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14. ABSTRACT
Measurements and modeling of the upper ocean boundary layer were conducted with the goal of developing improved understanding and models of this region. Total of 17 floats and surface autonomous platforms were deployed in a field experiment during March and April 2017 near Catalina Island California. A series of wind bursts resulted in multiple episodes of mixed layer deepening suitable for studying this problem. Data from the multiple platforms was in intercalibrated and extensive analysis undertaken to understand and compare the variety of different velocity measurements made including a detailed analysis of the motion of Lagrangian floats forced by surface waves. Modeling efforts resulted in new formulations of large eddy simulations, closures summarizing these simulations and suitable for use in larger-scale models, and a community-wide inter-comparison of such models.

15. SUBJECT TERMS
Physical oceanography, mixed layer, turbulence, Langmuir circulation

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Waves, Langmuir Cells, and the Upper Ocean Boundary Layer DRI

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LONG-TERM GOALS

We aim to understand the dynamics of the upper ocean boundary layer and use this understanding to improve the parameterizations used in operational models as part of the ONR Waves, Langmuir Cells and the Upper Ocean Boundary Layer Departmental Research Initiative (LCDRI). In particular, we aim to make definitive experimental tests of the hypothesis that Langmuir Turbulence, specifically the equations of motion with the addition of the Craik-Leibovich vortex force and advection by the surface wave Stokes drift, can accurately describe turbulence in the upper ocean boundary layer under conditions of wind and wave forcing. We anticipate that this hypothesis will need to be modified to include the effects of surface wave breaking and aim to understand how to reformulate it most effectively. We aim to use this knowledge to refine parameterizations of upper ocean turbulence, to validate them through model-data comparisons and transition them into high-resolution regional and global ocean models.

OBJECTIVES

Specifically, we aim to first, measure upper ocean structure, turbulent kinetic energy, turbulent kinetic energy dissipation rate in a region with variable and known air-sea fluxes and surface wave field. And second, compare the results of these measurements with Large Eddy Simulation and closure model, thereby directly testing a hypothesis and improving models.

Fig 1 APL/UW Lagrangian Float with Nortek 1000 ADCP.

APPROACH

The measurements were made using APL/UW Lagrangian floats updated by the addition of Nortek 1000 ADCPs sensors (see figure 1). The combination of a stable, autonomous and fluxible platform provided by the float, and the ability to measure profiles of vertical and horizontal velocity on scales from millimeters to many meters, provided by the ADCP, makes this an excellent platform for upper ocean studies. The enhanced floats were first tested in a turbulent tidal channel in Puget Sound, and then used during the Langmuir DRI main field experiment in March and April 2017.

Modeling activities have focused on using Large Eddy Simulations (LES) to make model-data comparisons against the field observations, using in-situ meteorological forcing and observed spectra of surface waves. This served to guide further improvements in the parameterizations of upper ocean mixing in Second Moment Closures (SMC) or in nonlocal first moment closures (i.e. KPP).

WORK COMPLETED

The Langmuir DRI main field experiment in March and April 2017 between Catalina and San Nicolas Island off the coast of Southern California.

Field operations occurred within a 15nm circle centered on FLIP, with additional exclusions due to Navy restricted areas (Figure 2). The operations region was characterized by highly variable winds both in time, with periods of near calm interrupted by 3 major storms, and in space, with nearly calm winds occurring only a few 10's of kilometers away from the maximum winds even during the storms. This produced highly variable wind and wave conditions that were well-suited for testing upper ocean models under a variety of conditions.

