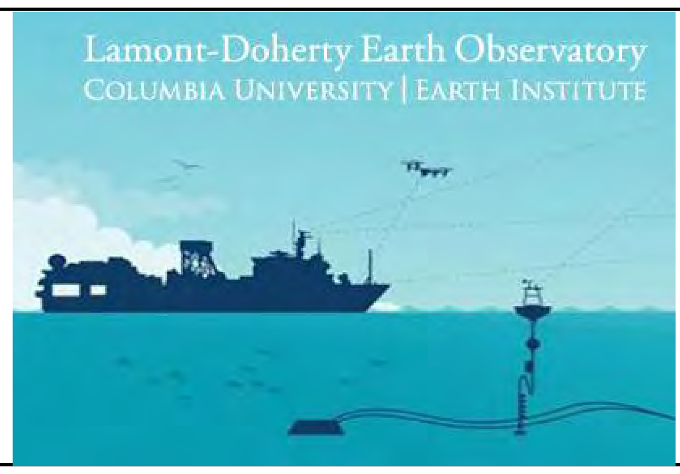

Direct Measurement of the Air-Sea Momentum Flux, Near-Surface Ocean Currents, and Wave Hydrodynamics Using a Hybrid Imaging System

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Abstract

Improving fundamental in-situ air-sea interaction measurement capabilities is critical to the advancement of modeling the earth's weather and climate. As wind blows over the ocean, waves form, grow, interact with each other, and eventually break, shifting the balance of viscous stress to wave form drag. While this transition has been extensively studied in the laboratory and through numerical modeling, it is exceptionally difficult to observe, and therefore quantify, in the real ocean. We are currently developing an innovative research capability for a dedicated air-sea interaction measurement apparatus, coupling a multispectral infrared camera system with an imaging polarimeter. The development will provide an operational field-deployable (e.g., ship, aircraft, tower, etc.) system for the direct measurement of momentum and heat flux at the ocean surface and the profile of near-surface ocean current in the top few centimeters. These will be recovered using the two-dimensional wave height/slope spectrum of ocean capillary-gravity waves and the two-dimensional mapping of sea surface temperature from multiple depths. This novel field-deployable air-sea interaction measurement system will be used to complement other air-sea interfacial fluxes of primary interest in atmospheric science and oceanography, including momentum, sea spray, heat and mass fluxes, wind-wave-current interaction, and upper ocean energy dissipation rates.

Polarimetry – Polarimetric Slope Sensing (PSS)

- Measures the polarization state of a bundle of light rays
  - Stokes parameters S = (S0, S1, S2, S3)
    - Amount of circular polarization
    - Orientation and degree of linear polarization
    - Intensity
  - Each CCD camera measures a unique linear combination of the polarization state.
  - Mueller Calculus $S_{OUT} = M(\hat{n})\, S_{IN}$
    - Incident Light
    - Geometry and Material Properties of the Scattering Object
    - Scattered Light

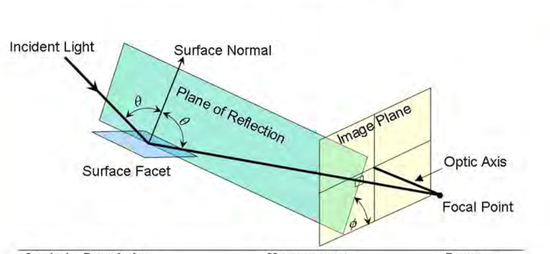
Zappa, C. J., M. L. Banner, H. Schultz, A. Corrada-Emmanuel, L. B. Wolff, and J. Yalcin (2008), Retrieval of short ocean wave slope using polarimetric imaging, *Measurement Science and Technology, 19*(055503), doi:10.1088/0957-0233/19/5/055503.a

Stoke's Vector $S=(S_0,S_1,S_2,S_3)=R_{AM}S_{SKY}$

PSS uses the change in polarization from scattering, reflection or refraction to infer the orientation of the interface. For negligible upwelling and for an unpolarized sky, the Degree of Linear Polarization is defined by

$$DOLP(\theta,n)=\sqrt{\frac{S_1^2+S_2^2}{S_0^2}} \quad \text{or} \quad DOLP(\theta,n)=\frac{\alpha(\theta,n)-\eta(\theta,n)}{\alpha(\theta,n)+\eta(\theta,n)}$$

