Quantifying Sea State Gradients from Airborne Lidar Observations

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Motivation and Background:

Surface waves play a key role in the air-sea transition zone. Thus, understanding and quantifying how **currents modify the sea state in the meso-to-submesoscale range** is crucial for a wide range of applications such as air-sea fluxes and upper-ocean mixing parametrizations.

Surface wave observations in the meso-to-submesoscale range show **sharp H_s gradients** caused by **wave groups** at scales where **current-induced H_s gradients are expected to dominate.**
Can we disentangle the contribution of groups and currents **to sea state gradients** at these scales?

Data and Methods:

The Modular Aerial Sensing System (MASS): MASS is a scanning lidar that observes the sea surface elevation (η) at 1 m resolution over swath widths ranging from 100 m to 1 km [Melville et al., 2016].

Wavegliders: Infer the wave spectrum from the motion of the platform [Colosi et al. 2023].

Synthetic surface elevation: Derived from buoy frequency spectra assuming a cosine-type directional distribution. Note that we only consider cases with a single wave system.

$$E(f,\theta) = E(f)D(f,\theta) \text{ where } D(\theta) = cos(\theta - \theta_p)^{2s}$$

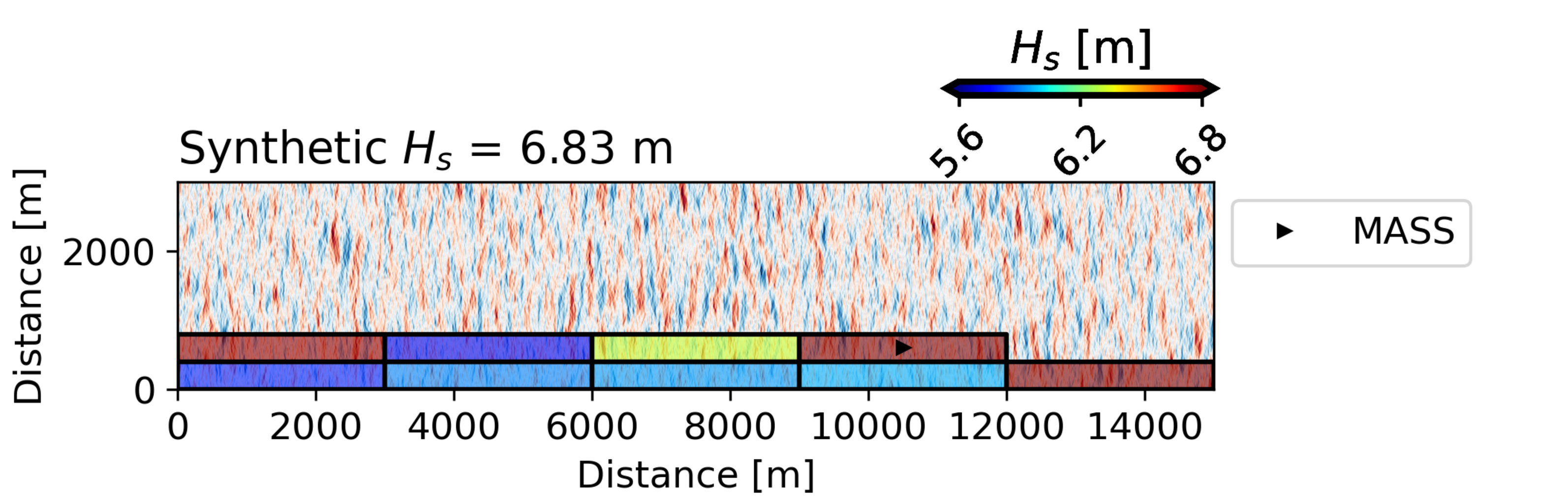


Figure 1: Synthetic 15 km x 3 km sea surface elevation for a narrow-banded wave spectrum. H_s computed over 3 km x 400 m boxes simulating MASS sampling is overlaid in jet.

H_s computed from synthetic sea surface elevation that does not include current effects but does have group modulation (Fig. 1) results in sharp H_s gradients at kilometer-scale.

Results: What wave conditions lead to grouppier sea states?

