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

Bia Villas Bôas

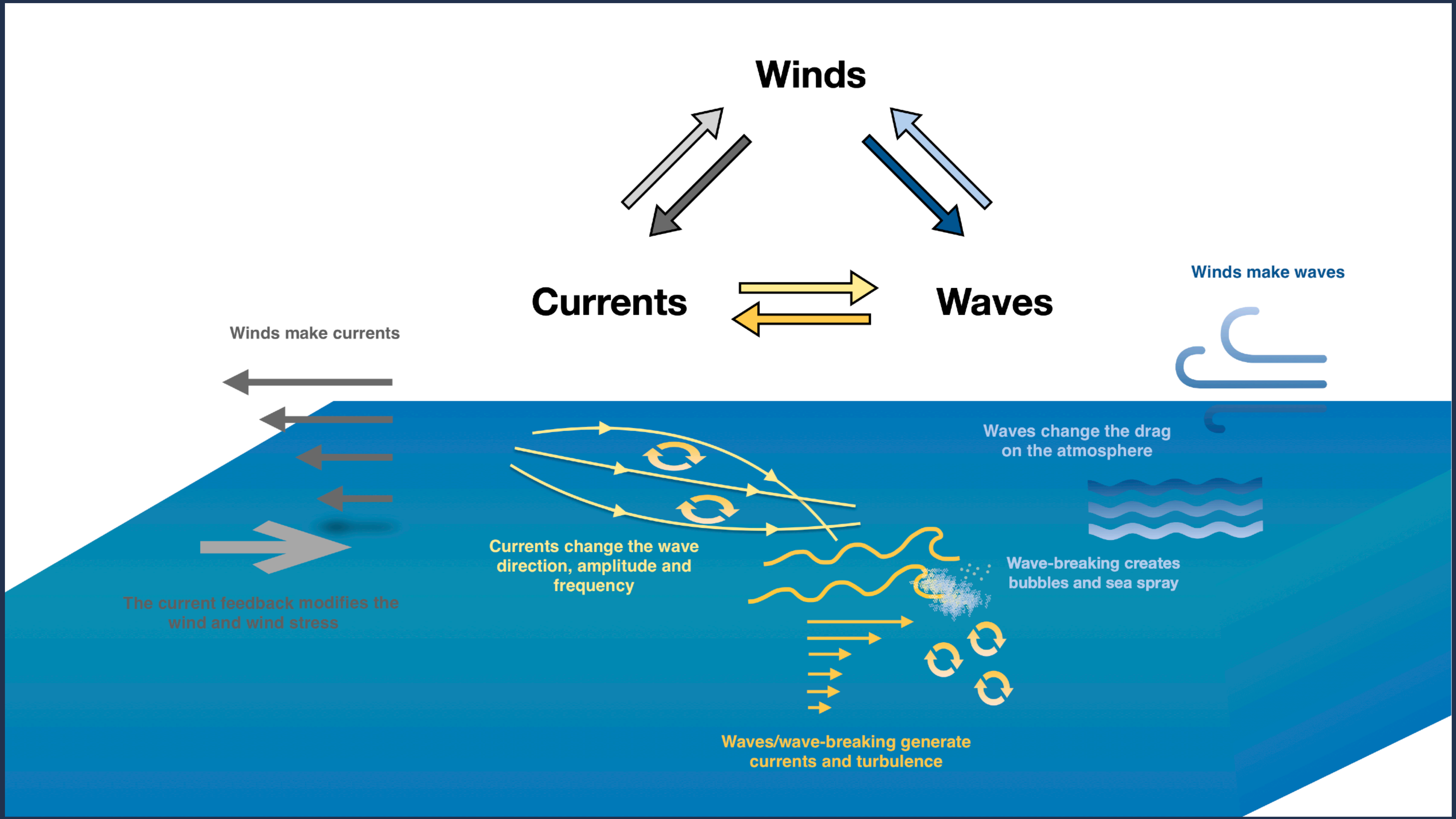
Team: *Gwendal Marechal (Mines), Matt Mazloff and Rui Sun (Scripps)*

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

MINES OCEANOGRAPHY

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

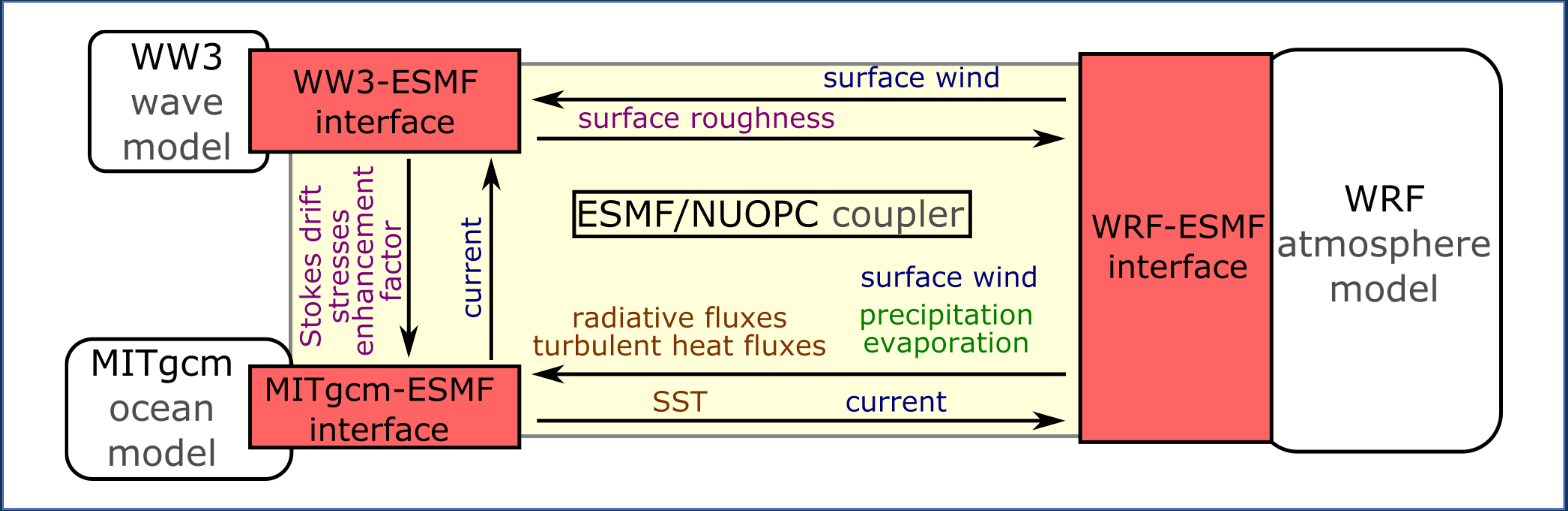
- Waves impact momentum, energy, heat, and gas fluxes
- Enhance mixing (Langmuir turbulence)
- Affects pathways of pollutants, plastics, ice, and algae.
- Impact the retrieval and interpretation of remote sensing measurements



Villas Bôas and Pizzo (2021)

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

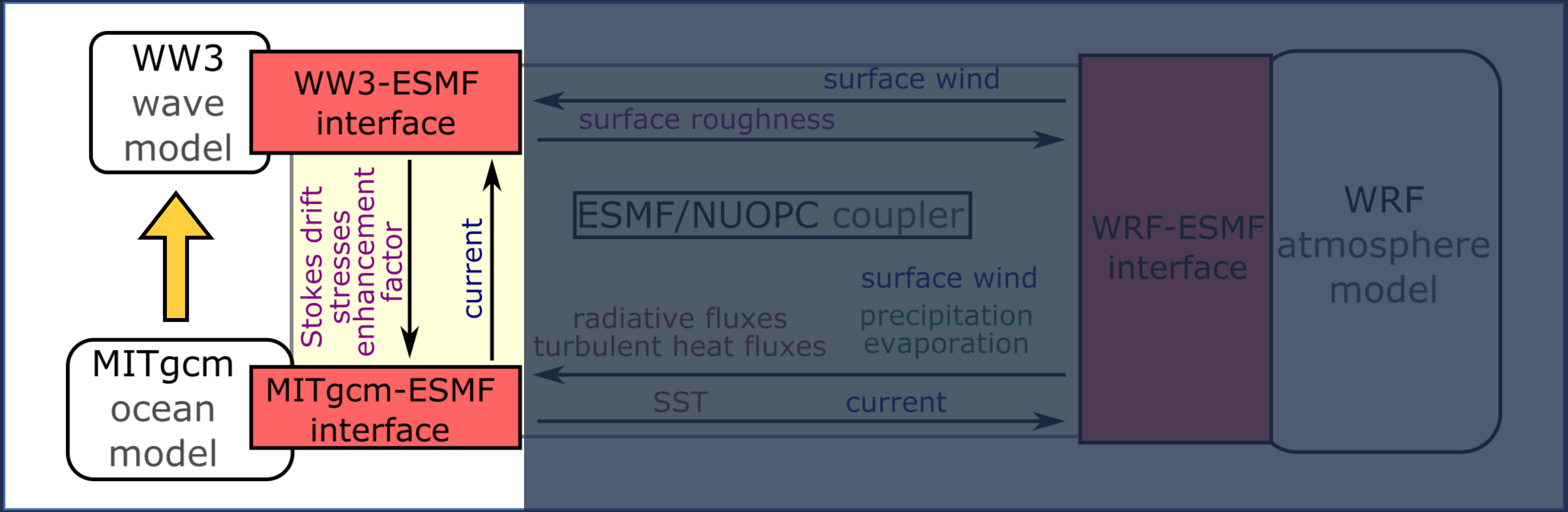
The SKRIPS model framework (Sun et al., 2021)



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

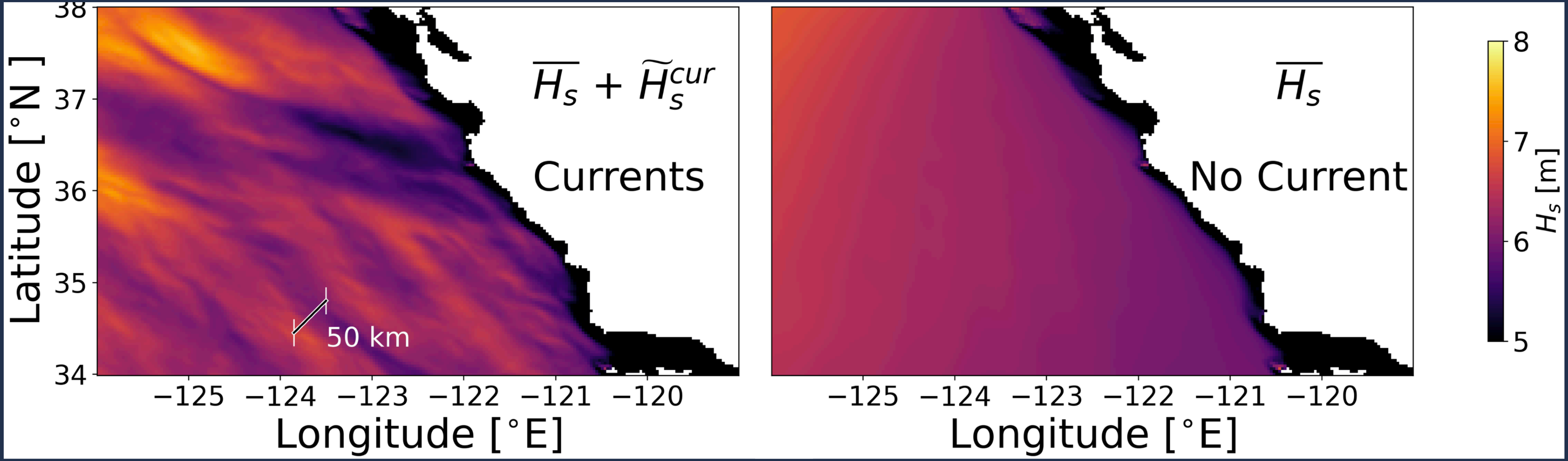
Waves, currents, and winds are **coupled**

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



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

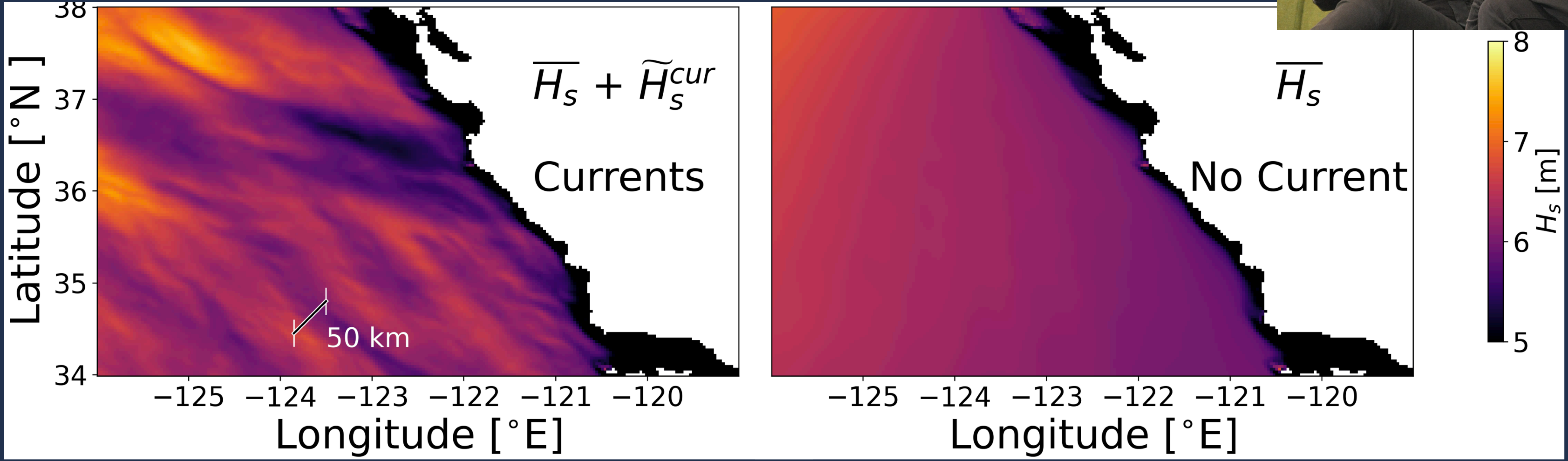
Models suggest that the **spatial variability of Hs** at scales between 10-100km is **driven by currents**



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

The spatial variability of H_s is highly dependent on the nature of the flow

Villas Bôas et al, (2020); Villas Bôas and Young (2020)

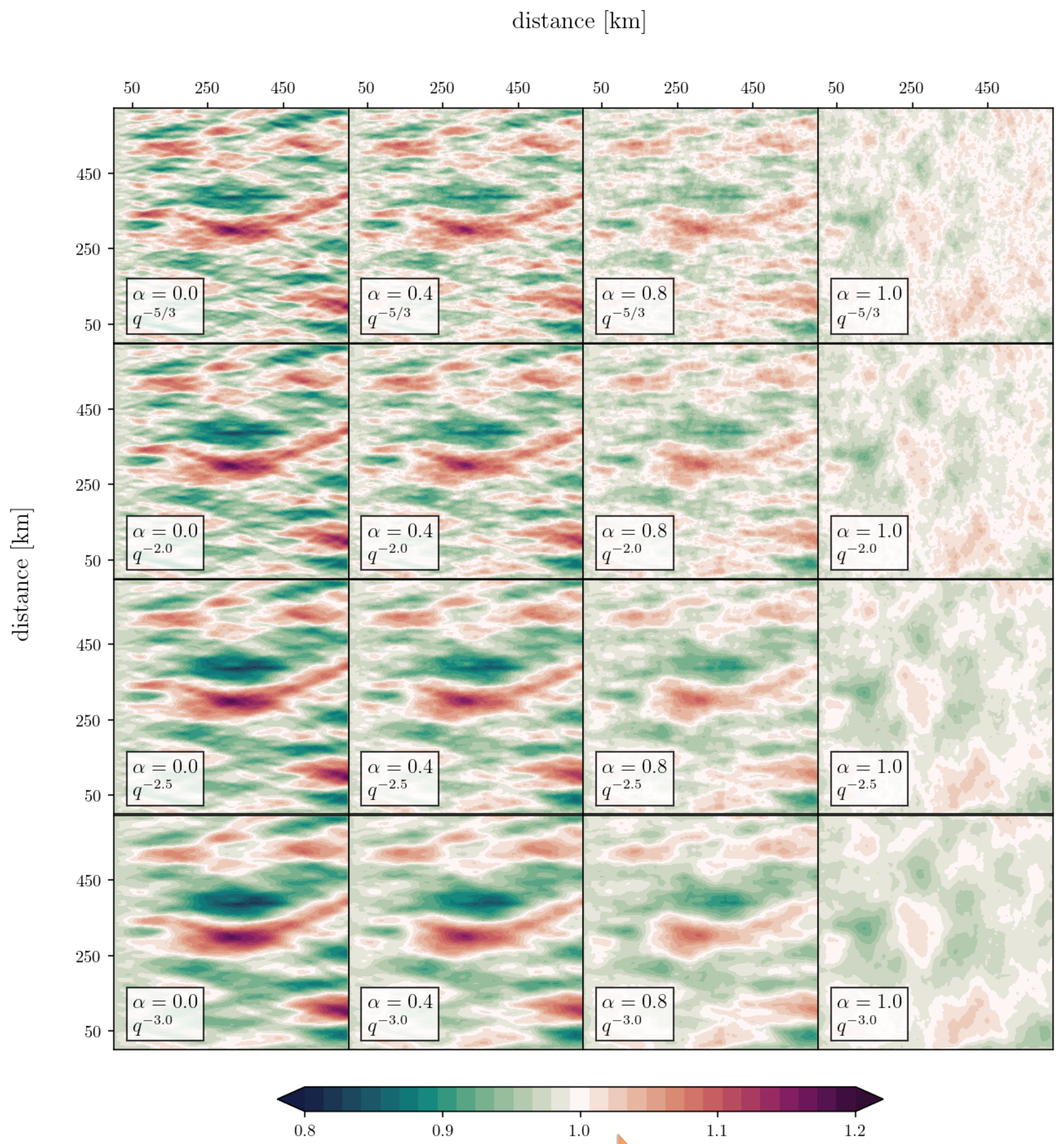
- Rotational currents lead to stronger gradients than divergent currents.
- Highly anisotropic H_s (streaks aligned with the wave propagation)
- Shallower KE spectral slopes imply finer structures in H_s

Theory supports modeling results:

Wang et al. [JFM 2023], Part B finishing revisions [available on arXiv], Part C on the works

More vorticity → More divergence

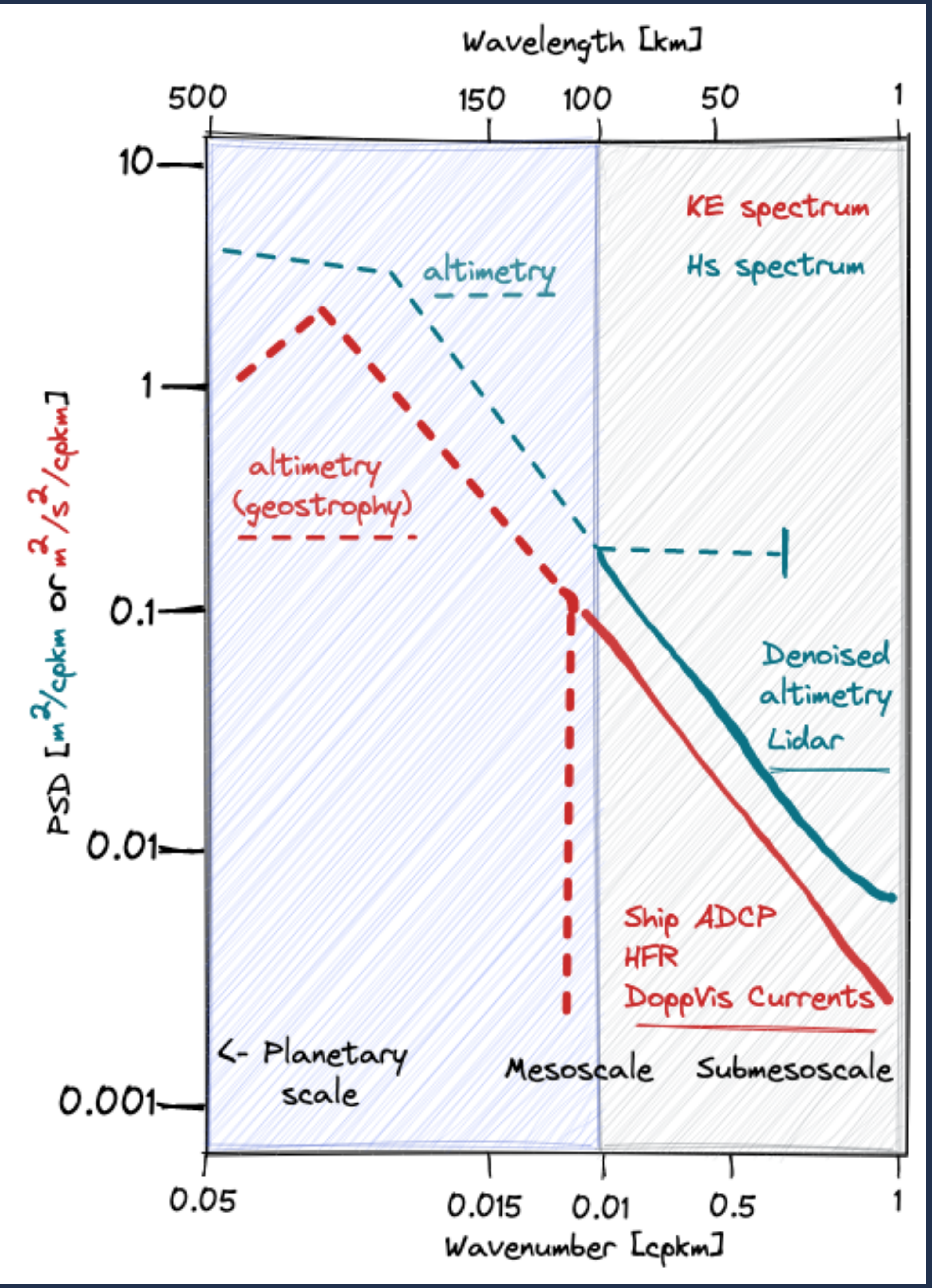
Shallower spectral slope ↓ Steeper spectral slope



