

Observations and modeling of wind-wave-current interactions at meso and submesoscales

Bia Villas Bôas

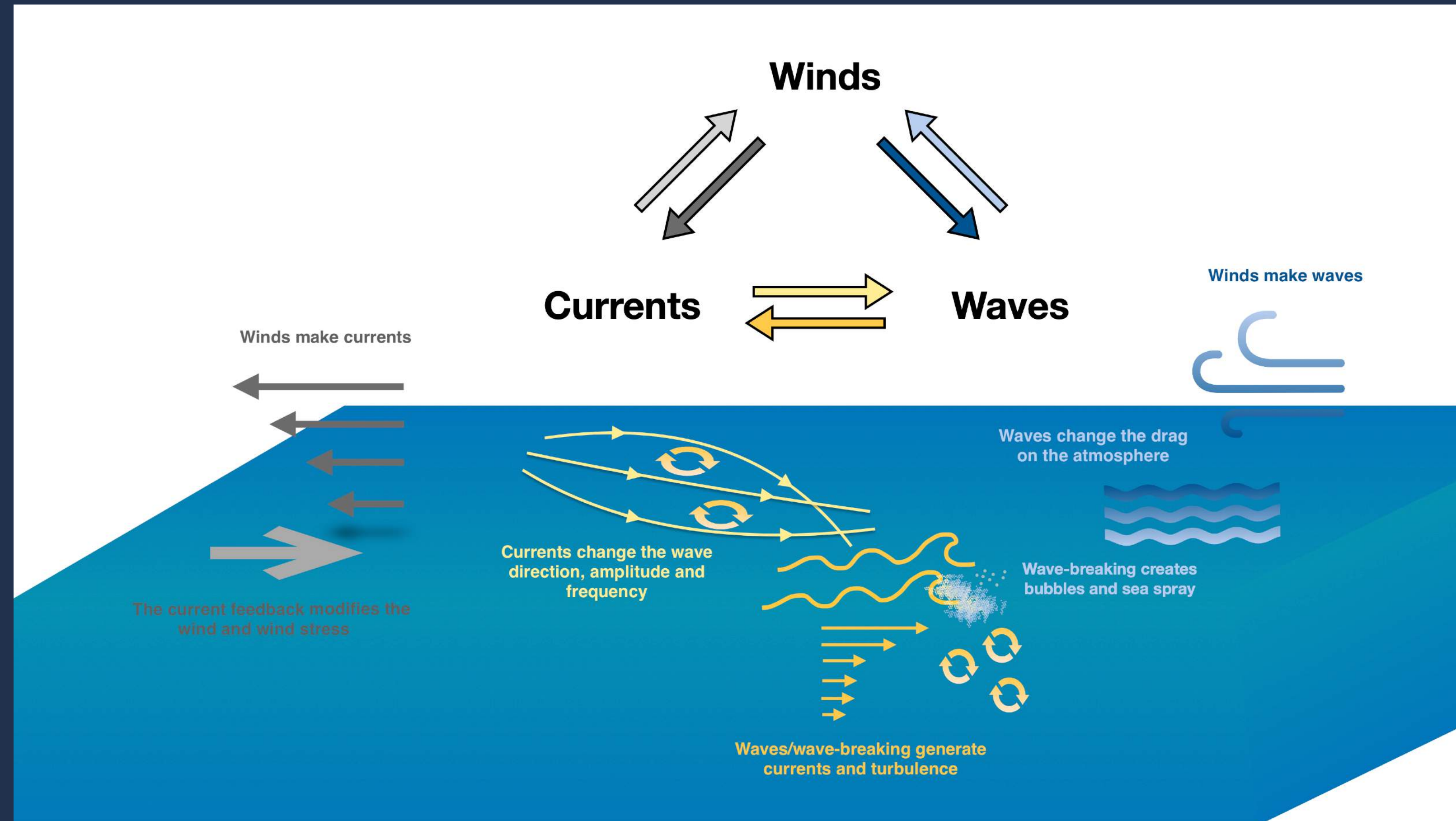
Team: *Gwendal Marechal (Mines), Matt Mazloff and Rui Sun (Scripps)*

Collaborators: *Nick Pizzo, Luc Lenain, Han Wang, Jacques Vanneste, and Bill Young.*



Waves, currents, and winds are **coupled**

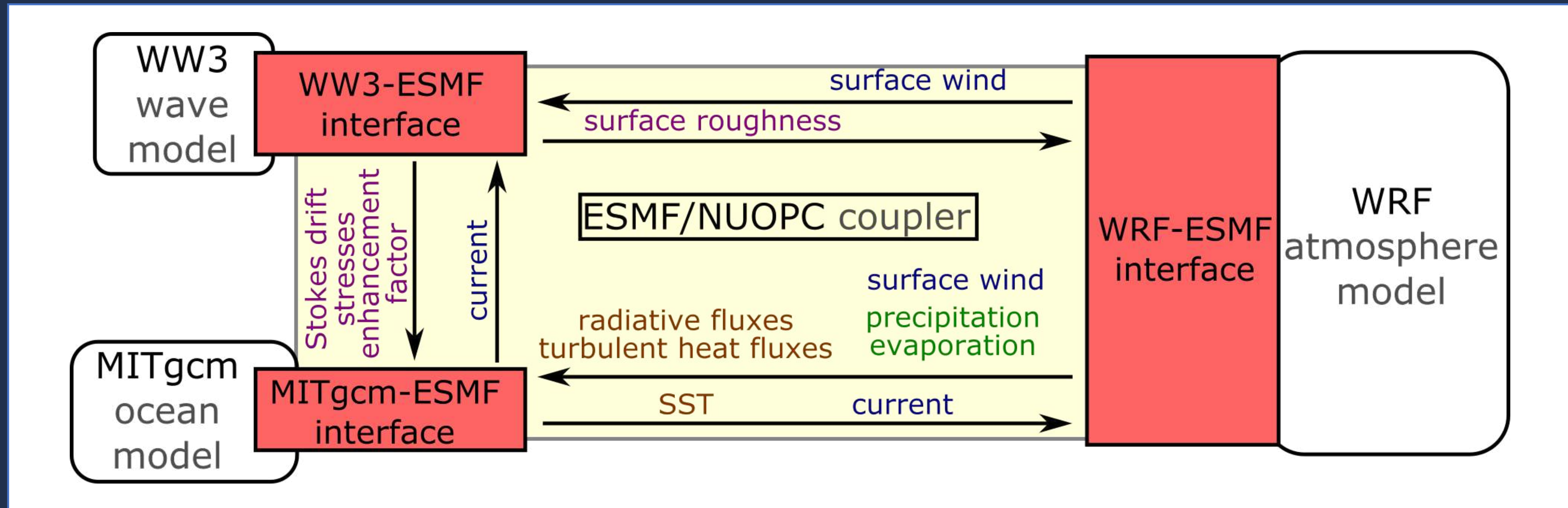
- Waves impact momentum, energy, heat, and gas fluxes
- Enhance mixing (Langmuir turbulence)
- Affects pathways of pollutants, plastics, ice, and algae.
- Impact the retrieval and interpretation of remote sensing measurements



Villas Bôas and Pizzo (2021)

Waves, currents, and winds are **coupled**

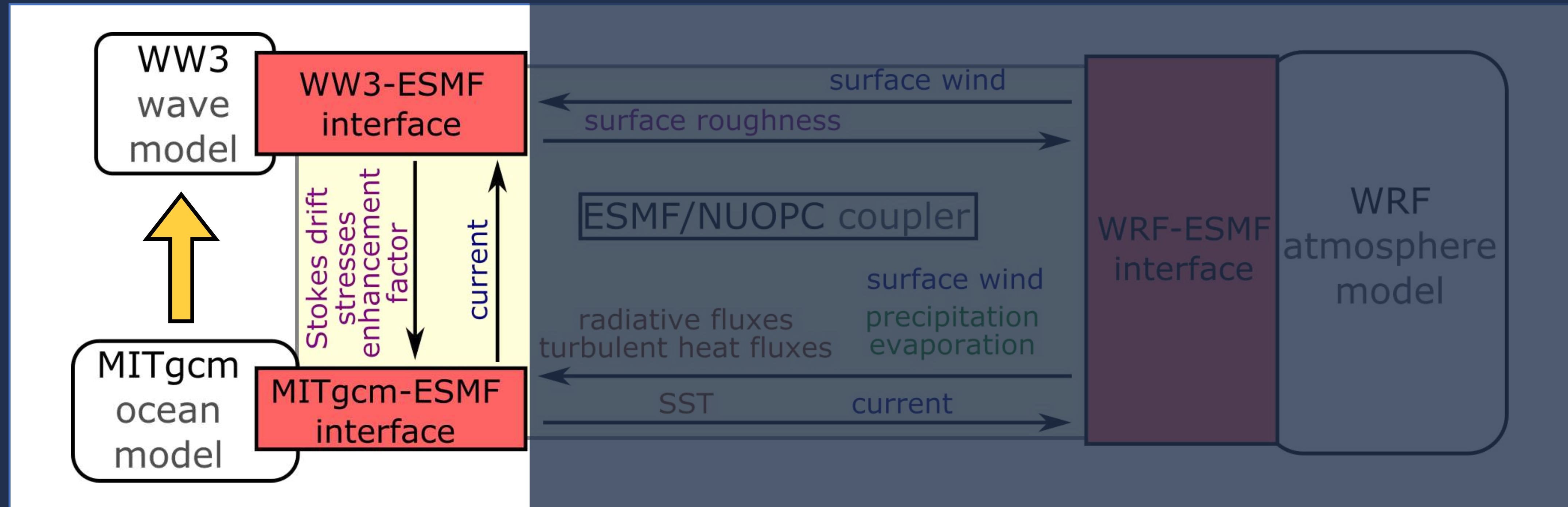
The SKRIPS model framework (Sun et al., 2021)



See also Sun et al. (2019, 2021, 2022)

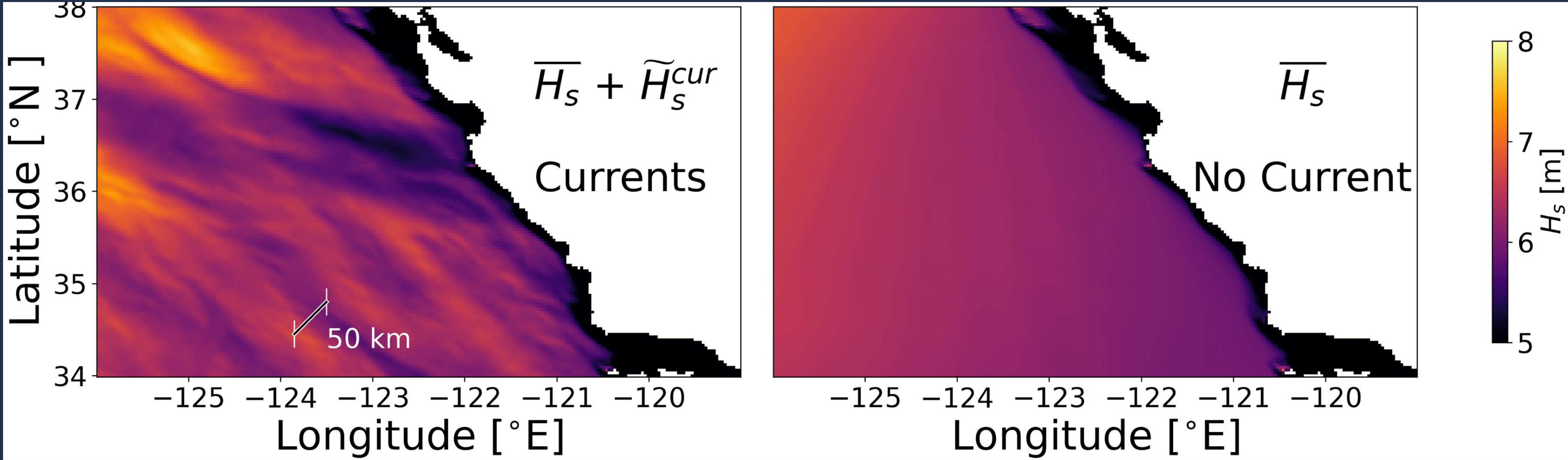
Waves, currents, and winds are **coupled**

The SKRIPS model framework (Sun et al., 2021)



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Models suggest that the **spatial variability of H_s** at scales between 10-100km is **driven by currents**



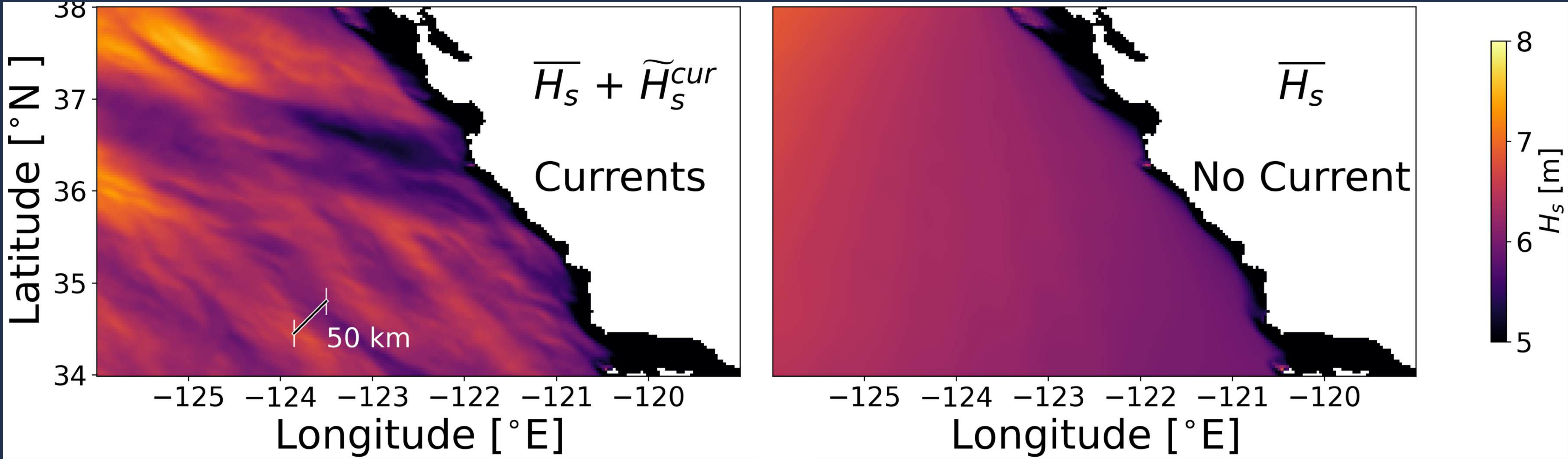
See also: Romero et al (2017, 2020), Ardhuin et al. (2017), Villas Bôas et al. 2020, Marechal and Ardhuin 2021

Models suggest that the **spatial variability of Hs** at scales between 10-100km is **driven by currents**

with

or

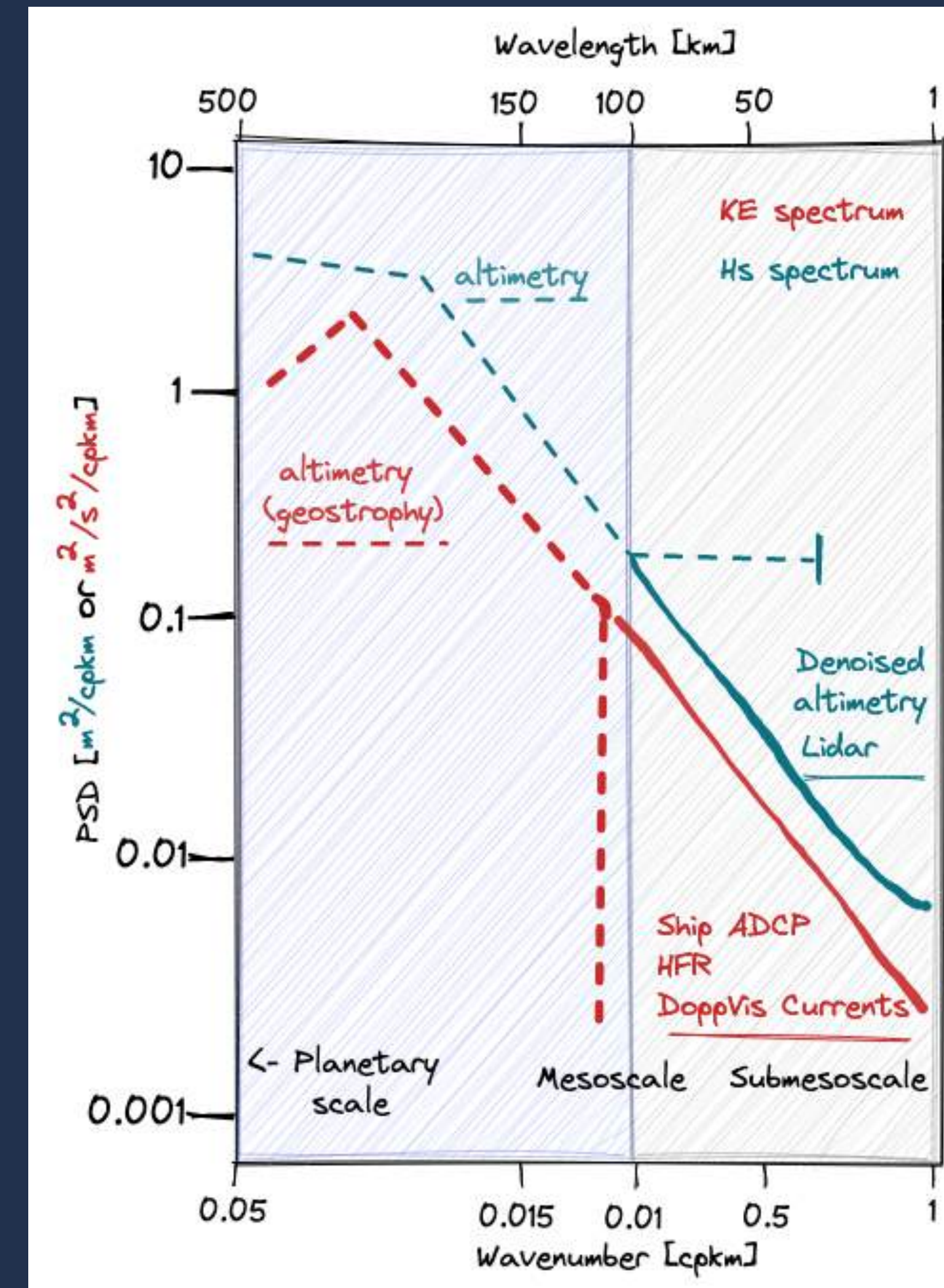
without U



See also: Romero et al (2017, 2020), Ardhuin et al. (2017), Villas Bôas et al. 2020, Marechal and Ardhuin 2021

✓ What we know

- Modeling and theory suggest a scale dependence between currents and significant wave height
- Vorticity/Refraction is the main mechanism driving the spatial variability of Hs at scales shorter than storm-scale
 - Not necessarily the case for higher moments - See for example *Rascle et al. (2016)* and *Lenain and Pizzo (2021)*.

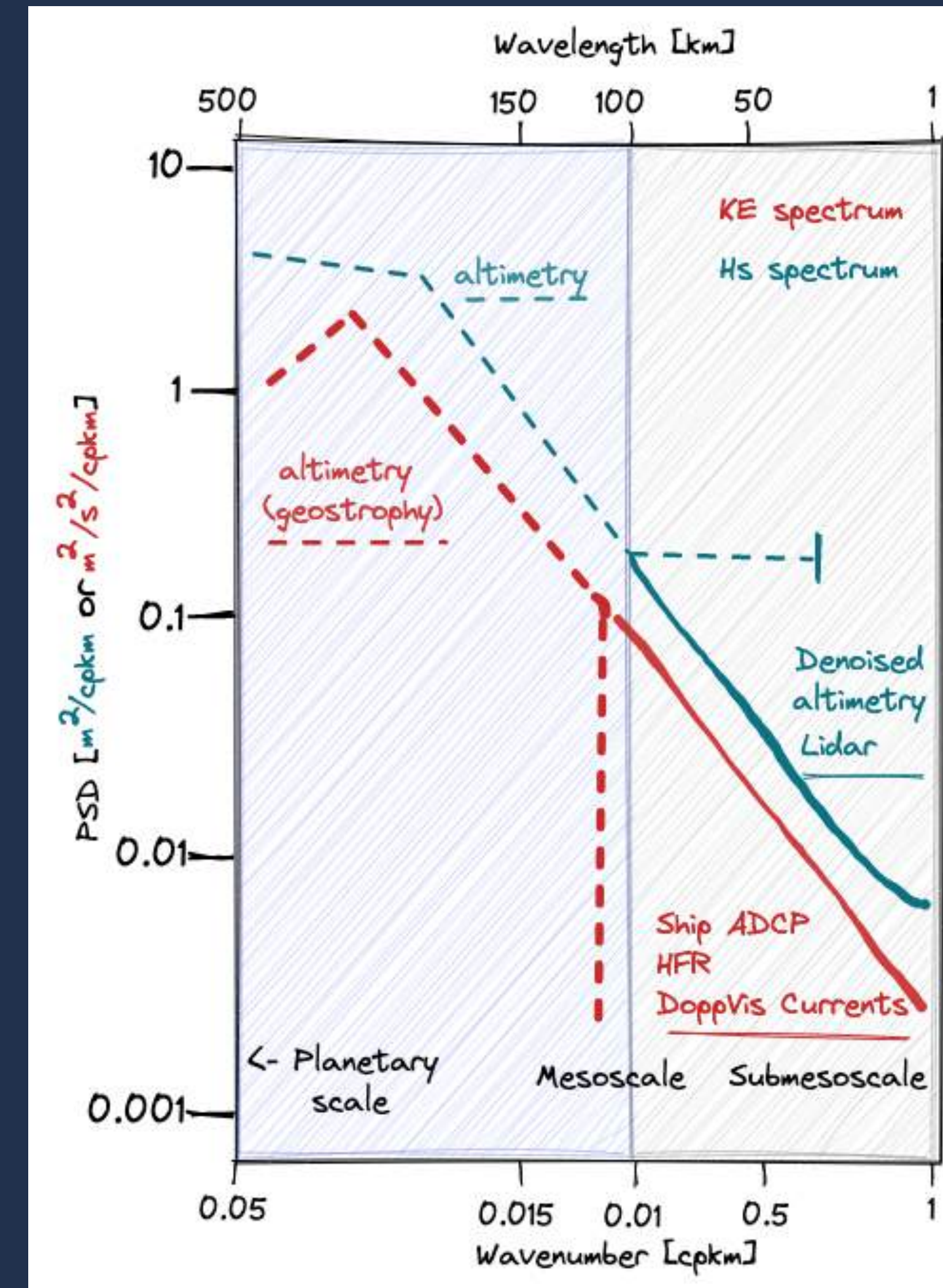


✓ What we know

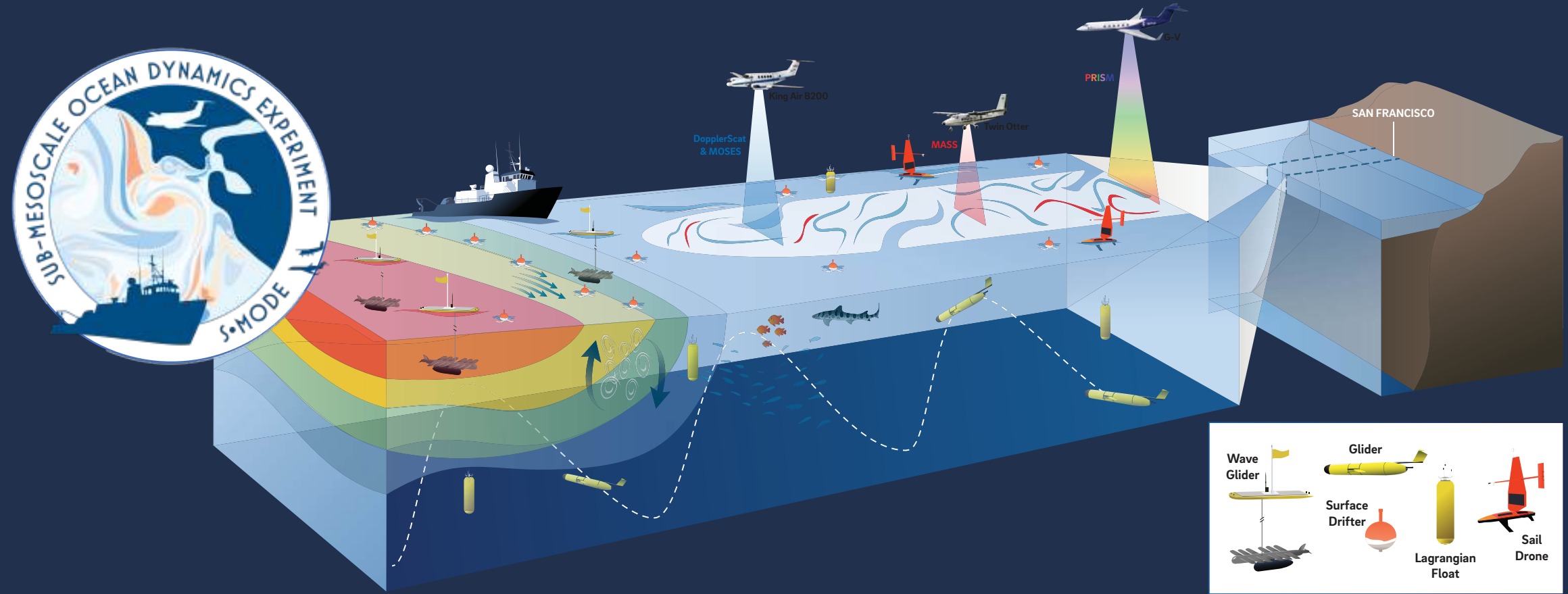
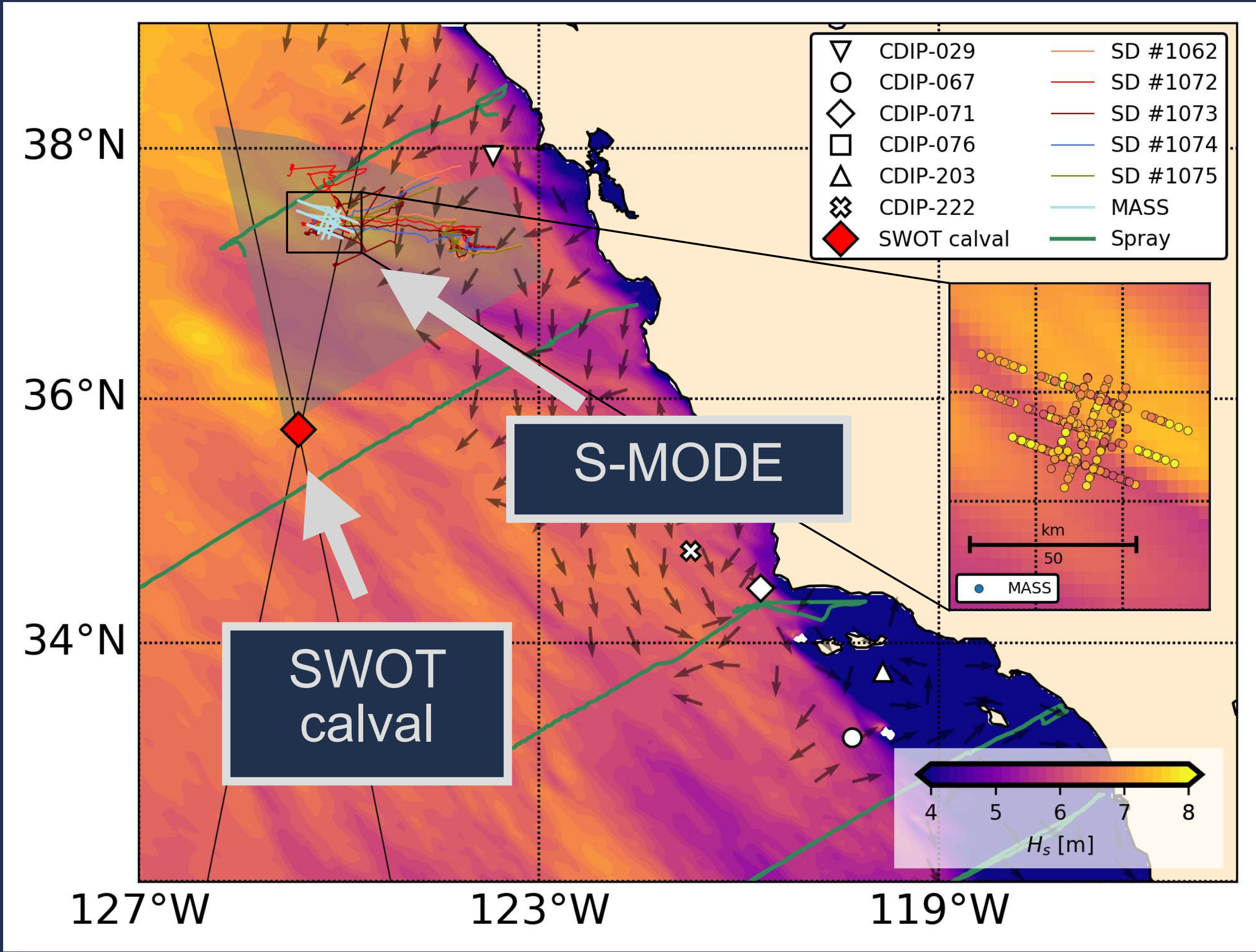
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🤔 What we don't know

