Surface Waves

Opportunities and challenges in the context of SWOT

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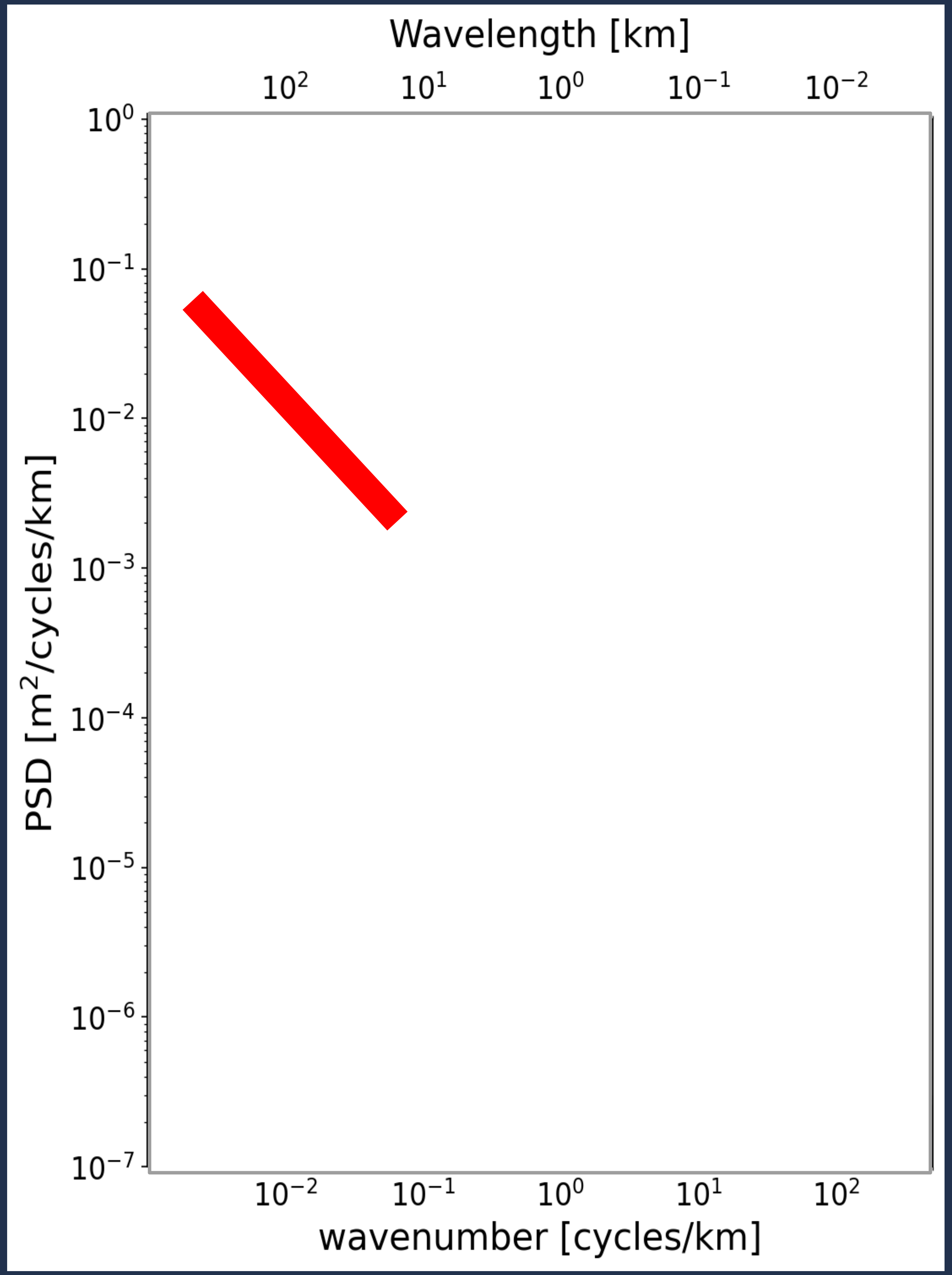
with Luke Colosi, Yao Yu, Luc Lenain, David Sandwell, Matt Mazloff, Bruce Cornuelle, and Sarah Gille.

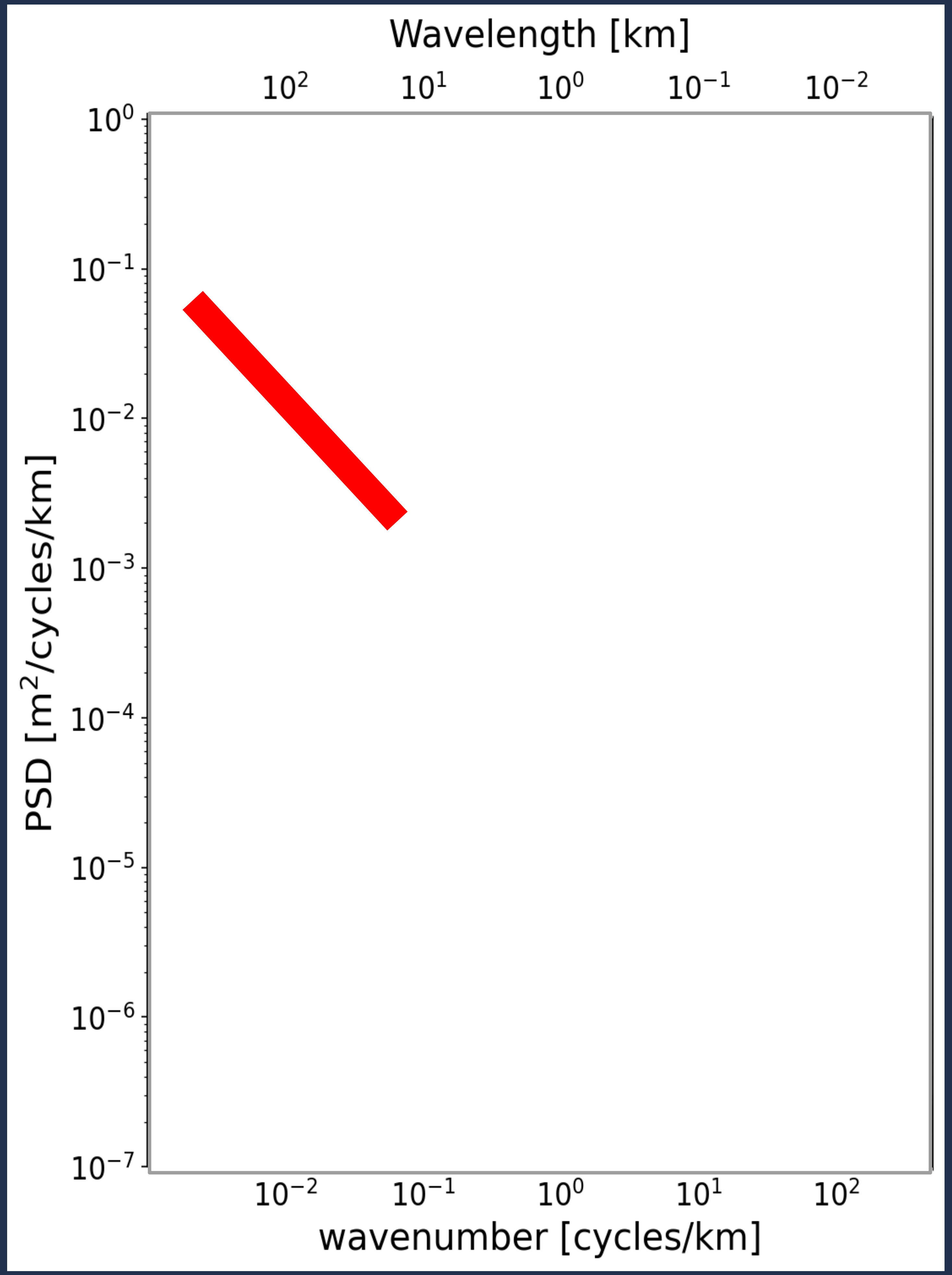
- The contribution of surface waves to the SSH variability
- Refresher on surface waves climatology

This is how we usually picture the SSH spectrum:

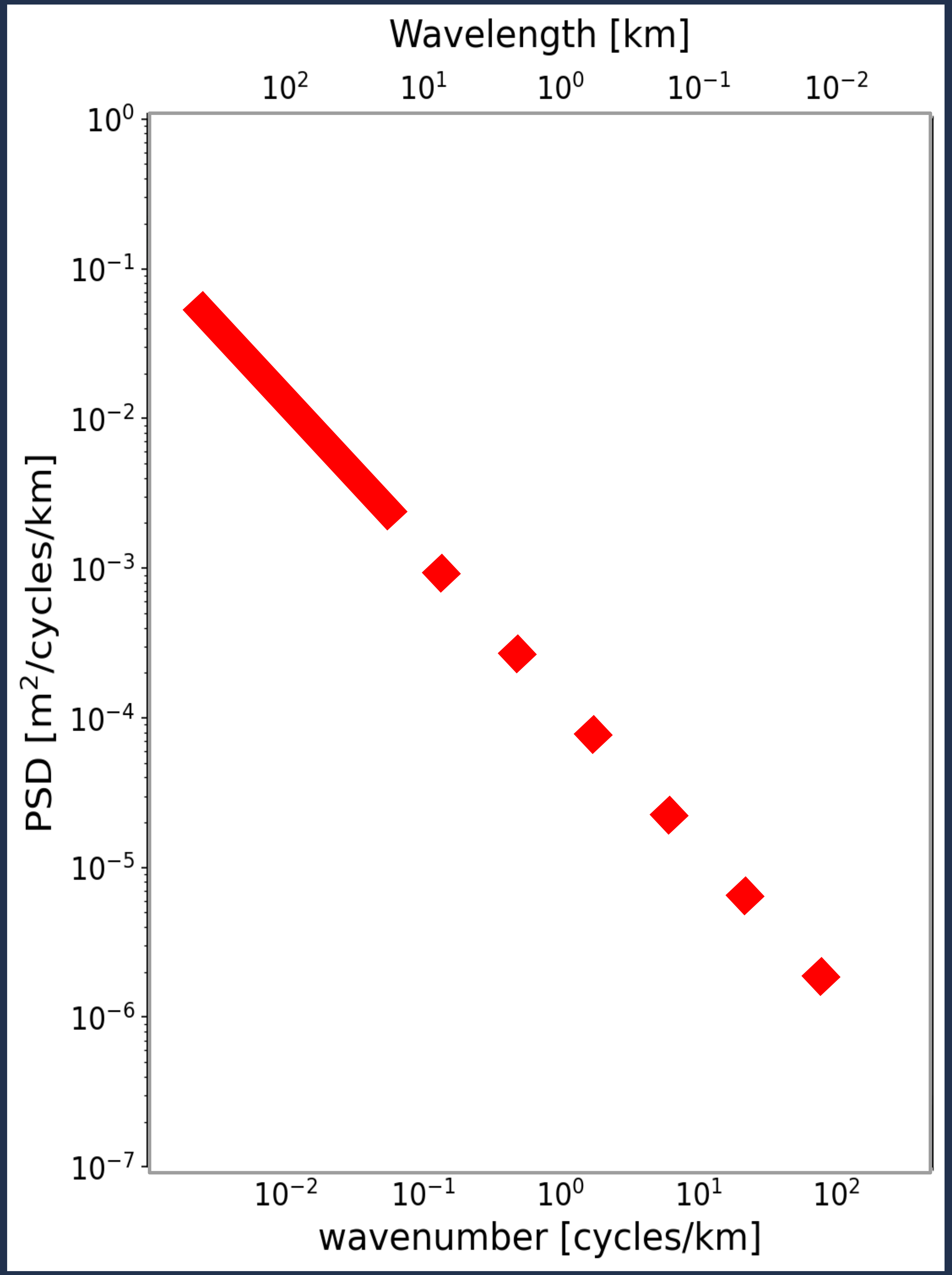


This is how we usually picture the SSH spectrum:

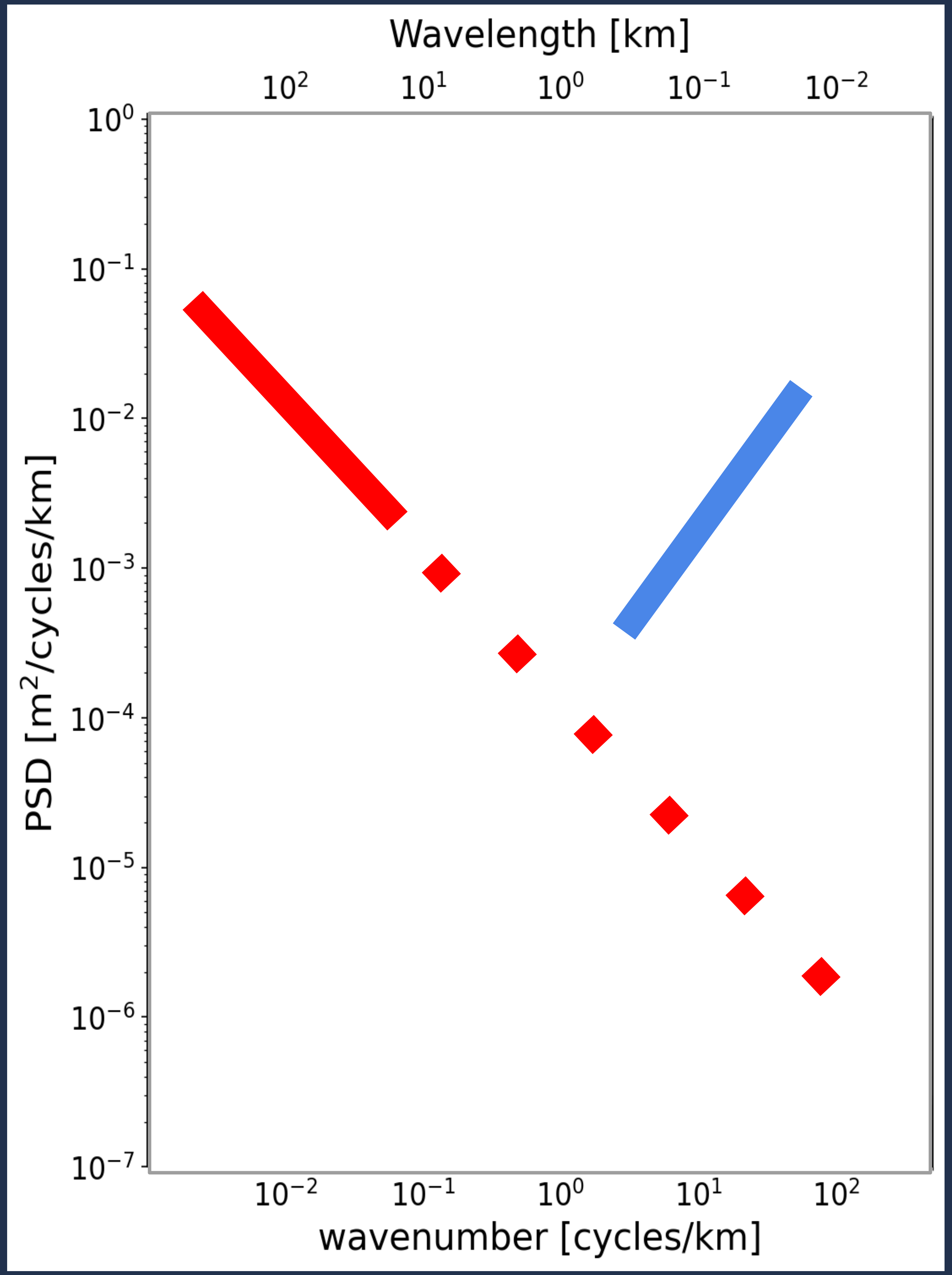
- Red spectrum: variance decreases with wavenumber
- Consistent with QG turbulence theory



It's tempting to extrapolate ...

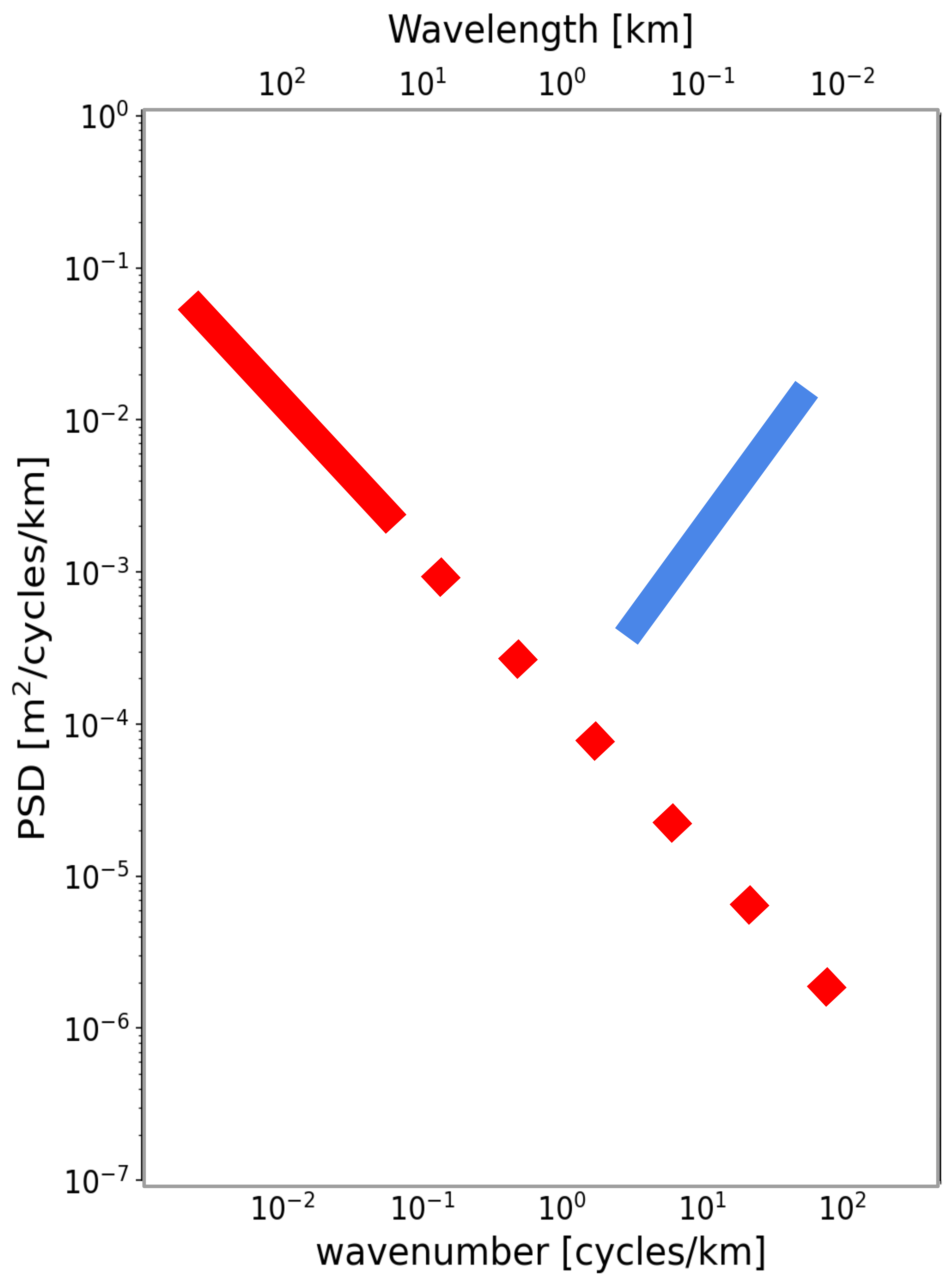


but ... surface waves!



