Modulation of Surface Gravity Waves at a Submesoscale Front

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Surface waves interacting with a submesoscale front

Surface waves mediate the exchange of momentum, energy, heat, and gases between the ocean and atmosphere. Quantifying the influence of surface waves on air-sea exchange and determining the processes modulating these sea-state dependent fluxes is needed for improving our understanding of air-sea interactions and how they are represented in climate models.

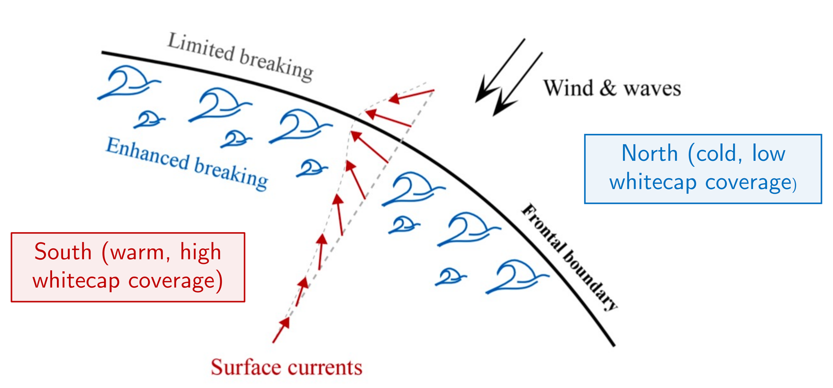
Interactions between winds, waves, and currents occurring over a broad range of space and time scales modulate the wave field, These interactions are pronounced near submesoscale fronts where strong currents lead to enhanced wave steepening and breaking.

We present novel high-resolution airborne remote sensing observations of wave-current interactions at a submesoscale front near the island of O'ahu, Hawaii and ask:

1. How do surface submesoscale currents modulate the surface wave field and, in turn, the sea-state dependent air-sea fluxes?
2. How do surface waves modify frontal dynamics and do observations corroborate theoretical models of these processes?
3. What are the spatial scales and distributions of the surface wave field and the underlying currents at a submesoscale front? What controls these distributions?

Wave-current Interactions

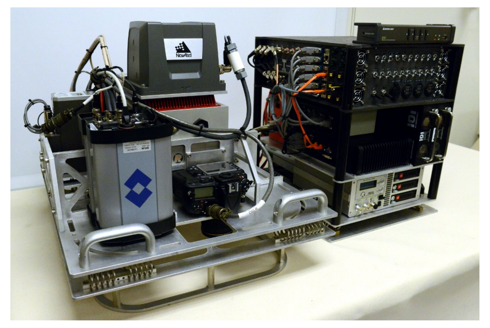
Waves are modulated by ocean currents via wave-current interactions which lead to variations in direction, frequency, and amplitude. These modulations result in **significant inhomogeneities of the wave field** and **enhanced nonlinear effect**s such as wave breaking at a frontal boundary.



The conceptual schematic shows wave-current interaction processes near the submesoscale front off the coast of O'ahu. Wave steepening is due to an interaction with opposing currents leading to enhanced breaking.

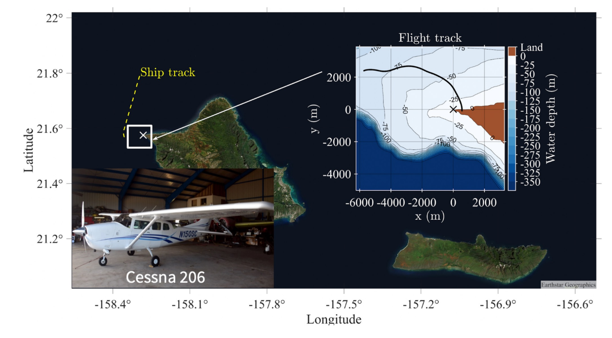
Observing a submesoscale front from airborne remote sensing

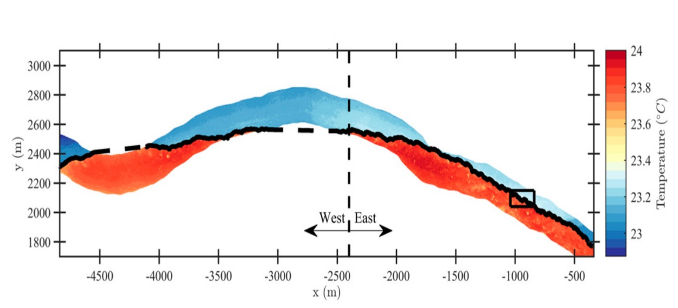
The Modular Aerial Sensing System (MASS; Melville et al. 2016) is an airborne remote sensing payload equipped to simultaneously collect high-resolution observations of winds, waves, currents, and other sea-surface properties.



