Estimating vertical velocity variances from fully-focused SAR altimetry

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OSTST 2023 · 7-11 November 2023, Puerto Rico

Outline

Background

Study design
  - Method
  - Data

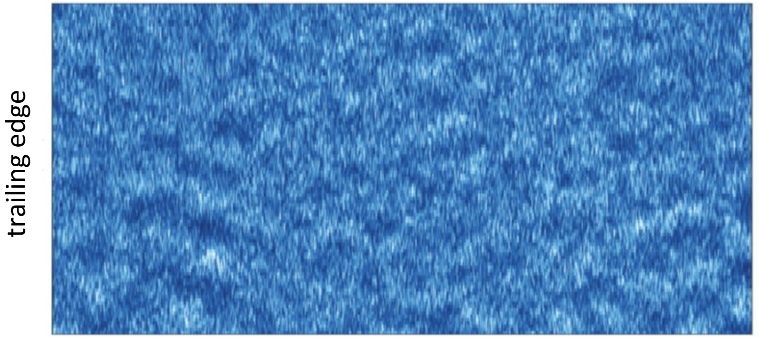
Evaluate the method

Key findings

Background (1/2)

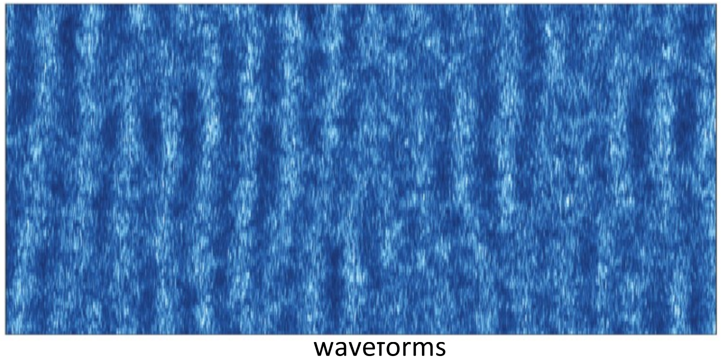
SAR nadir-looking altimeters can image ocean waves in the trailing edge of the waveforms

short-period swells



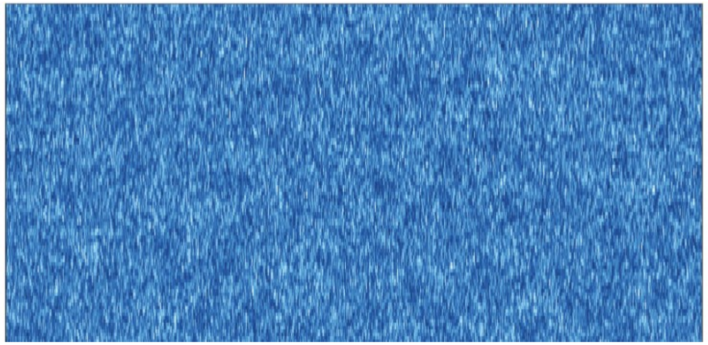
wind speed = 4.9 m/s, swh = 2.8 m, Tp = 12.3 s
relative wave angle = -91 deg

long-period swells



wind speed = 6.6 m/s, swh = 2.5 m, Tp = 16.6 s
relative wave angle = 177 deg

wind seas



wind speed = 13.7 m/s, swh = 3.8 m, Tp = 8.4 s
relative wave angle = 28 deg

The surface scatterers, moving toward or backward the satellite, are displaced in the along-track direction by (Kerbaol and Chapron, 1998):

$$\xi = \frac{R}{V}\upsilon$$

The intensity modulation mechanisms can be either constructive or destructive: **increasing surface motion reduces the nominal azimuthal resolution** (Alpers and Bruening, 1986)

Ocean waves' vertical motion has a significant impact on the SAR altimetry signal (Egido and Ray, 2019; Reale et al., 2020; Buchhaupt et al., 2023)

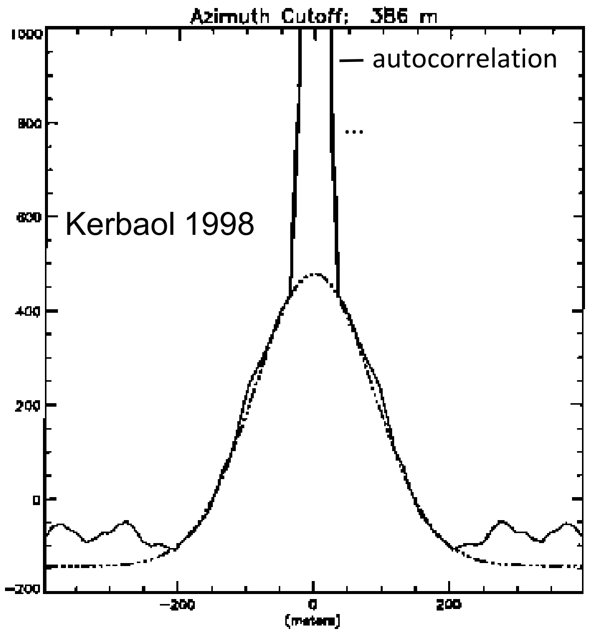
Background (2/2)

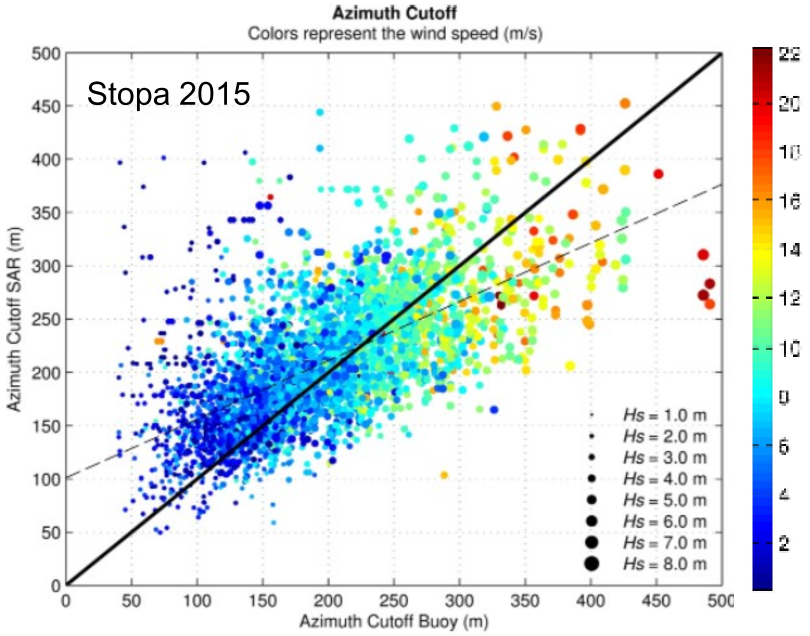
Increasing vertical wave motion leads to **distorted modulation spectra** and a strong **cutoff** ($\boldsymbol{\lambda_c}$) in the azimuth direction (Lyzenga 1986)

