Assessing submesoscale sea surface height signals from the SWOT mission

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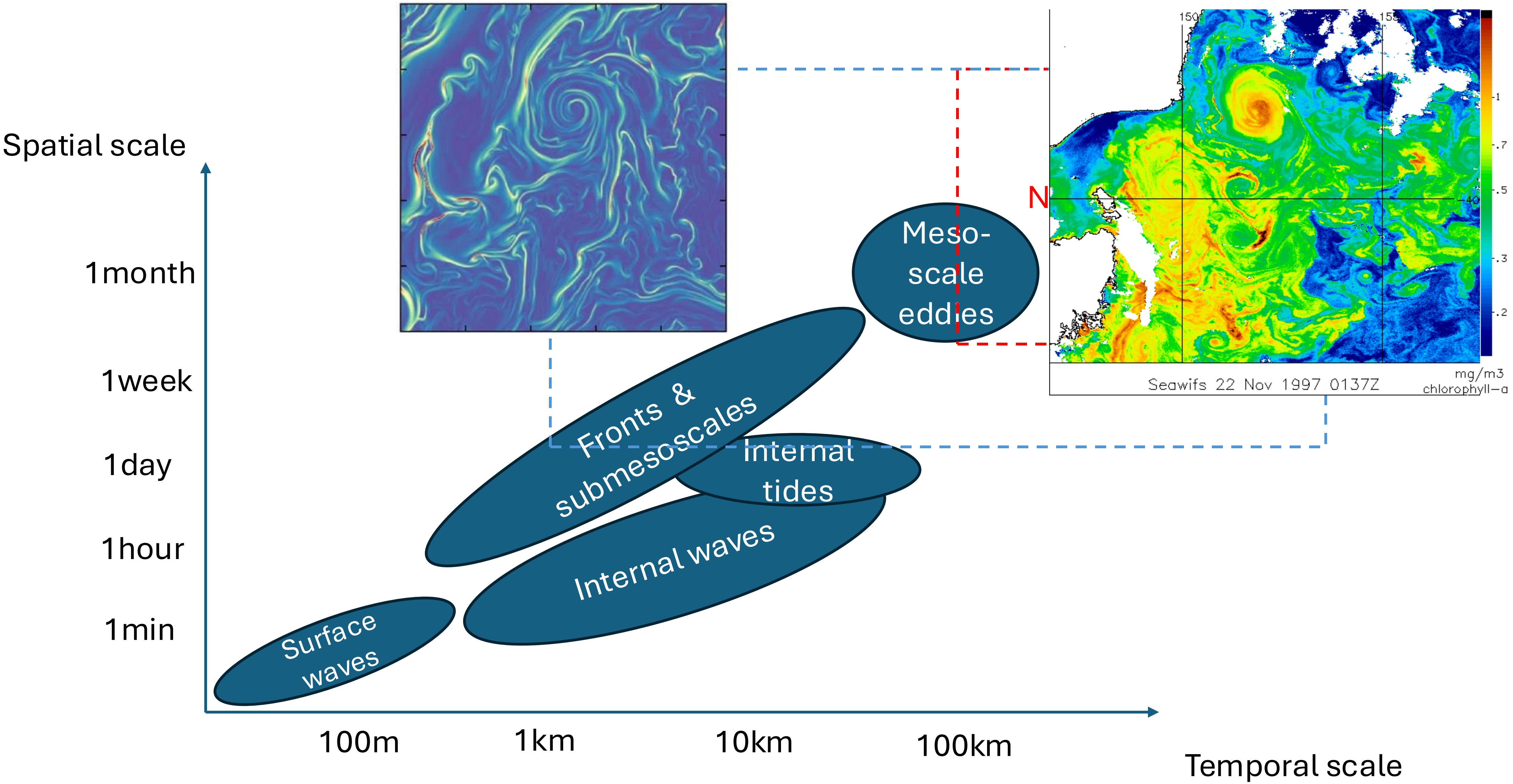
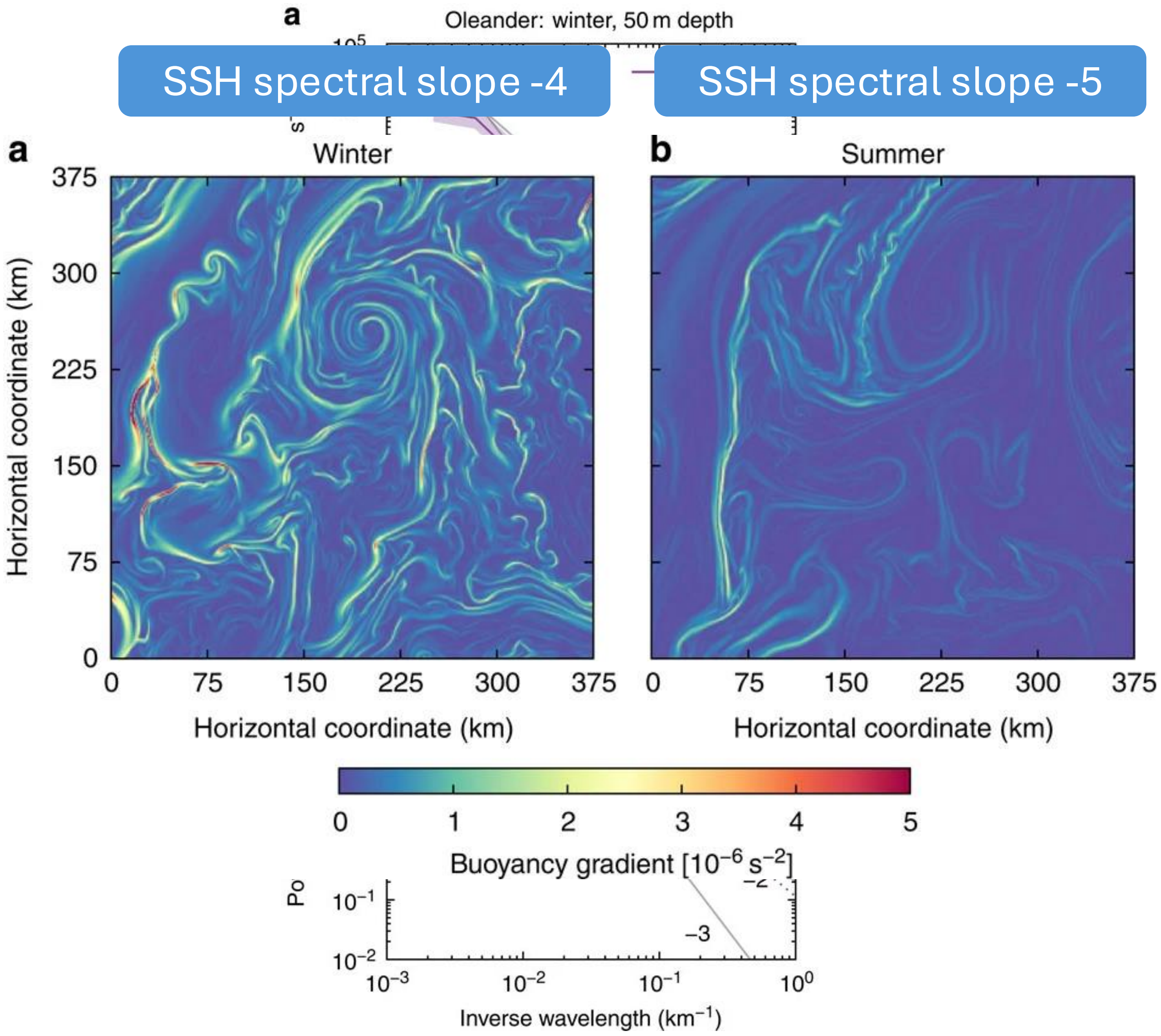
Background – spatial and temporal scales of multiple ocean processes