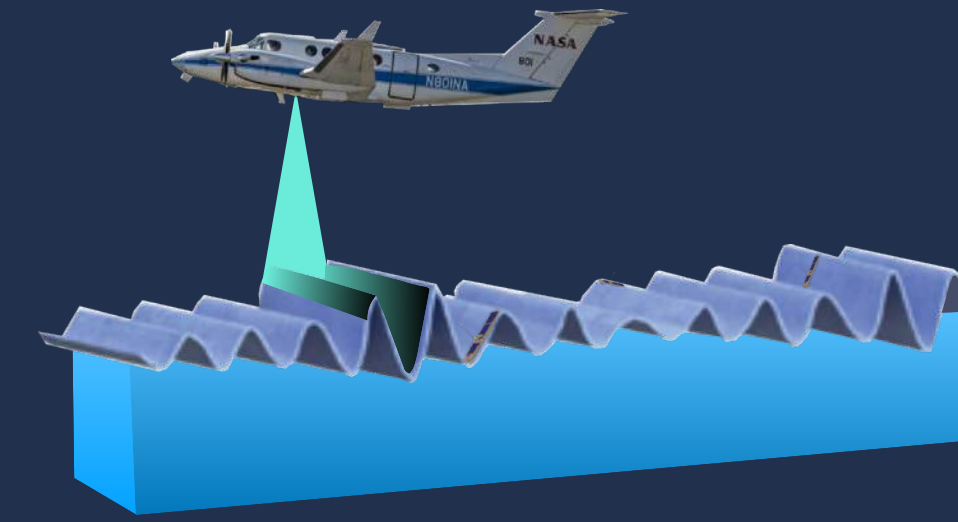
- Can we observe this relationship? Does it break down at any particular scale?
 - Present evidence is limited to ~30 km (Quilfen and Chapron, 2019)
 - We lack collocated observations of waves and currents
- What is the impact of current-induced refraction on higher moments (e.g., Stokes Drift) and air-sea fluxes?



Observing sea state gradients from S-MODE and SWOT

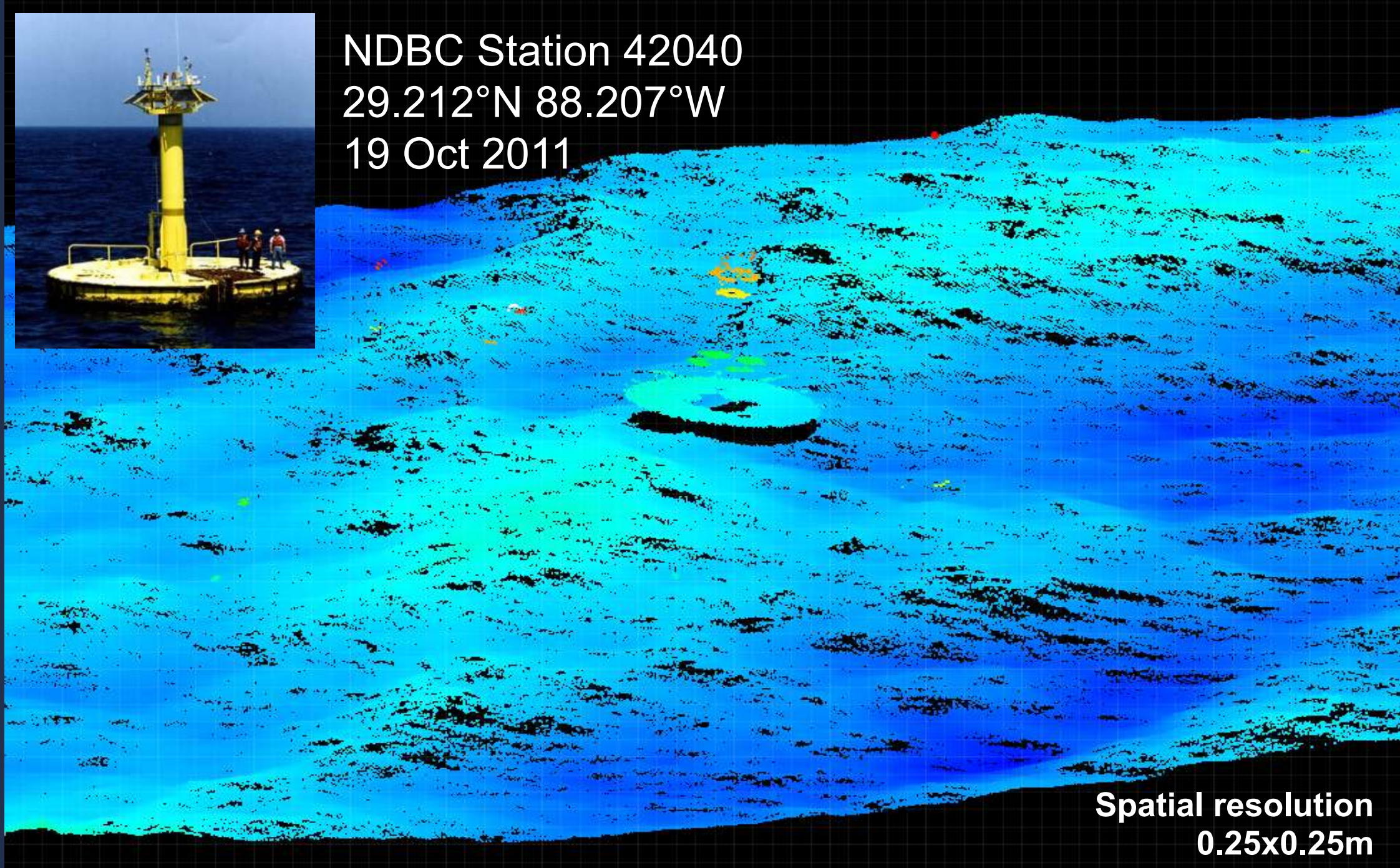


MASS airborne lidar observations

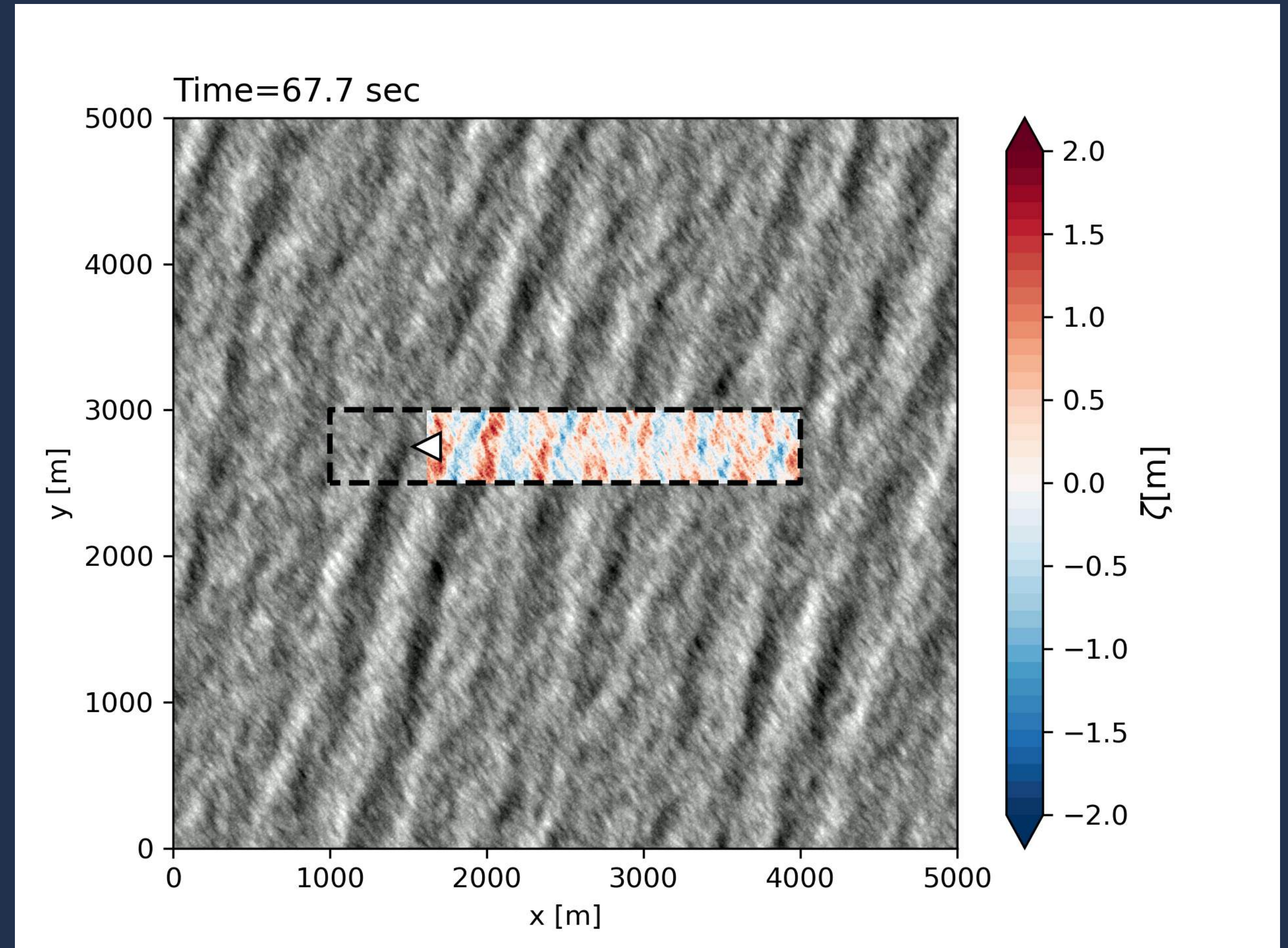


Scripps Air-sea lab
Modular Aerial Sensing System (MASS)

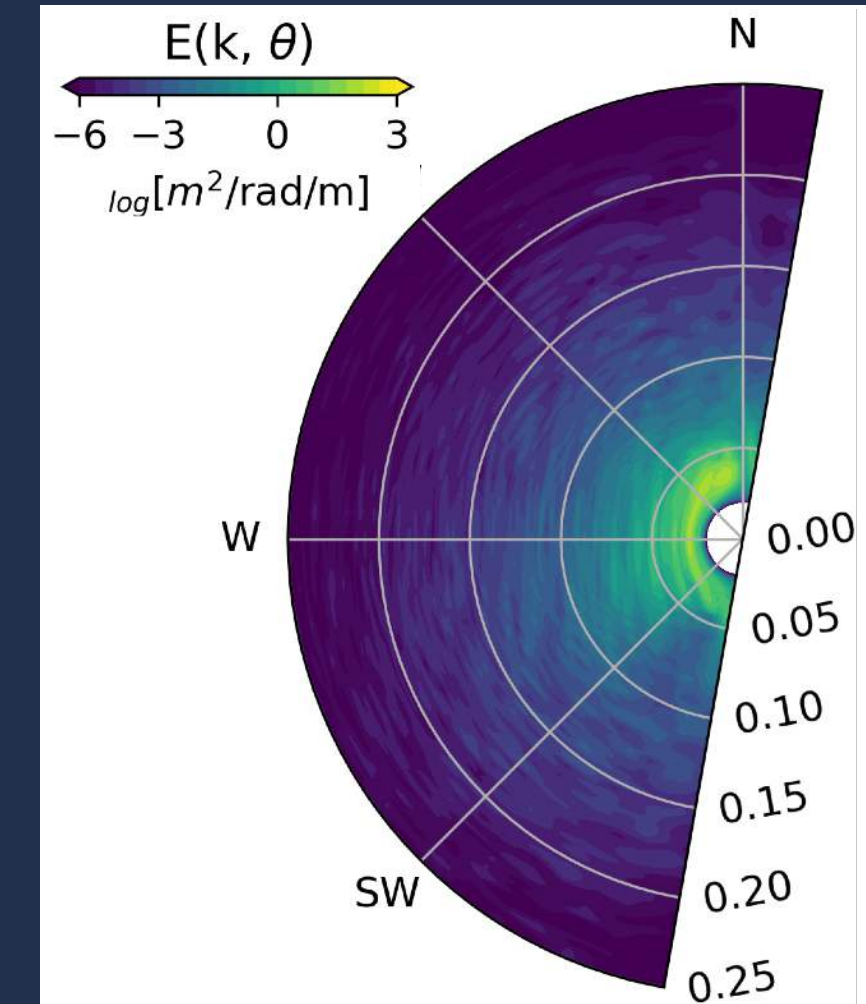
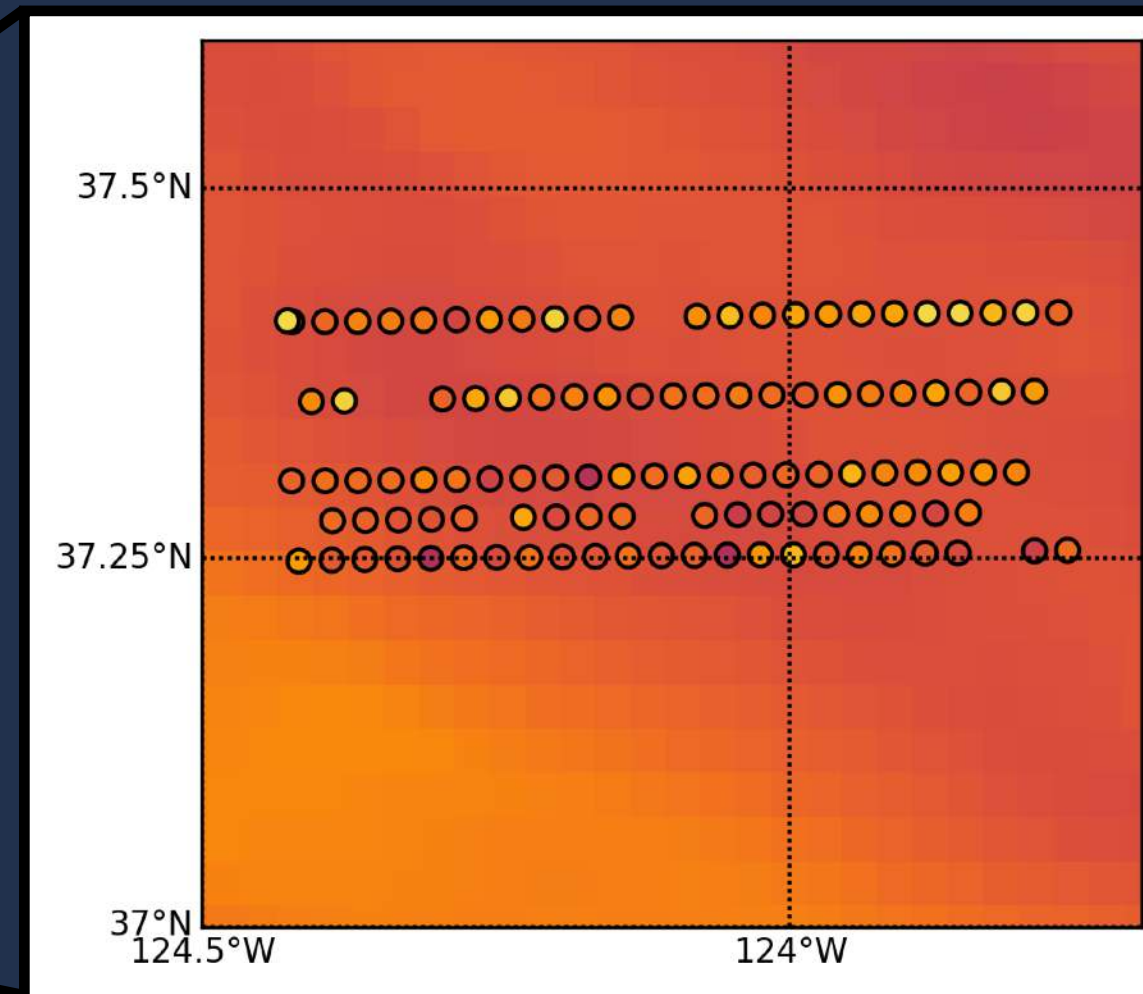
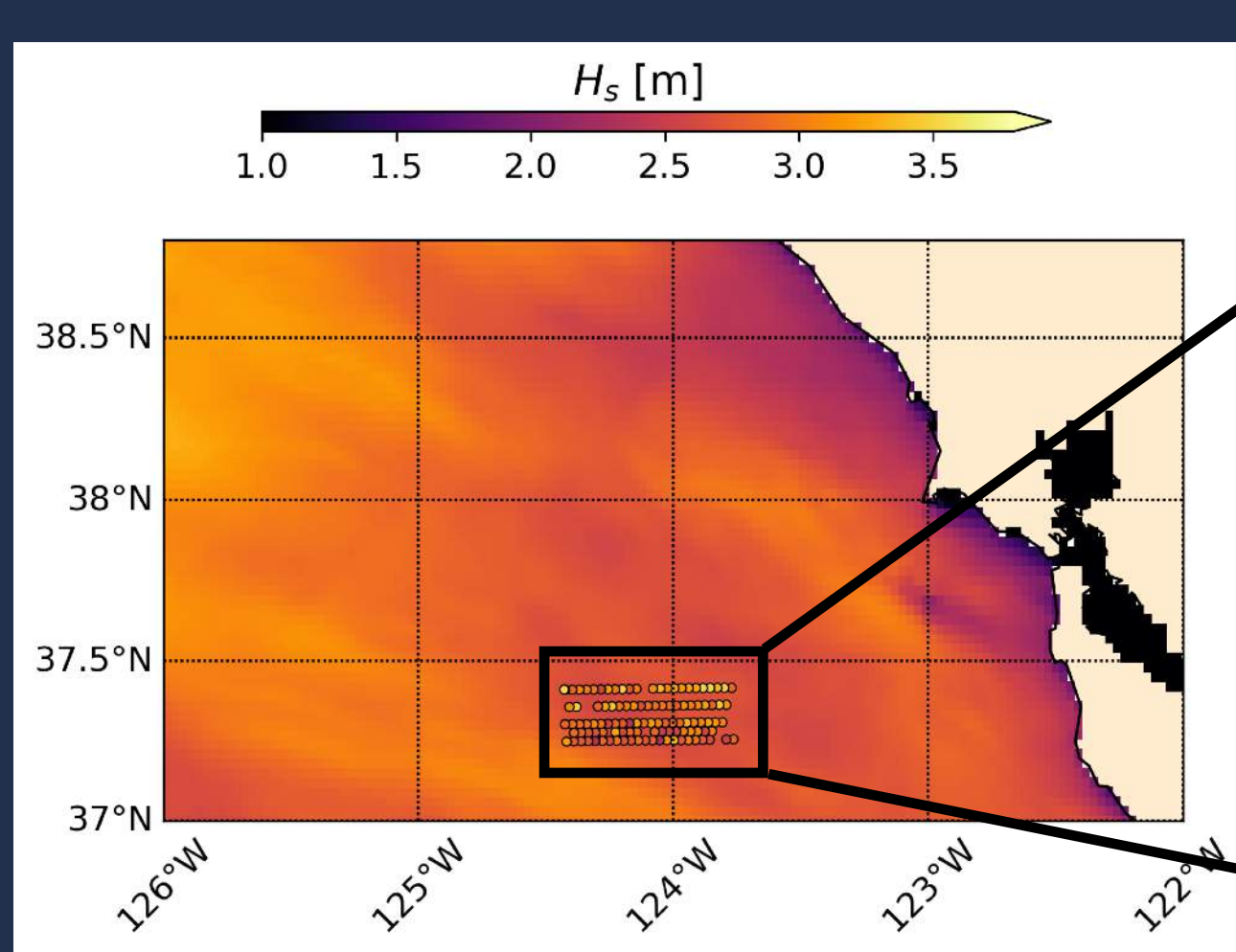
NDBC Station 42040
29.212°N 88.207°W
19 Oct 2011



From Luc Lenain (SIO)