$\boldsymbol{\lambda_c}$: minimum detectable waves by a SAR system under certain wind and wave conditions

$$\left.\begin{aligned}\lambda_c &= \pi\sqrt{\rho_{\xi\xi}(0)}\\ \rho_{\xi\xi}(0) &= \left(\frac{R}{V}\right)^2 \int_0^\infty \omega^2 S(k)dk\end{aligned}\right\} \qquad \lambda_c = \pi\frac{R}{V}\sqrt{\int_0^\infty \omega^2 S(k)dk} = \pi\frac{R}{V}\sqrt{\sigma_\upsilon^2}$$

The azimuth autocorrelation function of a SAR image depends on the sea state and is dominated by the **velocity variance of the ocean surface** under moderate sea state conditions (Kerbaol and Chapron, 1998)





Study design – azimuth cutoff and vertical velocity variance

SAR altimetry image I (4km x 10km)

Remove artifacts:

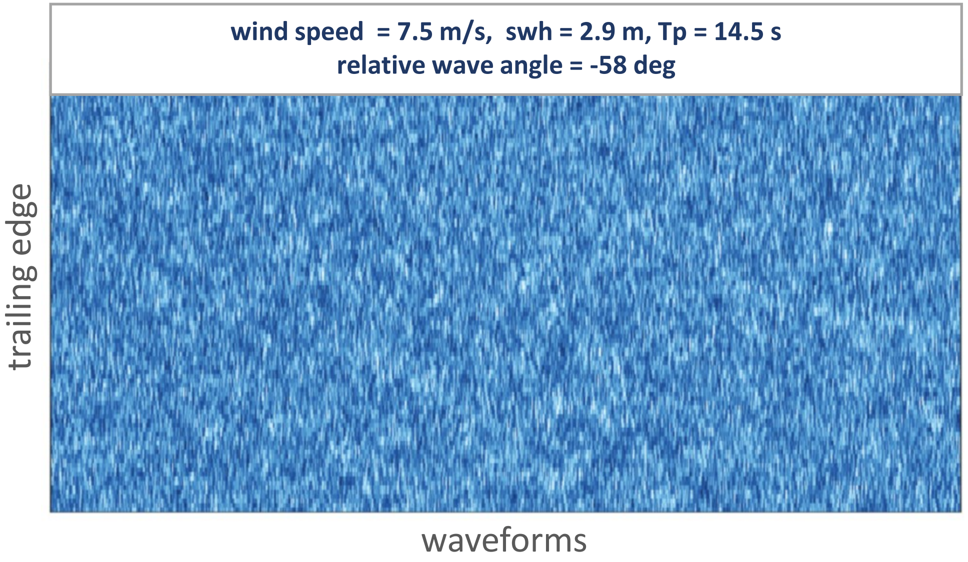
- a. Fit a polynomial model of 5th order in along-track
- b. Detrend signal

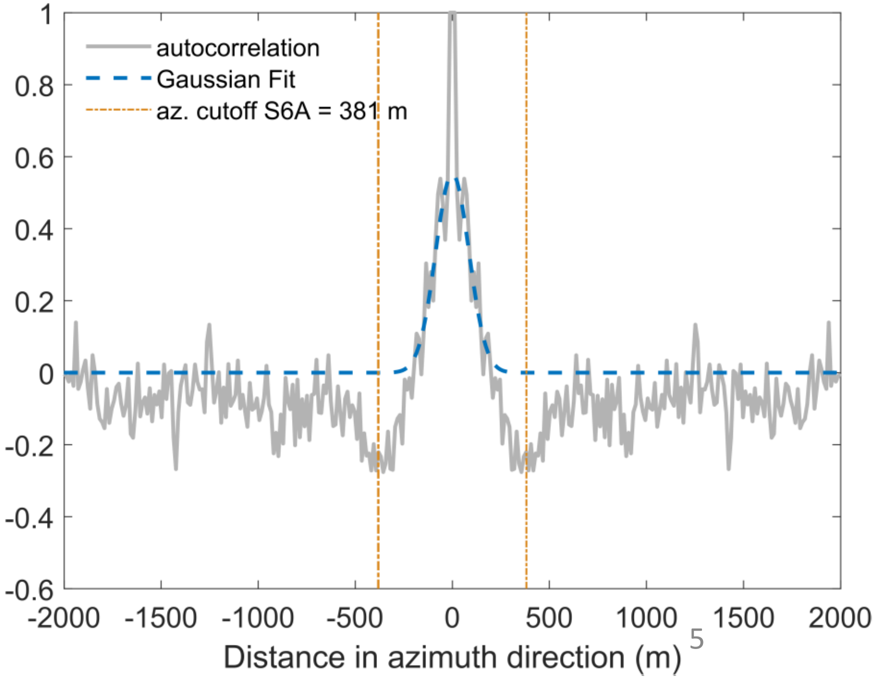
$\boldsymbol{\lambda_c}$ is estimated by minimizing the residuals of the functional:

$$\Delta\varepsilon = \int dy \left\{ Rxx(y) - e^{-\left(\frac{\pi y}{\lambda_c}\right)^2} \right\}$$

$Rxx(y)$: autocorrelation function (ACF) in the azimuth direction y

Vertical velocity variance $\left(\boldsymbol{\sigma_v^2}\right)$ is estimated as: $\sigma_v^2 = \left(\frac{\lambda_c}{\pi}\frac{V}{R}\right)^2$