Adapted from Villas Bôas, et al., 2019

Background – Spectral analysis for submesoscales

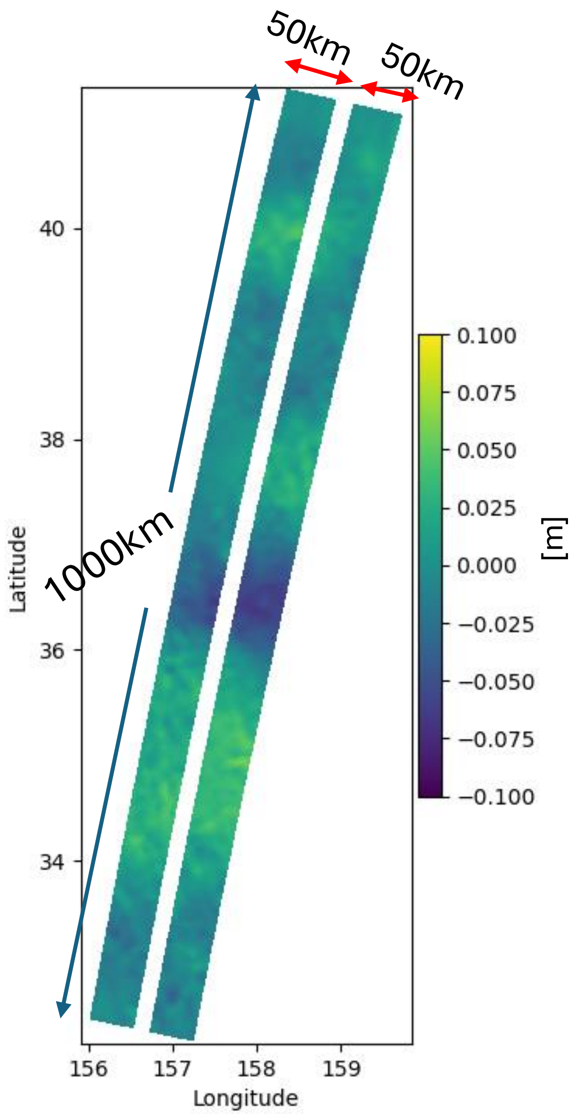


Callies et al 2015

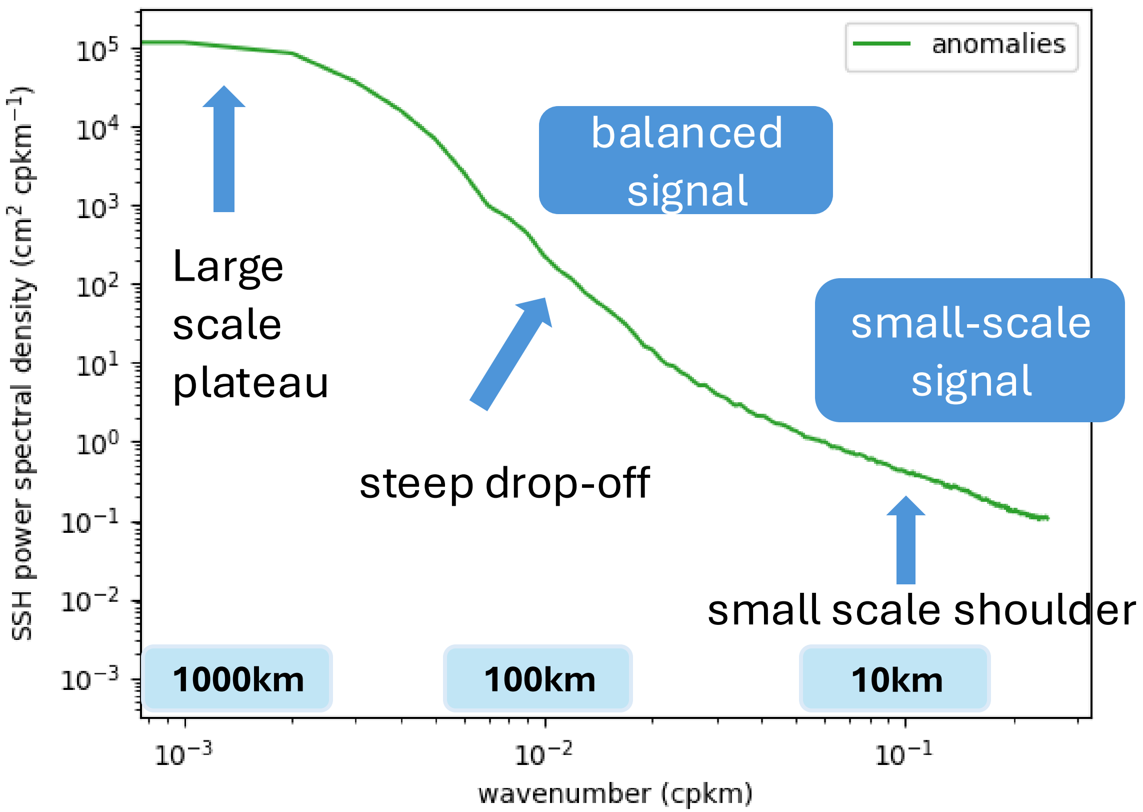
$$|\hat{h}|^2 = \frac{f^2}{g^2k^2}|\hat{v}|^2$$

- In-situ observations including ADCP and gliders show the seasonality of submesoscale motions (e.g., Thompson et al 2016).
- In-situ observations show KE spectrum has slope of around -2 (strong submesoscale) or -3 (weak submesoscale), corresponding to -4 and -5 SSH spectral slope, respectively.
- Its seasonality indicates the mechanism of submesoscale (energized by baroclinic instability in mixed layer).
- Internal wave continuum has spectral slope of -2 for both KE and SSH (Garret-Munk spectrum).

Method/Dataset : SWOT 1-day rapid repeat orbit and SSH spectral analysis (SWOT_L2_LR_SSH_2.0)