Instrumentation	Measurement
Scanning Waveform Lidar (Riegl VQ-820G)	Directional Wave Spectra
High-Resolution Video (Flare 12M125-CL)	Wave Breaking Statistics
Long-wave IR camera (FLIR SC6000)	Sea Surface Temperature
GPS/IMU (Novatel SPAN-LN200)	Georeferencing and Trajectory

Observations of a submesoscale front by MASS, taken near the island of O'ahu, Hawaii in April 2018, show a sharp temperature gradient (0.5 °C in less than 100 m) at the frontal boundary.





Computing wave breaking statistics from video imagery

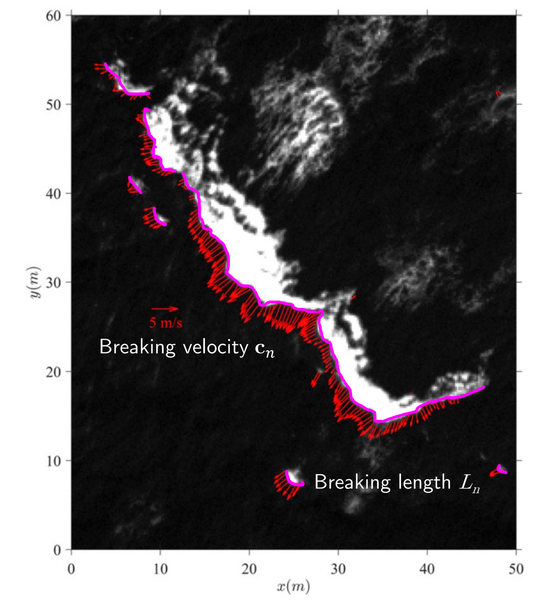
For a statistical measure of wave breaking, we use the breaking distribution $\Lambda(\mathbf{c})$ defined by Phillips (1985), such that

$$\Lambda(\mathbf{c})d\mathbf{c}$$

is the average total length per unit sea surface area of breaking crests with velocities in the range $\mathbf{c}$ to $\mathbf{c}+d\mathbf{c}$. Here, we compute $\Lambda(\mathbf{c})$ as

$$\Lambda(\mathbf{c}) = \frac{1}{A\Delta \mathbf{c}}\sum_n \left(L_n \middle| \mathbf{c} - \frac{\Delta \mathbf{c}}{2} < \mathbf{c}_n < \mathbf{c} + \frac{\Delta \mathbf{c}}{2} \right)$$

where L_n and $\mathbf{c}_n$ are the length and velocity of breaking for a given wave breaking event, with A the total area of the image. Many physically important variables can be derived from its spectral moments:



Total length of breaking front per unit surface area: $L = \int \Lambda(\mathbf{c})d\mathbf{c}$

The fraction of total surface area turned over per unit time: $R = \int c\Lambda(\mathbf{c})d\mathbf{c}$

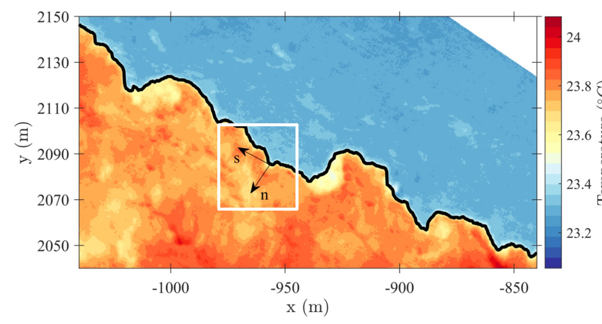
Fractional whitecap coverage: $W = \int cT\Lambda(\mathbf{c})d\mathbf{c}$

Rate of air entrainment per unit surface area: $V_a \propto \int c^2\Lambda(\mathbf{c})d\mathbf{c}$

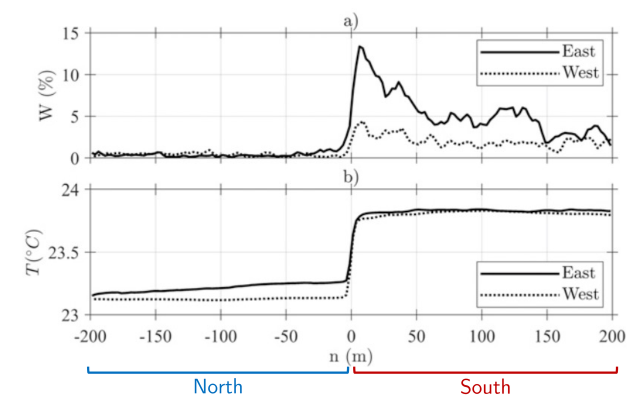
Momentum flux per unit surface area: $\mathbf{M} = \frac{\rho w}{g}\int bc^3\mathbf{c}\Lambda(\mathbf{c})d\mathbf{c}$

A rational frame for wave-current interactions at a front

To illustrate how wave and wave breaking statistics vary in the direction normal to the front, we define a curvilinear orthogonal coordinate system (s,n) that is tangent and normal to the front.