Study design – Data

Sentinel-6A L1A Baseline F07 products: cycle 77 (December 2022)

SMAP Omega-Kappa software: L1b multilooked waveforms processed using 680Hz posting rate (~ 12m)

ECMWF ERA5 reanalysis (31 km x 31 km, hourly)

A) Sea state conditions:

significant wave height: 0-10 m
wind speed: 0-25 m/s
peak wave period: 8-20 s
STD of vertical velocity σ_{υ} : 0-3 m/s

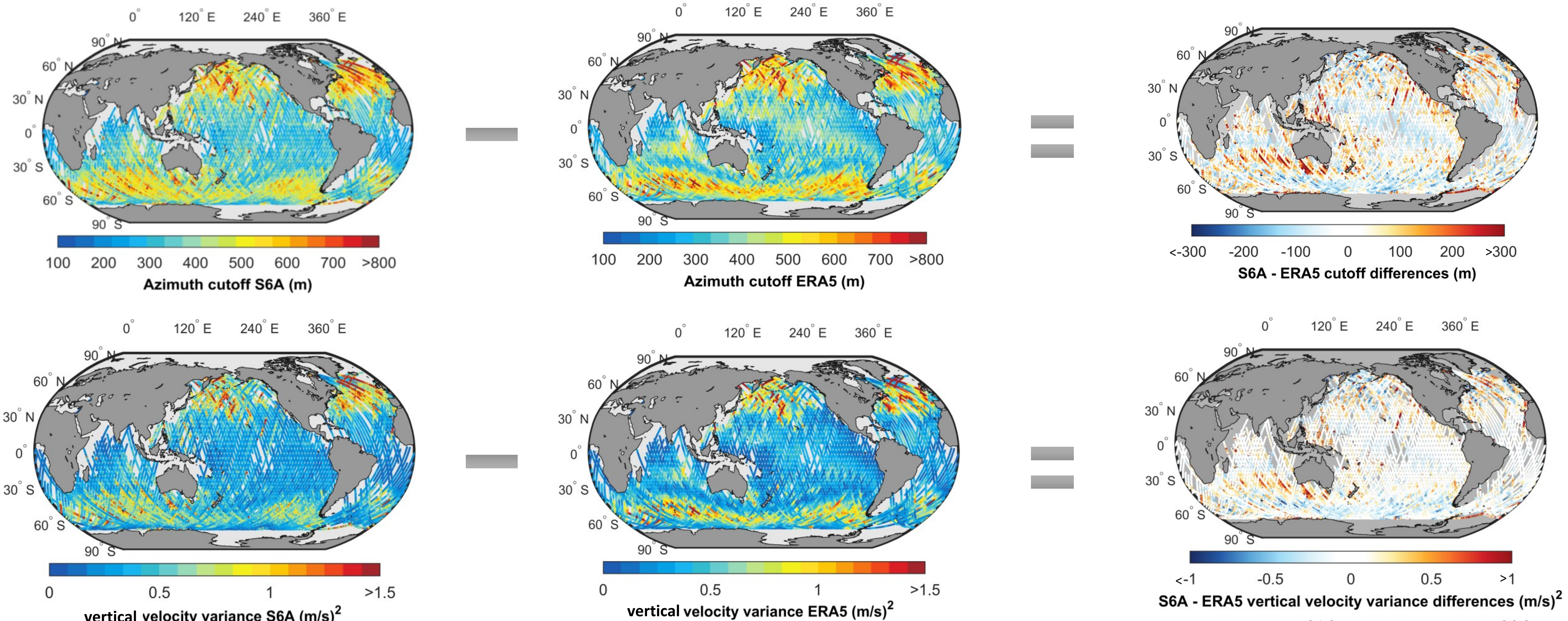
B) Bilinear interpolation of ERA5 gridded data into S6A tracks

C) Assuming deep-water waves we compute **ERA5** $\boldsymbol{\sigma_{\upsilon}^{2}}$ and $\boldsymbol{\lambda_{c}}$ as:

$$\sigma^2_{\upsilon_{era5}} = \left(\frac{\pi}{2}\frac{H_s}{T_{02}}\right)^2 \qquad \lambda_{c_{era5}} = \pi\frac{R}{V}\sqrt{\sigma^2_{\upsilon_{era5}}}$$

Evaluate the method

paper to be submitted



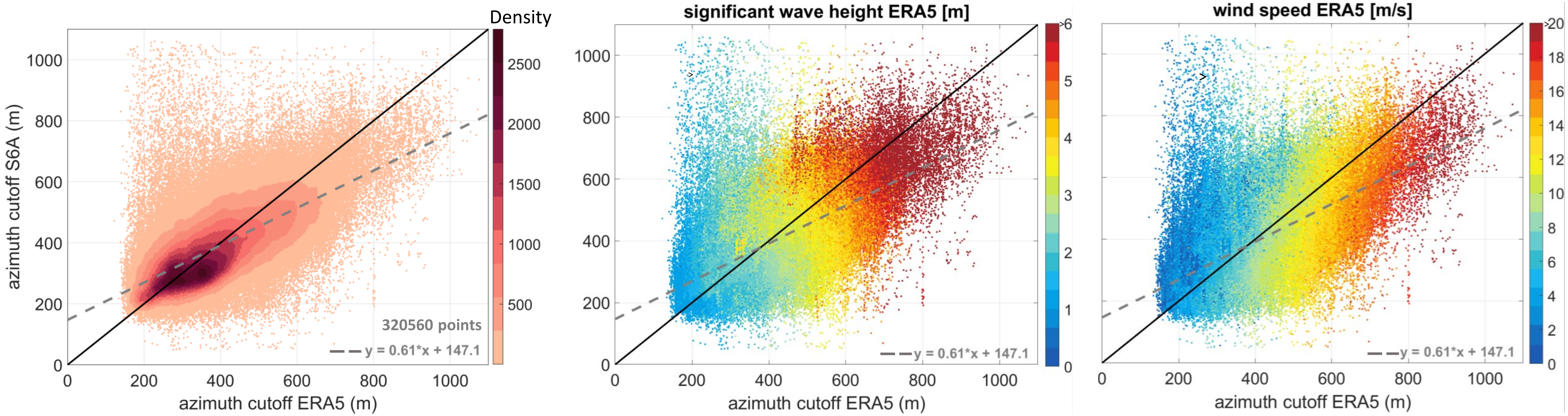
Min :-2.1 m^2/s^2 **Std. Dev. : 0.26 m^2/s^2**