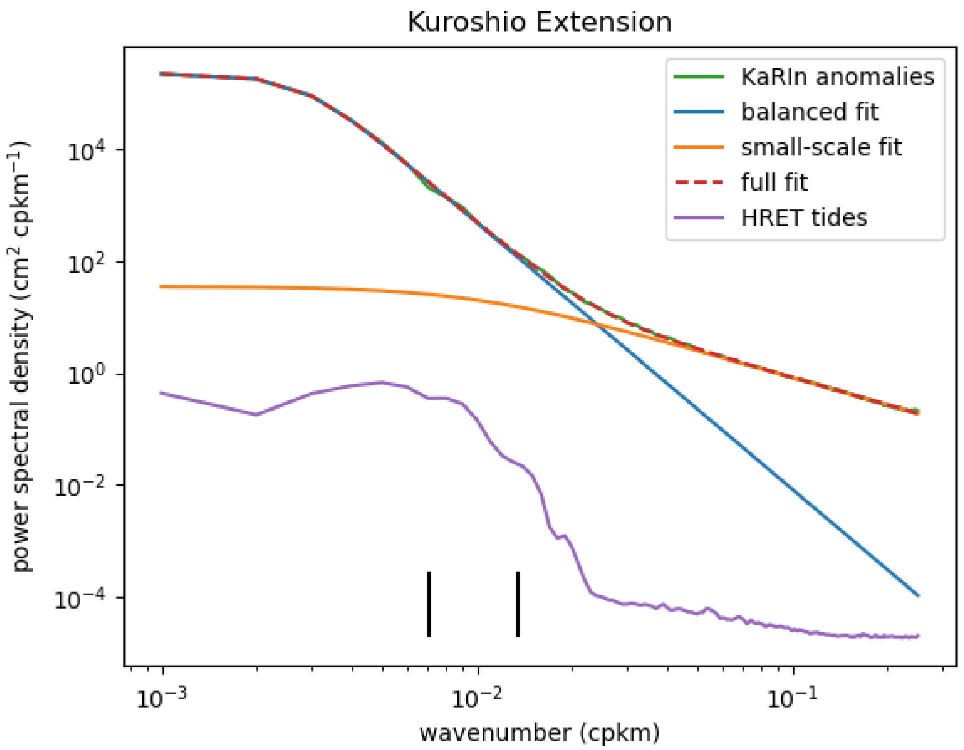


- CALVAL orbit (1-day period)
- March 26 – July 10, 2023 (104 cycles, each cycle has 28 passes.)
- Two 50km-width strips
- Separate each pass into 1000 km segments in along-track direction.
- Nyquist wavenumber is 4km.



- The SSH spectral slope has an abrupt change from meso- and submesoscale to smaller scale signals.
- We refer the part before the slope transition as 'balanced signal' and the rest as 'small-scale signal'.

Results: SSH spectral slope estimate



$$p(k;\theta) = \frac{A_b(\lambda_b k)^{p_b}}{1+(\lambda_b k)^{s_b+p_b}} + \frac{A_s}{[1+(\lambda_s k)^2]^{s_s/2}}$$

$$\theta = (A_b, \lambda_b, s_b, p_b, A_s, \lambda_s, s_s)$$

Balanced:

p_b: slope of plateau

s_b: spectral slope of balanced signal

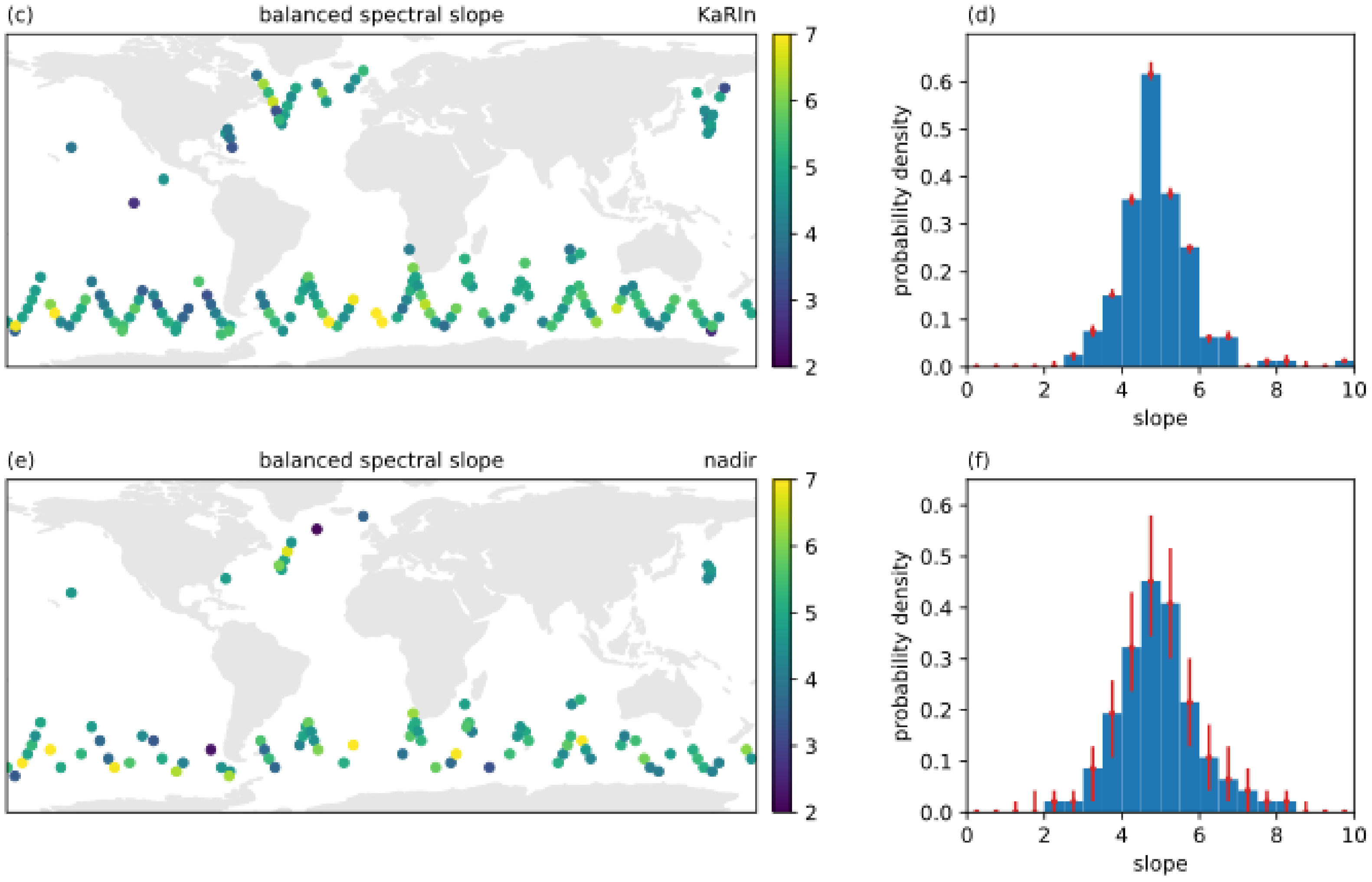
λ_b: transition scale from plateau to roll-off

