Stokes drift and current coupling at the submesoscale

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Submesoscale wave-current coupling impacts air-sea fluxes

The evolution of submesoscale features occurs in the ocean surface boundary layer, inciting large vertical velocities that modulate air-sea fluxes. Surface gravity waves also modulate air-sea fluxes and induce transport in the ocean's surface boundary layer through Stokes processes. Simulations resolving Langmuir turbulence and submesoscale features suggest that their evolution depends on their alignment with the wave field [5]. Additionally, horizontal buoyancy gradients have been observed to coincide with horizontal gradients in the wave field (figure 1a). This study is part of a larger effort to **determine the role waves play in the evolution of submesoscale features** by understanding whether Stokes forces induce, respond to, or are independent of the velocity gradient fields generated.

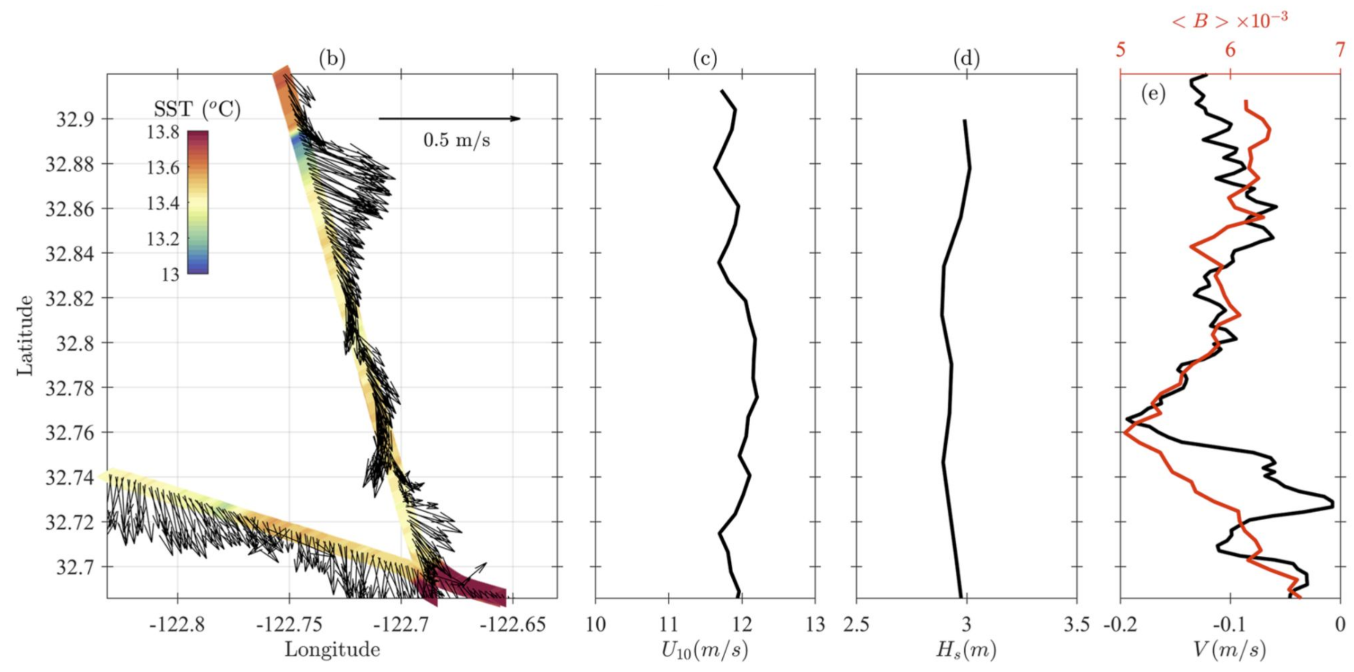

Figure 1. (a) Enhanced wave breaking at a submesoscale front photographed during the S-MODE IOP1 field campaign. (b) Modular Aerial Sensing System Sea Surface Temperature (SST) collected during the Task Force Ocean experiment on 19 May 2021. (c and d) show the wind speed U_{10} and significant wave height H_s collected along the North-northwest-South-southeast track shown in panel (b). (e) North component of the current V and mean spectral saturation ⟨B⟩, all plotted over the same range of latitude as in panel (b). Note the modulation of ⟨B⟩ associated with changes in V, the component of the current aligned with the waves, hinting at local wave-current interaction. [3]