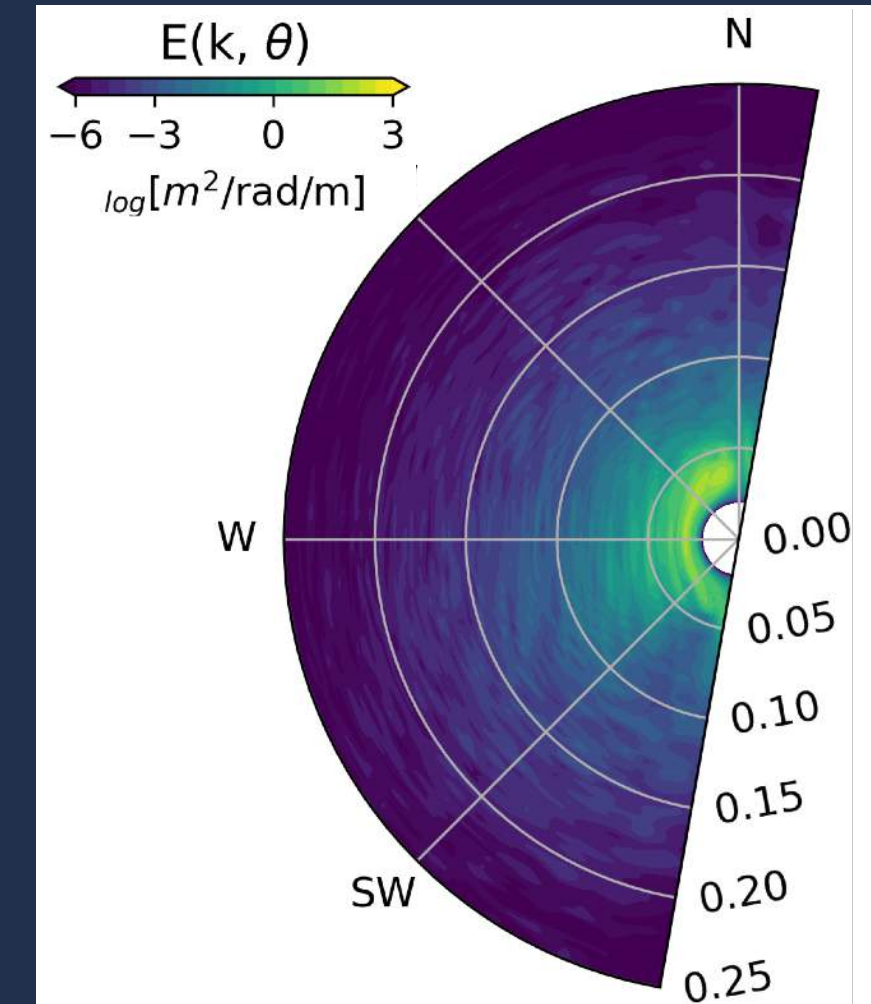
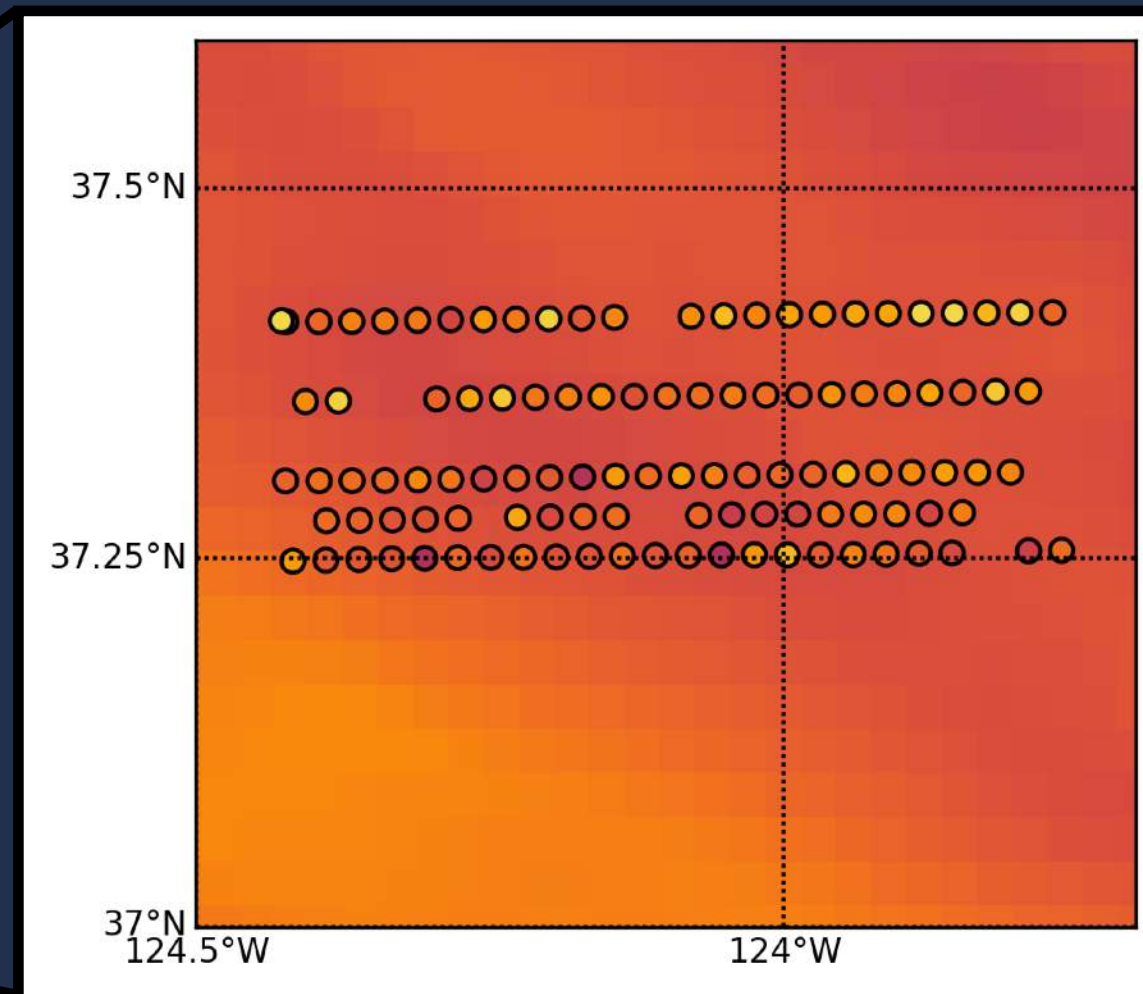
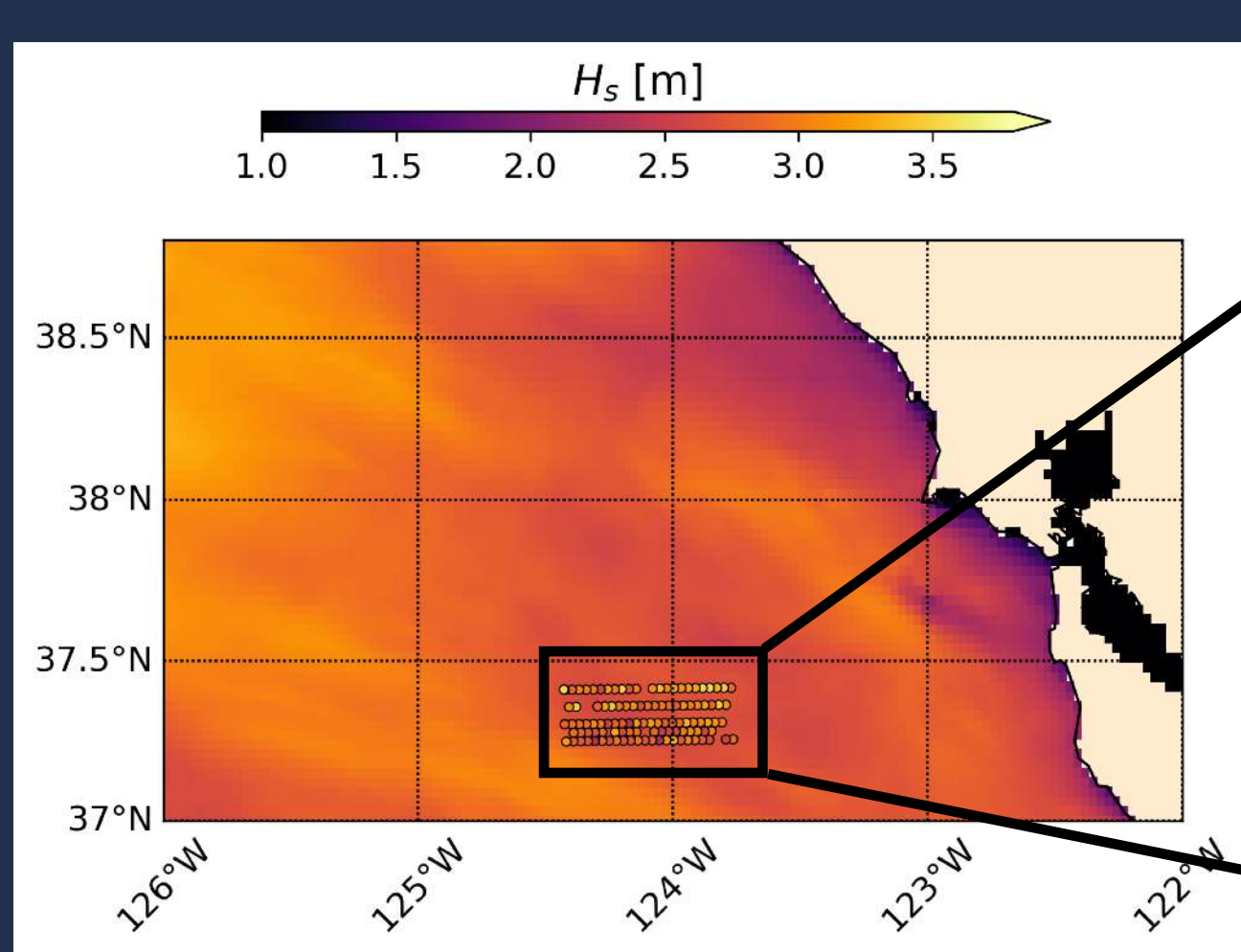
MASS observations of H_s under two different wave conditions



S-MODE pilot (Nov 2021)

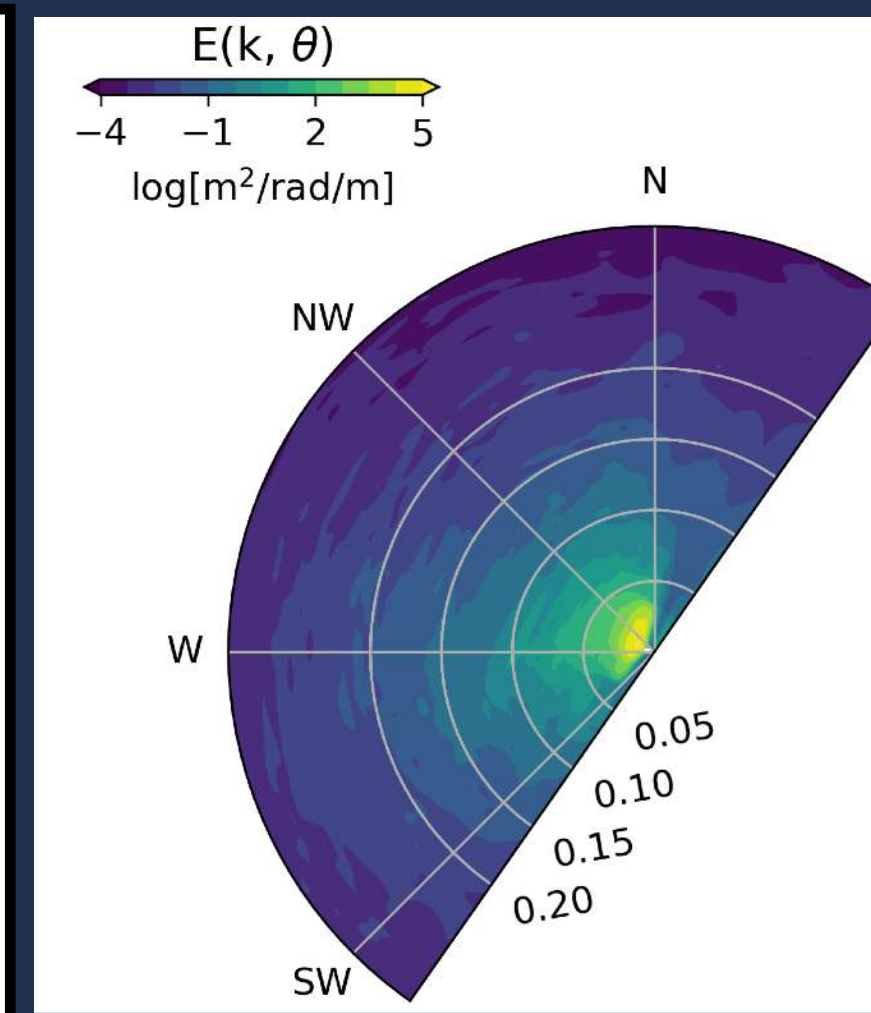
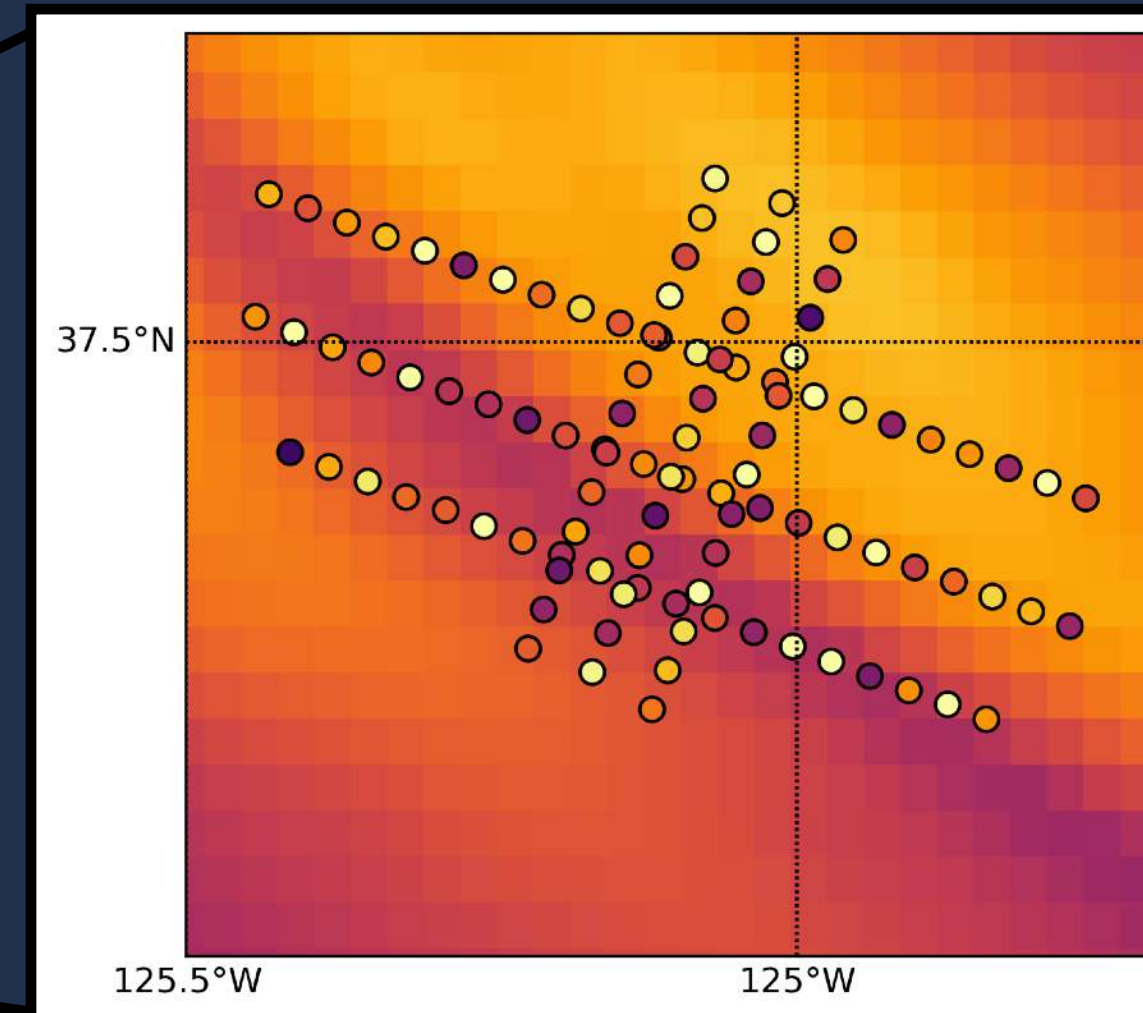
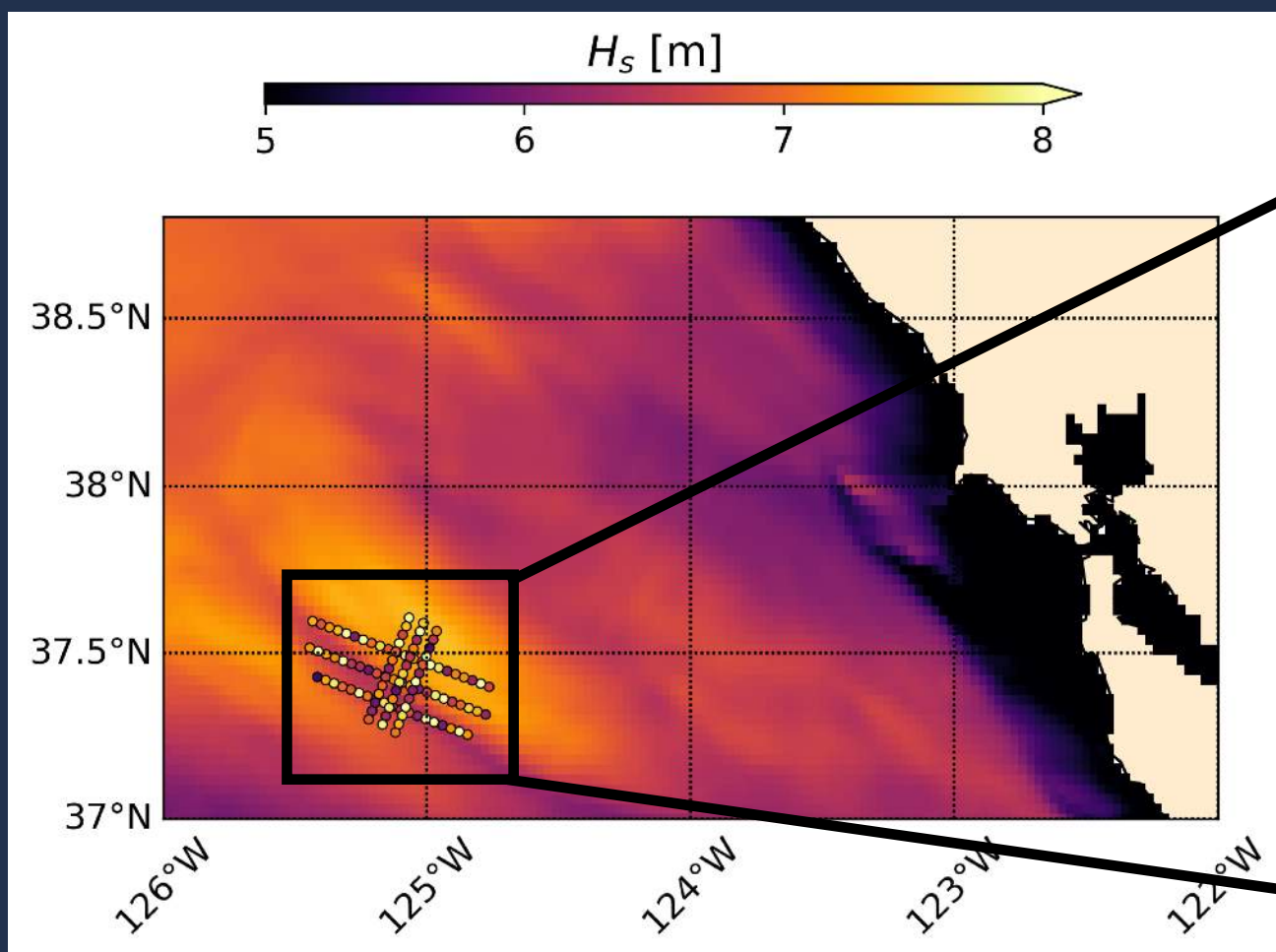
- Wind sea, high frequency and directional spreading, relatively low H_s (~ 3 m).

MASS observations of H_s under two different wave conditions



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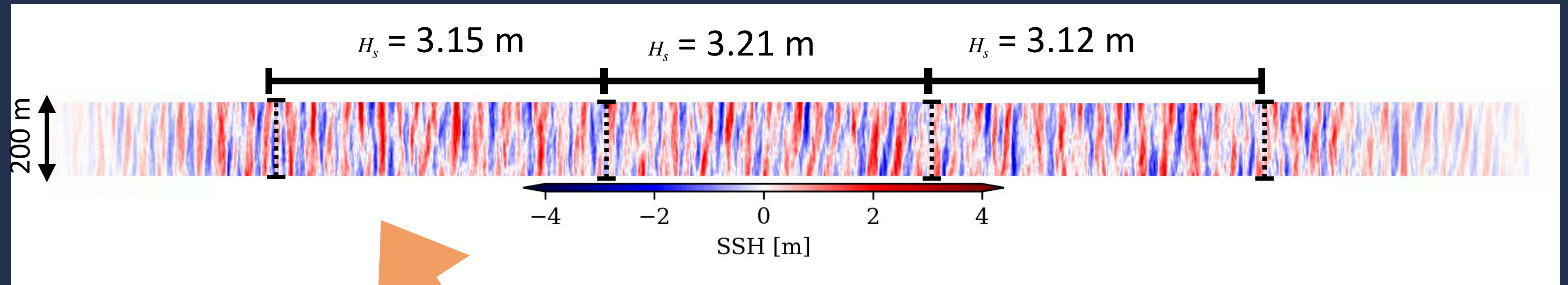
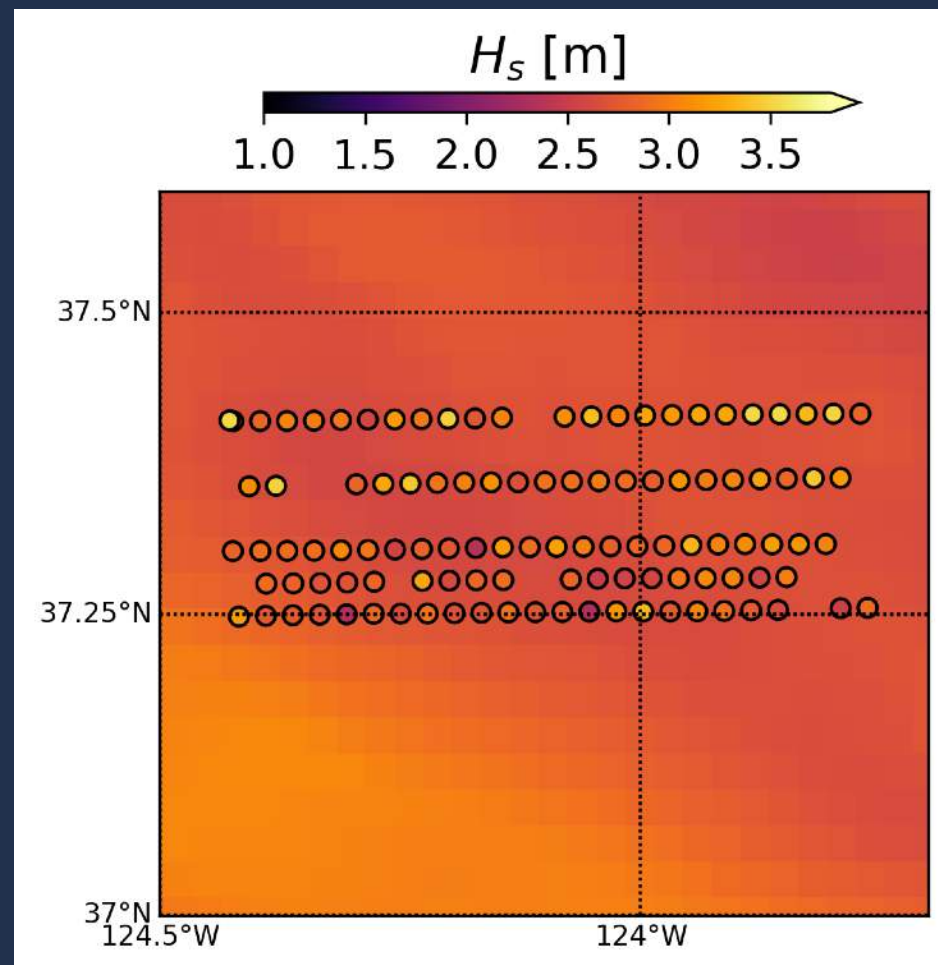
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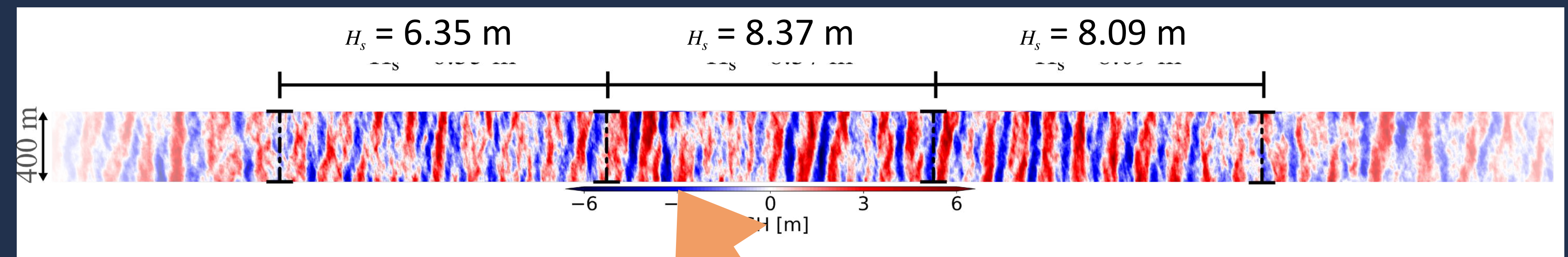
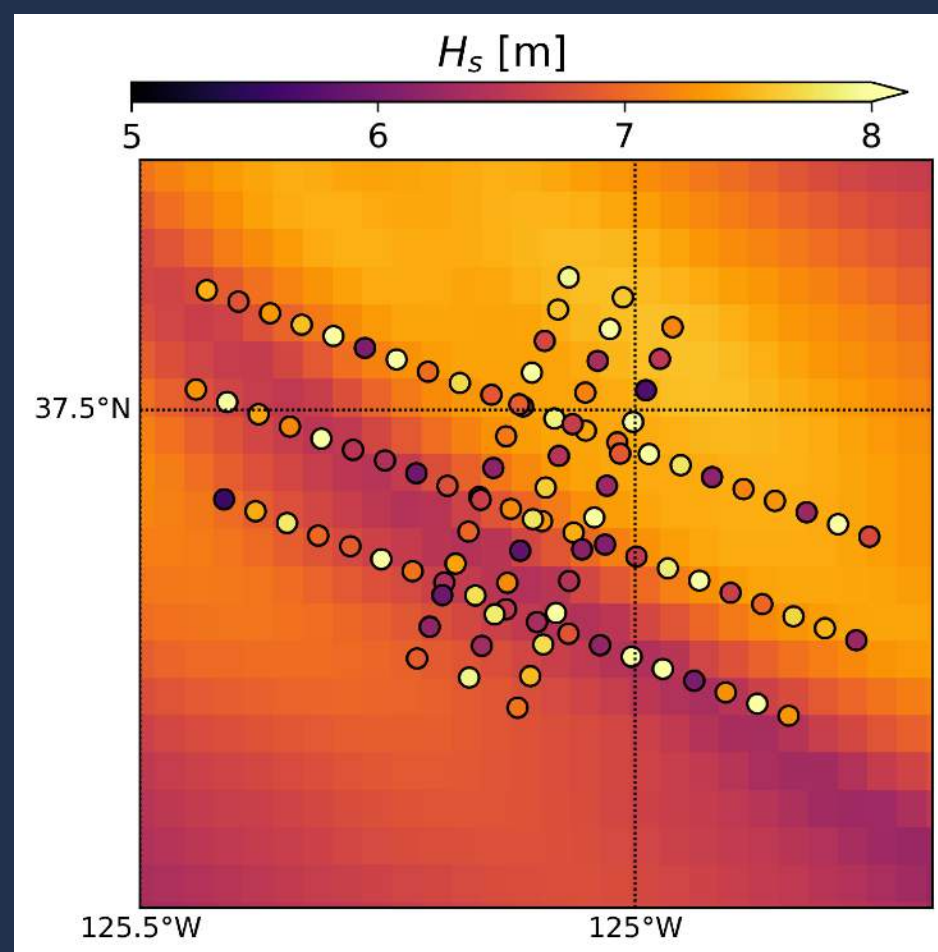
- Swell, low frequency and directional spreading, high H_s (~ 8 m) 🤯