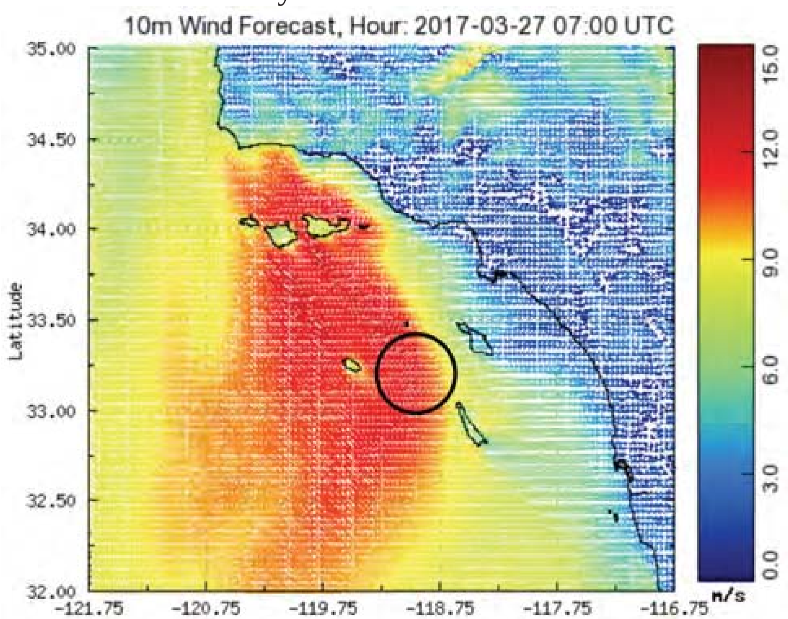

Fig. 2. Operations area off southern California superimposed on typical COAMPS map of wind speed.

Measurements were made using 4 different kinds of autonomous oceanographic vehicles for a total of 17 platforms (Fig. 3). The three Lagrangian floats funded by this project were complemented by 6 EM-APEX floats, made available by Tom Sanford, and 8 SWIFT floats, made available by Jim Thomson, both from APL/UW. The key new sensor system on each Lagrangian float is a Nortek Signature 1 Mhz, 5 beam ADCP. A unique aspect of this ADCP is that it can flexibly intersperse pulse-pulse coherent sampling, with mm/s single-ping precision, with broadband sampling, with cm/s single-ping precision but longer range and a larger velocity ambiguity. This combination allows the float to measure both the mean profiles of temperature, salinity and velocity, and of turbulent kinetic energy and kinetic energy dissipation. Complementing these boundary layer measurements, the EM-APEX floats profiled hourly over the upper 150m measuring temperature, salinity and velocity. The SWIFTS floated on the surface, measuring surface wave spectra and breaking statistics, air-sea fluxes and turbulent kinetic energy and kinetic energy dissipation in the top few meters.

Figure 3. Equipment used during the main LCDRI experiment. A total of 17 surface or subsurface drifting or profiling instruments were repeatedly deployed from the *R/V Sproul*.

Our operations were conducted from the *R/V Gordon Sproul*, a small (120') research vessel, usually operated on short cruises. Our 19-day cruise was the longest *Sproul* cruise in memory. The high maneuverability and low freeboard of the *Sproul* made it excellent for rapid deployment and recovery of many autonomous vehicles. We deployed and recovered km-scale arrays of up to 17 vehicles during calmer weather and allowed them to drift for several days. In lighter weather, *Sproul* surveyed near the array. In heavy weather, *Sproul* retreated to more sheltered waters near Catalina Island, while continuing to control and gather data from the autonomous platforms. Figure 3 shows the evolution of one of the autonomous arrays.

Four major events were measured during the cruise (Figure 4). Each of the three major storms resulted in a deepening mixed layer and dramatic mixing of the transition layer at the base of the mixed layer. Overall, each of these resulted in the evolution of the mixed layer from only a few meters thick to about 40m thick. The last 4 days of milder weather then showed a strong diurnal warming layer resulting in a growth of the near-surface stratification. These strong and diverse events measured in detail by both our instruments and the other DRI components, provided an excellent dataset for model testing.