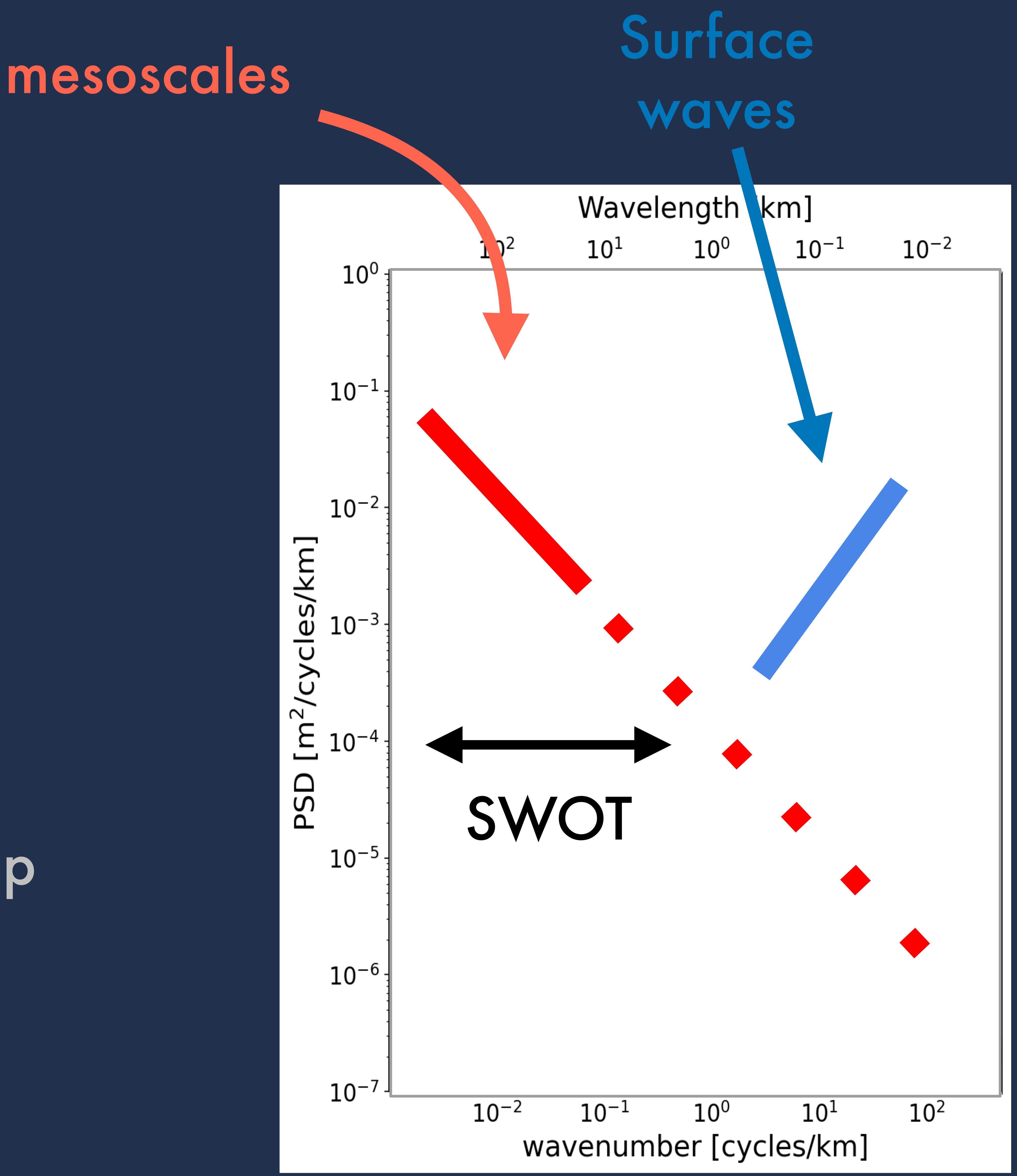
but ... surface waves!

- At scales between 1-500 the SSH is dominated by *surface gravity waves*
- Blue spectrum: variance *increases* with wavenumber



So what?

- Scale separation between QG turbulence and surface wave dynamics:
  - The red and blue zones have been traditionally explored independently
- SWOT will resolve scales where many processes overlap



So what?

- Scale s
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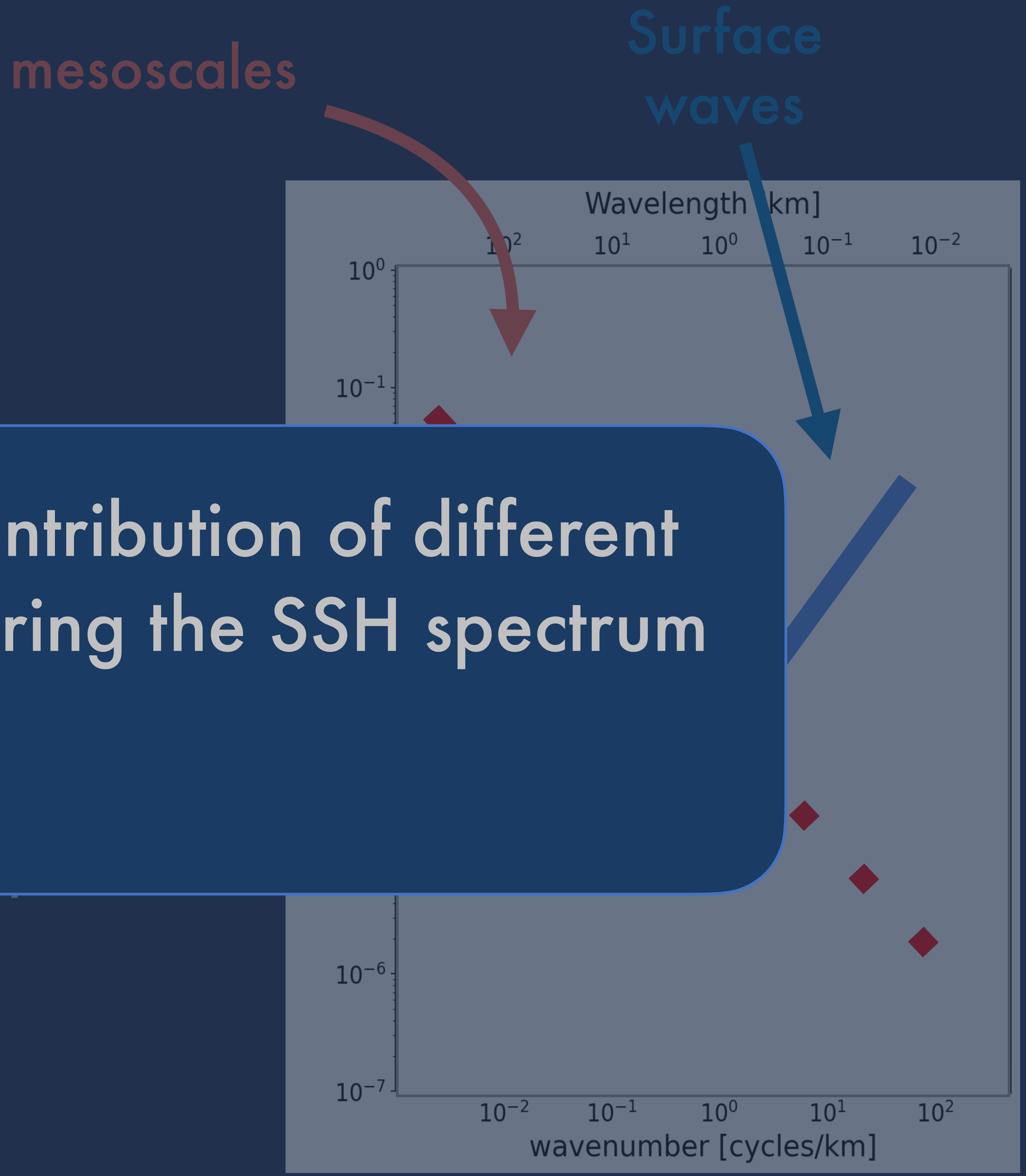
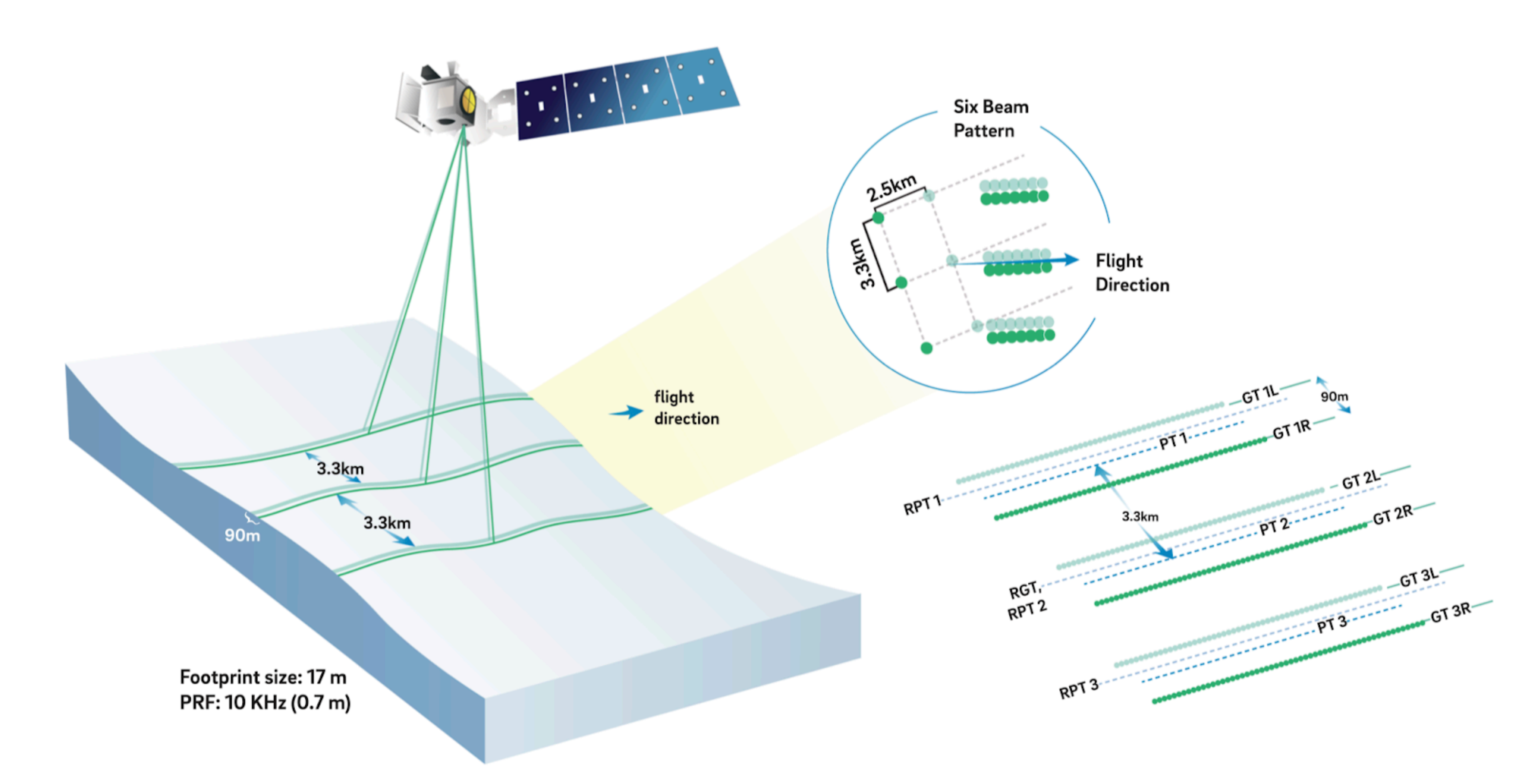
  - The
    inde
- SWOT

There is a need to understand the contribution of different physics to the SSH variability considering the SSH spectrum as a *continuum*



Spaceborne laser altimetry: ICESat-2



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doi: 10.1093/gji/ggab084
Advance Access publication 2021 March 02
GJI Gravity, Geodesy and Tides

Assessment of ICESat-2 for the recovery of ocean topography

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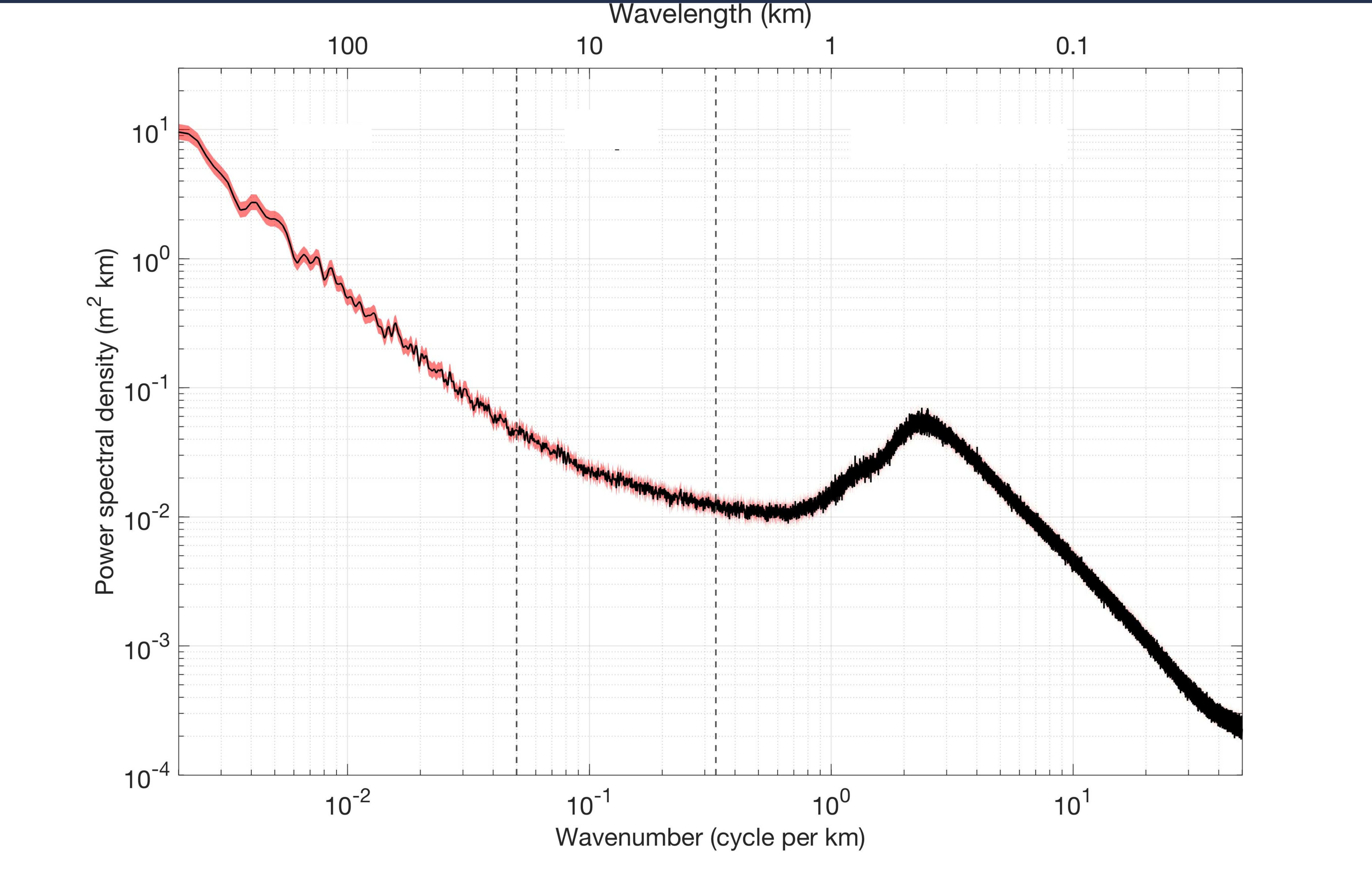
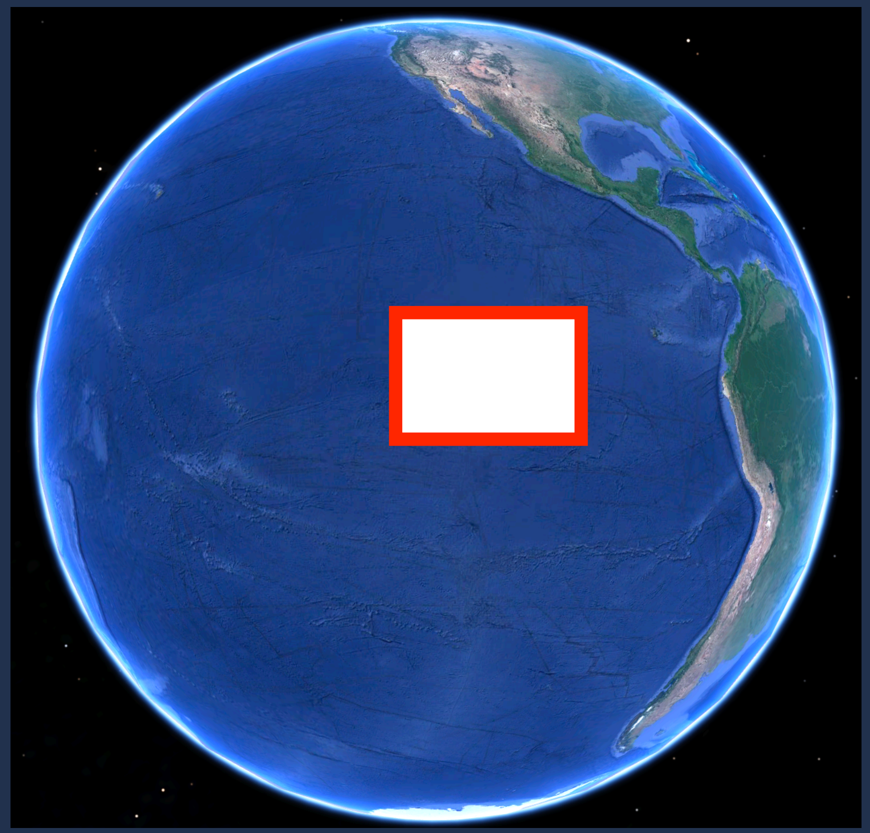
- Can the ICESat-2 ocean data improve the accuracy and resolution of the marine geoid/gravity field?