Wave groups lead to spatial variability of H_s



Wind-sea, broad-banded spectrum

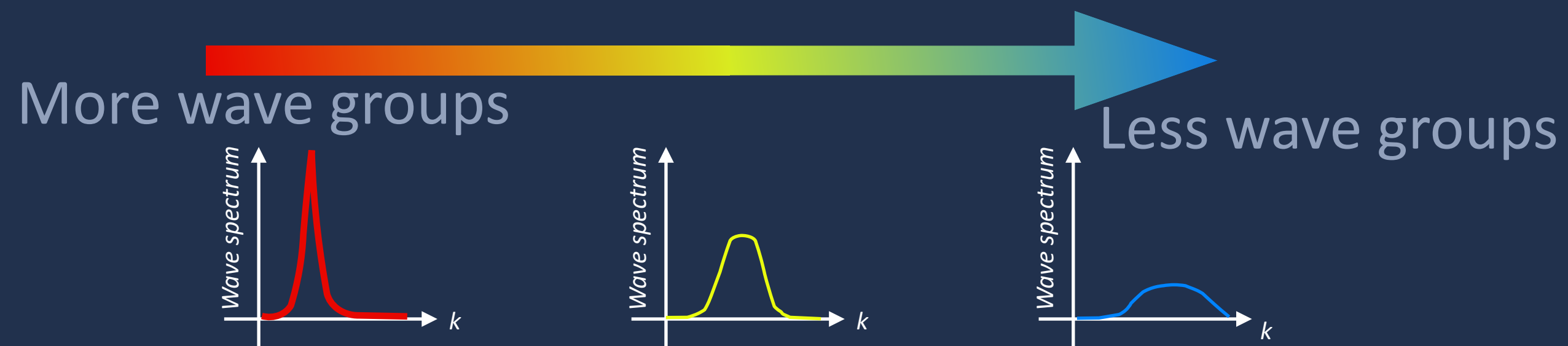
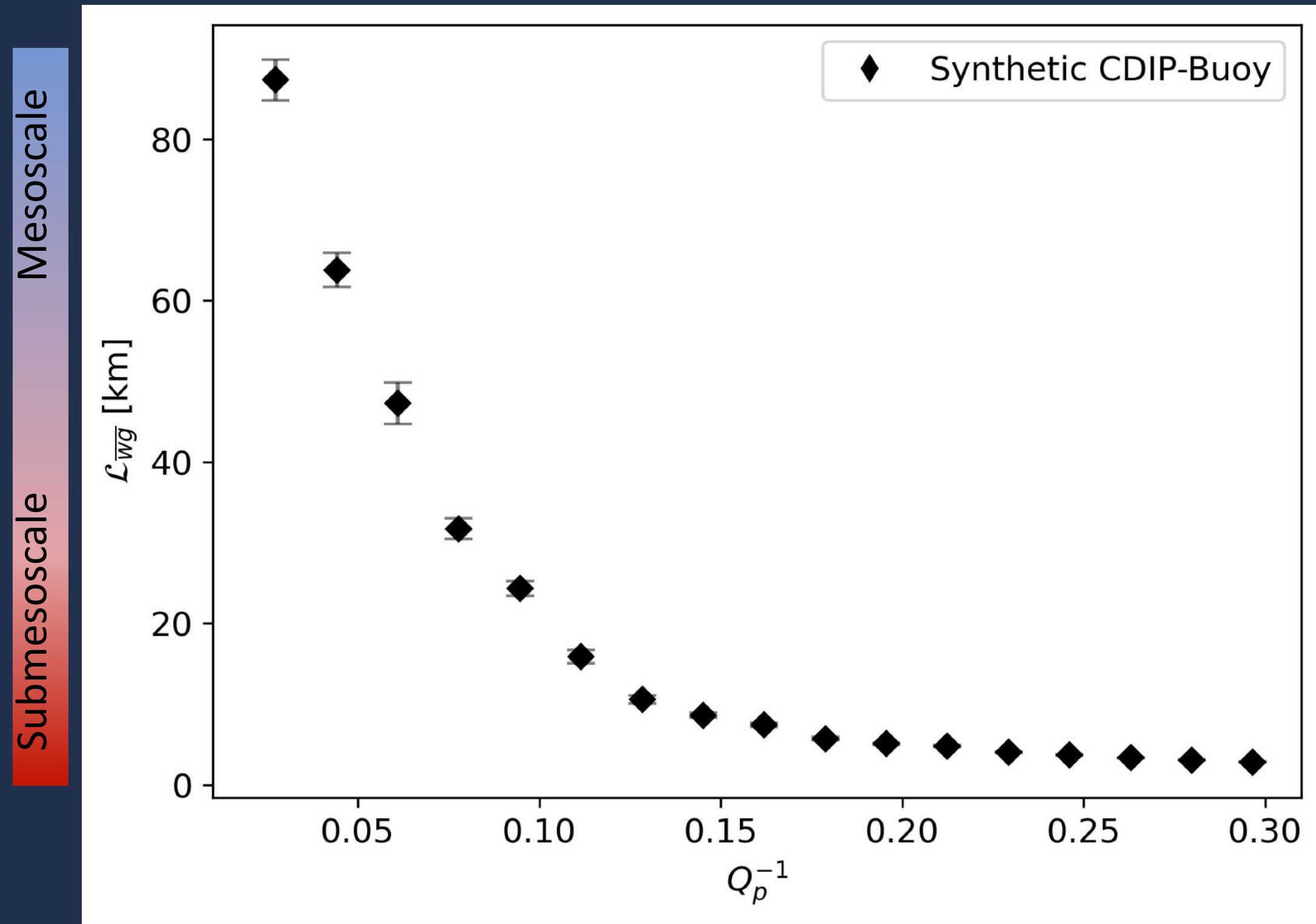
More homogeneous SSH field



Strong swell, narrow-banded spectrum

SSH field modulated by groups

There is **no** (spatial) **scale separation** between group and current modulation of H_s

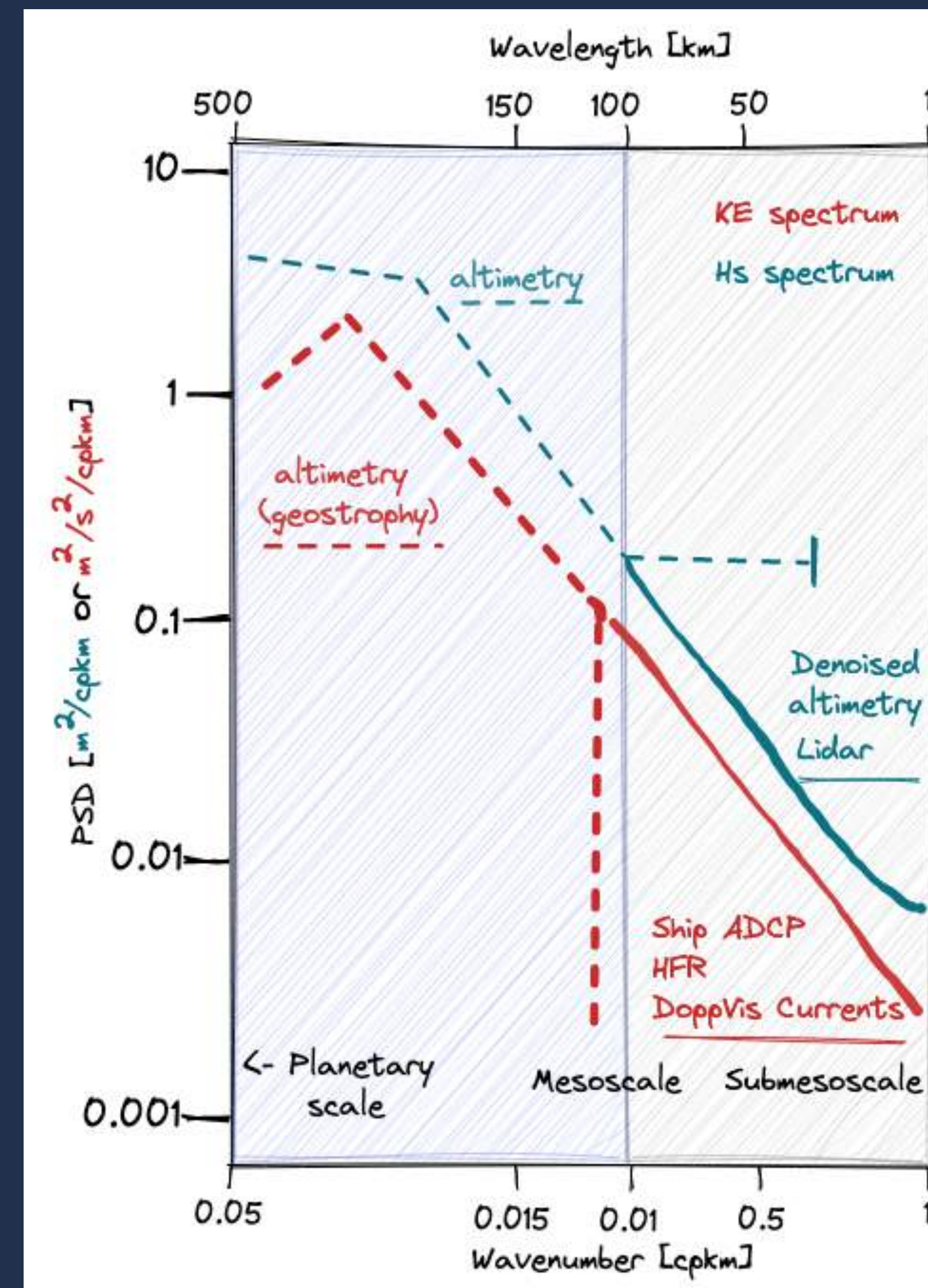
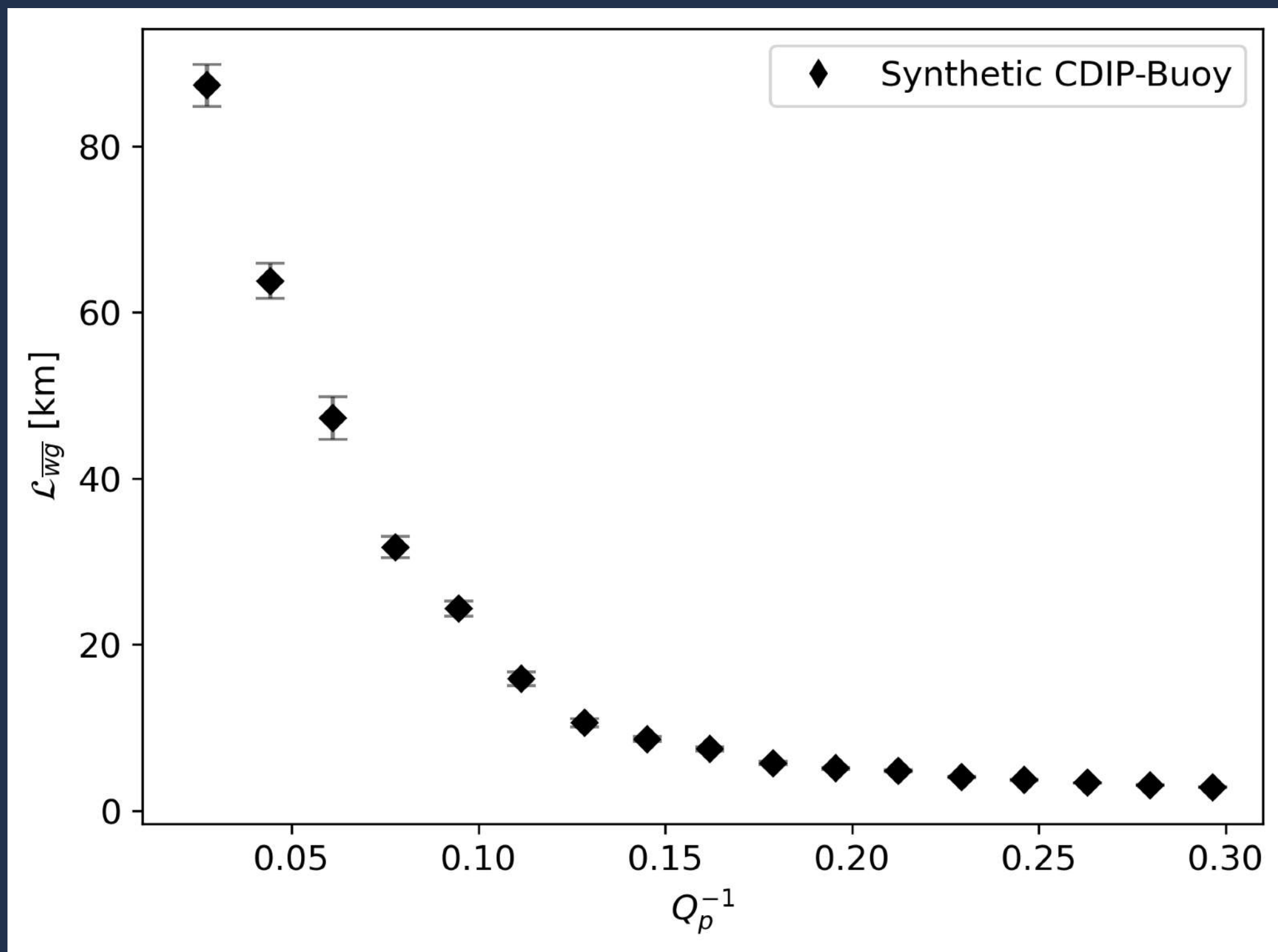


There is **no** (spatial) **scale separation** between group and current modulation of H_s

Expectation 😊

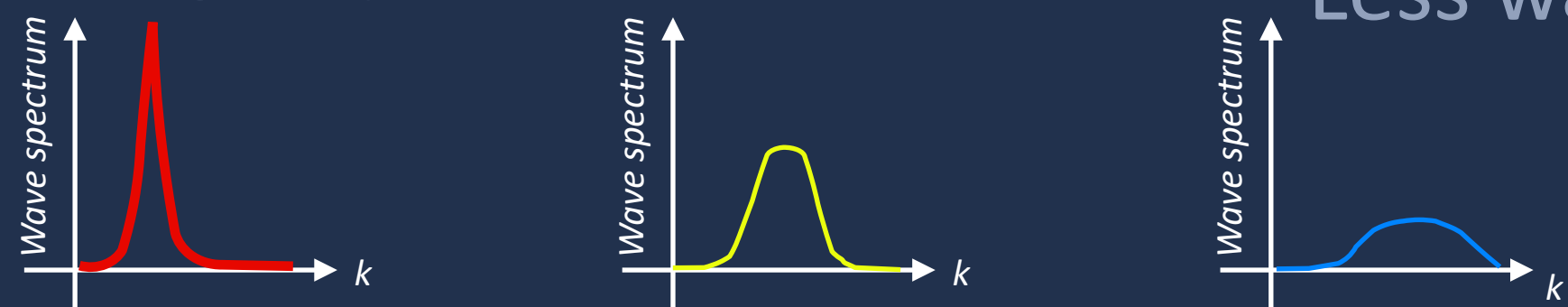
Submesoscale

Mesoscale



More wave groups

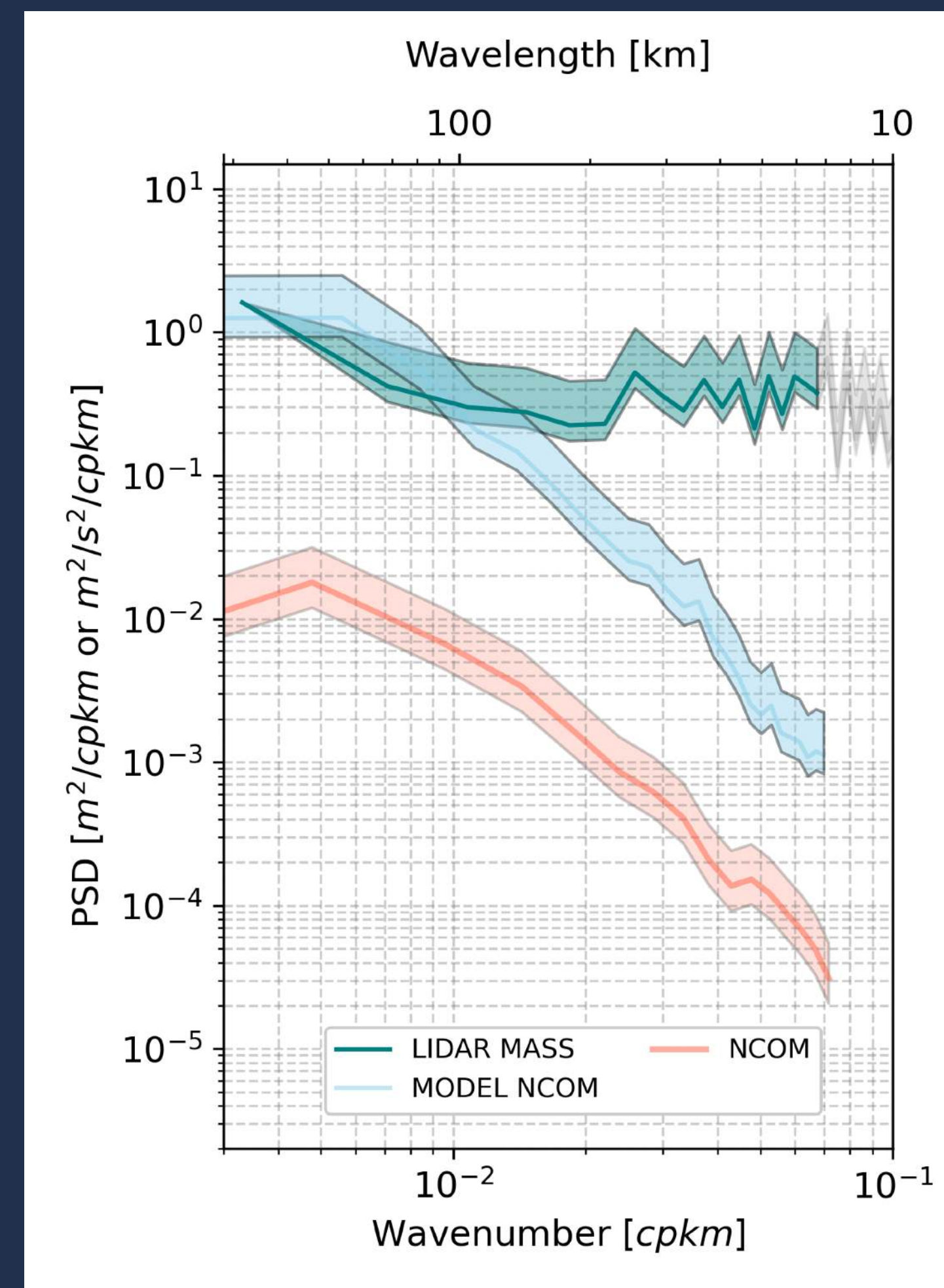
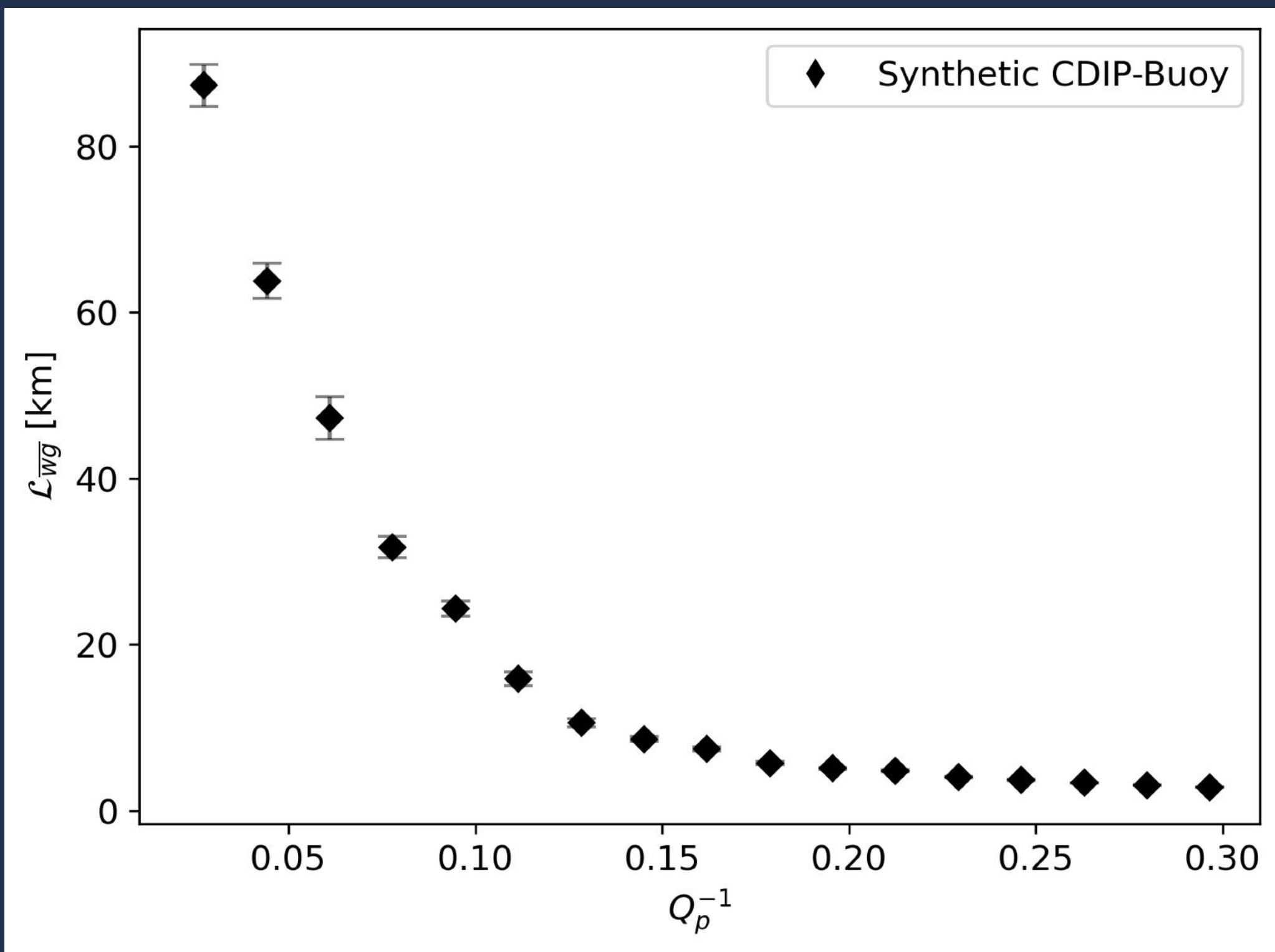
Less wave groups



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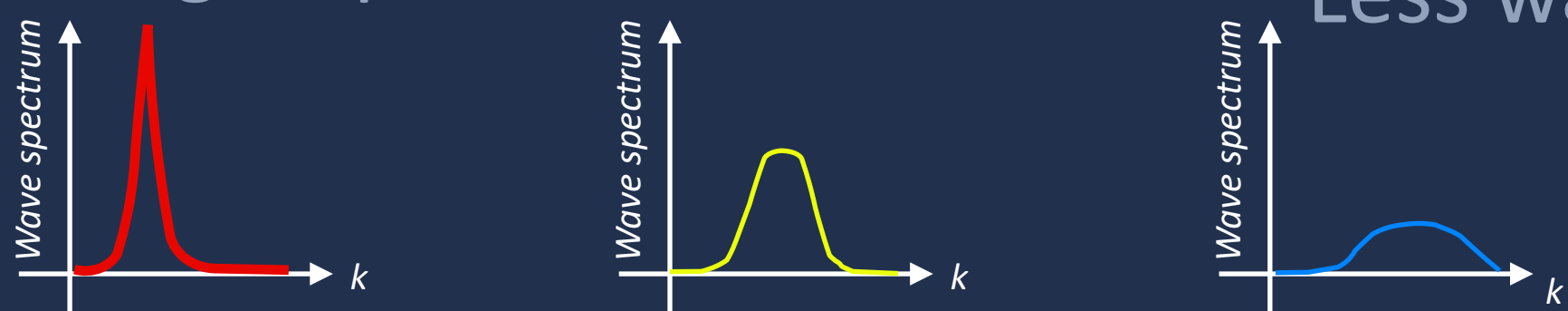
Reality 😬

Mesoscale
Submesoscale



More wave groups

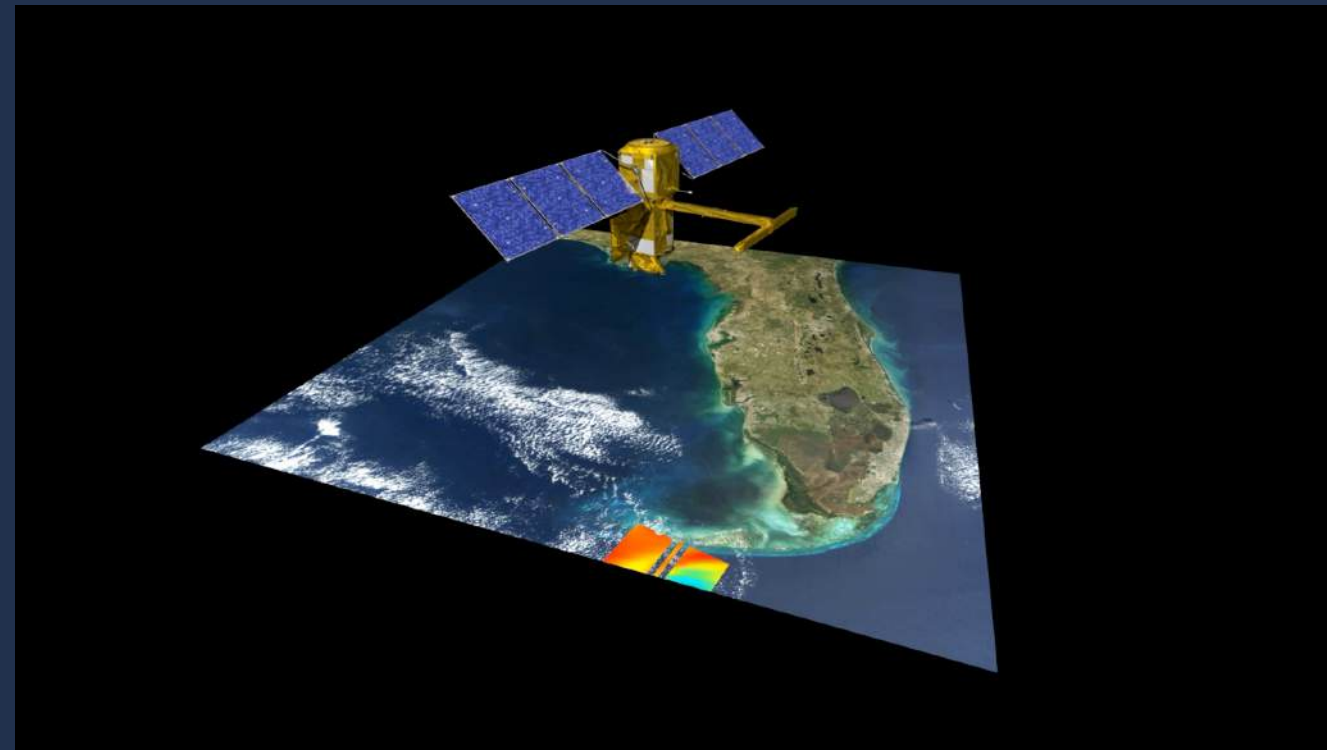
Less wave groups



Observing waves from SWOT

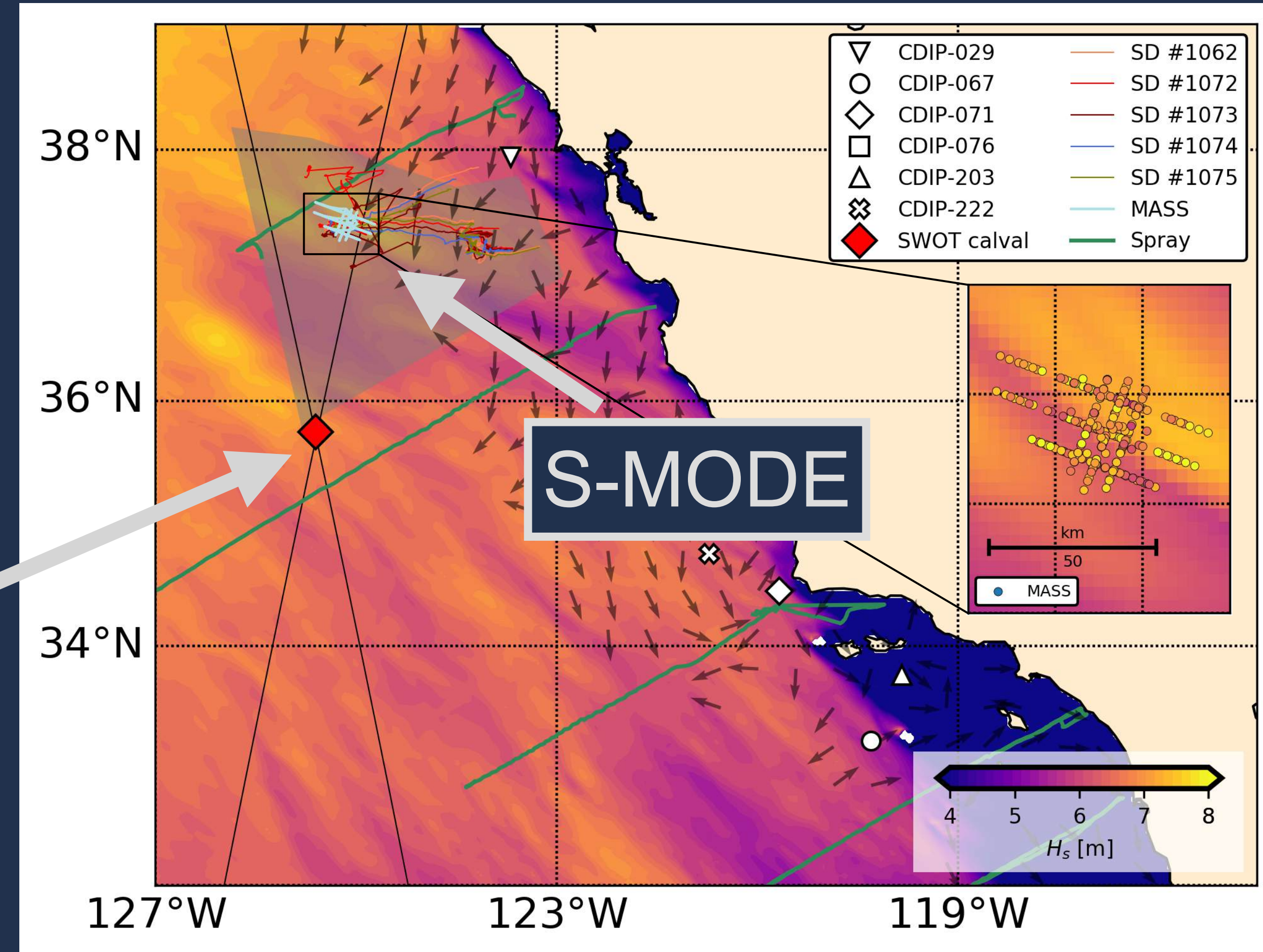
Observing waves from SWOT

- SWOT maps the ocean surface topography via two parallel 50 km-wide swaths every 21 days