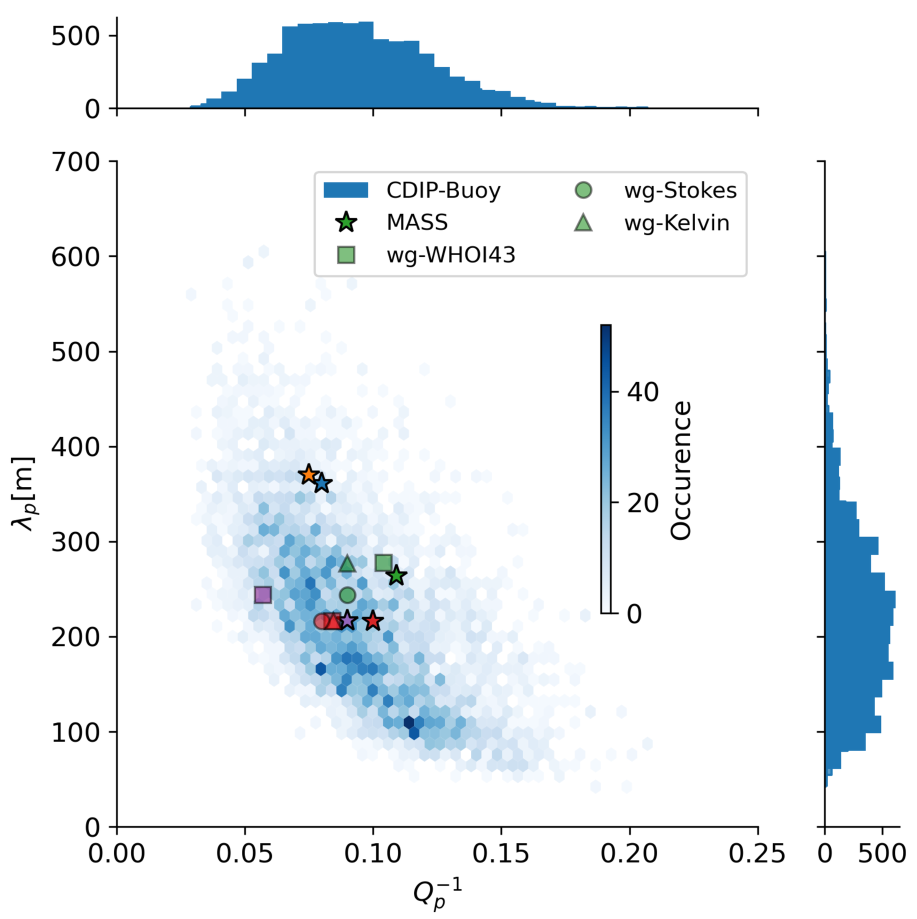


Figure 2: Joint probability density function of dominant wavelength and peakedness parameter.

The surface wave field is "grouppier" for narrow-banded spectra i.e., low values of Q_p^{-1} , where:

$$Q_p^{-1} = \frac{m_0^2}{2}\int_0^\infty f^{-1}E(f)^{-2}df.$$

The "grouppier" the sea states, the greater the influence of wave groups on H_s at longer scale; sea states are associated with **longer groups** and **the wavelength of the dominant waves (λ_p) tend to be longer** (Fig 2).

Spectral wave models capture current-induced sea state gradients ...