https://doi.org/10.1093/gji/ggab084

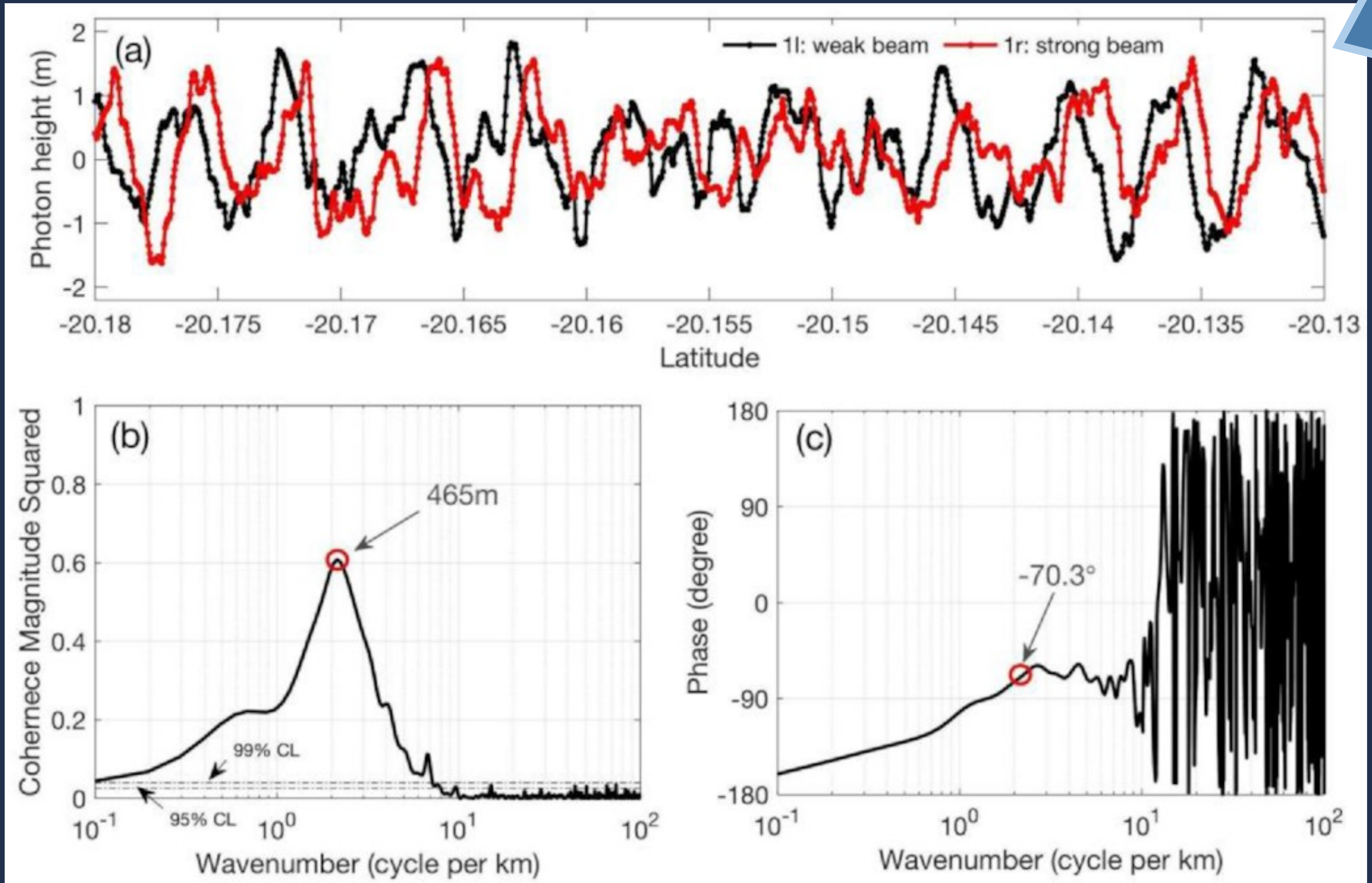
Sea surface height wavenumber spectrum





- Average across 341tracks from strong beams in the Tropical Pacific

- Red spectrum at low wave numbers
- Broad peak in the surface wave (swell) band

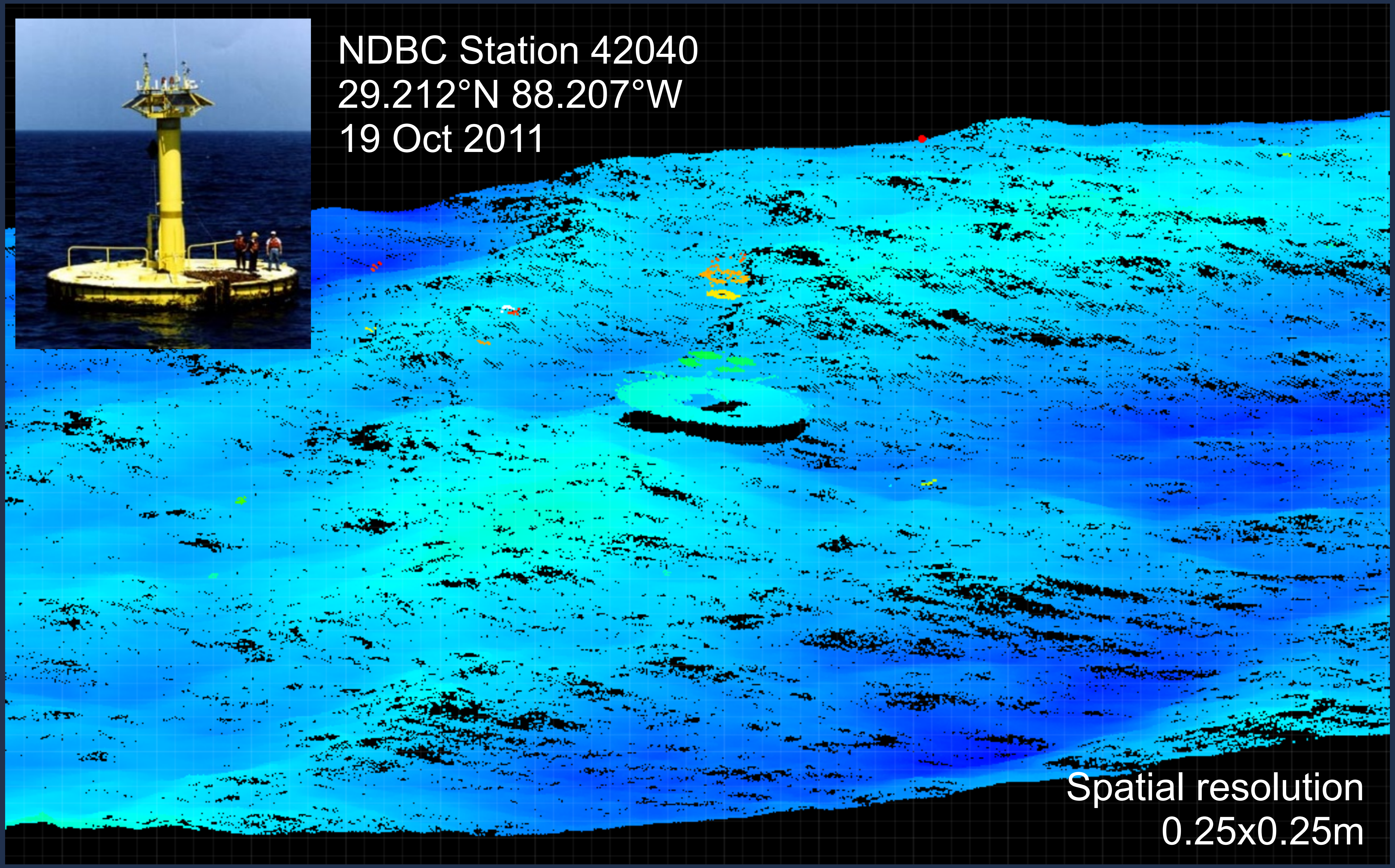


- ICESat-2 can observe individual waves …

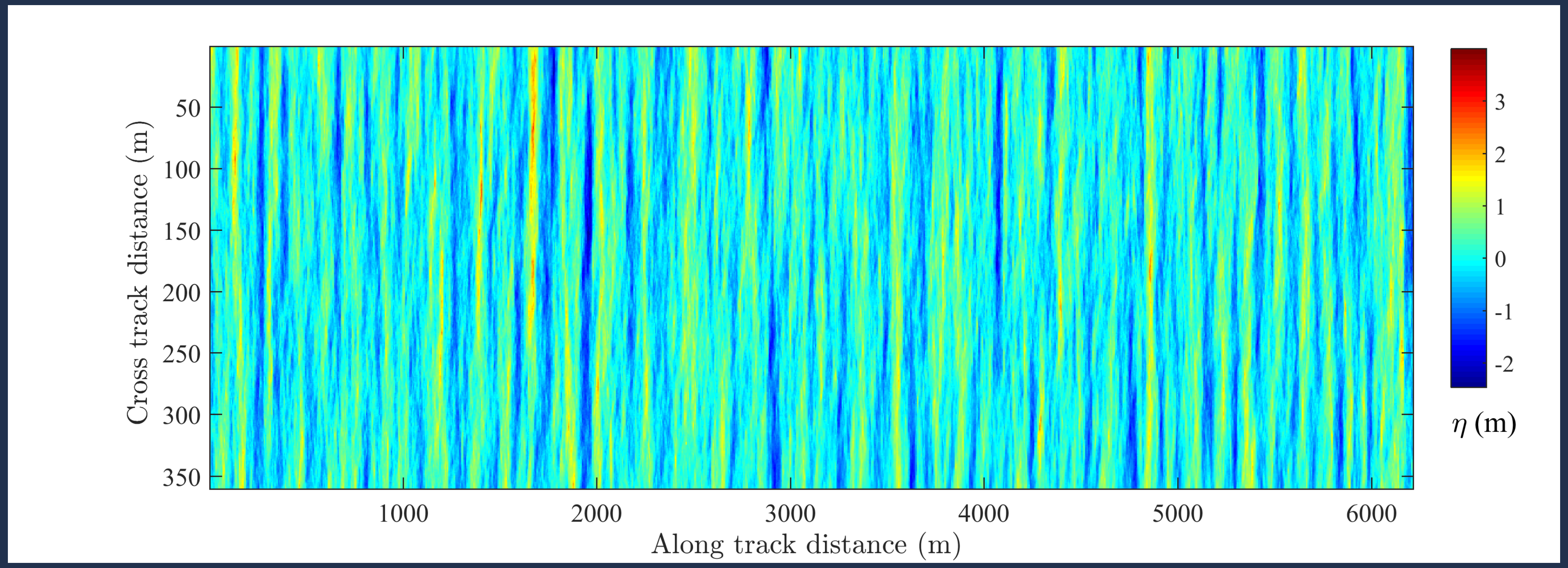
… but it's essentially a 1D measurements

Combination of strong and weak beams may be used to infer dominant wave properties (e.g., wavelength and direction)

Airborne laser altimetry: MASS



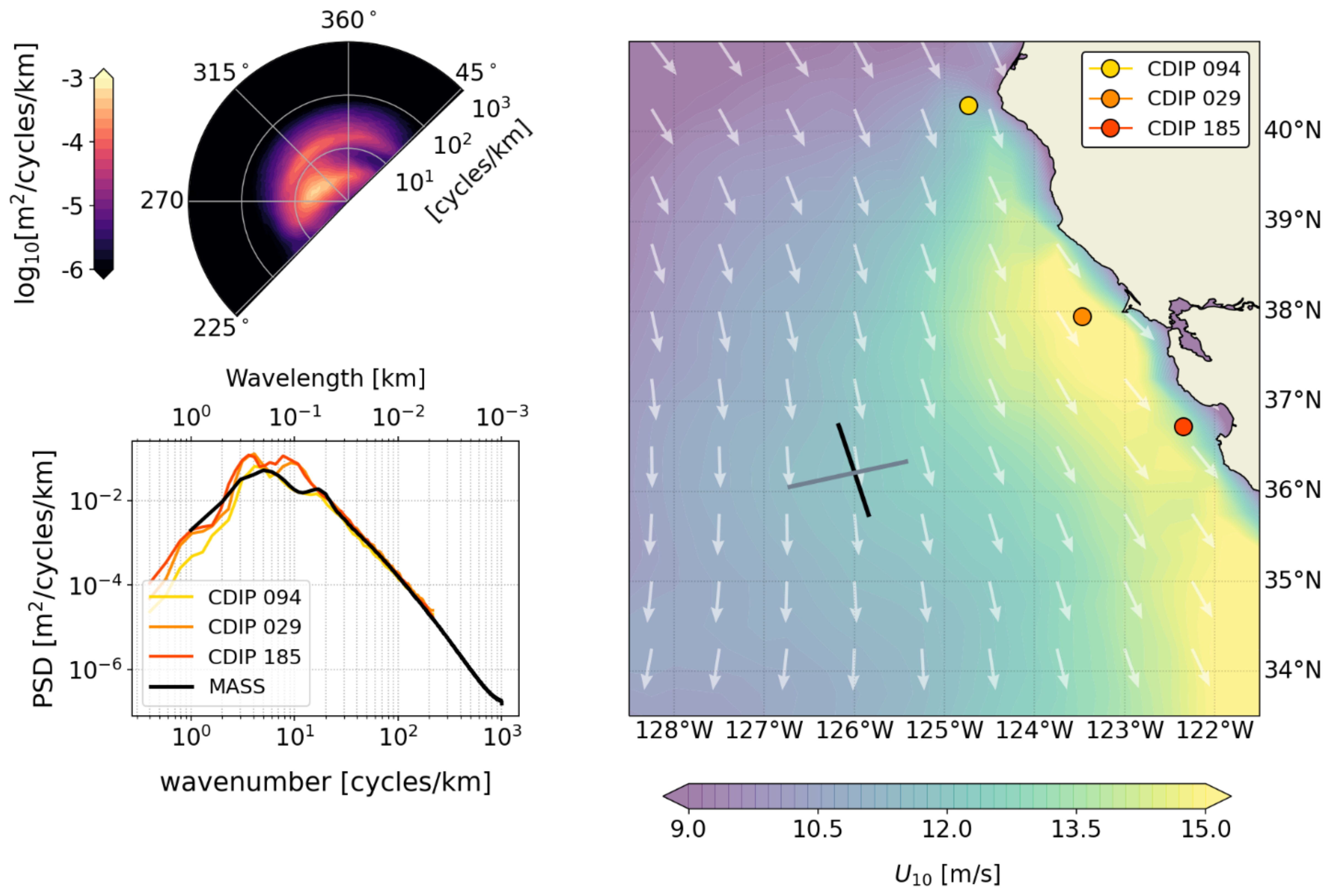
From Luc Lenain - SIO Air-sea lab



- Scanning Lidar (~ 500 m swath)
- Measures the SSH with sub-meter horizontal resolution
- Resolves the 2D wave field

SWOT pre-launch airborne campaign (Spring 2019)

- Measurements from the Scripps Institution of Oceanography (SIO) Modular Aerial Sensing System (MASS)



- Strong winds 11-15 m/s
- Swath width: ~ 500 m
- Hs = 3 m

Sea:

T_p = 6 s

λ_p = 60 m

θ_p = 321°

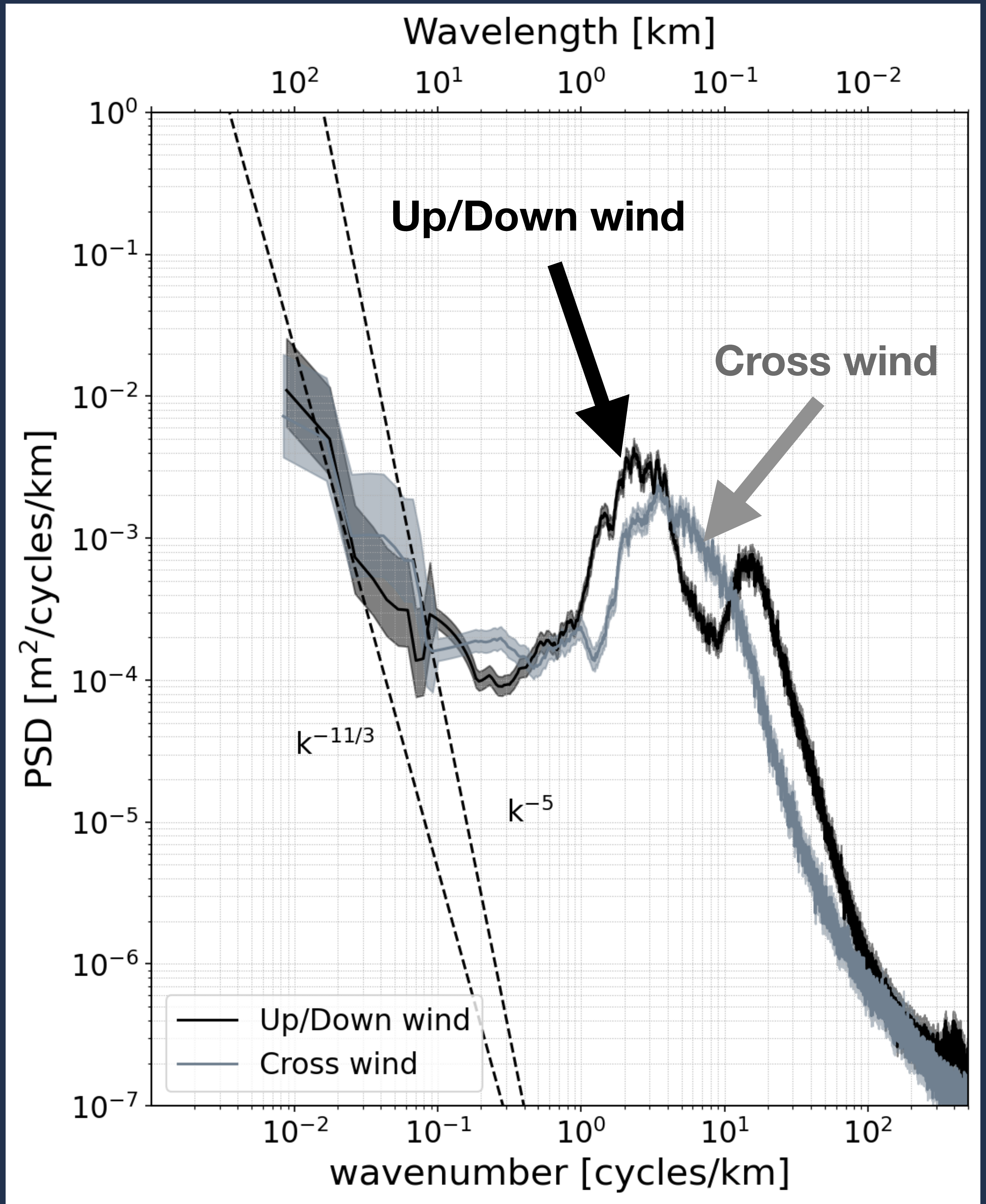
Swell:

T_p = 11 s

λ_p = 200 m

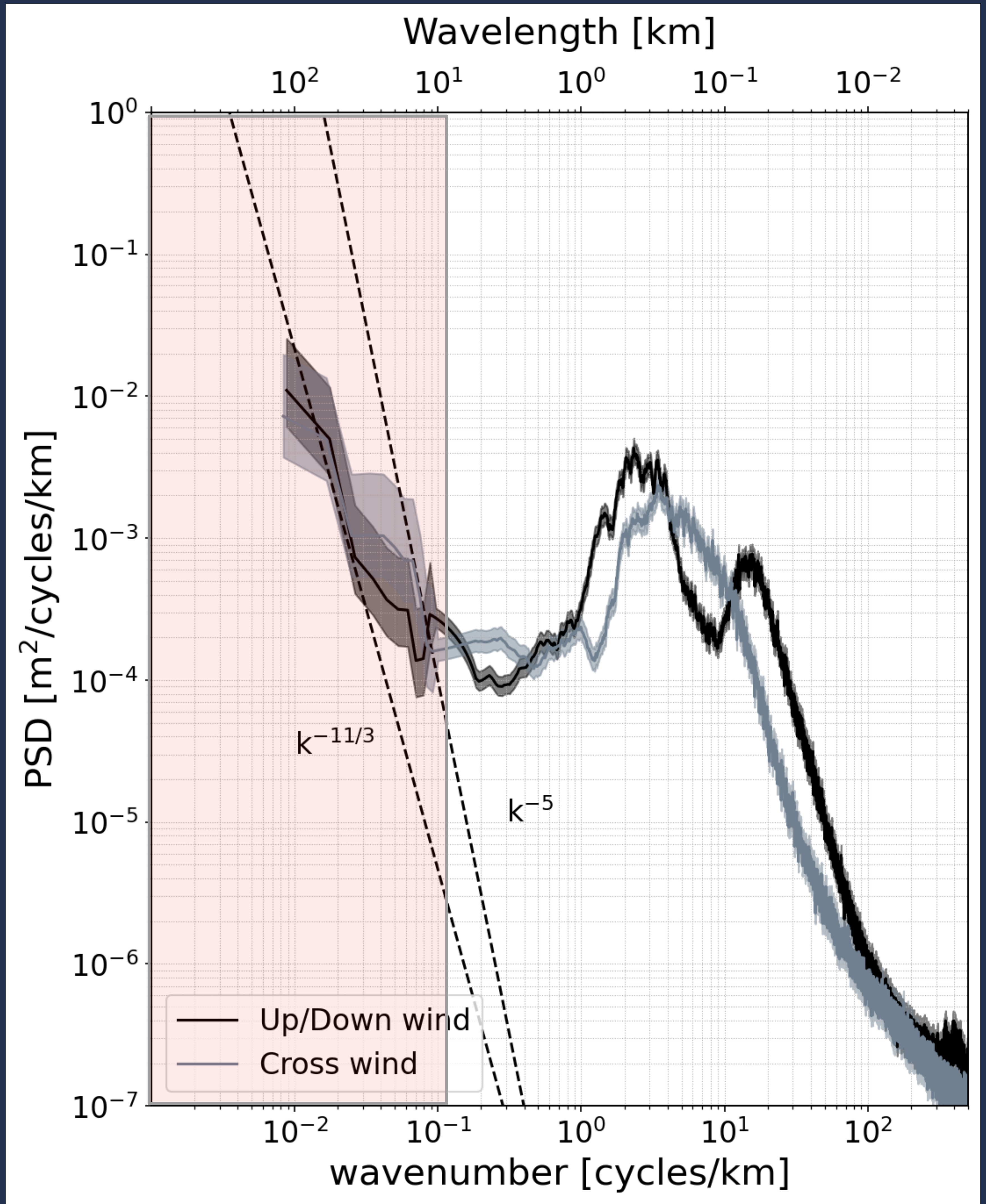
θ_p = 308°

Across-track averaged spectrum



Villas Bôas et al. (2022)
https://doi.org/10.1029/2021GL096699

Across-track averaged spectrum



- The red zone ($k < 10^{-1}$ cycles/km)
  - The spectrum from MASS is red and typical of mesoscale turbulence + GM
  - Falls with a $k^{-11/3}$ to k^{-5} slope