Modular Aerial Sensing System (MASS) *DoppVis* and *LiDAR*

The Modular Aerial Sensing System (MASS) collected a unique set of airborne observations during the **NASA Sub-Mesoscale Ocean Dynamics Experiment (S-MODE)**. The experiment aims to observe the significant contributions of submesoscale dynamics to upper ocean vertical transports. The MASS resolved the lateral temperature gradients and divergent horizontal surface currents that define the oceanic submesoscale, as well as their spatiotemporal evolution, making it integral to the mission [3]. This dataset contains the first airborne observations of collocated and coincident Lagrangian velocity profiles and Stokes drift profiles in the ocean surface boundary layer.

Instrumentation	Variables
DoppVis (Nikon D850 Video Camera)	Lagrangian surface current profiles **U**(z)
Riegl VQ-780 II-S Topographic LiDAR	Directional wavenumber spectra **F**(**k**), Stokes drift profiles $\mathbf{U_S}(z)$
Heitronics KT19.85 II IR thermometer	Sea surface temperature SST

Table 1. Instrumentation and variables measured for the Modular Aerial Sensing System (MASS).

Directional surface wave spectra are derived from 2D sea surface elevation, $\boldsymbol{\eta}$, swaths retrieved by the MASS topographic *LiDAR* (figure 1). These spectra characterize the wave field and allow the underlying Stokes drift profiles, $\mathbf{U_S}(z)$, to be inferred.

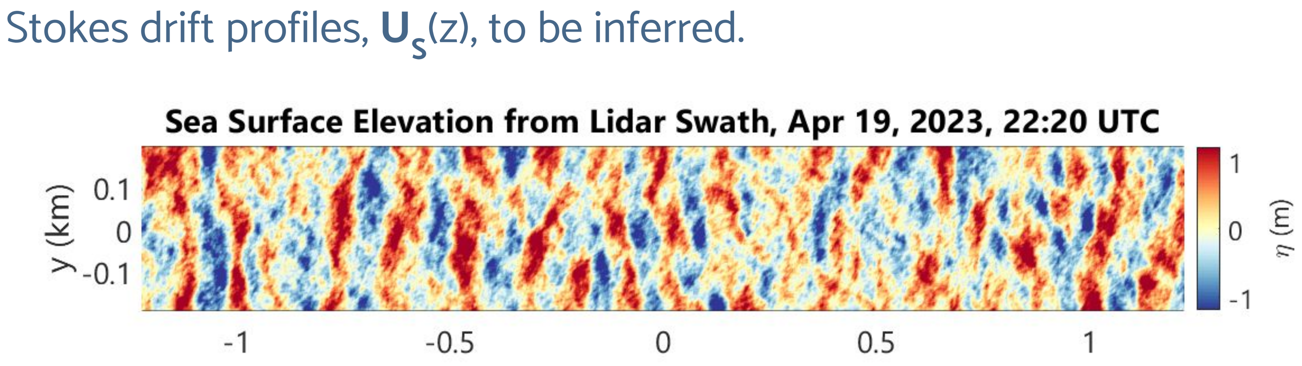

Figure 2. An example of a 2500-meter-length swath of sea surface elevation collected by the *LiDAR* component of the aircraft-mounted Modular Aerial Sensing System (MASS).

Concurrently, the MASS *DoppVis* airborne electro-optical sensor (figure 2) records surface gravity waves to infer surface Lagrangian current profiles, **U**(z). A Lagrangian current profile is a sum of the Stokes drift profile $\mathbf{U_S}(z)$ and the Eulerian surface current profile $\mathbf{U_E}(z)$,