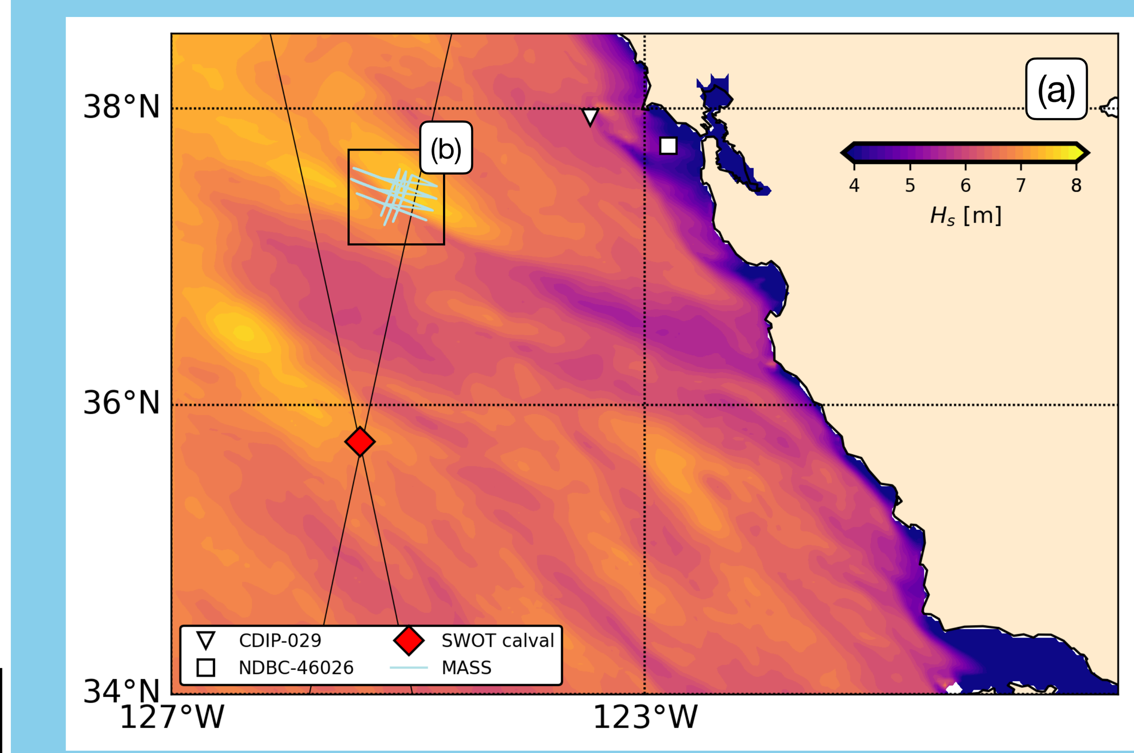


Figure 3a: Snapshot of H_s obtained from a WW3 run in the California Current Region during the S-MODE Pilot campaign. The model was forced with NCOM currents on a 3 x 3 km spatial grid.

Spectral wave models (e.g., WaveWatch III) forced with currents show **H_s gradients** in the **meso-to-submescale range** (Fig 4a). These gradients arise from **current-induced changes in wave direction (refraction)** and **frequency (Doppler shift)** and appear at scales **similar to the scales of the underlying current gradients.**

... but can't represent wave-group-induced gradients.

H_s observations from MASS reveal **sharp spatial gradients** that are not captured by the model. These gradients are associated with **wave groups** and appear in the observations at scales that overlap with scales where currents were previously thought **to dominate** the surface wave variability.