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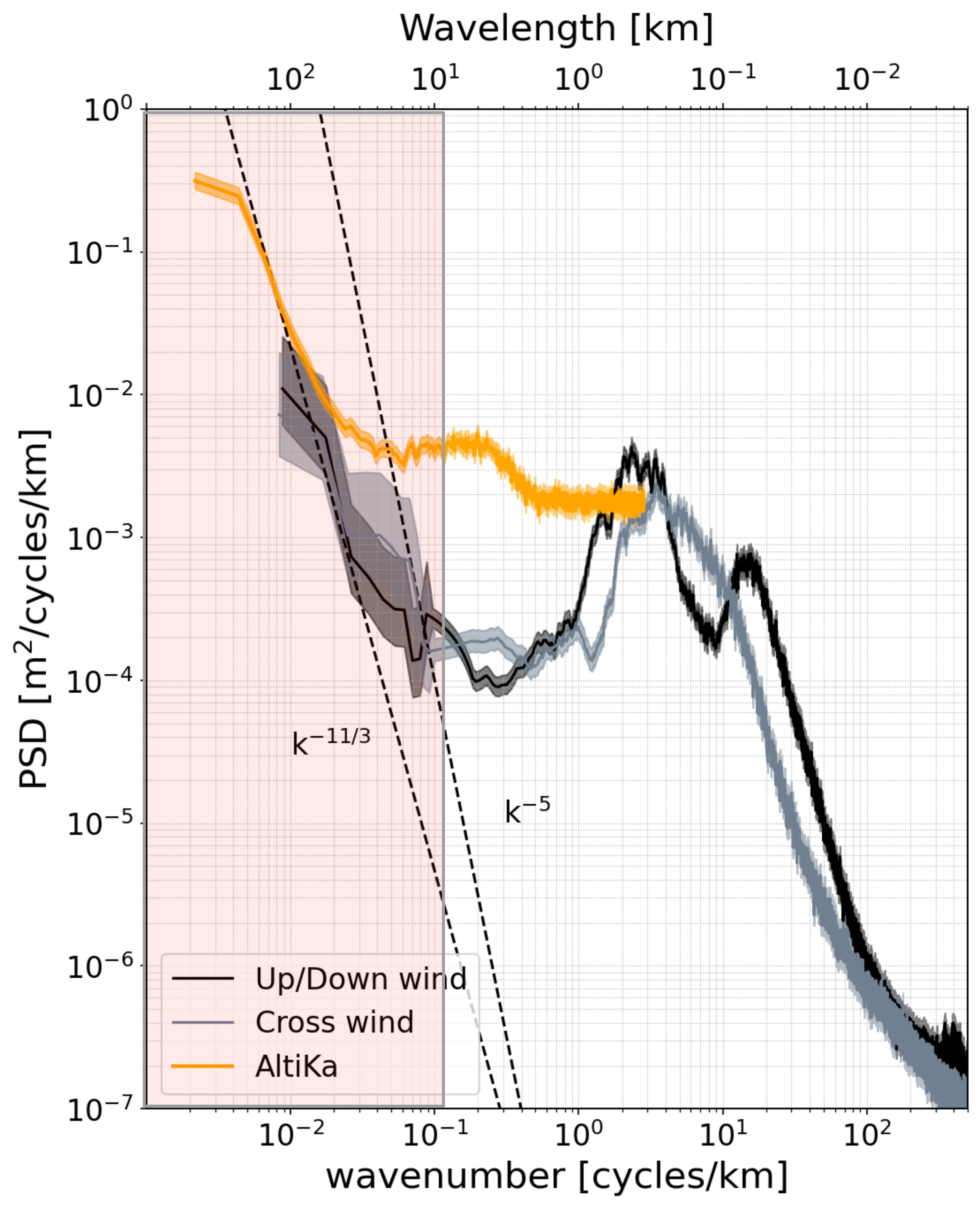

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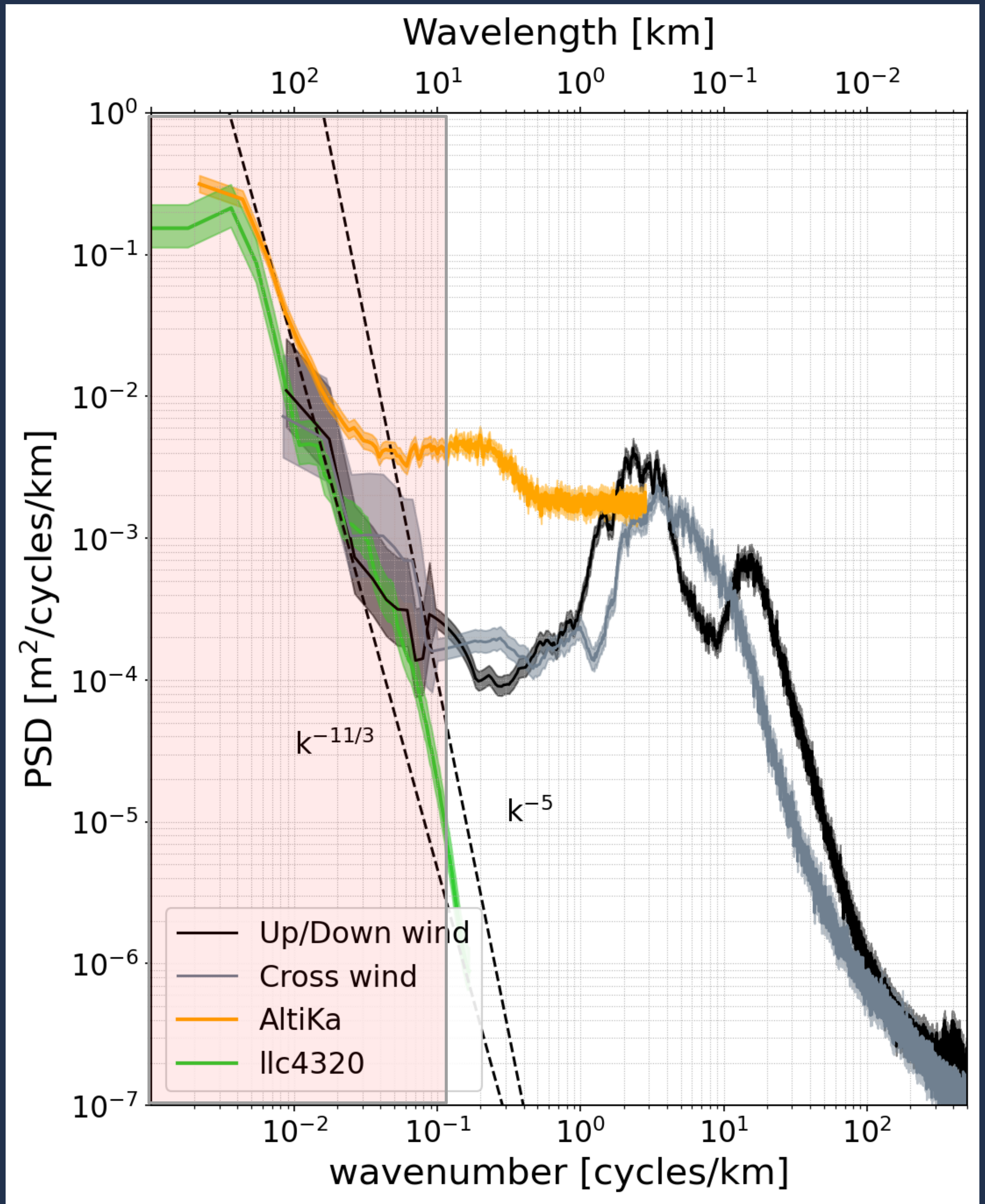

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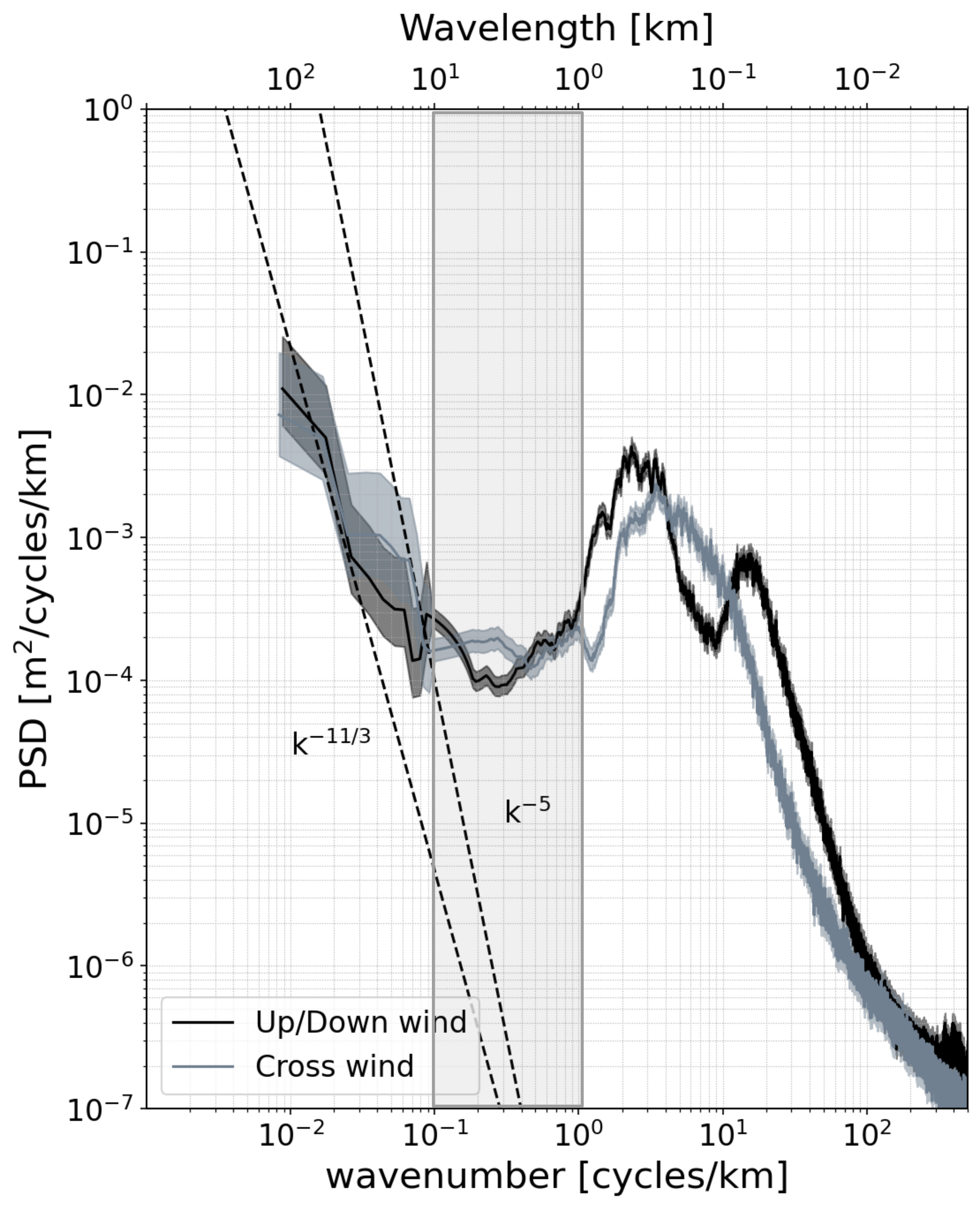
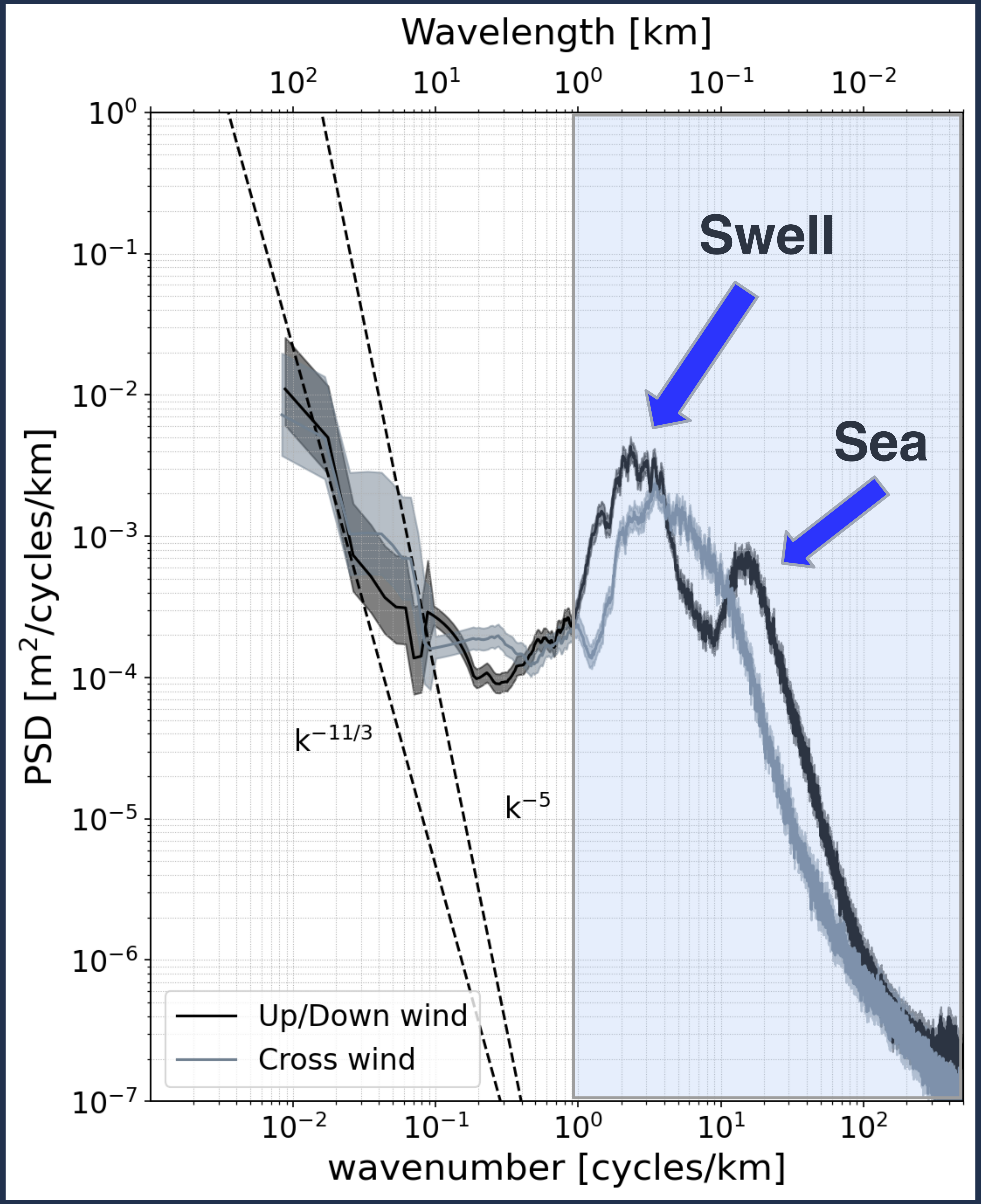
  - Consistent with the llc4320

Across-track averaged spectrum



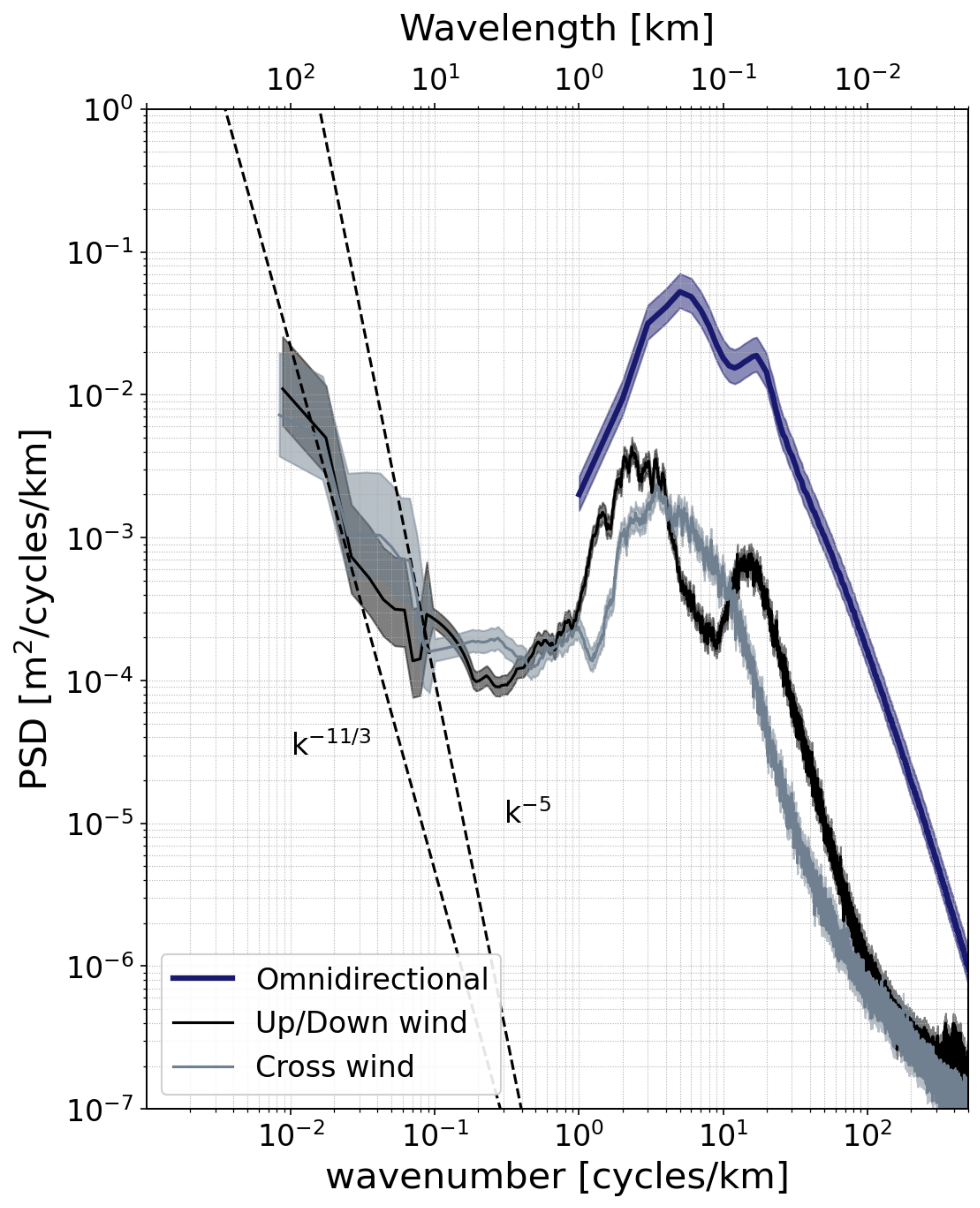
- The gray zone ($10^{-1} < k < 1$ cycles/km)
  - The spectrum flattens out becoming fairly white
  - Many dynamical processes could be contributing to the SSH variance at these scales
  - Consistent with energy levels from IG waves (e.g., Ardhuin et al, 2013; Aucan & Ardhuin, 2013)

Across-track averaged spectrum



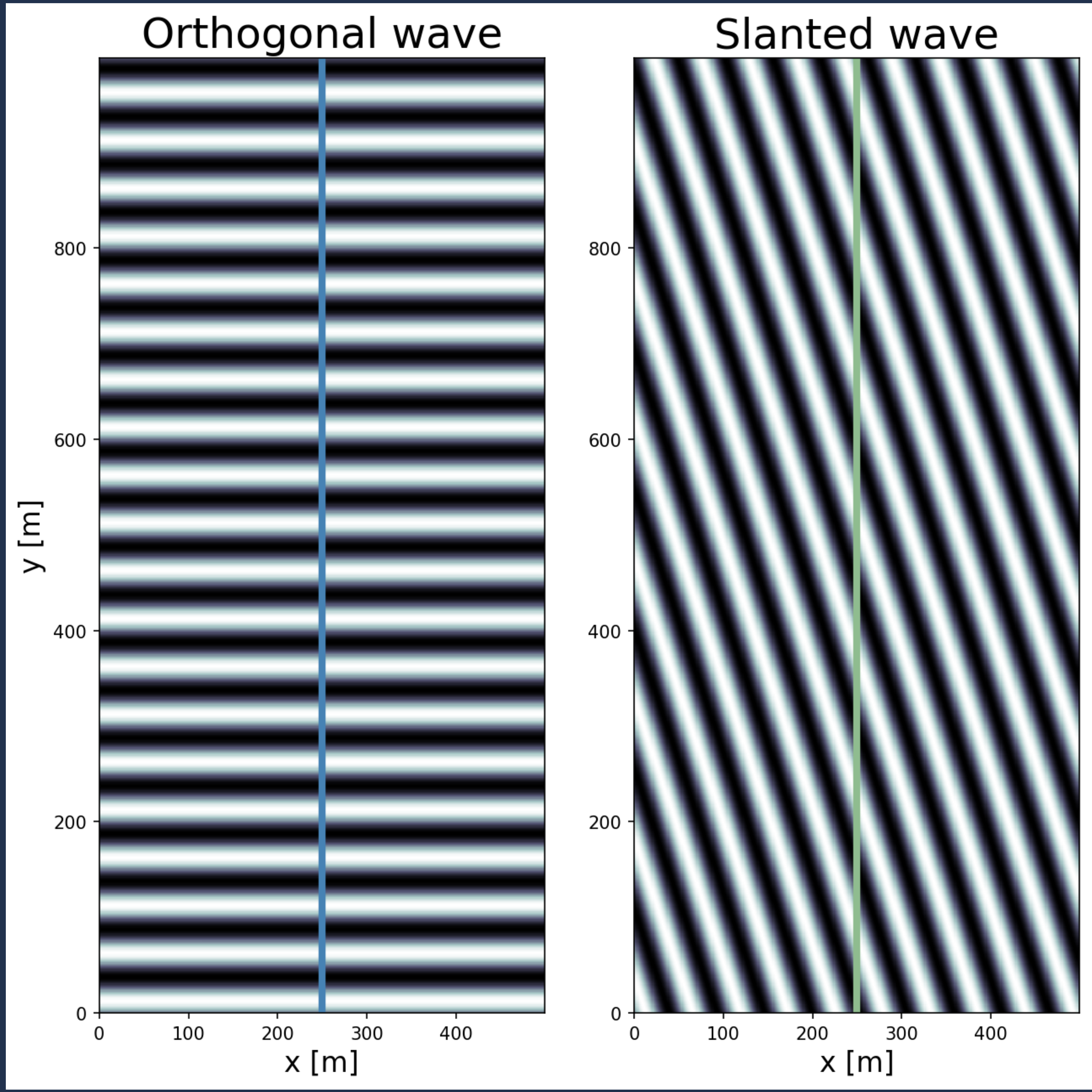
- The blue zone (k > 1 cycles/km)
  - At high wavenumbers the spectrum is blue and dominated by surface waves
  - We see both the swell and sea peaks
  - Up/down-wind and cross-wind are remarkably different