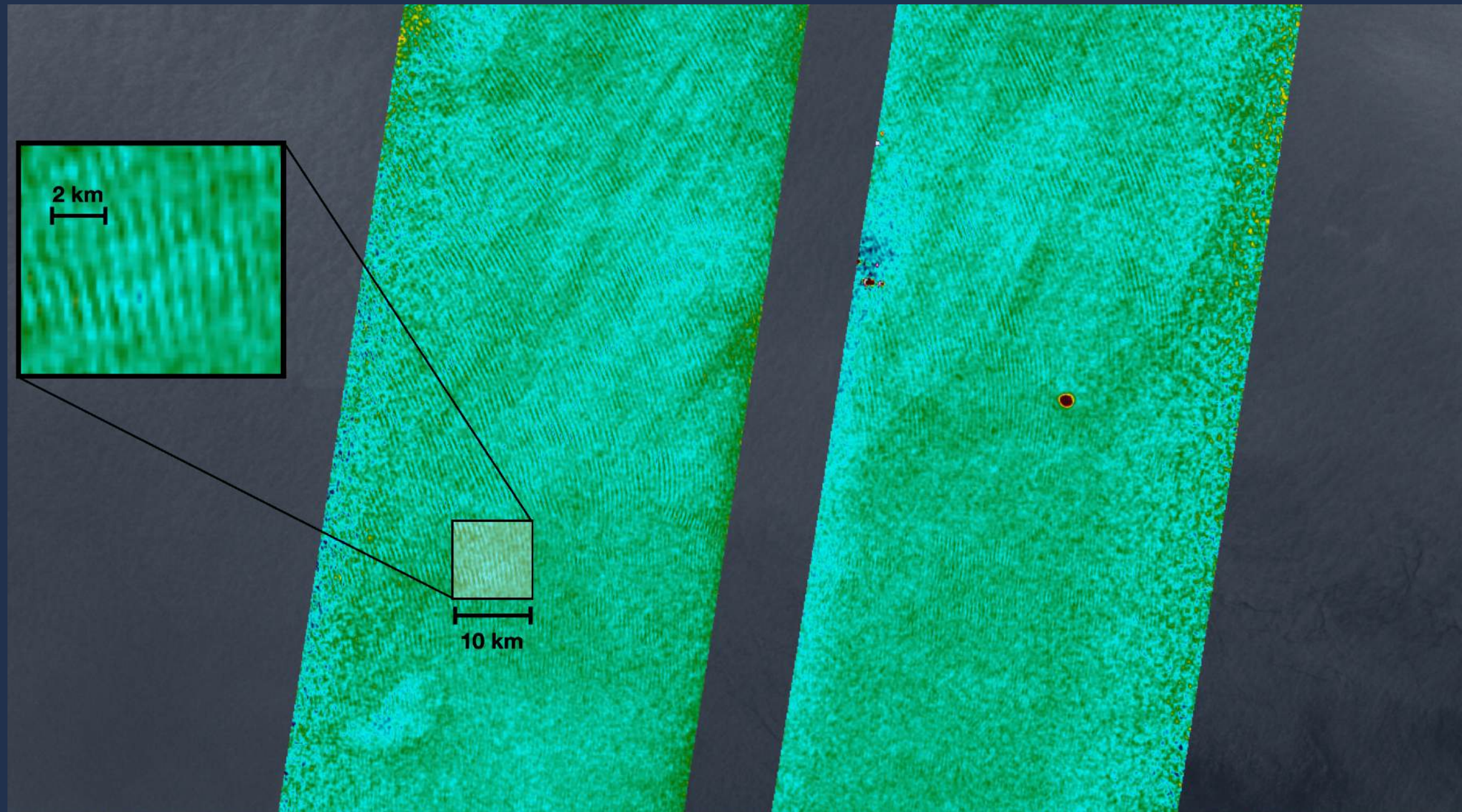
- SWOT's focuses on SSH measurement but surprise, surprise....

SWOT calval



Opportunities and challenges from SWOT observations

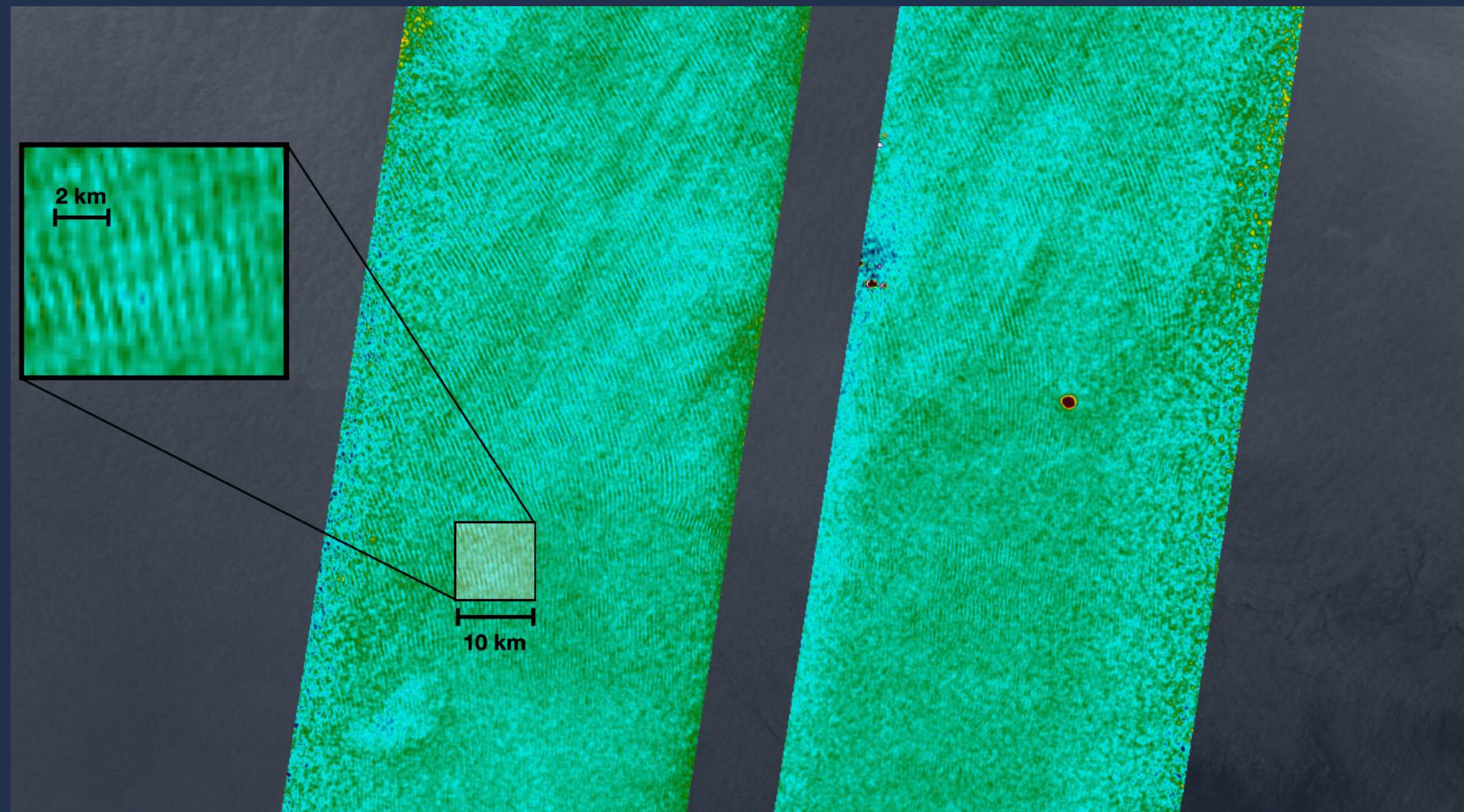
SWOT can see long swells and groups!



What is the role of group modulation on air-sea fluxes?

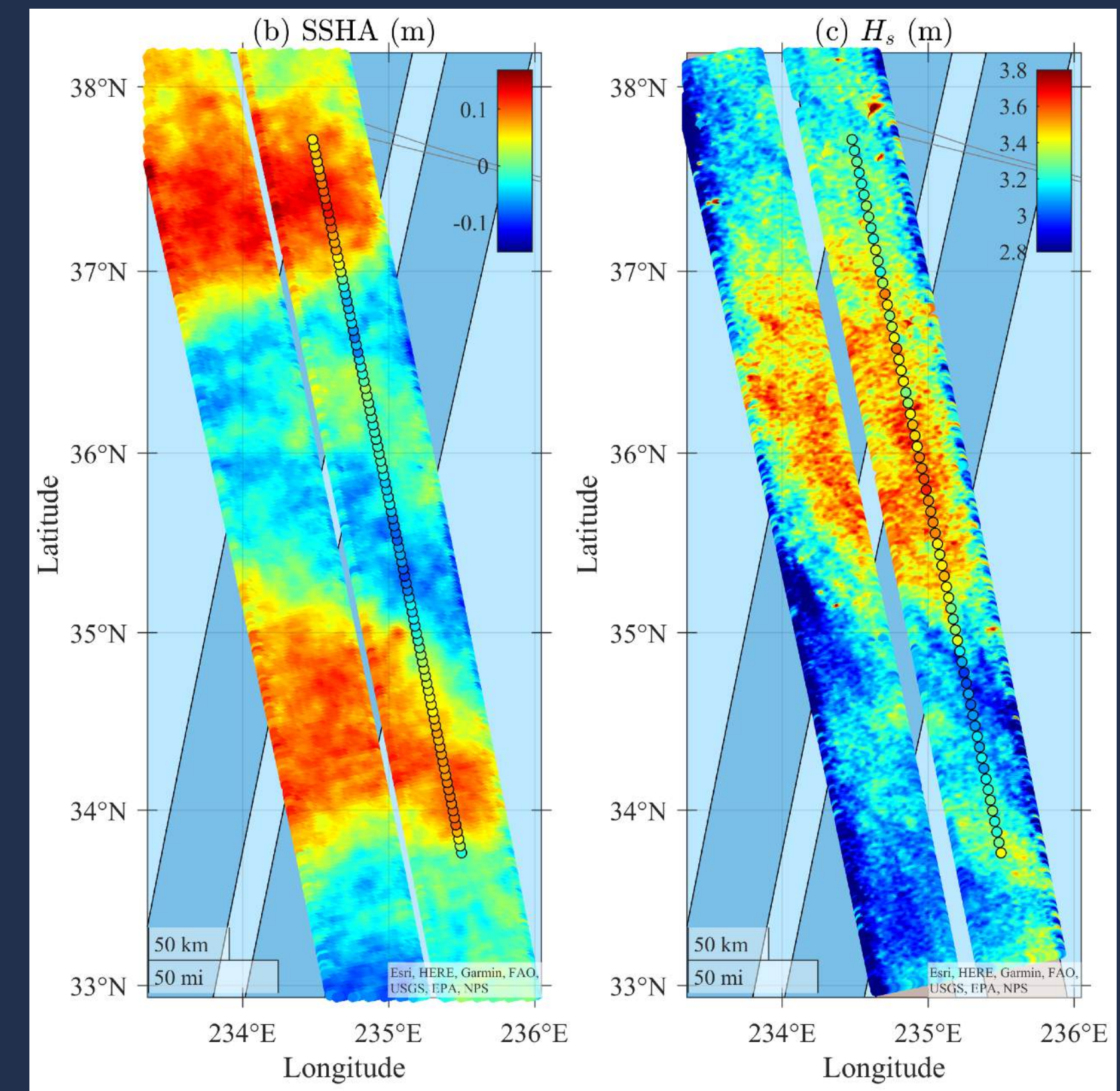
Opportunities and challenges from SWOT observations

SWOT can see long swells and groups!



What is the role of group modulation on air-sea fluxes?

And map the 2D significant wave height
(thanks to Alejandro Bohe's algorithm)



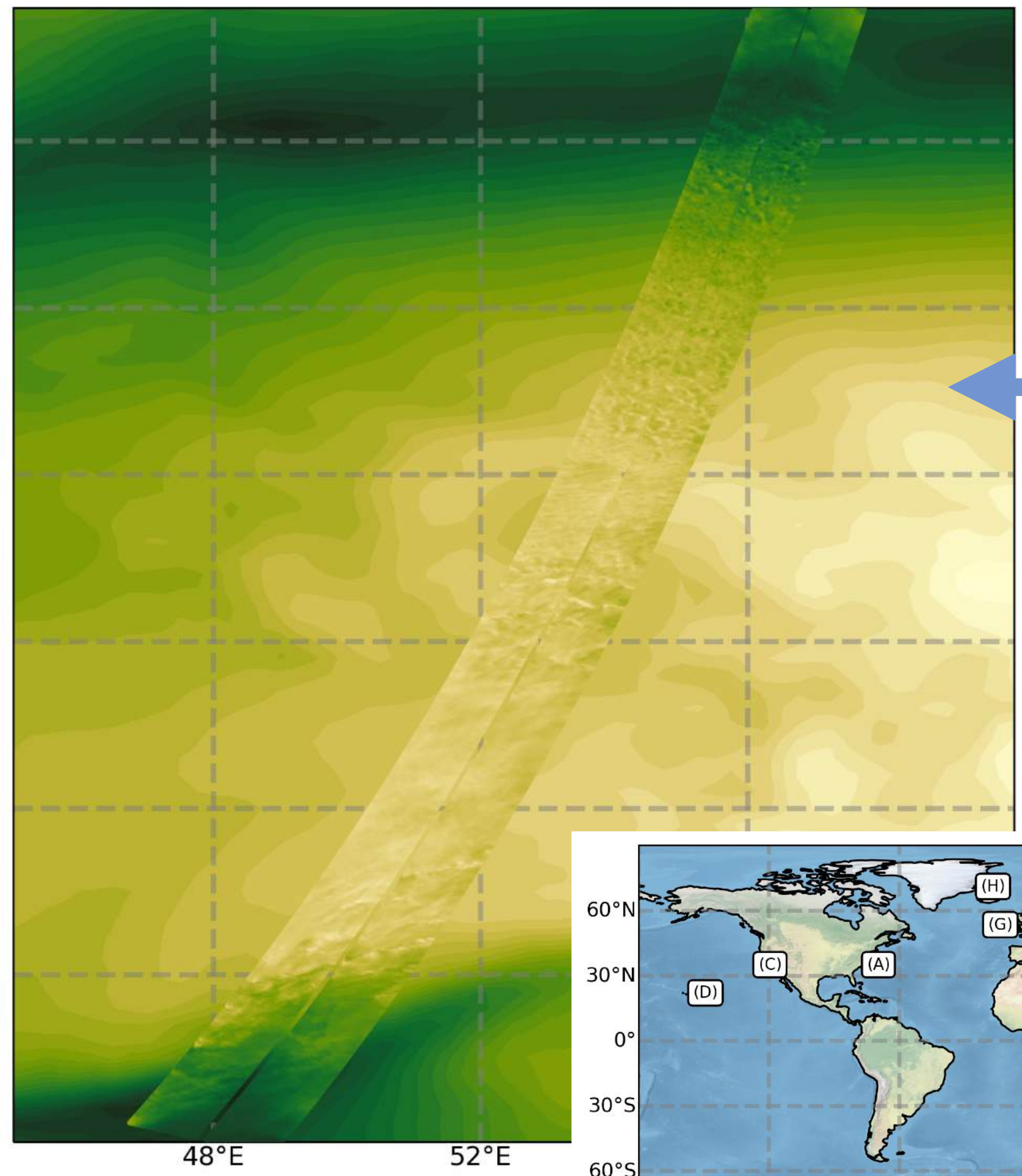
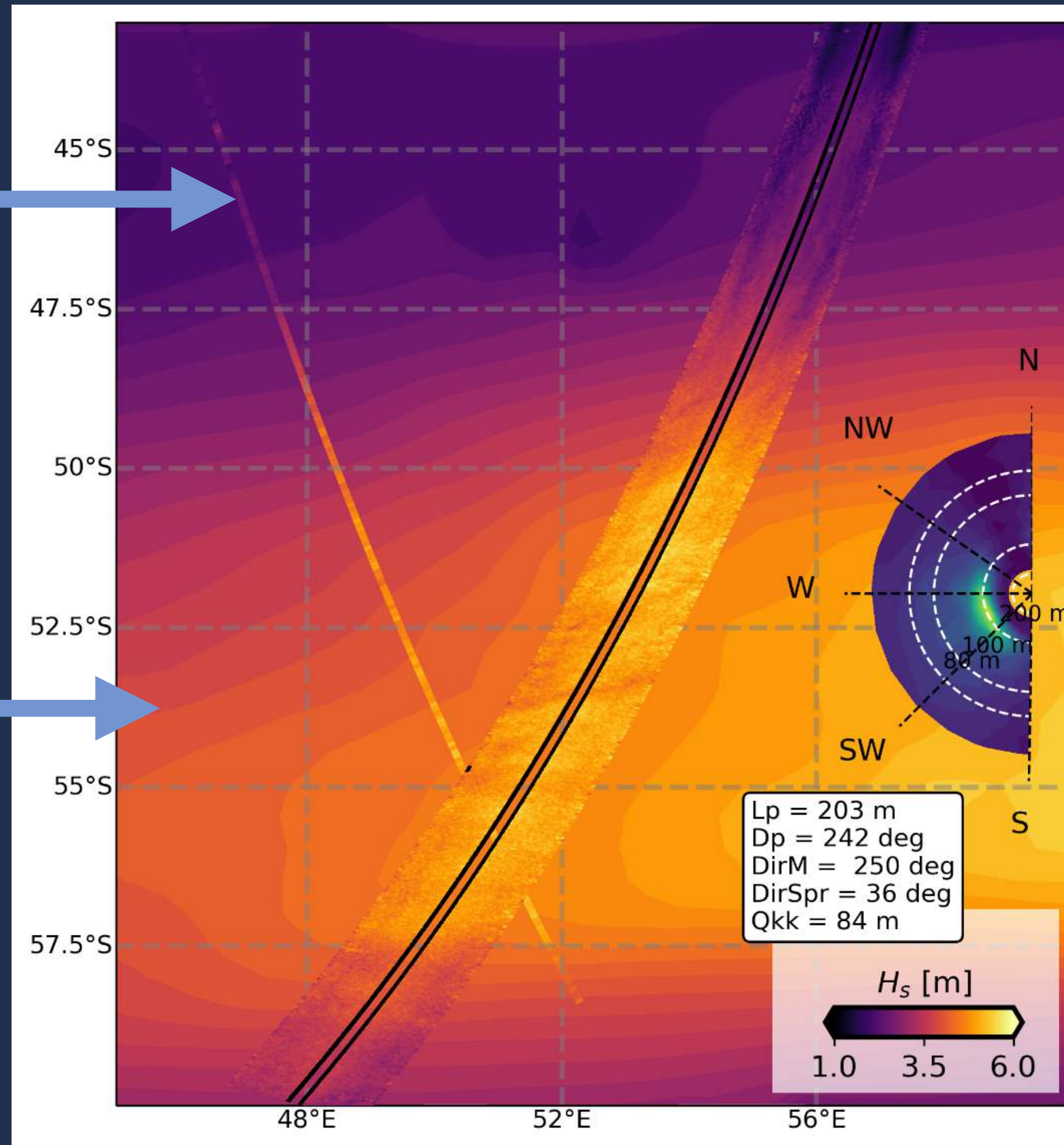
Comparison between MASS and SWOT observations