Polarization Geometry



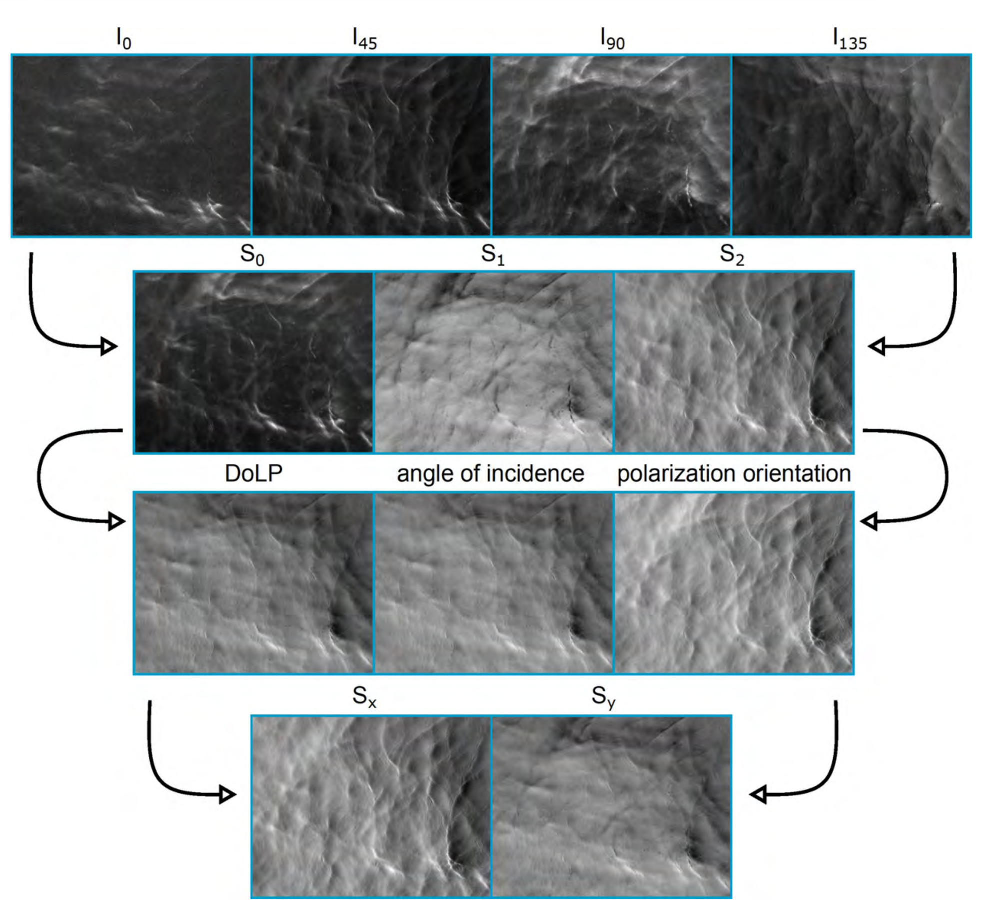
Symbol	Description	Measurement	Range
ϕ	Projected Surface Orientation	Polarization Orientation	[-90°,90°]
θ	Incidence Angle	Degree of Linear Polarization	[0,1]

The Polarization Orientation is not affected by upwelling and is given by

$$\Phi=\frac{1}{2}\tan^{-1}\left(\frac{S_2}{S_1}\right)$$

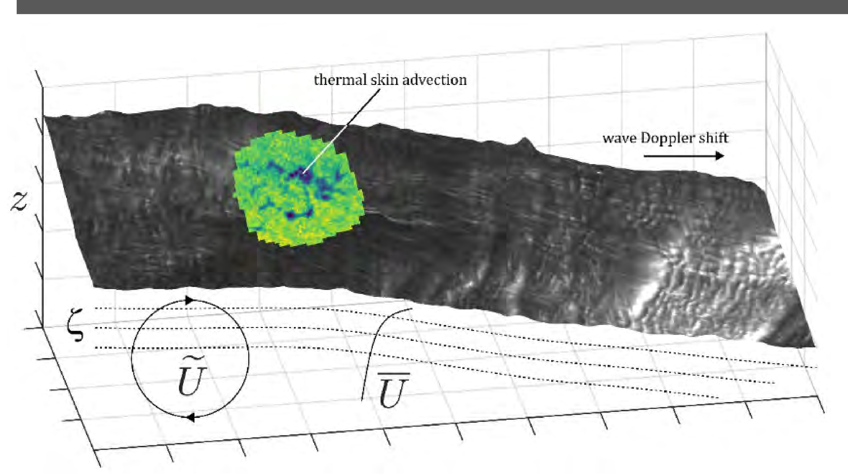
where $\phi=\Phi+90°$

The geometric relationship between the surface normal, incidence angle relative to the surface facet (θ) and polarization orientation (ϕ).