Small-scale:

S_s:spectral slope of small-scale signal

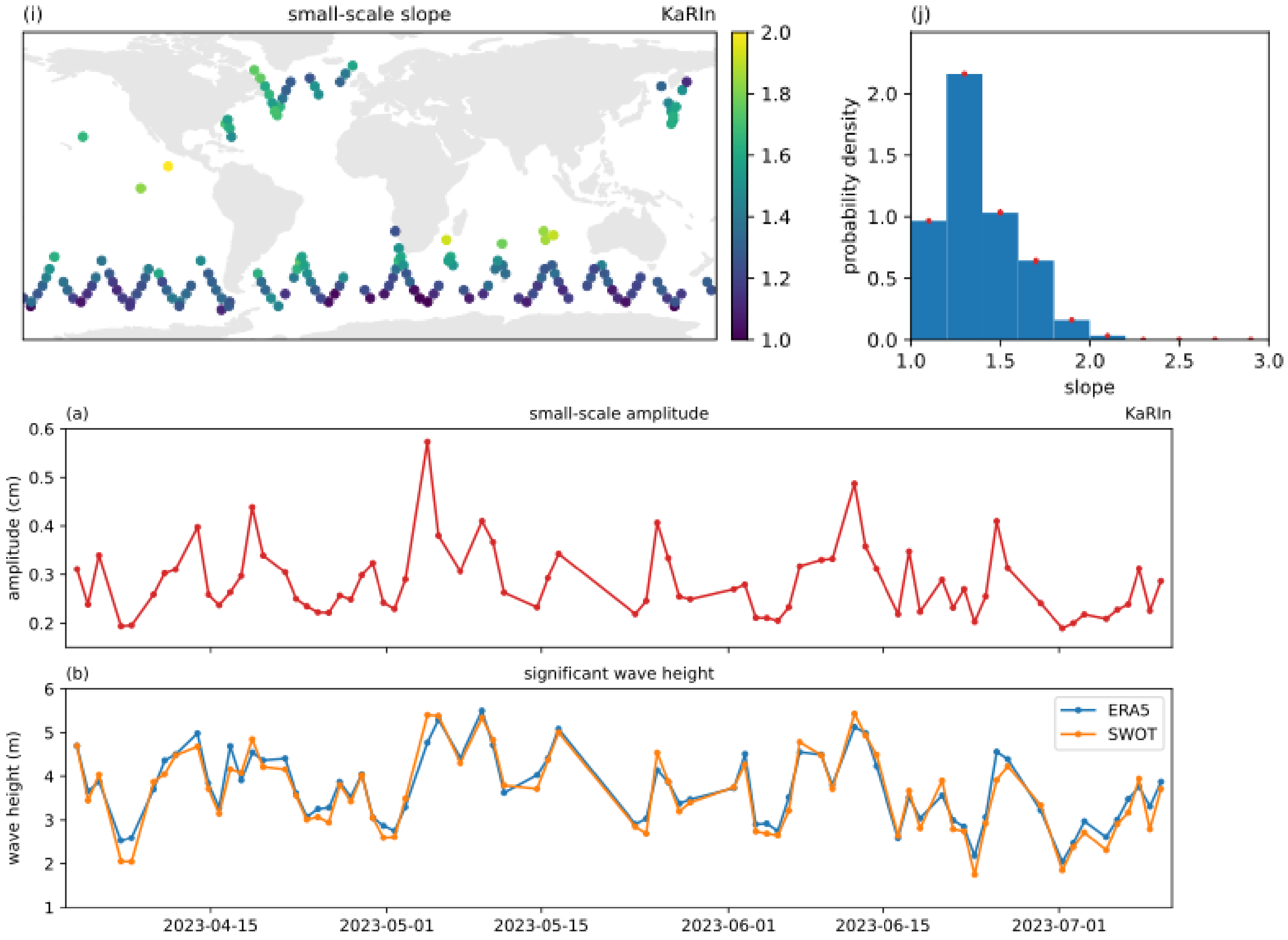
- Tropical Atlantic segments are strongly affected by M2 tides.
- Kuroshio segment is an example of regions where currents is strong and not affected by tides
- The empirical expectation of slope is around 4 to 5