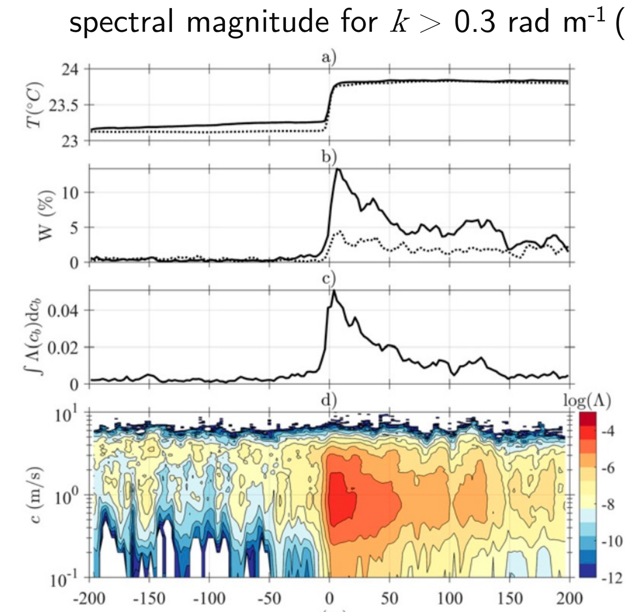


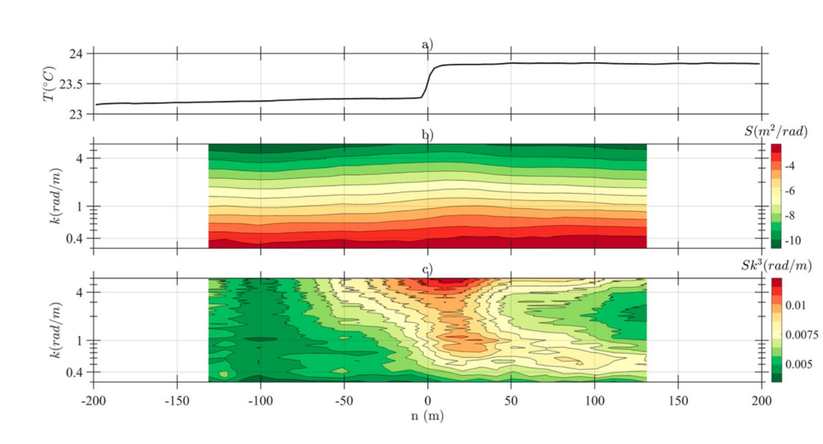
We see abrupt changes in whitecap coverage and SST as a function of distance n from the front.



Airborne observations of rapid changes of waves across the front

The wave breaking (left) and wave (right) statistics as a function of distance n to the front. We find that wave breaking statistics and its associated moments are strongly enhanced at the front. Similarly, waves steepen at the front, particularly at high frequencies, as seen by the increase in spectral magnitude for $k > 0.3$ rad m^{-1} (consistent with wave-current interactions).

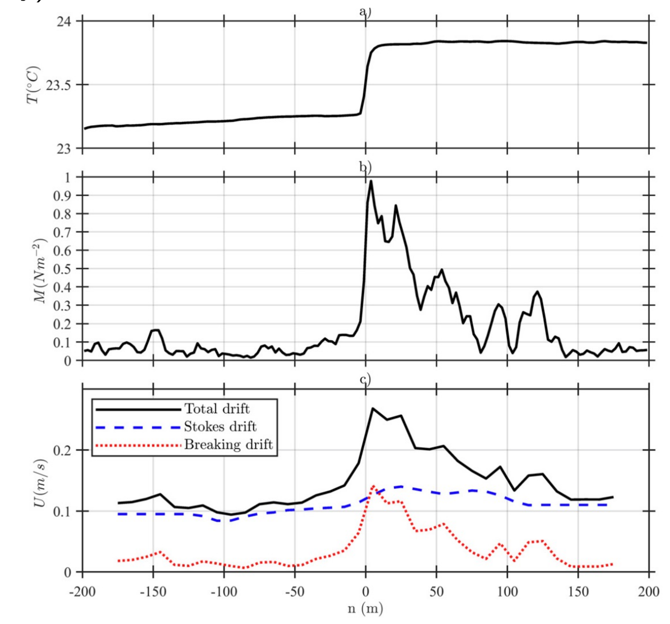




Breaking statistics and spectral properties of waves **vary significantly over very short spatial scales** on the order of a few meters illustrating strong inhomogeneities in the surface waves field.