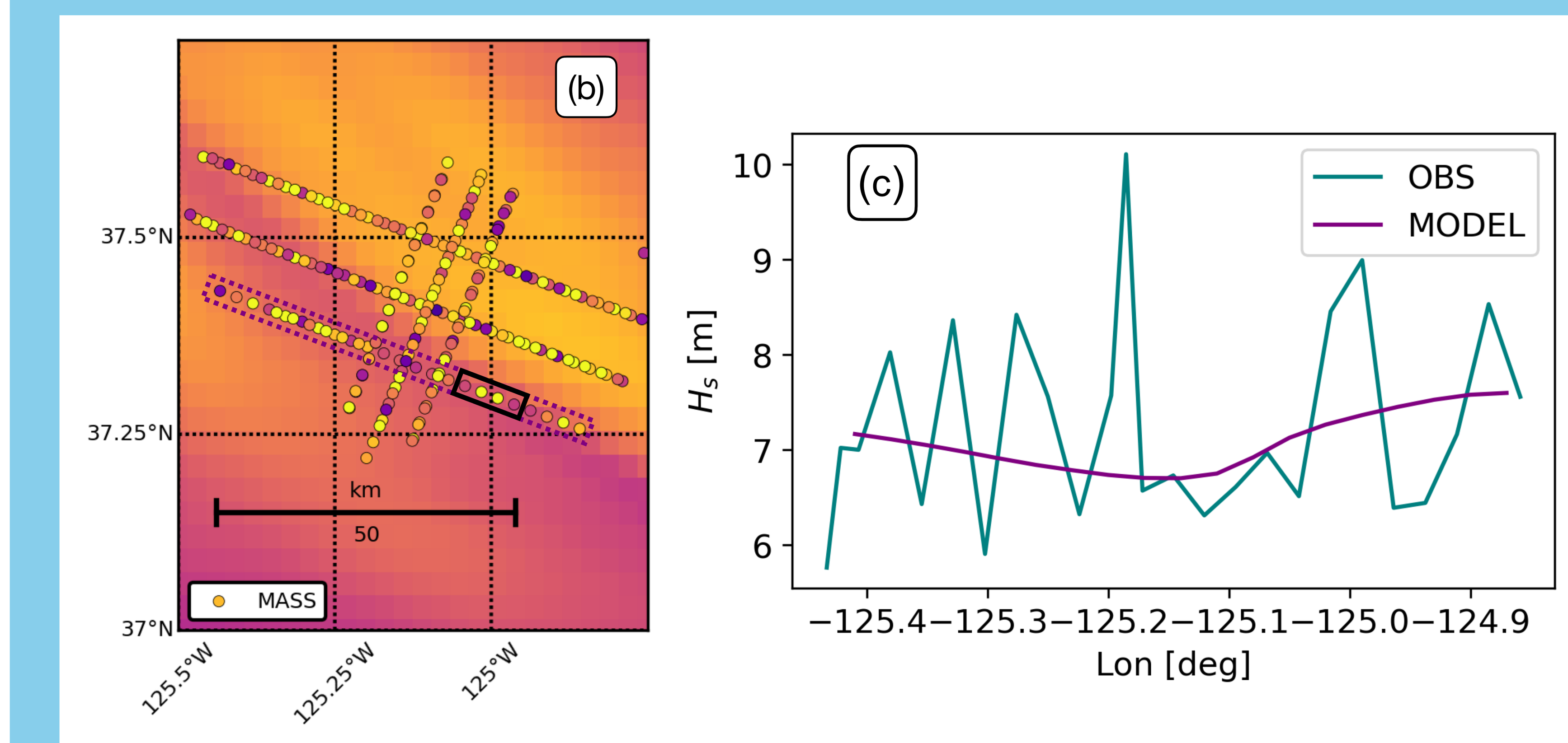


Figure 3: (b) Zoom on the snapshot shown in 3a with MASS observations superimposed in circles. (c) Comparison between model and MASS observations in the outlined purple dashed box in (b).

The presence of wave groups result in kilometer-scale changes in H_s that can exceed 2 meters

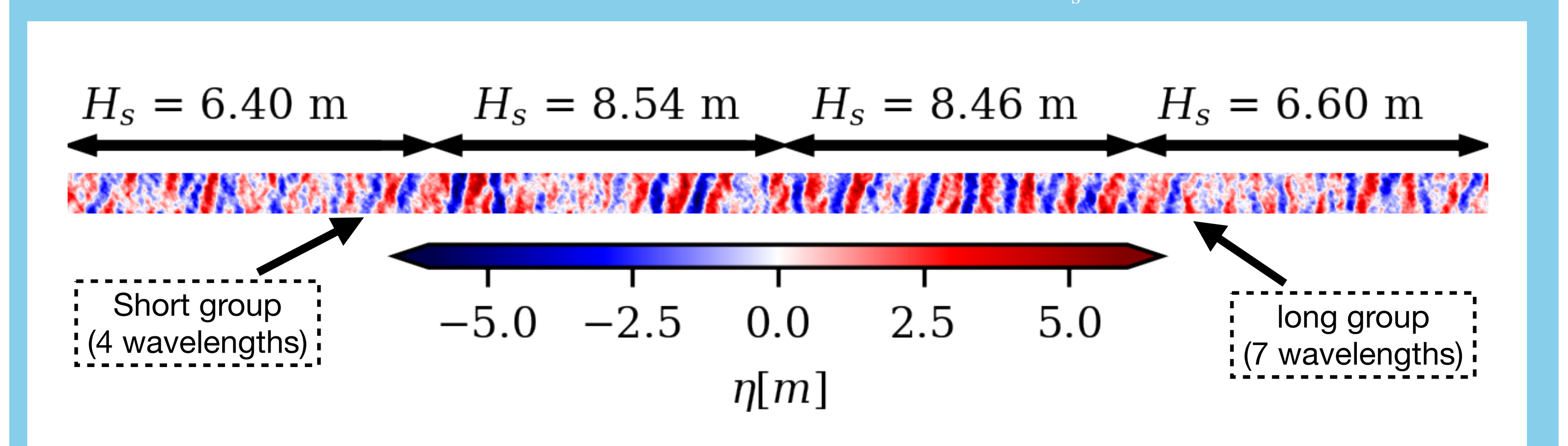


Figure 4: sea surface elevation observed from MASS over a 10 km x 400 m area (indicated in the black box on Fig 3b). The top arrows indicate the segment length (2.5 km) used to compute H_s shown in black.

At what spatial and temporal scales do groups impact the H_s variability?