Results: spectral slope estimate from KaRIn and Nadir



- Most of the slope is around 4-5
- The slope is in general consistent with pervious estimates (e.g., Lawerence and Callies 2022)
- Fewer segments are estimated than KaRIn as the uncertainties are higher

Results: understanding small scale signals



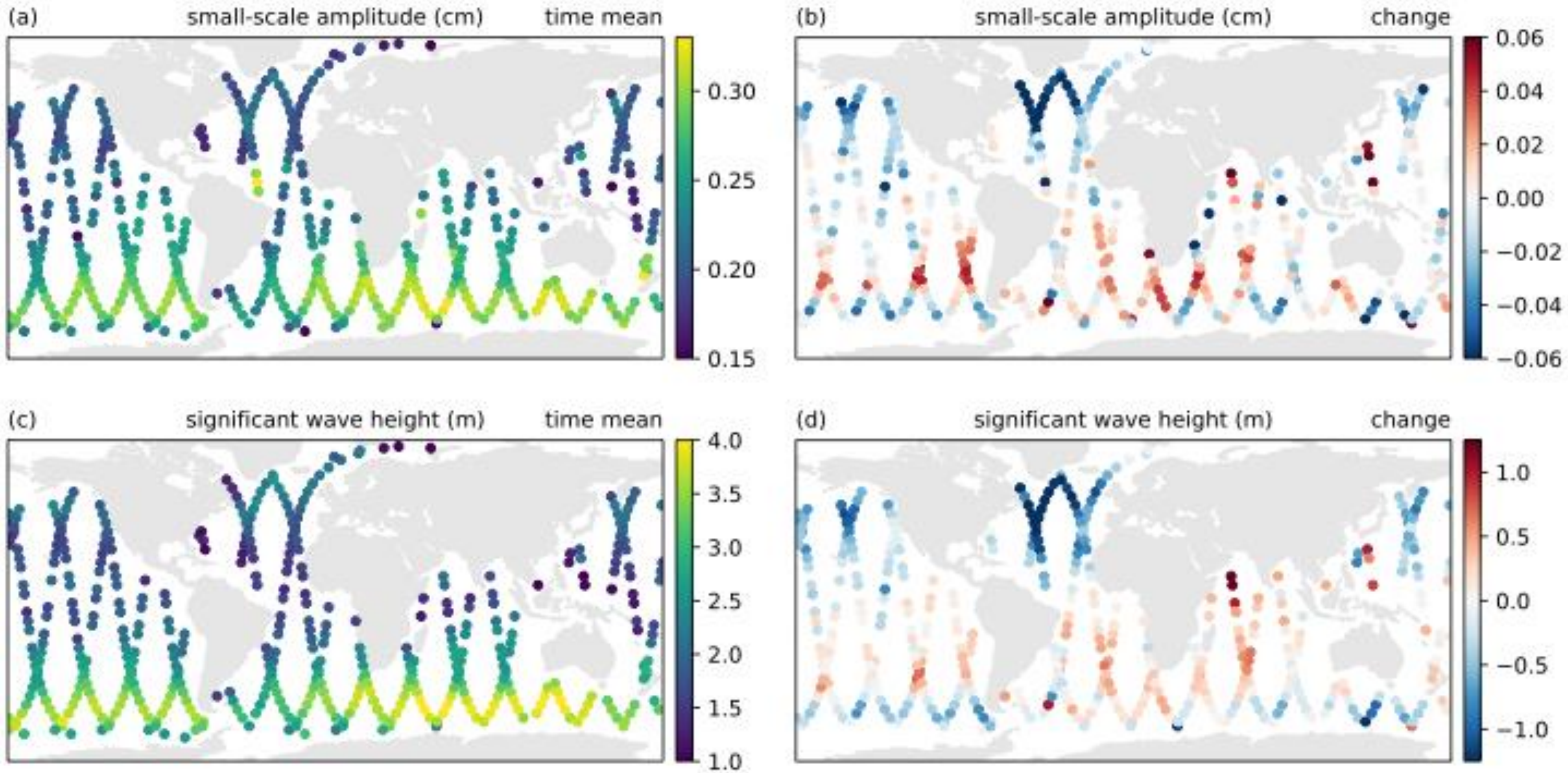
- The slope of small-scale signals is substantially smaller than 2.

- To quantify the strength of the small-scale signal, we integrate the power spectral density over 4 to 8km and take the square root, referred as 'small-scale amplitude'.

$$\sqrt{\int_{4km}^{8km} p(k)dk}$$

- The time series of small-scale amplitude in the South Pacific region is highly correlated to significant wave height from both ERA5 and SWOT (correlation coefficients are 0.72 and 0.84 respectively).