$$\mathbf{U}(z) = \mathbf{U_E}(z) + \mathbf{U_S}(z)\,. \qquad (1)$$

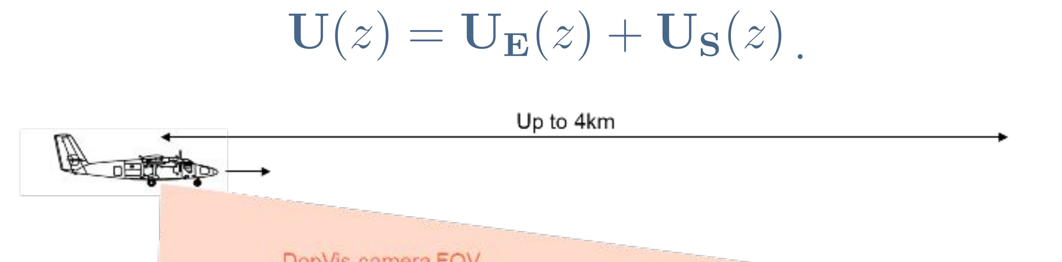

Figure 3. The *DoppVis* component of the aircraft-mounted MASS collects visible imagery of the ocean surface with a video camera pointed slightly ahead of the aircraft. The spatio-temporal information contained in this footage is synchronized with a GPS/IMU. It is then Fourier-transformed to obtain the wavenumber and frequency spectra of the evolving wave field.

Stokes drift magnitude and directionality varies with depth, modulating near-surface currents

For the first time, the Lagrangian flow has been decomposed into the wave-driven flow (Stokes drift) and the Eulerian flow at submesoscale features. Stokes drift profiles are computed from the lidar-retrieved directional wavenumber spectra based on the work of Kenyon (1969) [1] [2],

$$\mathbf{U_S}(z) = 2\int\int F(\mathbf{k})\sqrt{g|\mathbf{k}|}e^{2|\mathbf{k}|z}|\mathbf{k}|d\mathbf{k}\,. \qquad (2)$$

While limited by the aircraft velocity and its trajectory relative to propagating waves, the spectra resolve the equilibrium and saturation ranges of the wave field. Directional information from the spectra is translated into the Stokes drift profile, accurately incorporating contributions from swell and wind waves.