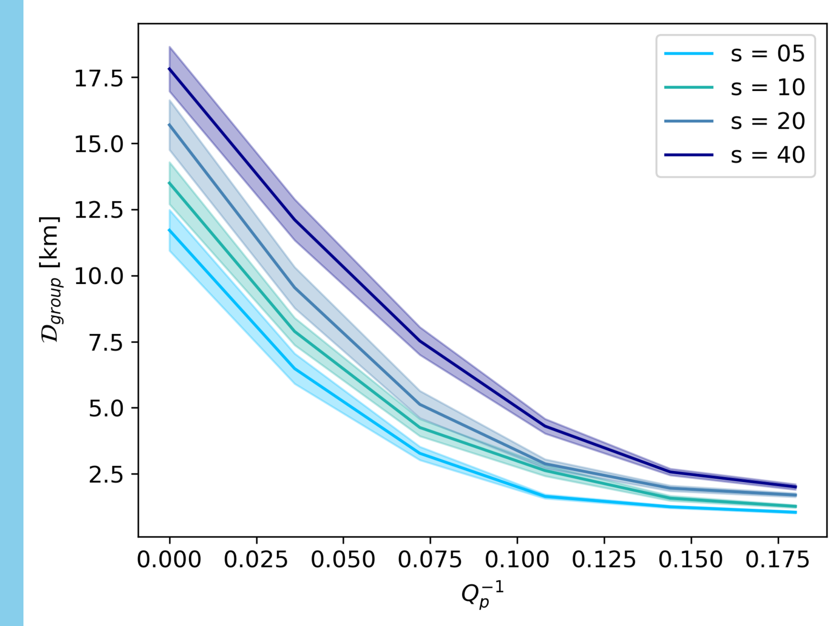


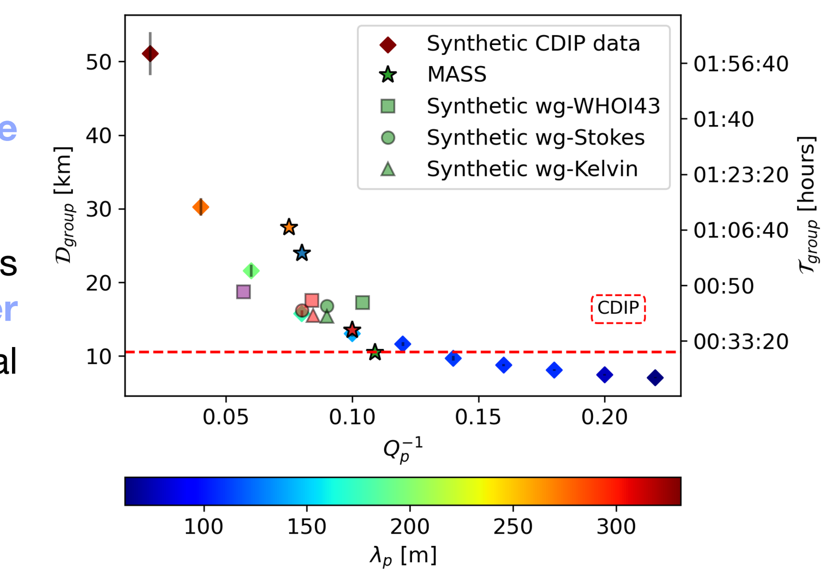
Figure 5: Spatial scales for which the effects of wave groups on H_s are averaged out. Estimated using synthetic wave fields within a 400 m swath.

The scales where groups affect H_s strongly depend on the **spectral shape of the wave spectrum** and can extend up to **several kilometers.**

For **swath-limited observations** (e.g., MASS), **both frequency and directional spreading** influence how groups impact H_s.

Understanding and quantifying how the **sampling geometry** changes how **wave groups modulate the observed signal** are essential for satellite remote sensing observations.

Figure 6: Spatial and temporal scales where the effects of wave groups on H_s are averaged out for one-dimensional observations.



Wave groups also introduce variability in **temporal wave records (e.g., wavegliders and buoys).**

However, the extent to which we can take longer averages to reduce the impact of groups **is constrained by other sources of temporal H_s variability** (e.g., tidal and diurnal currents, or changes in wind speed).

Takeaway 1: There is **no scale separation in space** between group- and current-induced H_s gradients. Both are noticeable in the meso-to-submesoscale range.

Can we mitigate the impact of groups by exploiting longer-lived H_s gradients induced by currents?