More structure → Less structure

✅ 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).*

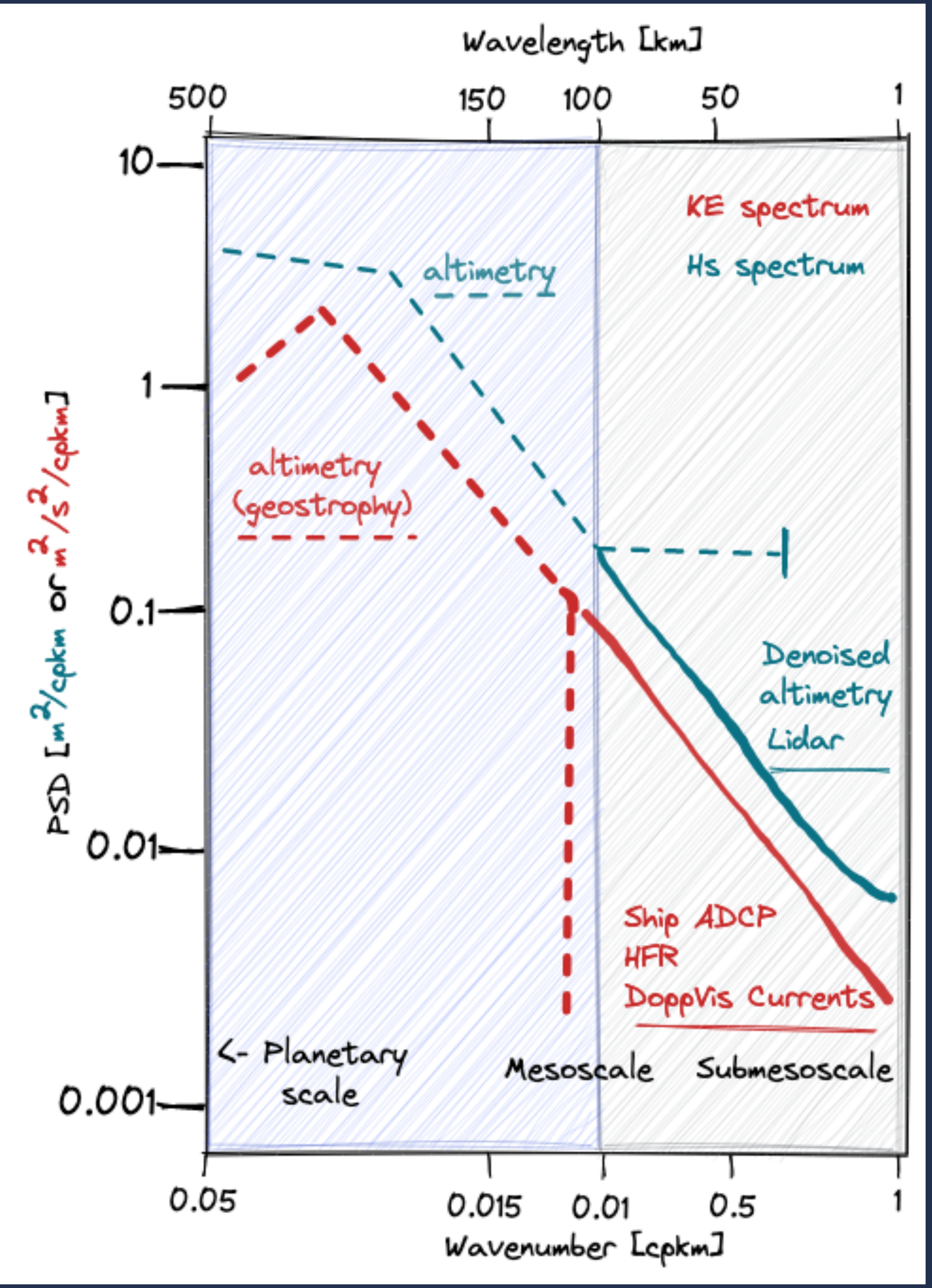


✅ What we know

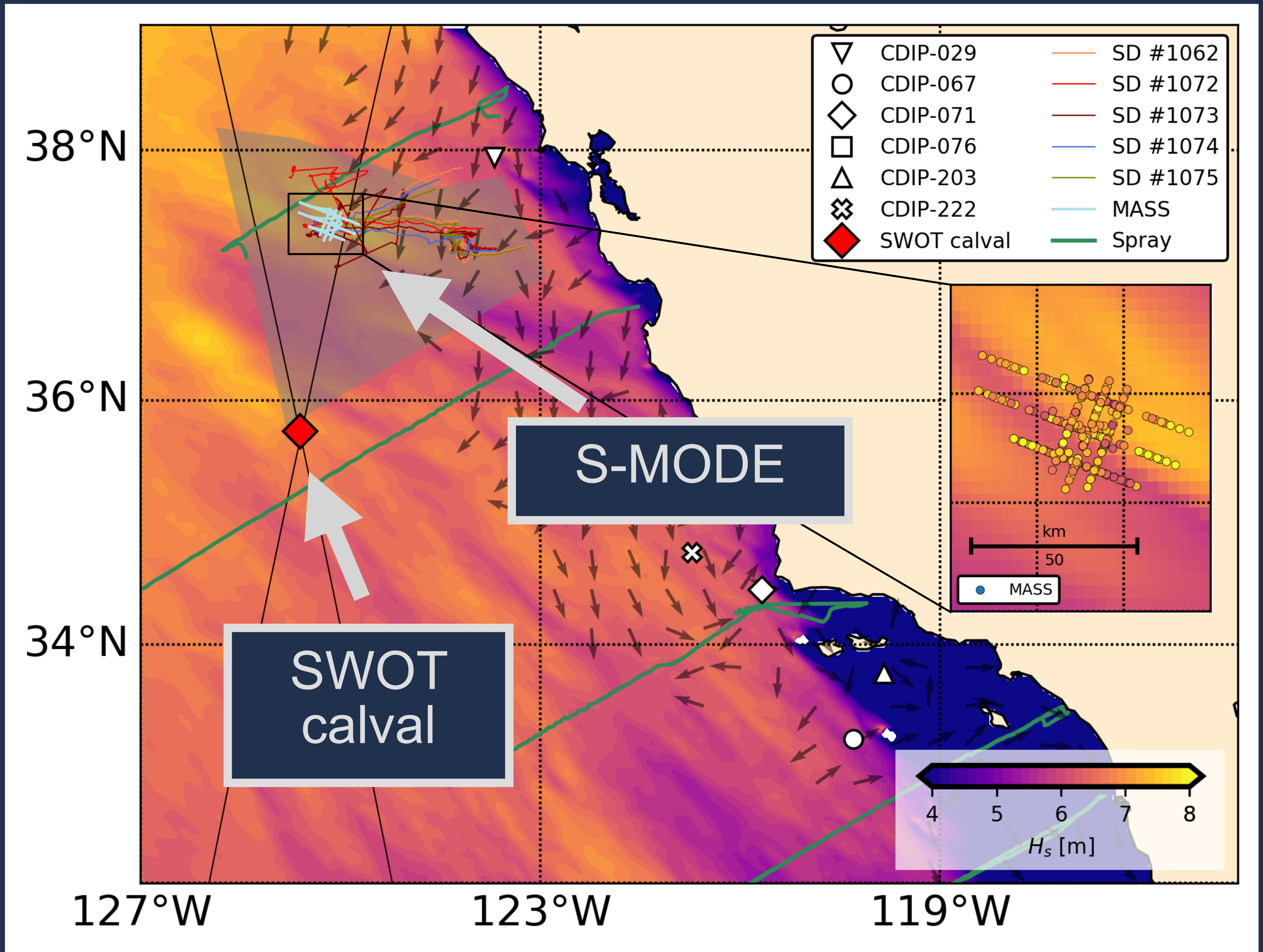
- Modeling and theory suggest a scale dependence between currents and significant wave height
- Vorticity/Refraction is the main mechanism driving the spatial variability of Hs at scales shorter than storm-scale
    - Not necessarily the case for higher moments - *See for example Rascle et al. (2016)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

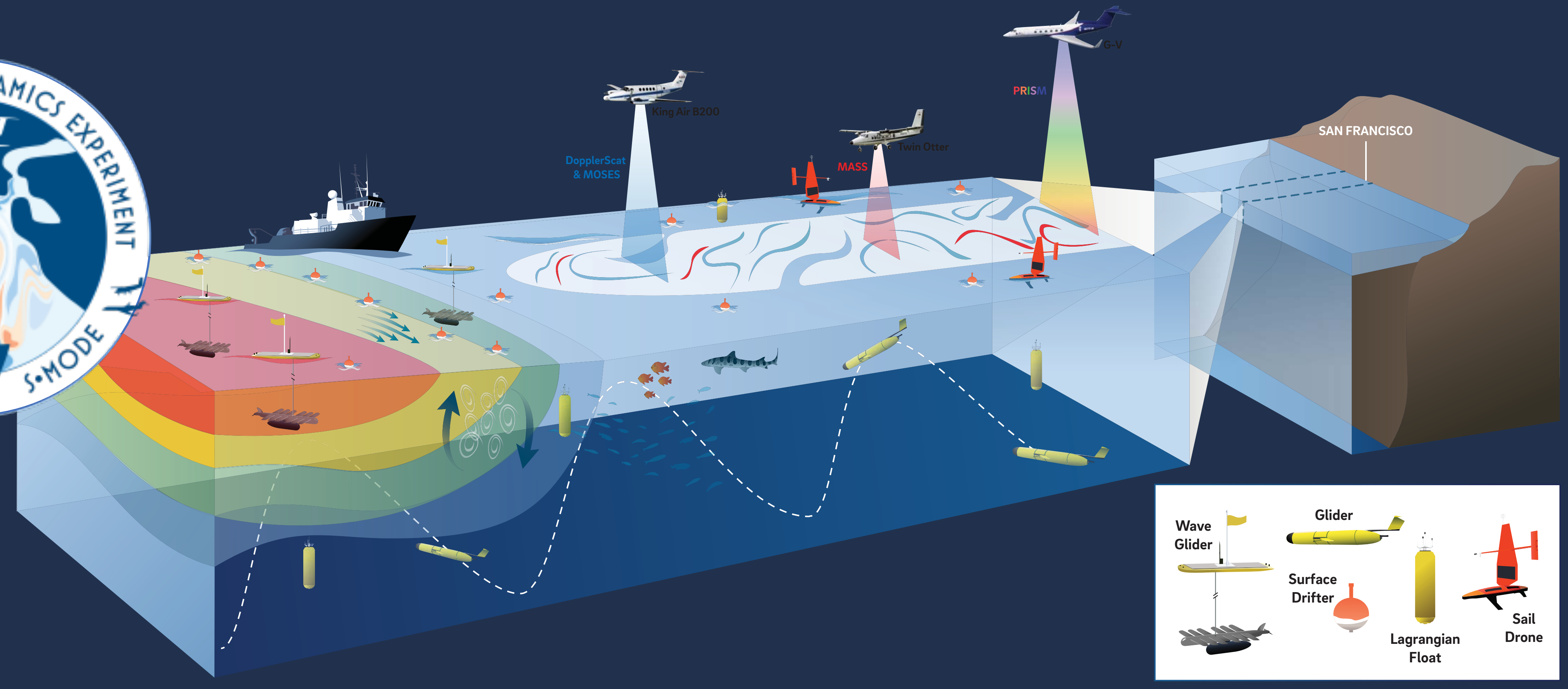
🤔 What we don't know

- 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?

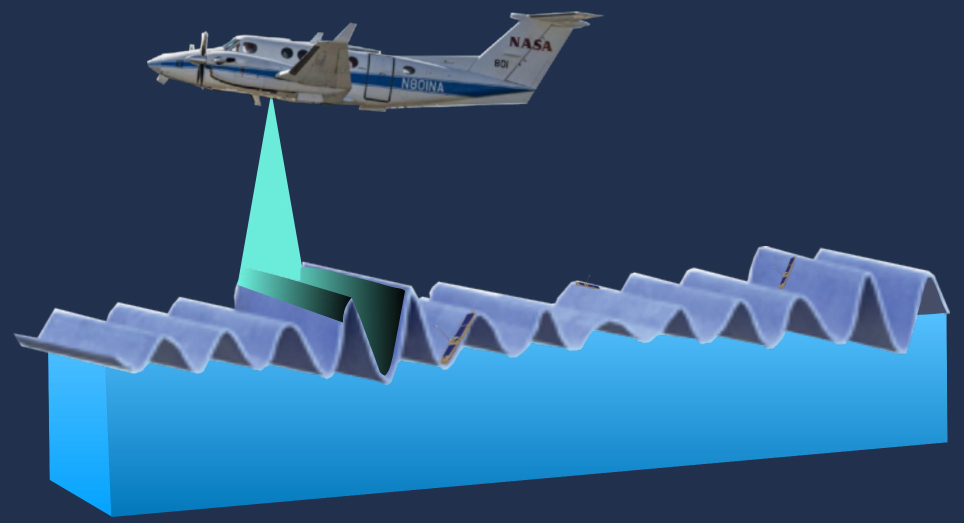


Observing sea state gradients from S-MODE and SWOT

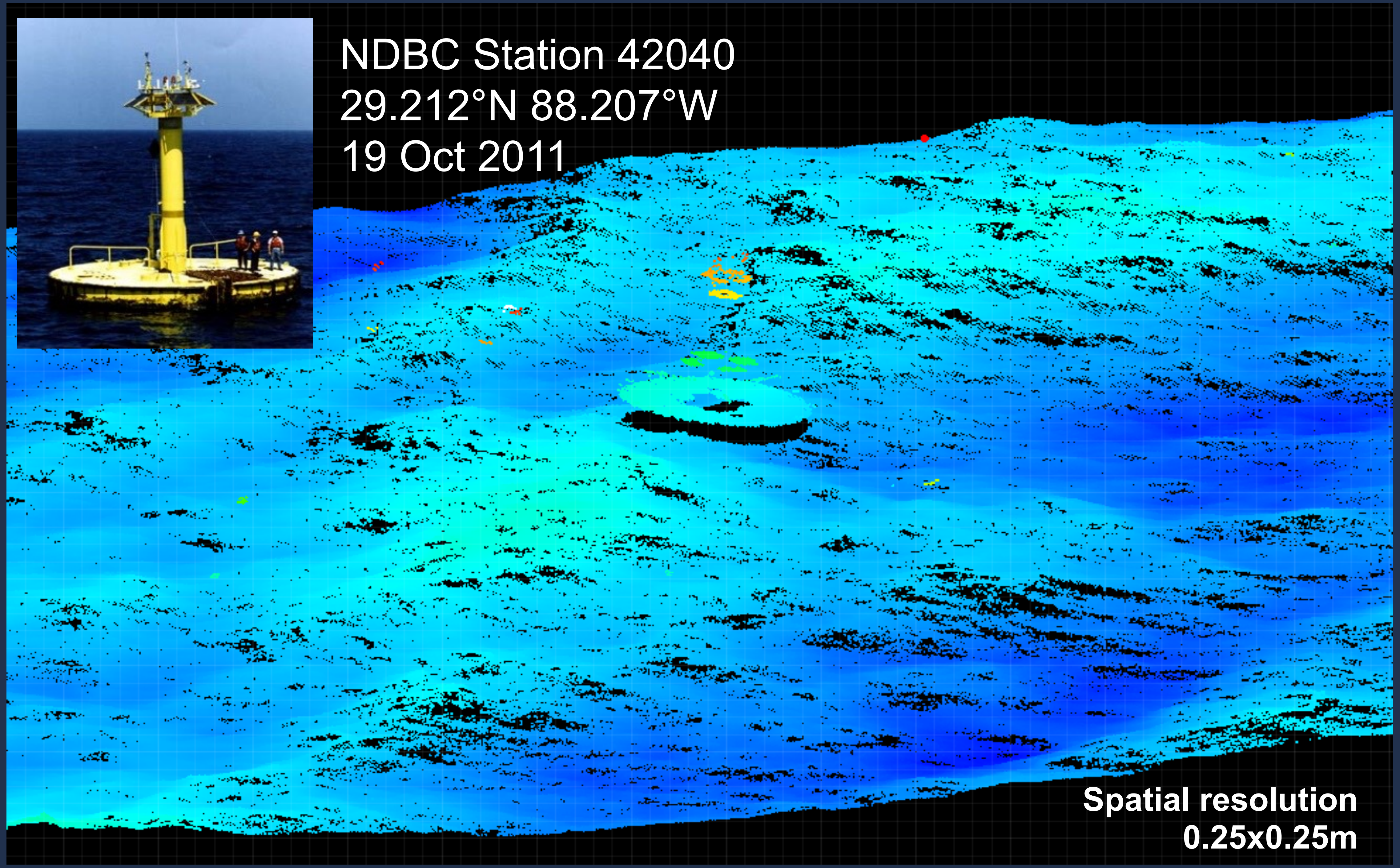




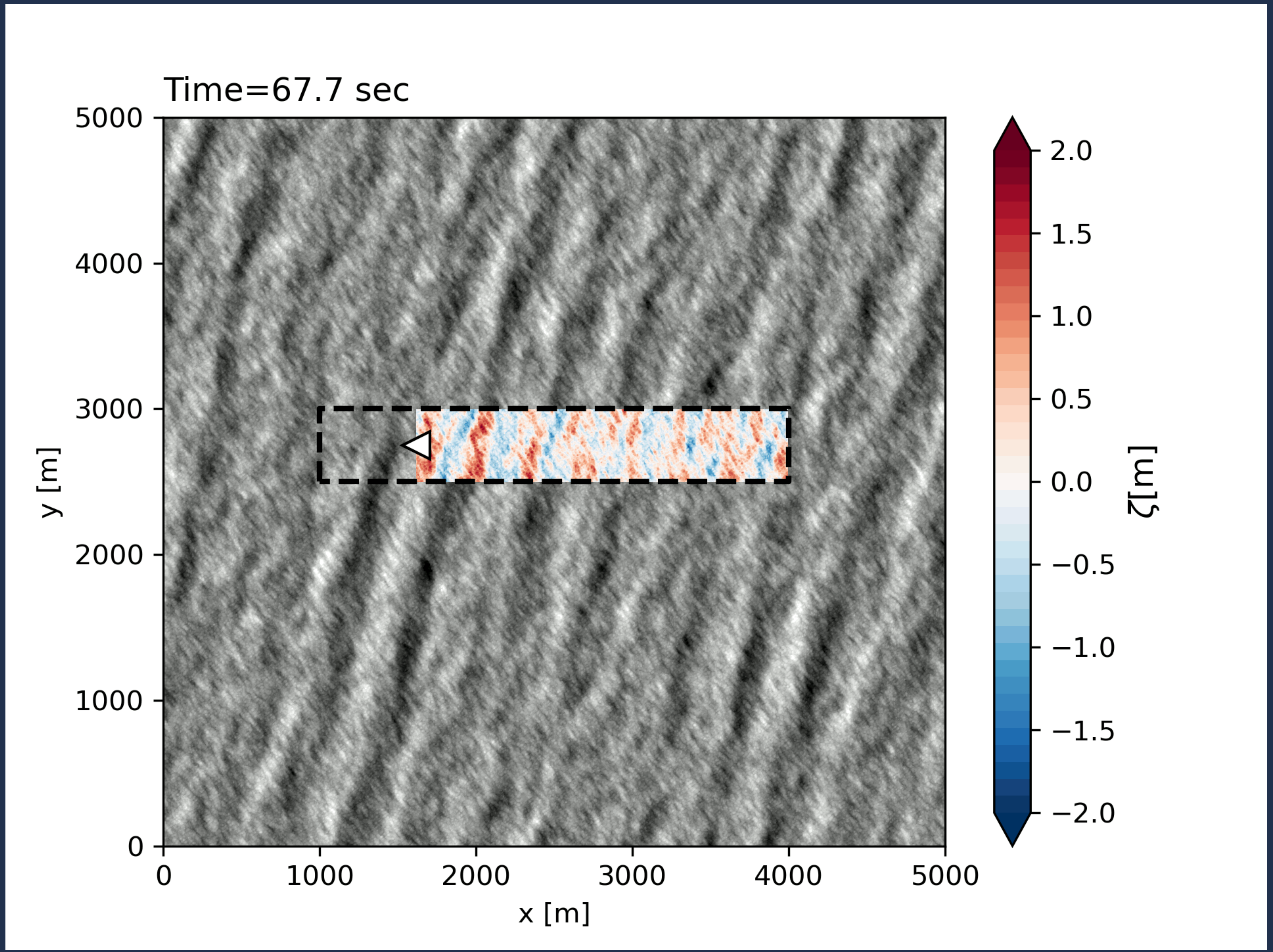
MASS airborne lidar observations



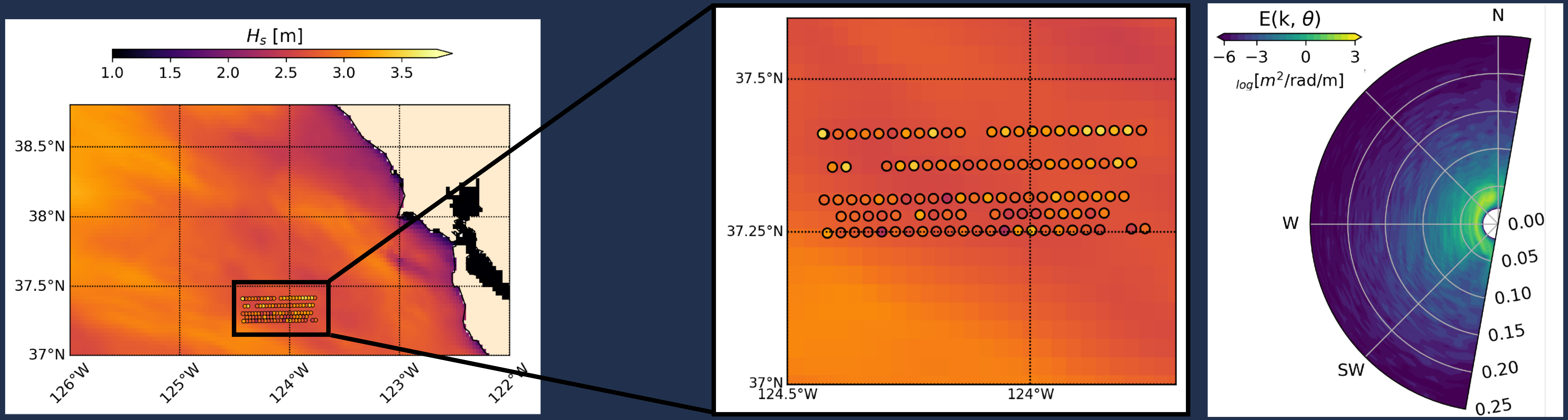
Scripps Air-sea lab
Modular Aerial Sensing System (MASS)