Max : 2.8 m^2/s^2 **Mean : -0.01 m^2/s^2**

The shortest detectable waves are of wavelengths larger than 100m

Underestimation in the Southern and Northern Oceans: prevailing wind seas

Evaluate the method: sea state

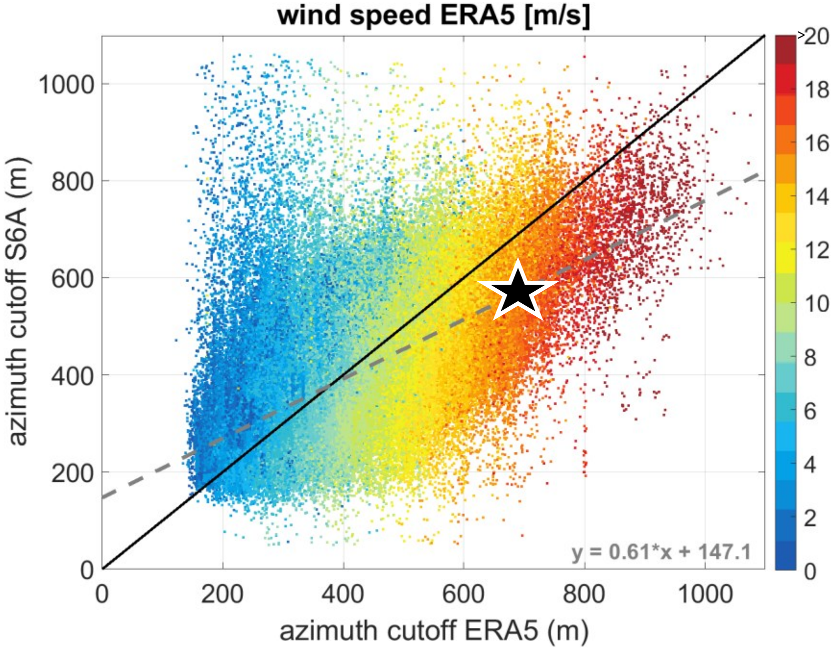


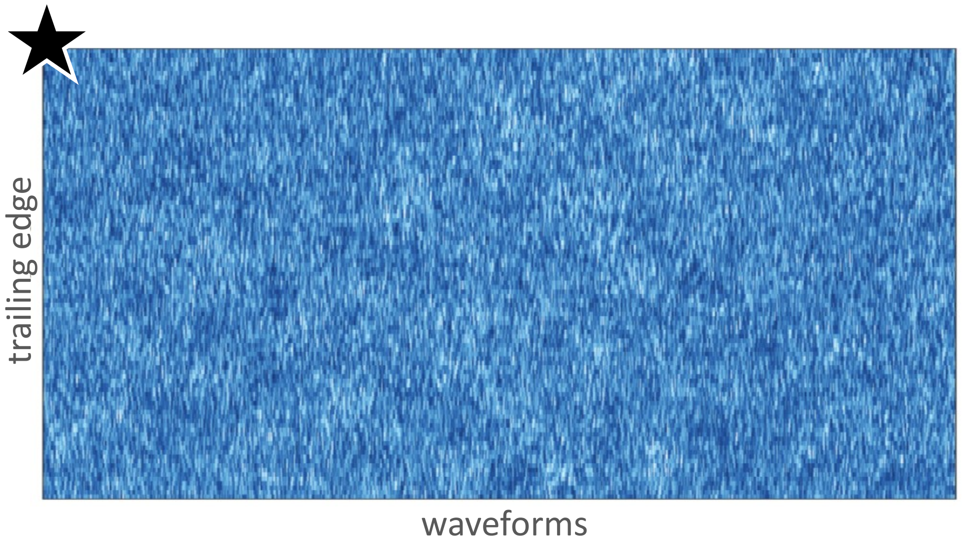
Azimuth cutoff increases with increasing significant wave height

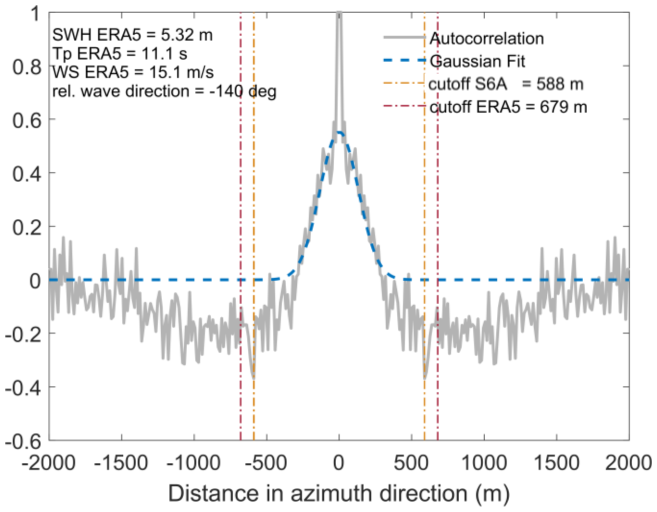
Overestimation in relatively **calm sea states**

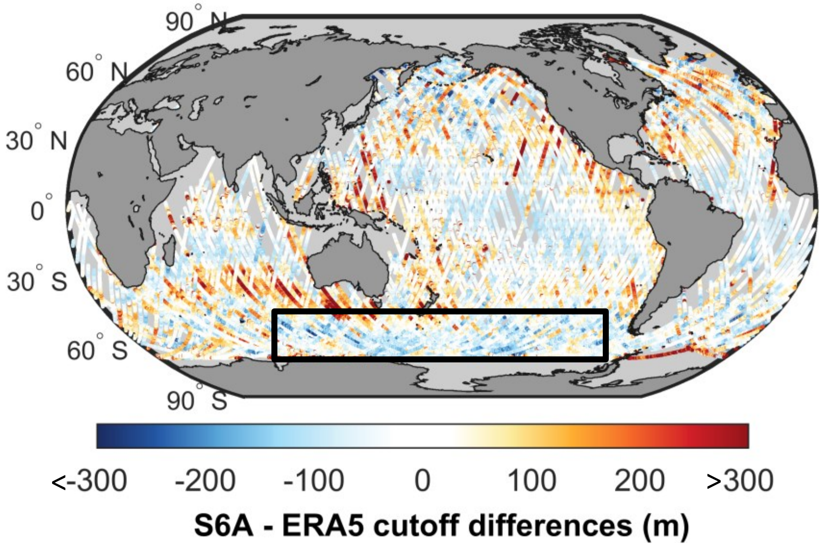
Underestimation with **increasing wind speed**