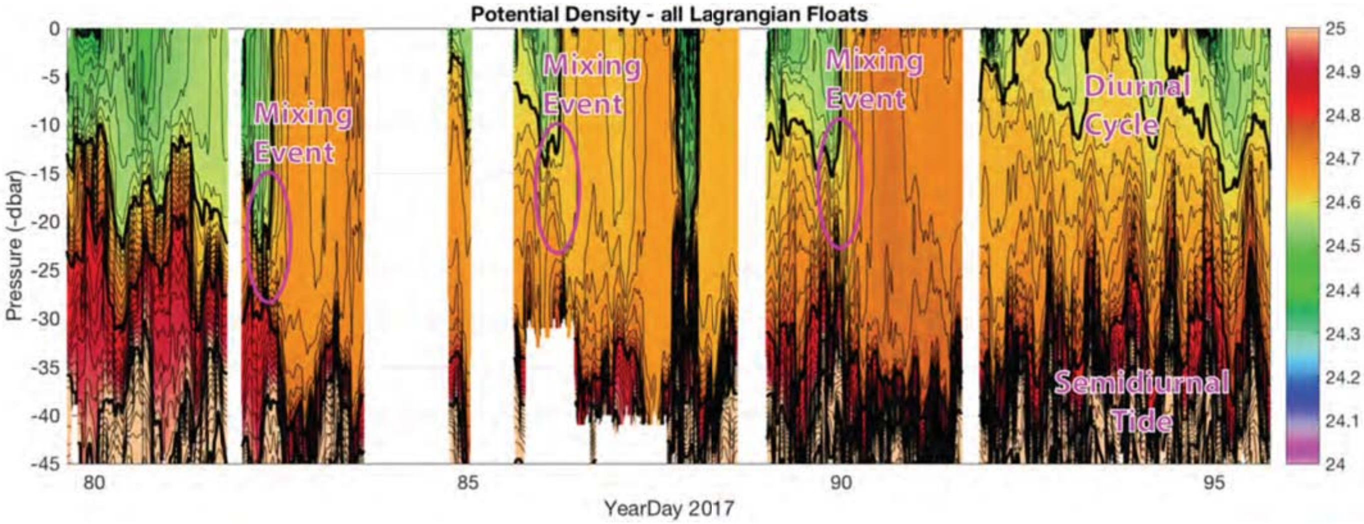

Figure 4. Time evolution of density from the Lagrangian floats. Three major mixing events, show the rapid deepening of the mixed layer in response to each of the three storms. The last 4 days of fair winds show a strong diurnal cycle with overall deepening of the surface stratification.

Data analysis has focused on validating the accuracy of the data, as described below. With a large number of platforms, considerable effort was spent intercalibrating the temperature and salinity sensors and, for the wave platforms, into intercalibrating the wave sensors. Similar efforts went into intercalibrating the velocity profiles from the EMAPEX and Lagrangian float measurements. The meteorological conditions were complex, with our observation region often on the edge of the strong when jet, as can be seen in figure 2. We thus spent considerable effort extracting and validating high-quality wind and thus air-sea flux measurements.

RESULTS

Accuracy of ADCP measurements: Shcherbina et al. (2018) report on the accuracy of the Nortek 1000 ADCP used on the floats. These units measure velocity using interleaved broadband (BB) and high-resolution (HR) pulse coherent sampling. The BB pulses have a spatial resolution of about 1 m, a range of about 20 m and an accuracy of about 1 cm/s per ping. The HR pulses have much higher resolution of a few centimeters, a shorter range, typically less than 10 m, and accuracy of a few mm/s. This gives them the ability to measure turbulent fluctuations in the ocean mixed layer. The paper addresses the issue of “unwrapping" the phase for HR measurements and demonstrates that this can be done. These techniques are applied to data from a turbulent tidal channel in Puget Sound, resolving the -5/3 inertial subrange and thereby measuring the dissipation rate with a noise level of about 10^{-8} W/kg. The instrument is complex with many settings and considerable effort was spent figuring out how to optimize these under different conditions so as to get the best measurements. A copy of Shcherbina et al. (2018) is appended to this report.

Inter-calibration of the LCDRI sensors: Ma et al. (2020) reports on the details of the field work and the inter-calibration of temperature, salinity and wave sensors between the different autonomous platforms. For the MLF vs. EM-APEX calibration, the average salinity of MLF #82 and #83 top and bottom sensors is used as a reference. The calculated salinity offset for EMAPEX #6667, #6672, and #6678 is ~ 0.004 psu, for EM-APEX #6671 and #6674 is ~0.001 psu, and for EM-APEX #6675 is ~−0.001 psu. For seven SWIFT drifters at 0.2, 0.5, and 1.2 m, the calculated temperature offset varies from −0.1 to 0.1°C and the salinity offset varies from −0.003 to 0.2 psu. The salinity data from SWIFT #16 and #17 at 0.2 m exhibited large offsets, which suggest data bias. These numbers are consistent with a very high accuracy and precision of the Seabird temperature and salinity sensors used in the EM-APEX and MLF floats, and the lower accuracy of the Aanderaa sensors used in the SWIFTS.