Rapid modulation of wave and wave breaking induced momentum flux across the front

The momentum flux M to the water column from breaking waves increases by an order of magnitude near the front. Using the formulation of Pizzo et al. (2019), we estimate the breaking induced drift and the Stokes drift (Lenain and Pizzo 2020). We see that the drift is greatly increased at the front (an order of magnitude and ~50% for breaking and nonbreaking (i.e., Stokes) drifts, respectively).



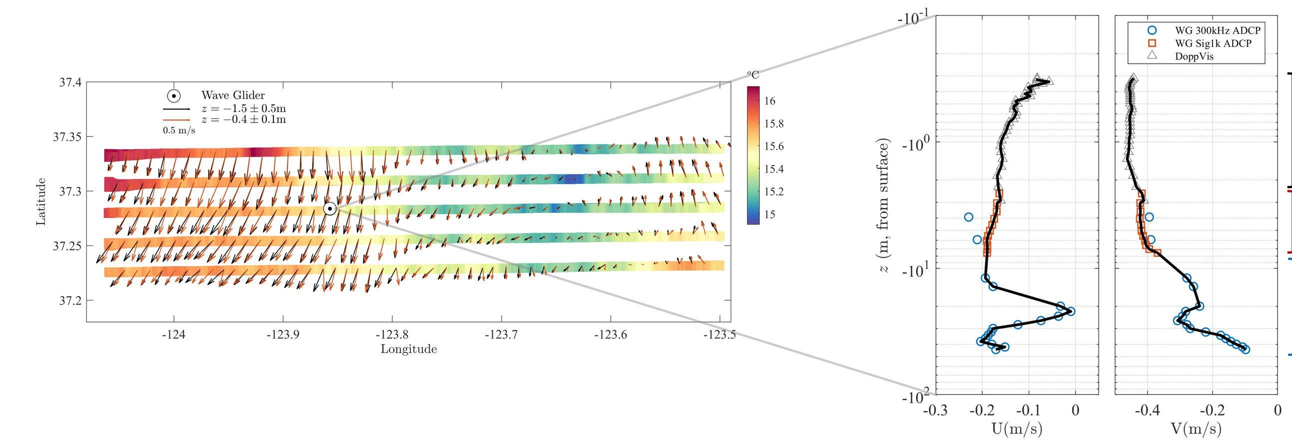
Localized breaking at the front provides an **important conduit for momentum transfer** from wind to the water column. These observations provides insight into realistic spatial distributions of momentum flux for coupled air-sea models.

Conclusions

- We find strong modulation of the surface wave field across the frontal boundary, including enhanced wave breaking, that leads to **significant spatial inhomogeneities in the wave and wave breaking statistics at scales on the order of meters.**
- The increase in wave steepness and wave breaking implies that other important quantities for **air-sea interaction**, e.g., increase in gas transfer (Deike 2022), **should also be increased** at the front.
- The momentum flux from the wave field to the water column due to wave breaking is **enhanced by an order of magnitude** at the front with similar significant increases in nonbreaking and breaking induced drifts over a distance of 50 m or less.
- We find that the distribution of momentum and the total wave induced drifts, key components governing submesoscale fronts, can **vary significantly in the presence of wave-current interactions** at fronts, impacting frontal stability and frontogenesis.

Concurrent airborne and in-situ observations of winds, waves, and currents from S-MODE

Missing from the observation presented here are measurements of near-surface currents, their horizontal gradients, and vertical shear. Velocity gradients are crucial for understanding submesoscale dynamics and their interactions with winds and waves. The development of DoppVis instrument (Lenain et al. 2023), a visible imagery camera that infers current profiles from the spatio-temporal evolution of surface waves, combined with observations from instrumented in-situ platforms, provides the opportunity to collect **collocated and coincident observations of winds, waves, and near-surface currents at the submesoscale.**



These novel observations, collected during S-MODE, will improve our understand of how submesoscale currents modulate surface waves and their associated air-sea fluxes and the role of surface waves in modifying submesoscale dynamics.

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