Near-Surface Ocean Currents

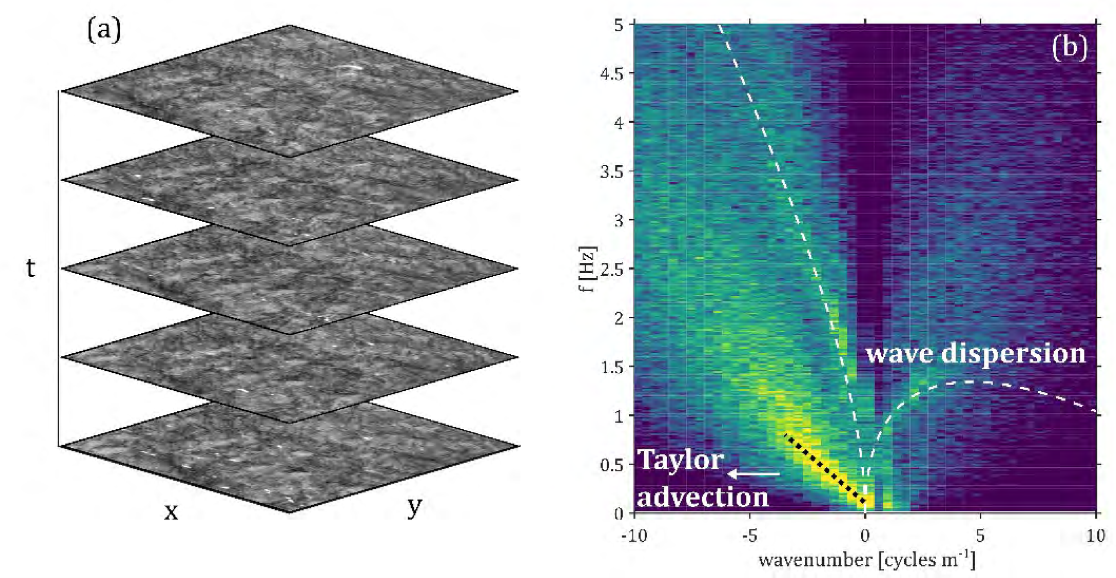
Introduction



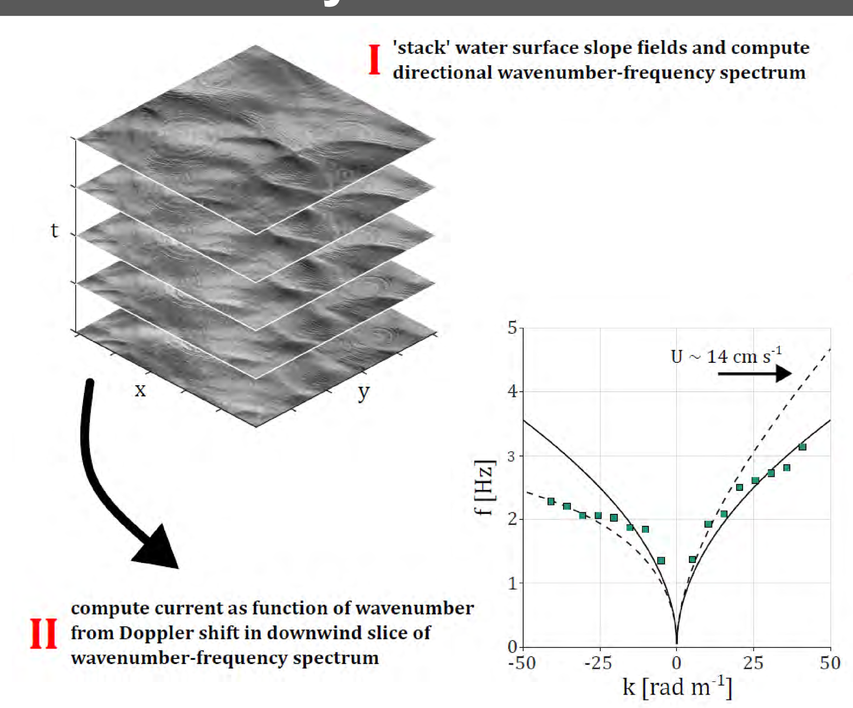
Stylized breakdown of the mean and wave orbital flow components $\bar{U}$ and $\tilde{U}$ underneath an undulating surface (in this case, the water surface displacement field produced through integration of the water surface slope field, supplemented with a representation of skin brightness temperature). The fixed and interface following vertical coordinates z and ζ are shown for reference.