Comparison of wave energy measurements between SWIFT drifters and a Datawell Waverider buoy moored at CDIP station 299 are described. Excluding the periods when the mean separation distance was greater than 30 km (periods 3−1, 3, 5, 6, 8, 12), the root-mean-square error (RMSE) of significant wave height (Hs) is 0.25 ± 0.08 m, the RMSE of integrated wave energy is 0.057 ± 0.029 m2, and the average percent error of Hs is ~13%. In general, given the temporal, spatial, and spectral differences in the sampling strategy of SWIFT drifters and the CDIP buoy, the comparison suggests no significant bias in either dataset. A copy of Ma et al. (2020) is appended to this report.

Homogeneity of the LCDRI environment: The array of intercalibrated floats accurately measured the lateral density gradients on the scale of the array, typically a few kilometers, over the upper 100m. These were used to assess the homogenity of the region and thus whether lateral processes were likely to be important. The analysis found that the geostrophic Richardson number averaged over a few days and a few kilometers was always greater than 2 and, for deployment #5, greater than 10. The maximum apparent Rossby number estimated from the float motion is about 0.1 This environment thus has moderate or low submeoscale variability and is a good location for testing boundary layer models. This analysis is unpublished.

Analysis of EM-APEX accuracy: The horizontal velocity measurements from the EM-APEX and from the Lagrangian floats were intercompared. The obvious lower resolution of the EM-APEX float lead to a detailed analysis of their vertical resolution. The float processing was simulated and analyzed with the assistance of Thomas Sanford and John Dunlap, who designed these instruments. The processing was found to be equivalent to a 50 second boxcar filter sampled every 25 seconds to an accuracy of 5%. First difference shears from the EM-APEX are thus biased low. For typical fall rates, 10m shears are biased low by 20%. A more sophisticated processing could probably increase the vertical resolution by a factor of at least 2. This analysis is unpublished.

Analysis of Lagangian float motion: Although the Lagrangian float is a very stable platform compared to moorings or ships it does move and tilt under the influence of surface waves. Simple modeling indicates that this rectifies some of the surface wave velocity into the velocity measured by the ADCP. We thus undertook a large effort to understand the motion of the float under these conditions with the goal of producing a useful model of the float motion and then using that model to estimate the resulting velocity errors. The ADCP on one the floats deployed during the LCDRI field program carried an AHRS attitude system, which we hoped would provide good orientation data. However, analysis of both the field data and of laboratory (and backyard) tests in which the ADCP was swung on pendulums, showed that the AHRS did not always work properly. Accordingly, we undertook a systematic set of laboratory measurements to understand the accuracy and consistency of the orientation sensors and to develop our own algorithm to compute orientation from the measured acceleration, rate Gyro and magnetometer measurements. The orientation is best measured using the rate gyros in the surface wave frequency band and the accelerometers at lower frequencies. Using this information, we developed a model of the float response to surface wave forcing based on the field measurements during LCDRI. The float behavior could be accurately modeled as a resonant damped oscillator with a Q of about 5 and a resonant frequency with a period of about 2 seconds. This work has been completed and we are now working on understanding the associated velocity measurement errors. This analysis is unpublished but we expect it to result instrumentation publication.

Modelling Results: The modeling team (Harcourt) working in collaboration with Kukulka (U. Del) has resulted in a simplified equilibrium TKE model of wave-driven mixing that combines both wave breaking & Langmuir (CL) forcing. This effort addresses a long-standing schism among researchers in this field over the relevant dimensional forcing velocity for scaling upper ocean mixing intensity in Langmuir turbulence, and does so by providing a clear physical model for using a near-surface average of the Stokes drift rather than the surface value. A copy of Kukulka and Harcourt (2017) is appended to this report.

