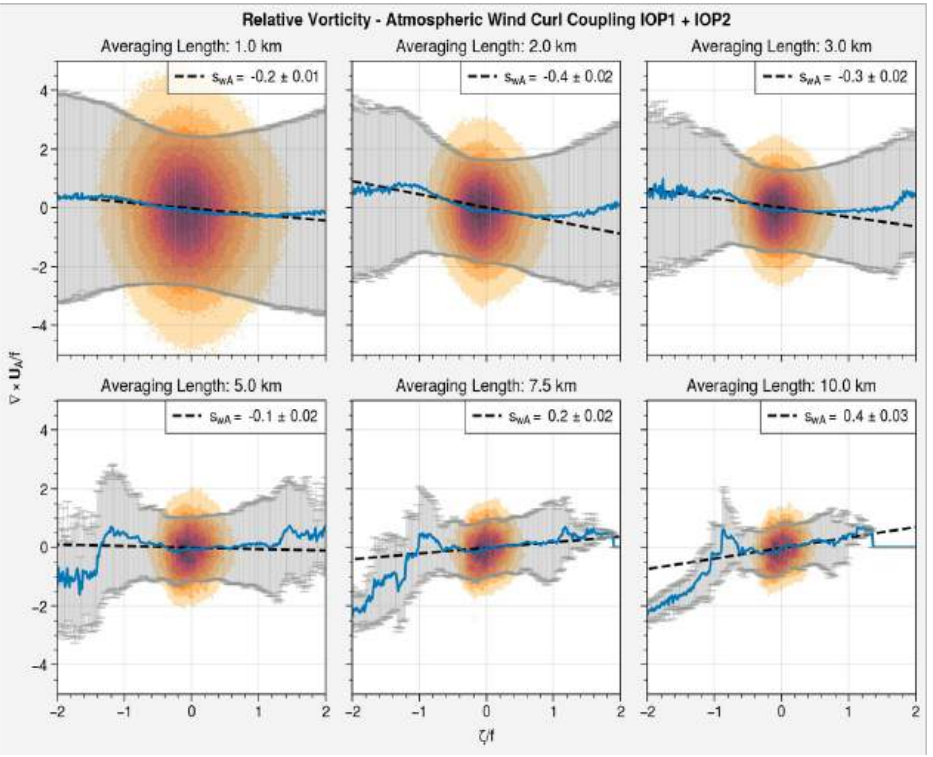


Current Divergence - Wind Stress Divergence Coupling IOP1 + IOP2



Relative vorticity and atmos. wind curl coupling

Divergence and atmos. wind divergence coupling





Curl Coupling

Divergence Coupling

wind stress

atmospheric wind

wind stress

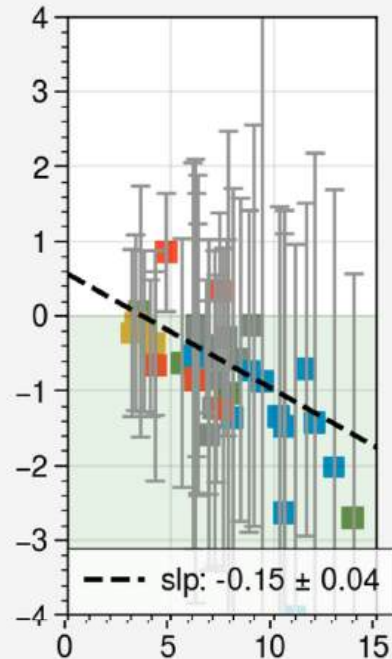
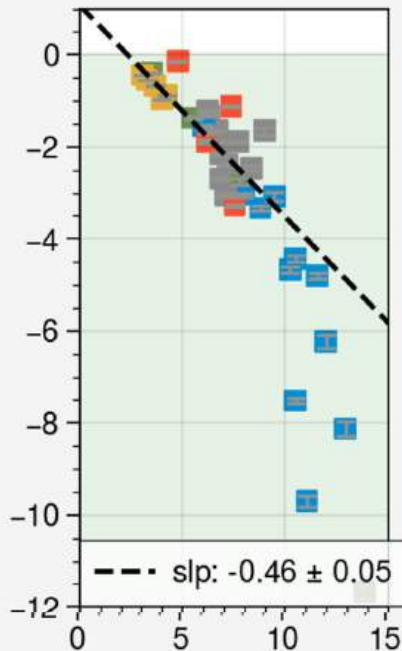
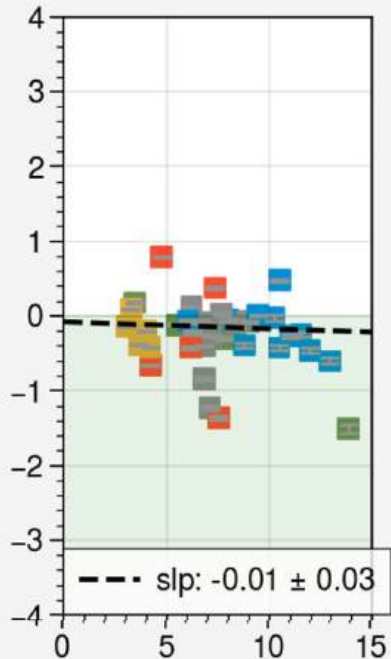
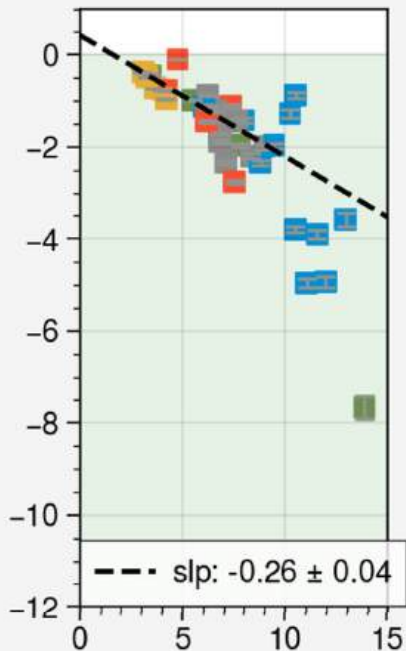
atmospheric wind

$$10^2 \times s_{\zeta\tau}$$

$$s_{\zeta w}$$

$$10^2 \times s_{\delta\tau}$$

$$s_{\delta w}$$



Wind Speed (m/s)

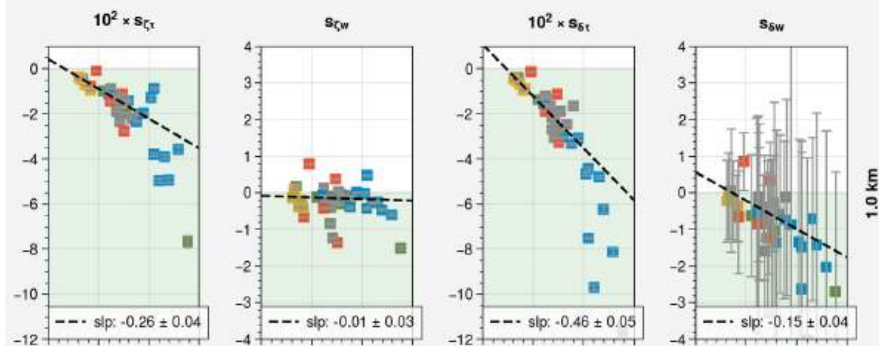
1.0 km



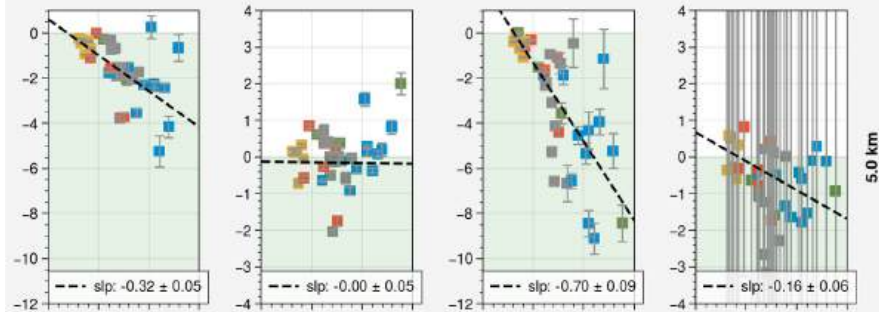
Coupling coefficient scale dependence



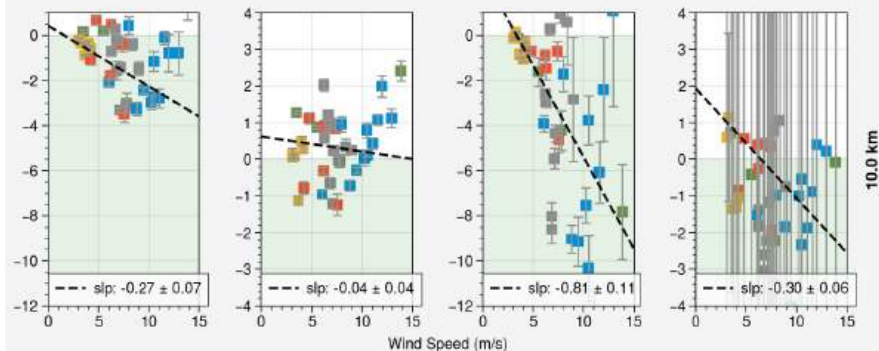
1 km



5 km



10 km



Correlation Coefficients

Wind Stress Correlation
curl
divergence

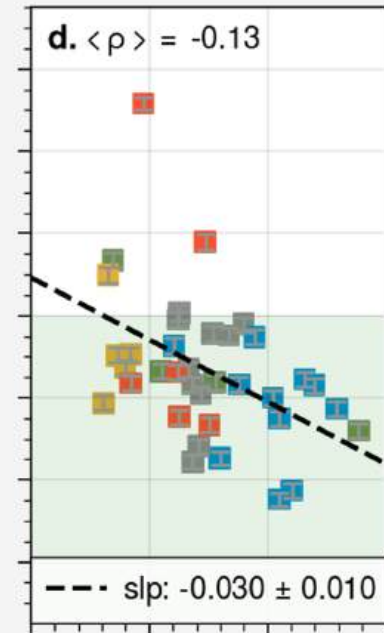
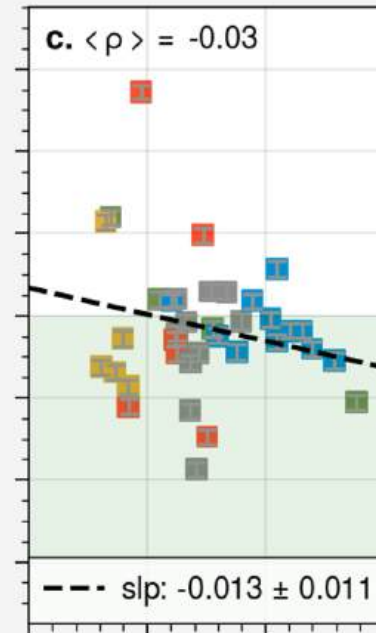
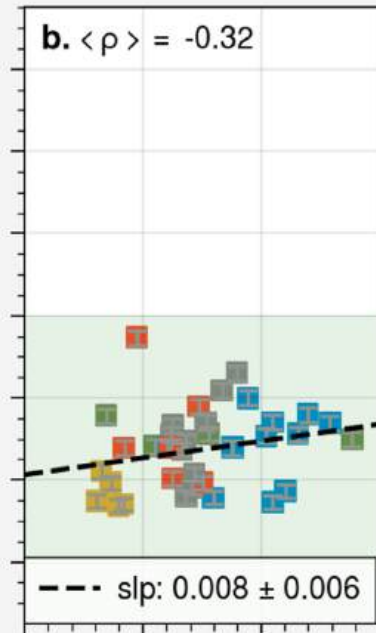
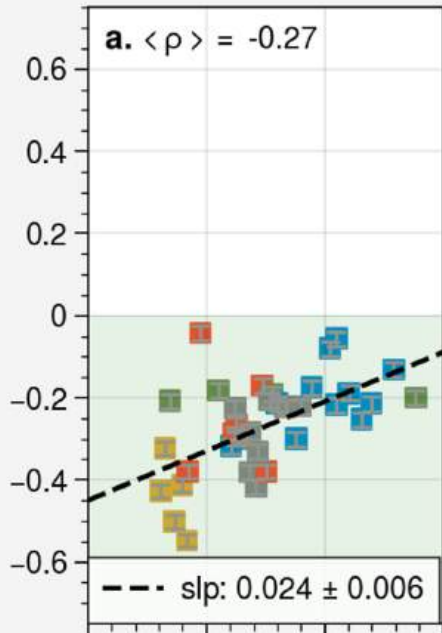
Atmospheric Wind Correlation
curl
divergence

$\text{Corr}(\zeta/f, \nabla \times \tau)$

$\text{Corr}(\delta/f, \nabla \cdot \tau)$

$\text{Corr}(\zeta/f, \nabla \times \mathbf{U}_{10N})$

$\text{Corr}(\delta/f, \nabla \cdot \mathbf{U}_{10N})$



1.0 km



Wind Coupling Summary

- High-resolution measurements validated previously obtained ranges and wind speed dependence of the **vorticity to wind-stress curl** coupling coefficient
 - The **divergence to wind-stress divergence** coupling coefficient is almost 2x the curl coefficient.
- The **vorticity to wind vorticity** coupling coefficient can be positive or negative, and generally increases with decreased resolution
 - It is not generally > 0 at high resolution (as in Renault et al, 2016)
- Coupling coefficients for **vorticity and divergence** can be best explained assuming that the **correlation** value is primary, and the slope of the coupling relationship is governed by the ratio of the standard deviations of wind and current derivatives.
 - The wind dependence is driven by the non-linear dependence of wind stress derivative standard deviation on the wind speed.
- At high resolutions, winds and currents are tightly coupled, showing similar 2D spectral characteristics:
 - angular spreads
 - Spectral breaks
- Atmospheric rolls (high-winds) and filaments (low-winds) couple winds and currents in different ways
 - Rolls: drive current modulation in the direction perpendicular to the roll axis (**wind-driven**)
 - Filaments: couple both components to similar degrees (**current driven**)



Backups

Relation between coupling coefficient and correlation for Gaussians

$$\langle \nabla \times \tau \rangle_{\zeta} = \left(\frac{\sigma(\nabla \times \tau)}{\sigma(\zeta)} \rho(\zeta, \nabla \times \tau) \right) \zeta$$