Across-track averaged spectrum

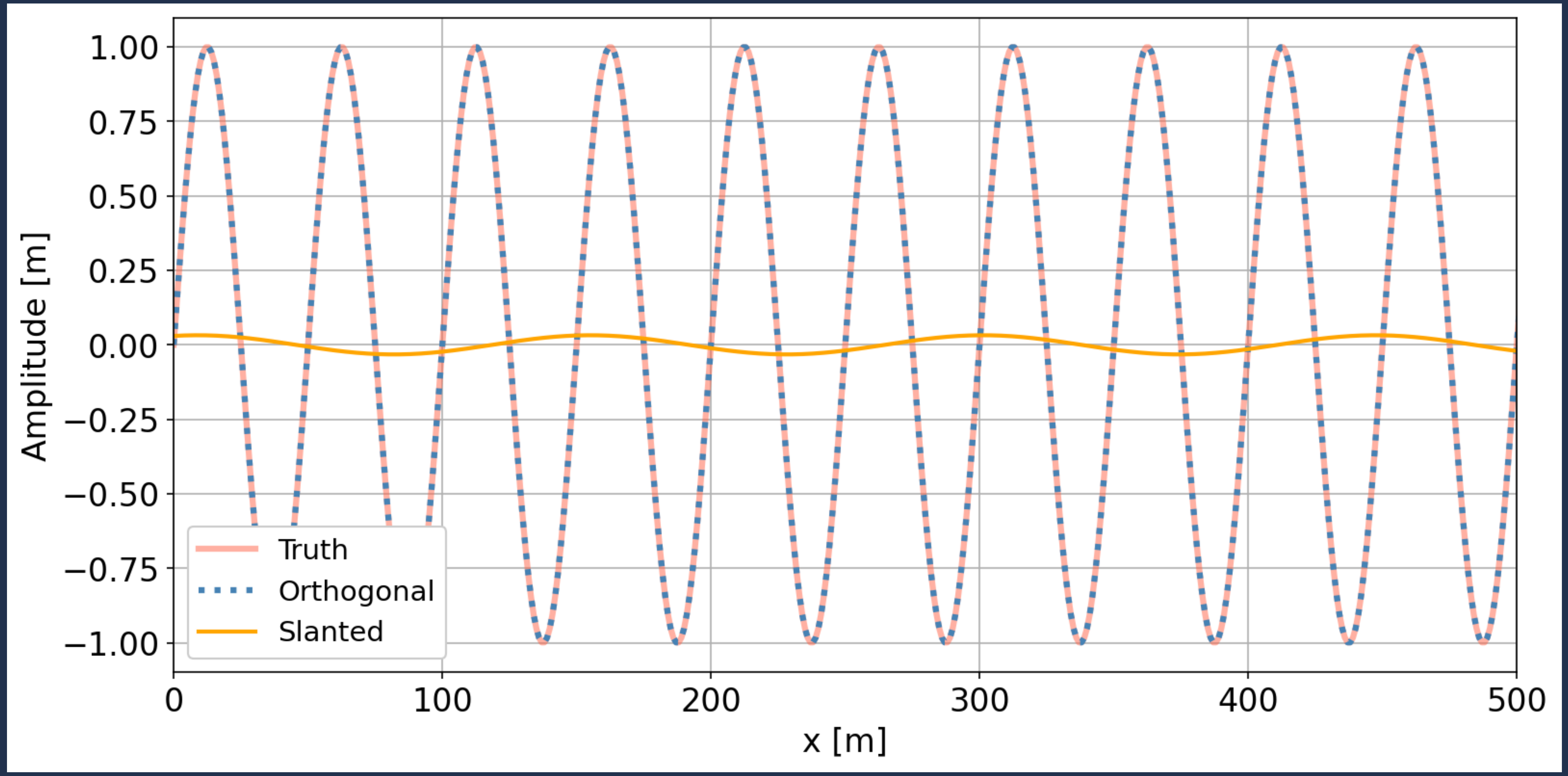


- The blue zone (k > 1 cycles/km)
  - The peak is shifted towards lower wavenumbers (especially for the swell)
  - The variance is much lower in comparison to the omnidirectional spectrum

Surface waves are highly directional:

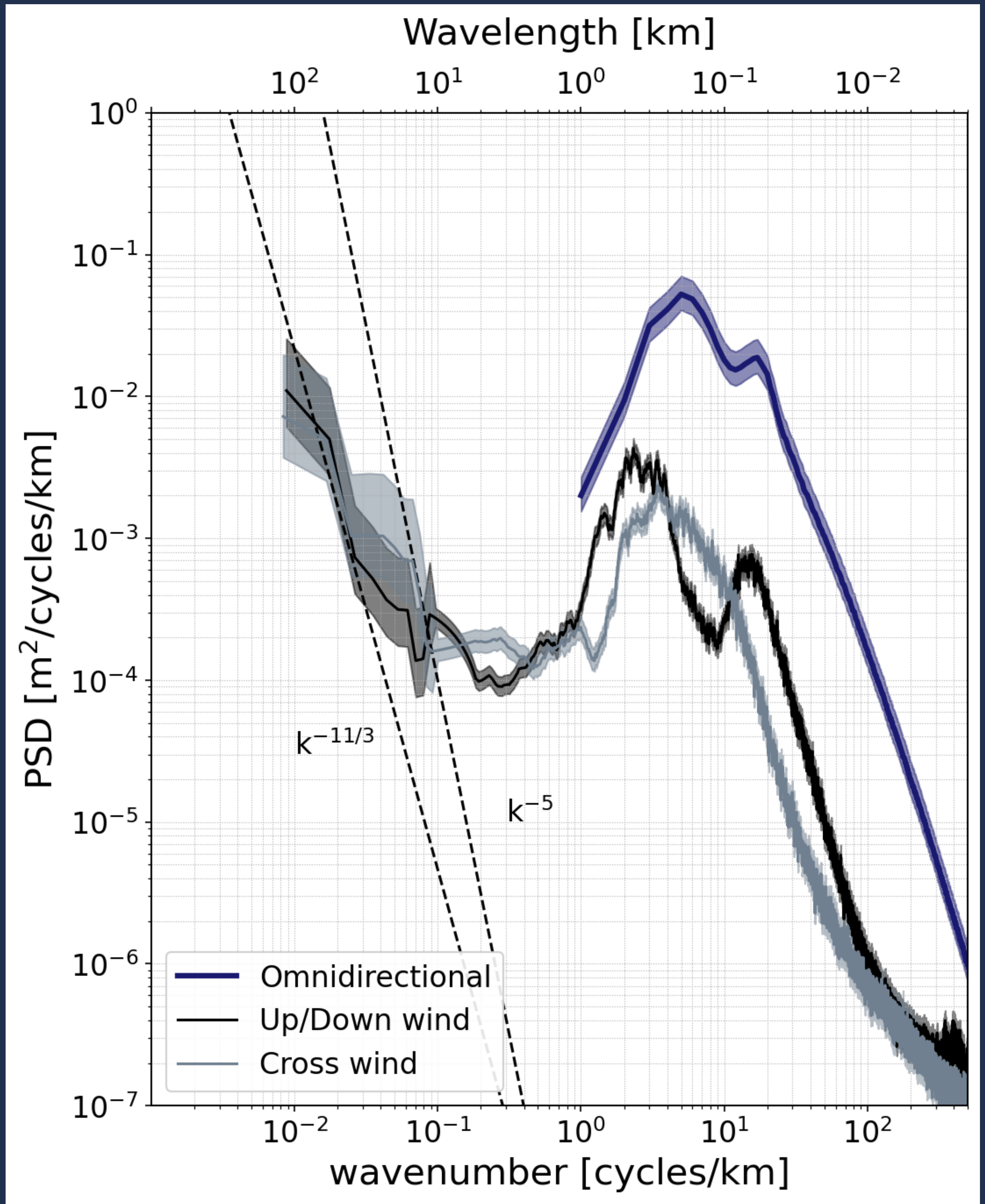


- Across-track averaging lowers the wavenumber and attenuates the amplitude of oblique waves



*Similar to Ray and Zaron (2015) for internal tides

Across-track averaged spectrum



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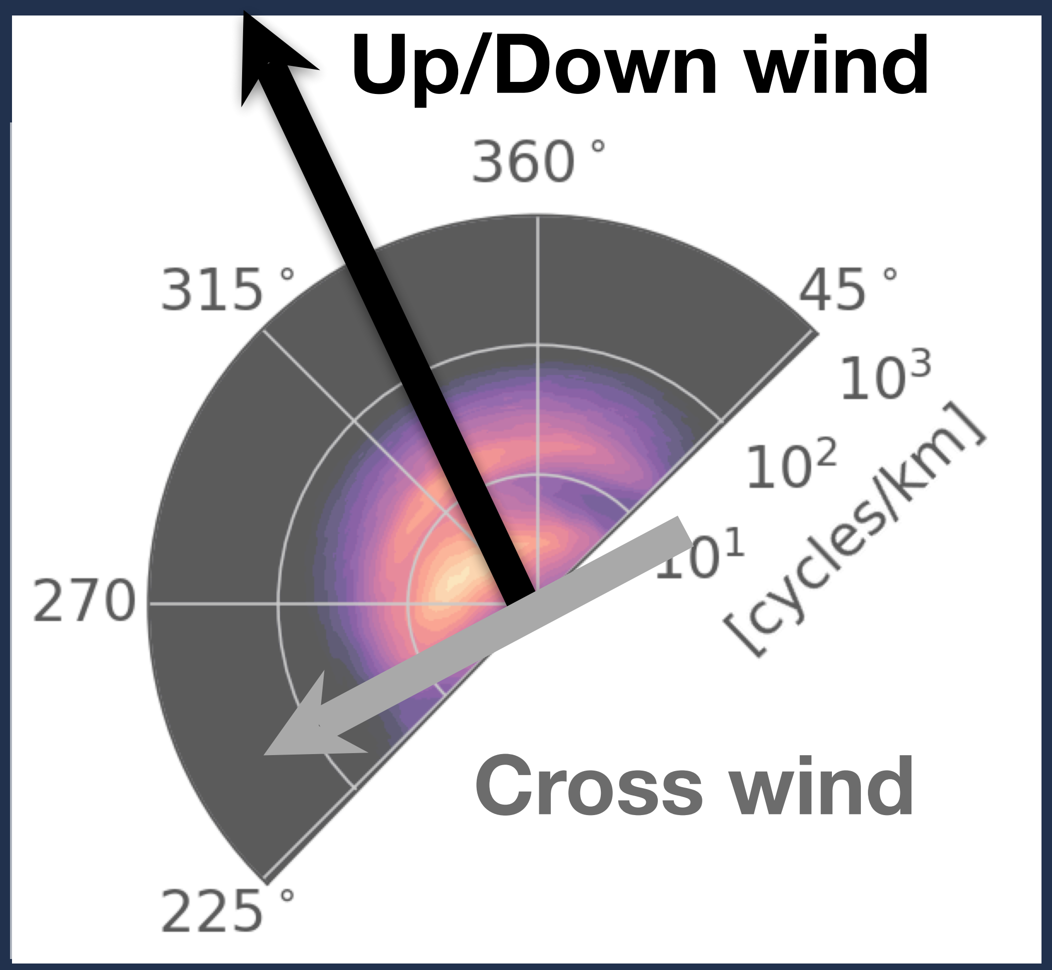
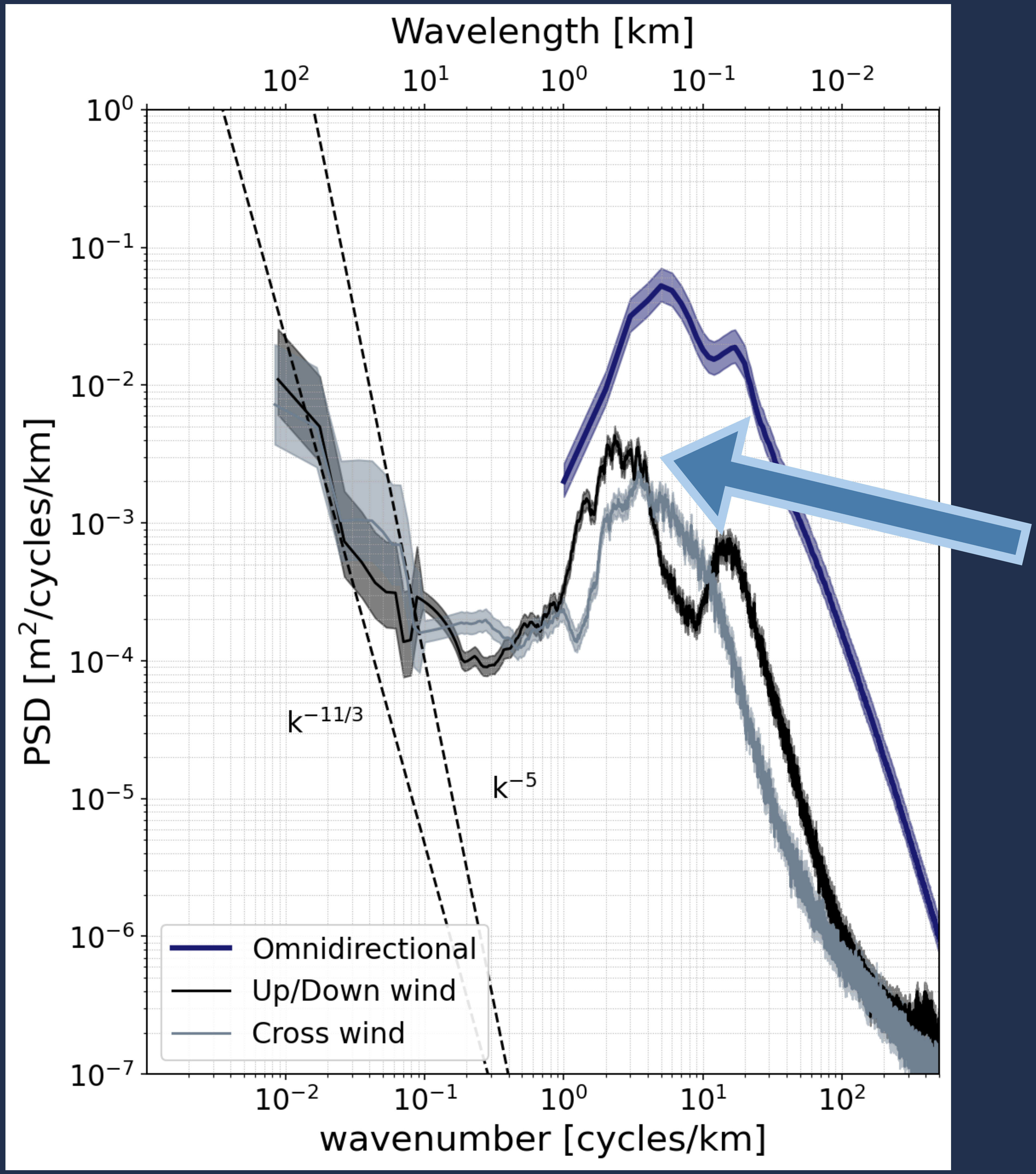


- Surface waves are highly directional
- Across-track averaging oblique waves:
  - Shifts the energy towards lower wavenumber + attenuates the amplitude

Across-track averaged spectrum

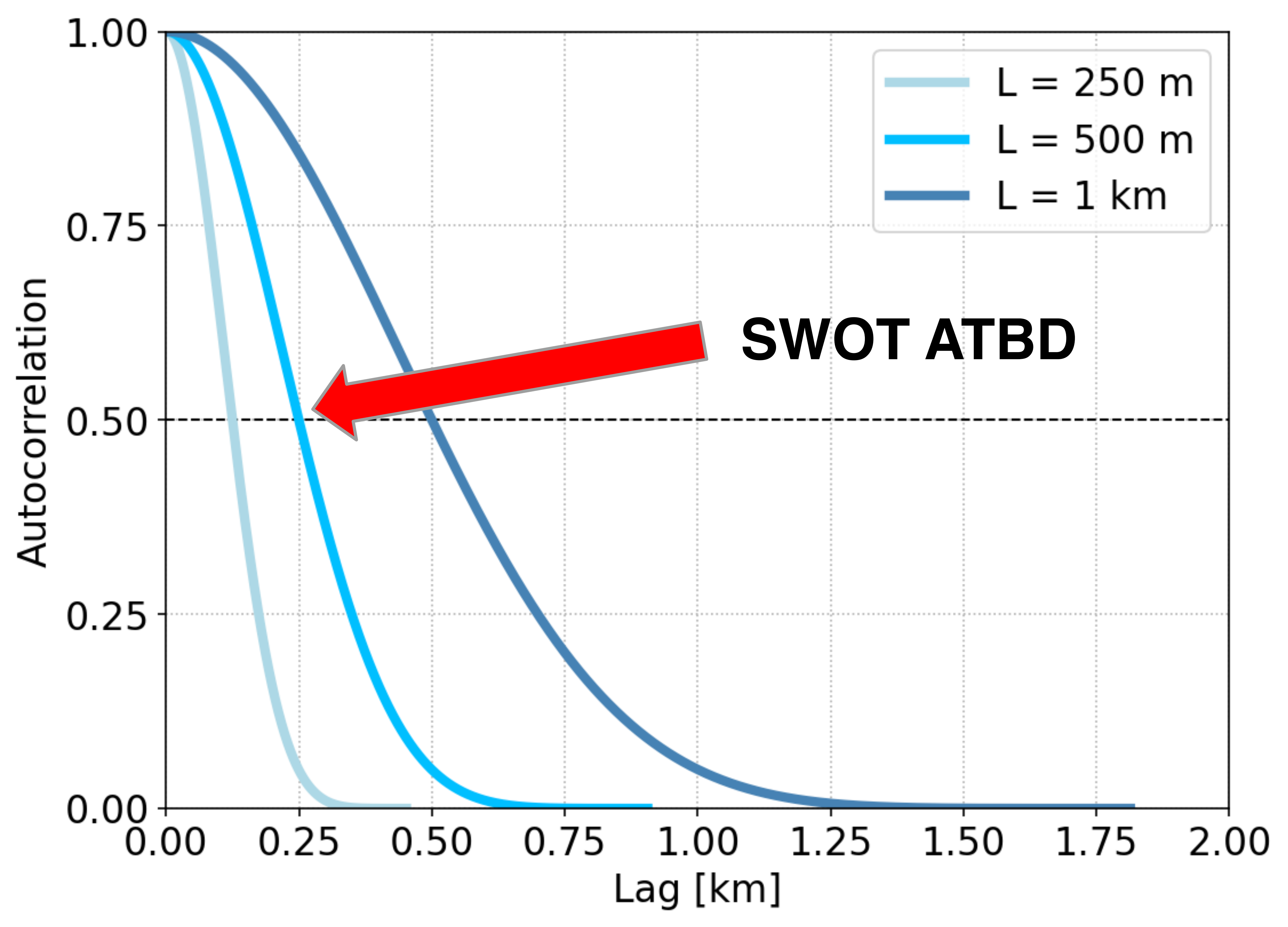


- The blue zone (k > 1 cycles/km)