Ocean Surface Velocity from Infrared Imagery

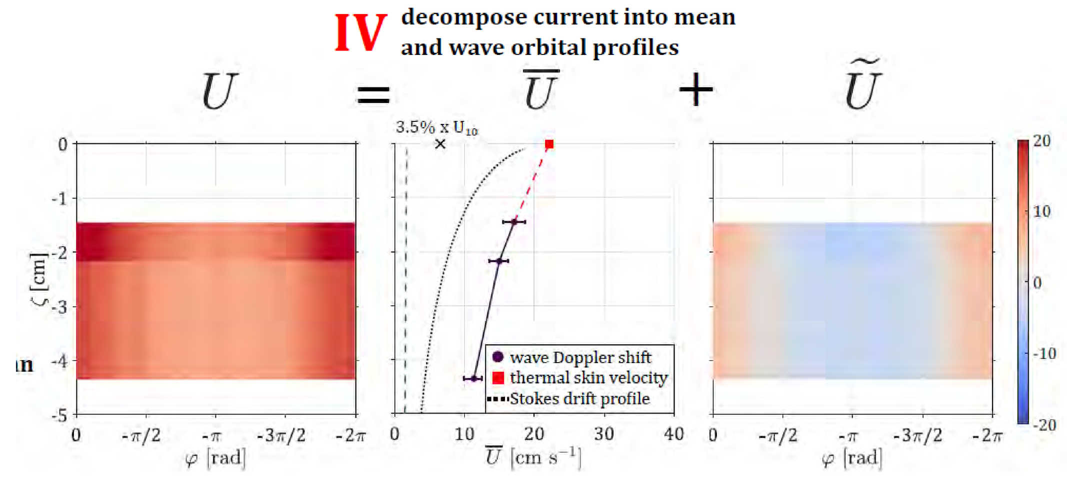
By invoking Taylor's frozen turbulence hypothesis, it is possible to remotely infer the mean advective velocity of a fluid through quantification of the spatiotemporal evolution of turbulent eddies at a single depth. This is most readily done in wavenumber-frequency space, as developed and introduced in Dugan et al. (2012) through 3D Fourier transforms applied to thermal infrared imagery in the same way, this time recovering advection of features in the skin layer.



Near-Surface Velocity Profiles from Polarimetry



Mean and Orbital Wave-Coherent Velocity Profile



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Observations of mean and wave orbital flows in the ocean's upper centimetres