From Luc Lenain (SIO)



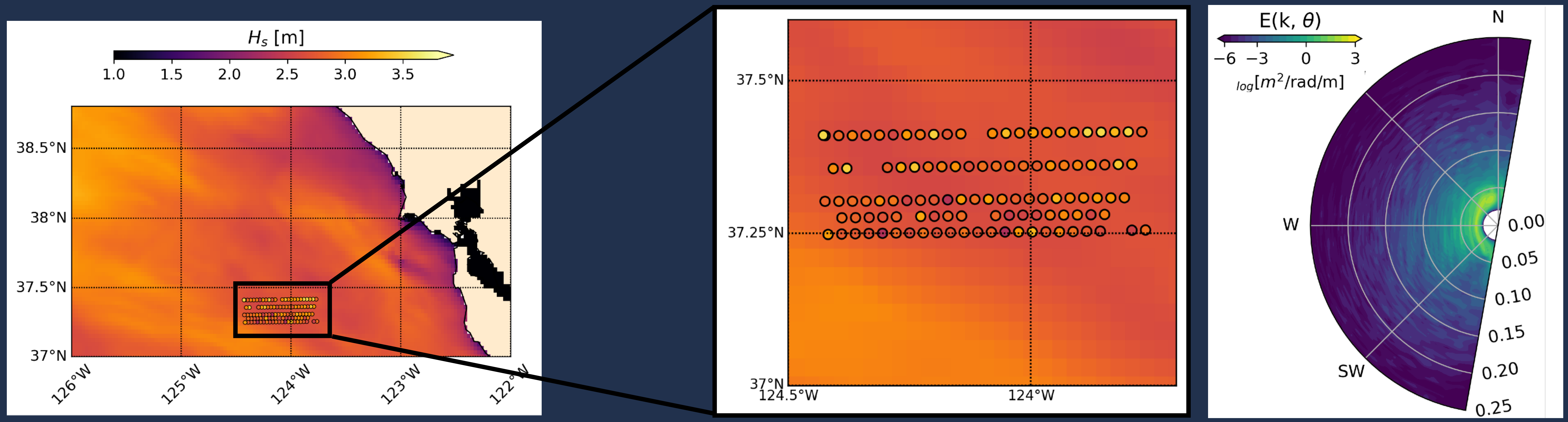
MASS observations of H_s under two different wave conditions



S-MODE pilot (Nov 2021)

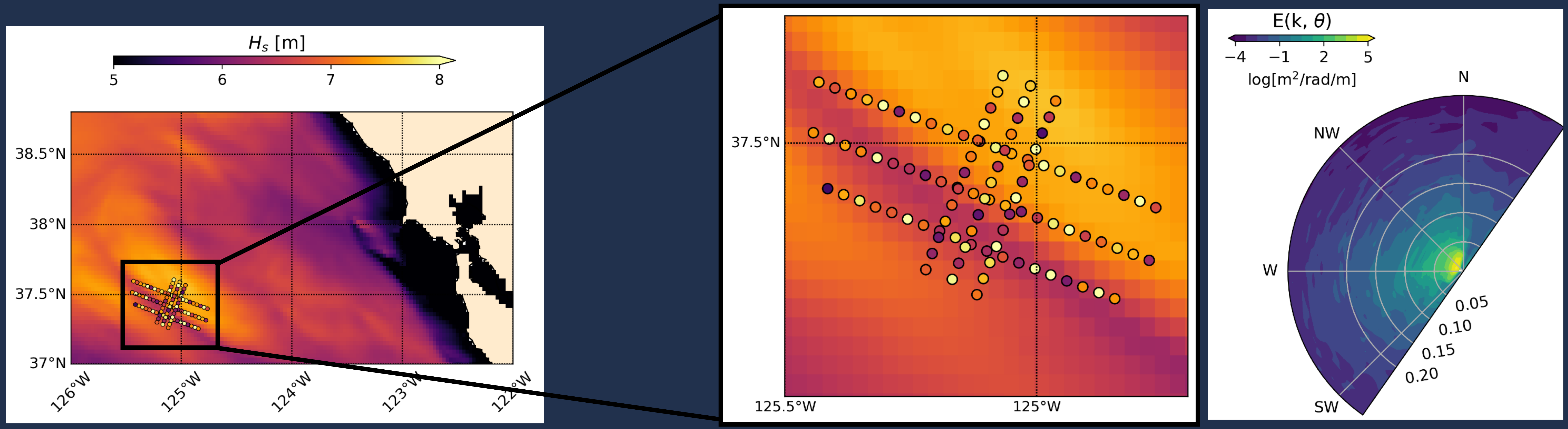
- Wind sea, high frequency and directional spreading, relatively low Hs (~ 3 m).

MASS observations of H_s under two different wave conditions



S-MODE pilot (Nov 2021)

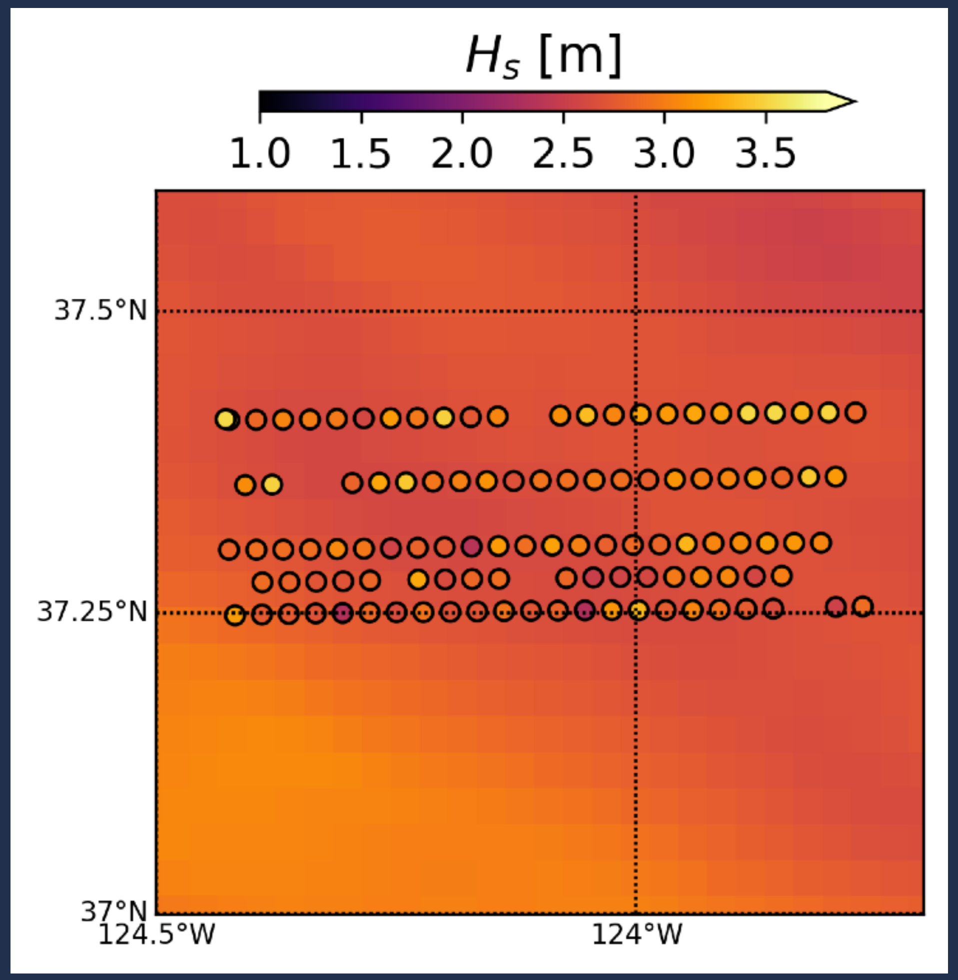
- Wind sea, high frequency and directional spreading, relatively low Hs (~ 3 m).

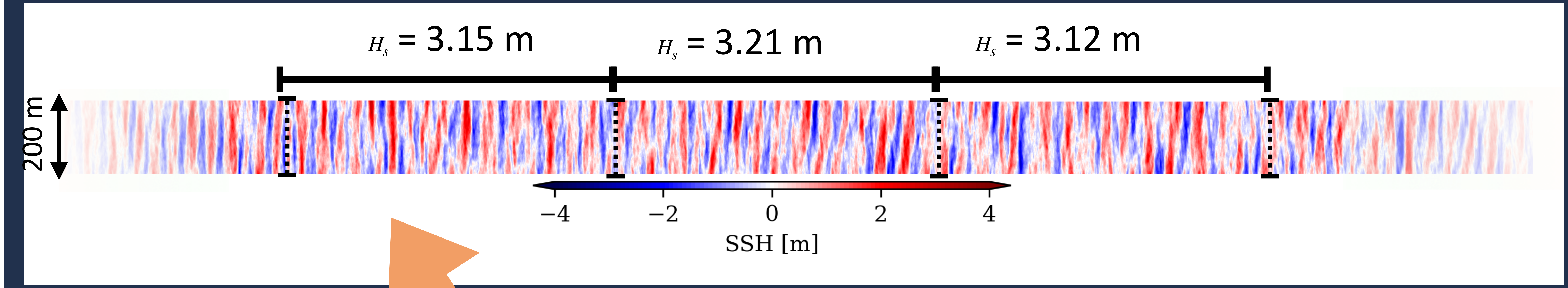


S-MODE pilot (Oct 2021)

- Swell, low frequency and directional spreading, high Hs (~ 8 m) 😱

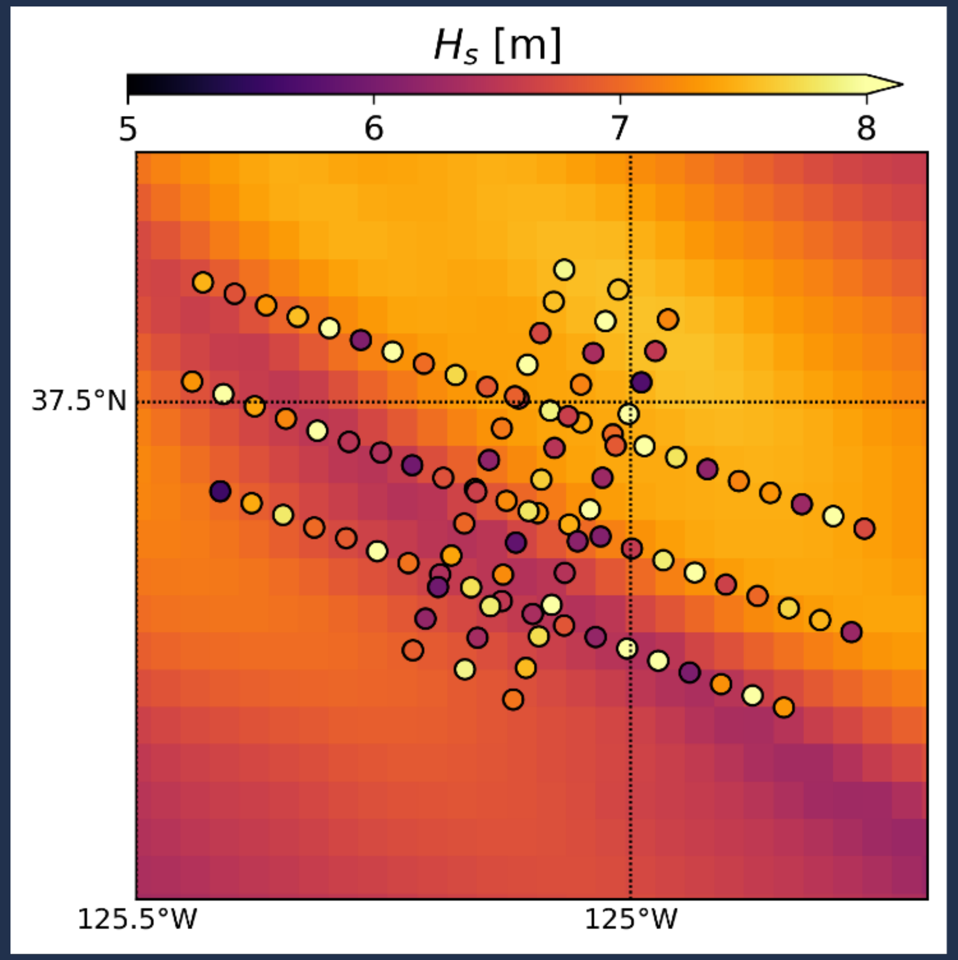
Wave groups lead to spatial variability of H_s