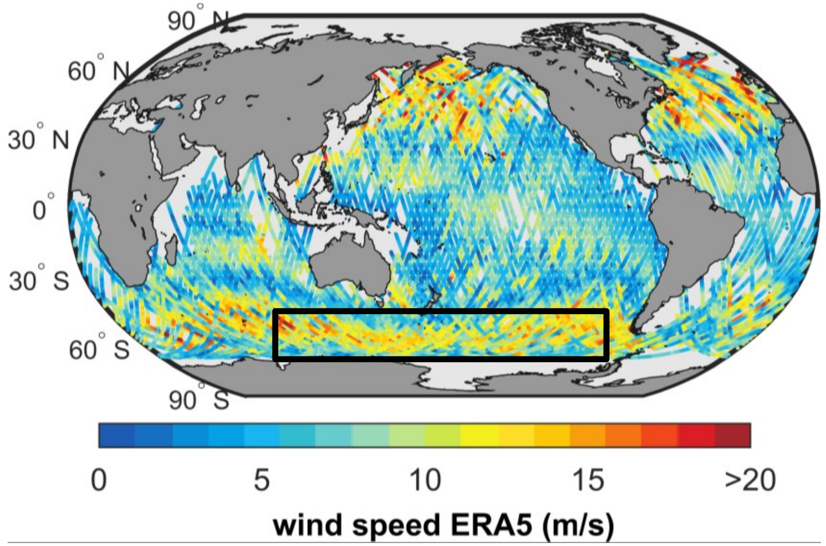
Evaluate the method: wind speed









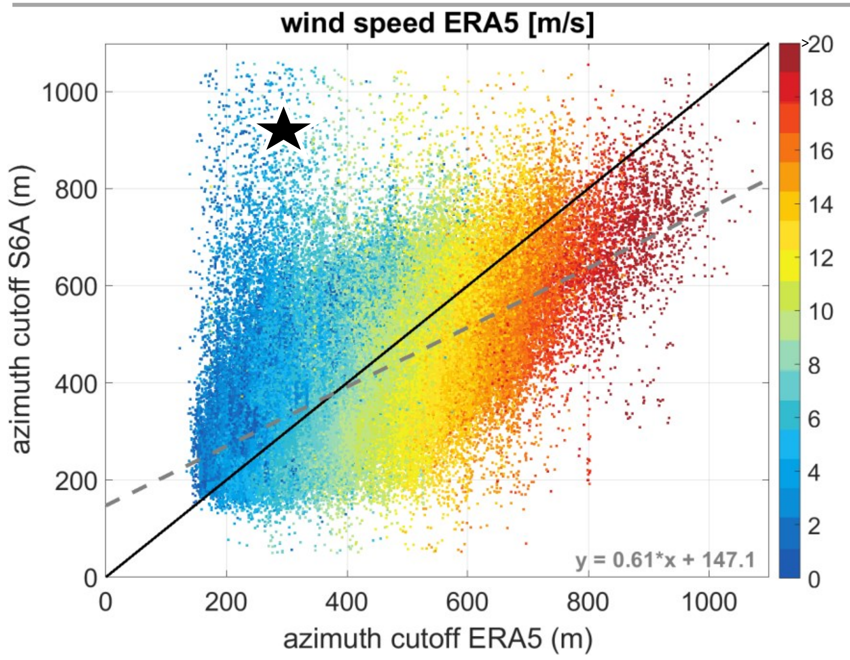


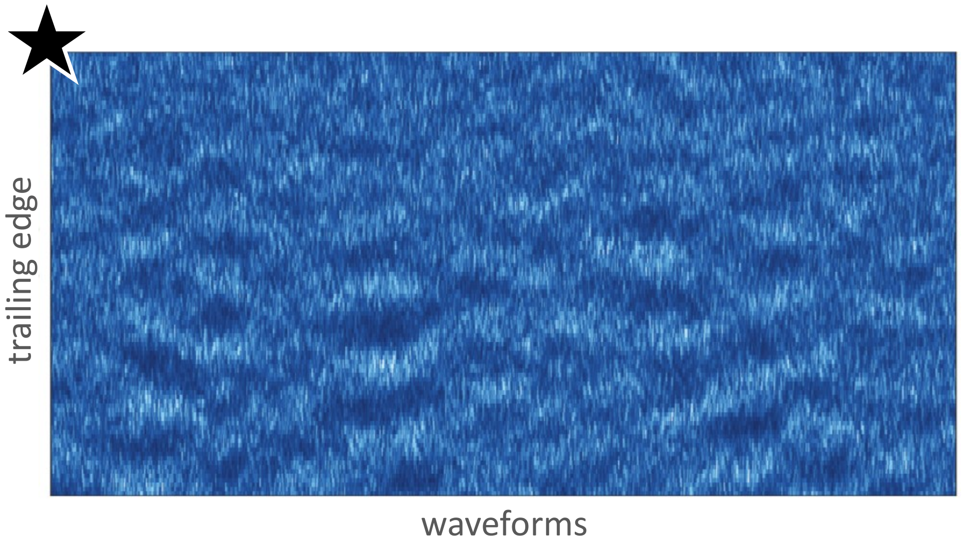
underestimation in wind seas:

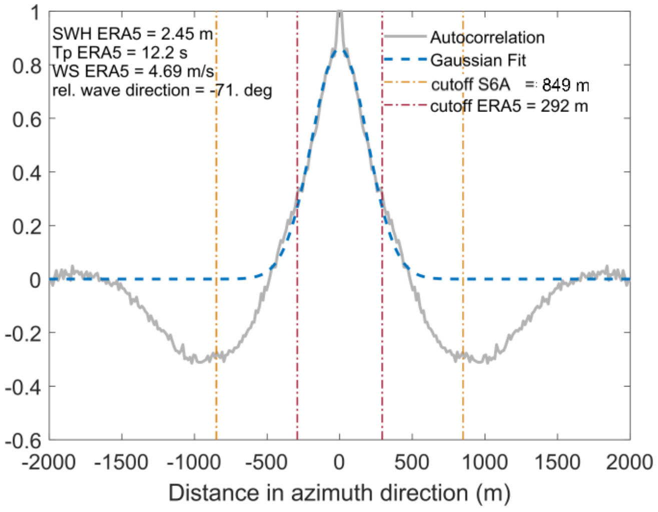
increased wave steepness

wave breaking

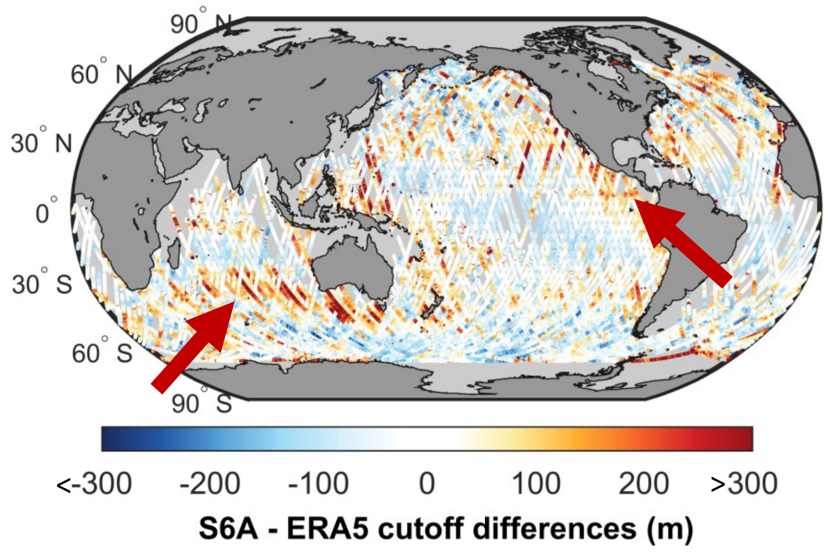
Evaluate the method: **wind speed**

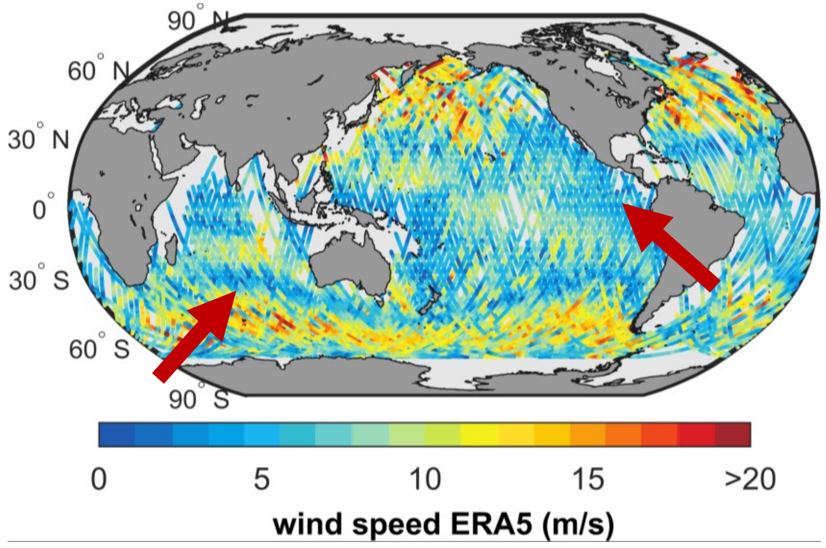


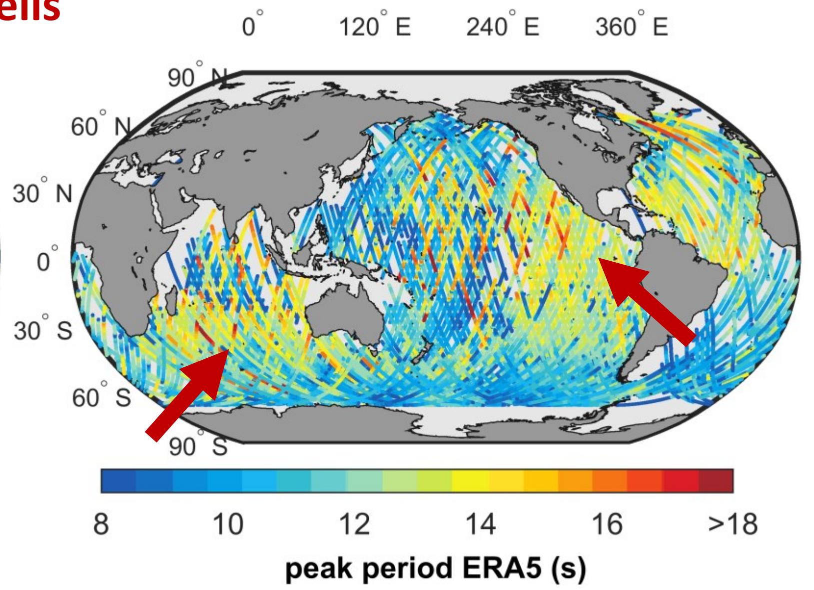




overestimation: low wind speed and swells

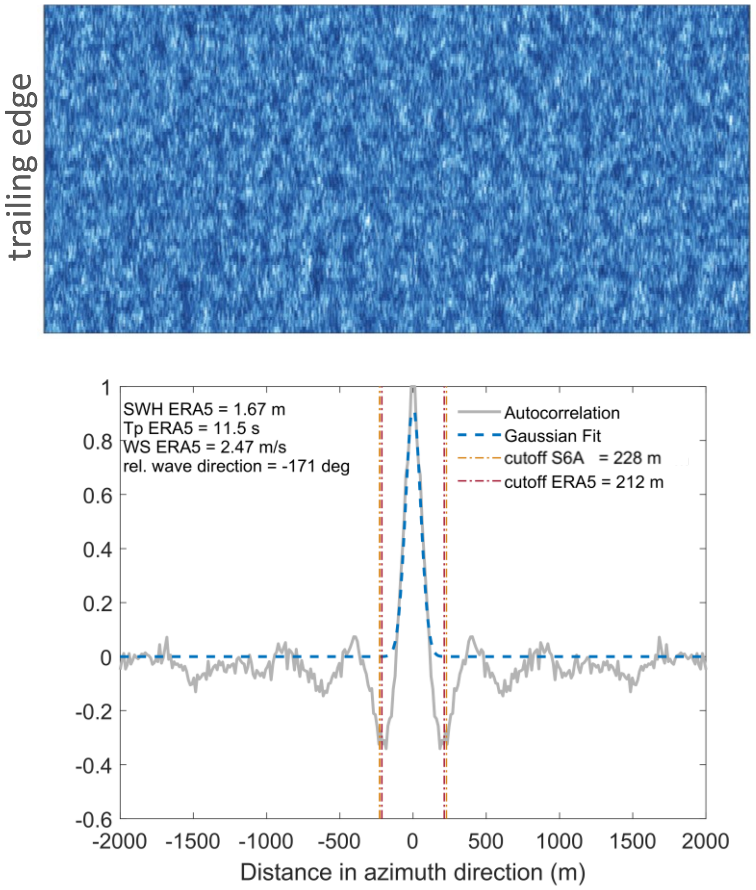




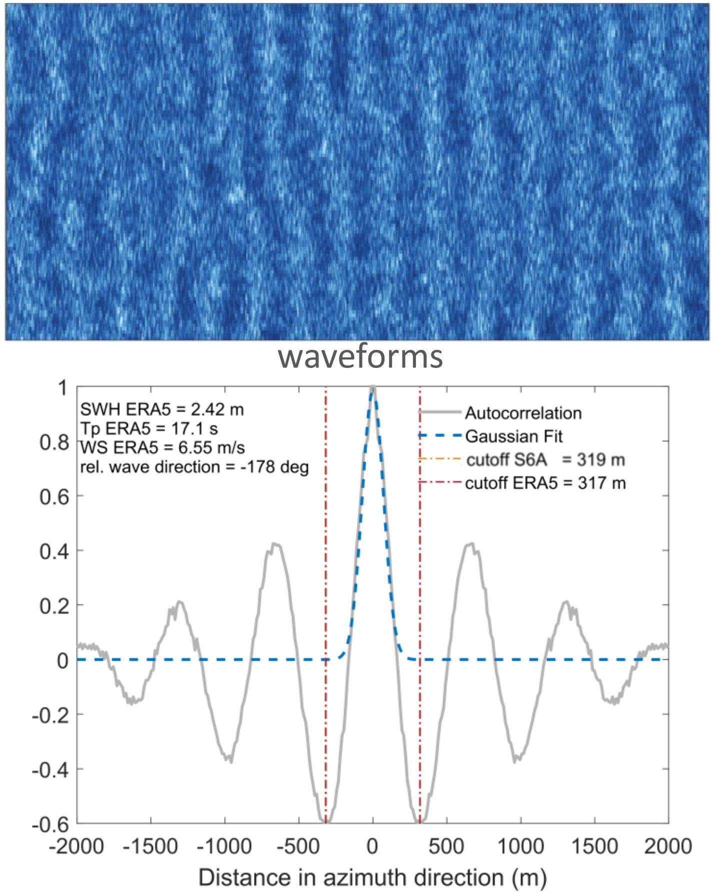


Evaluate the method: swells