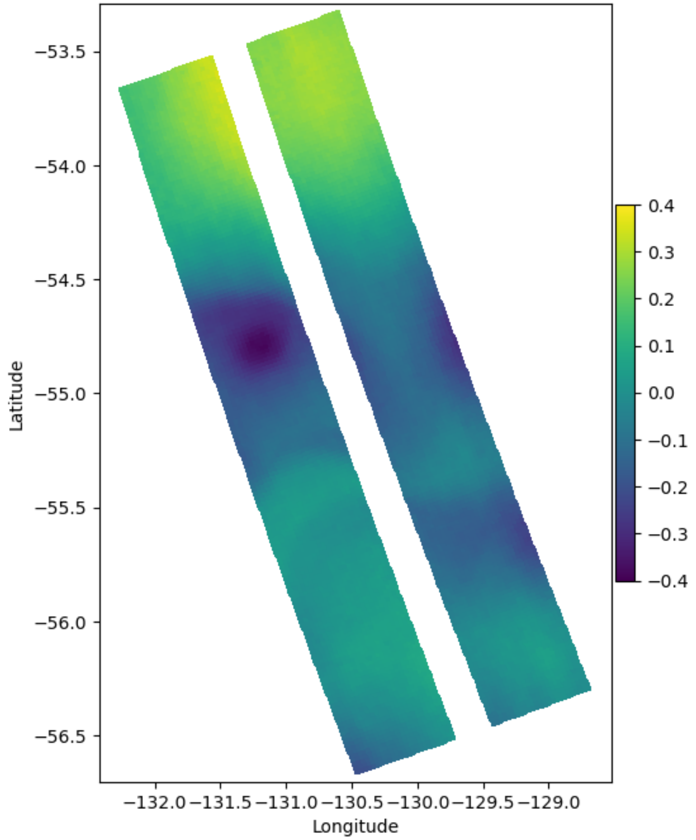
Results: understanding small scale signals

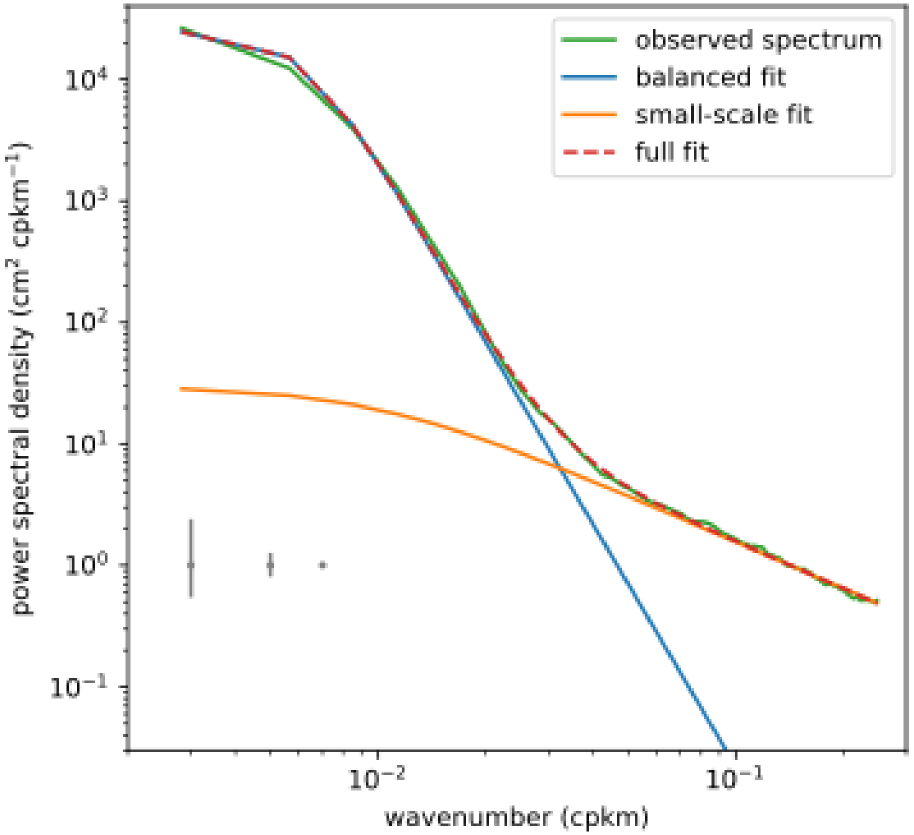


- Maps of time-mean small-scale amplitude and significant wave height (SWH)
- They show high spatial correlation (around 0.85)
- The signal becomes weaker in NH in transition to summer; stronger in SH in transition to winter

- Small-scale amplitude and significant wave height (SWH) show similar temporal and spatial distribution.
- The small-scale signals are likely due to surface waves.