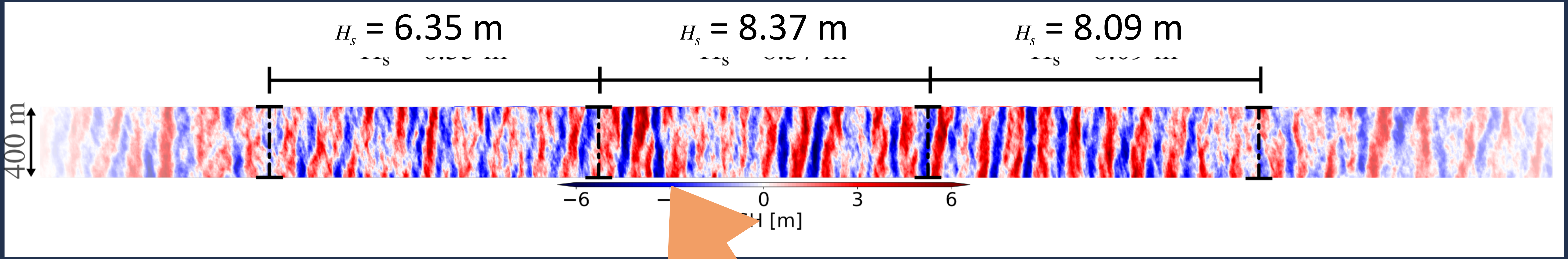




Wind-sea, broad-banded spectrum

More homogeneous SSH field

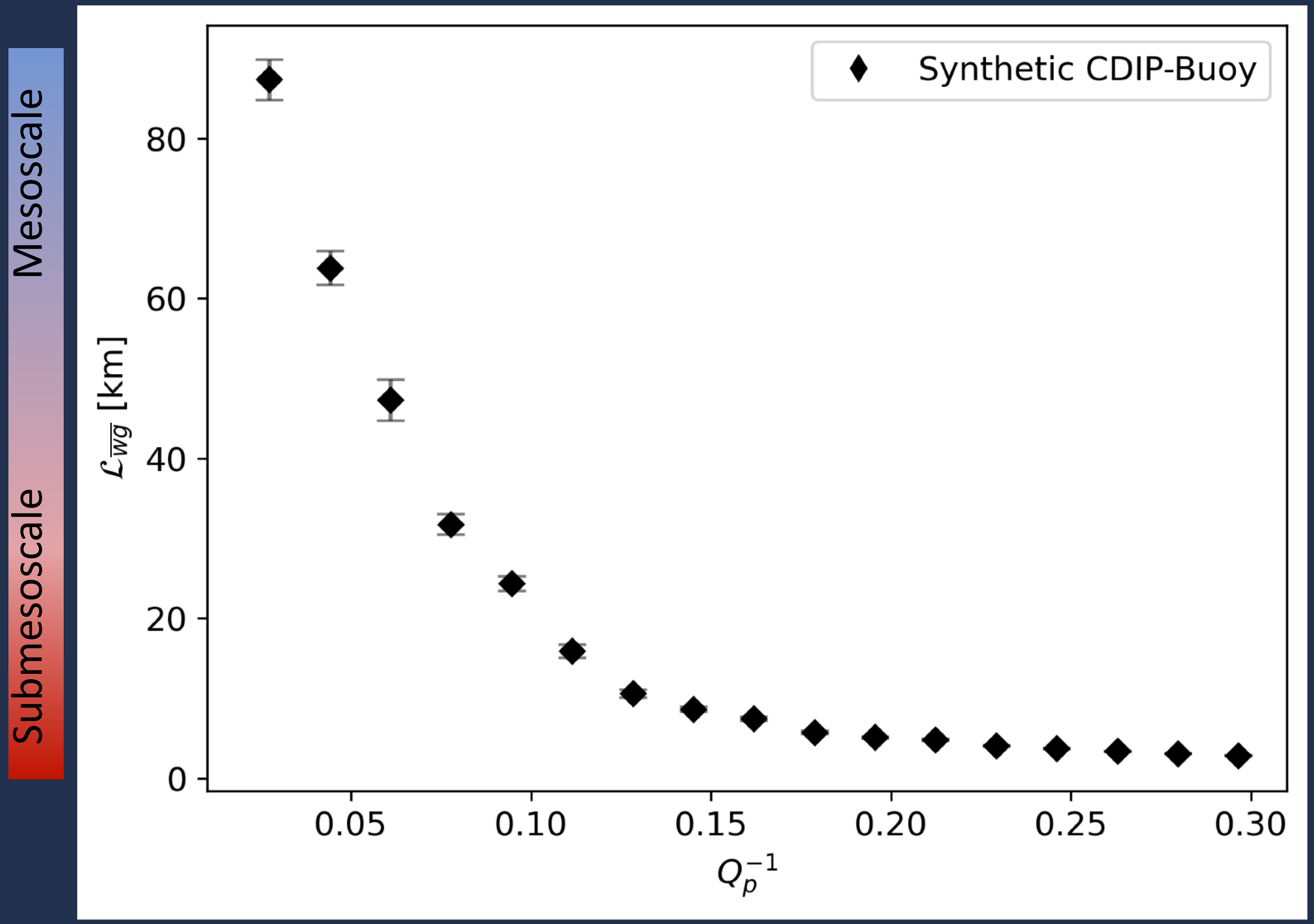


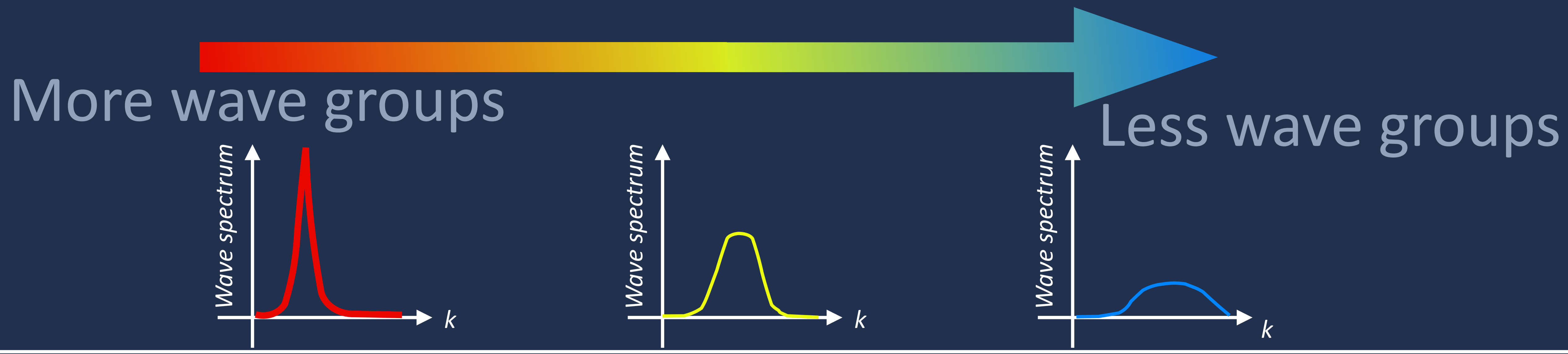


Strong swell, narrow-banded spectrum

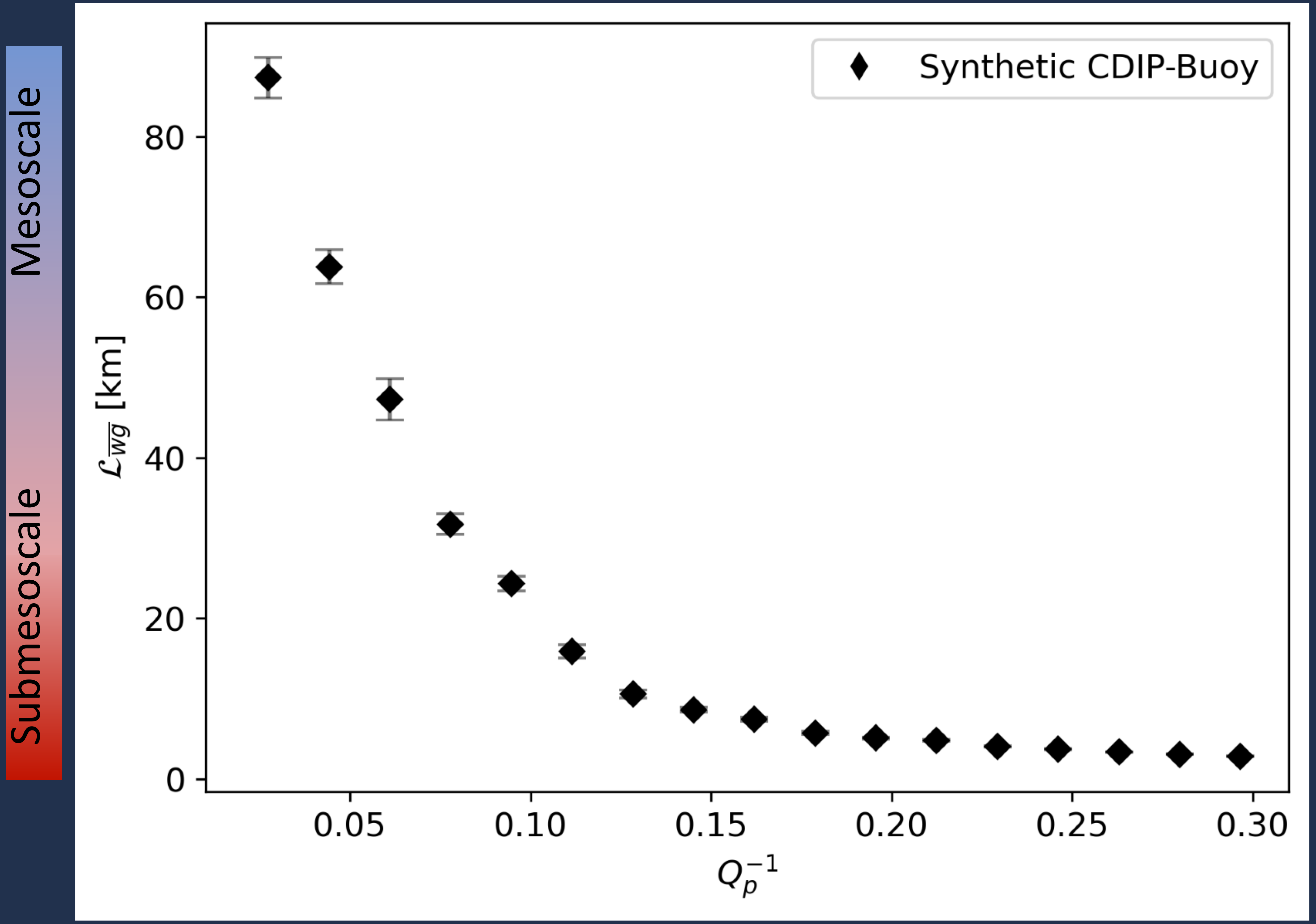
SSH field modulated by groups

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



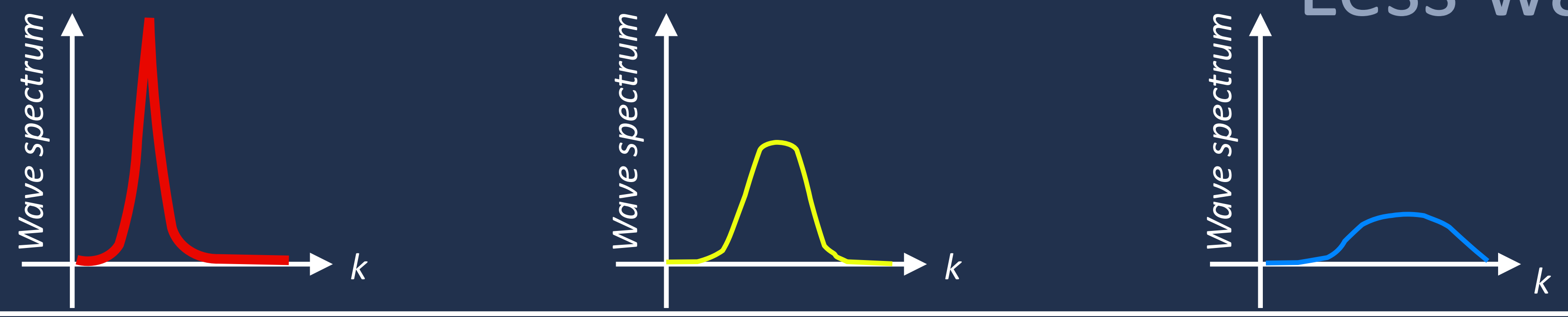


There is **no** (spatial) **scale separation** between group and current modulation of H_s

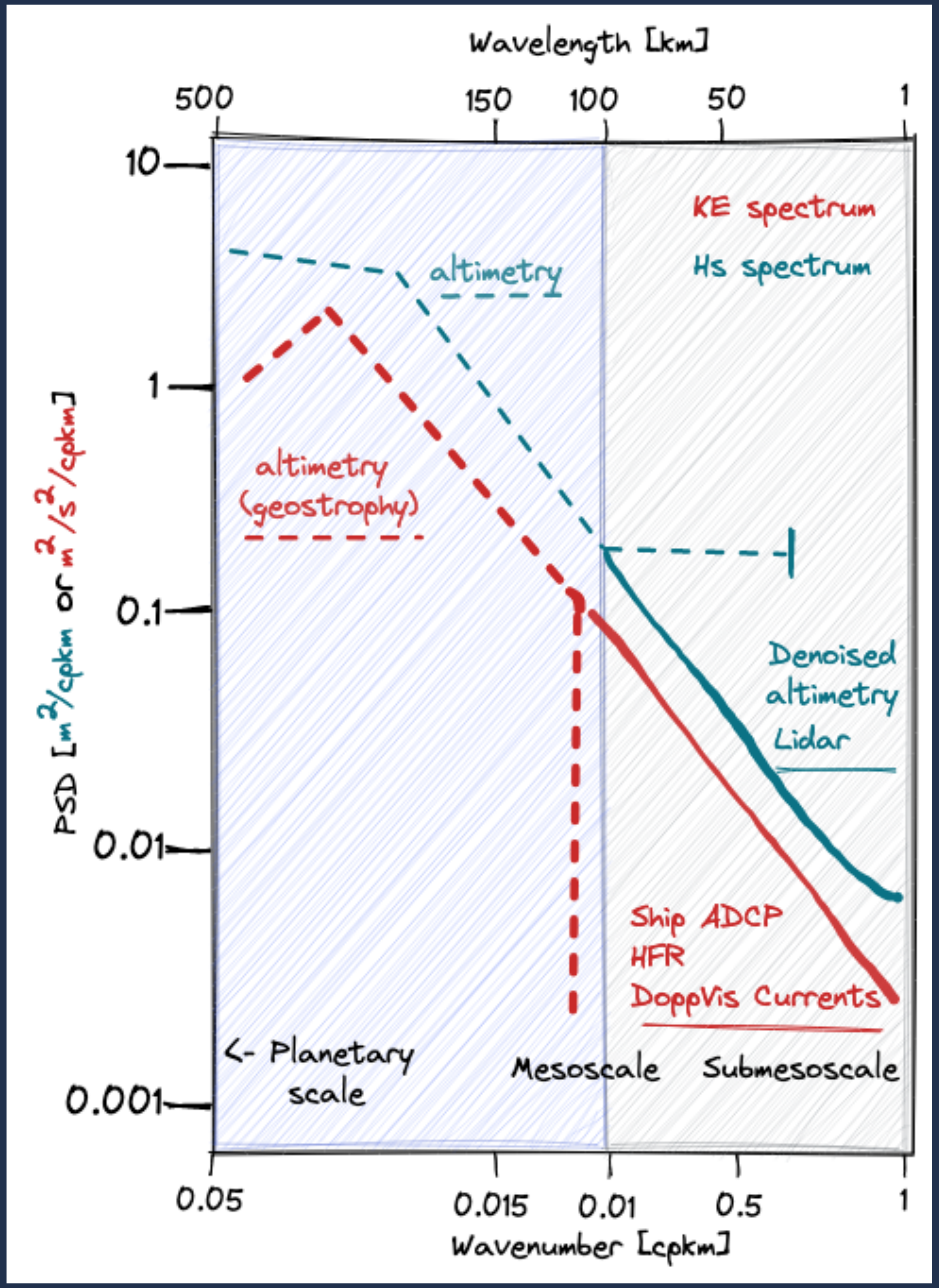


More wave groups

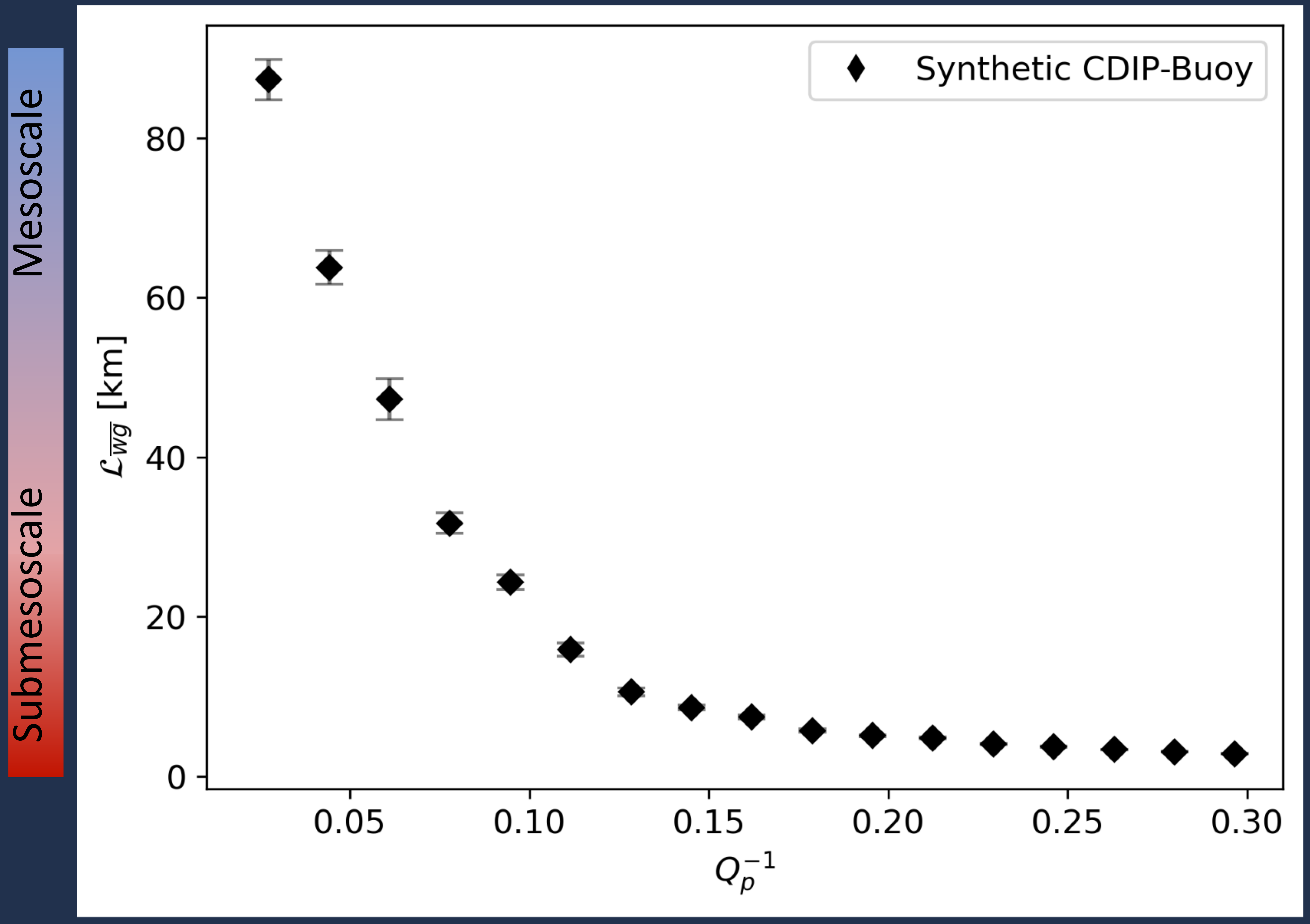
Less wave groups



Expectation 😃

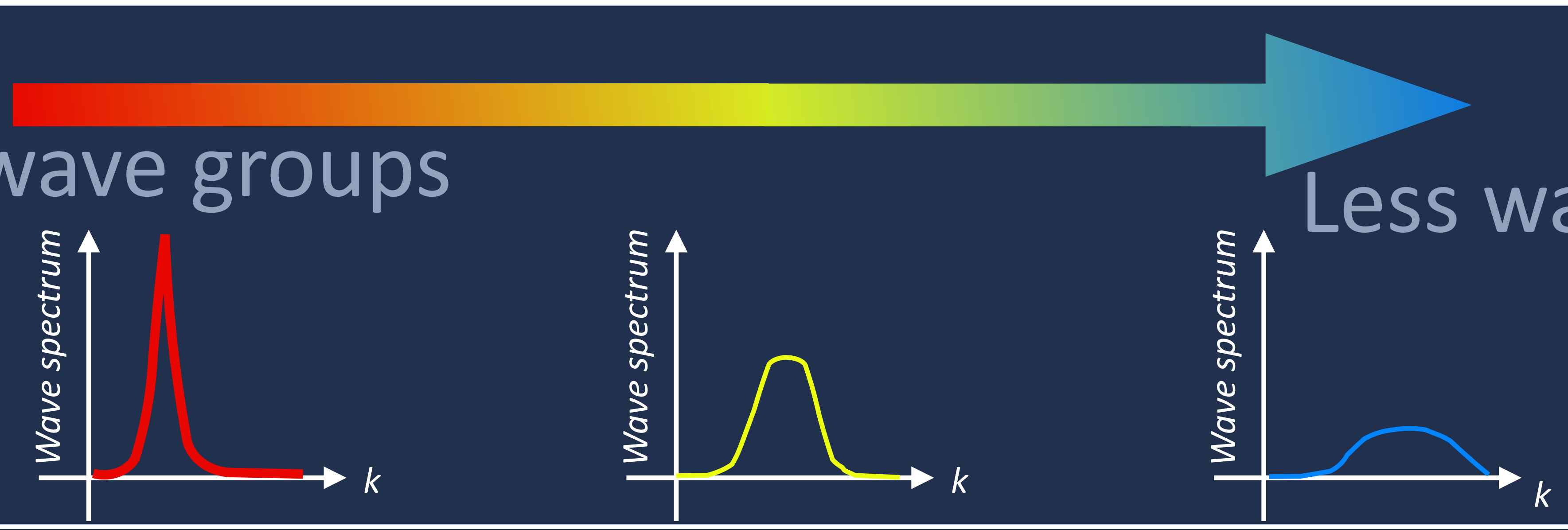


There is **no** (spatial) **scale separation** between group and current modulation of H_s