Over 20x larger than the variance at submesoscales

Filtering the surface wave signal

- Blackman-Harris window in the azimuth direction



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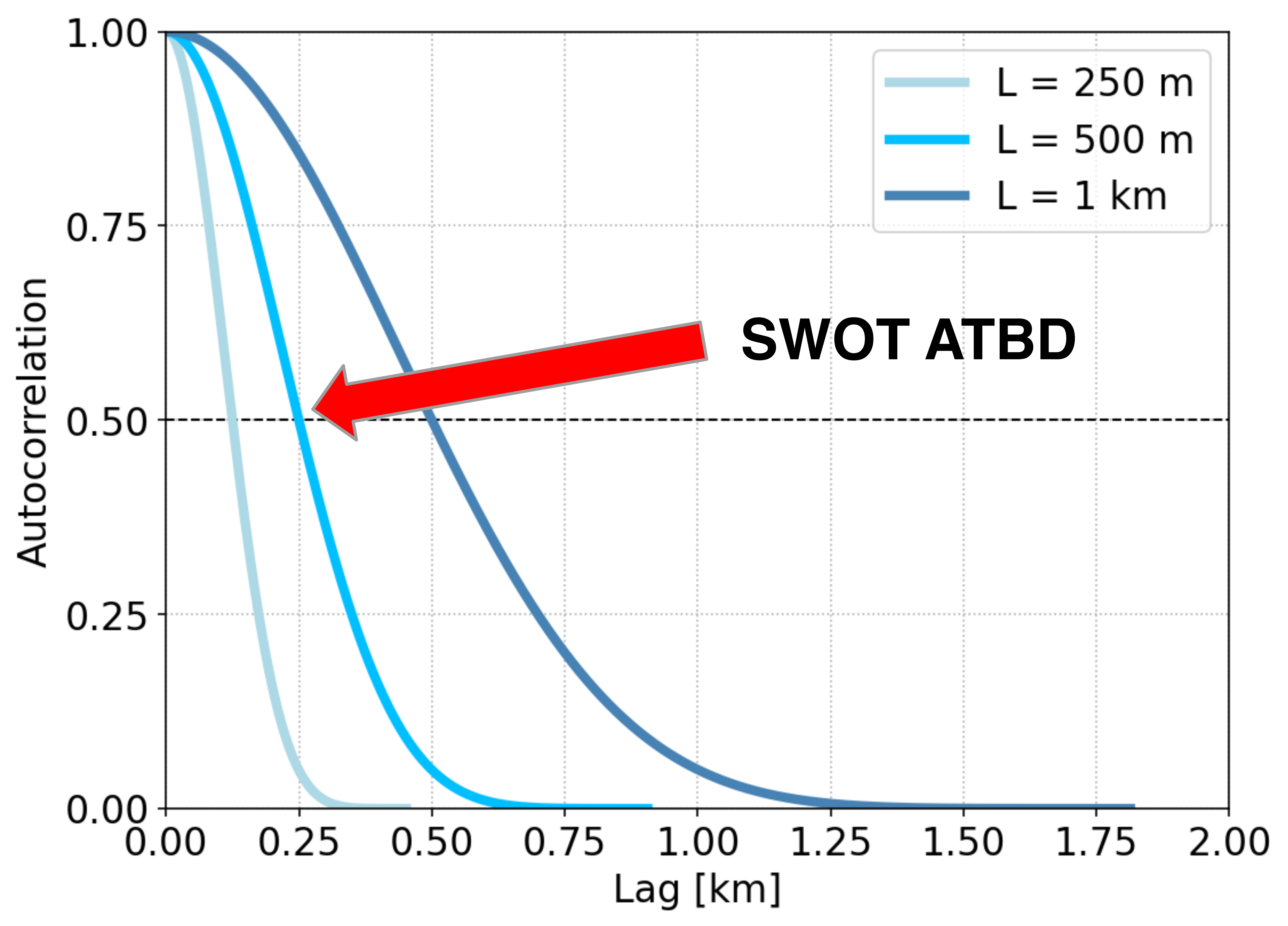
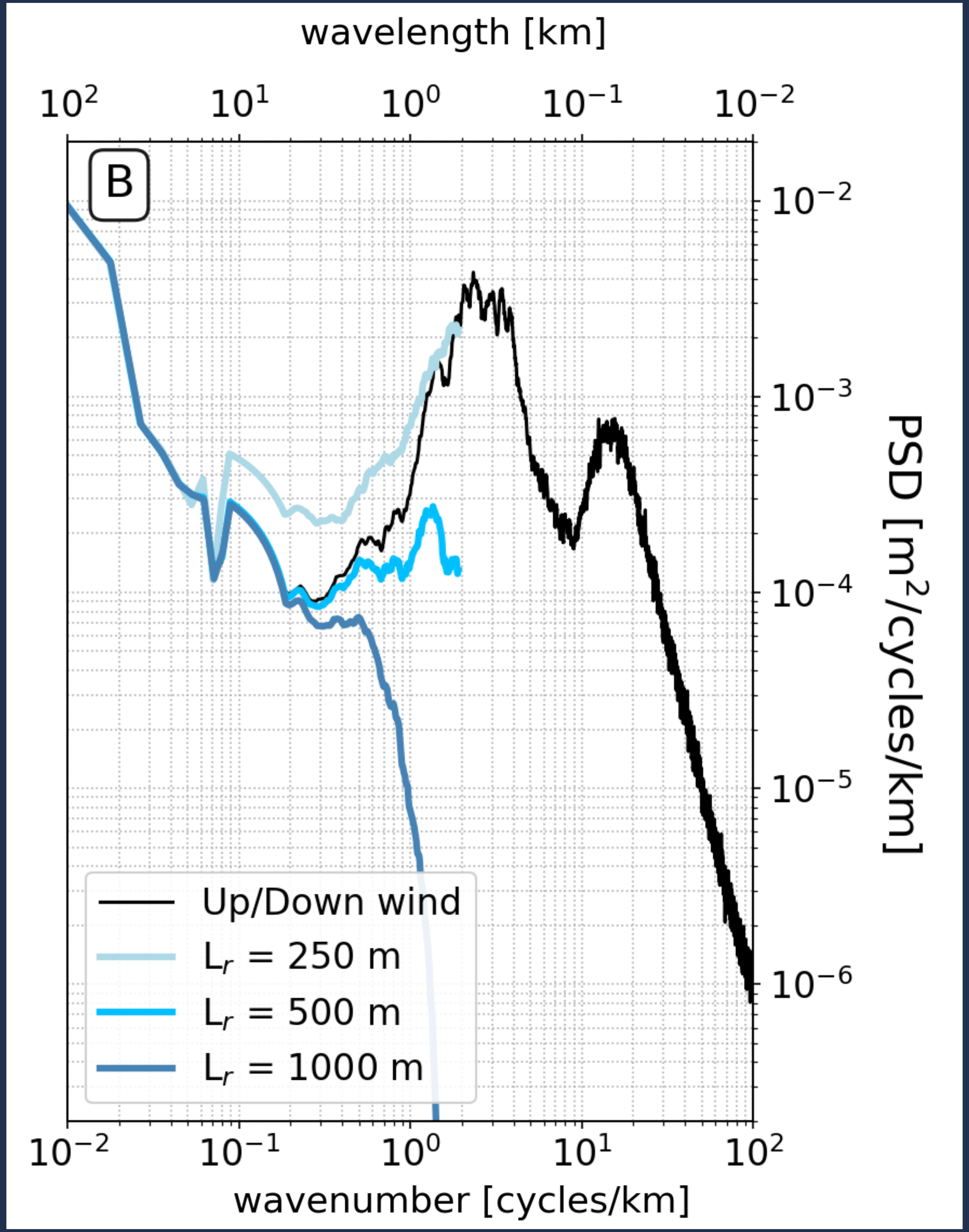
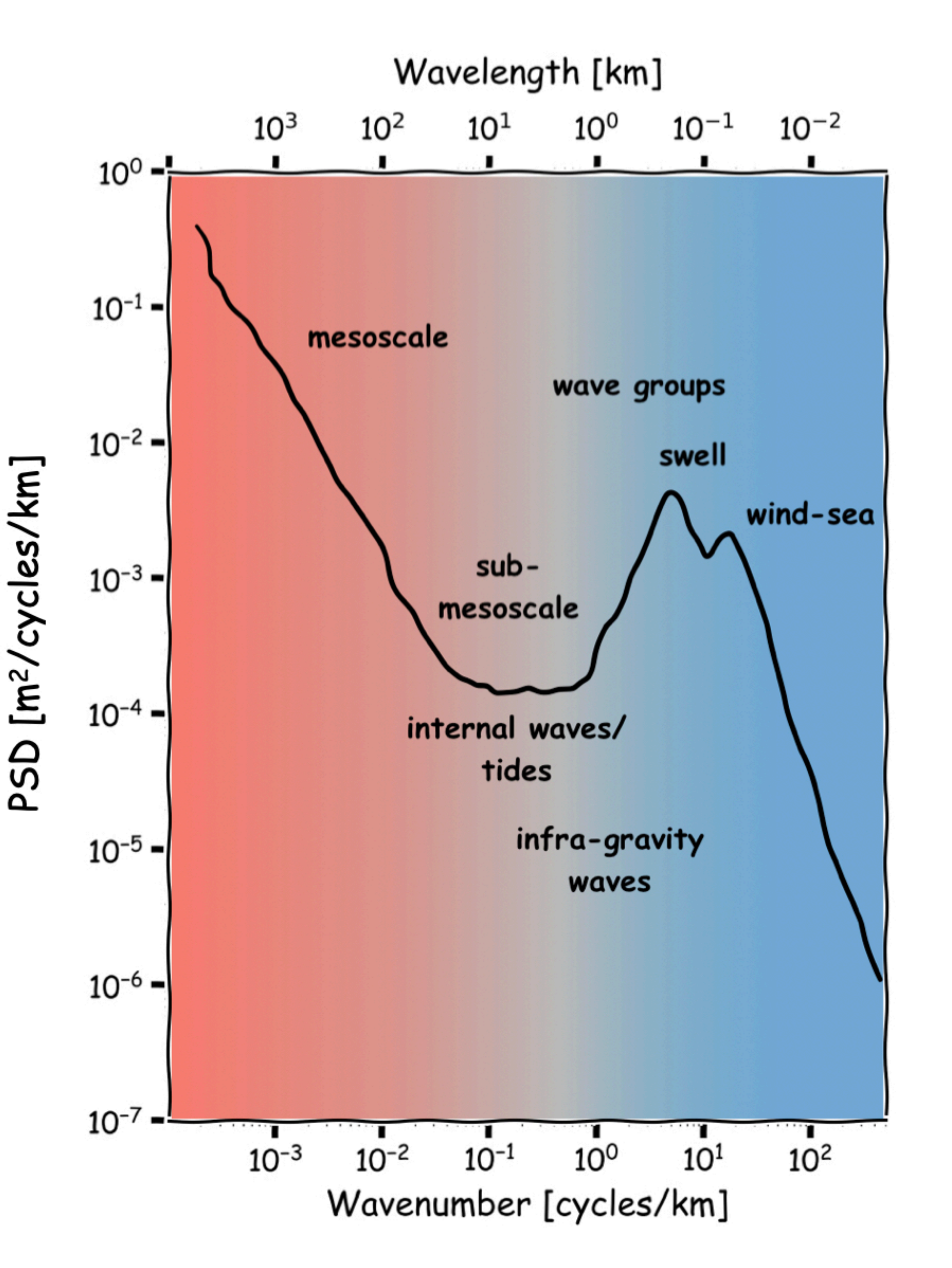


250 m posting



Take aways

- The variance in the **surface wave** band can be **over 20 times larger** than the variance at submesoscales.
- Without directional wave information, it could be challenging to interpret the SSH variability at scales from 1 km to 100s of meters
- SWOT's OBP filter should remove most of the surface wave energy. The potential for aliasing will depend on dominant wavelength, height, and direction.
    - Higher waves → filtering is less effective
    - Higher relative angle → filtering is less effective



The surface wave field in a given region results from the combined effect of both **local** and **remote** forcing

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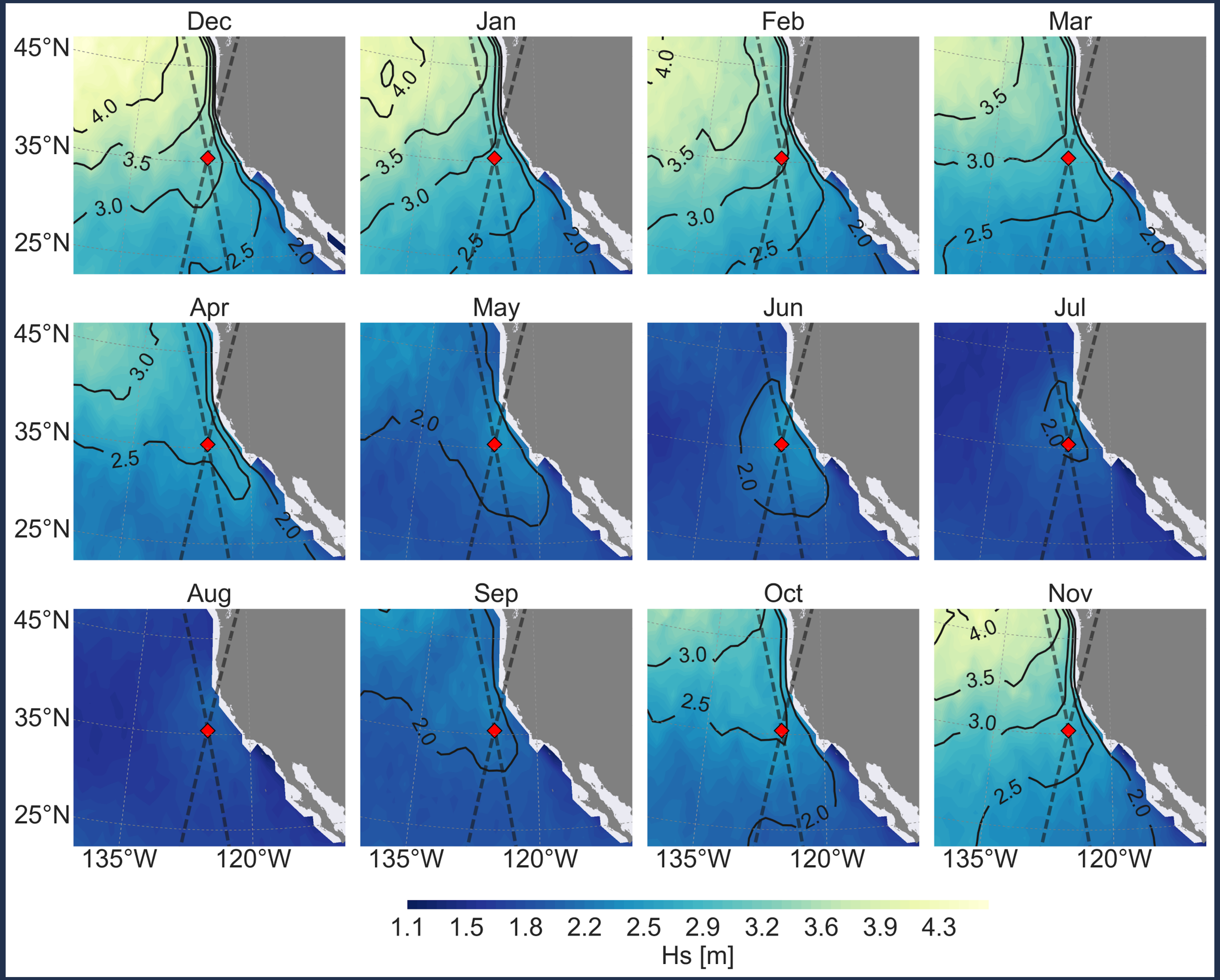
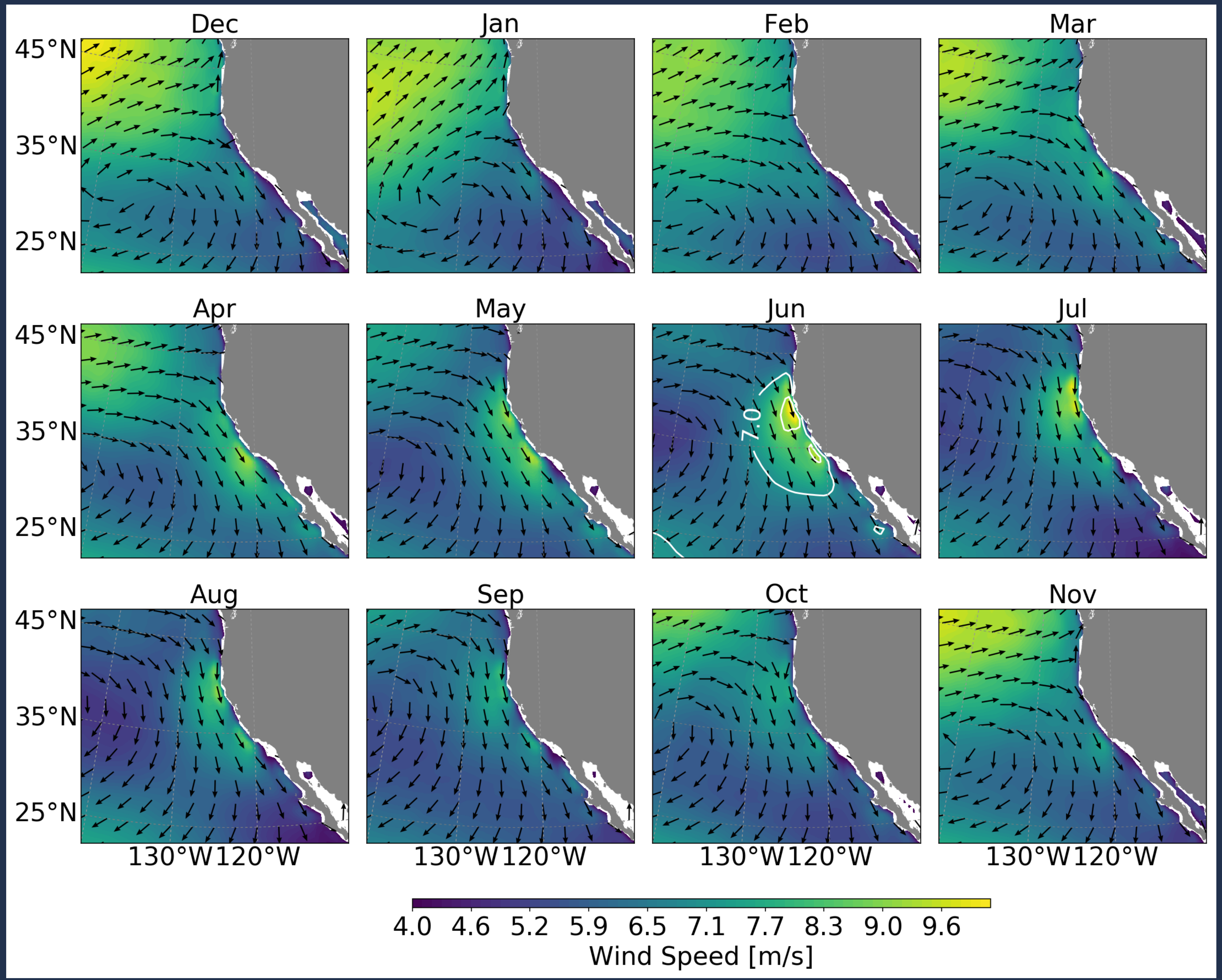
Villas Bôas et al. (2017)

Significant Wave Height



Ocean Surface Winds



The surface wave field in a given region results from the combined effect of both **local** and **remote** forcing

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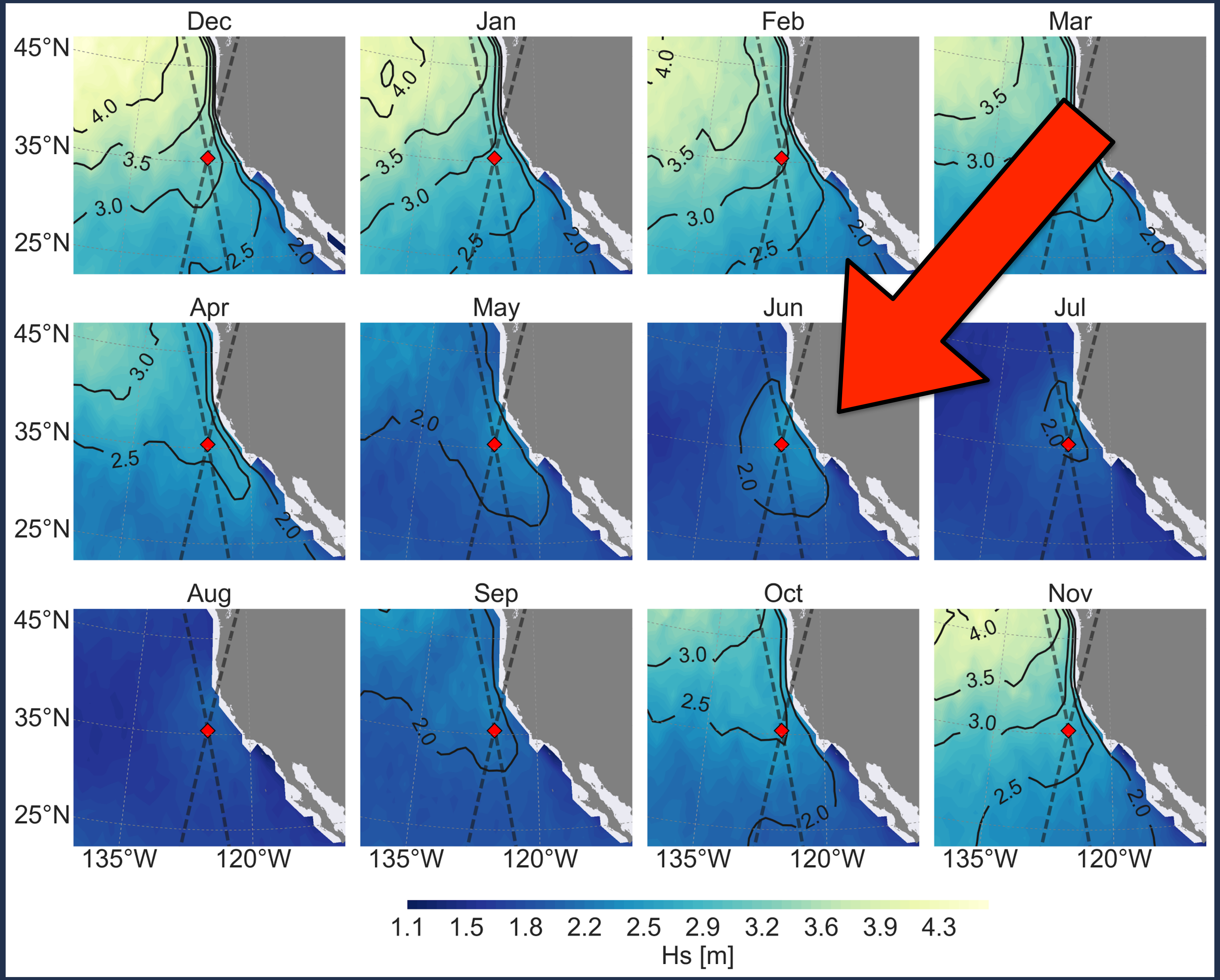