Waves and winds from SWOT in the Southern Ocean

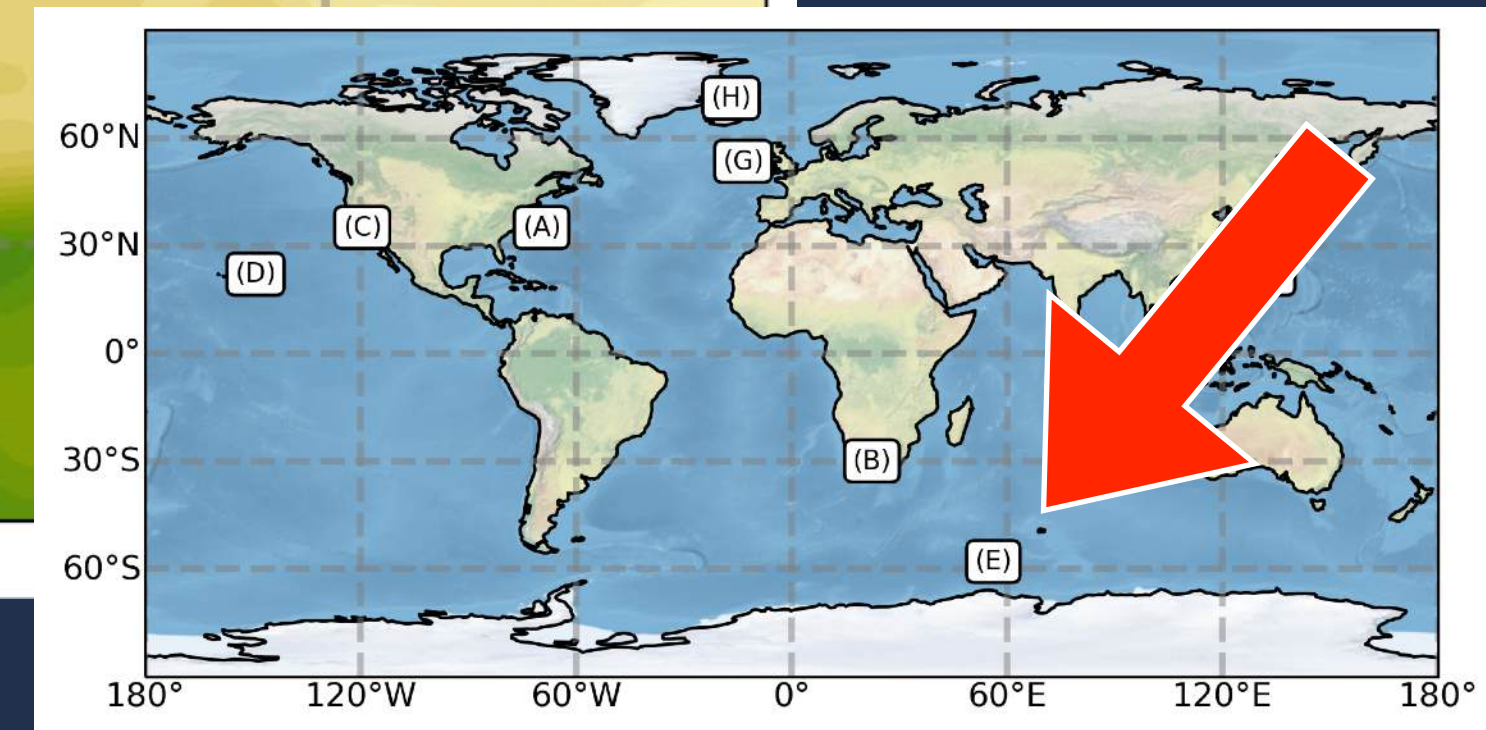
CFOSAT



WW3

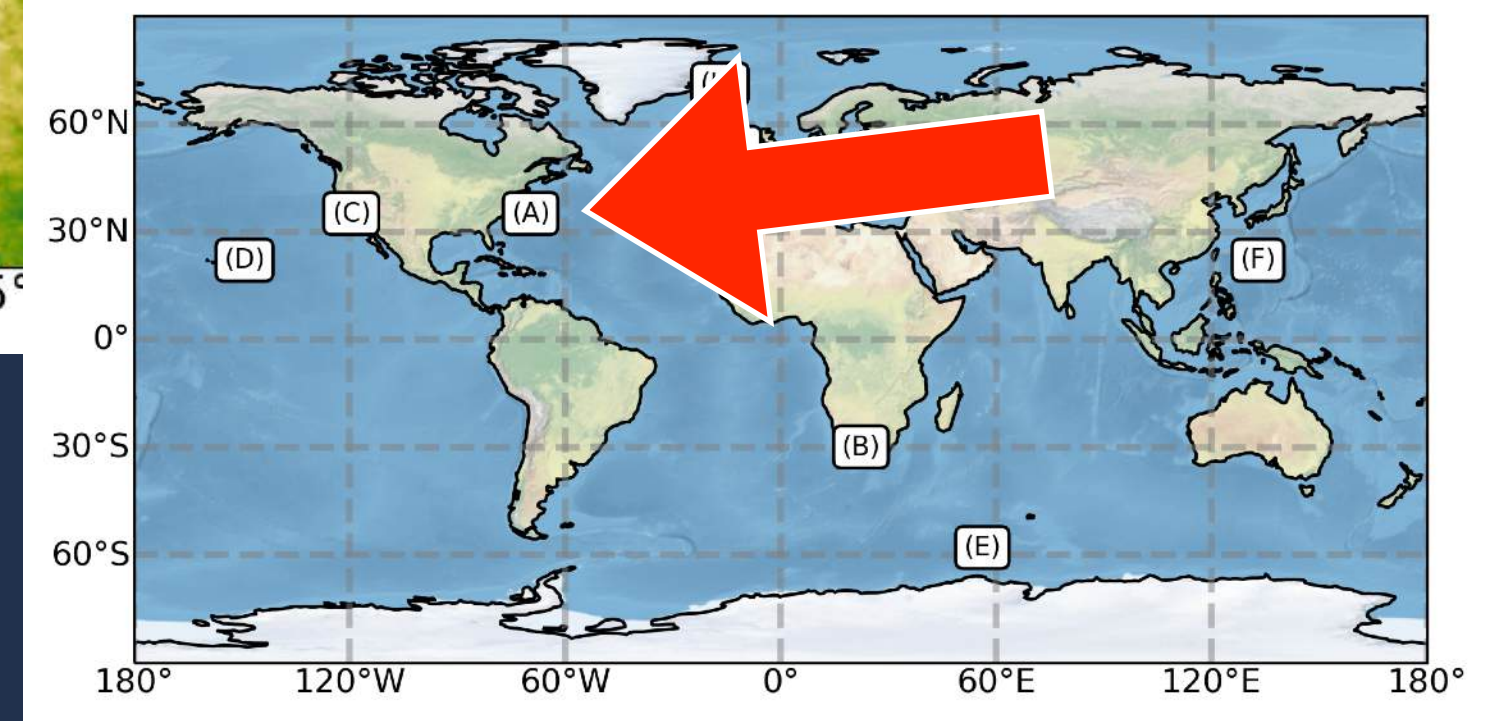
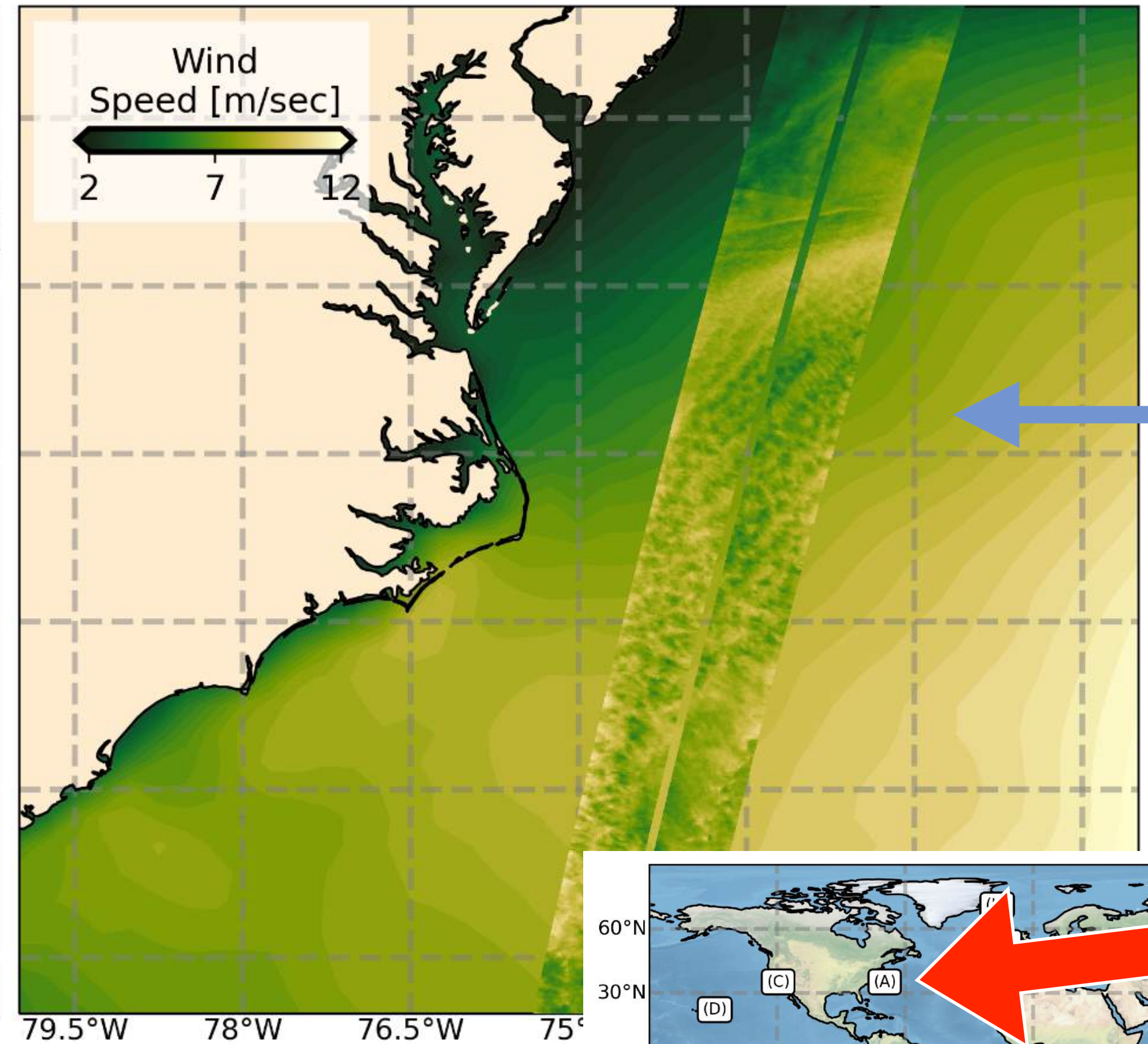
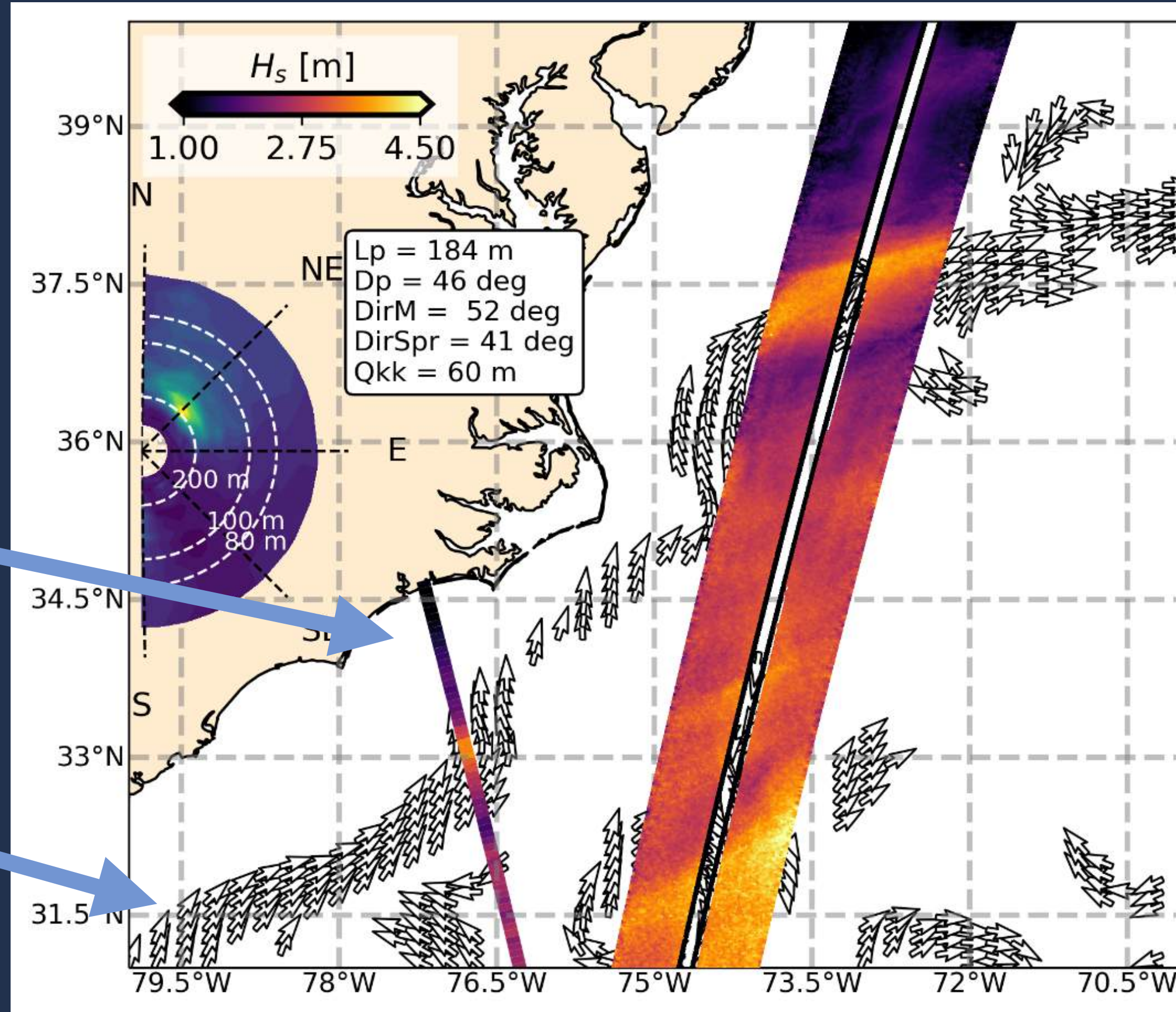


ERA5



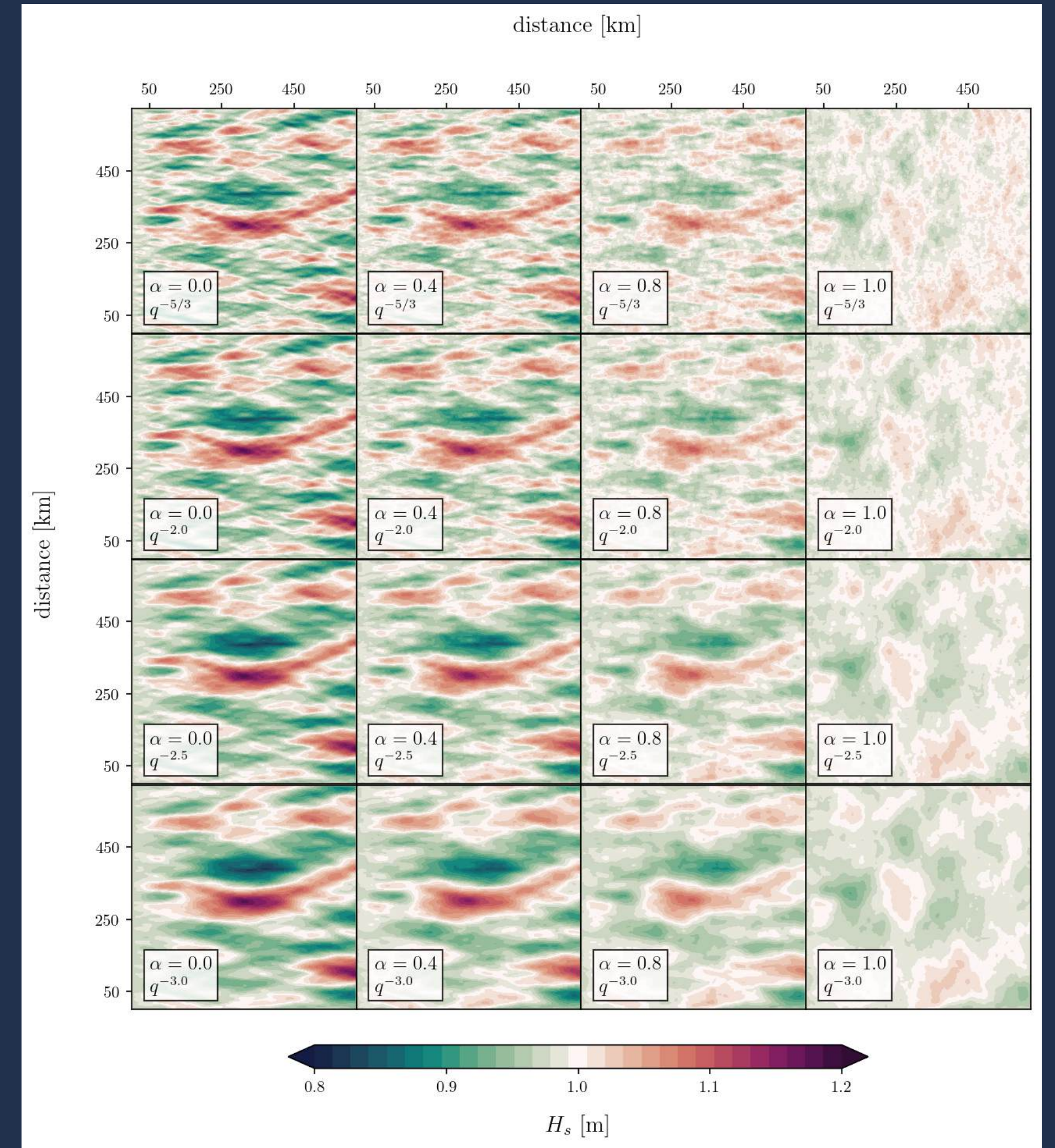
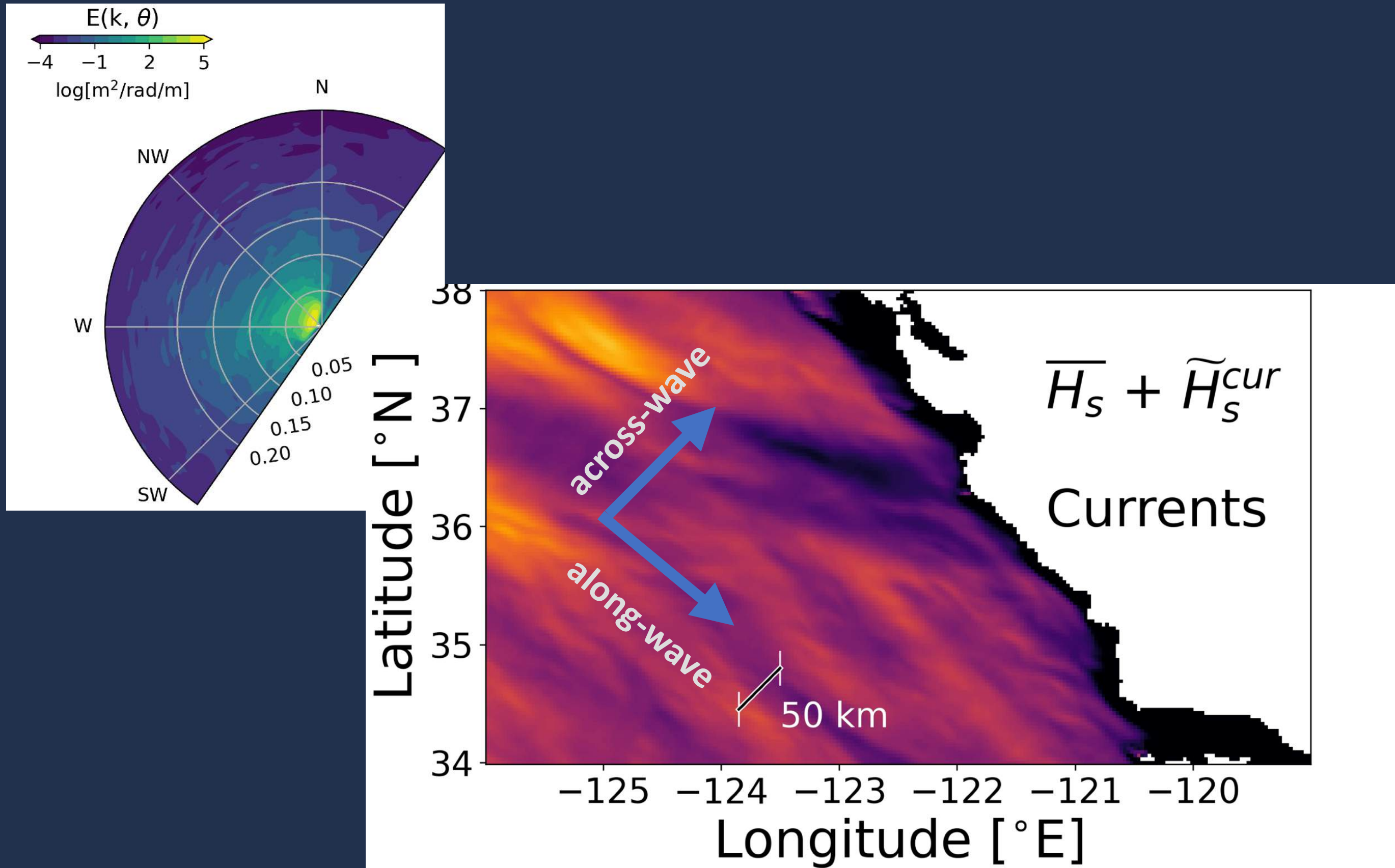
Villas Bôas et al (in prep)

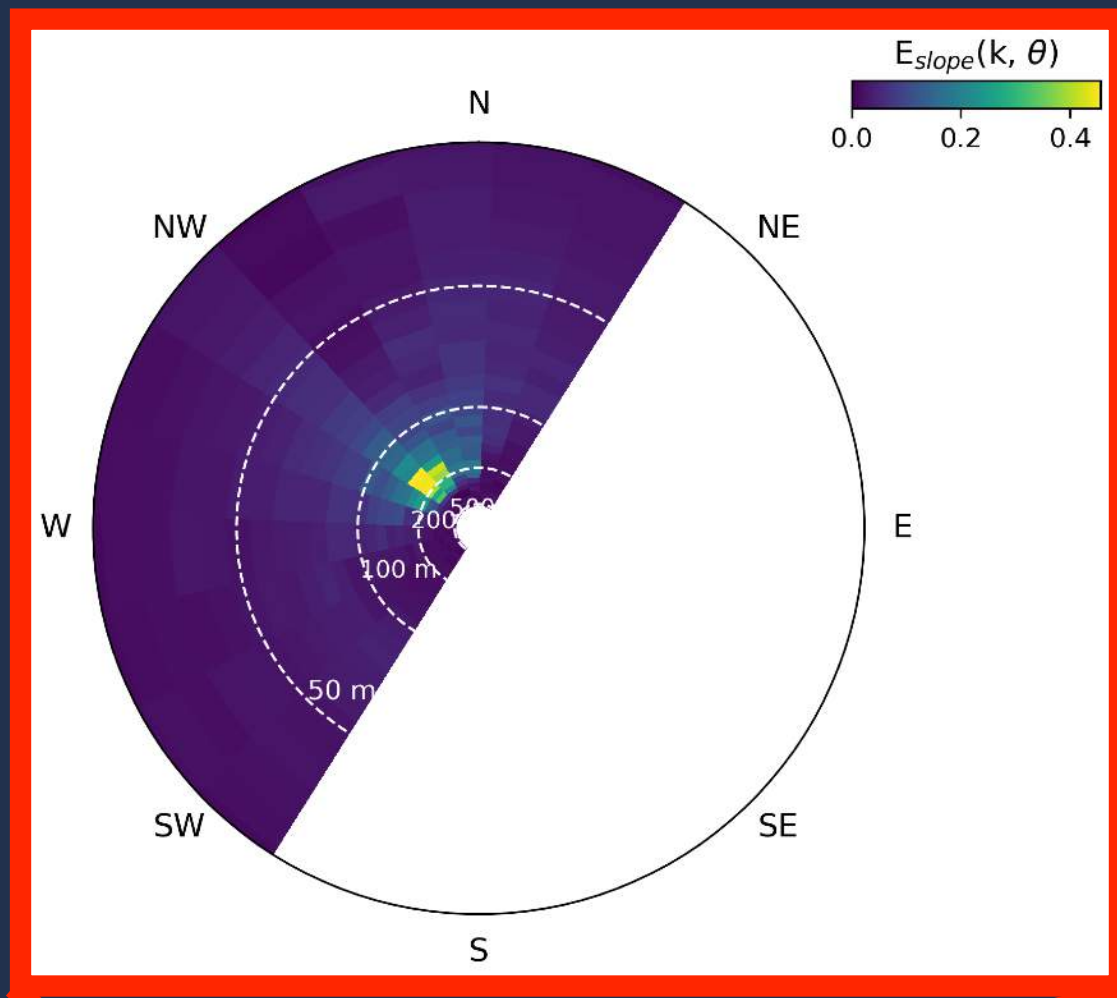
Wind-Wave-Current coupling in the Gulf Stream