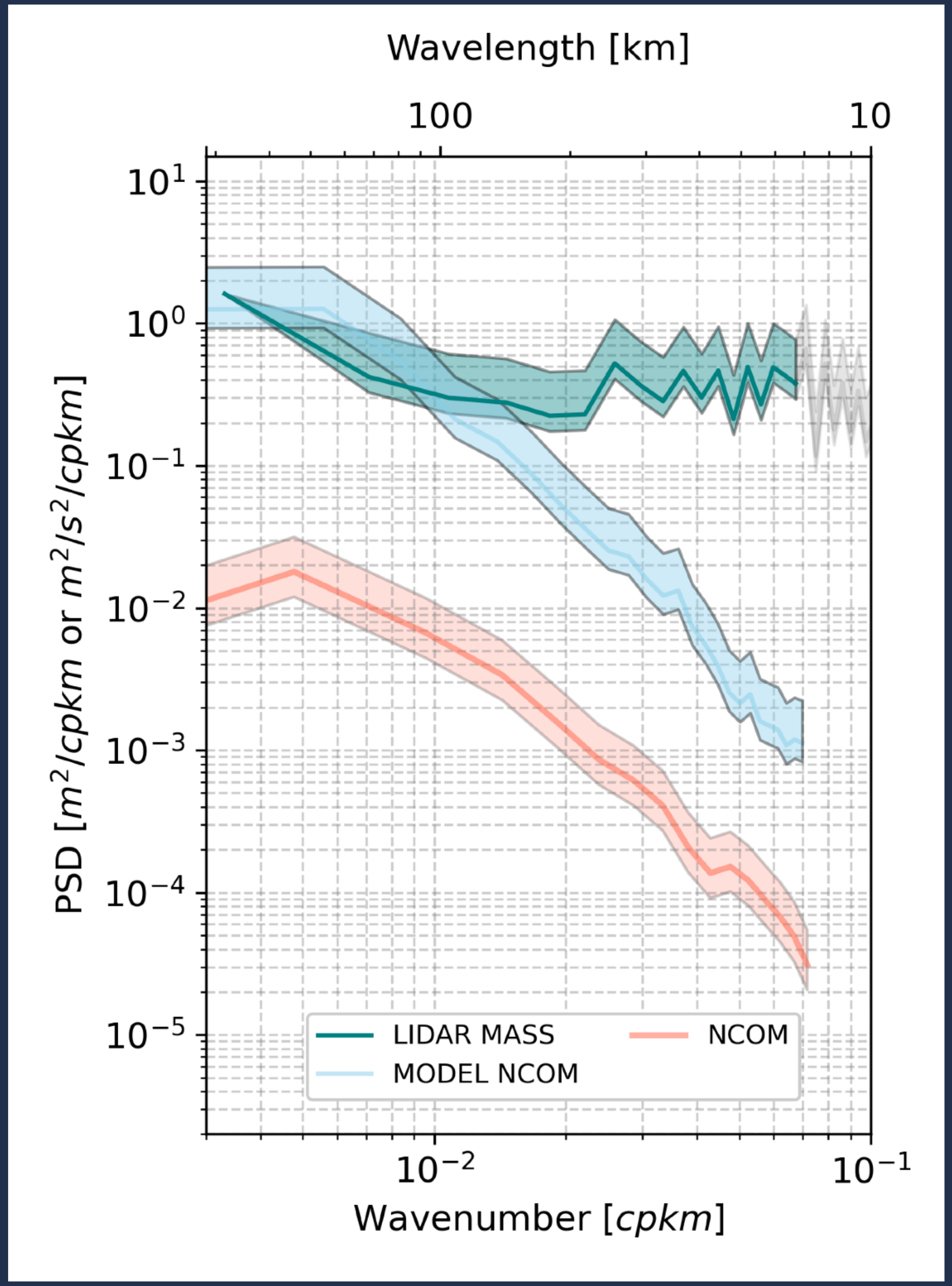


More wave groups

Less wave groups



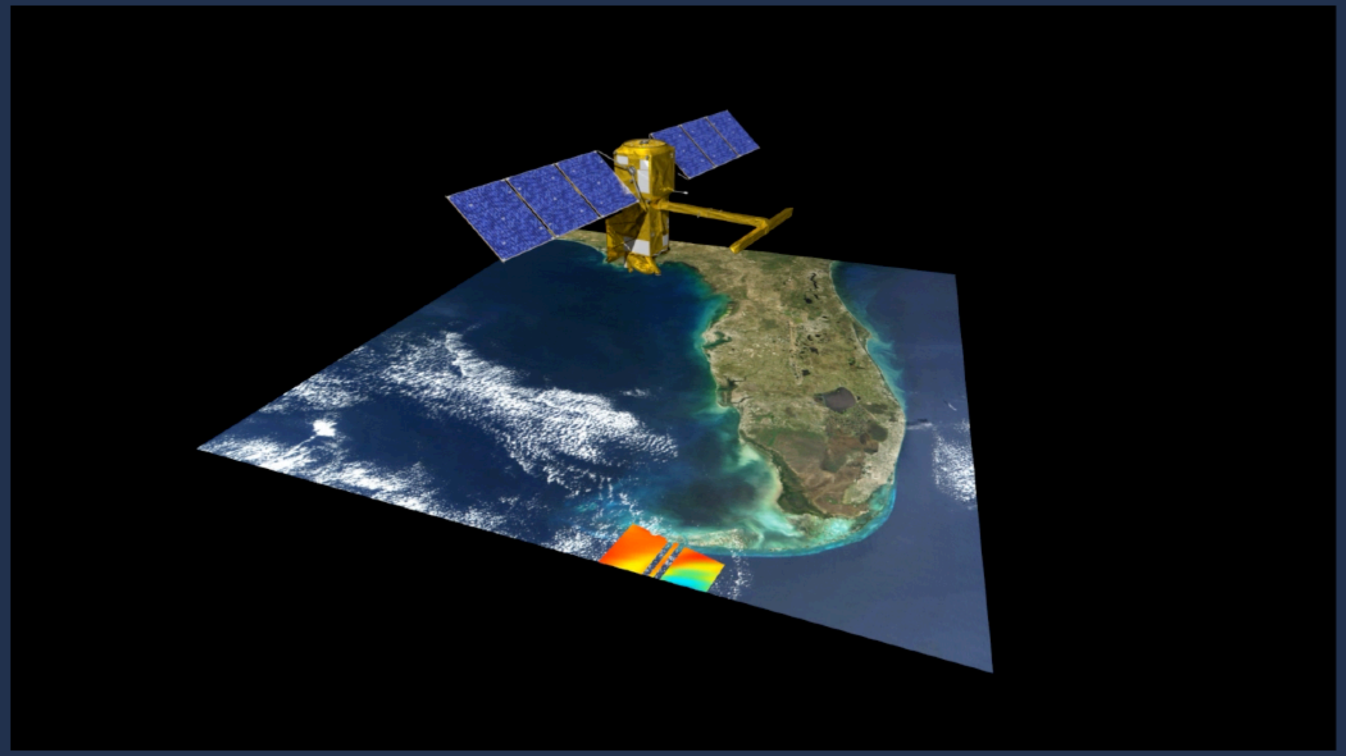
Reality 😬



Observing waves from SWOT

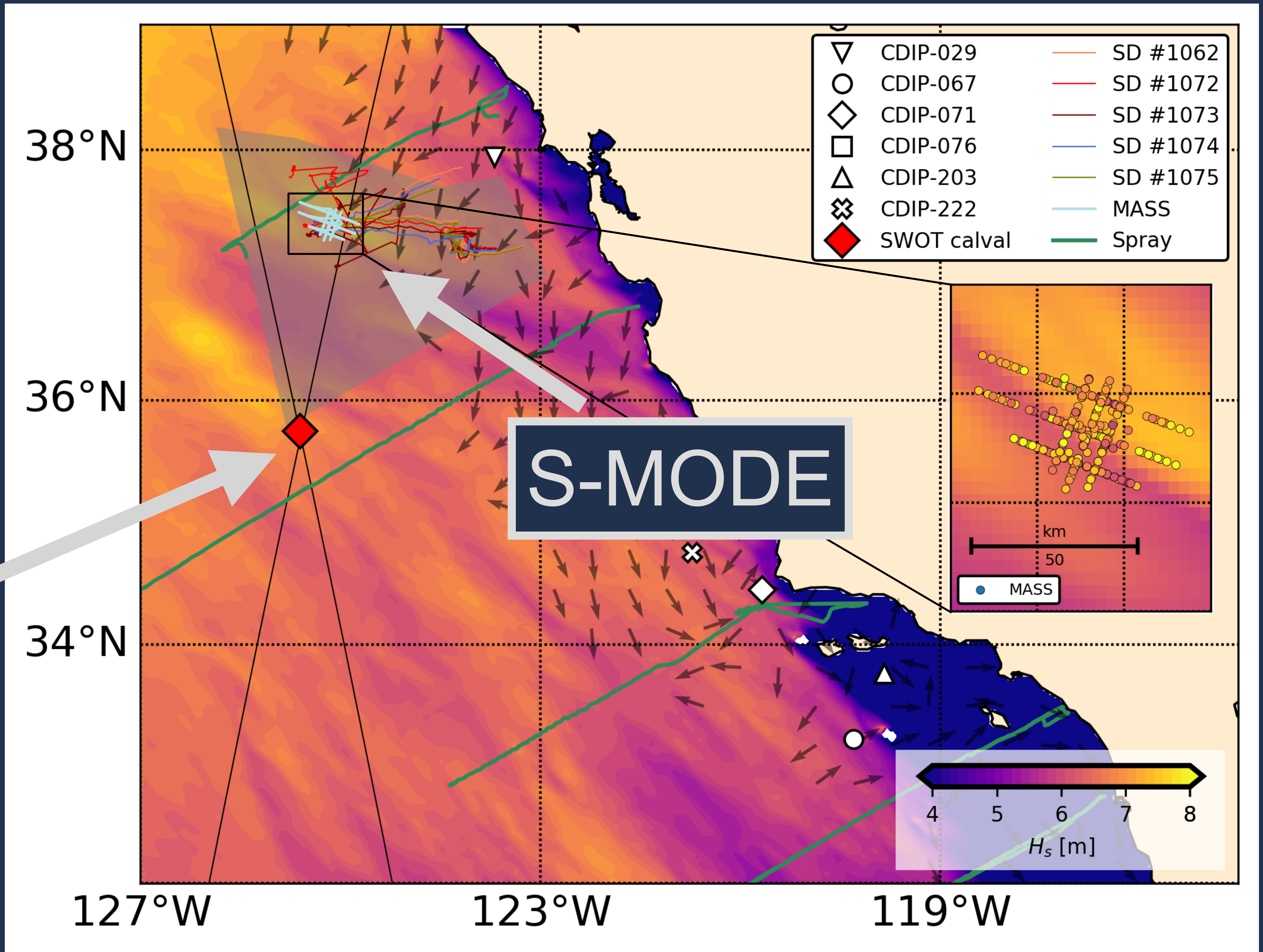
Observing waves from SWOT

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



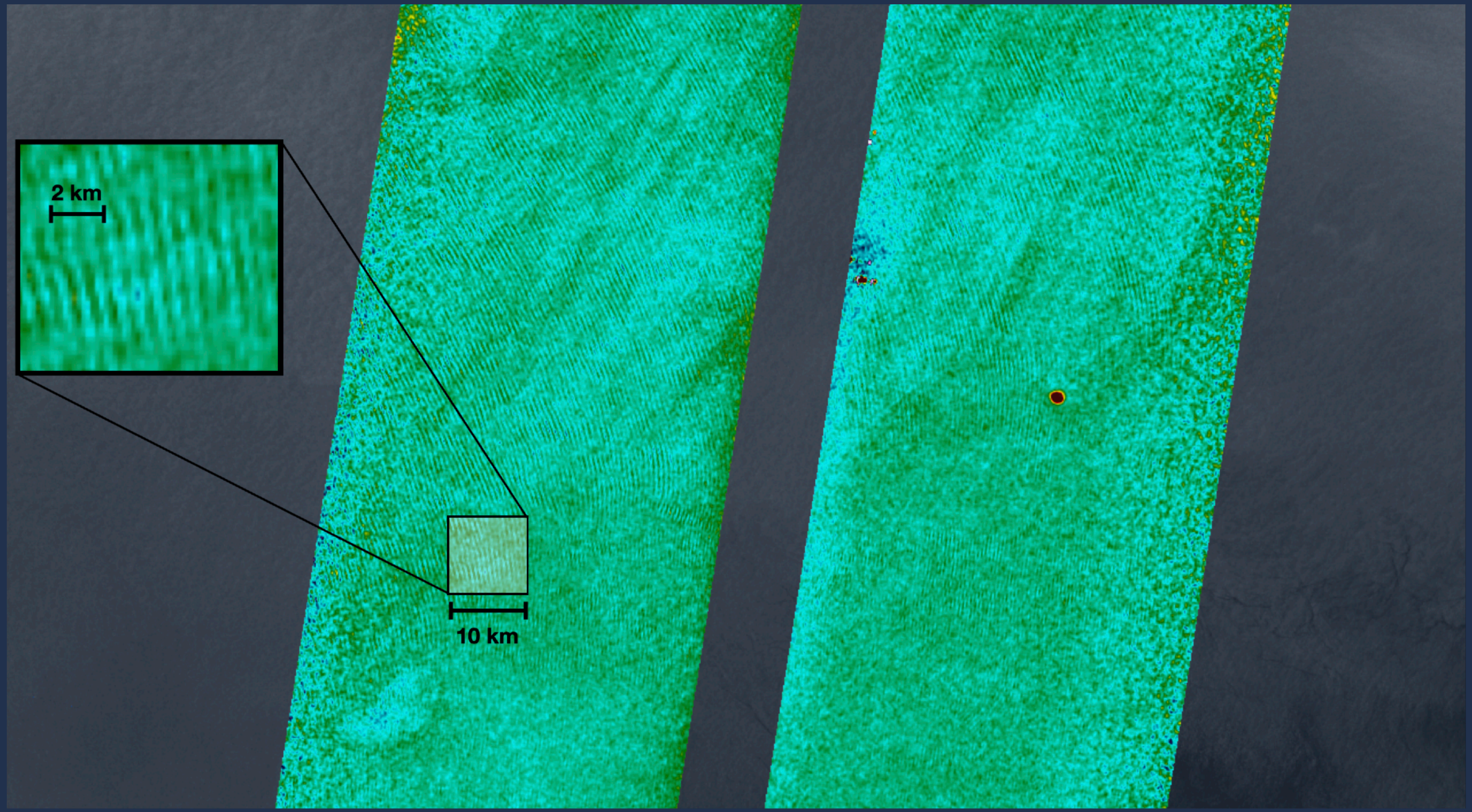
- SWOT's focuses on SSH measurement but surprise, surprise….

SWOT calval



Opportunities and challenges from SWOT observations

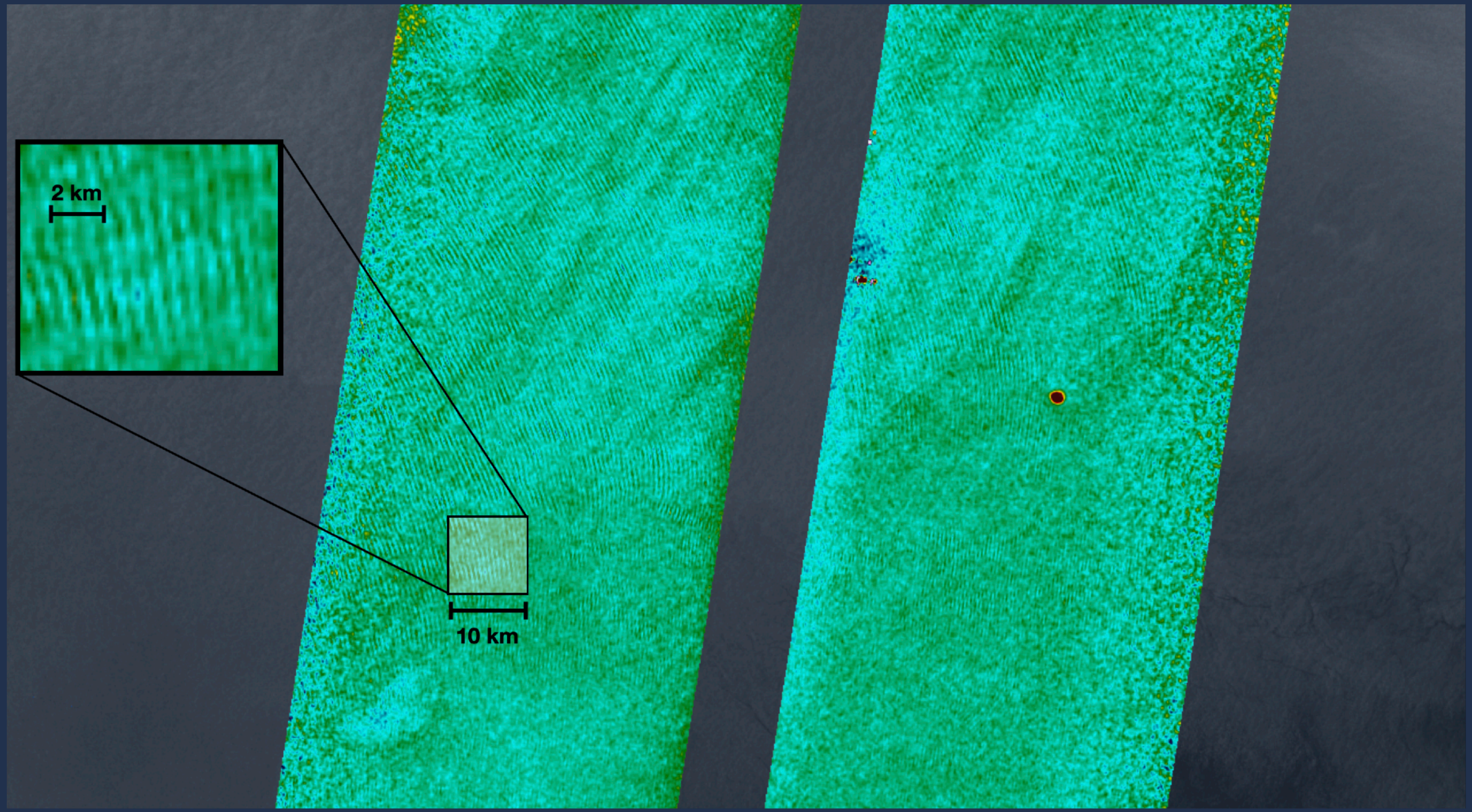
SWOT can see long swells and groups!



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

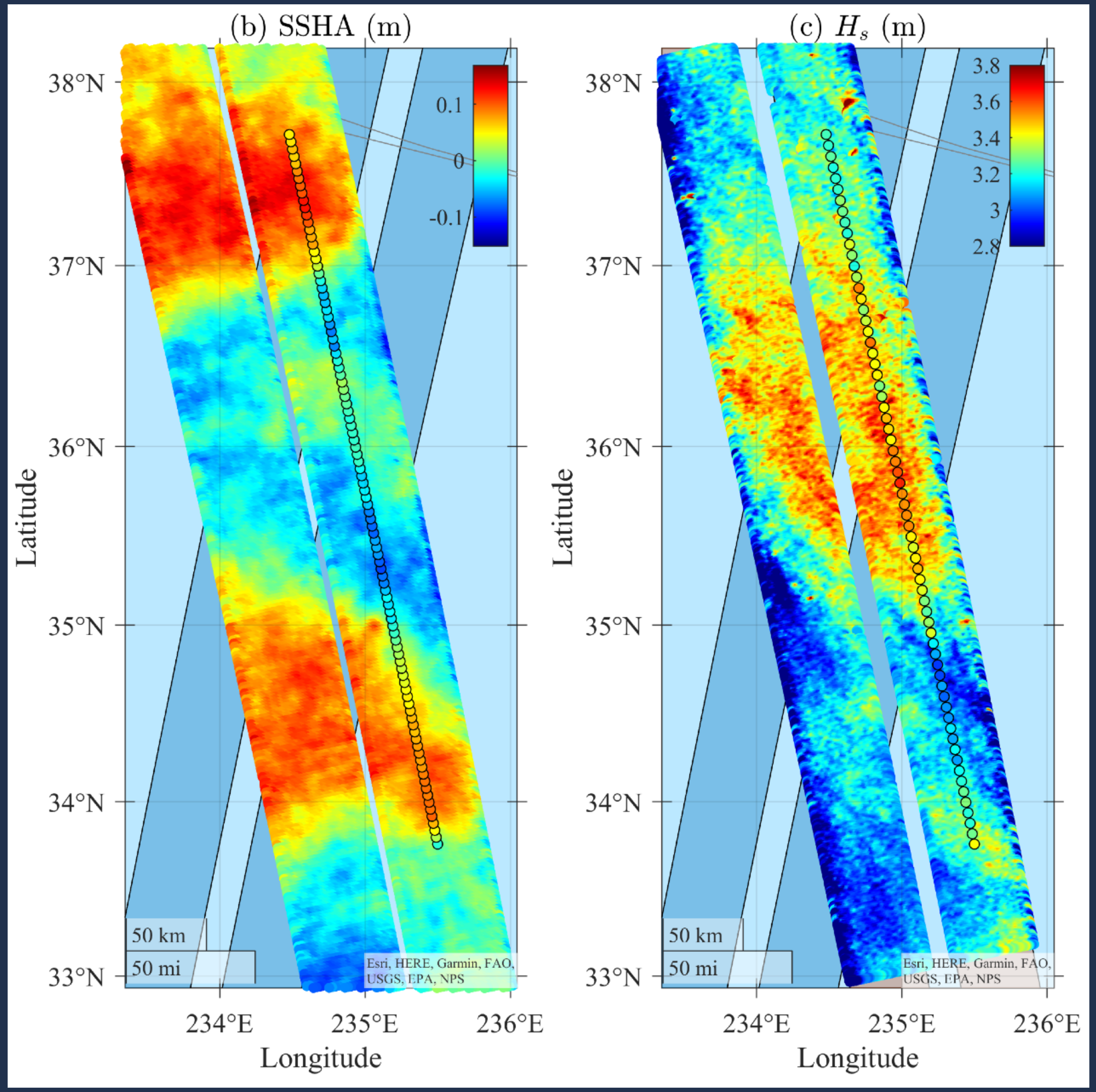
Opportunities and challenges from SWOT observations

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

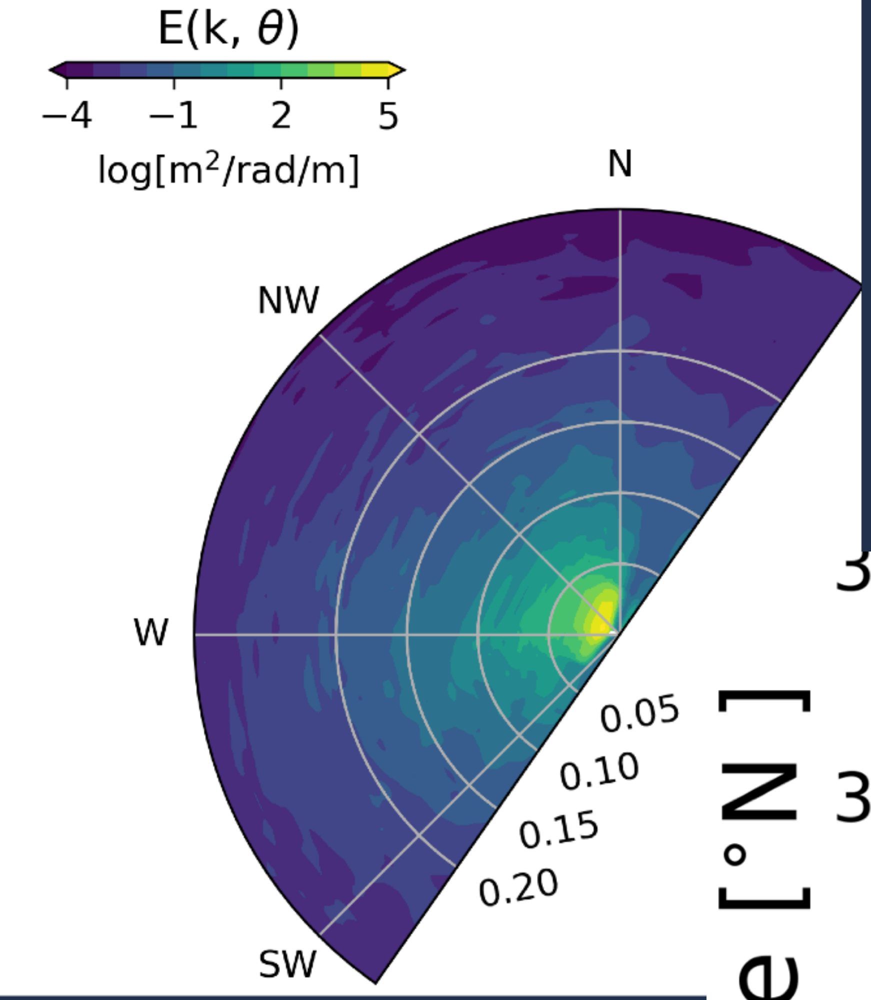
Waves and winds from SWOT in the Southern Ocean

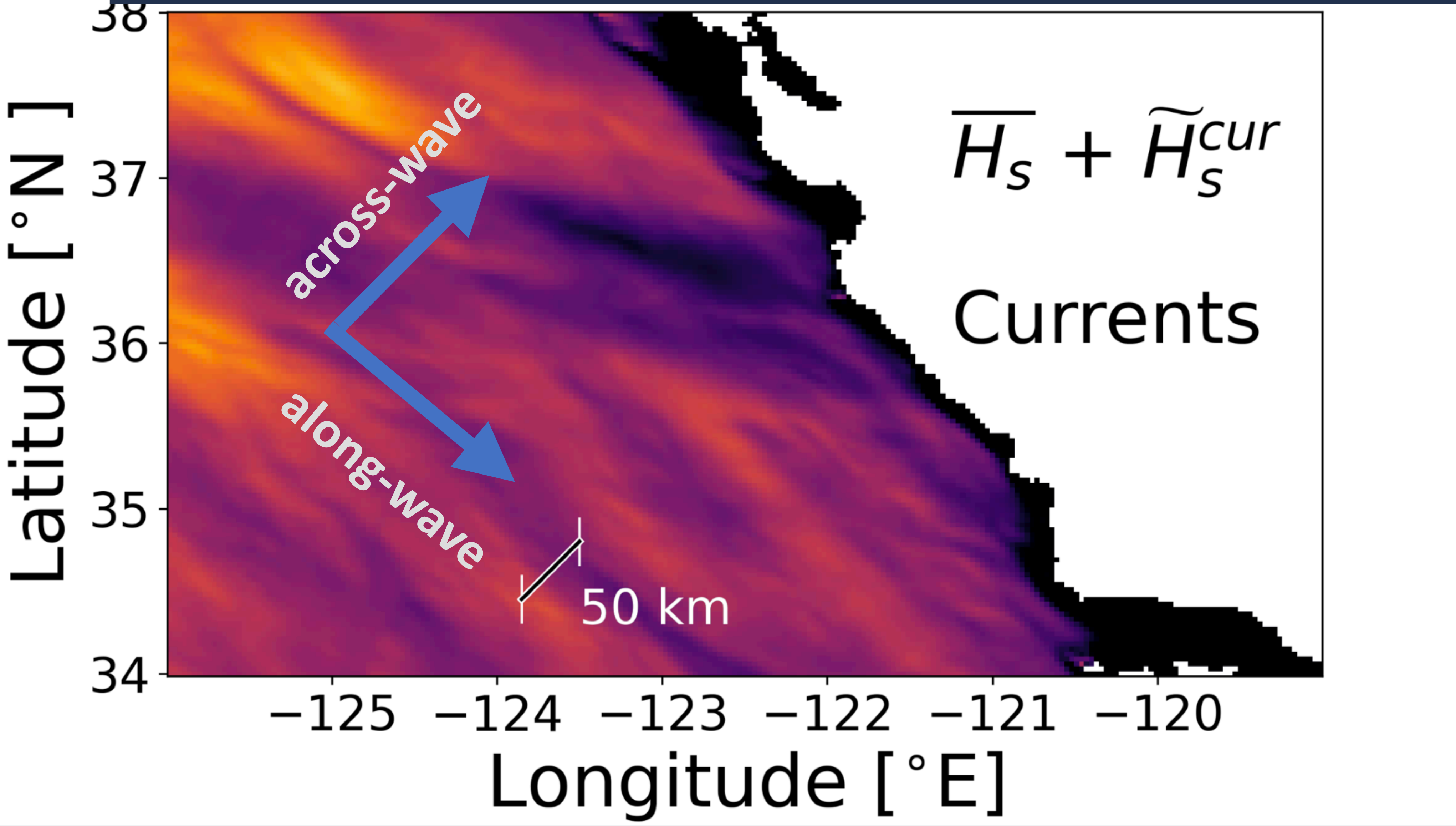
Villas Bôas et al (in prep)