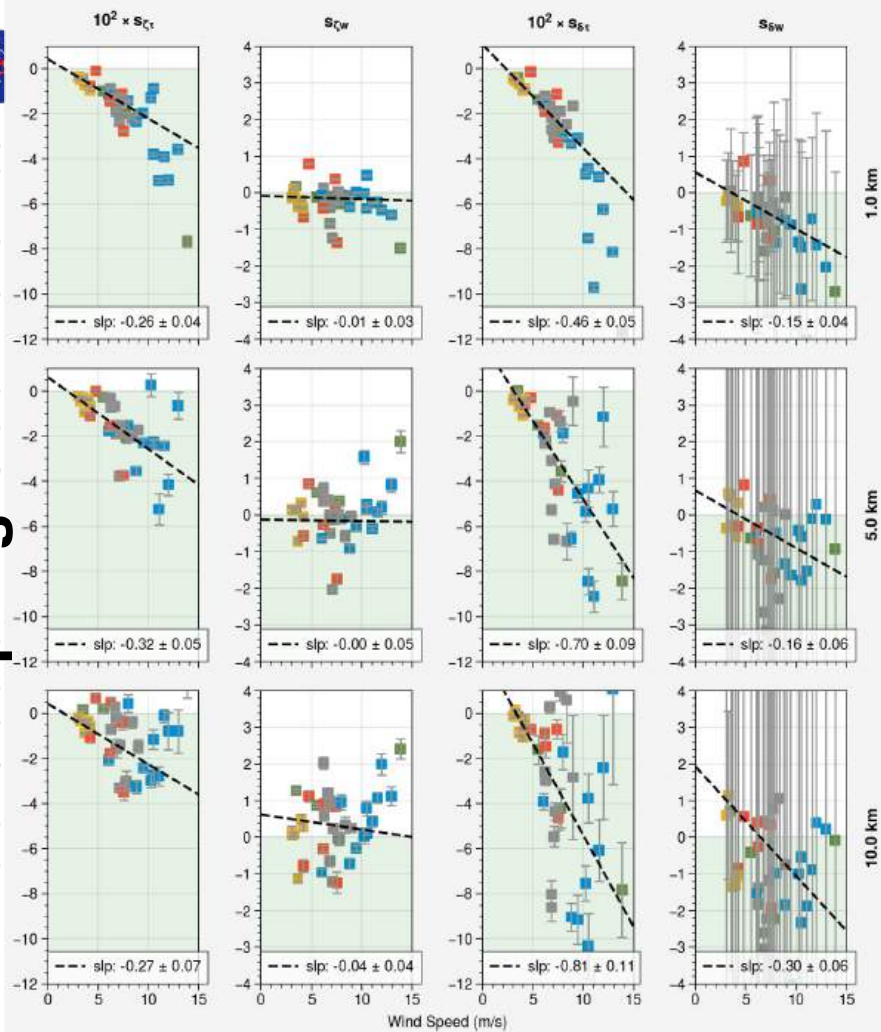
$$\langle \nabla \cdot \tau \rangle_{\delta} = \left(\frac{\sigma(\nabla \cdot \tau)}{\sigma(\delta)} \rho(\zeta, \nabla \cdot \tau) \right) \delta$$

σ Standard deviation

ρ Correlation coefficient

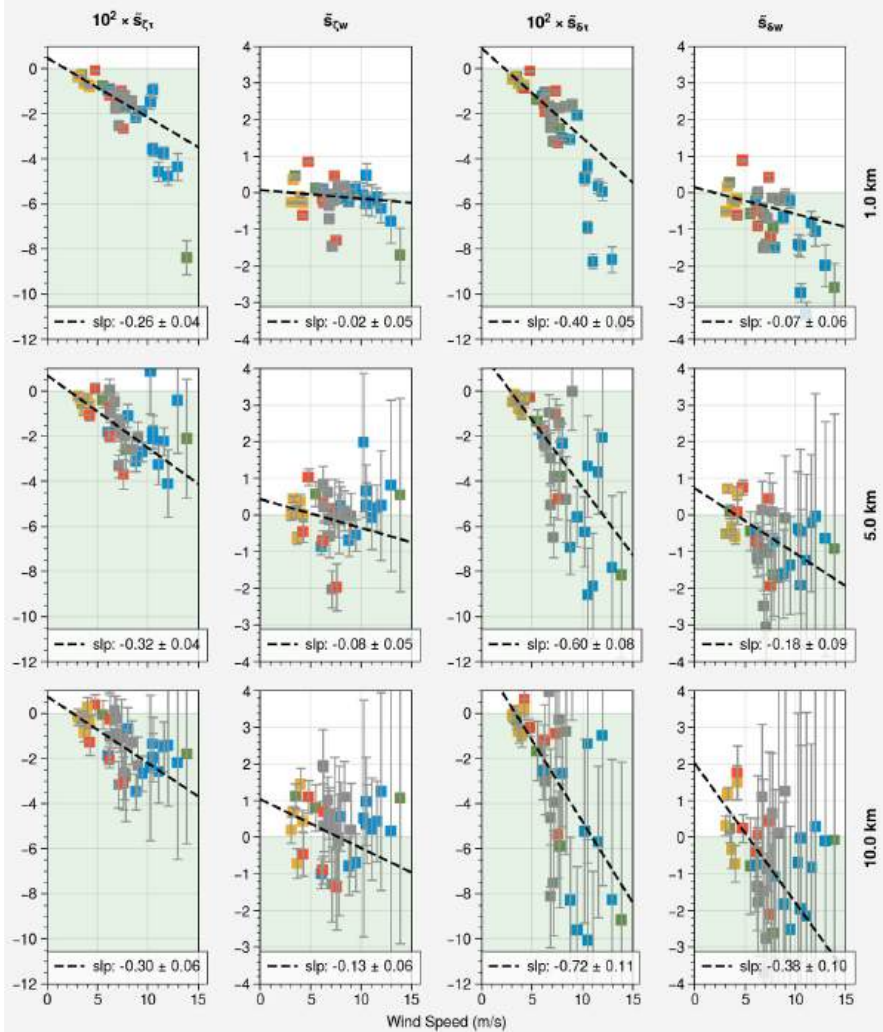
$$\sigma(\delta) < \sigma(\zeta) \implies |\langle \nabla \times \tau \rangle_{\zeta}| < |\langle \nabla \cdot \tau \rangle_{\delta}|$$

True Coupling Coefficients



■ atmospheric rolls ■ filaments ■ normal ■ unstable ■ mixed

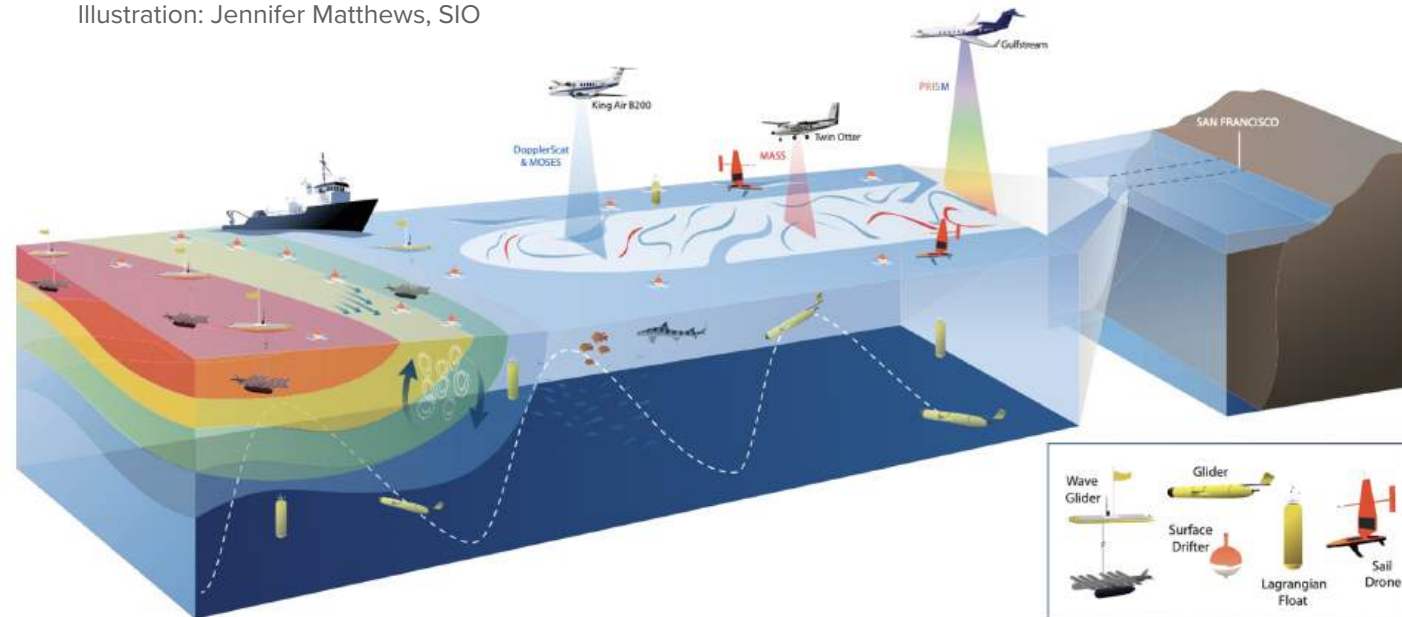
Gaussian Coupling Coefficients



■ atmospheric rolls ■ filaments ■ normal ■ unstable ■ mixed

Sub-Mesoscale Ocean Dynamics Experiment (S-MODE)

Illustration: Jennifer Matthews, SIO



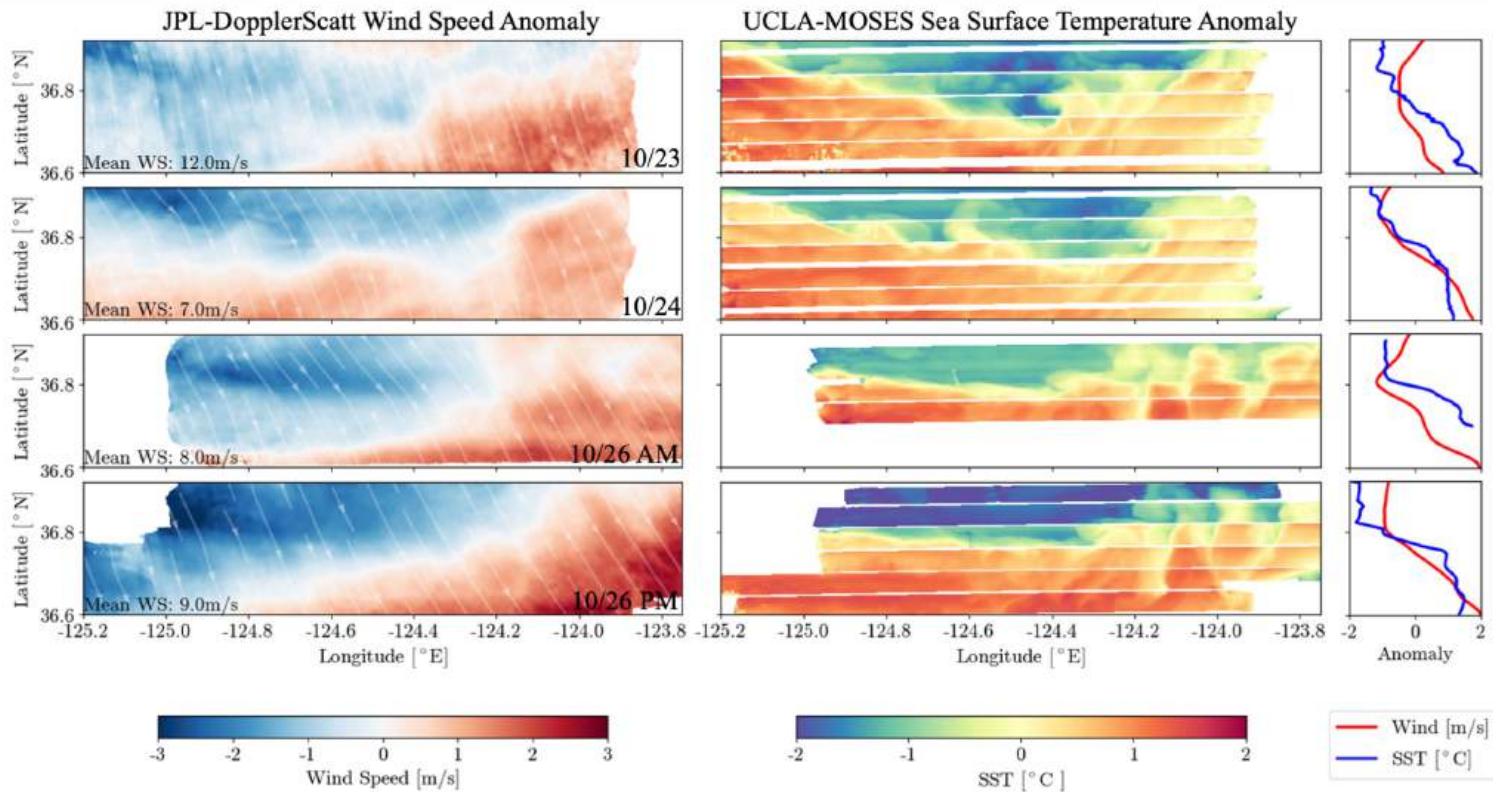
Data collected off the shelf in the California Current west of San Francisco.

54 Wind-Current flights collected over 3 campaigns in 2021, 2022 and 2023.

DopplerScatt data validated against multiple sources of wind and current measurements.