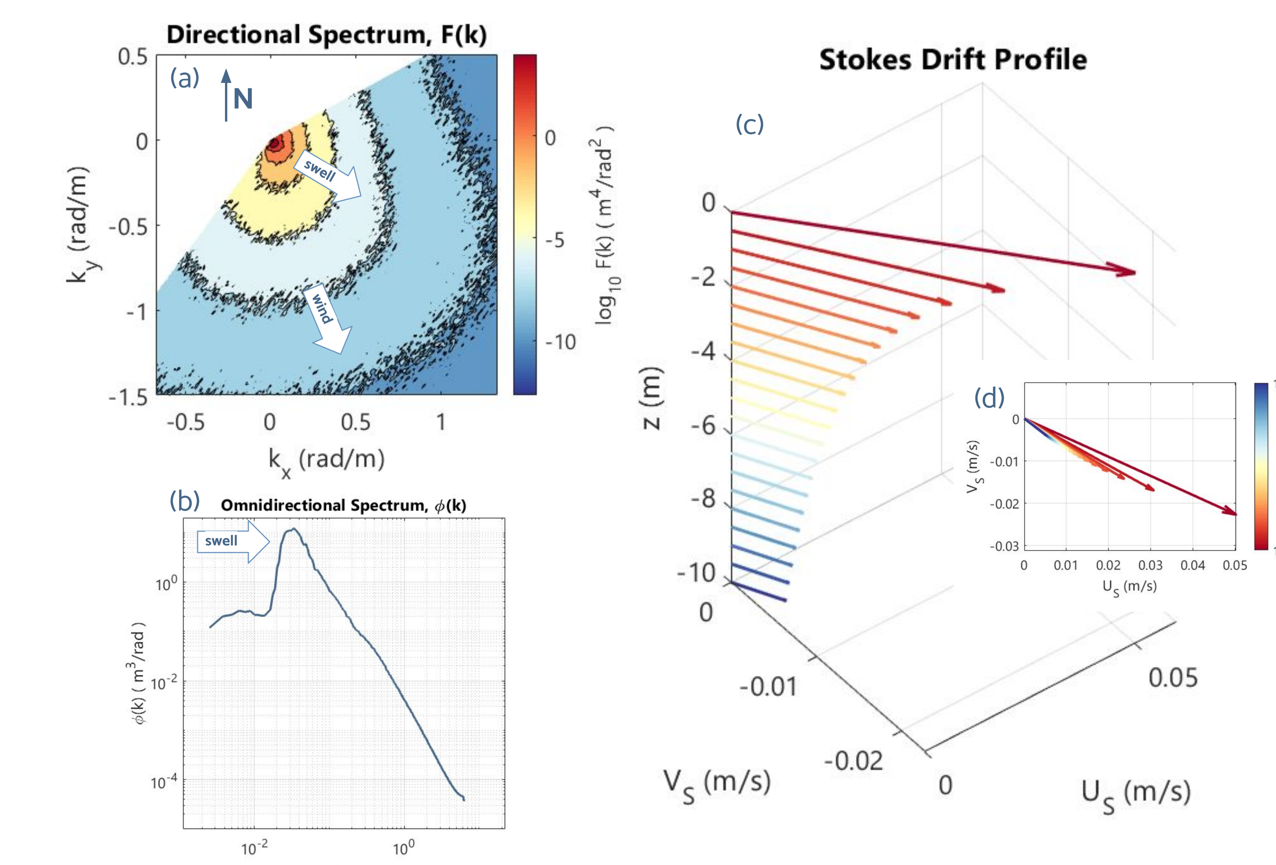

Figure 4. (a) Directional and (b) omnidirectional spectra averaged over the transect in figures 6 and 7. The Stokes drift profile $\mathbf{U_S}$ is computed from the averaged directional wavenumber spectrum F(k) in (a) with direction from north (clockwise) indicated by the color scale in the 3D (c) and 2D (d) views. The wind direction is coming from approximately 350° from true north, obtained from wave glider observations.

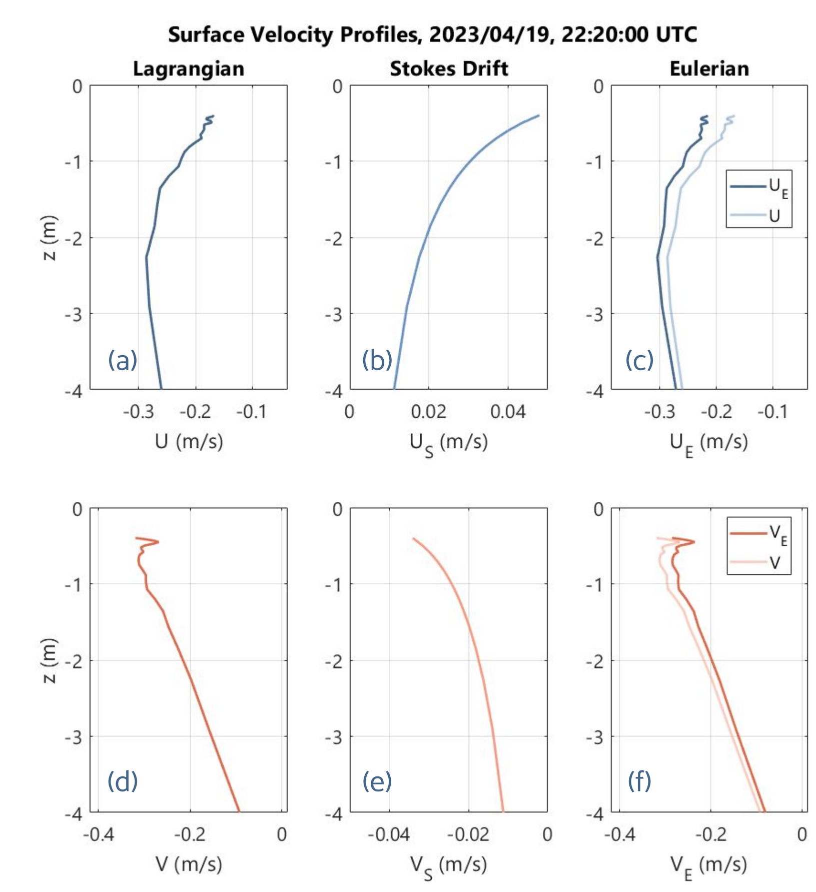

Figure 5. Zonal (a-c), and meridional (d-f), components of sample surface Lagrangian (a and d), Stokes drift (b and e), and Eulerian (c and f) velocity profiles (bold).

Subtracting Stokes drift from Lagrangian flow profiles reveals alterations to the flow. Individual cases exhibit changes to the flow structure with depth, such as in figure 6c, in which the Stokes drift contributed to the vertical shear of the flow. The alteration by the Stokes drift is strongest close to the surface (z = 0 m) and increases as wind speed increases over the record on April 19th (not shown).