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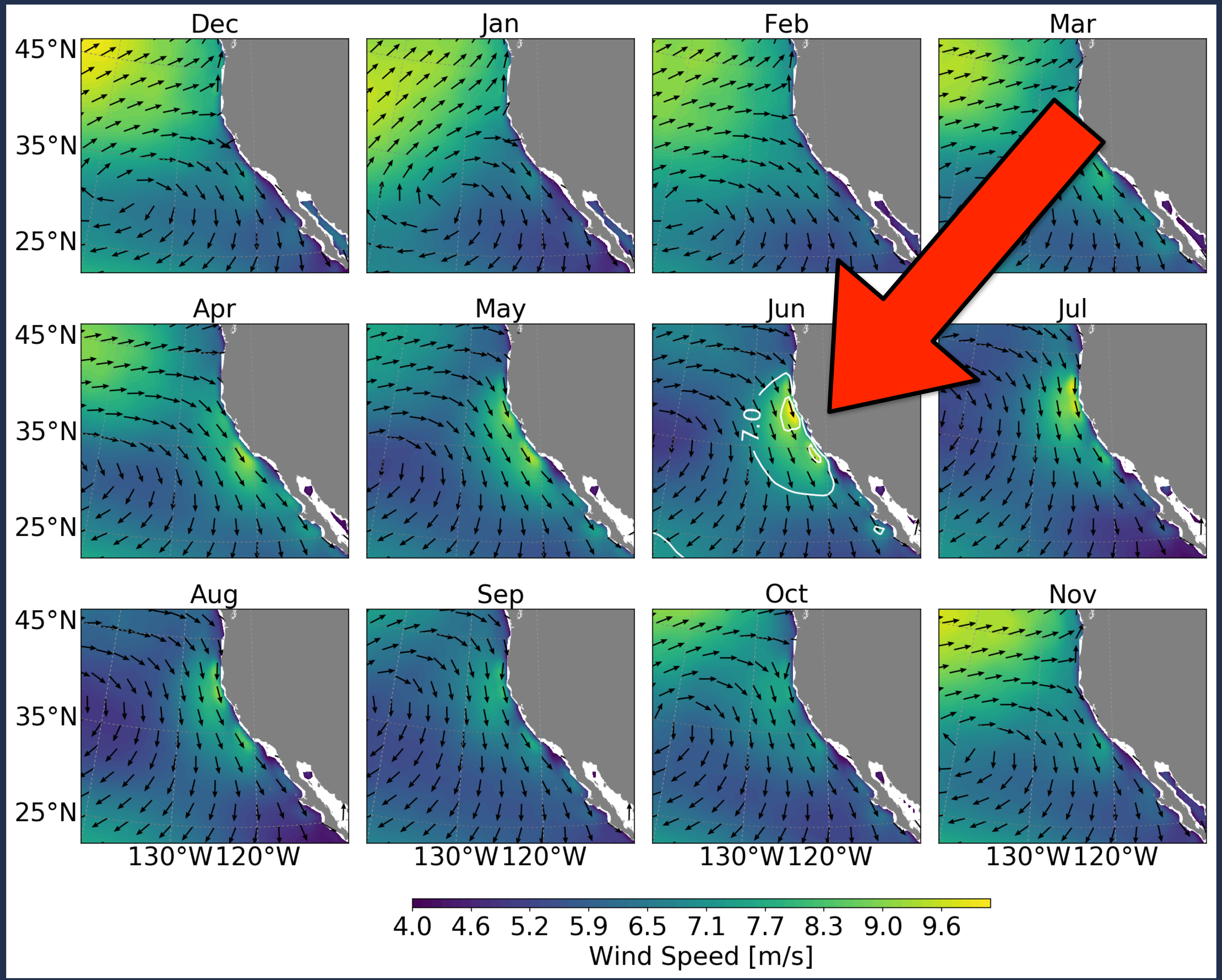
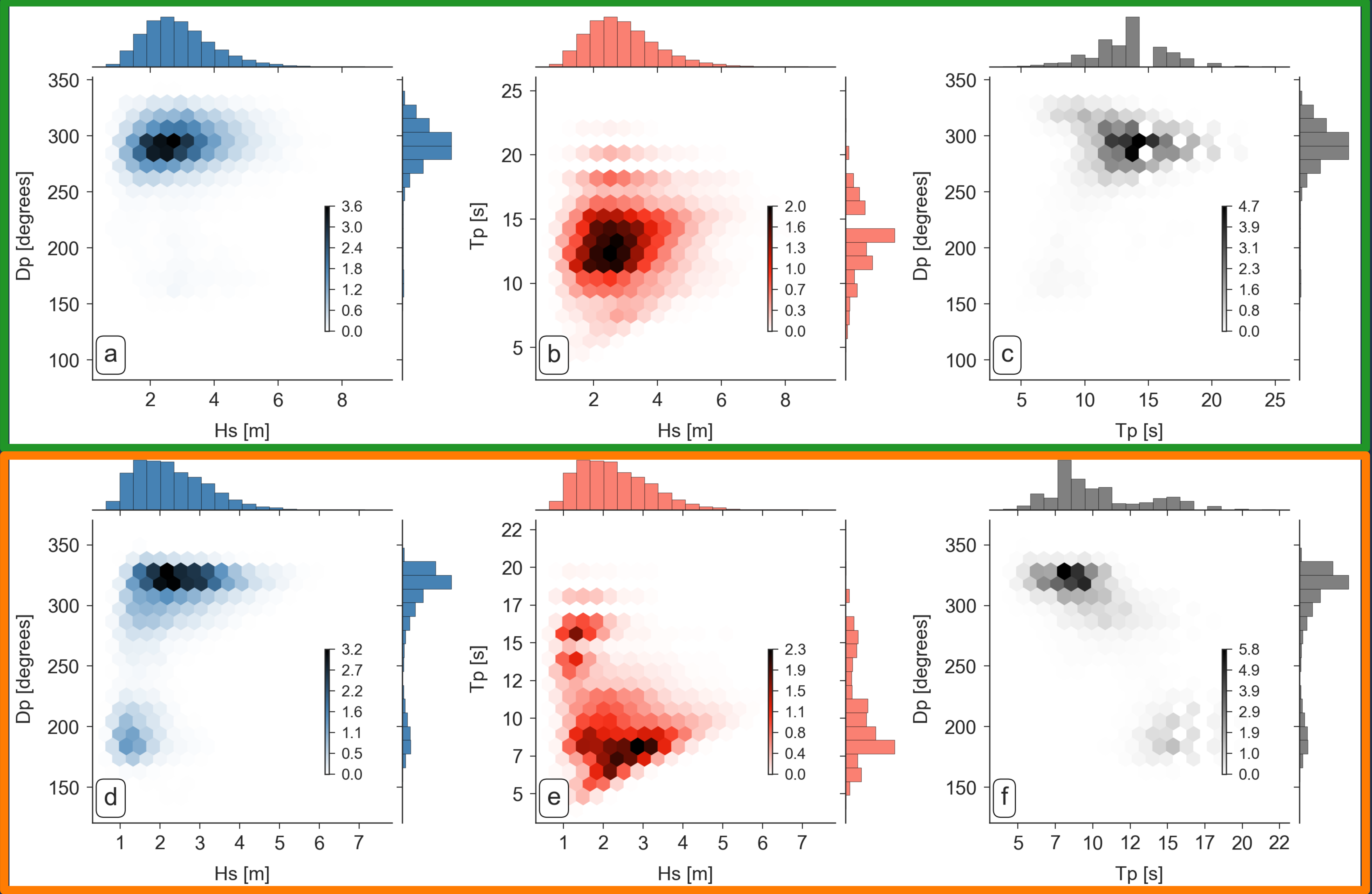
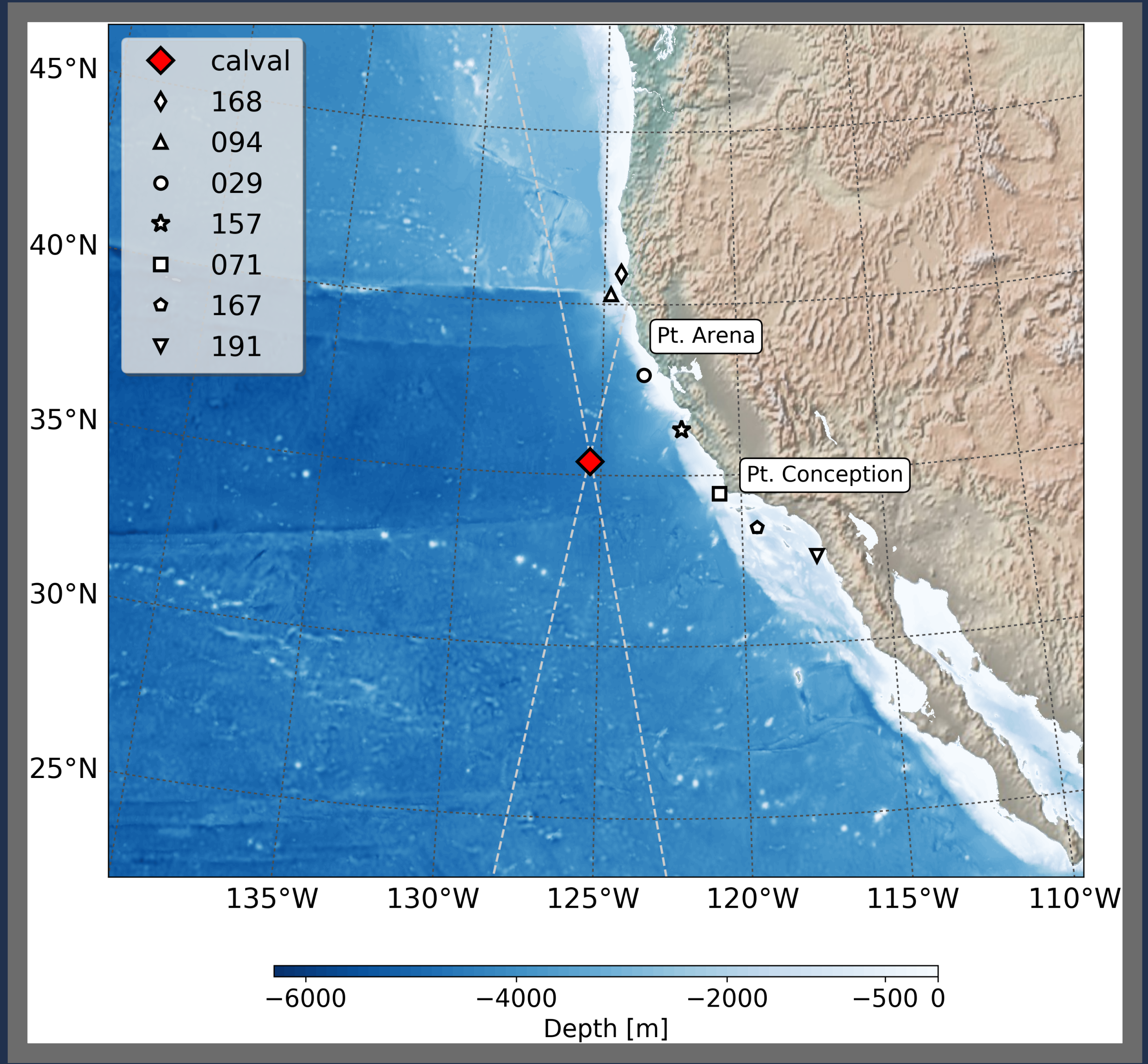


@ CDIP 029

Winter

Spring/Summer





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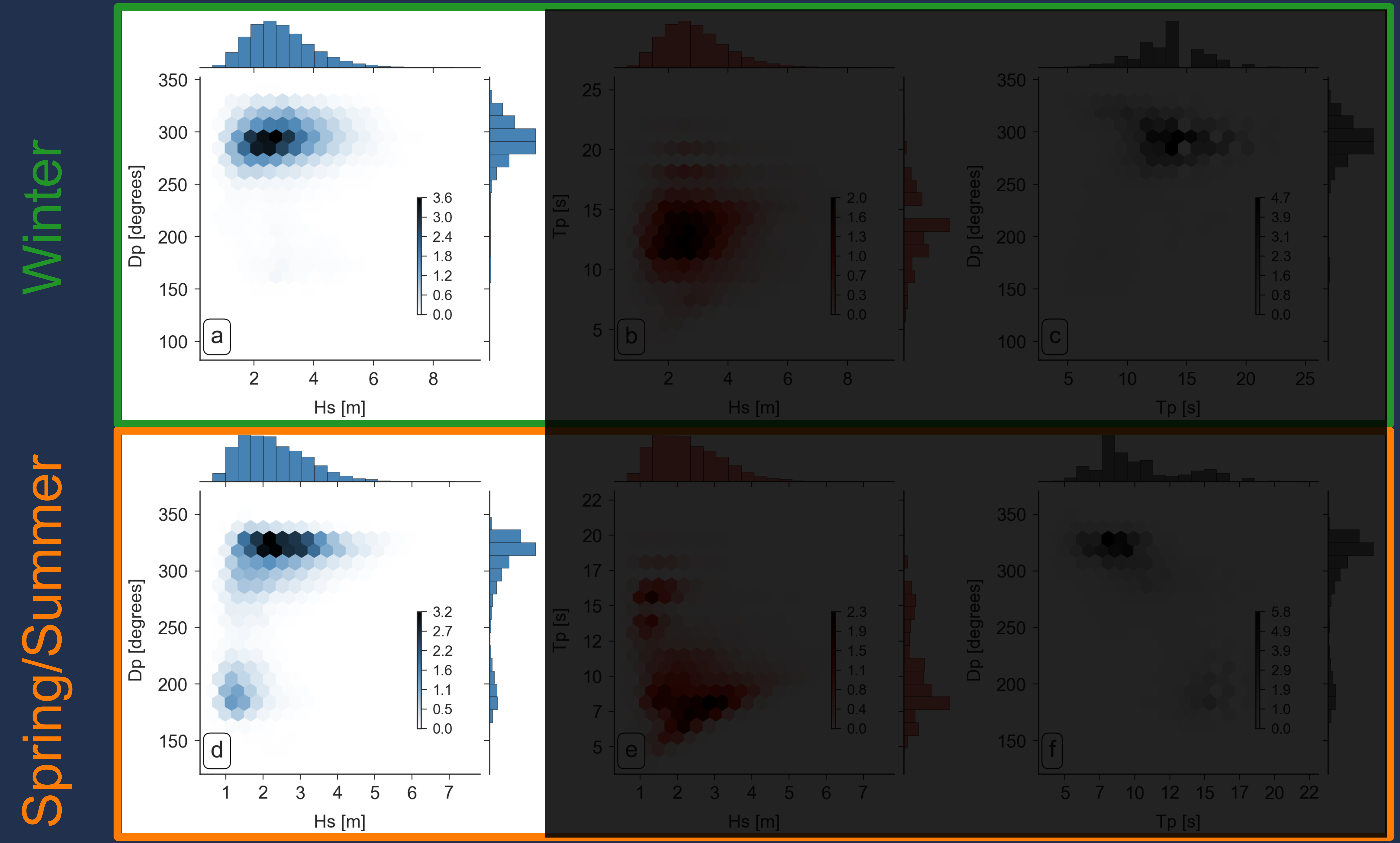


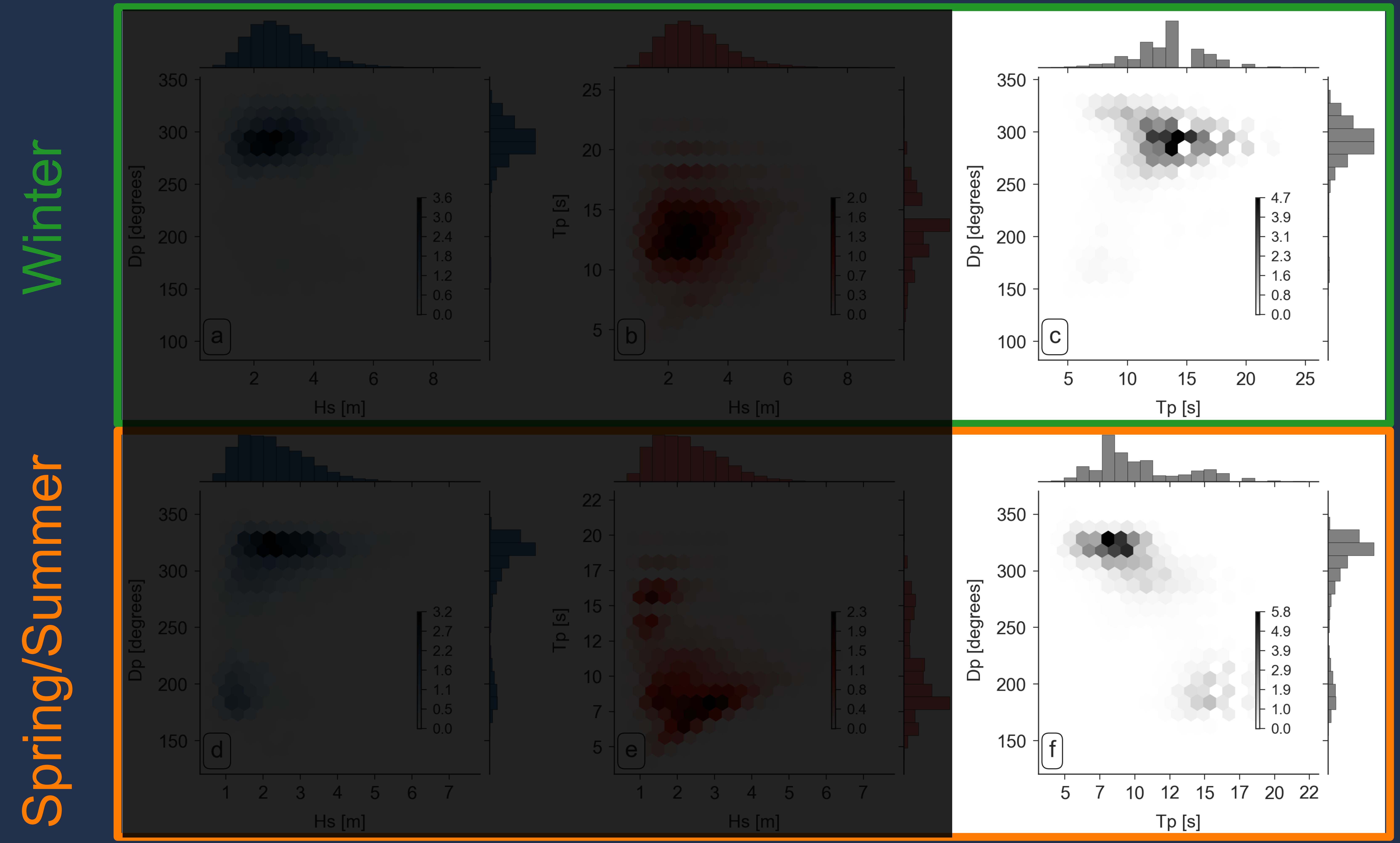
Winter:

- Unimodal distributions
- Waves coming from W/NW directions (270° ≤ *Dp* ≥ 315°)
- Hs between 2 m and 4 m

Spring/Summer:

- Bimodal distributions
- Waves with *Hs* ≥ 2 m come from NW (315° ≤ *Dp* ≥ 330°)
- Smaller waves come from S/SW (180° ≤ *Dp* ≥ 220°)

@ CDIP 029



Winter:

- Unimodal distributions
- Waves coming from W/NW directions (270° ≤ *Dp* ≥ 315°)
- Long period (12s-20s)