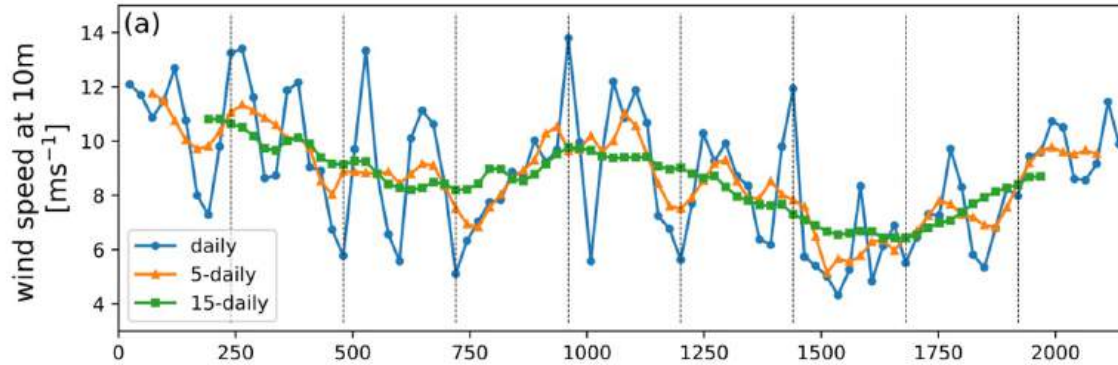
J. T. Farrar (PI), NASA EVS-3 mission

Modulation of winds by SST & currents: S-MODE example

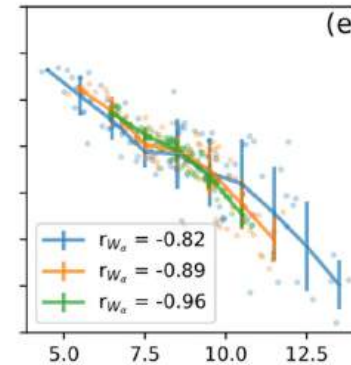
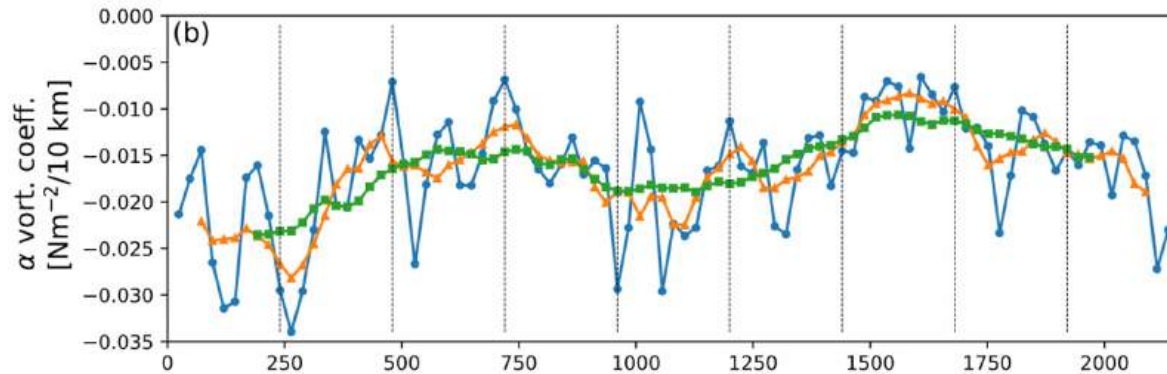


Courtesy A. Wineteer (JPL)

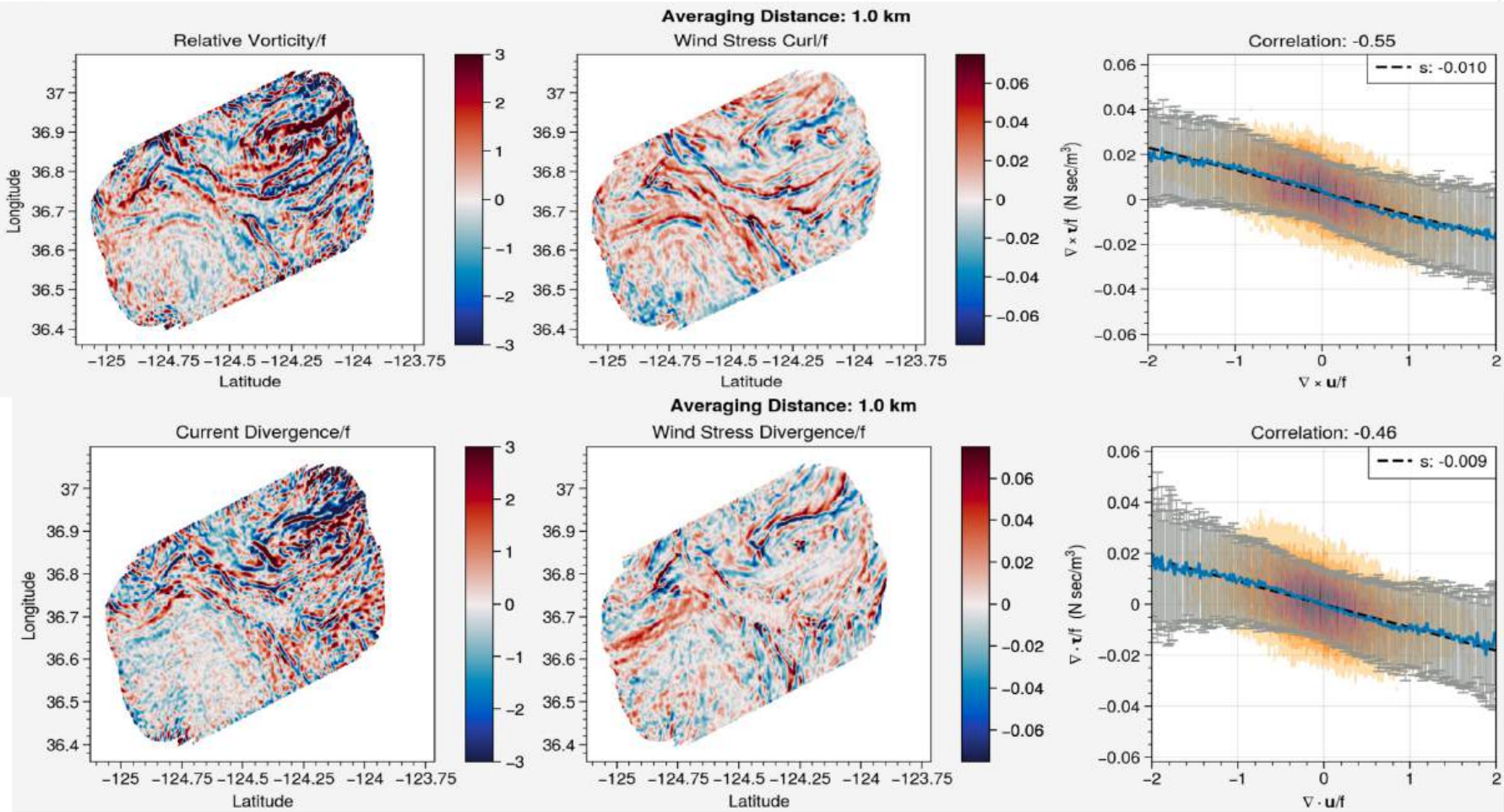
Bai et al. (GRL, 2023) results



Bai, Y., Thompson, A. F., Bôas, A. B. V., Klein, P., Torres, H. S., & Menemenlis, D. (2023). Sub-Mesoscale Wind-Front Interactions: The Combined Impact of Thermal and Current Feedback. *Geophysical Research Letters*, 50(18). <https://doi.org/10.1029/2023gl104807>

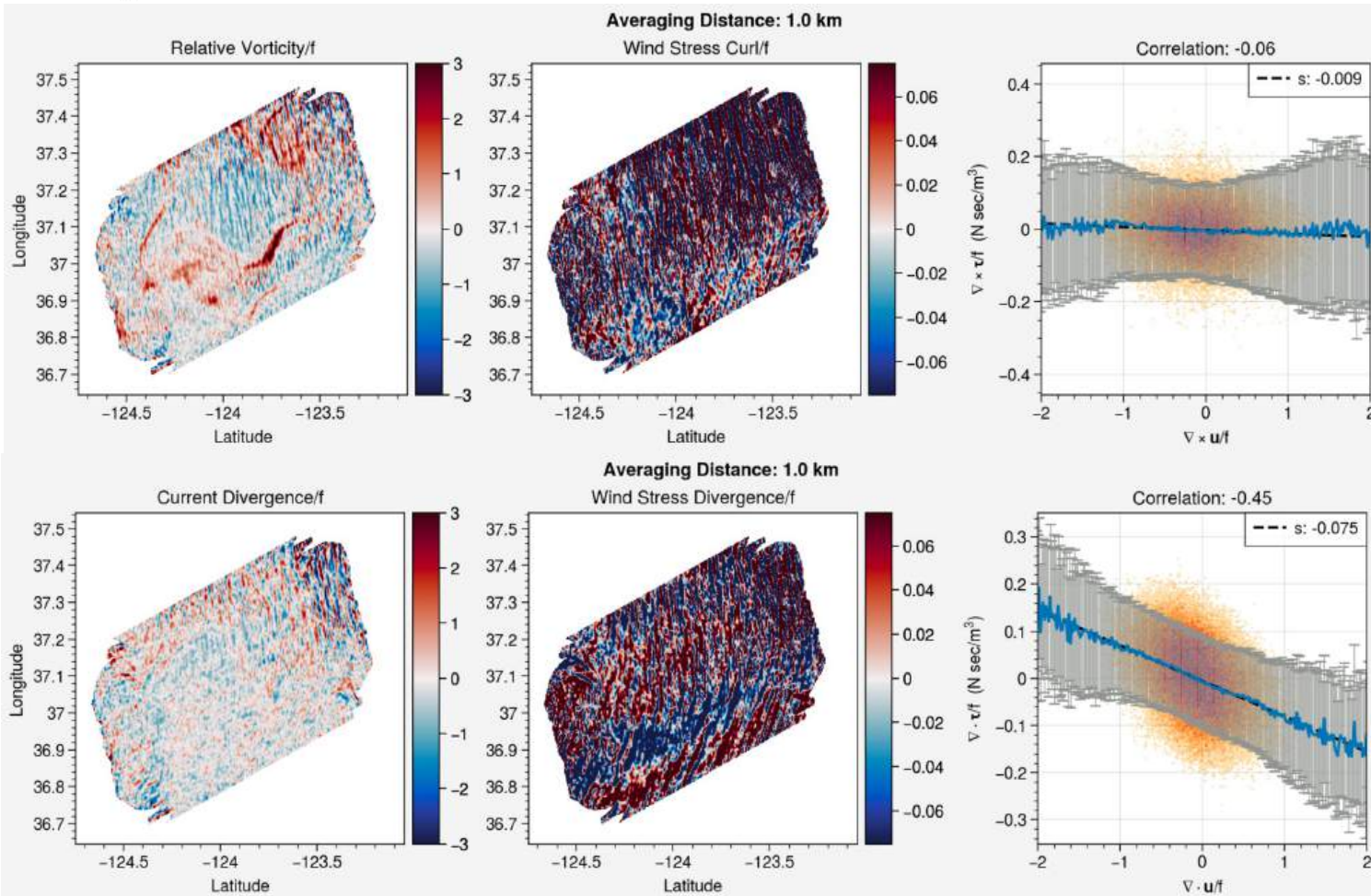


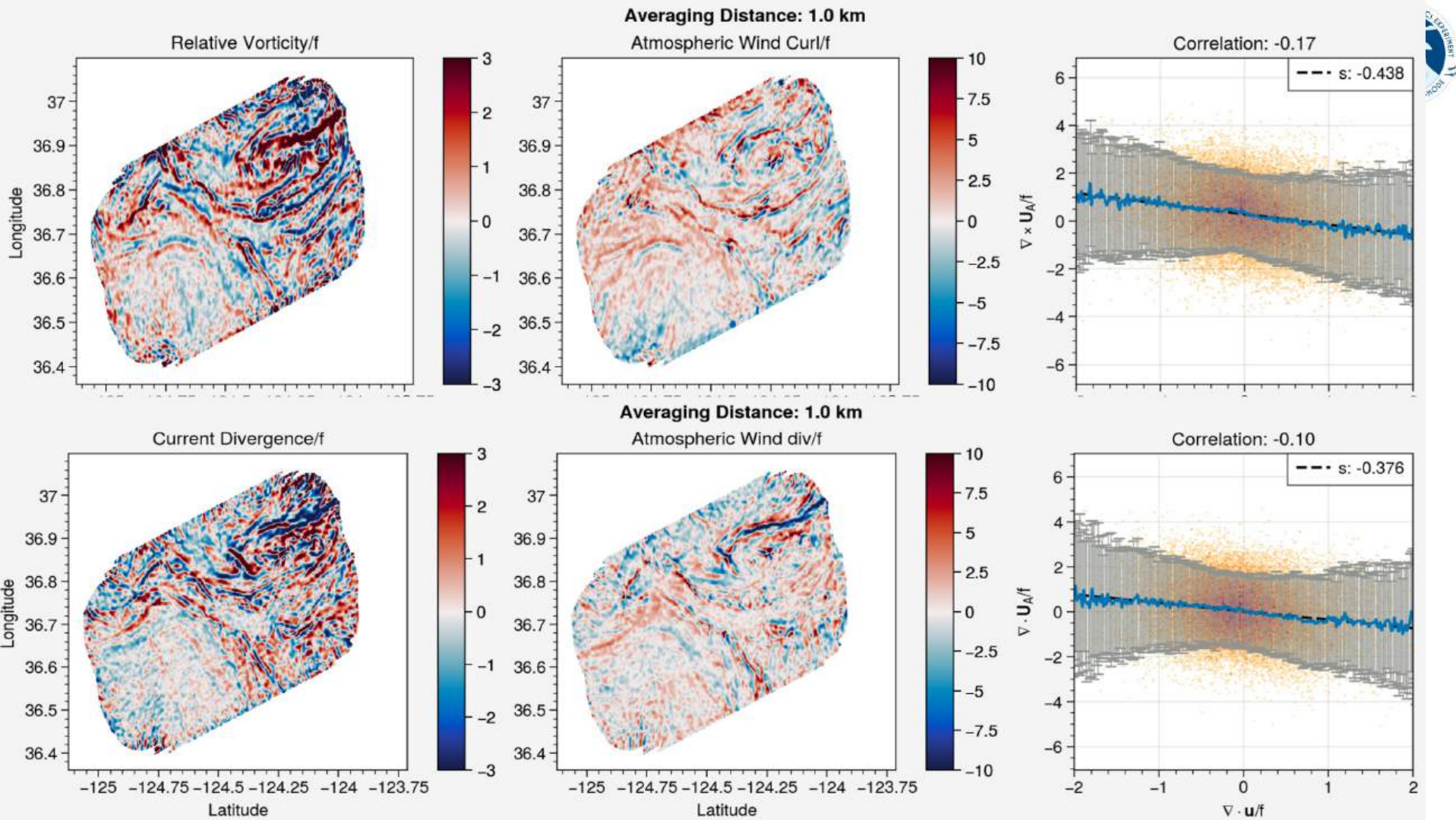
Filaments (low winds), wind stress derivatives