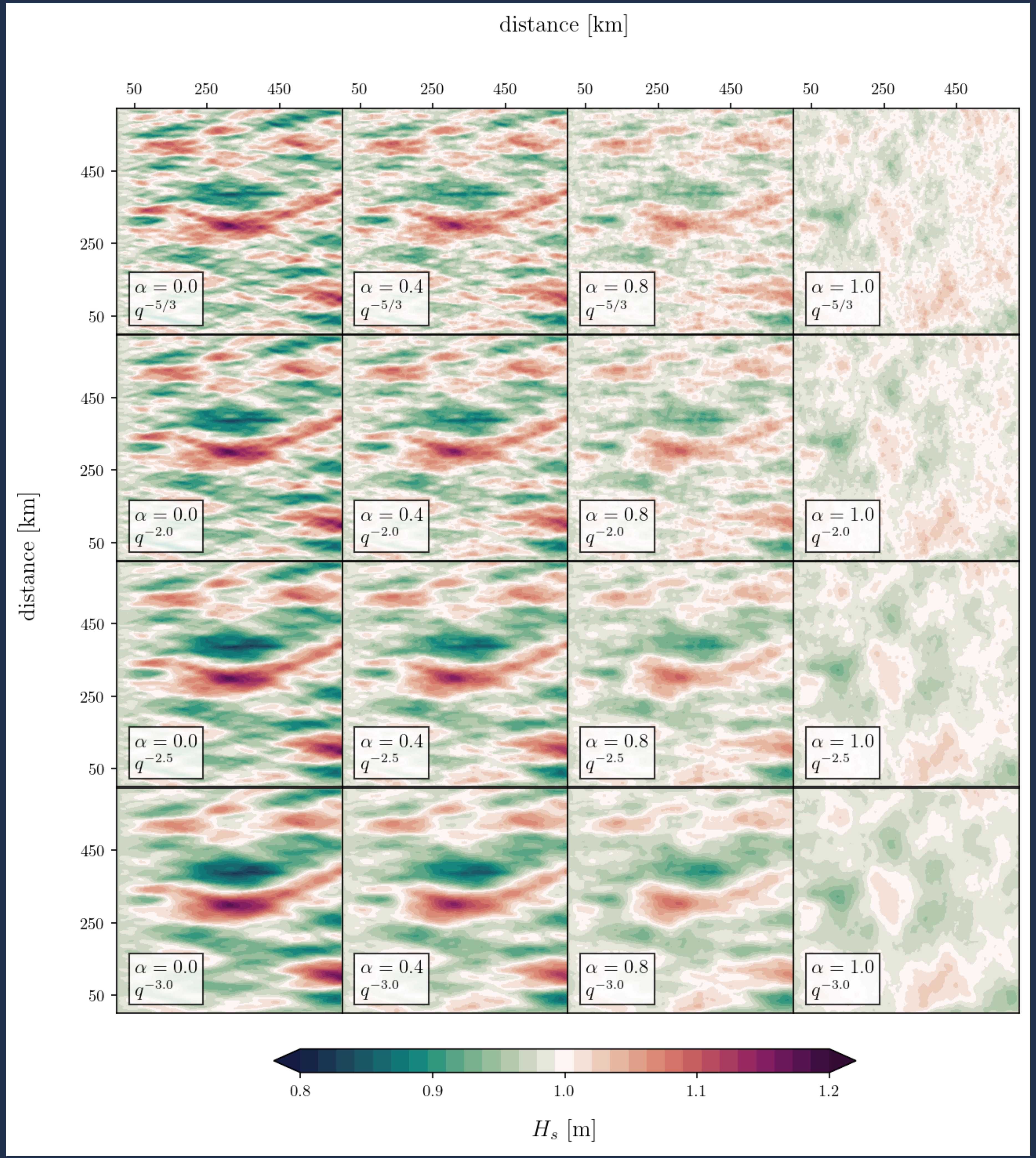
Wind-Wave-Current coupling in the Gulf Stream

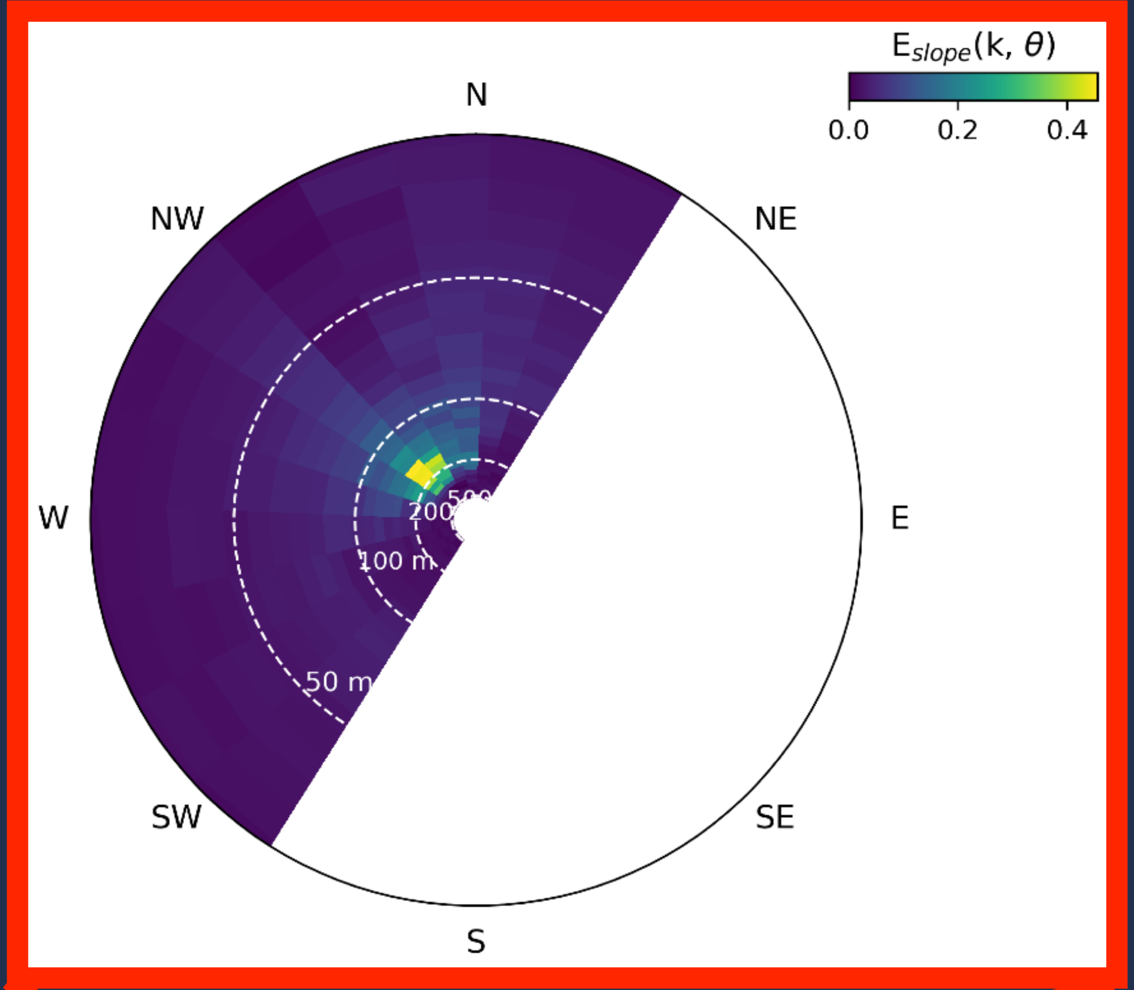
Villas Bôas et al (in prep)

Remember the anisotropy in the models?

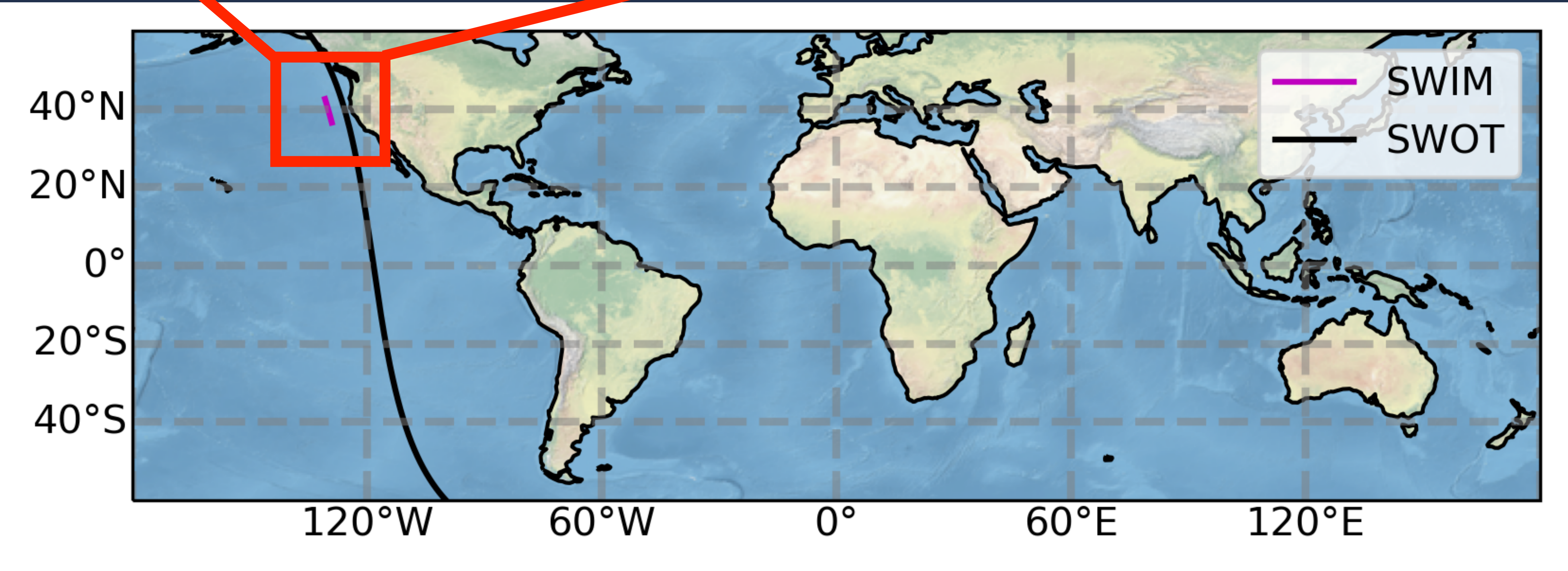


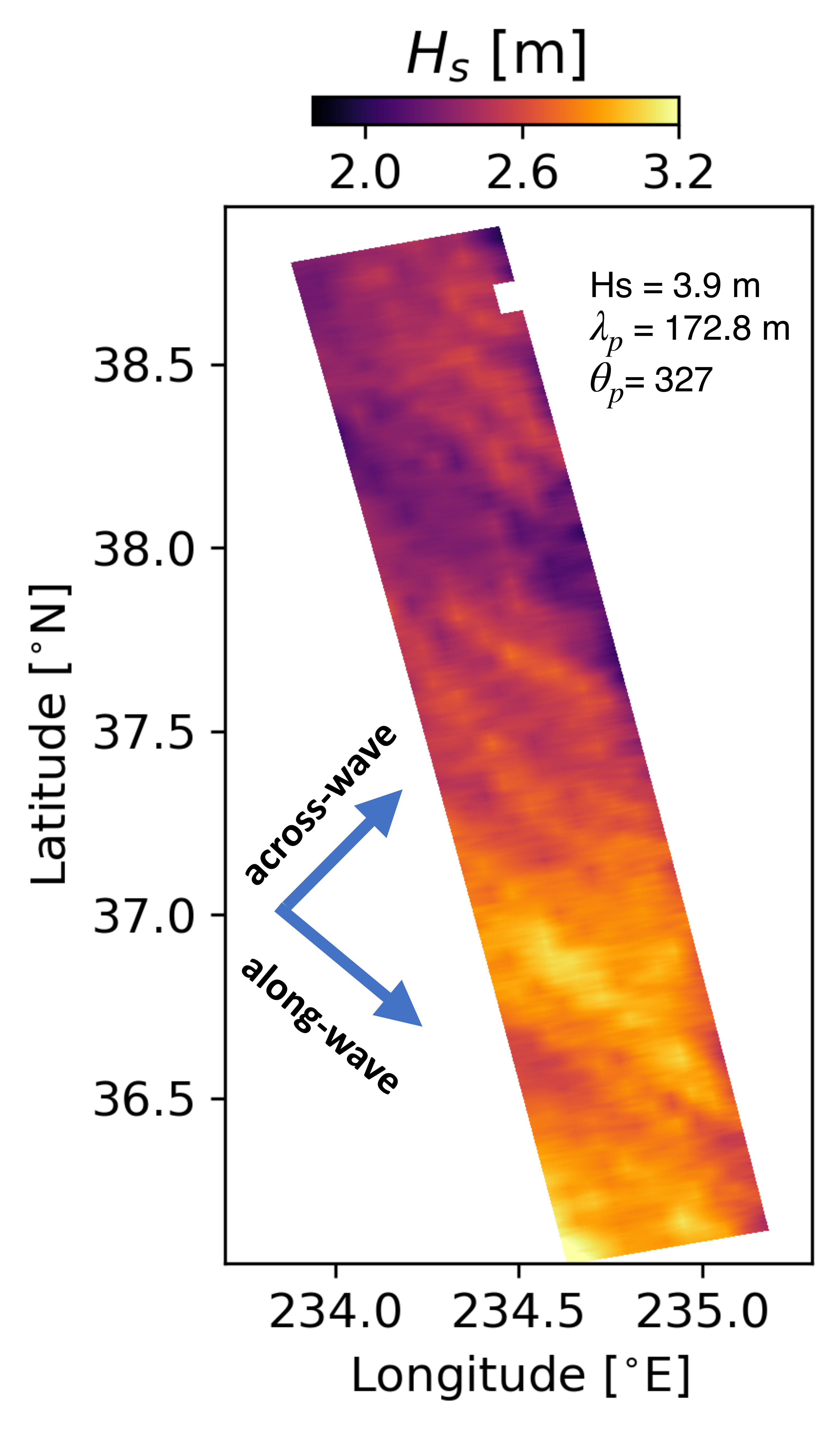


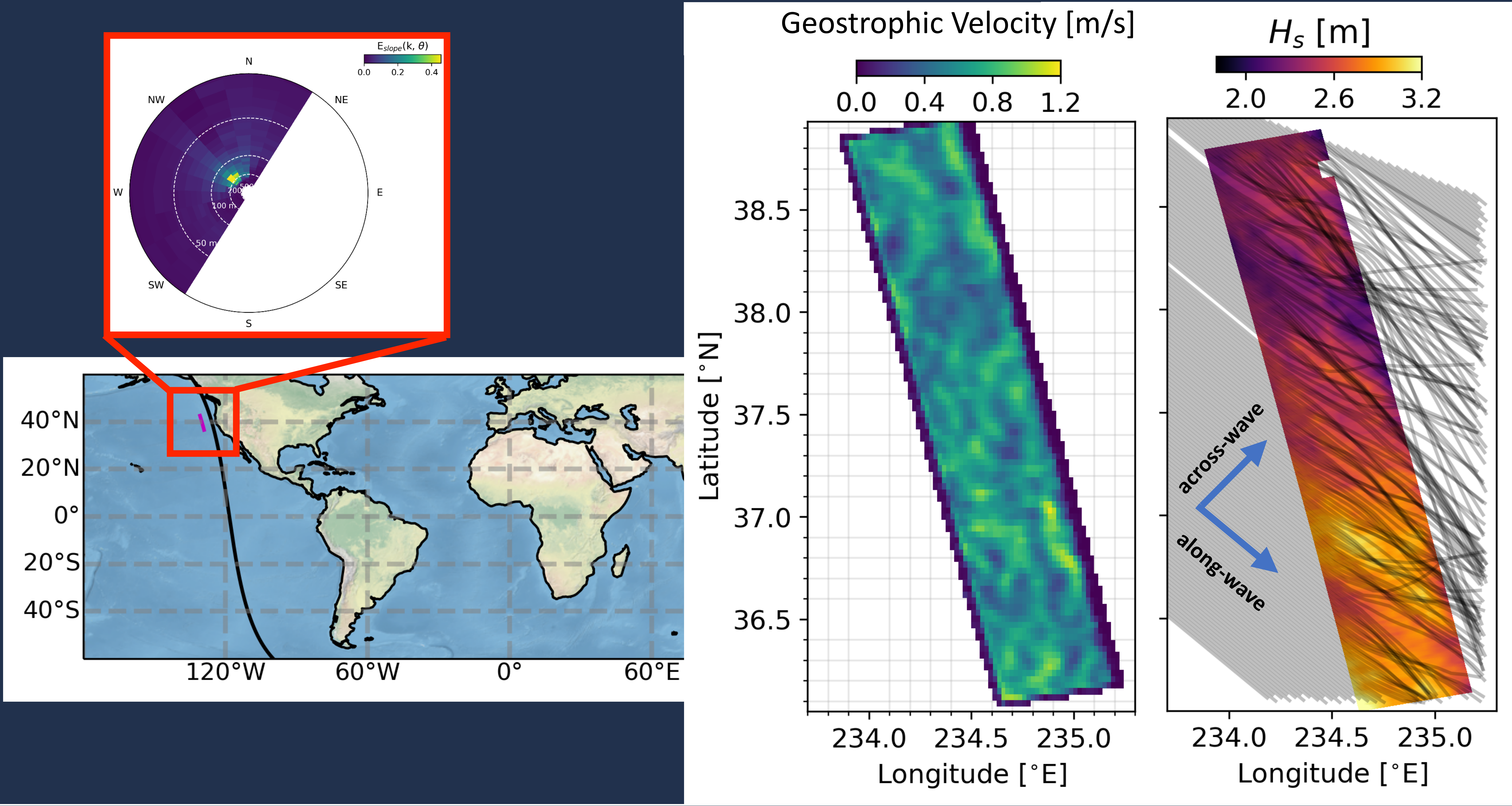




- **SWOT** observations reveal highly anisotropic H_s that agrees with predictions from model and U2H



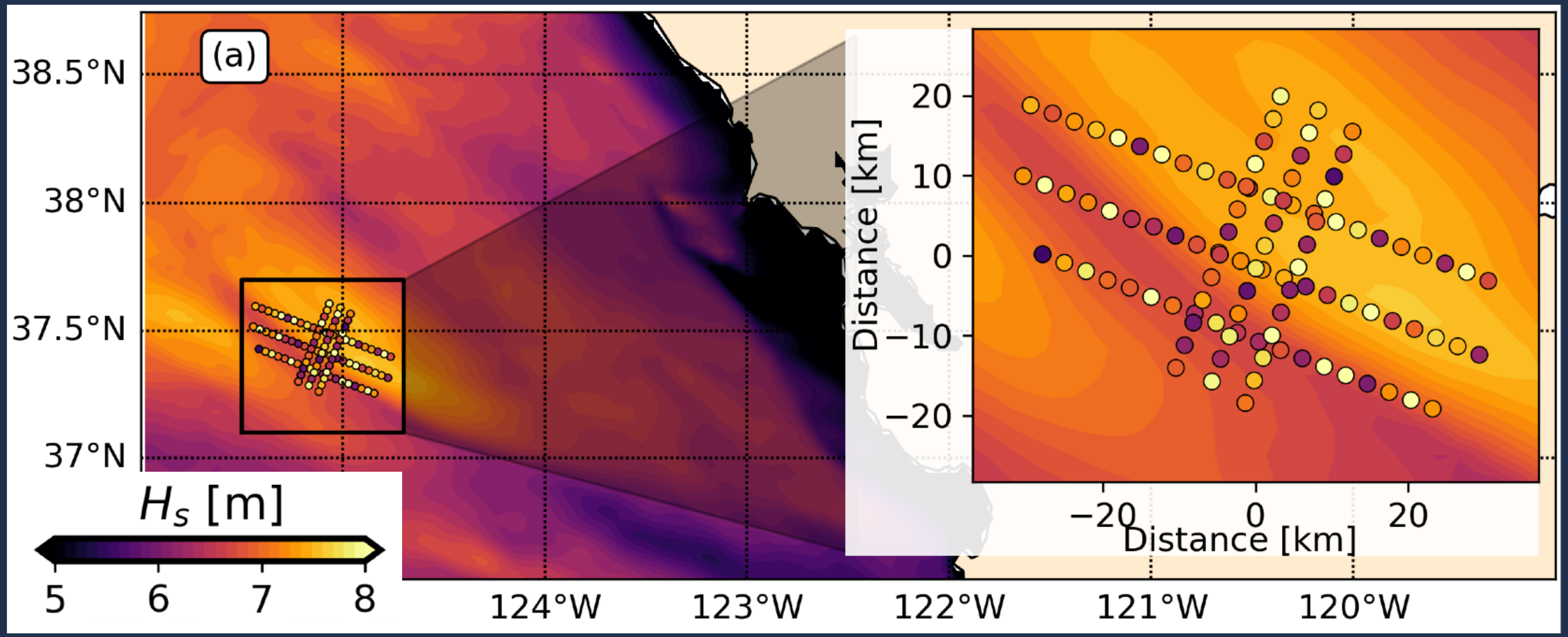



$E_{slope}(k, \theta)$
0.0
0.2
0.4
N
NE
E
SE
S
SW
W
NW
100 m
50 m
40°N
20°N
0°
20°S
40°S
120°W
60°W
0°
60°E
Geostrophic Velocity [m/s]
0.0
0.4
0.8
1.2
Latitude [°N]
38.5
38.0
37.5
37.0
36.5
234.0
234.5
235.0
Longitude [°E]
H_s [m]
2.0
2.6
3.2
across-wave
along-wave
234.0
234.5
235.0
Longitude [°E]