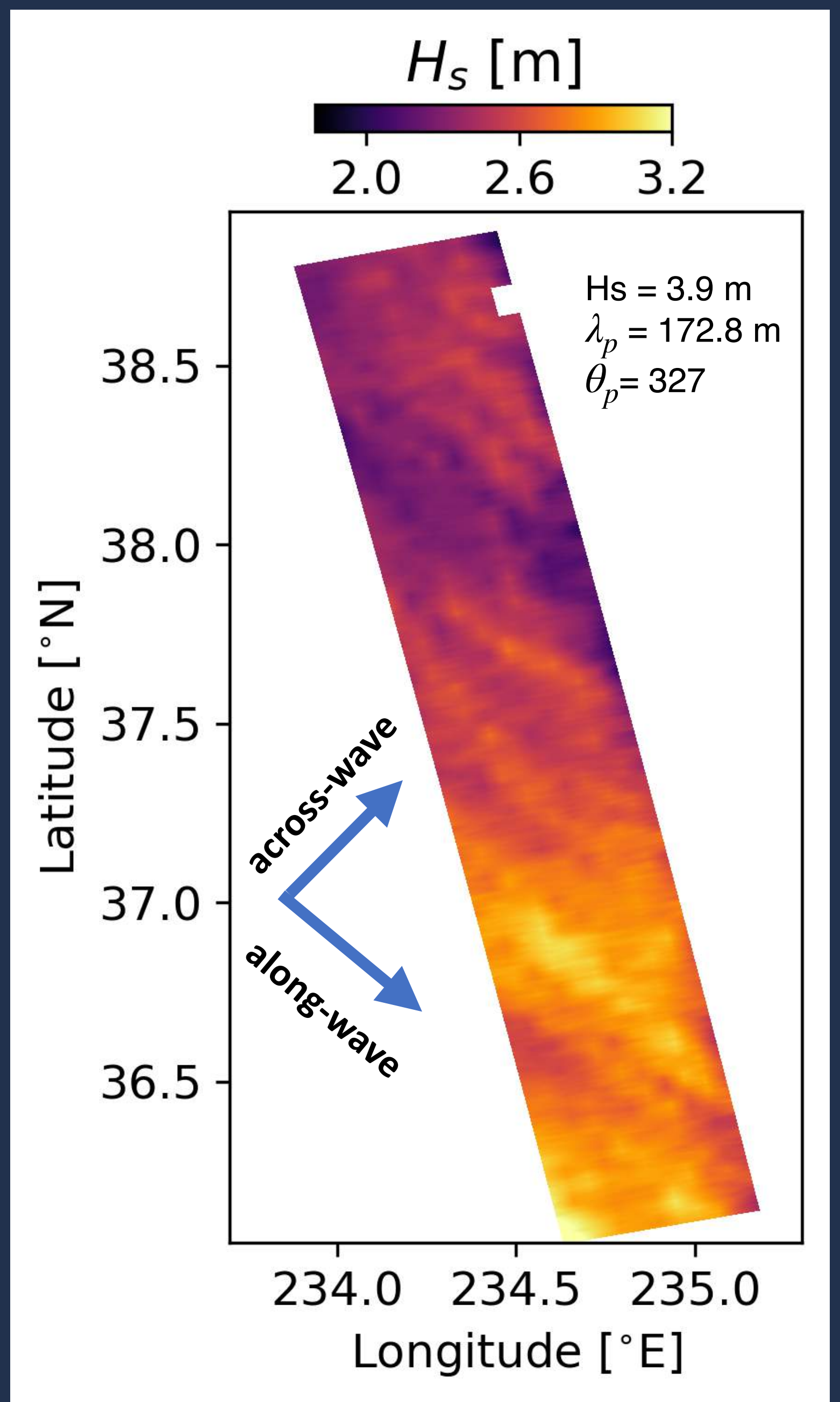
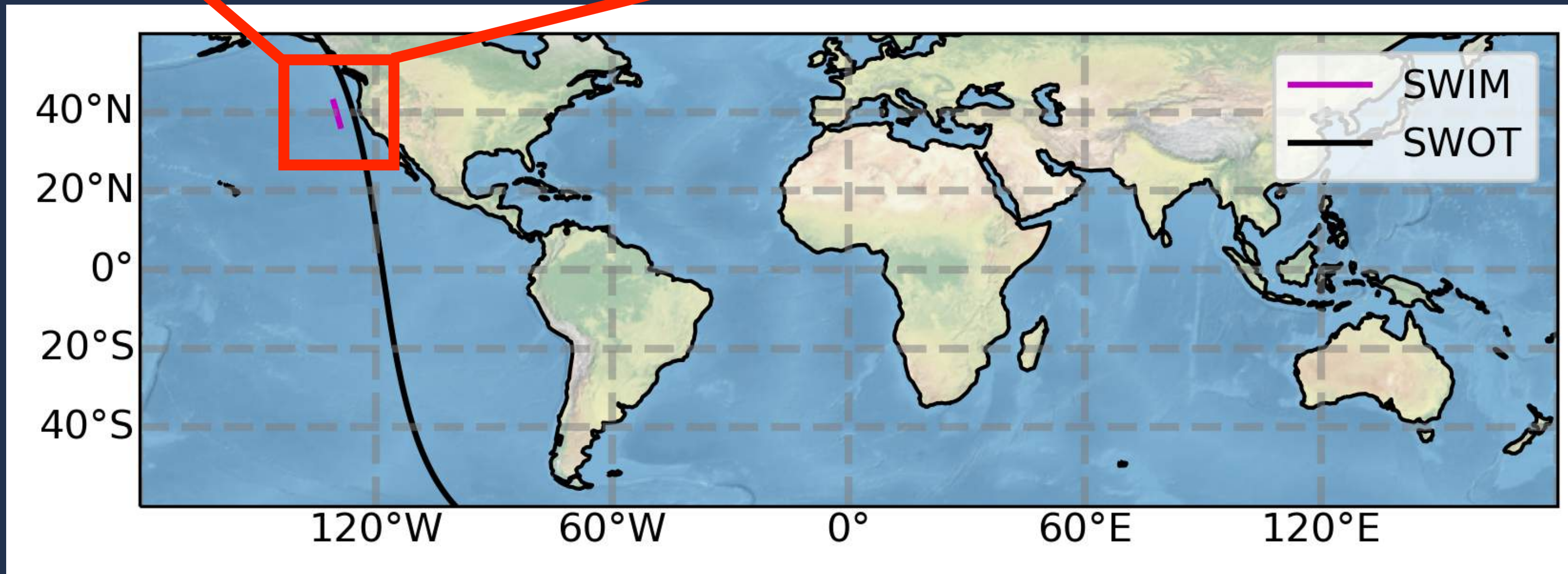
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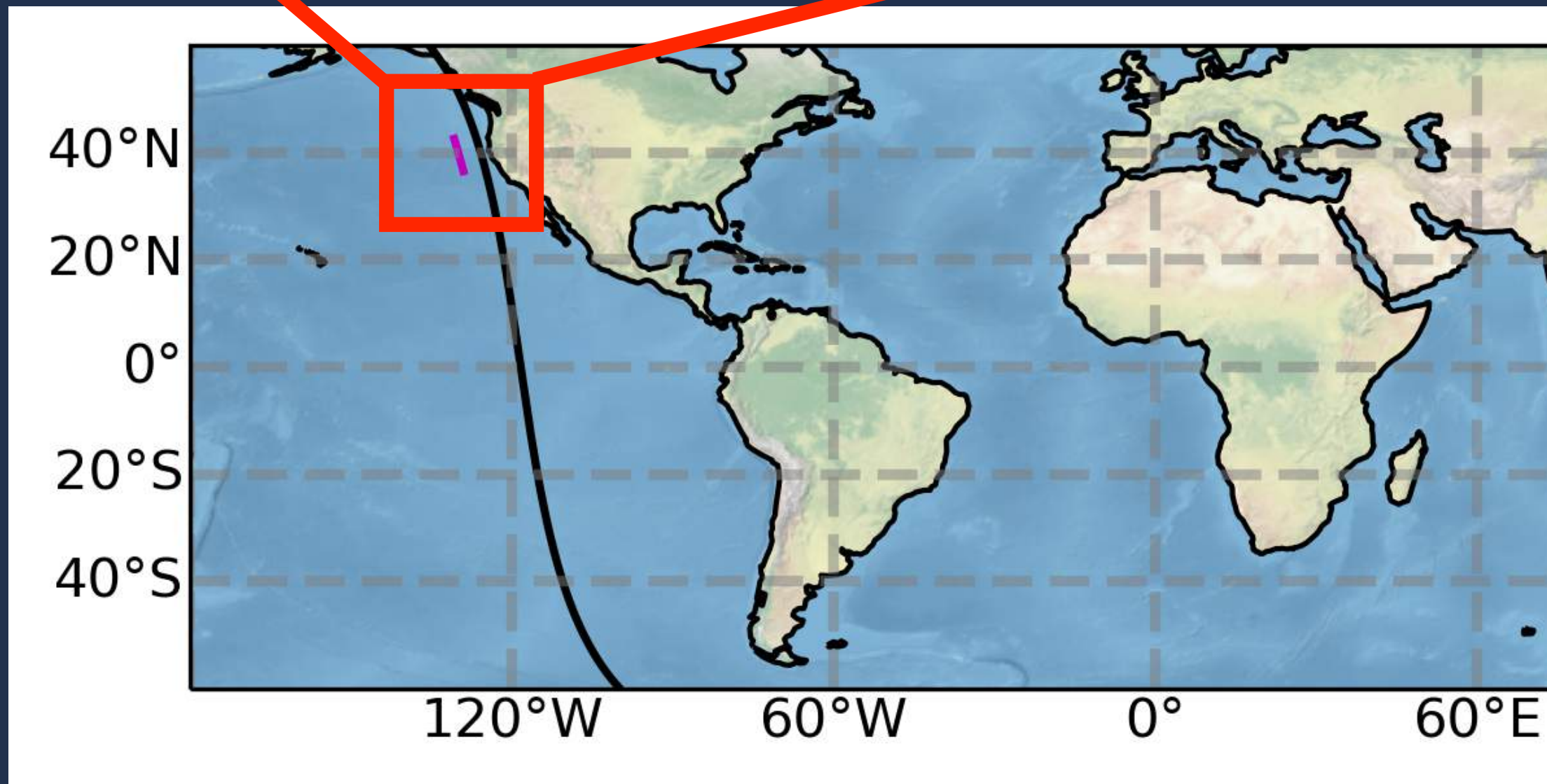
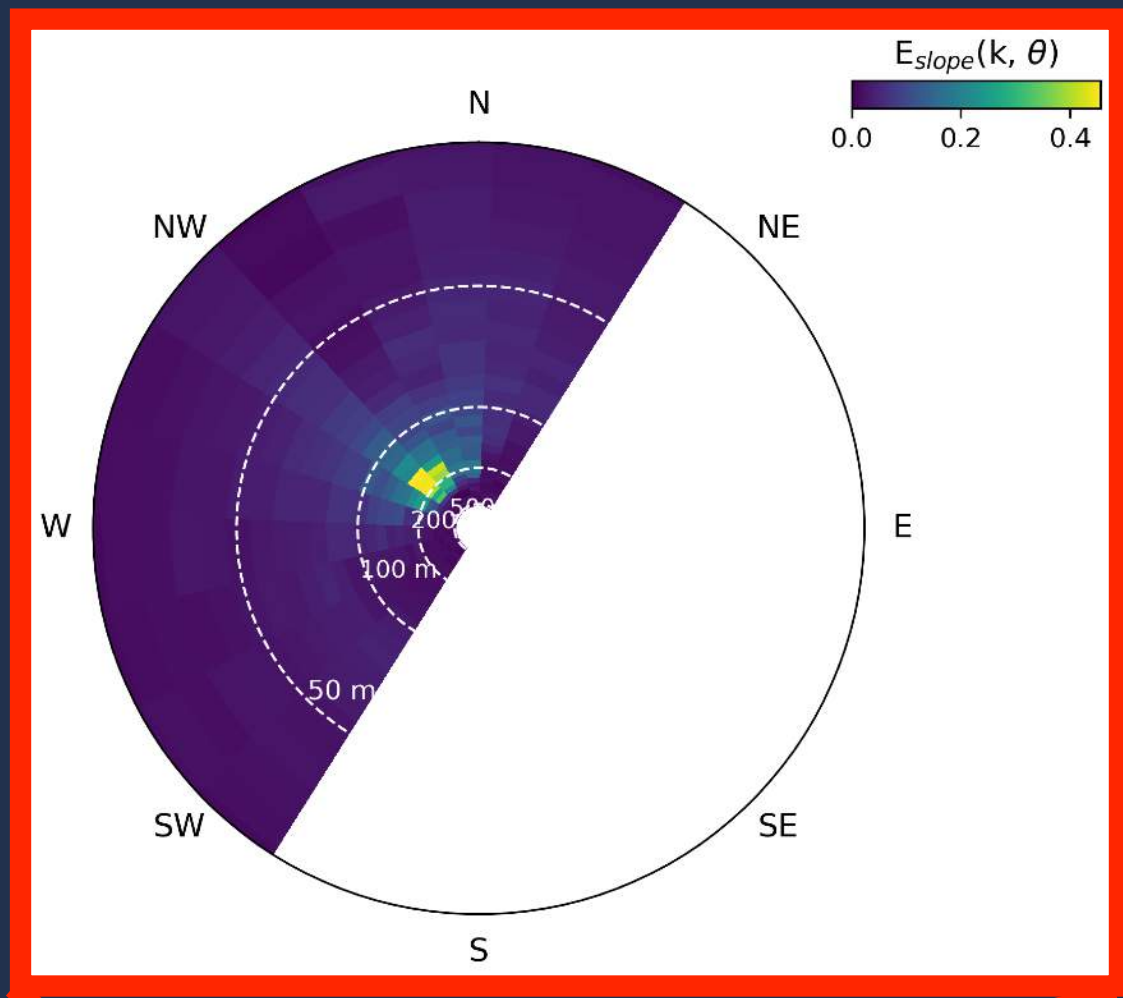
Remember the anisotropy in the models?



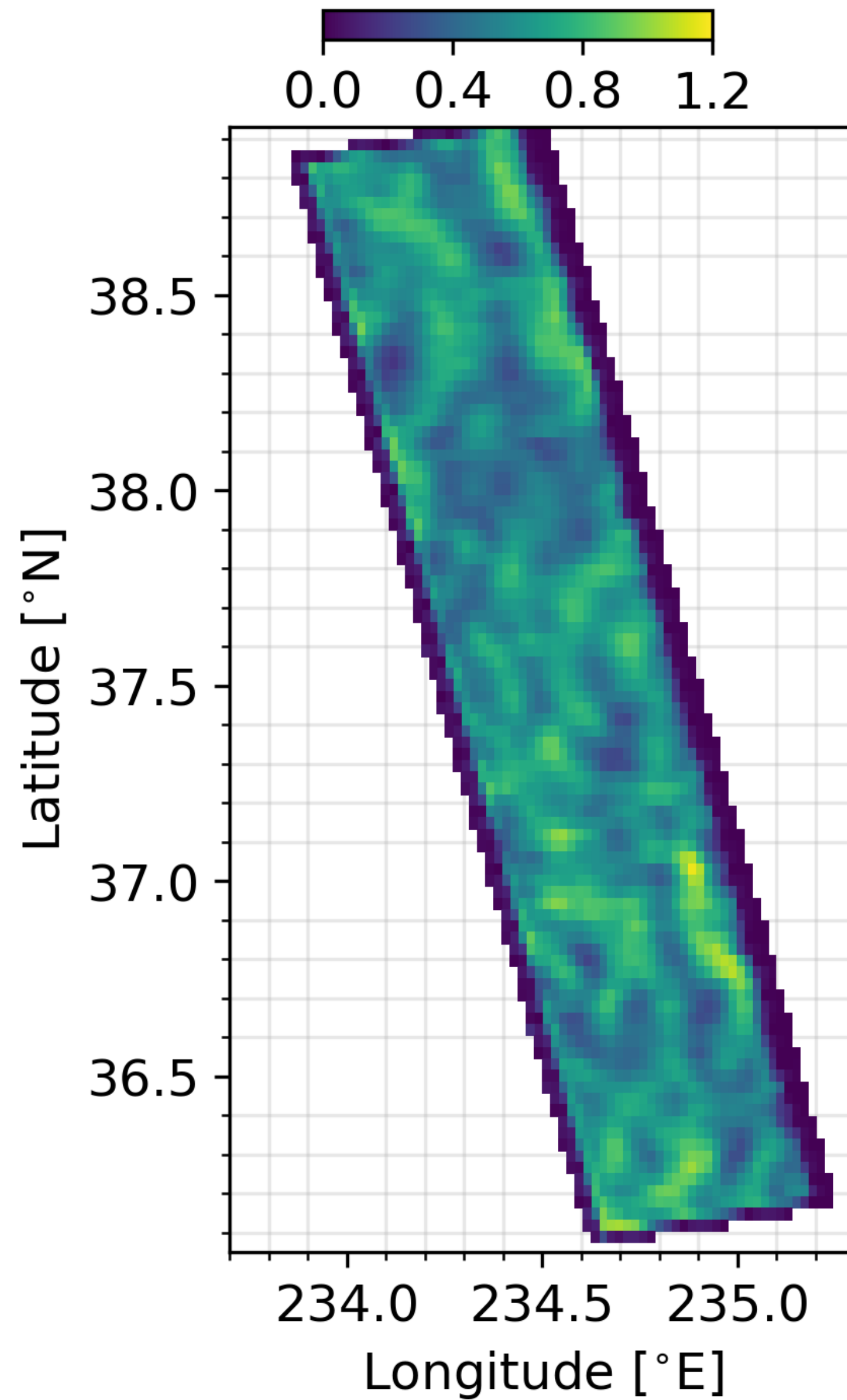


- **SWOT** observations reveal highly **anisotropic H_s** that **agrees** with predictions from **model** and **U2H**

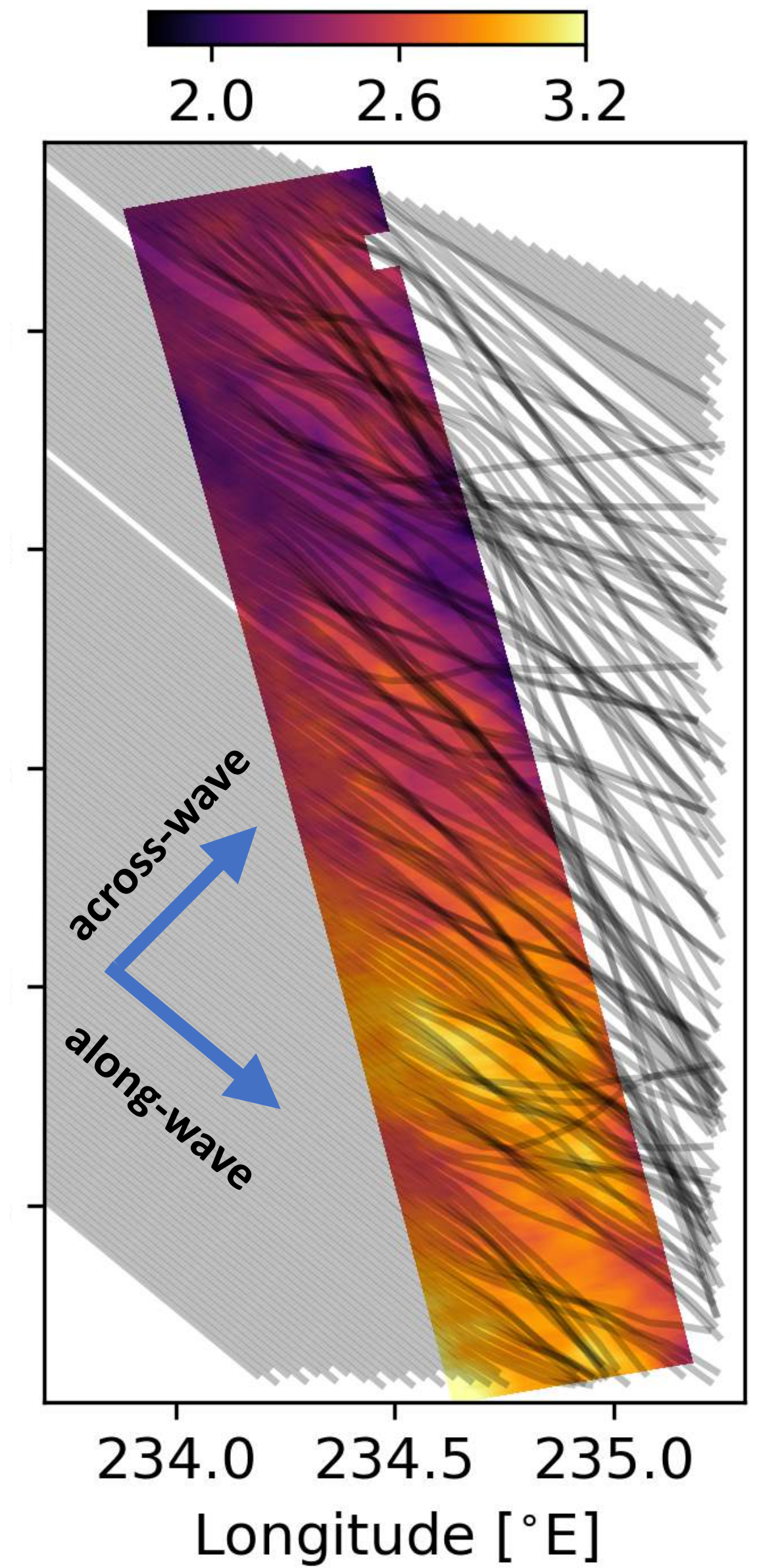




Geostrophic Velocity [m/s]



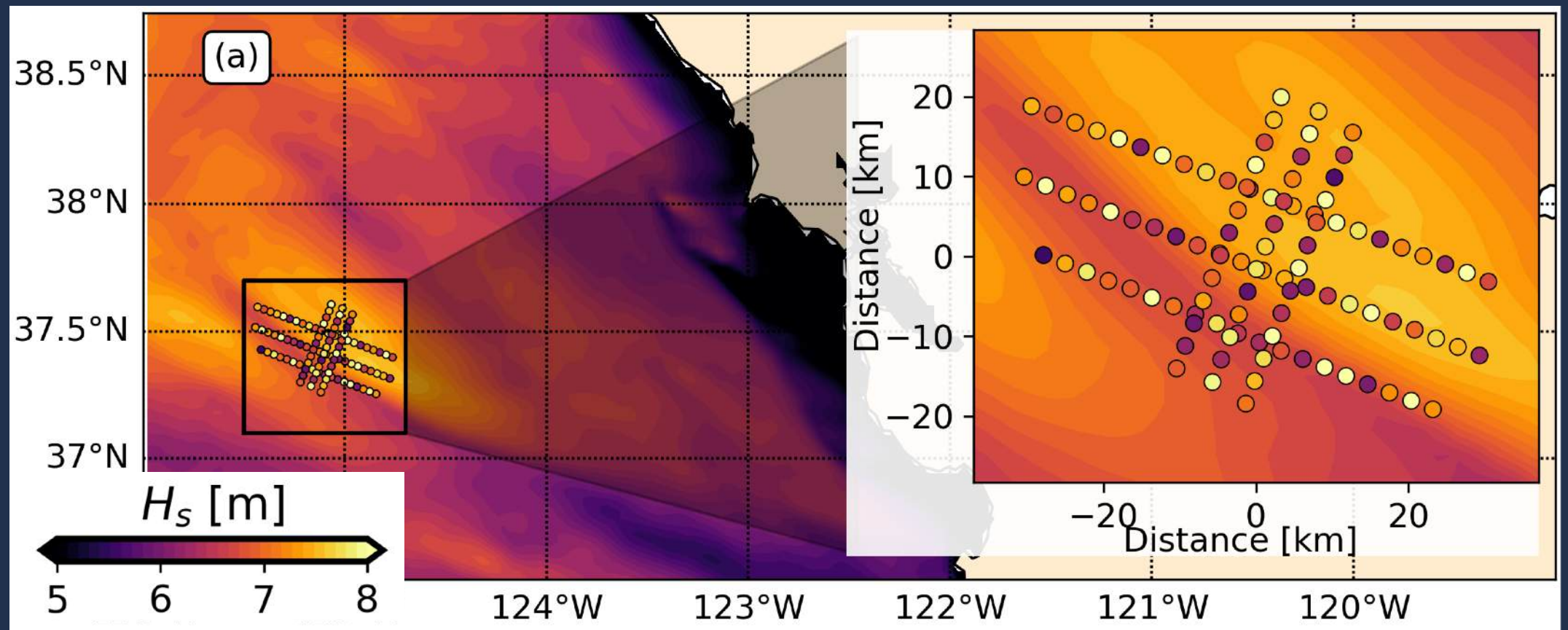
H_s [m]



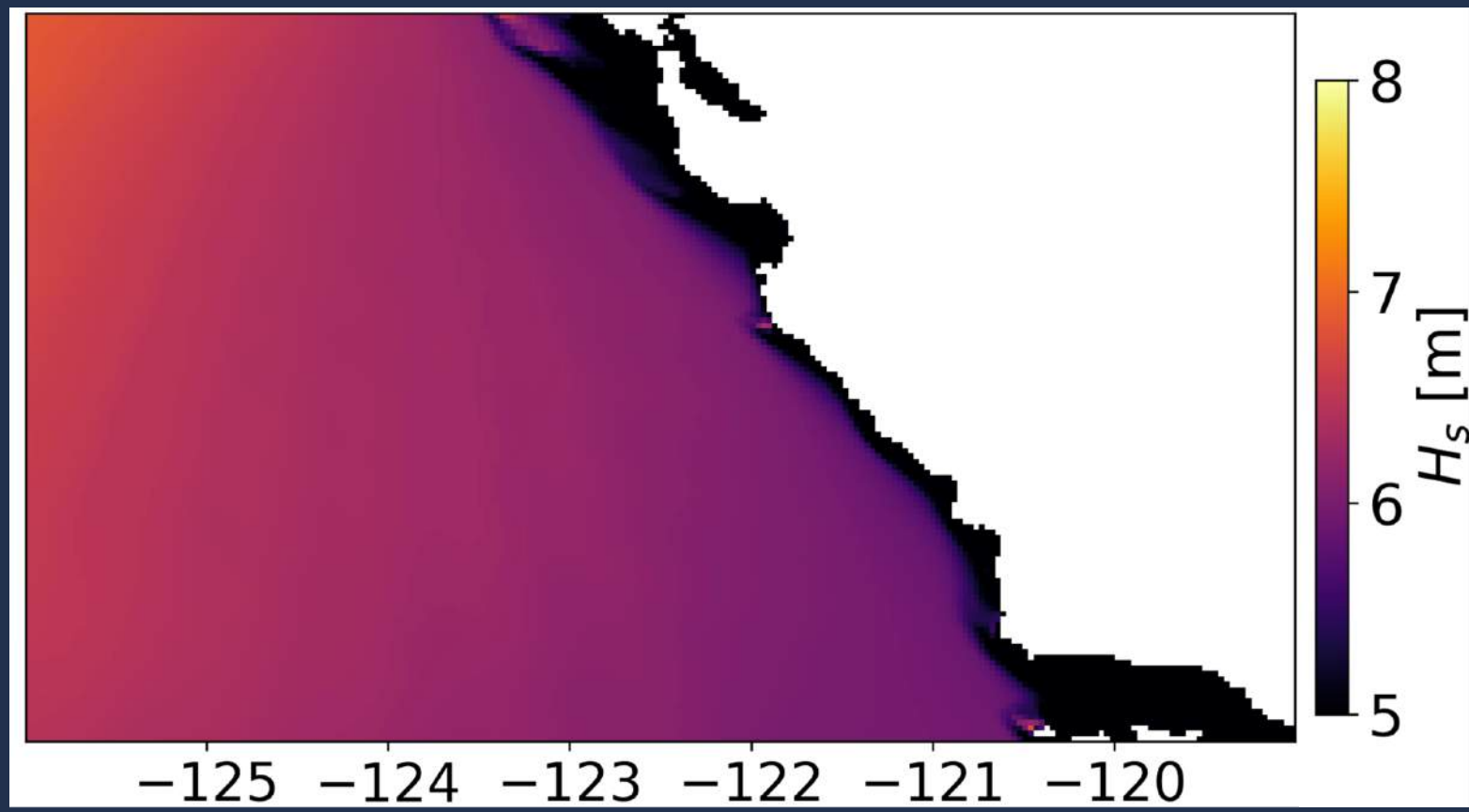
Take home:

Take home:

✓ The wave field looks like this



✗ Not like this





We're hiring!

Mines Oceanography has 1 PhD and 2 postdoc positions open in air-sea interaction

villasboas@mines.edu



MINES IS NUMBER 5!!

The latest US News and World Report ranking of Geophysics and Seismology graduate programs shows MINES Geophysics at #5!