Wind Rolls (high winds), wind stress derivatives

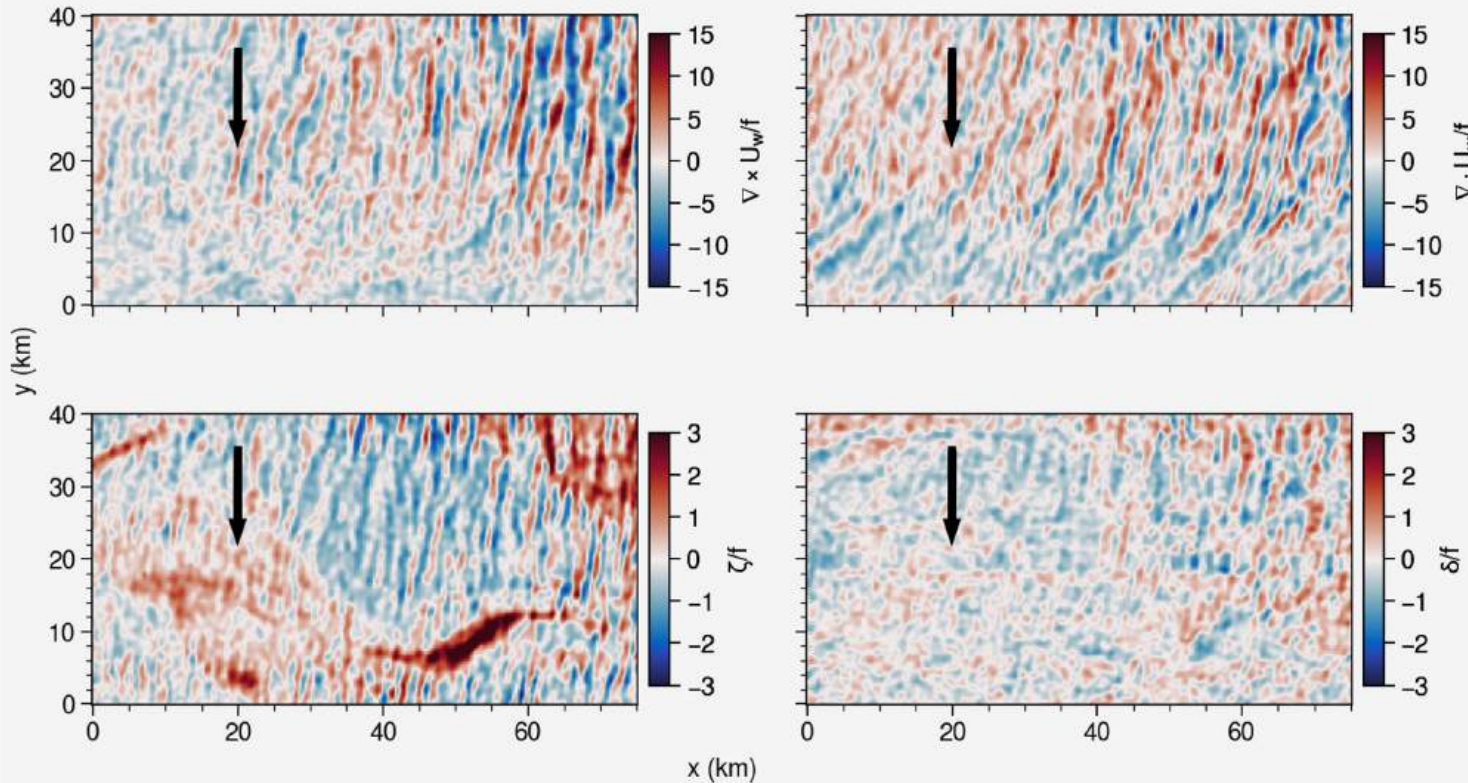




Wind Direction



2023-04-21T08

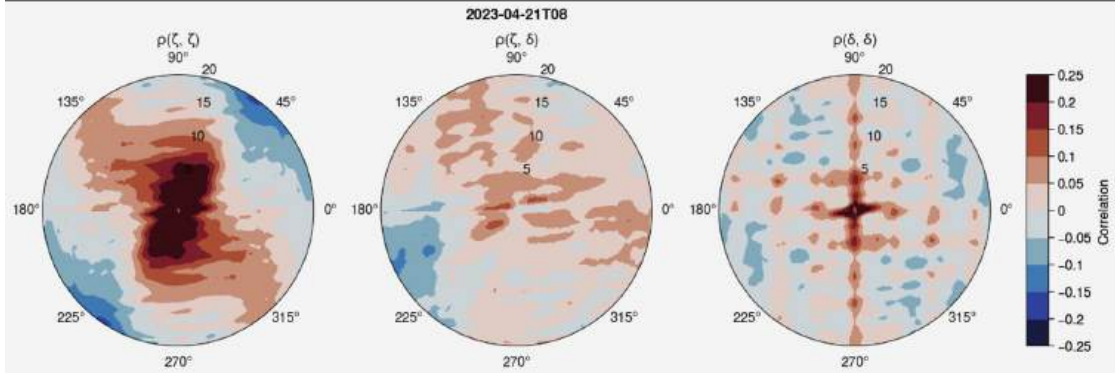
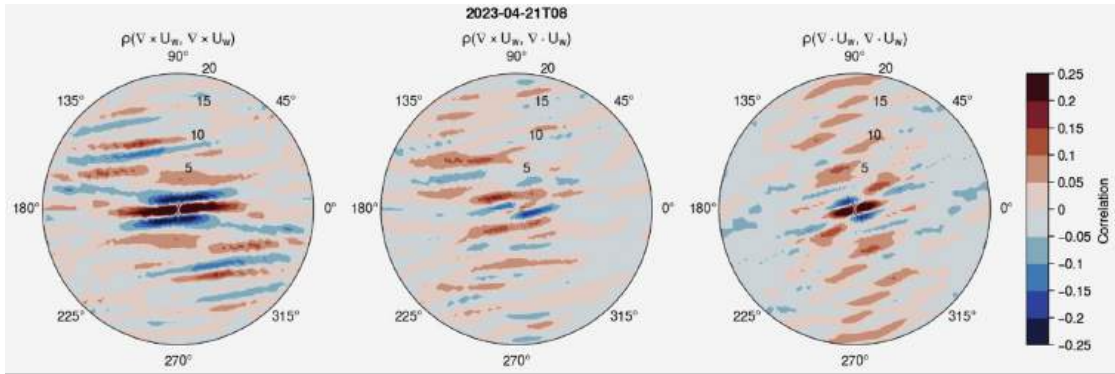


Wind

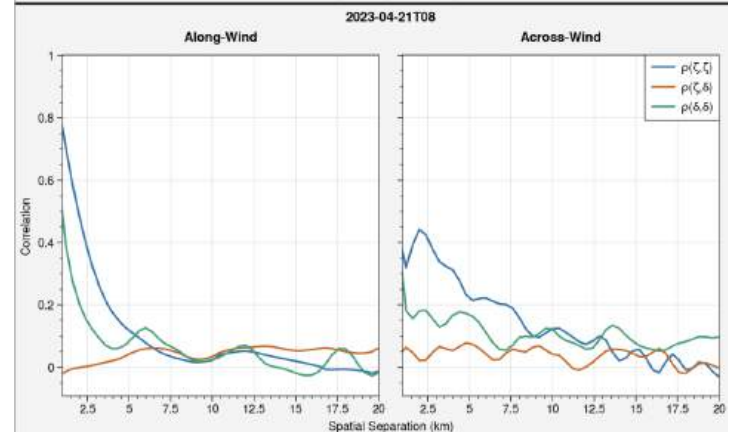
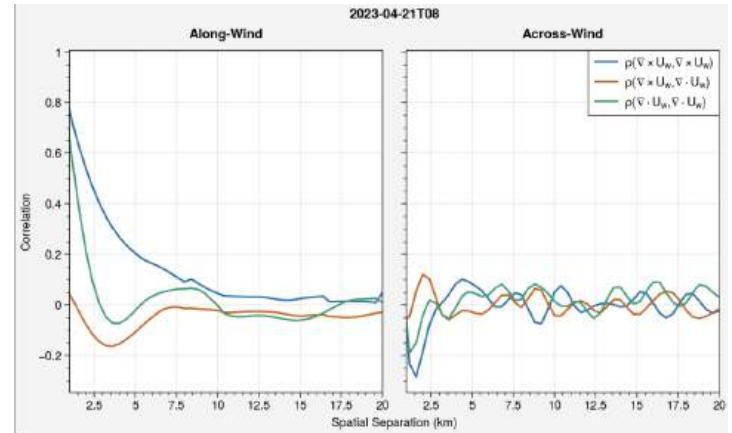
Currents

Curl

Divergence



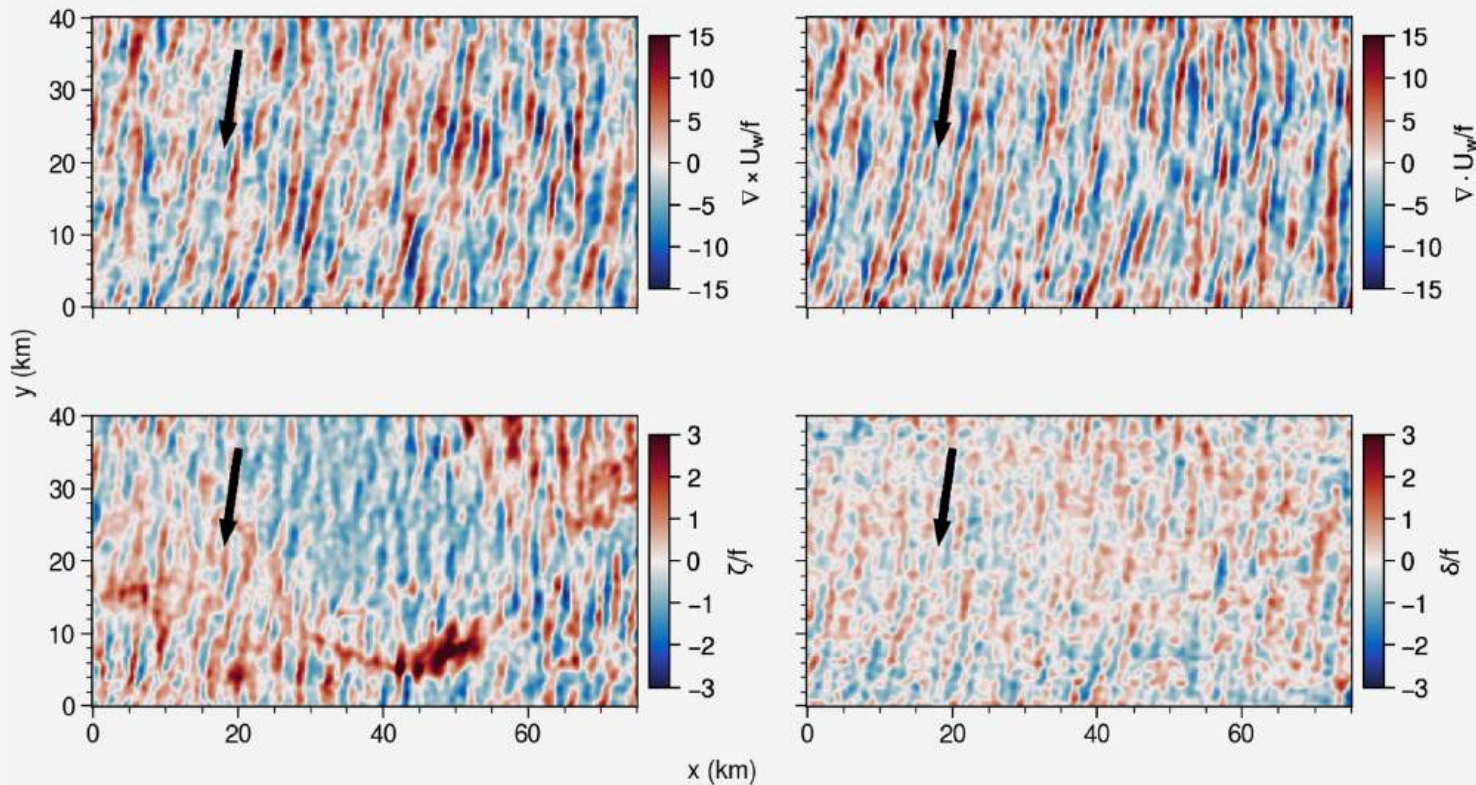
0° is along the wind direction



Wind Direction



2023-04-21T14

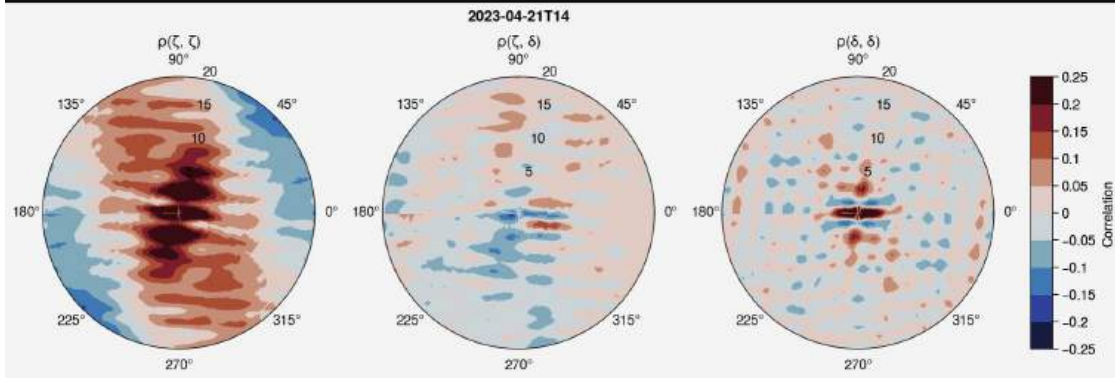
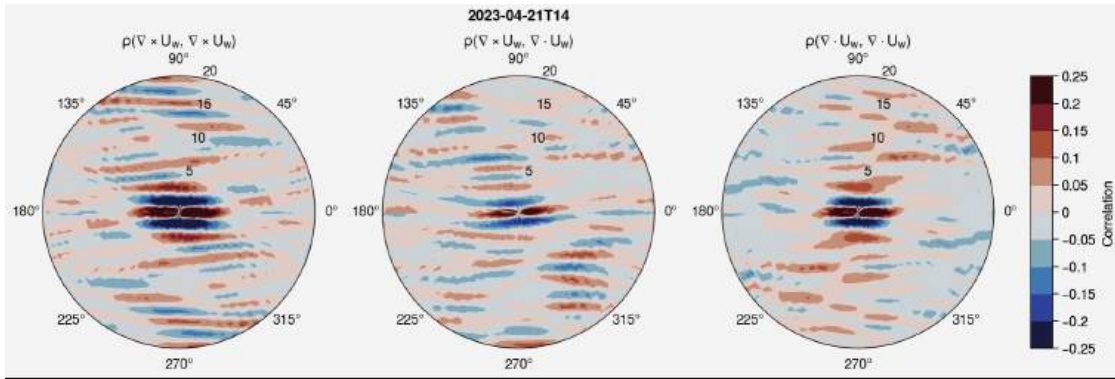