Results: Extraction of balanced signals





- Assume observed SSH is consist of balanced and small- scale parts.
- Fit the spectrum to get covariance functions (Fourier transform).

$$\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{\eta}$$

Observed SSH — Balanced — Small scale

Assume Gaussian process: $x \sim \mathcal{N}(0, \hat{C})$, $\eta \sim \mathcal{N}(0, N)$,

Bayesian estimate:

Estimate of balanced signal

$$x|y \sim \mathcal{N}(m, C)$$

where $C = (\hat{C}^{-1} + N^{-1})^{-1}$

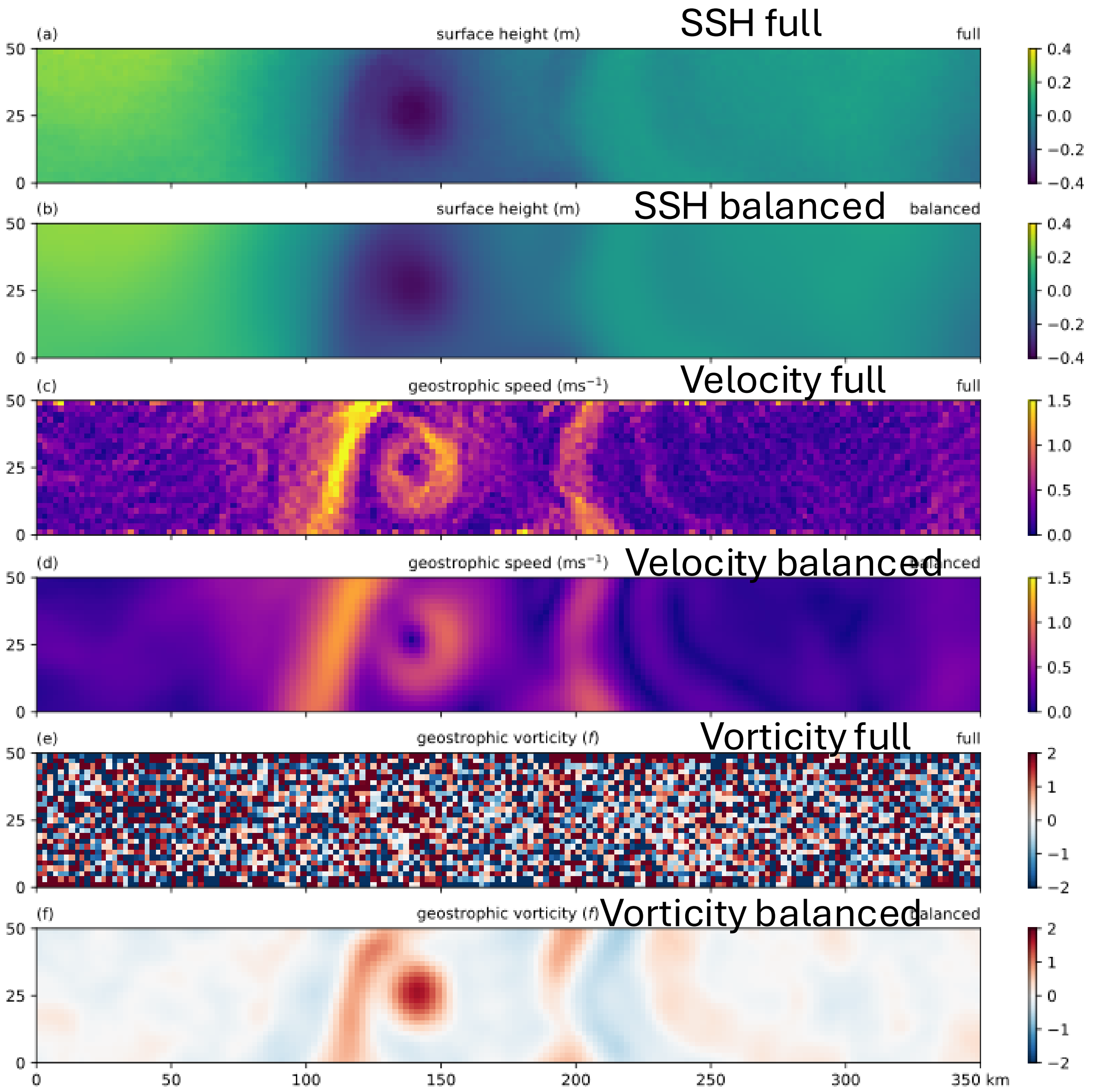
$$m = CN^{-1}y$$

Results: Extraction of balanced signals

H

$\sqrt{u_g^2 + v_g^2}$

ζ_g / f



where

$$u_g = -\frac{1}{f}\frac{\partial \varphi}{\partial y},$$

$$v_g = \frac{1}{f}\frac{\partial \varphi}{\partial x},$$

$$\zeta_g = \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} + \frac{1}{f}\frac{\partial(u_g, v_g)}{\partial(x, y)}$$

Summary

- SSH power spectra are computed with 1-day rapid repeating CALVAL phase data from SWOT.
- Spectral slope is estimated for regions not strongly affected by tides, and most of the slope is around 4 to 5, consistent with previous expectations with model and in-situ observations.
- For the small-scale component, its temporal variability and spatial distribution are highly correlated with those of significant wave height, so it is likely dominated by surface gravity waves rather than internal wave continuum.
- We converted the balanced part back into 2D maps, which can facilitate further studies on structure of submesoscale eddies.
- The 2D maps of balanced signal indicate the dynamics may not be QG anymore, challenging the customary interpretation of balanced signals in altimetry data

Archive link: https://arxiv.org/abs/2505.09856

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Research Article

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