This work has led to a new approach to include the TKE injection by breaking waves into LES simulations. This approach is more consistent with the LES model construction, wherein the subgrid TKE is located with vertical velocity at the surface and at subsequent interfaces between depth layers of U,V,T and Salinity. This approach modifies the traditional one of specifying a surface flux of TKE to one specifying its surface value as a Drichlet boundary condition. This produces profiles of dissipation and net TKE that are broadly consistent with the classical solutions of Craig and Banner for both net TKE and dissipation, and in ways that are in turn impacted by the presence or omission of CL Vortex forcing. However, because the TKE injection as a subgrid TKE in the LES adopts the subgrid length scale as effective roughness length, this should be expected to overestimate the breaker TKE injection effects, as this ~0.5m length scale is generally smaller than the $O(H_s/10)$ current research attributes to this scale. Nevertheless, the impacts on the large eddy dynamics of the mixed layer from including this breaking waves' TKE injection are small in the LES-modeled LCDRI environment, typically much smaller than impacts from CL vortex forcing.

These results have been incorporated into a revised version of the Harcourt (2015) SMC closure model of Langmuir Turbulence (H15-SMCLT) along with changes making the model code more stable and useful for time-dependent forcing cases and climate model comparisons. The improved model was coded into the General Ocean Turbulence Model (GOTM) framework with additional modifications to improve its existing implementations of second moment closures. This has led to its inclusion in a broad intercomparison study of Langmuir turbulence mixing models, and has put in the groundwork for continuing comparisons in LCDRI and other experiments where upper ocean mixing, meteorological forcing and surface wave spectra are well-measures. Fig 5 provides an example of the intercomparisons of this study, where observed temperature and salinity profiles and surface fluxes from ocean stations were used to initialize and force GOTM5 simulations in this test case. For Ocean Climate Station Papa Stokes drift was determined from waverider buoy data (J. Thomson, APL-UW), Three sets of simulations were conducted, focusing on the deepening of mixed layer in winter, shoaling of mixed layer in spring and a full seasonal cycle, respectively. Fig. 1 Shows the model intercomparisons for the full seasonal cycle, all relative to the standard implementation of KPP in the CVMix suite of boundary layer mixing parameterizations. A copy of Li et al. (2019) is appended to this report.