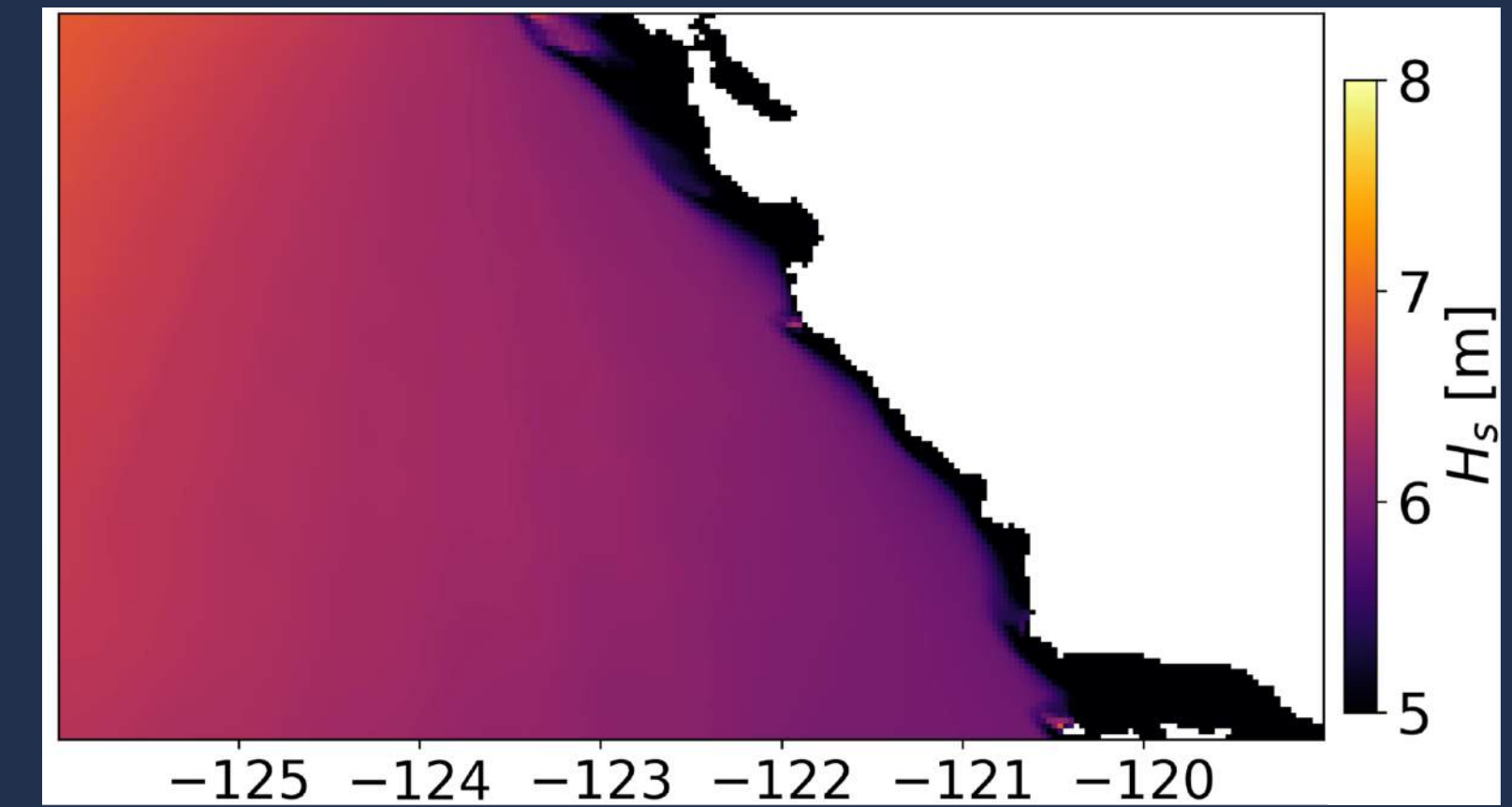
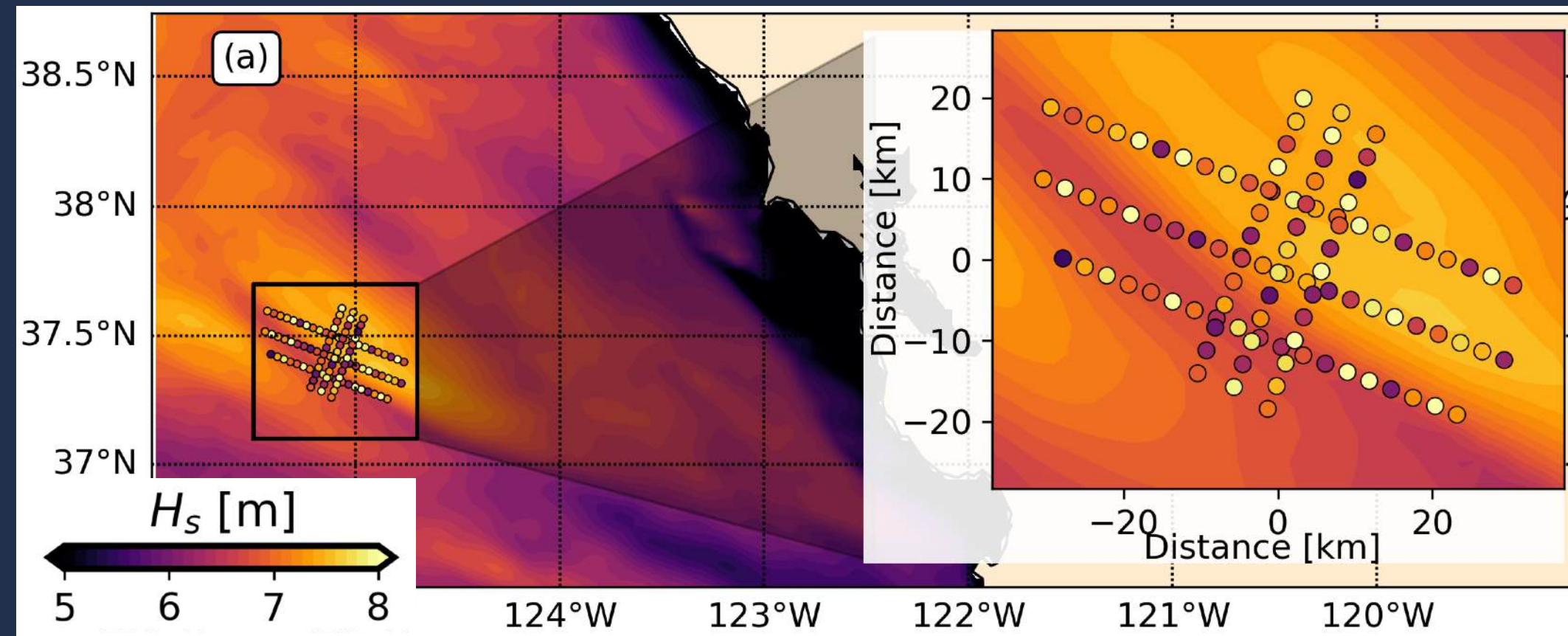
1. Caltech
2. Berkeley
3. MIT
4. Stanford
5. **MINES**



Take home:

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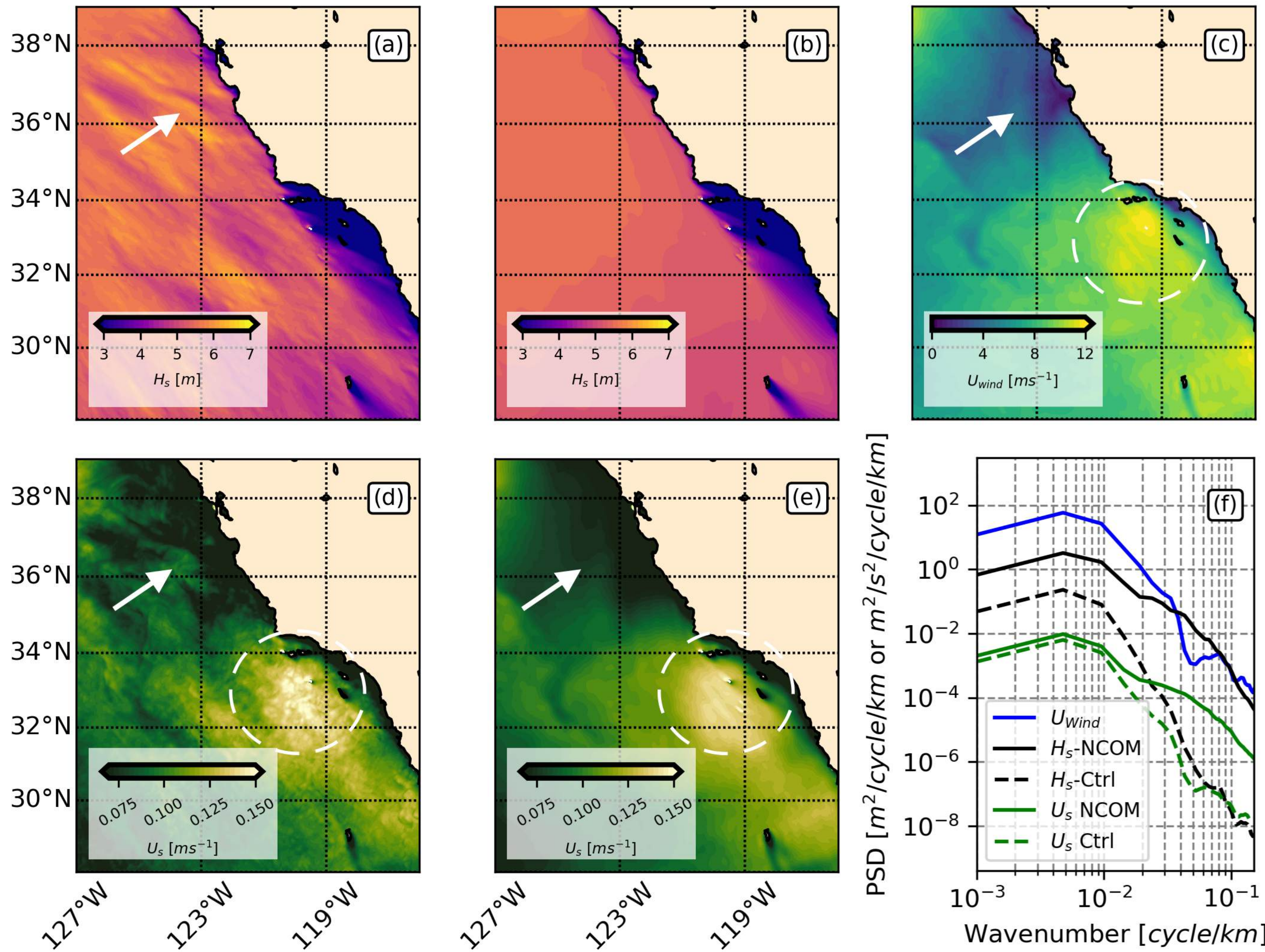


- ▶ How do current-induced **sea state gradients feedback** into the coupled **Earth system**?
- ▶ Do these relatively **small scale variability** have a net **effect on large (climate) scales**?
- ▶ Should we be thinking about this when developing **wave-aware parametrizations** for **coupled models**?
 - ▶ We focused on H_s here, but some of this can be extrapolated to Stokes drift, mss, etc.
- ▶ Should we be thinking about this when **developing GMF's** and/or using wave model output to constrain **satellite obs**?

Backup

Numerical modeling suggests that:

- The spatial variability of Stokes drift results from a combined response to wind forcing and amplitude/frequency modulation due to currents
- What is the relative importance of refraction and bunching (concertina)?*



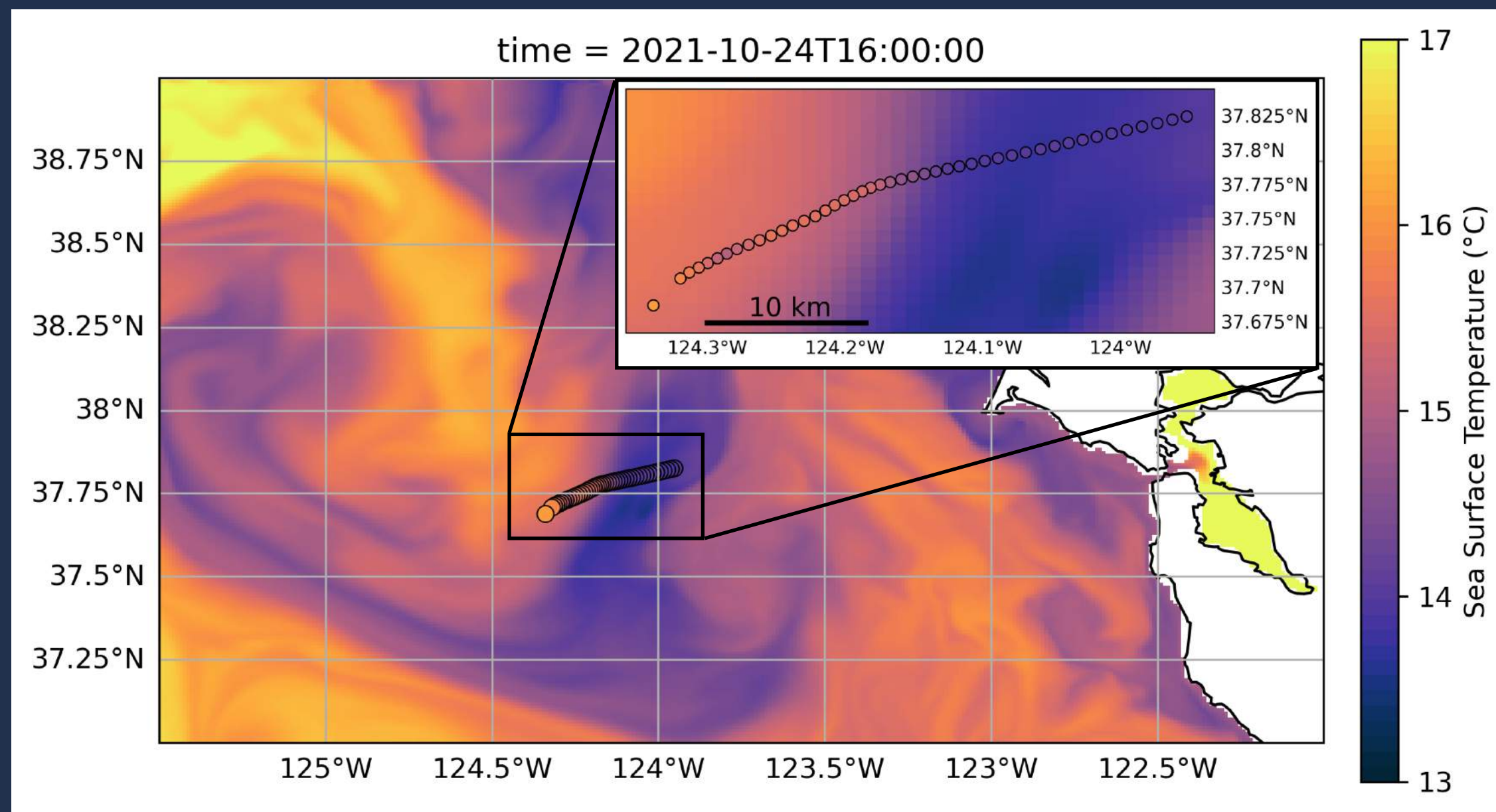
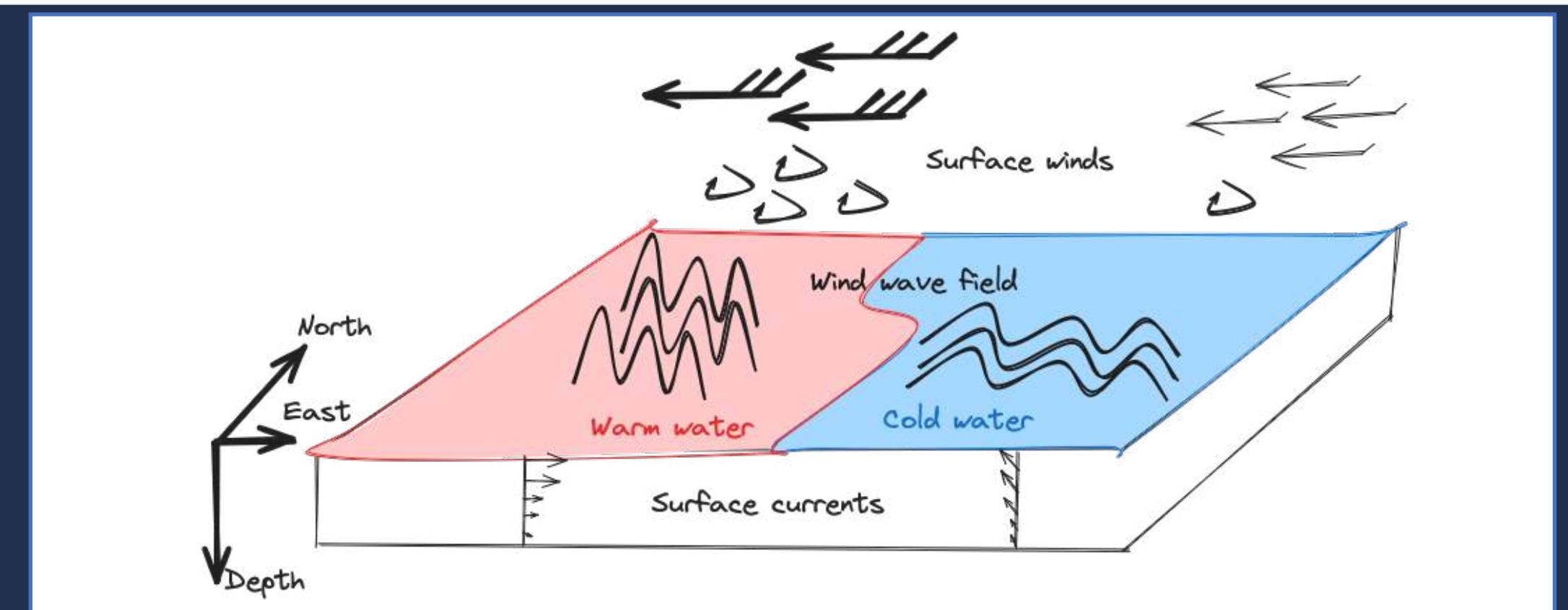
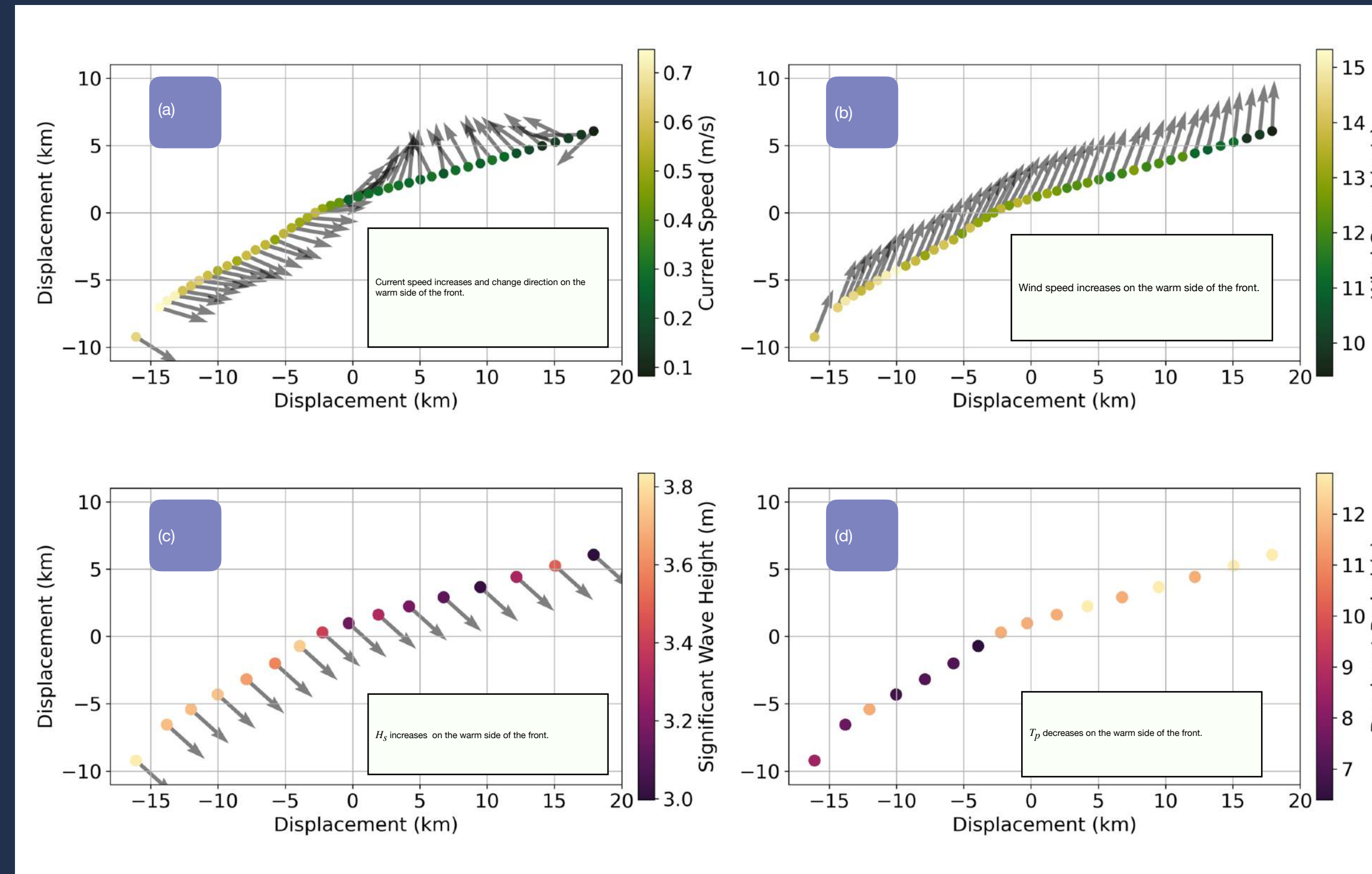


Figure 4: Sea surface temperature from the Navy Coastal Ocean Model (NCOM) with Salidrone sea surface temperature overlaid. The inset provides a zoom in the vicinity of a temperature front.



The **U2H** map: theory corroborates numerical results

- Maps the surface current (“**U**”) to H_s (“**H**”) anomalies

Assumptions:

1. Scale separation between waves and currents.
2. No sources/sinks of action.
3. Weak current $\rightarrow \varepsilon = U/c \ll 1$

$$\partial_t A + \nabla_k \omega \cdot \nabla_x A - \nabla_x \omega \cdot \nabla_k A = 0$$

magic asymptotics
tricks



$$\hat{h}_s(\mathbf{q}) = \hat{L}(\phi) \cdot \hat{U}(\mathbf{q})$$

Wang, Villas Bôas, Young, and Vanneste [JFM 2023 – Part A accepted. Parts B-C coming soon.]

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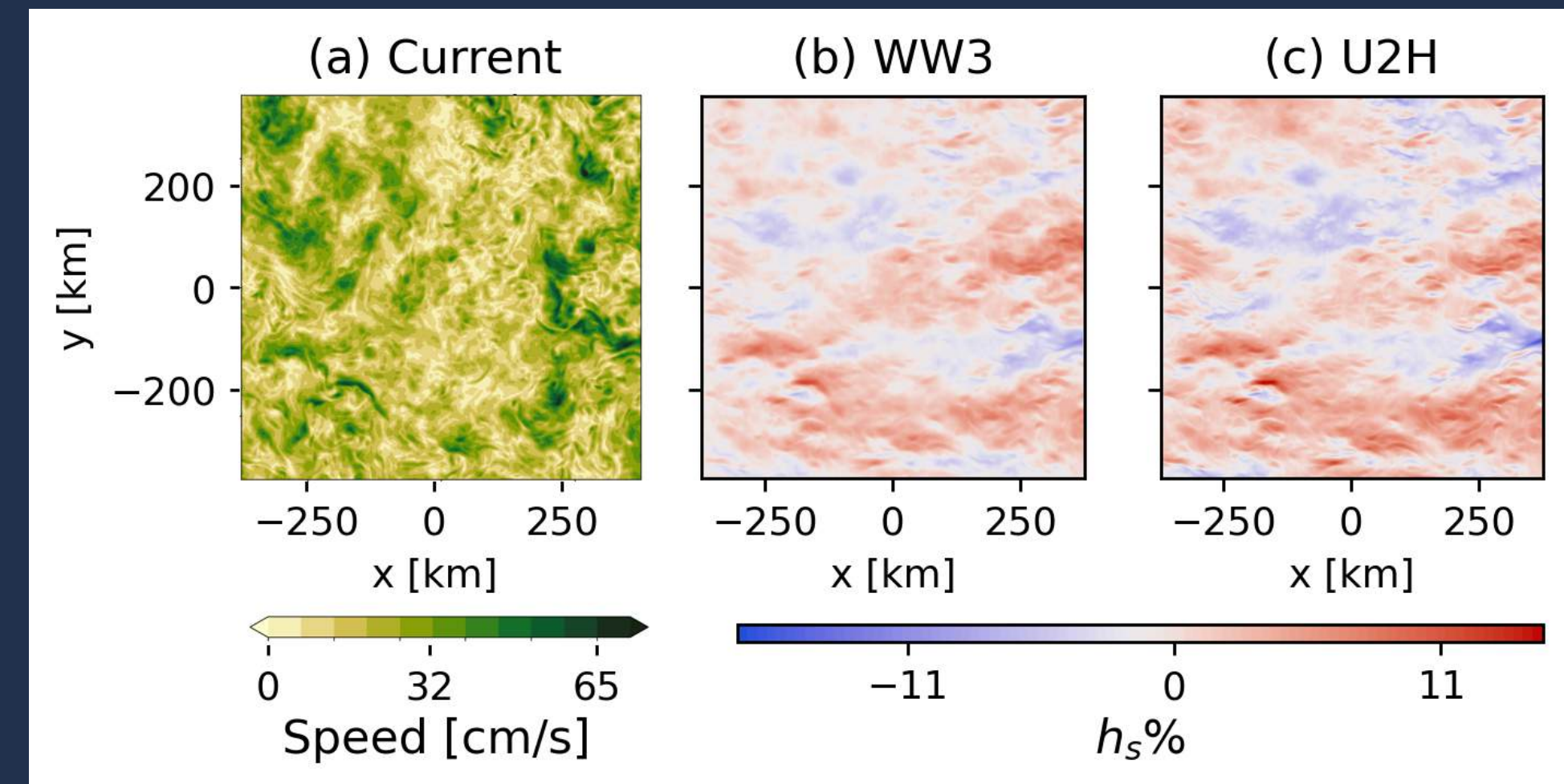
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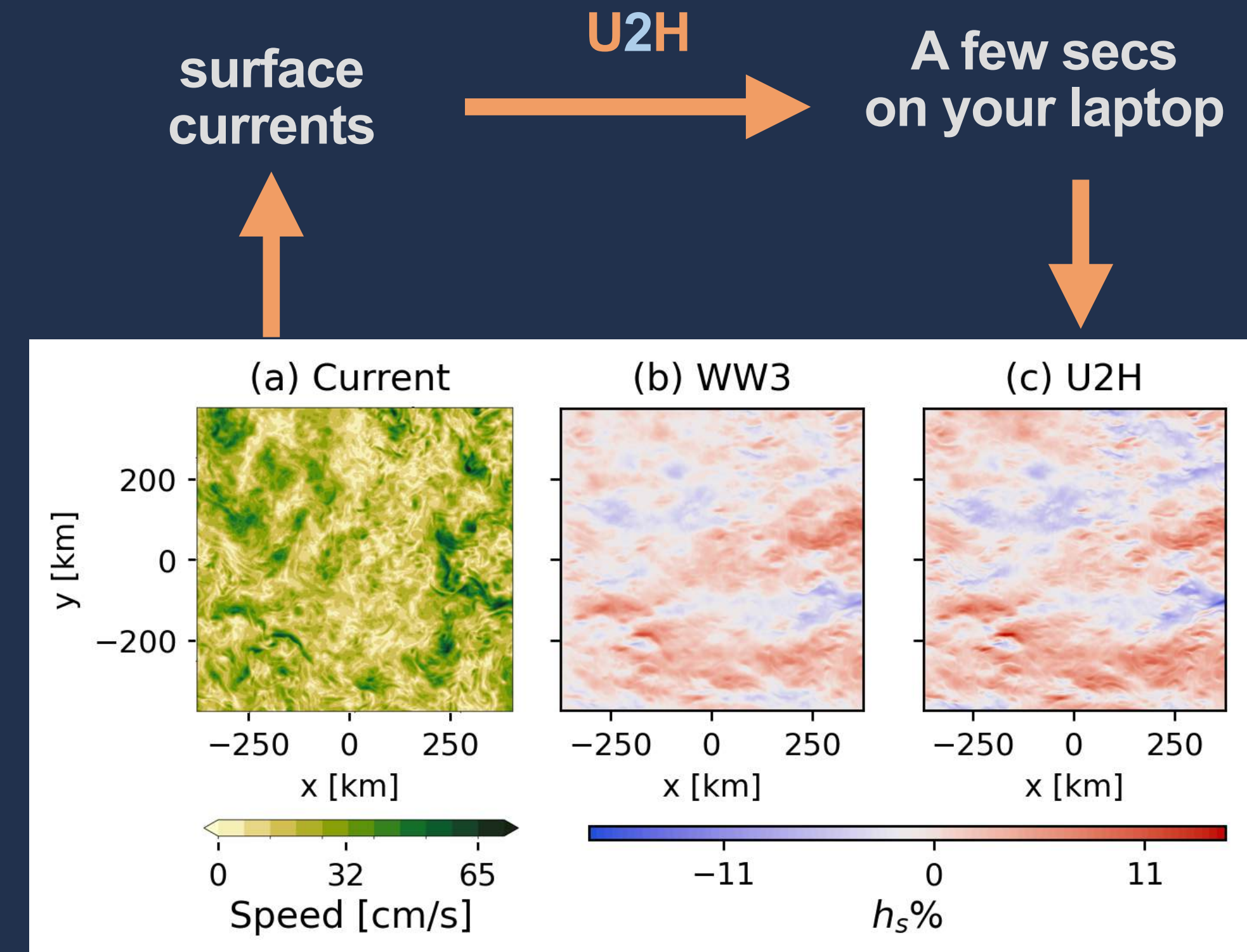
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