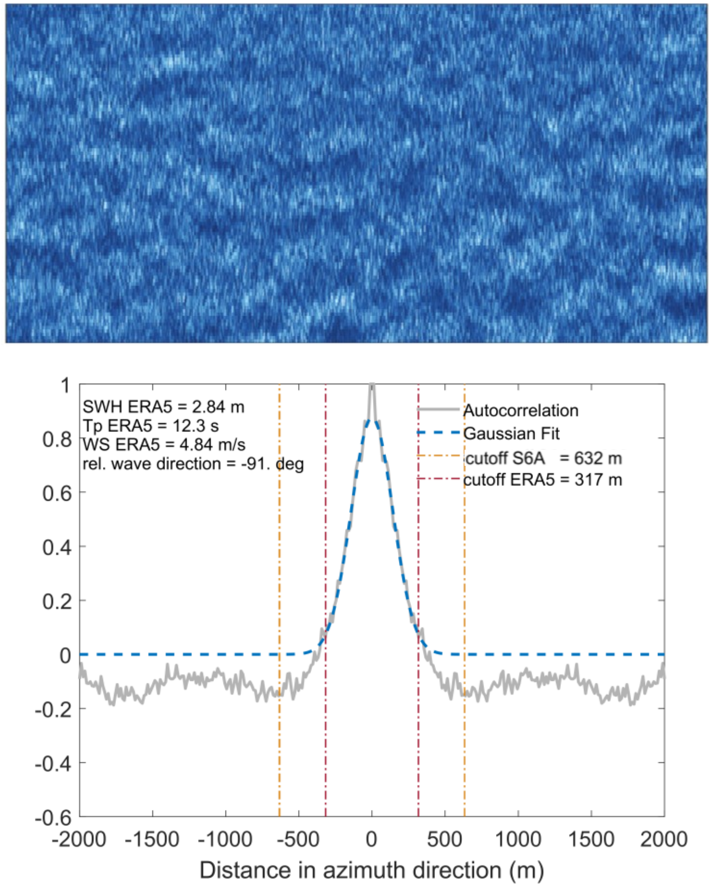
short-period swells travelling in **along track**



long-period swells travelling in **along track**



short-period swells travelling in **range**

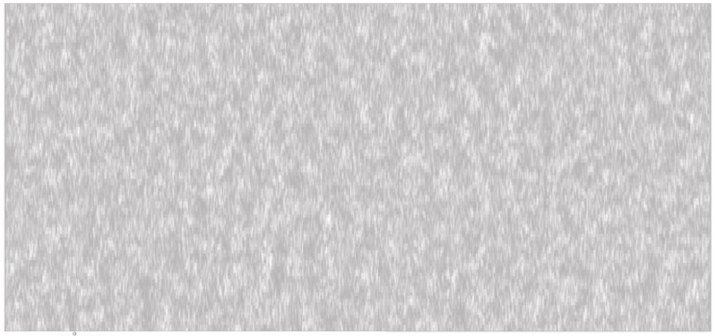


sinc-shaped azimuth ACF for along-track propagating swells: **the longer the swells, the larger the side lobes, without apparent impact on the cutoff estimation**