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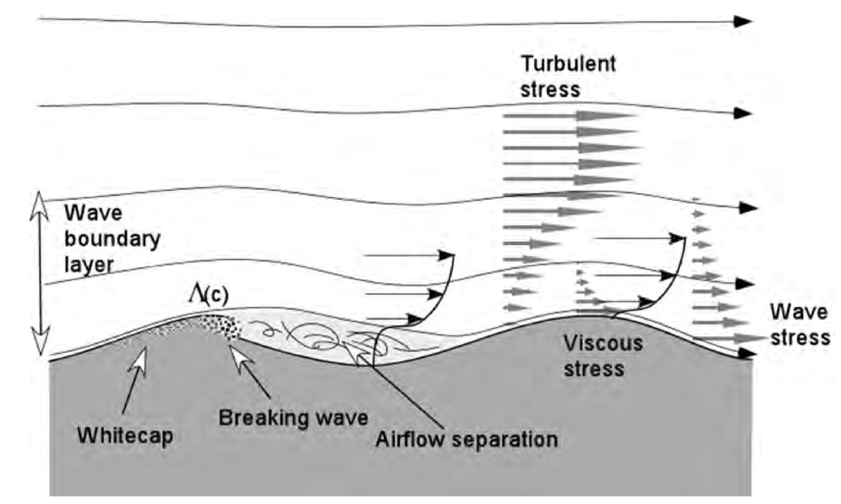
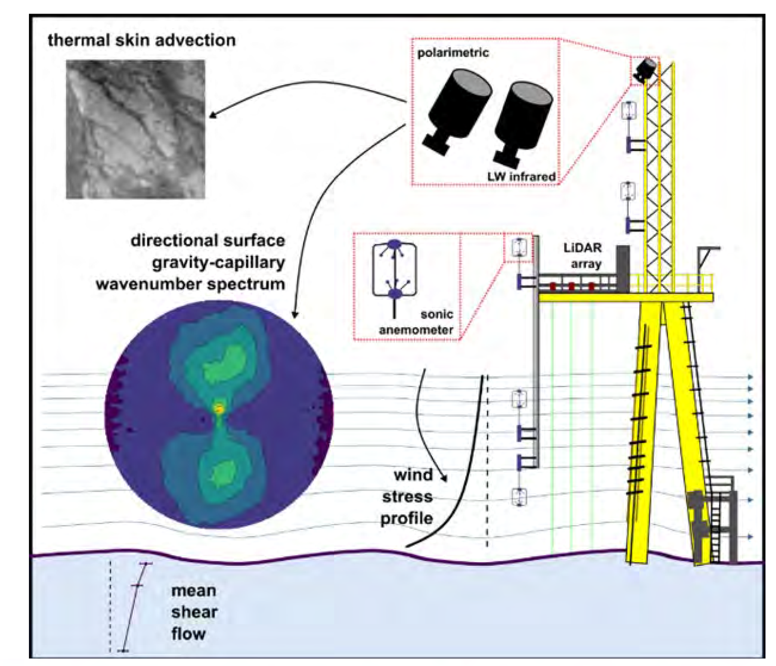
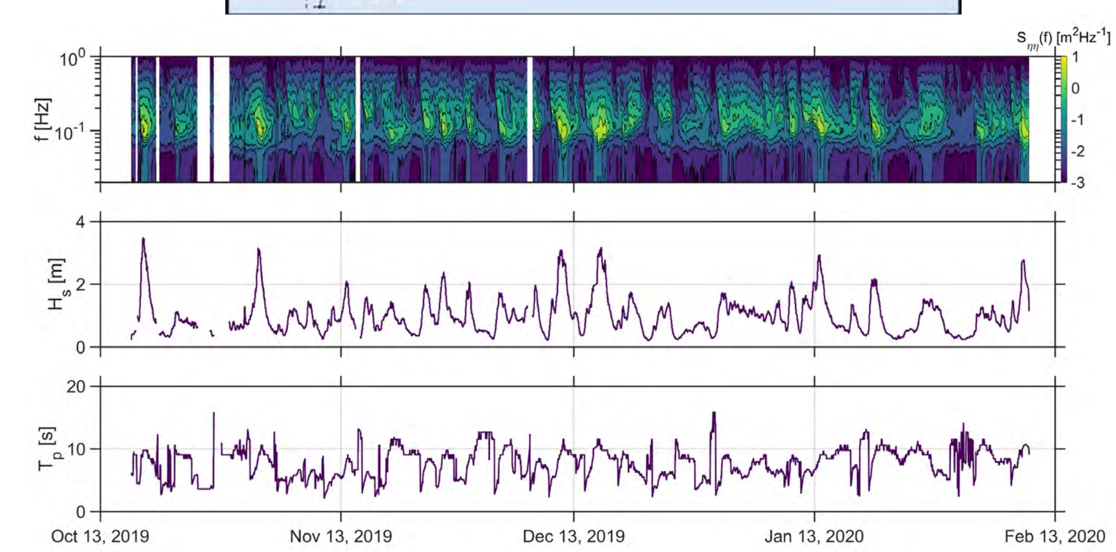
Direct Air-Sea Momentum Flux