Wind

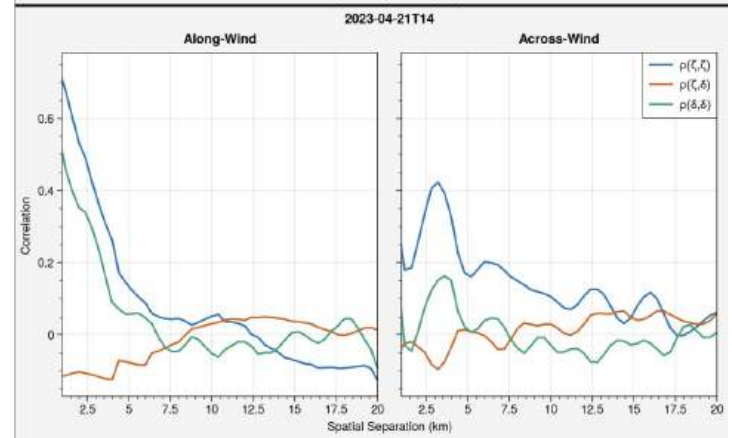
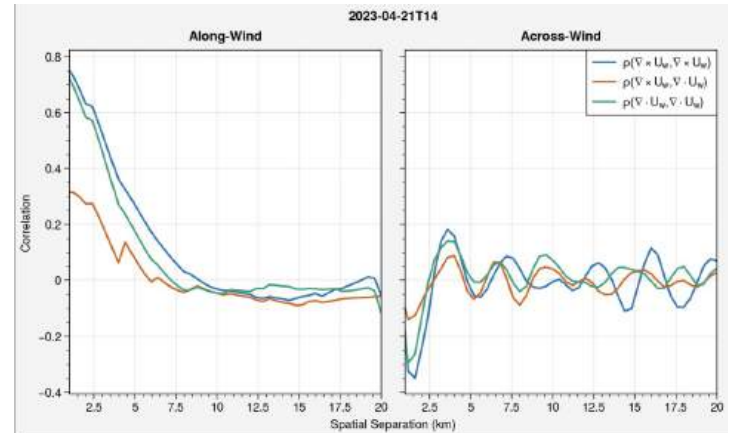
Currents

Curl

Divergence



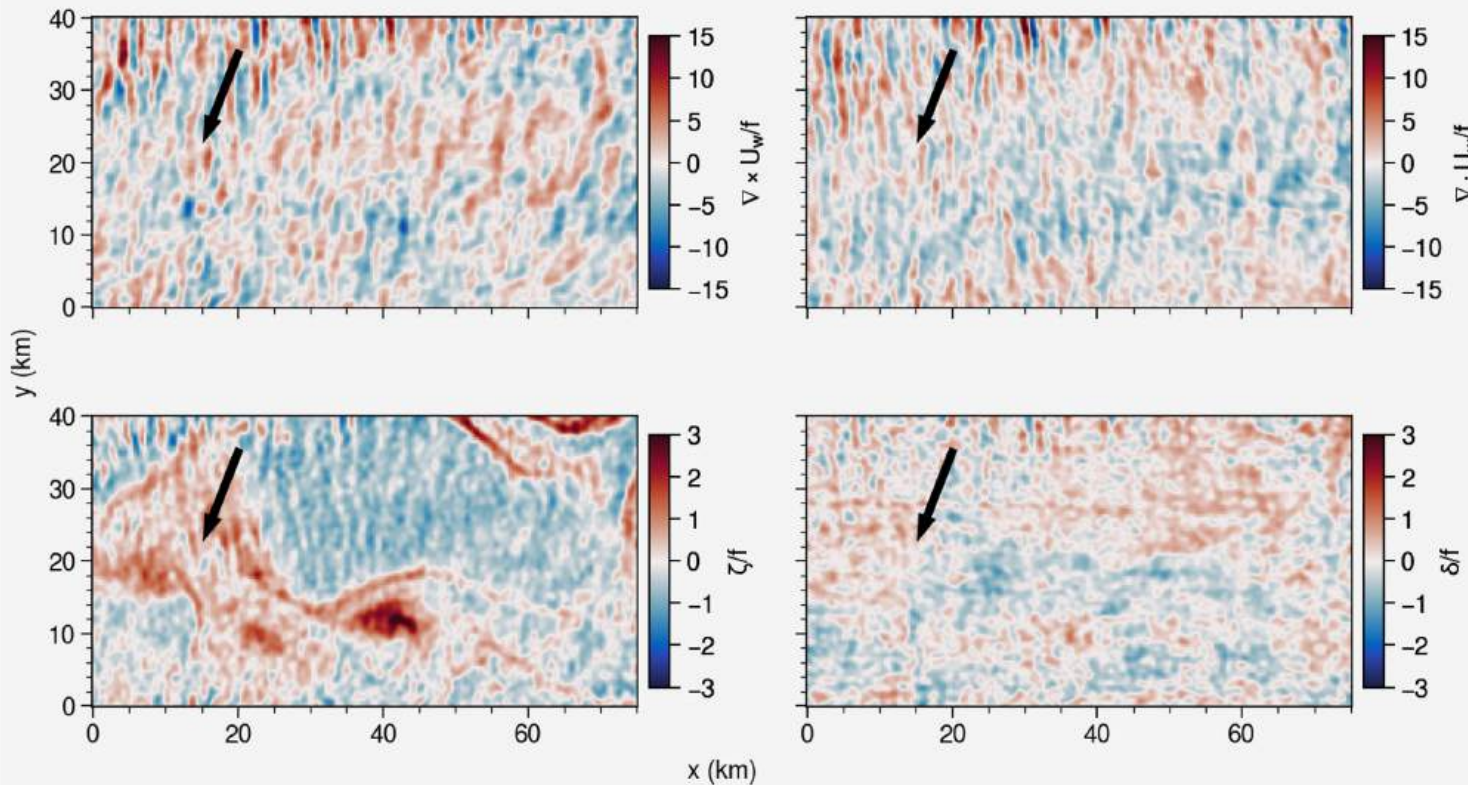
0° is along the wind direction



Wind Direction



2023-04-22T12

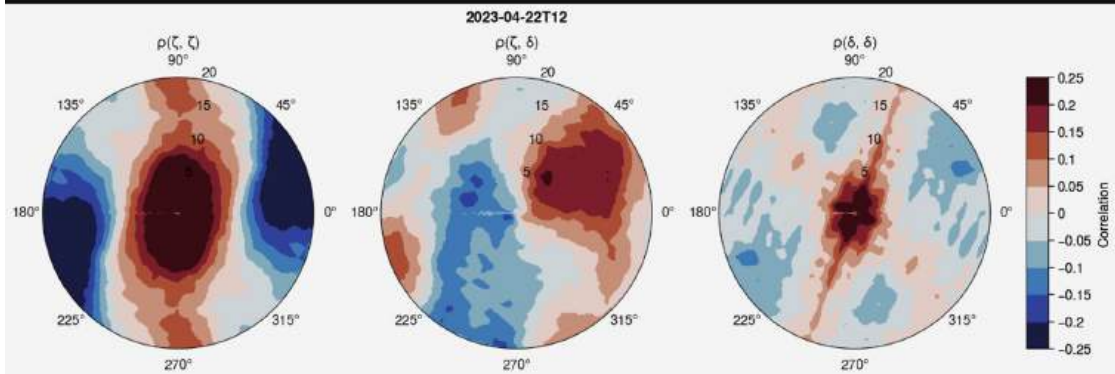
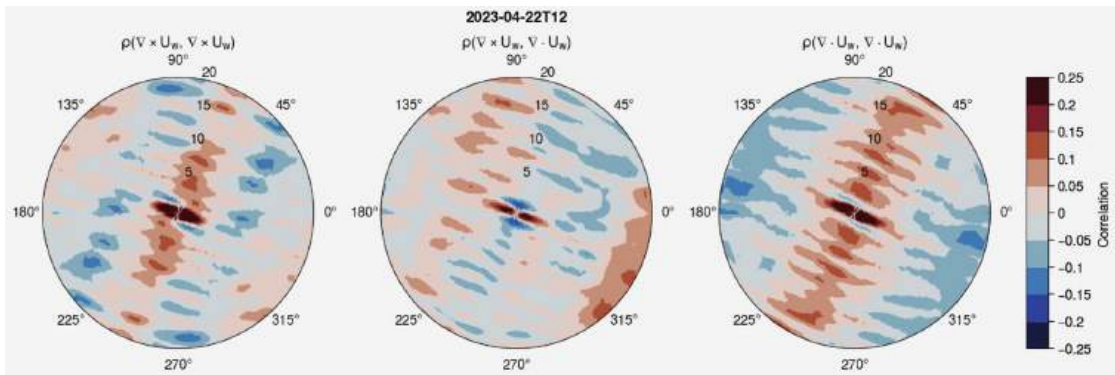


Wind

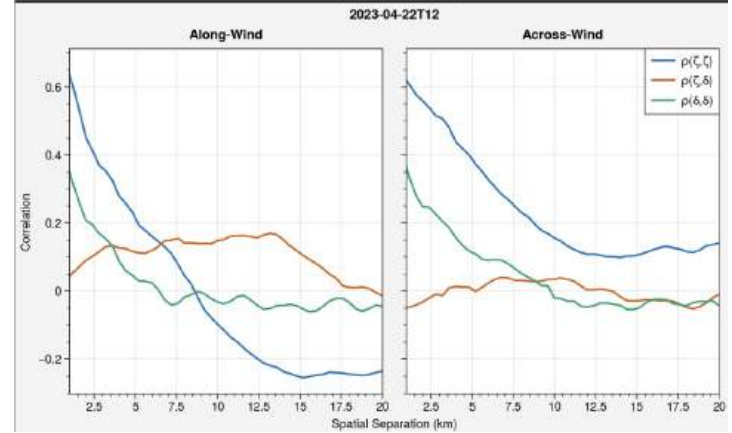
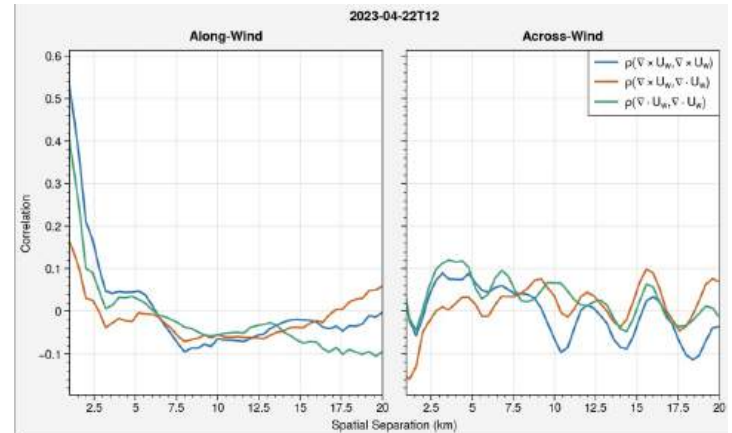
Currents