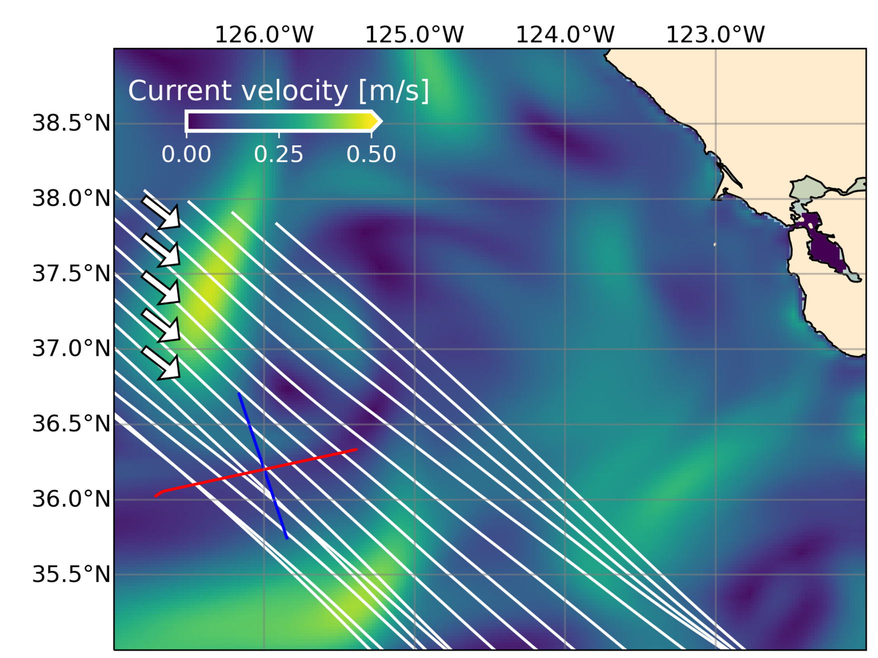


Figure 7: Current-induced refraction emphasized with ray tracing (white lines). The grid size is 2 km x 2.5 km.

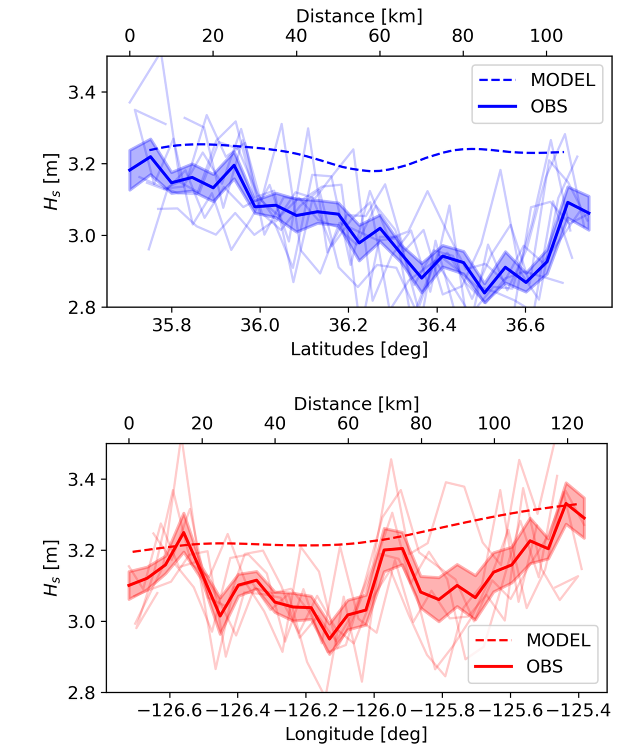


Figure 8: observations from reciprocal MASS tracks (solid light) and average (solid dark) compared with WW3 output in the same region (dashed).

There are persistent **anisotropic gradients** in averaged MASS data consistent with numerical and theoretical work [Villas Bôas et al., 2020, Wang et al., 2023].

Takeaway 2: The H_s comparison between model and observations **is still limited by the effective resolution** (both in amplitude and phase) of the current forcing.

What is next?

- The combination of observations from **Dopplerscatt, Dopvis,** and **SWOT** with reciprocal observations of the wave field from **MASS** will provide insights into both deterministic and statistical aspects of current-induced sea state gradients.
- We will also leverage current, wind, and wave observations acquired during the S-MODE and SWOT campaigns to examine quantities that depend on higher moments of the wave spectrum (e.g **Stokes drift**).

References

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