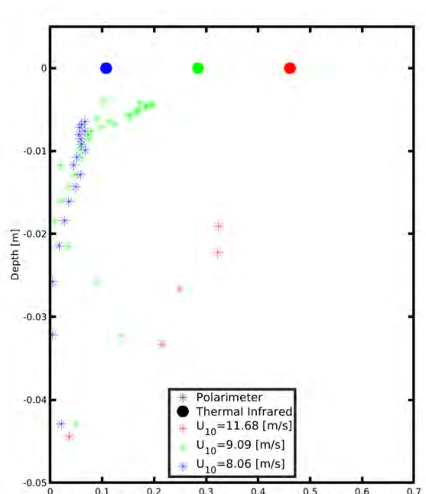
ASIT Field Measurements

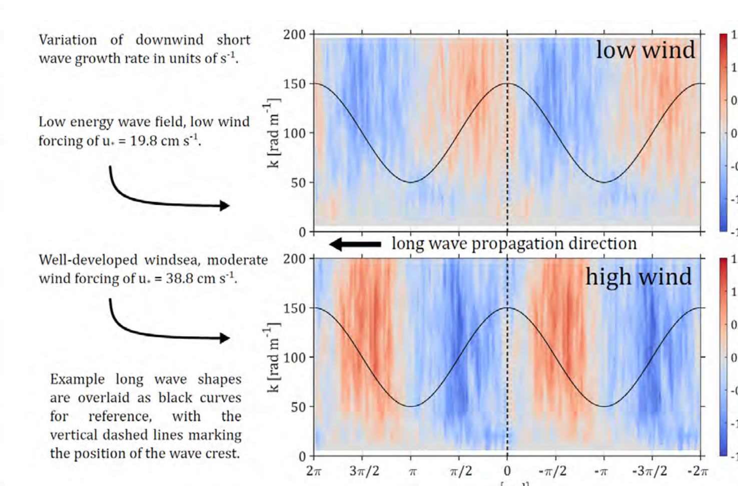


Conceptual schematic of the constant stress layer above the wave surface where surface waves break, create whitecaps, and induce flow separation. At the surface, the total turbulent stress is partitioned to the surface tangential viscous stress and the form drag.