Curl

Divergence

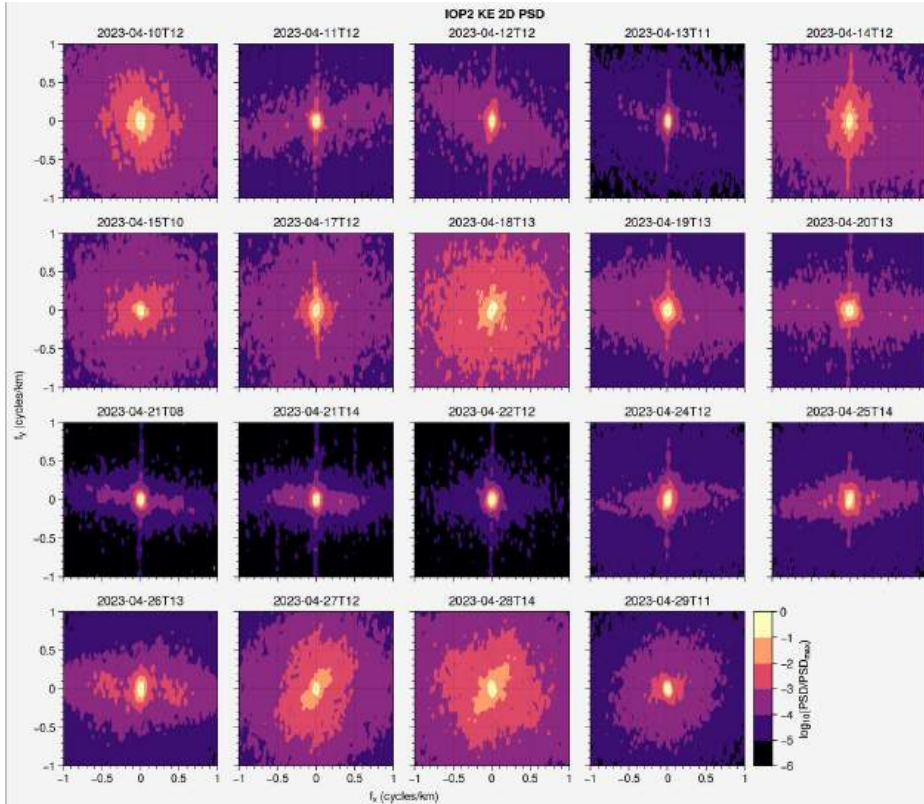


0° is along the wind direction

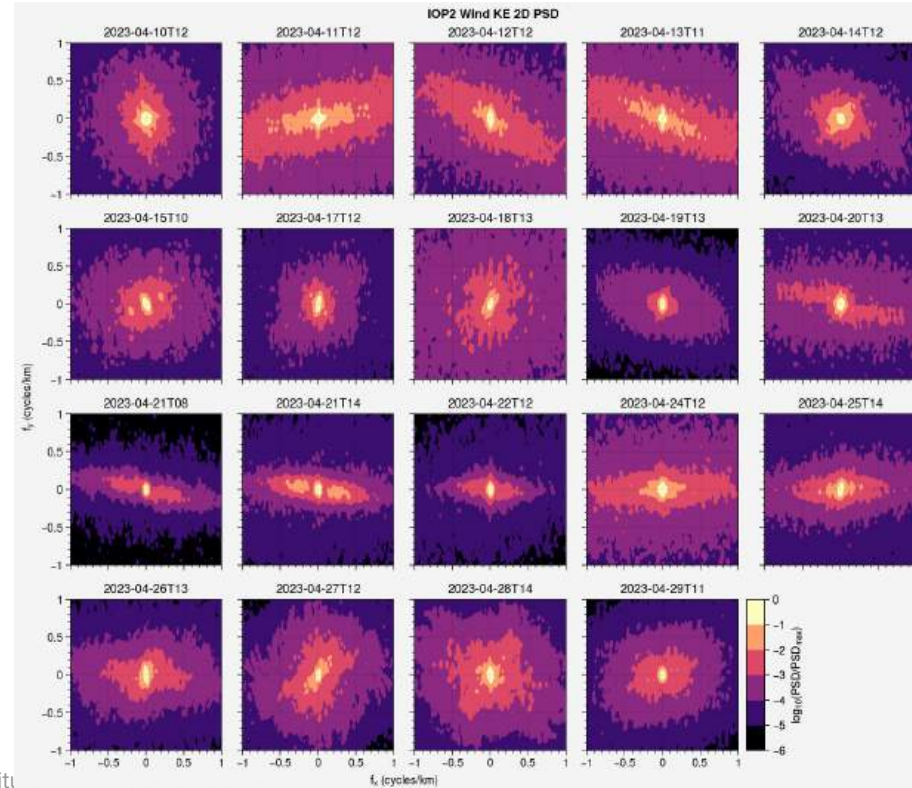


IOP2 2D Current & Wind Kinetic Energy PSDs

Current



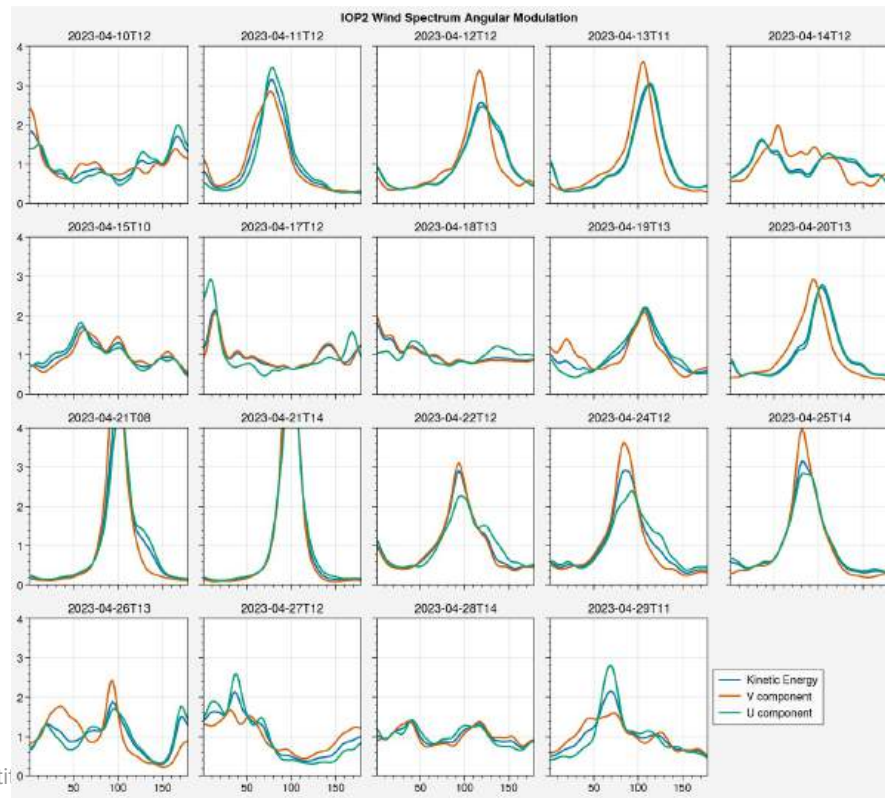
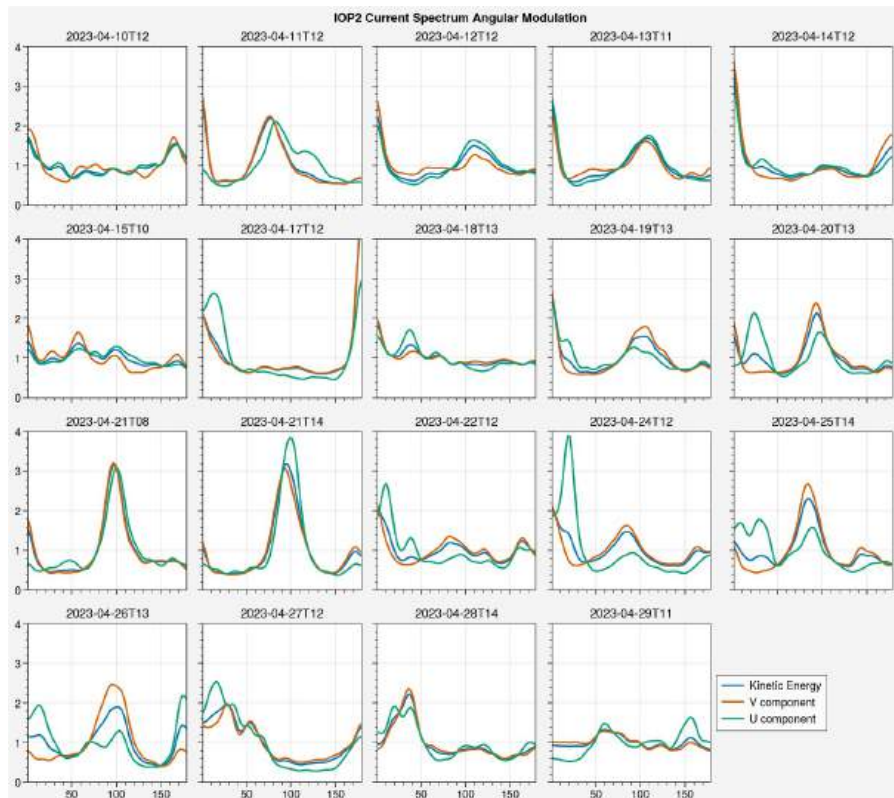
Wind



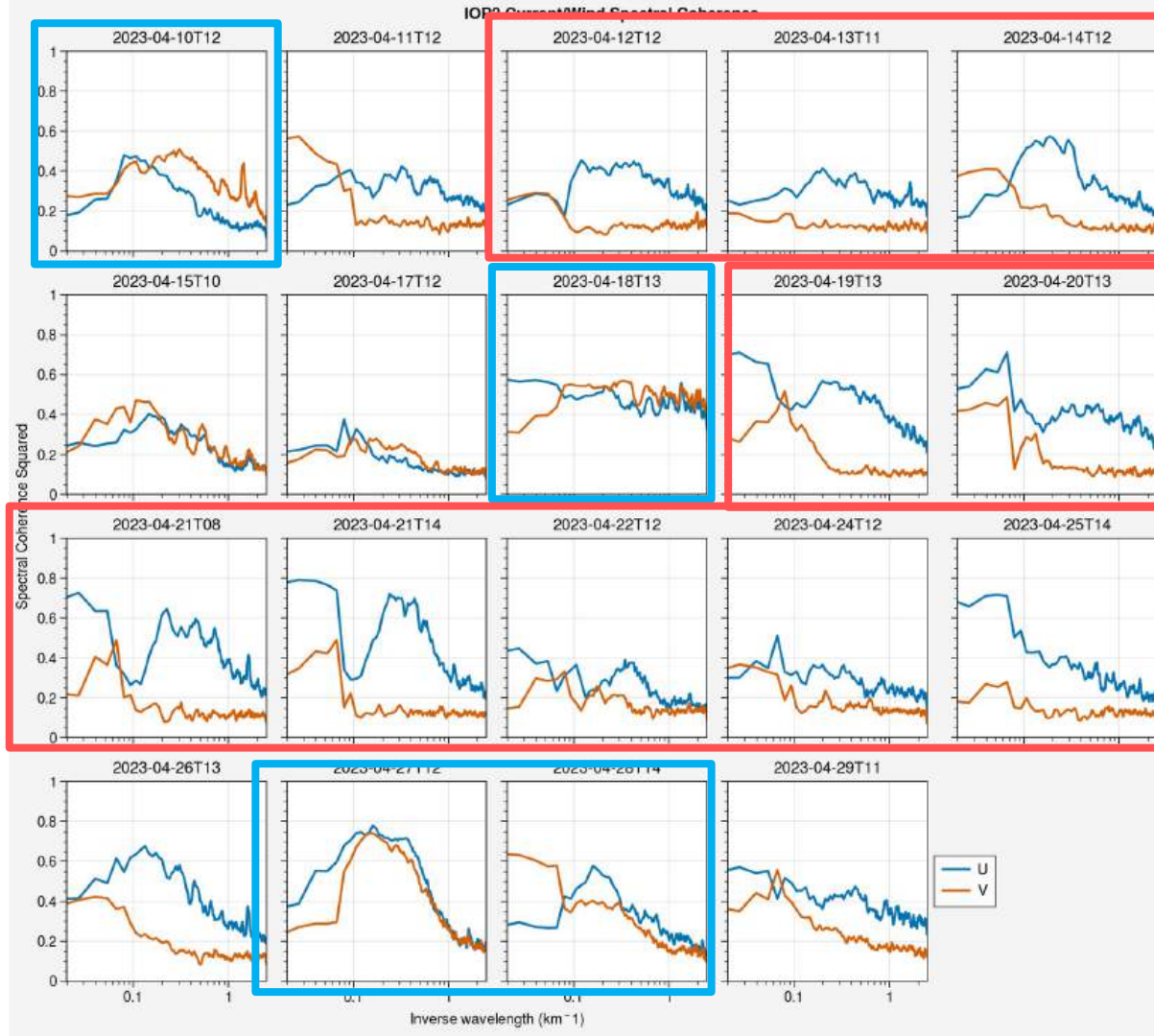
$$\mu(\theta) = \frac{\int df f S(f, \theta)}{\int df d\theta f S(f, \theta)}$$

Current

Wind



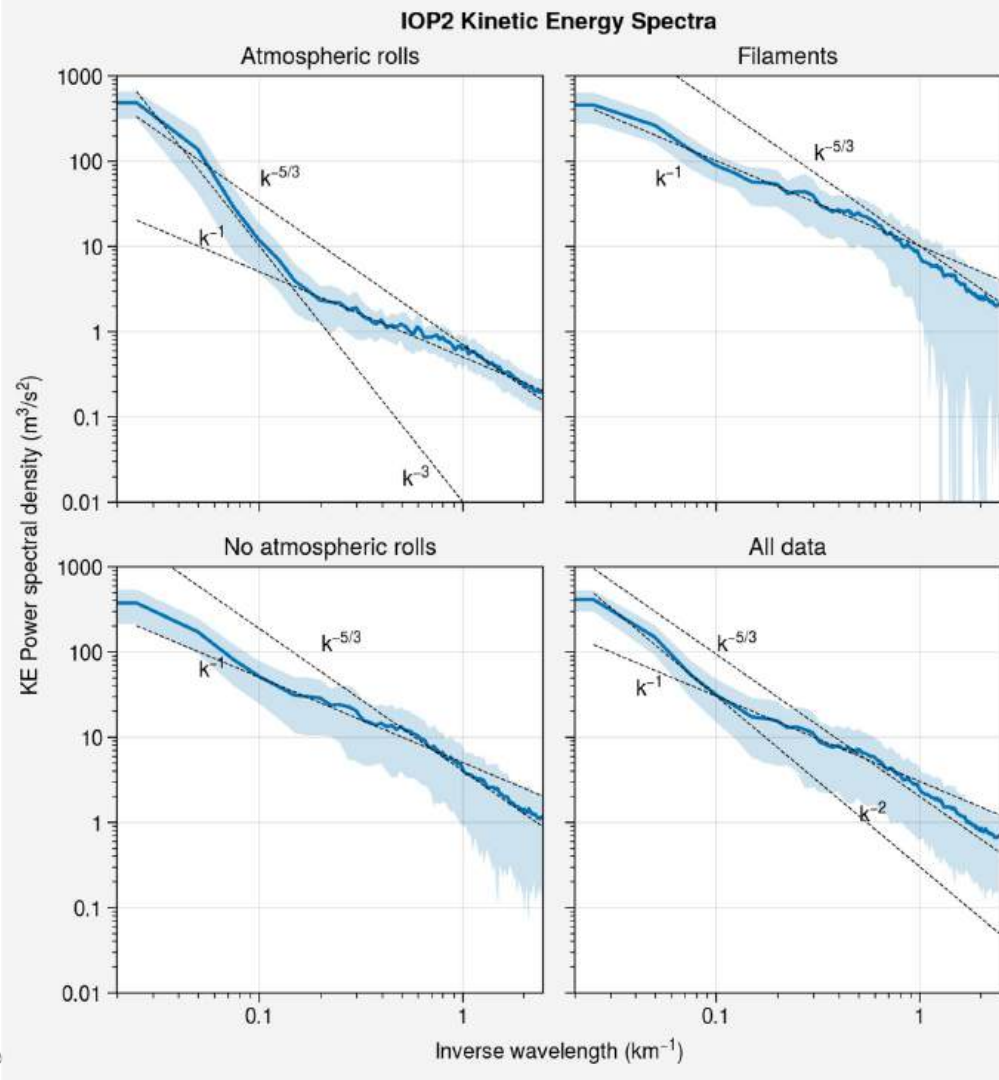
IOP2 Current-Wind Cross-Spectral Density