Wave-induced Stokes drift contributes to submesoscale variability

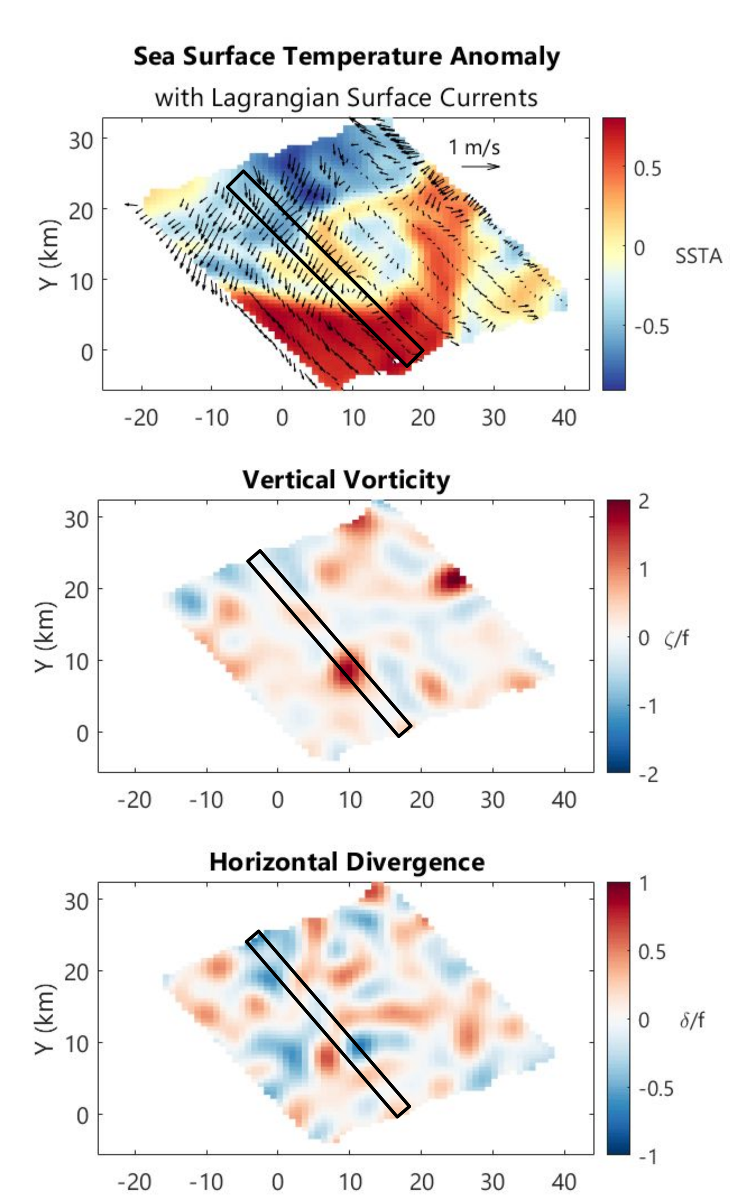

Figure 6. (a) Sea Surface Temperature Anomaly (SSTA) and Lagrangian current measurements at 0.5 m depth from the MASS during the S-MODE IOP2 field campaign on April 19, 2023. (b) Vertical vorticity and (c) horizontal Divergence computed from lagrangian velocities at 0.5 m depth for April 19, 2023.

Examining a MASS transect containing a sea surface temperature front and a submesoscale eddy,

- SST fronts are collocated with higher strain, consistent with strain-driven frontogenesis [4].
- Zonal and meridional components of Lagrangian velocity exhibit vertical shear in the cyclonic eddy.