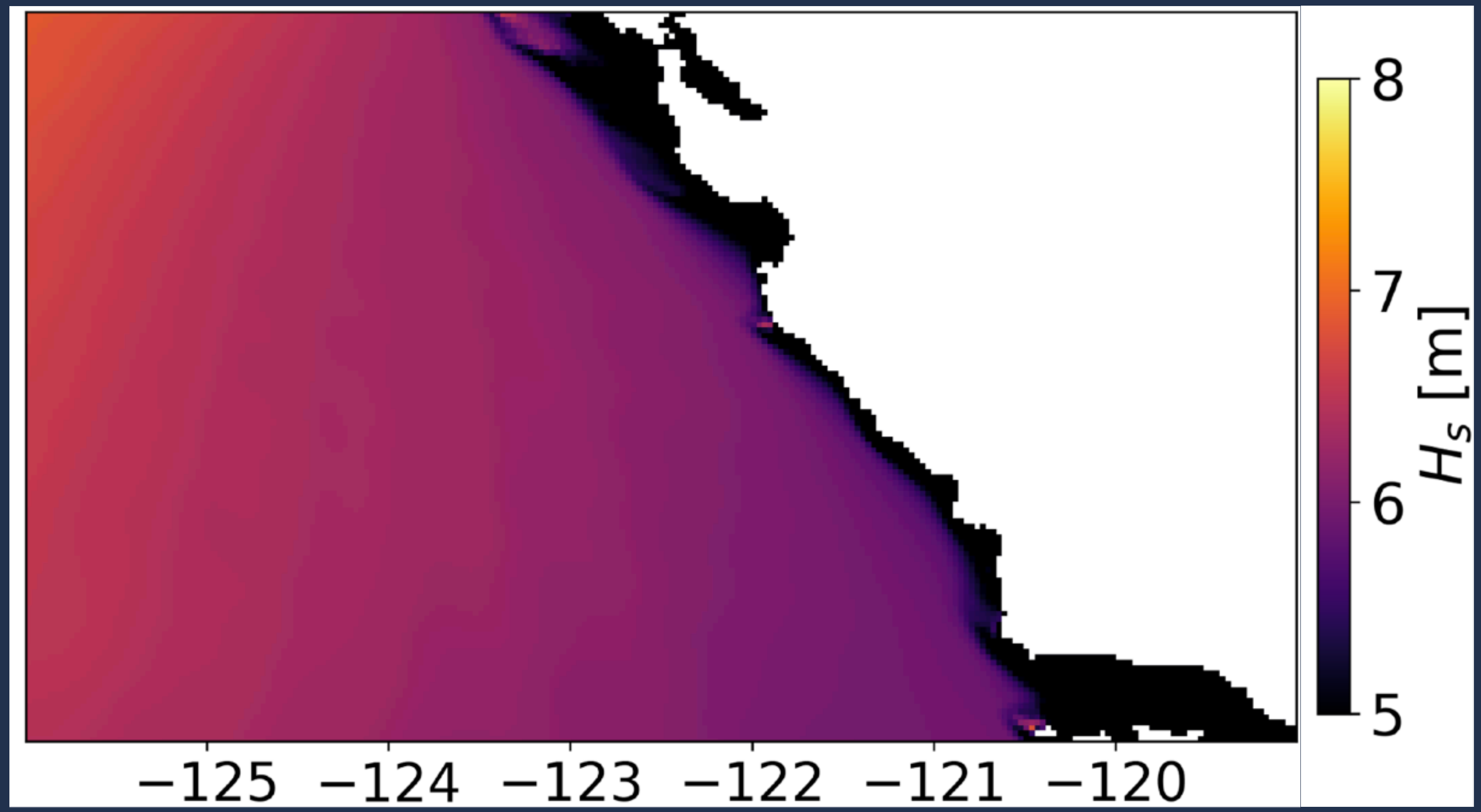
Take home:

Take home:

✅ The wave field looks like this

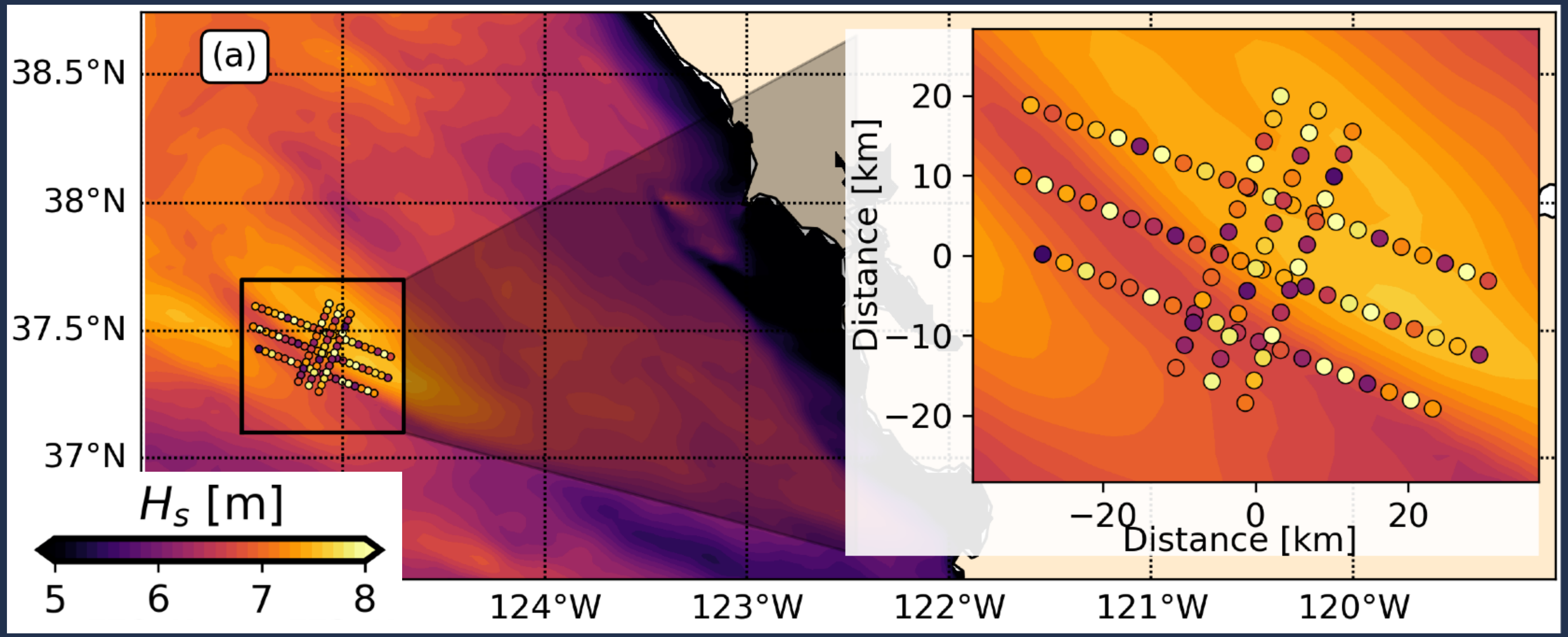


❌ Not like this

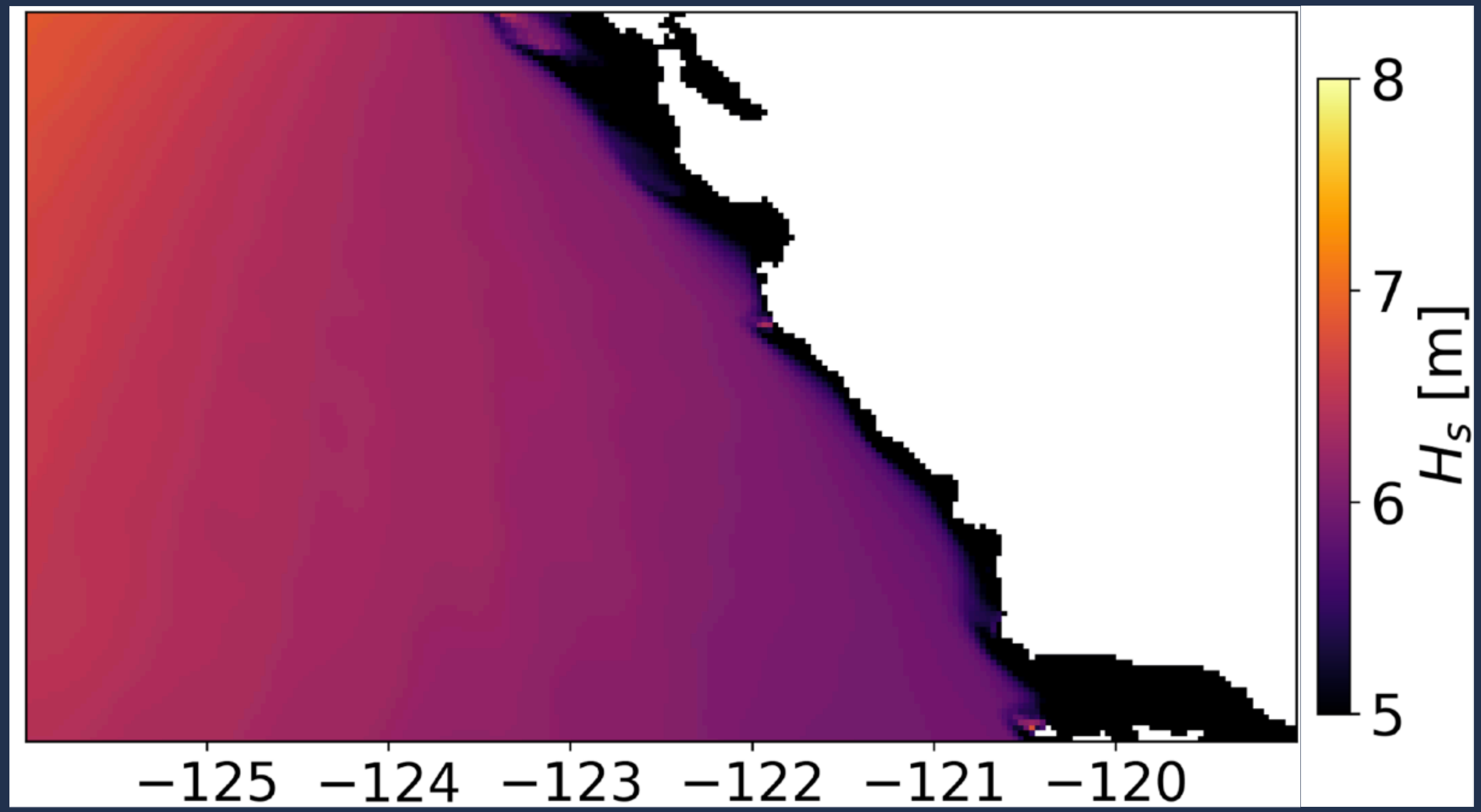


Take home:

✅ The wave field looks like this



❌ Not like this



- 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 contrains satellite obs?

MINES OCEANOGRAPHY

We're hiring!

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

villasboas@mines.edu

MINES IS NUMBER 5!!

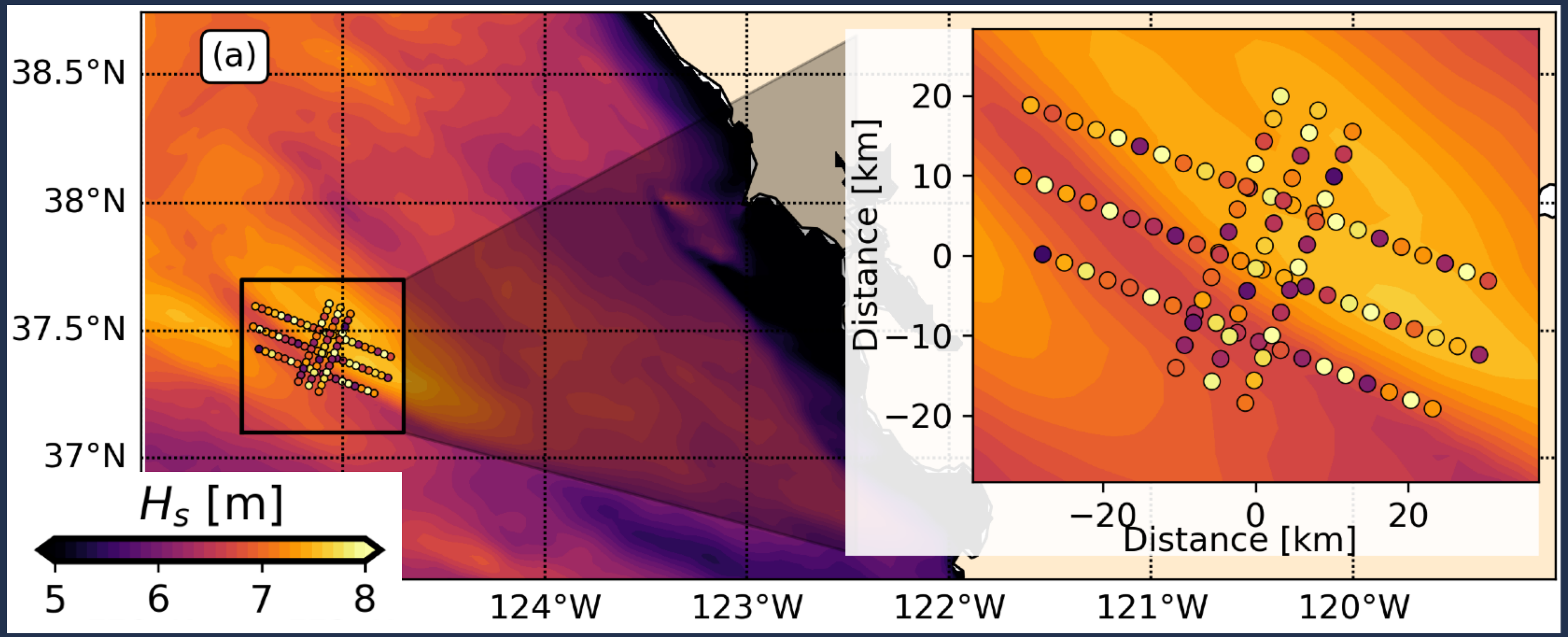
The latest US News and World Report ranking of Geophysics and Seismology graduate programs shows MINES Geophysics at #5!

1. Caltech
2. Berkeley UNIVERSITY OF CALIFORNIA
3. MIT Massachusetts Institute of Technology
4. Stanford University
5. COLORADO SCHOOL OF MINES

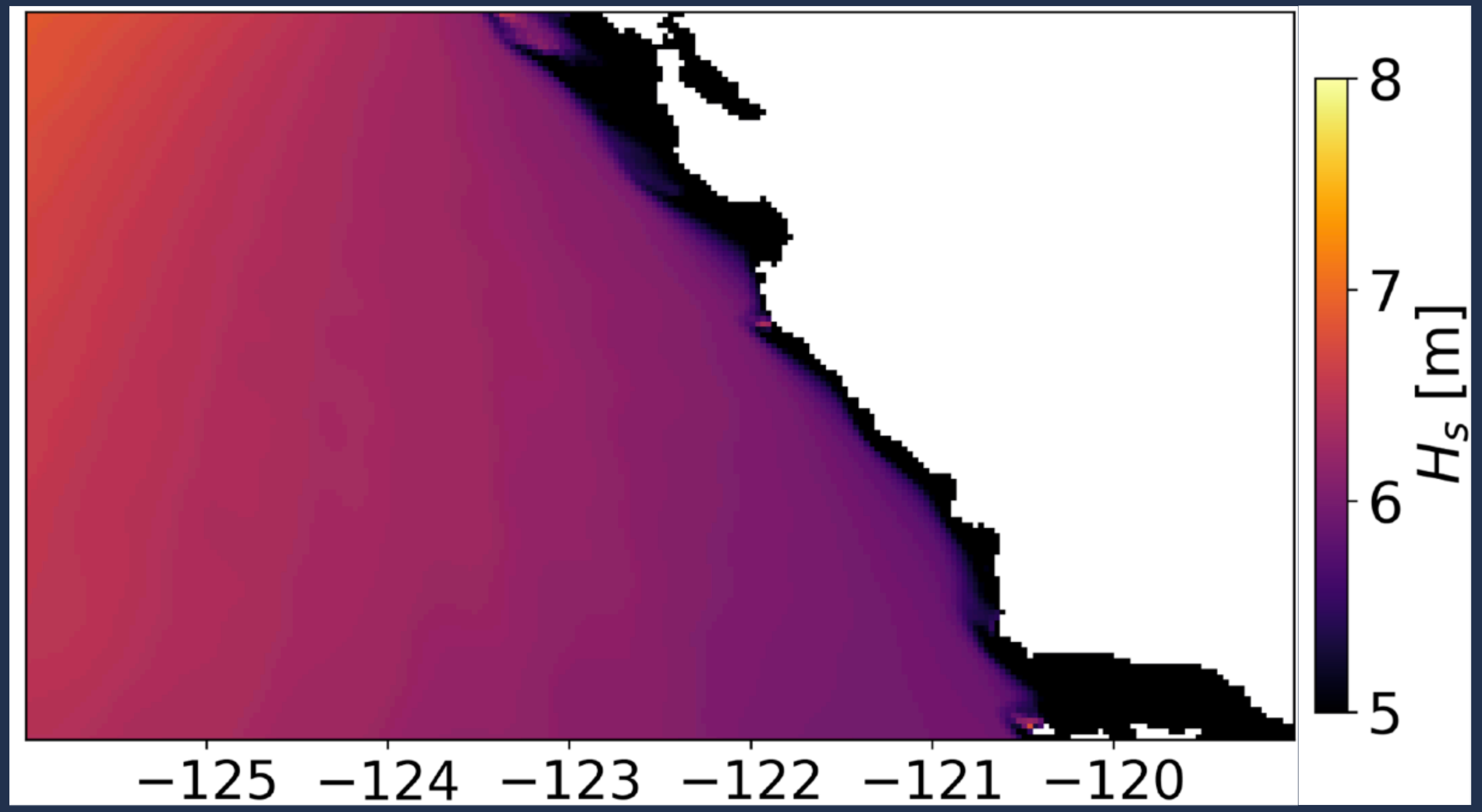
BEST GRAD SCHOOLS USNews

Take home:

✅ The wave field looks like this

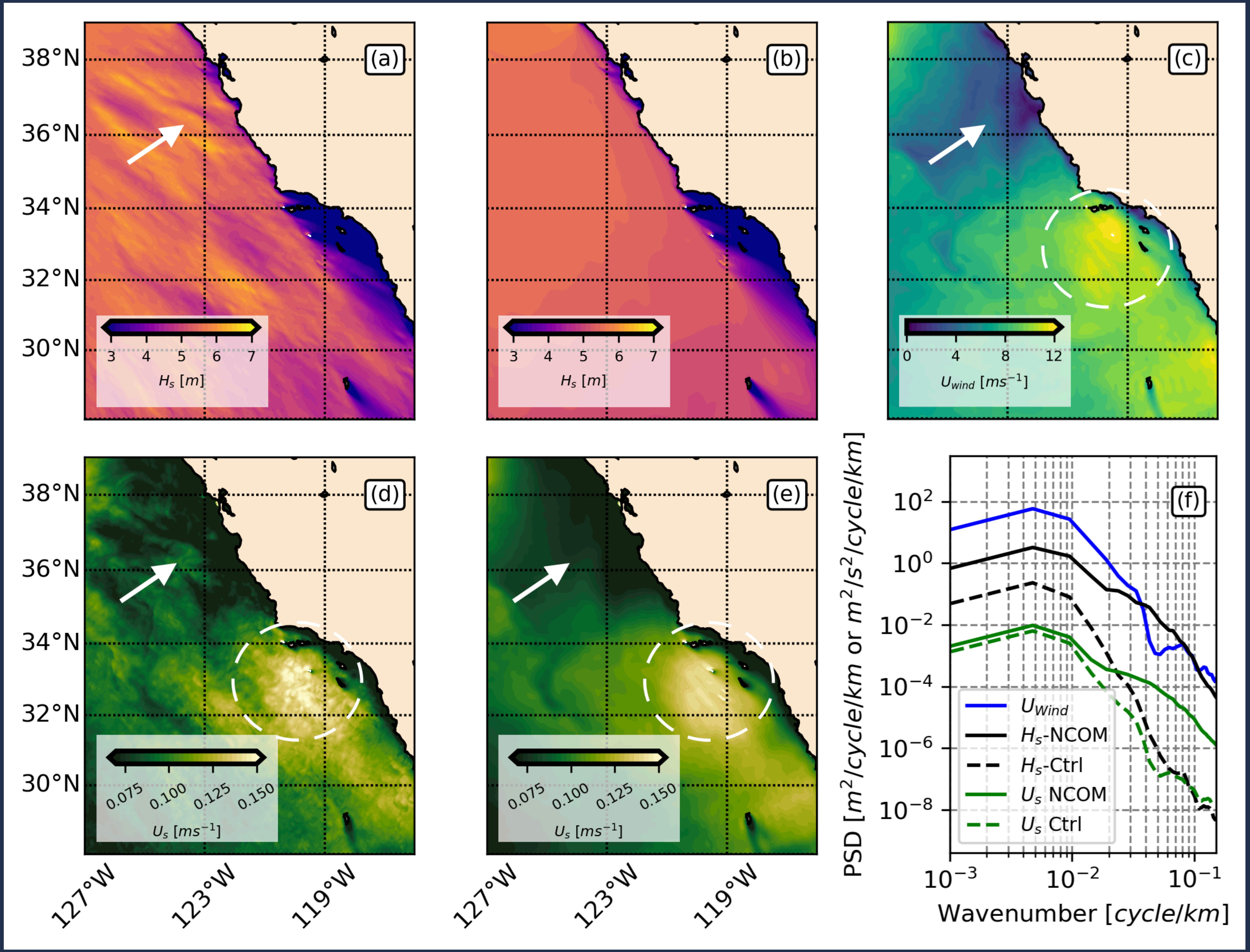


❌ Not like this



- 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 contrains satellite obs?