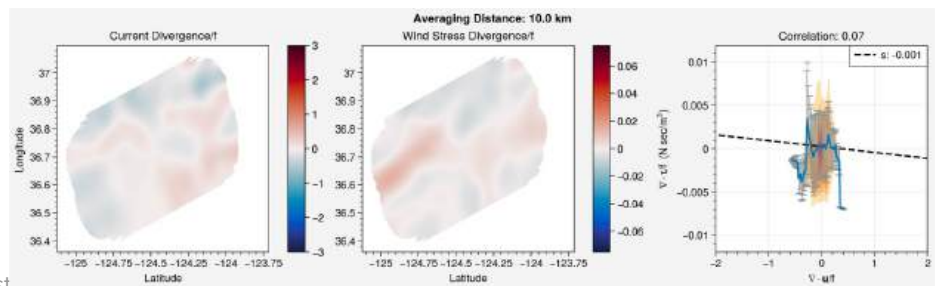
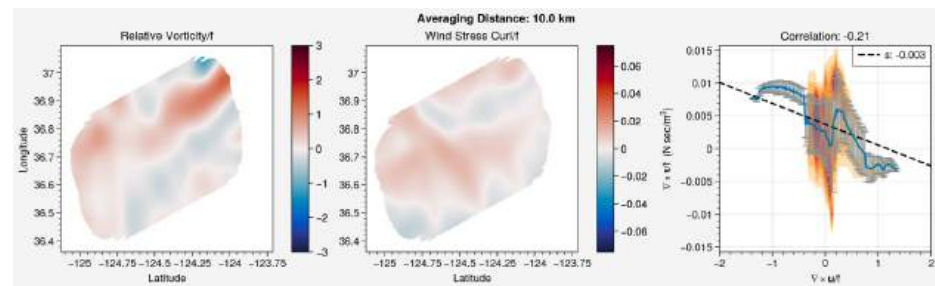
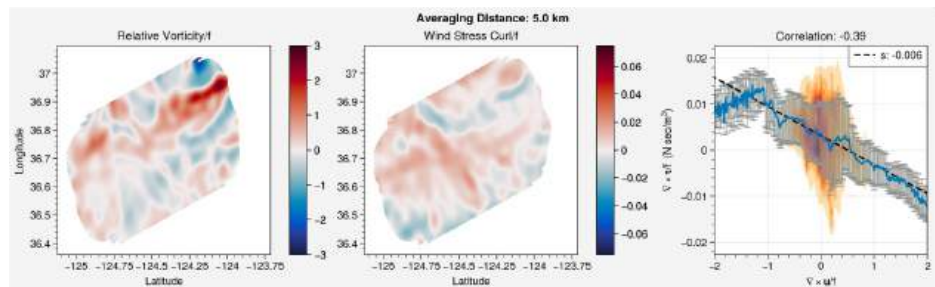
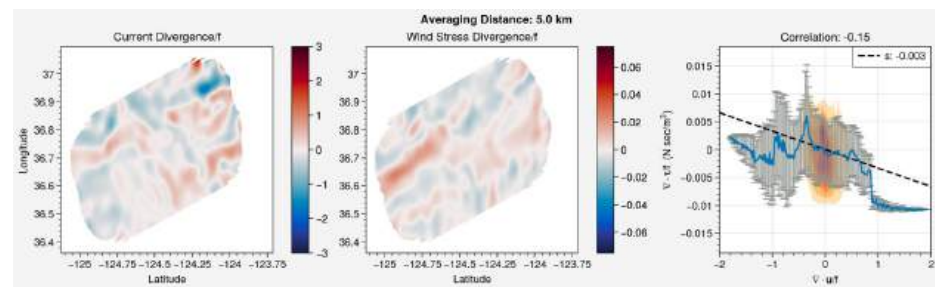
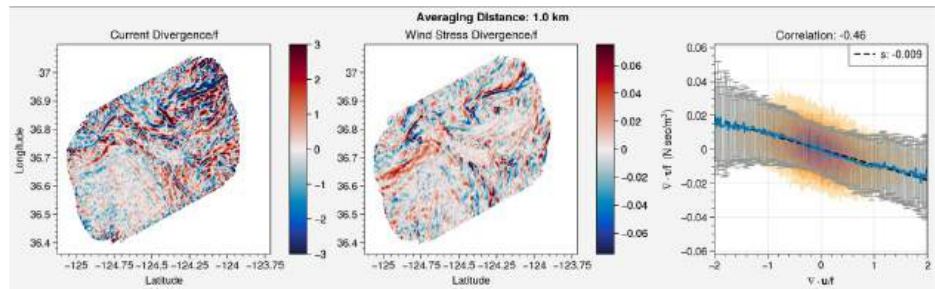
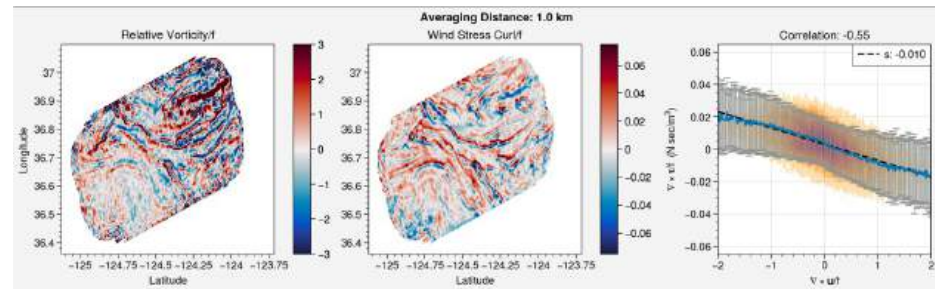
Atmospheric Rolls

Filaments

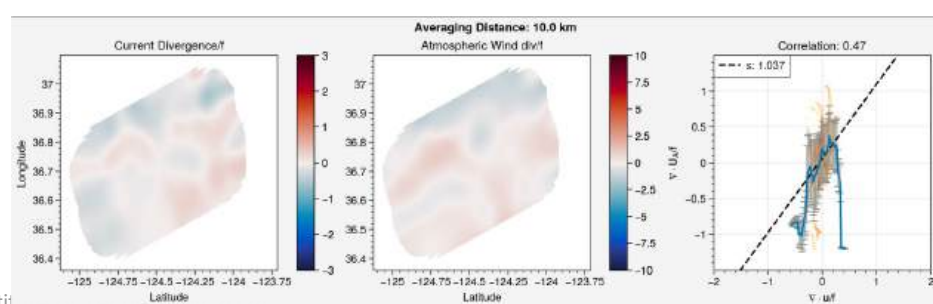
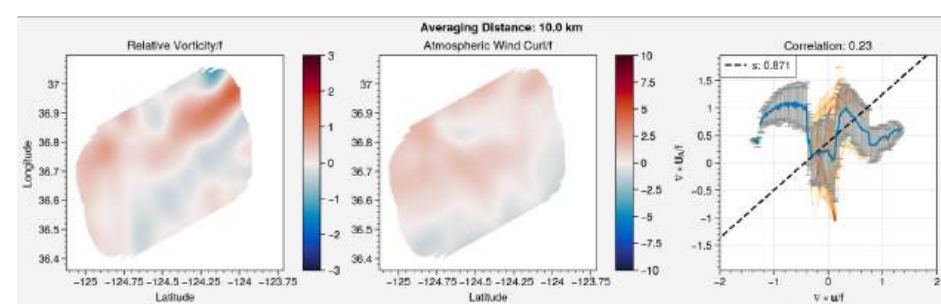
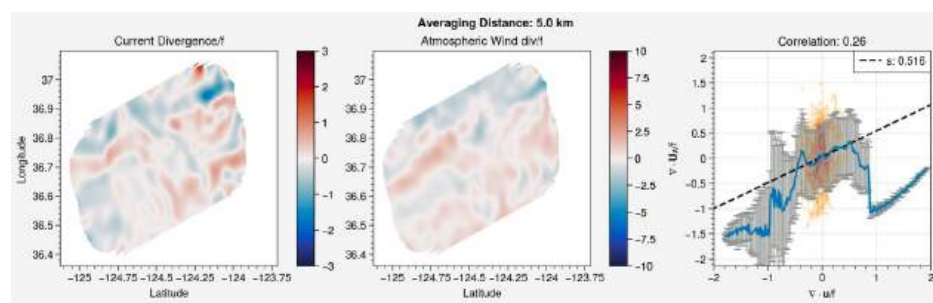
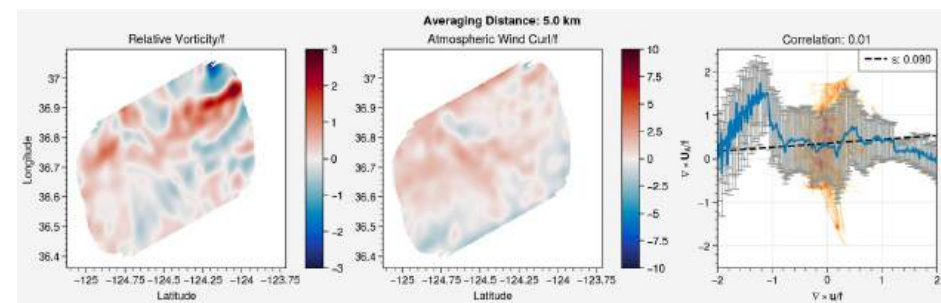
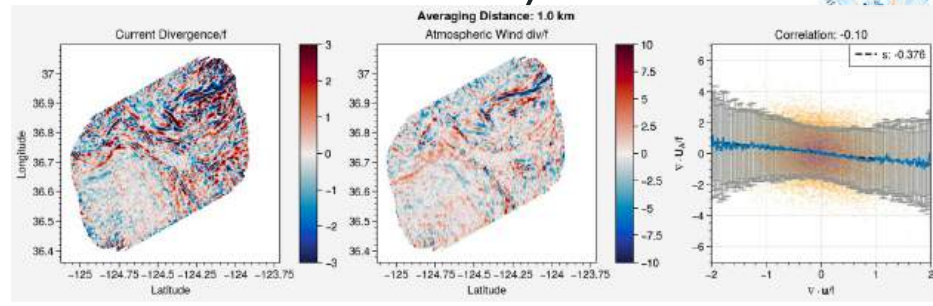
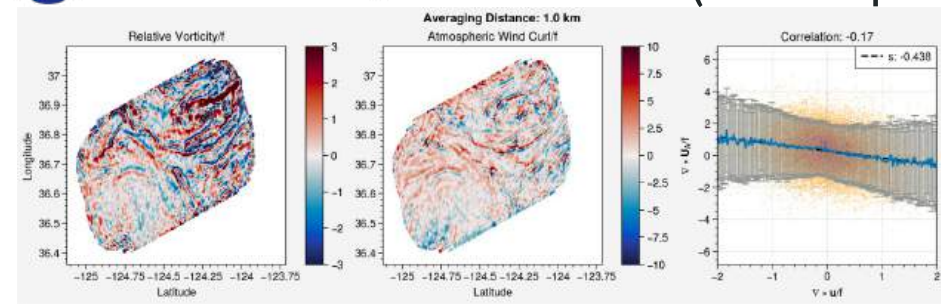
Surface current power spectral vs wind class



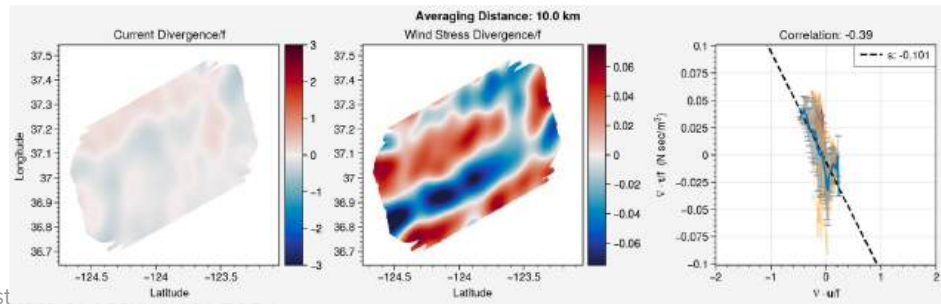
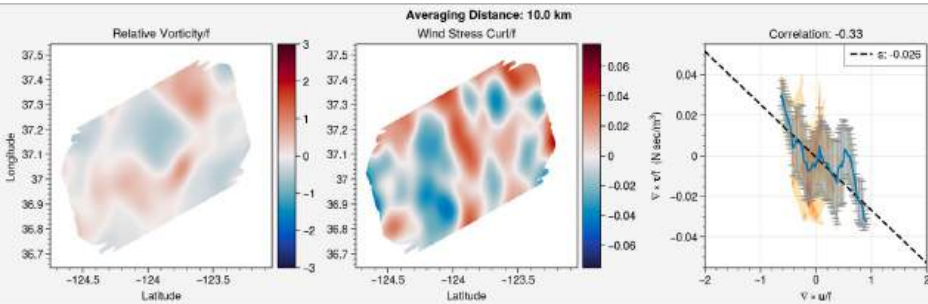
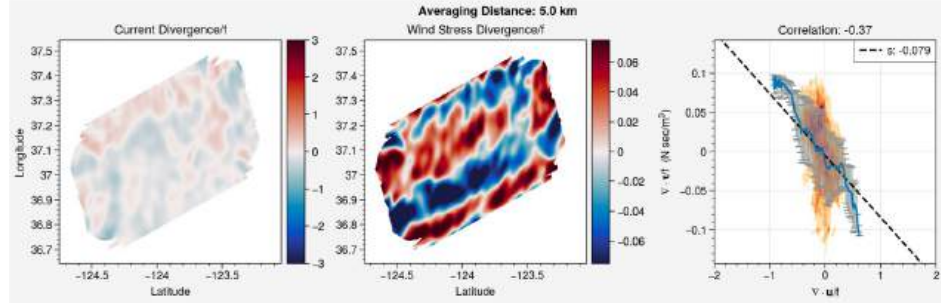
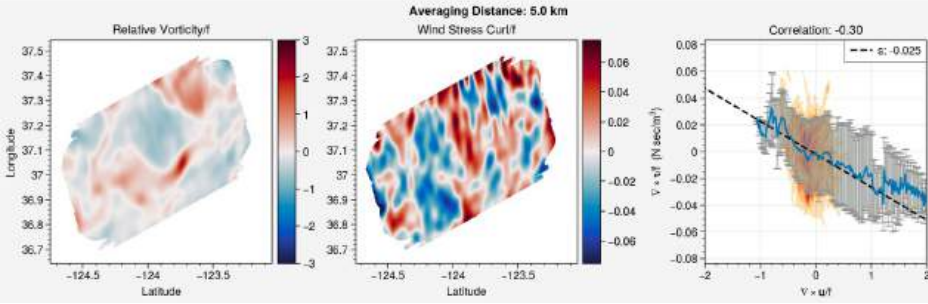
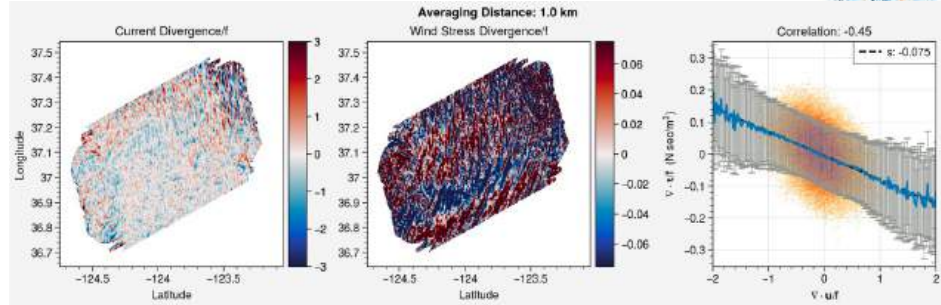
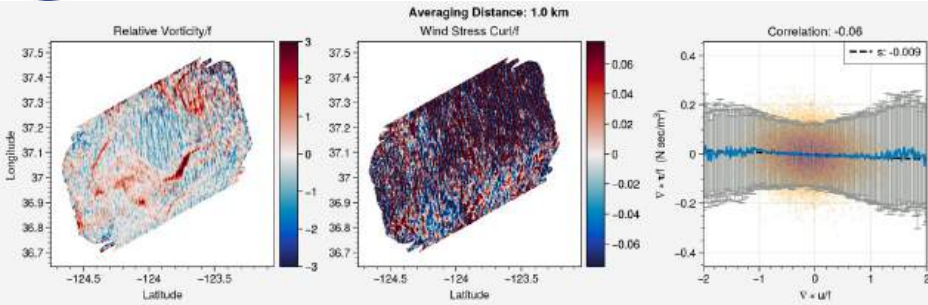
Filaments (wind stress derivatives)