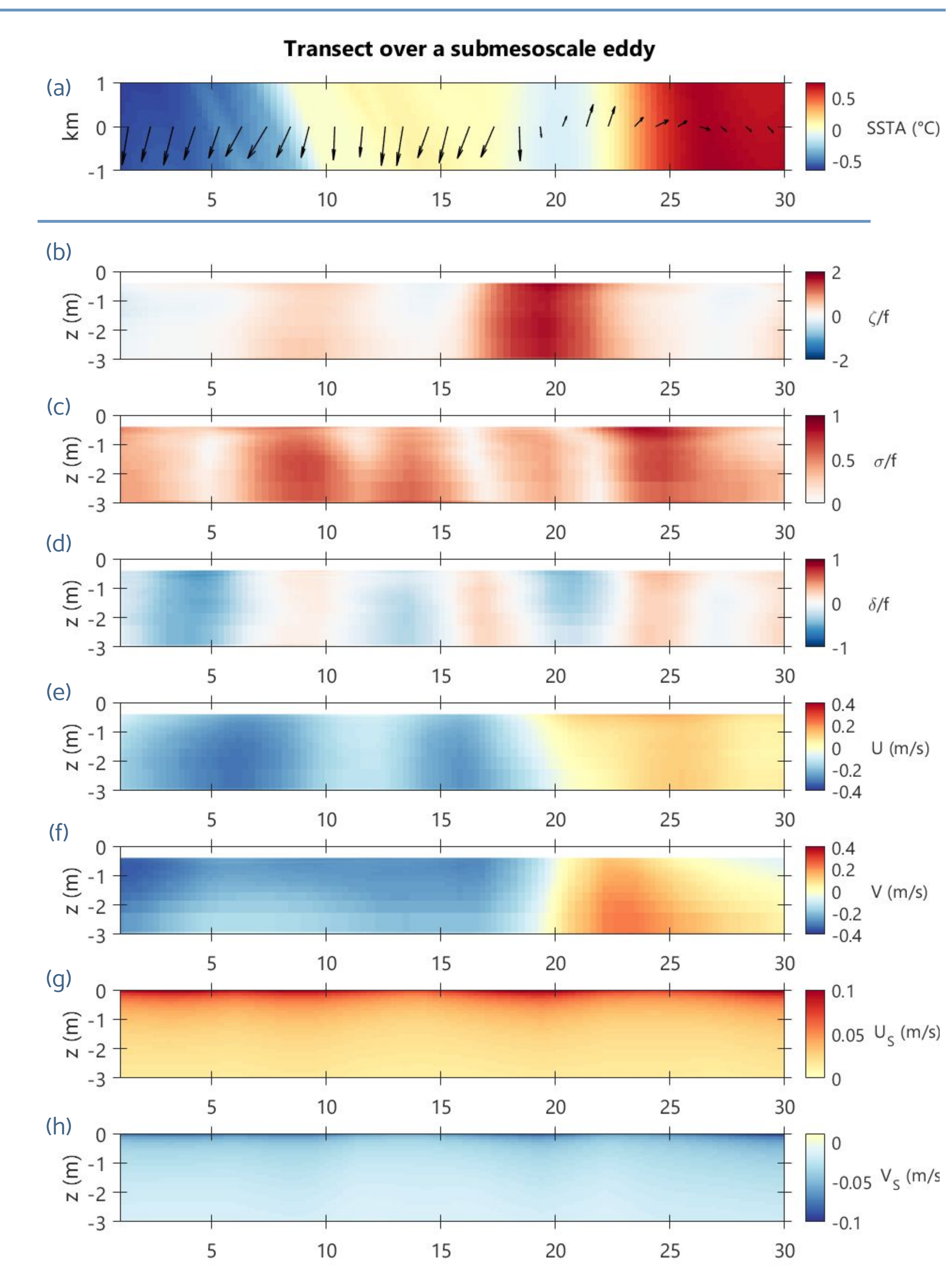

Figure 7. (a) Sea surface temperature anomaly (colorscale) and Lagrangian velocity at the surface (quivers) as a function of cross- and along-track distance. Vertical vorticity (b), strain (c), horizontal divergence (d), zonal (e) and meridional (f) Lagrangian velocity, and zonal (g) and meridional (h) Stokes drift as functions of depth and along-track distance (southward) across the boxed transect in figure 6.

Ongoing statistical and spectral investigation of Stokes drift influence at submesoscales

To further investigate how Stokes drift affects submesoscale processes, the next step is to examine how including or excluding the Stokes drift modifies kinetic energy spectra, cross-scale kinetic energy fluxes, and velocity gradient distribution skewness. The complex wave-current interactions that occur at submesoscale fronts and their influence on the variability of ocean-atmosphere fluxes is an ongoing investigation.

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