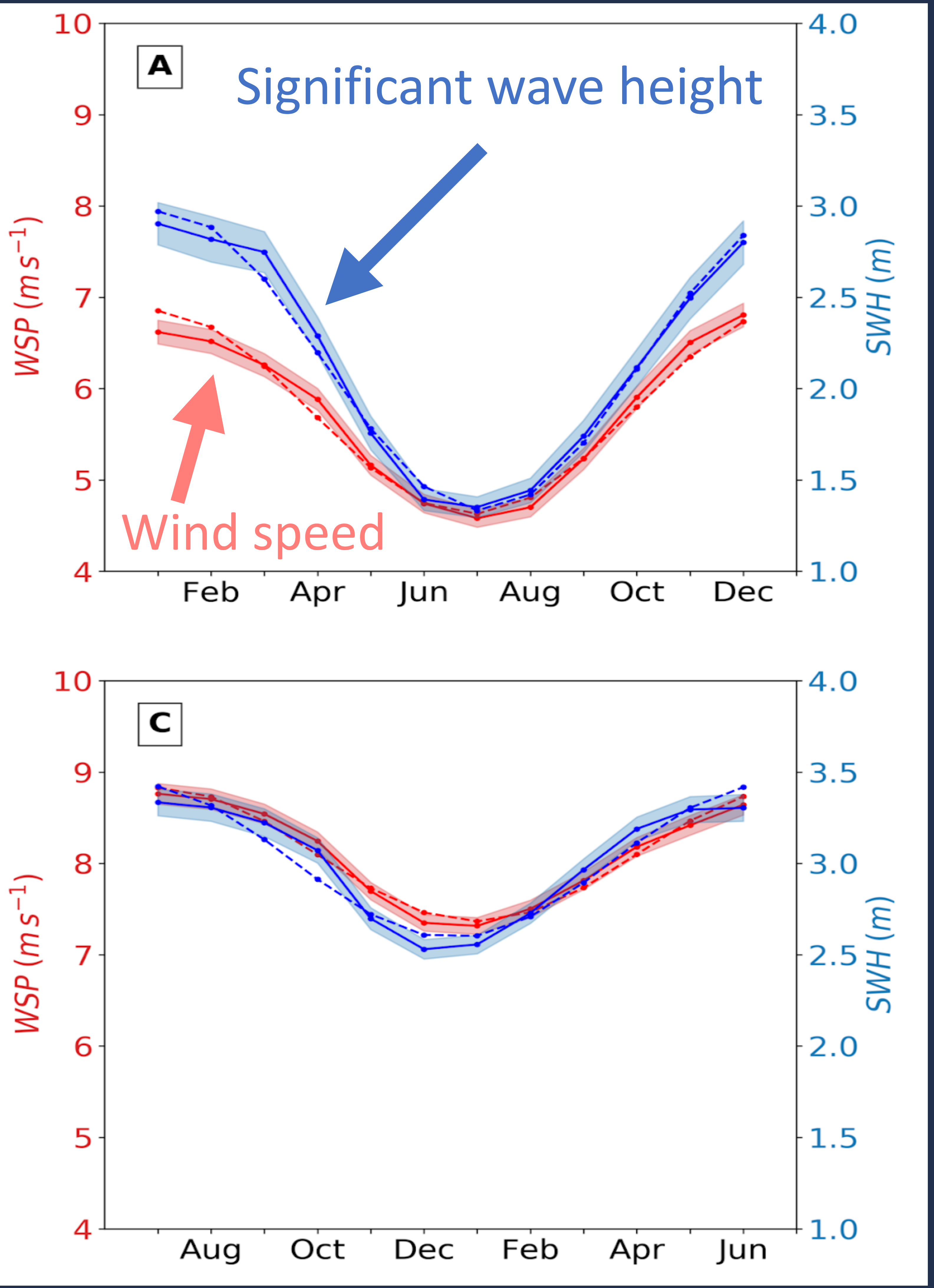
Spring/Summer:

- Bimodal distributions
- Waves from NW have short period
- Waves from S/SW have long period

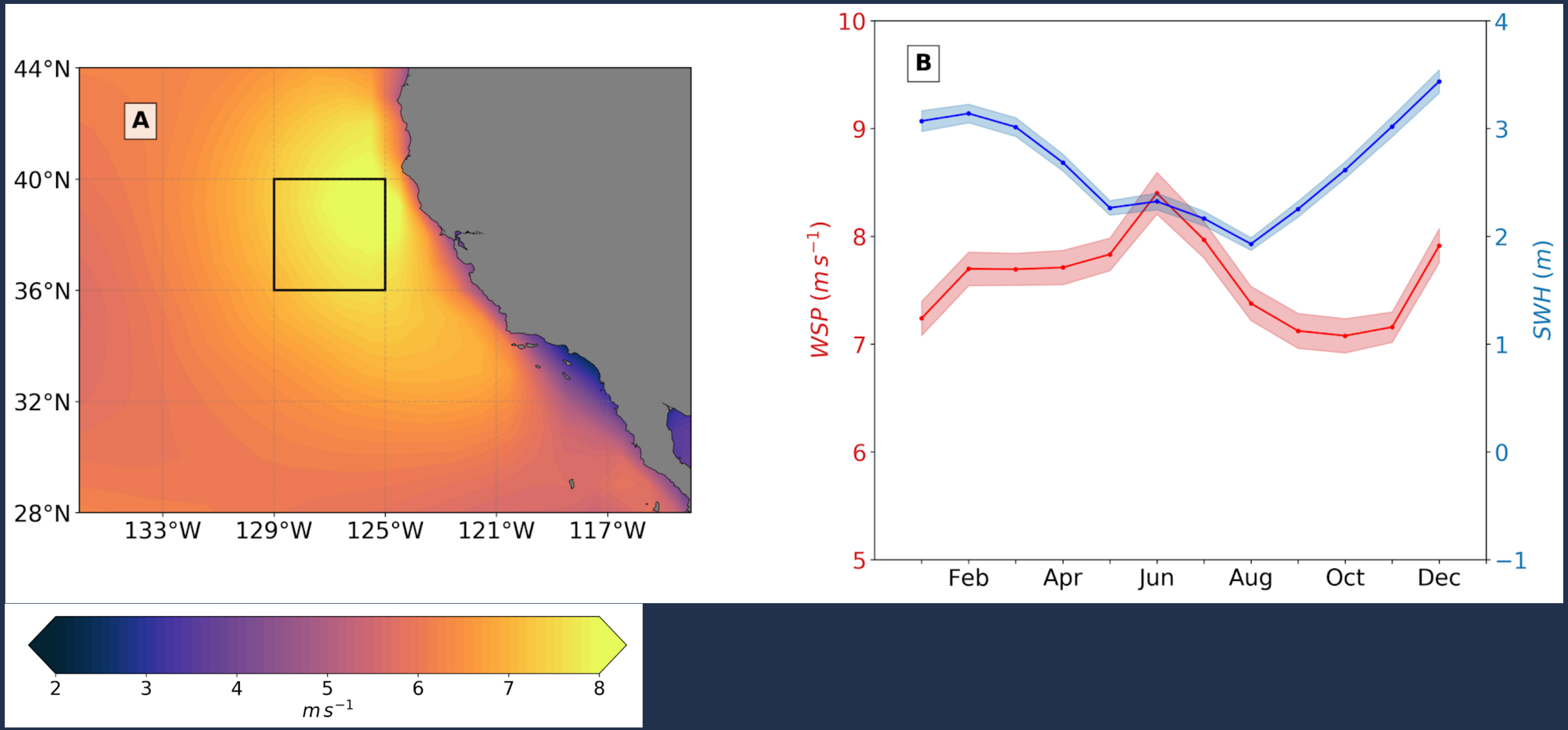
Basin-scale seasonal cycle

Northwest African Coast

Colosi et al. (2021)



Summer wind anomalies in California lead to higher waves



https://doi.org/10.1029/2021JC017198

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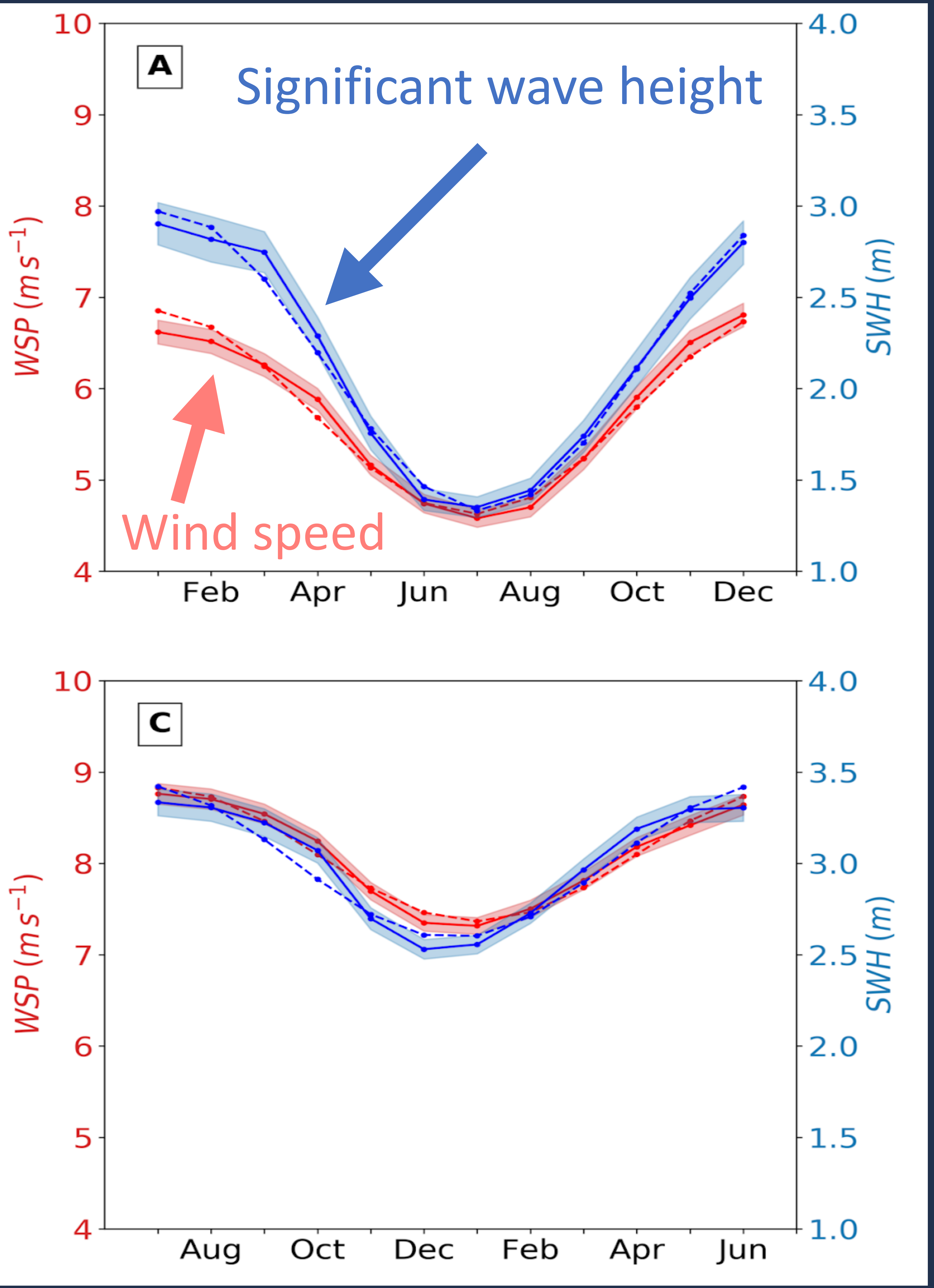
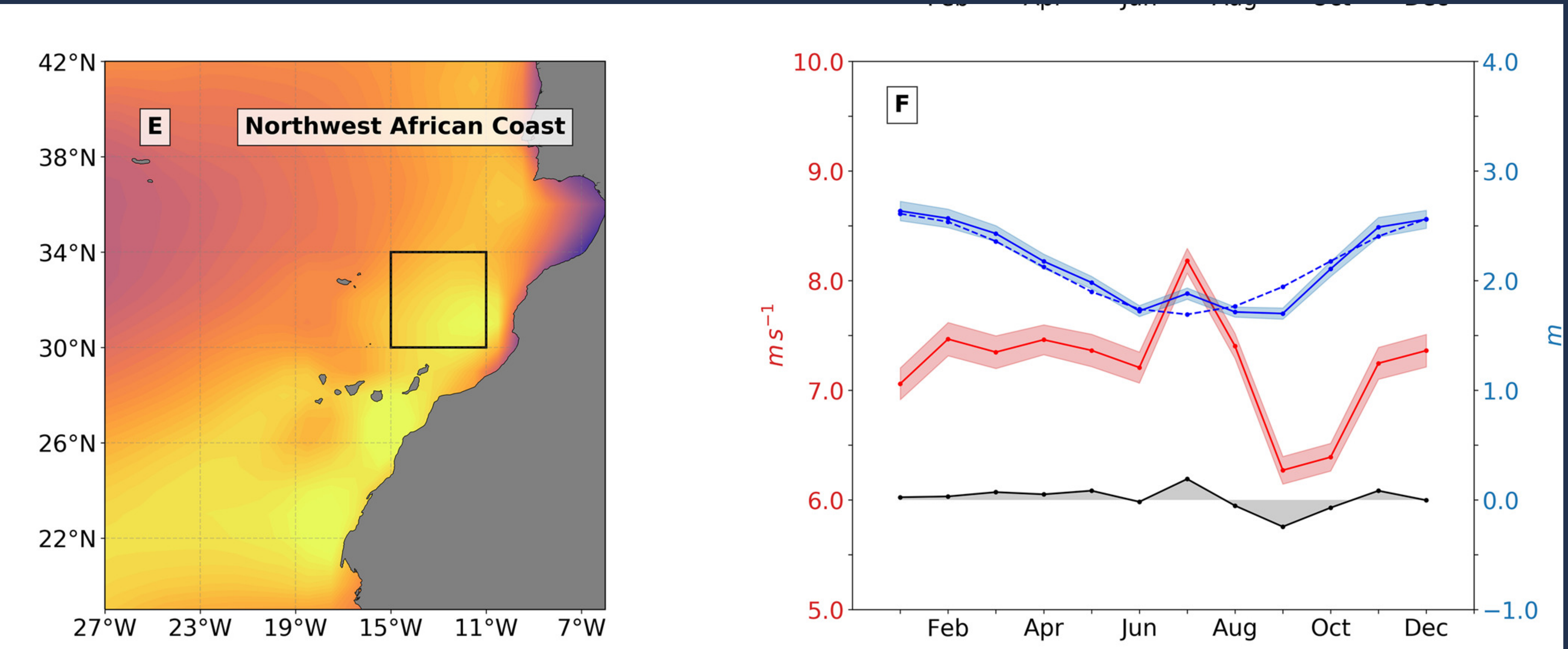
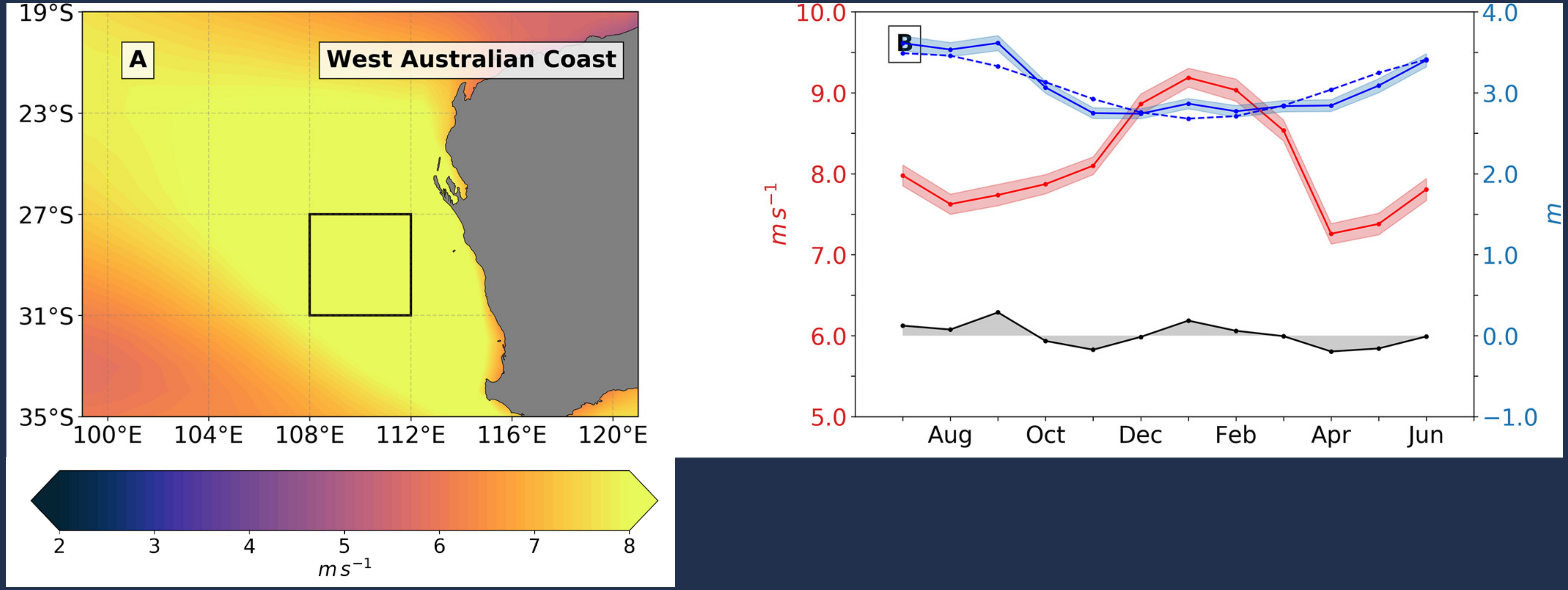
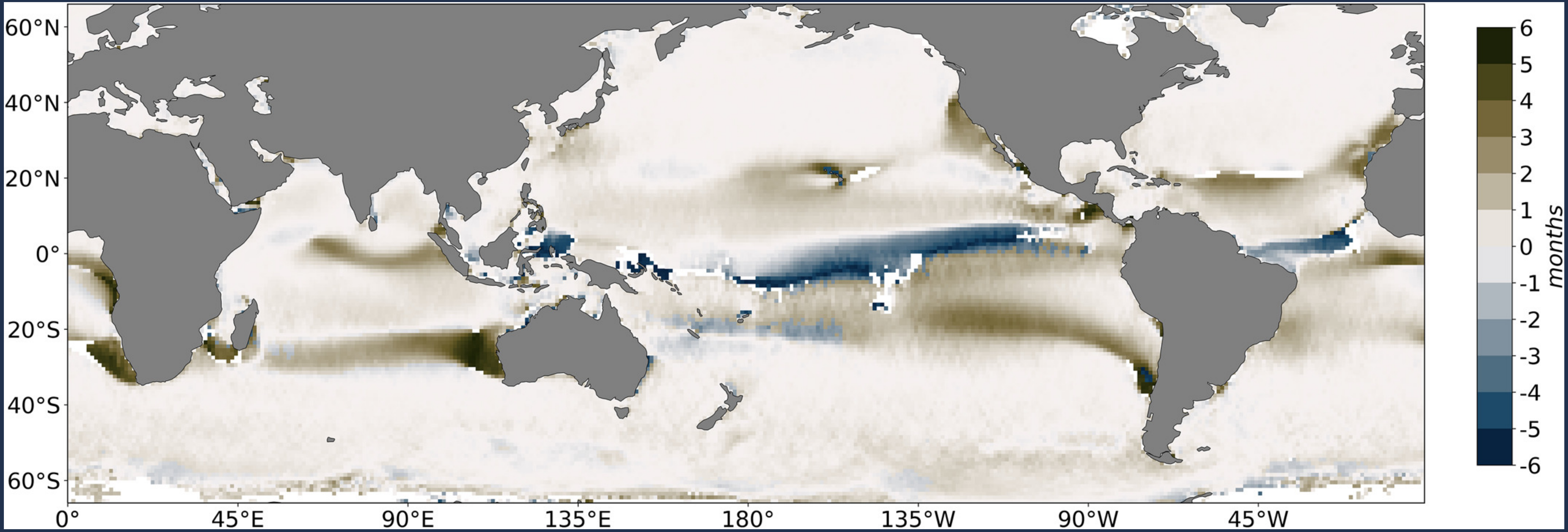


Summer wind anomalies are also observed in other regions





Annual cycle phase difference between winds and waves



Colosi et al. (2021)

Final remarks

- Although SWOT will not be able to observe individual waves, waves will be an important source of noise (sea state bias, surfboard effect, aliasing...)
- But also signal! Gradients of Hs, MSS, direction... contain information on current gradients (e.g., Ardhuin et al., 2017; Villas Bôas et al., 2020; Marechal et al., 2021)
- The contribution of surface waves to SWOT's error budget will depend on wave height, length, direction, and steepness.
    - Comprehensive understanding of wave climatology and
    - 2D wave measurements during calval

will be crucial for interpreting SSH measurements from SWOT