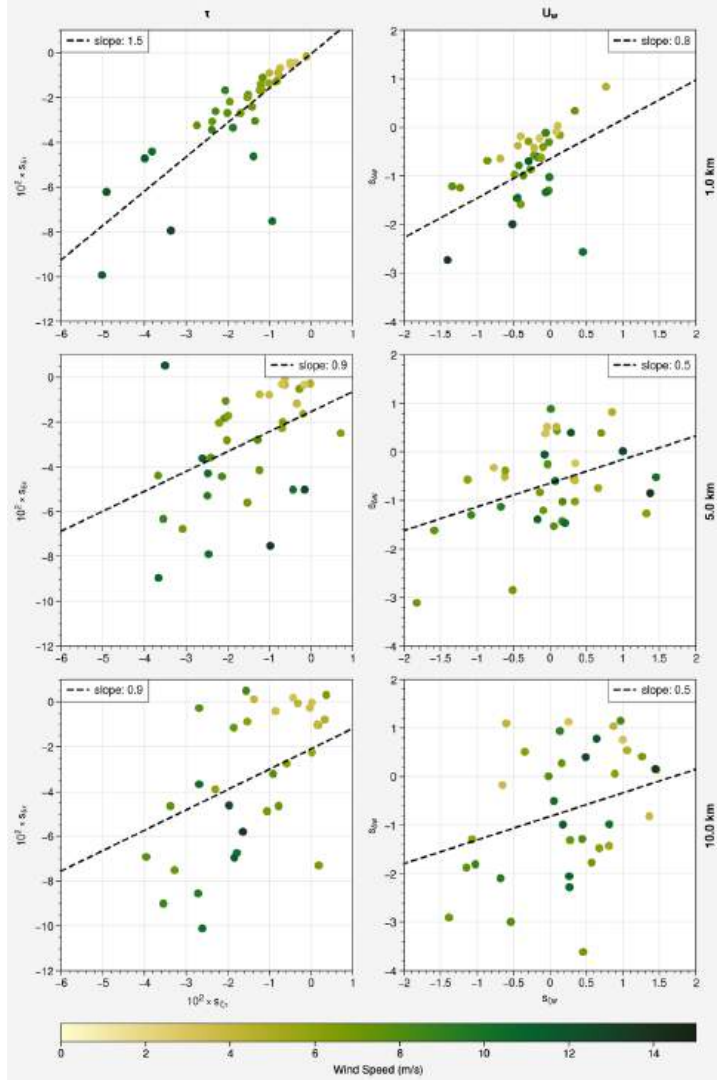


Filaments (atmospheric wind derivatives)



Atmospheric rolls (wind stress derivatives)





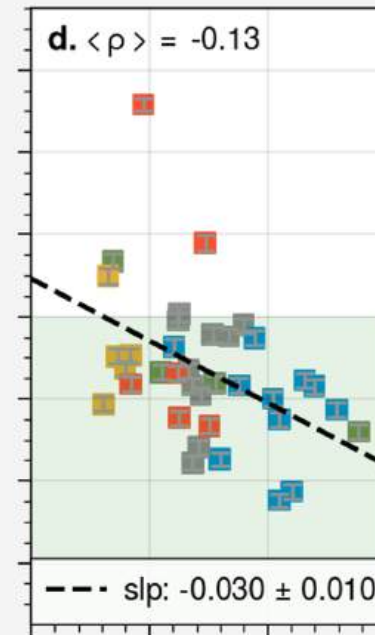
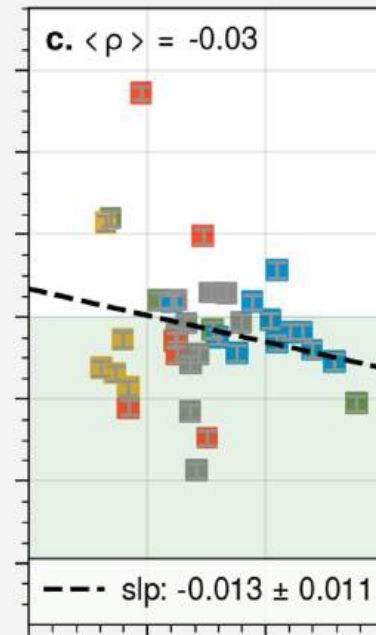
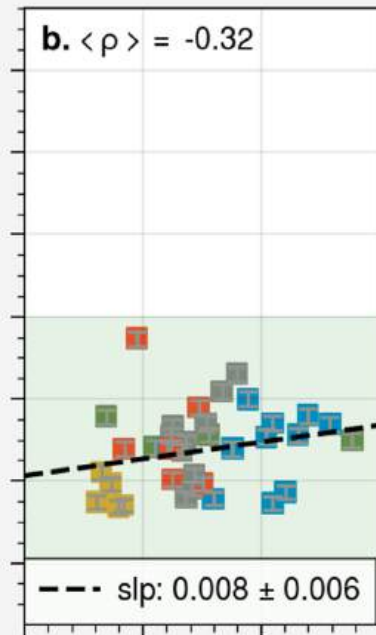
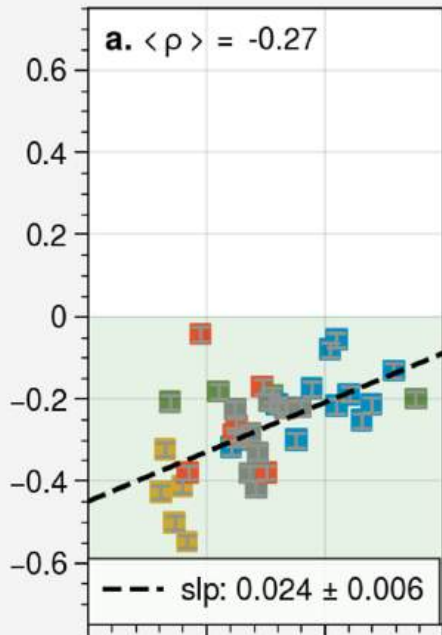
Correlation Coefficients

Corr($\zeta/f, \nabla \times \tau$)

Corr($\delta/f, \nabla \cdot \tau$)

Corr($\zeta/f, \nabla \times U_{10N}$)

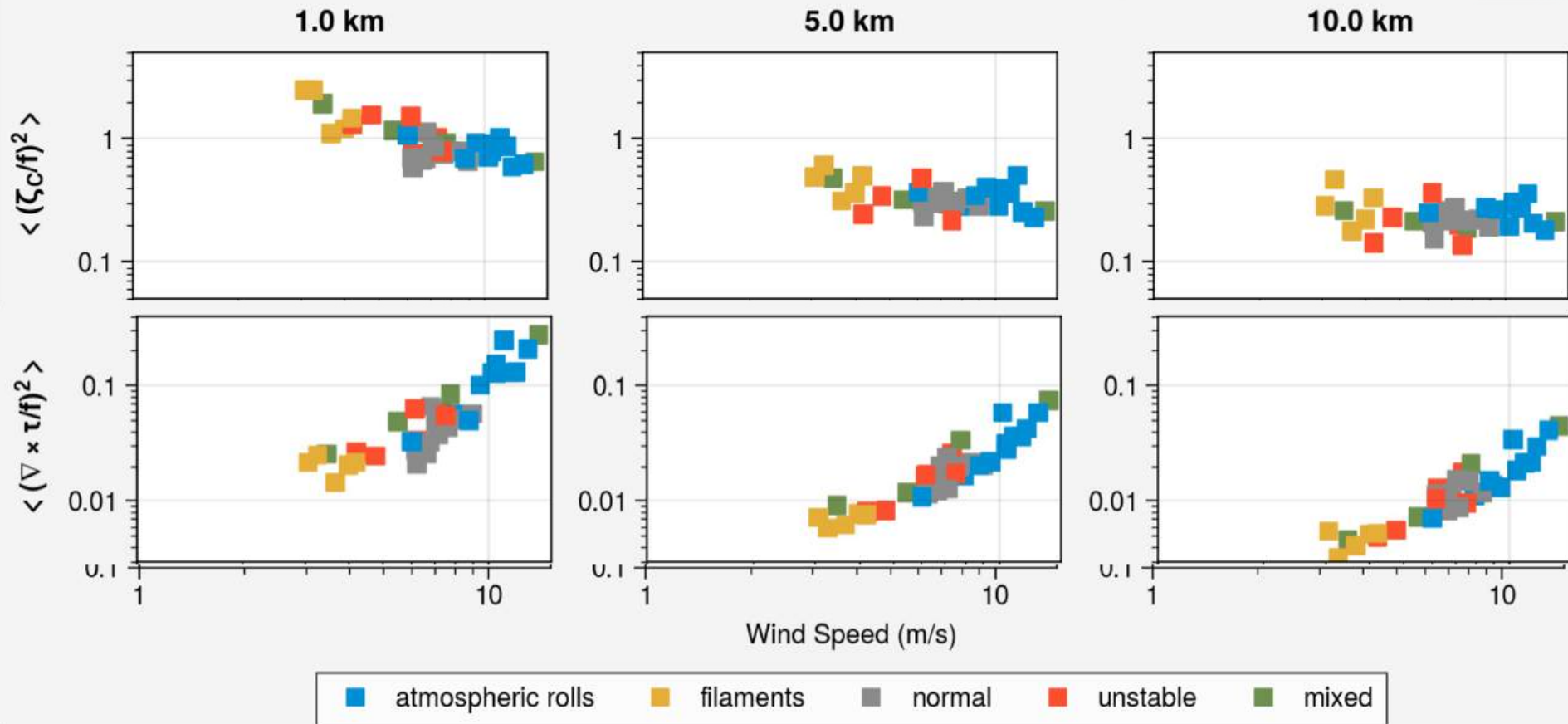
Corr($\delta/f, \nabla \cdot U_{10N}$)



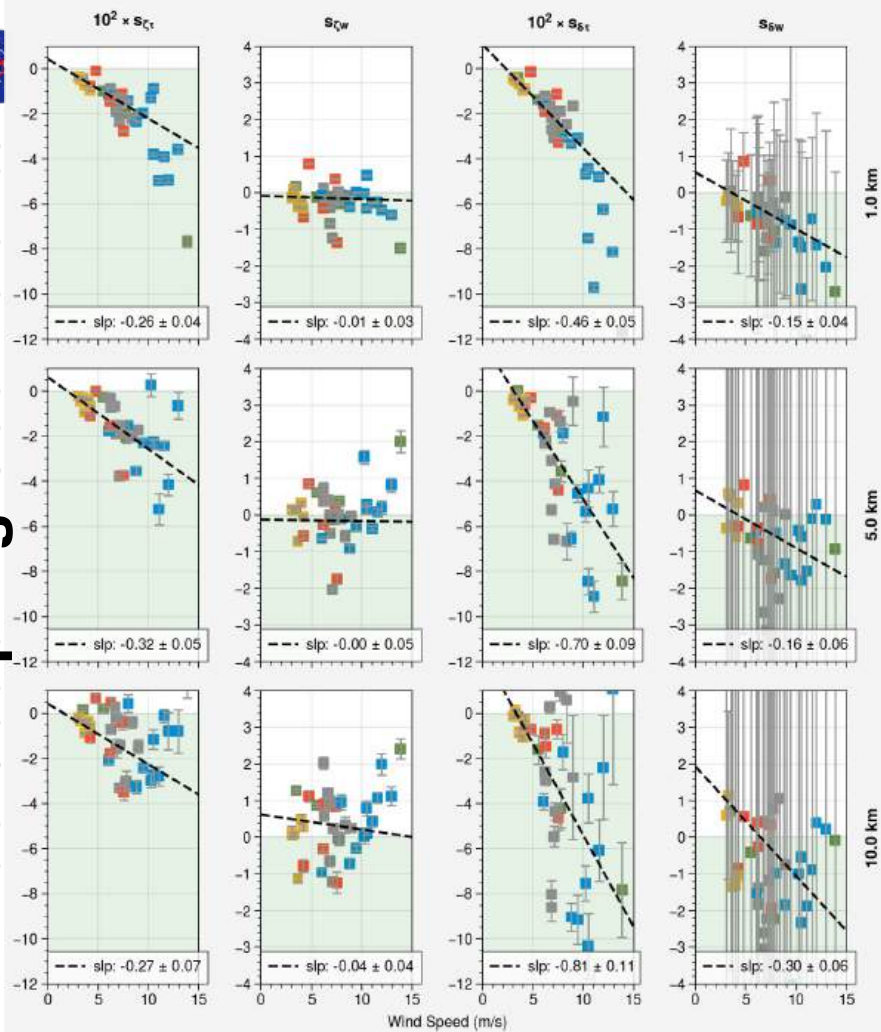
1.0 km



Wind dependence of the scaling factor



True Coupling Coefficients



Gaussian Coupling Coefficients