Backup



Marechal et al., in prep

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)?*

See also Romero et al., 2020

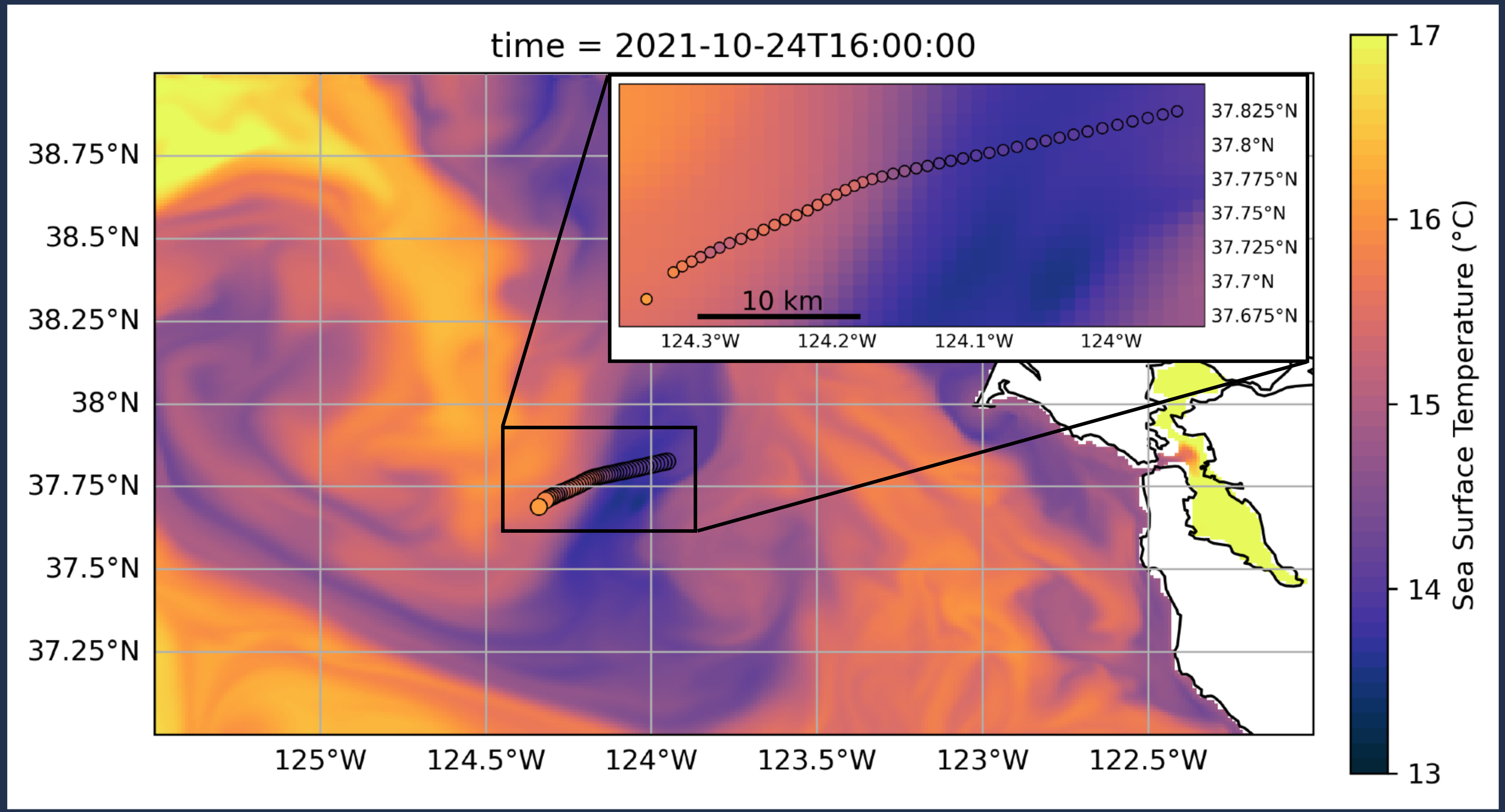
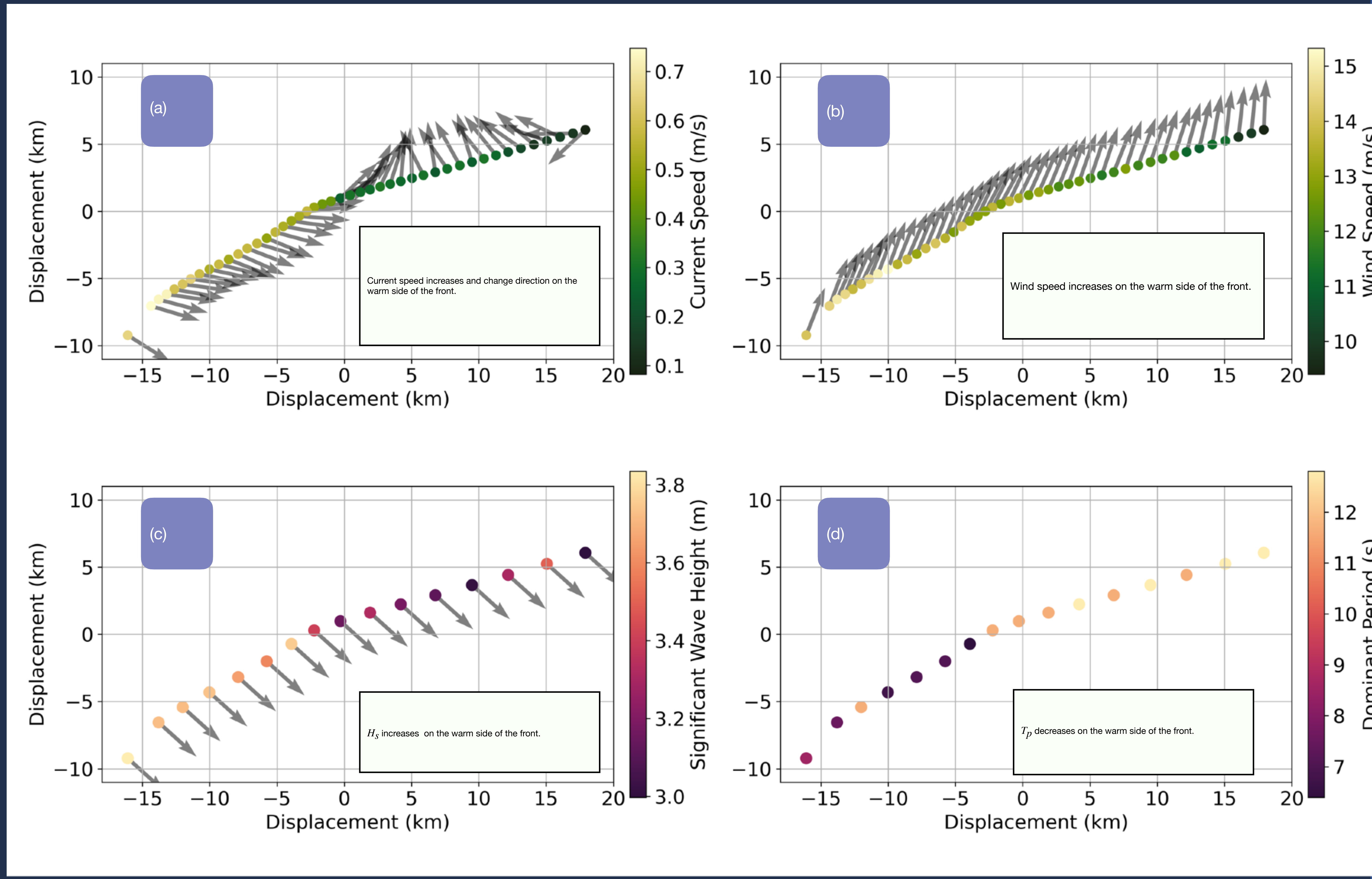
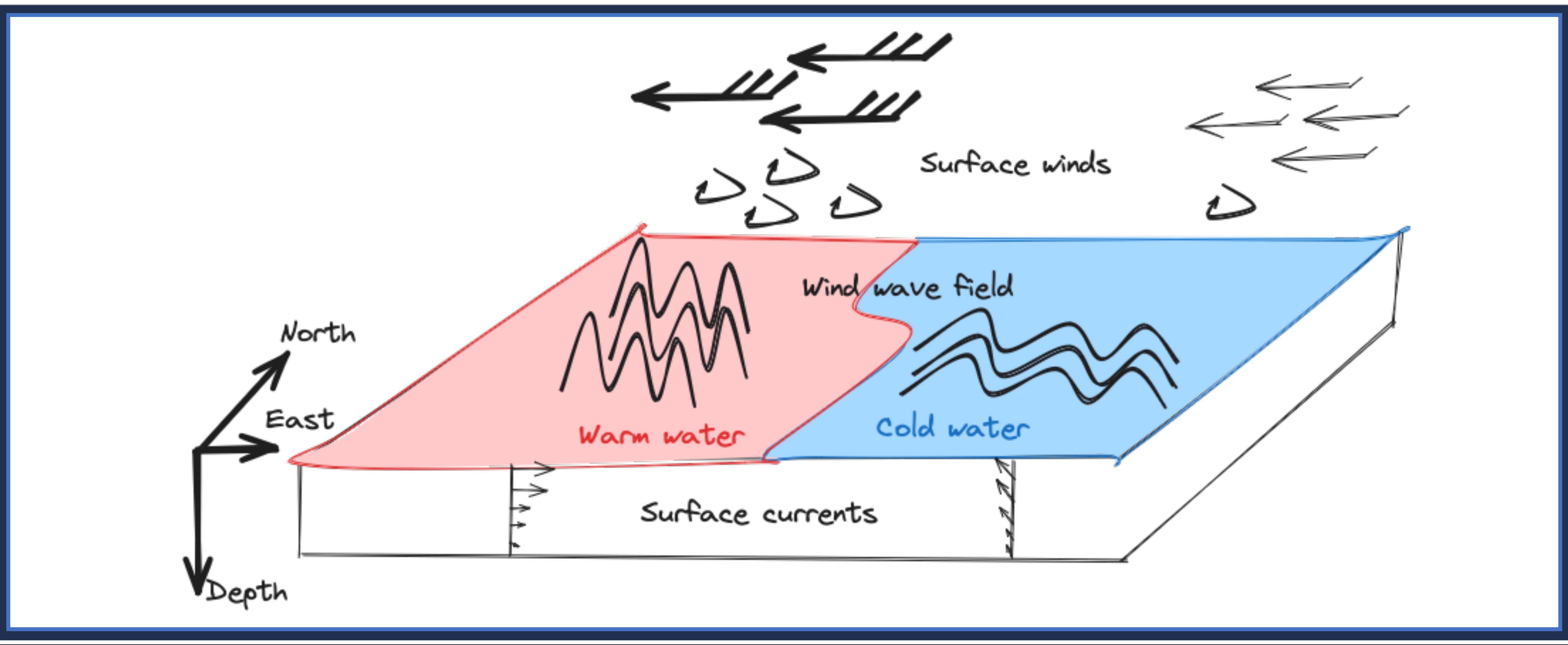


Figure 4: Sea surface temperature from the Navy Coastal Ocean Model (NCOM) with Saildrone sea surface temperature overlaid. The inset provides a zoom in the vicinity of a temperature front.





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 → $\varepsilon = U/c \ll 1$

$$\partial_t A + \nabla_{\boldsymbol{k}}\omega \cdot \nabla_{\boldsymbol{x}} A - \nabla_{\boldsymbol{x}}\omega \cdot \nabla_{\boldsymbol{k}} A = 0$$

magic asymptotics tricks

↓

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

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

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.

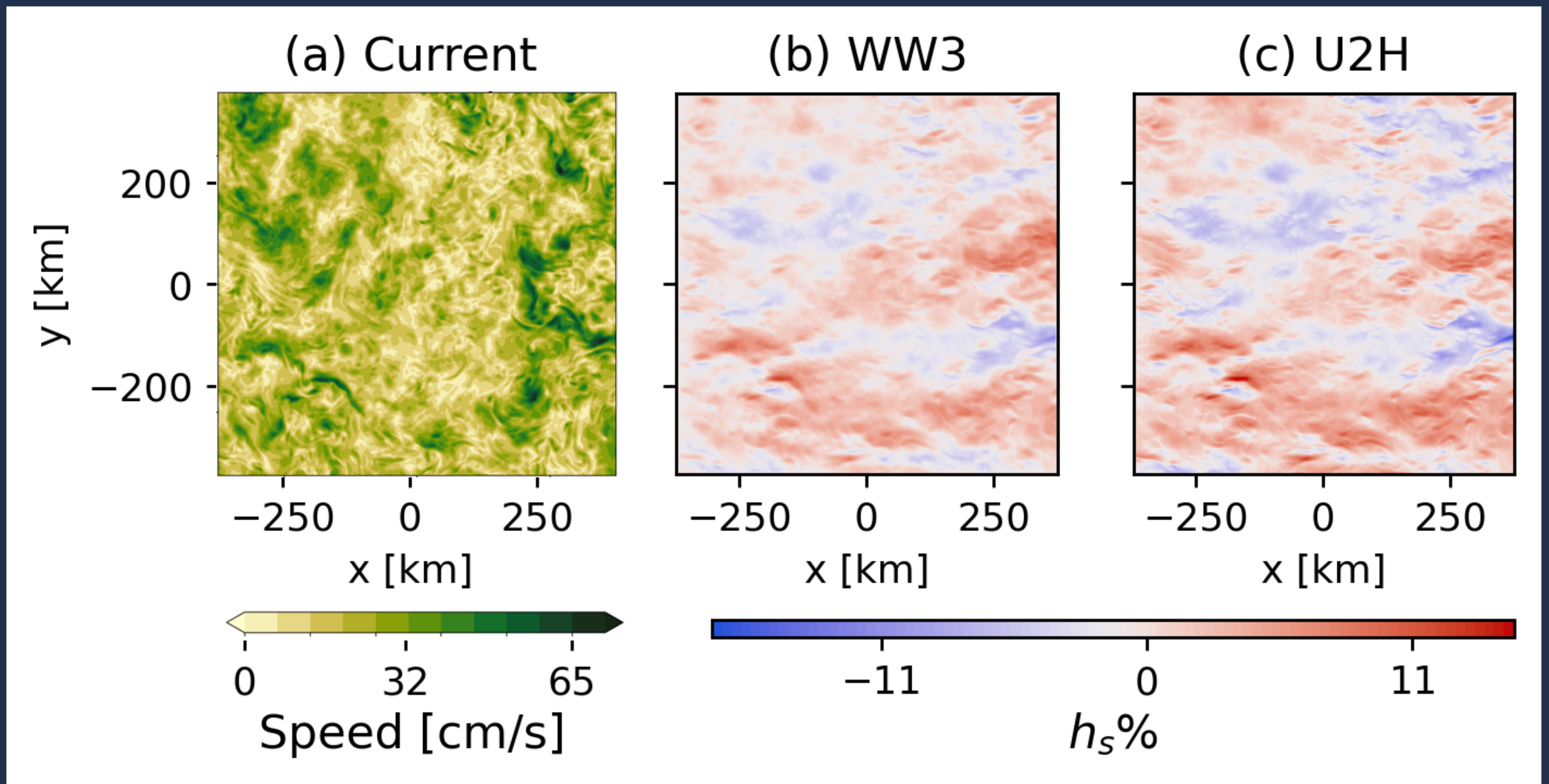
3. Weak current → $\varepsilon = U/c \ll 1$

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

magic asymptotics tricks

↓

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



surface currents → **WW3** → lots of CPU hours

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

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 → $\varepsilon = U/c \ll 1$

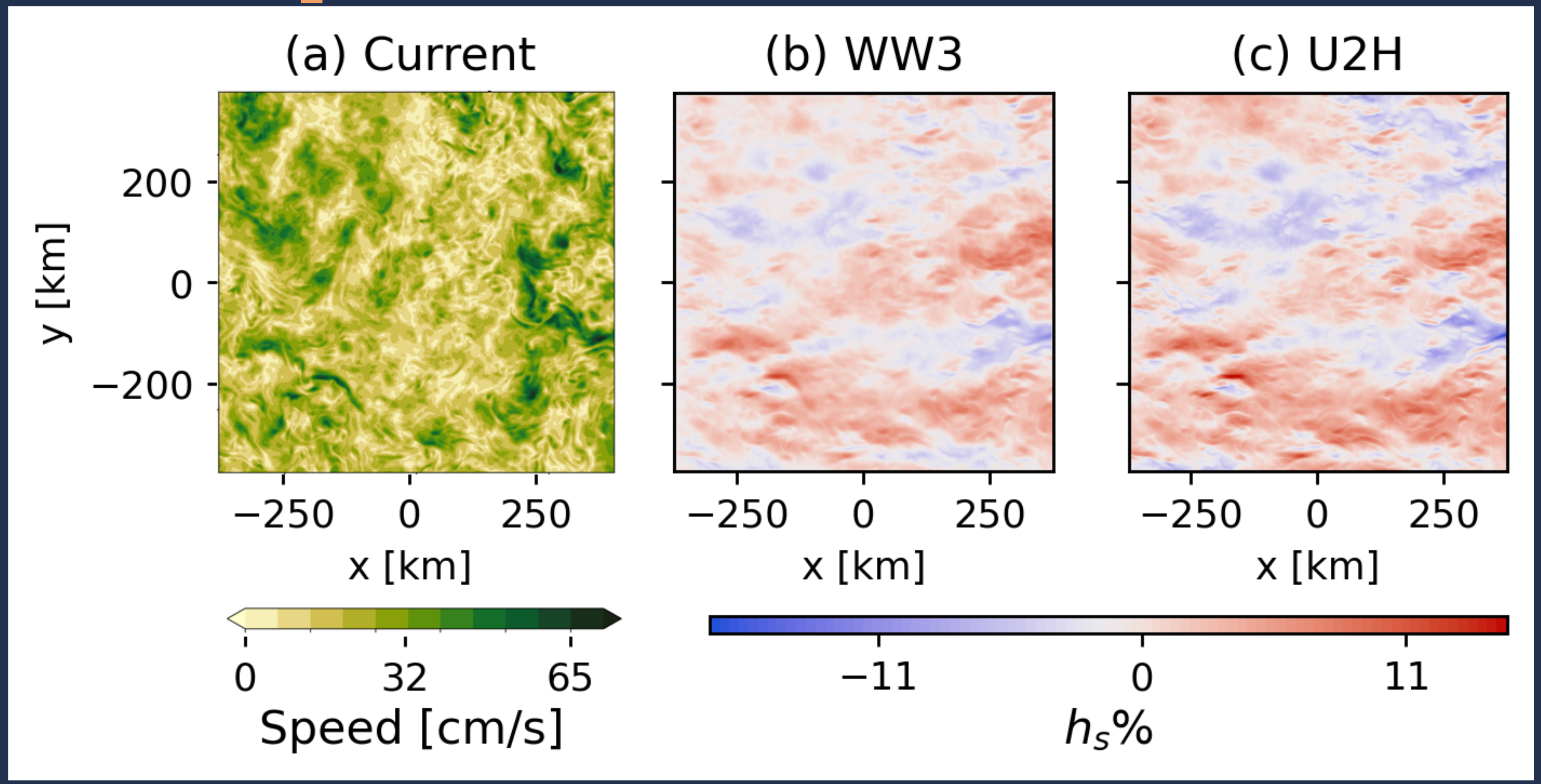
$$\partial_t A + \nabla_k \omega \cdot \nabla_x A - \nabla_x \omega \cdot \nabla_k A = 0$$

magic asymptotics tricks

↓

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

surface currents → (U2H) → A few secs on your laptop



surface currents → (WW3) → lots of CPU hours

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