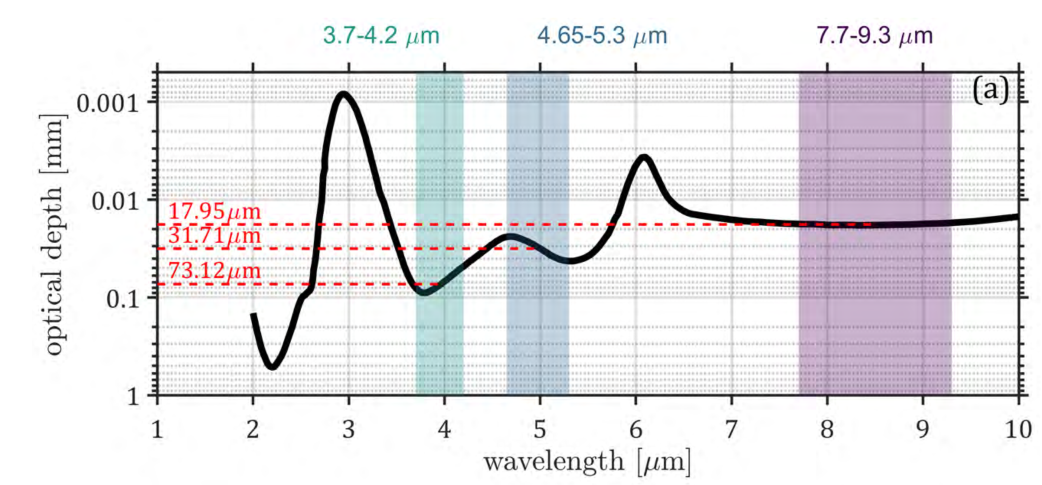


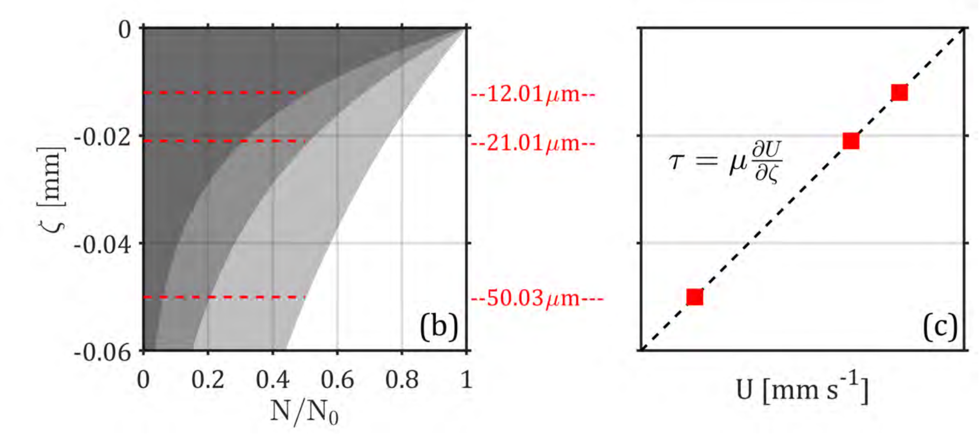
SUSTAIN Laboratory Experiments

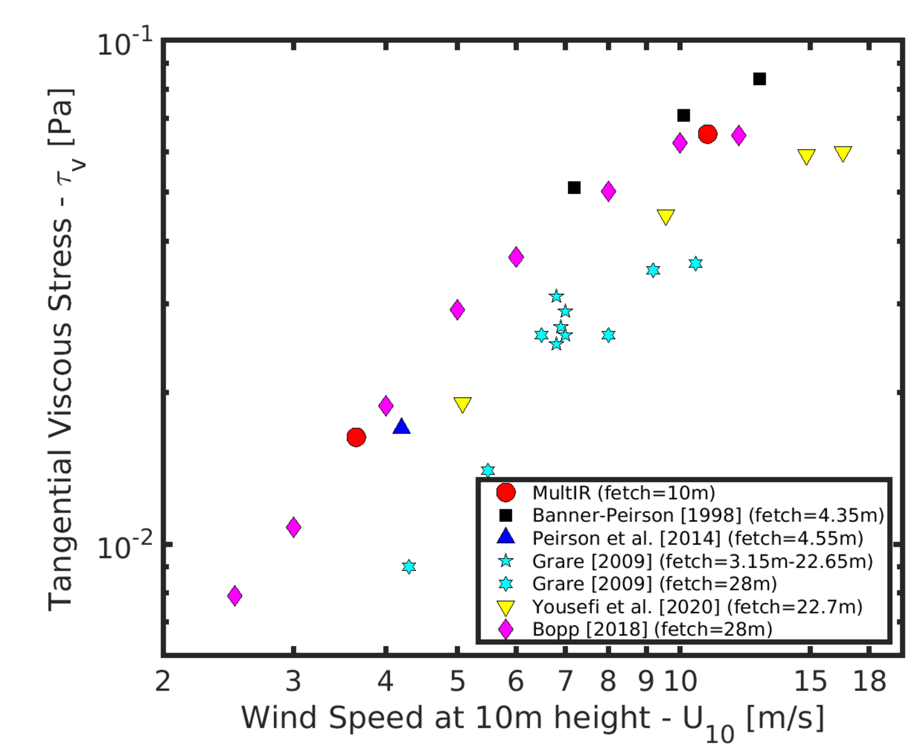
Our central hypothesis is that measurements of the velocity profile from thermal infrared (TIR) imagery within the top 100 µm of the water surface will provide a robust estimate of the surface ocean viscous stress. To test this hypothesis, we will conduct detailed measurements of the tangential stress structure beneath the air-water interface compared to form drag and the total stress in the wind tunnel using a recently developed infrared imaging technology under a range of wind-wave regimes.

$$\rho u_*^2 = \tau_v + \tau_{form}$$

The detailed structure of the tangential stress beneath the air-water interface will be investigated using a recently-developed infrared imaging technology. The new multi-spectral TIR camera system (MultIR) provides remotely sensed skin friction measurements within 10-100 µm of the water surface.







Concluding Summary

- Field observations of mean current shear in the ocean surface layer were found to be in general agreement with those of laboratory measurements (e.g., Cheung & Street, 1988).
- Observed wave orbital velocities were observed to be close to those described by linear wave theory. The greatest differences in magnitude were seen for high levels of wind forcing in which microbreaking was known to be occurring.
- Peak wave enhancement (relaxation) was observed to have occurred downwind (upwind) of the crest under low wind forcing, where long wave motions are the principal modulator. Peak wave enhancement (relaxation) occurred upwind (downwind) of the crest under low wind forcing, where the airflow is heavily modulated due to separation effects.
- Remote observations of the surface tangential viscous stress from the MultIR system and form drag, growth rate, Stokes Drift, total drift from polarimetry.