Observations and Modeling of Current Effects on Waves during the S-MODE Pilot Campaign

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Background: Surface currents modify the sea state via wave-current interactions. Satellite altimetry and idealized and realistic numerical simulations suggest that **the spatial variability of the significant wave height ($H_s = 4\sqrt{\langle \eta^2 \rangle}$) at oceanic meso and submesoscales is dominated by currents and that the H_s wavenumber spectrum follows the shape of the KE spectrum in the meso-to-submesoscale range.**

Motivation: **Surface waves play a key role in the air-sea transition zone.** Thus understanding and quantifying how the currents modify the sea-state down to $\mathcal{O}(1)$ km is crucial for a wide range of applications such as air-sea fluxes and the upper-ocean mixing parametrizations. Additionally, a number of recent studies have highlighted the potential for using wave observations to better understand and constrain ocean current variability. However, a **lack of simultaneous observations of waves and currents** at high spatial resolution limits our ability to validate numerical models and understand the physics driving **sea-state gradients.**

State of observations:

- **Ocean surface current:** Most ocean currents product at global scales are geostrophically balanced currents derived from altimetry (resolved at ~150 km).
- **Significant wave height:** Altimeter-derived H_s shows a correspondence between H_s gradients and current gradients in the mesoscale range (>100 km). Denoised altimeter data based on empirical filtering methods can resolve H_s down to ~30 km *(Dodet et al. 2020)*.

Here we use novel high resolution wave and current measurements from NASA's Sub-Mesoscale Ocean Dynamics and Vertical Transport Experiment (S-MODE) to investigate the spatial variability of H_s in the California Current System.

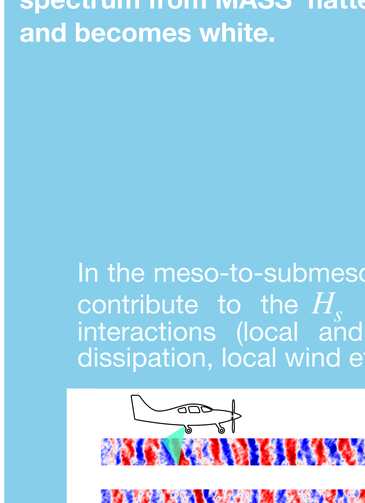
Snapshot of simulated H_s (WAVEWATCH 3) without (CTRL) and with (NCOM) current forcing during the S-MODE Pilot campaign.

H_s is consistent among all instruments as well as model.
Some discrepancies are due to the location of the measurements and the model forcings.

Inter-platform comparison of H_s measured/simulated during the S-MODE Pilot campaign

For more details:
Wavegliders (Grare et al. 2021), MASS (Melville et al. 2016)

Evolution of the H_s field during the S-MODE Pilot Campaign + supporting Information



Schematic representation of significant wave height and kinetic energy spectra.

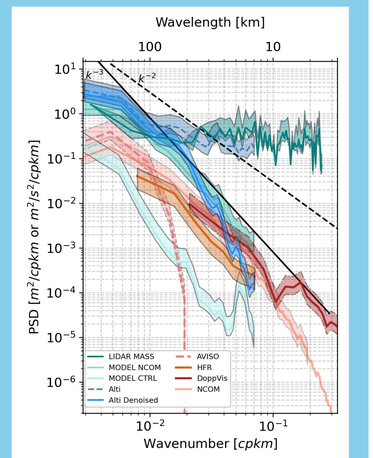
What we know:

Model and altimetry suggest that the H_s wavenumber spectrum is proportional to the KE spectrum at meso and submesoscales (Marechal and Ardhuin, 2021).

What we measure:

All H_s wavenumber spectra have a similar spectral slope to the KE spectra down 50 km.

At shorter scales, the H_s spectrum from MASS flattens and becomes white.