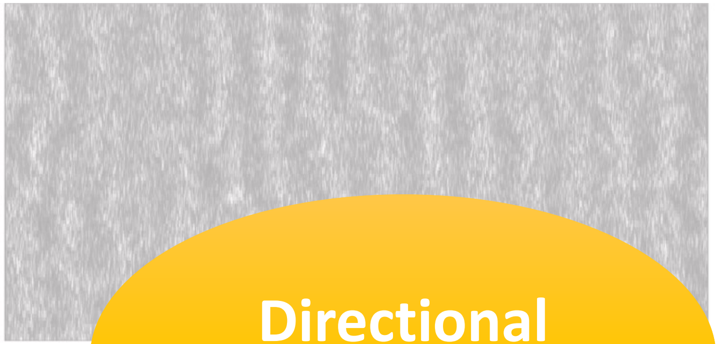
large discrepancies are observed when swells travel in **range direction**

Evaluate the method: swells

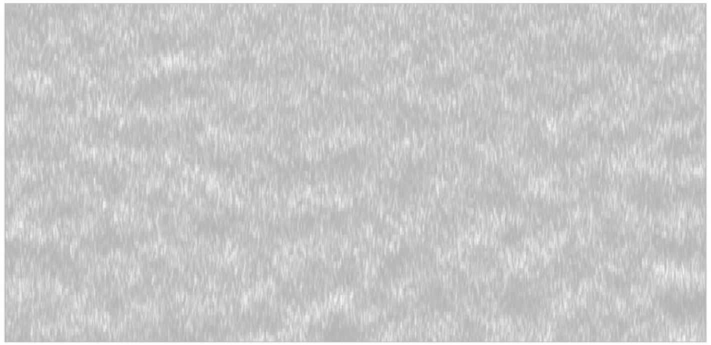
short-period swells travelling in **along track**

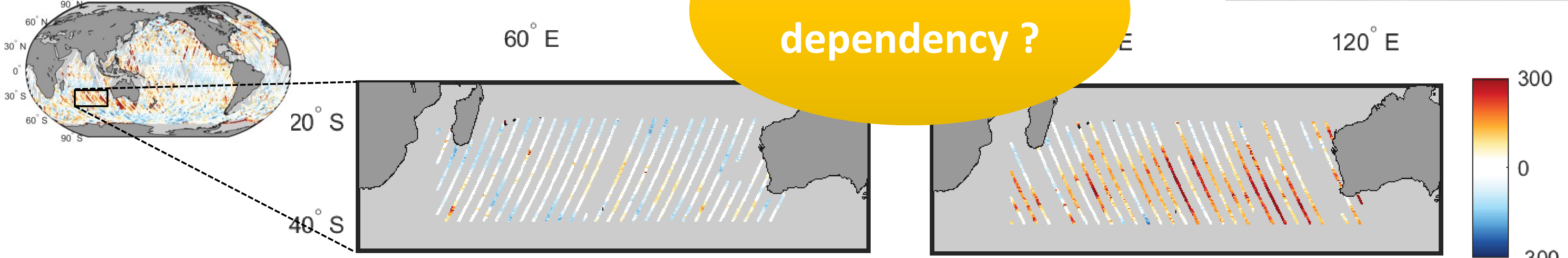


long-period swells travelling in **along track**



short-period swells travelling in **range**

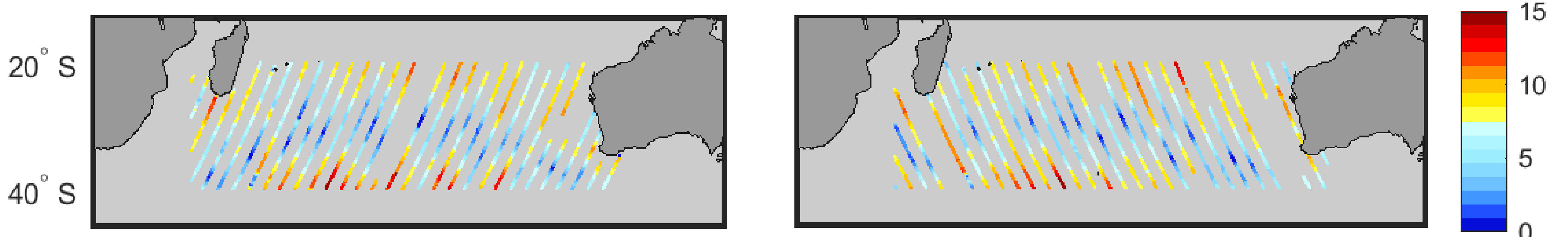




Directional dependency ?

S6A – ERA5 azimuth cutoff [m] - **ascending**

S6A – ERA5 azimuth cutoff [m] - **descending**



wind speed ERA5 [m/s]

wind speed ERA5 [m/s]

Key findings

- A global study of Sentinel-6A azimuth cutoff and vertical velocity variance using fully-focused SAR data has been conducted
- Azimuth cutoff can be interpreted as a proxy for the variance of the wave velocities under moderate wind and wave conditions but:
    - **in calm sea states overestimation is observed:** sea surface roughness is rather not adequate to resolve the scene
    - **in extreme sea states underestimation is observed:** increased wave steepness and wave breaking
    - **swells travelling in range** decrease the quality of the estimates

Further work

An azimuth cutoff analysis in the frequency domain may improve the quality of the estimates

Empirical corrections based on wind speed, significant wave height and sigma0 obtained from L2 products

Wind and swell wave system separation can be achieved by making use of azimuth cutoff, velocity variance, SAR modulation spectra and L2 geophysical parameters

Questions?

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Interested in more details?
Contact me by email: ***o.altiparmaki@tudelft.nl***