Wavenumber spectrum of: significant wave height (blue-shade) from model, altimetry, and MASS data ; kinetic energy from model, HFR, AVISO product, and DoppVis instrument (red-shade)

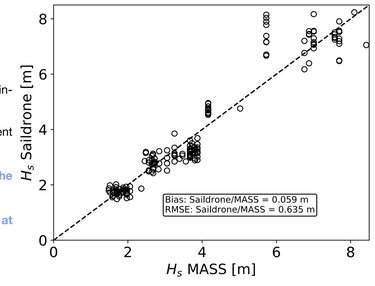
In the meso-to-submesoscale range, many processes may contribute to the H_s **variance** such as, wave-current interactions (local and non-local), wave groups, wave dissipation, local wind effects.

Four 7500 m x 300 m swaths of sea surface height measured by the MASS instrument

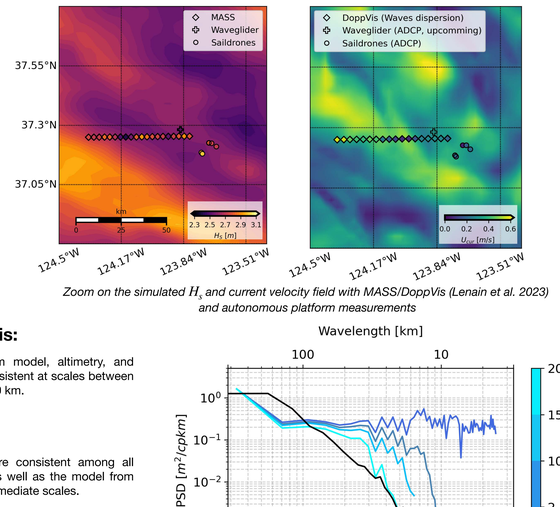
Results:

Numerical simulation vs data:

- There is a robust statistical agreement between MASS and in-situ measurements (see supporting information).
- H_s variability from model, altimetry, and MASS are consistent at scales between 300 km and 50 km.
- The **overall variability (large scale)** of H_s **is captured by the model.**
- **The model** **fails to reproduce the observed H_s gradients at scales of a few 10s of km ...**



...the **current forcing is poorly resolved at submesoscales**.



Zoom on the simulated H_s and current velocity field with MASS/DoppVis (Lenain et al. 2023) and autonomous platform measurements

Spectral analysis:

Variability from model, altimetry, and MASS are consistent at scales between 300 km and 50 km.

KE spectra are consistent among all instruments as well as the model from meso- to intermediate scales.

Spatially averaging H_s (MASS) leads to a "redder" spectrum.

Averaged wavenumber spectra of H_s measured by MASS and model. H_s measured by MASS have been smoothed at different scales with a moving average

Take away:

- **Wave-current interactions lead to H_s spatial inhomogeneity** in the mesoscale range. This variability is captured by MASS and altimetry observations at mesoscale.
- The H_s comparison between model and observations **is limited by the effective resolution** (both in amplitude and phase) of the current forcing.
- Numerical results suggest that the variance of H_s is proportional to the variance of KE in the meso-to-submesoscale range. This was **not corroborated by MASS observations** at scales smaller than 50 km. We found H_s variance one order of magnitude higher than suggested by altimetry and models which we hypothesize to be due to the contribution of a **superposition of unresolved of processes** that modulate H_s at these scales.

What is next? Further investigation is needed to understand what drives the H_s variability at intermediate scales and, more specifically, to quantify the role of currents on waves.

- Our preliminary investigation focused on the measurements from the S-MODE pilot campaign. Observations from the S-MODE IOPs and the upcoming SWOT calval campaign will provide more realizations and **longer tracks ⇒ higher spectral resolution.**
- Future work will leverage these observations examine quantities that depend on higher moments of the wave spectrum (e.g., **Stokes drift**).
- Multiple tracks over a broad range of sea states will also enable investigating the **anisotropy** in H_s observed in numerical models.