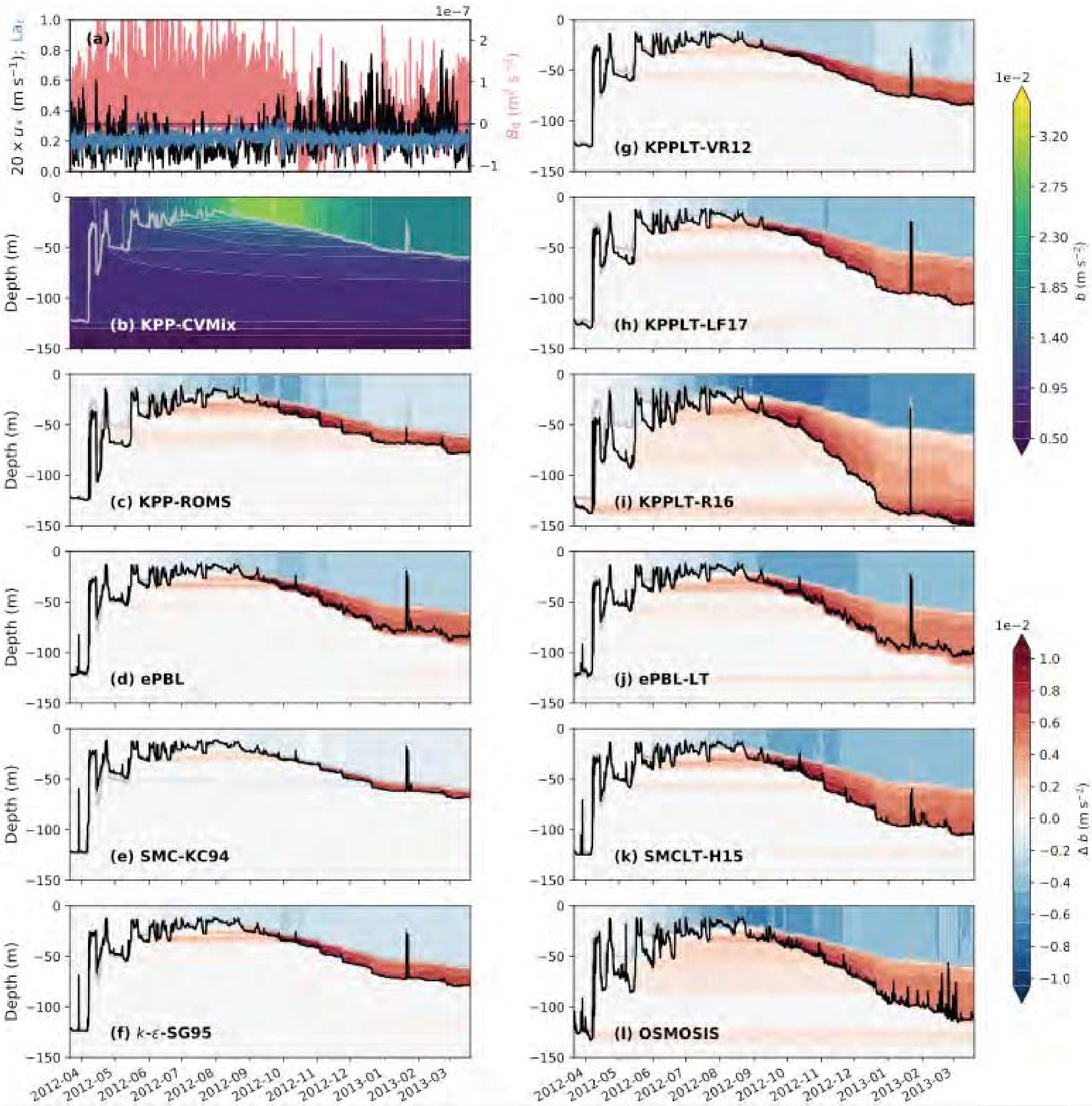

Figure 5. Comparison of simulated buoyancy with 6 Langmuir turbulence parameterization schemes and 5 non-Langmuir counterparts, for a modern test-bed case from OS-Papa for a full annual cycle. Panel (a) shows time series of water-side surface friction velocity u* (m/s) in black, turbulent Langmuir number La_t in blue (La_t = 0.3 in dark blue for reference), and surface buoyancy flux B_0 (m^2/s^3) in red (B_0 = 0 m^2/s^3 in dark red for reference). For clarity, $20u^*$ is shown, to share the same vertical axis with La_t on the left, whereas B_0 uses the vertical axis on the right. Panel (b) shows the simulated buoyancy b (m/s^2) for KPP-CVMix, with the mixed layer depth (MLD) defined by the 0.03 kg m^3 density criterion marked in gray. Panels (c)-(l) show the differences in simulated buoyancy from KPP-CVMix for all other schemes, with the MLD marked in black. For comparison, the MLD for KPP-CVMix is also shown in (c)-(l) in gray. Note that the order of the panels has panels on the left showing the results of non-Langmuir schemes, and panels on the right with results of Langmuir schemes. Only the upper 150 m of the domain is shown for clarity.

PUBLICATIONS

Li Q., B. G. Reichl, B. Fox-Kemper, A. J. Adcroft, S. Belcher, G. Danabasoglu, A. Grant, S. M. Griffies, R. W. Hallberg, T. Hara, R. Harcourt, T. Kukulka, W. G. Large, J. C. McWilliams, B. Pearson, P. Sullivan, L. V. Roekel, P. Wang, and Z. Zheng. Comparing ocean boundary vertical mixing schemes including Langmuir turbulence. *Journal of Advances in Modeling Earth Systems (JAMES)*, 11(11):3545-3592, November 2019

Kukulka, T. and Harcourt, R.R., 2017. Influence of Stokes drift decay scale on Langmuir turbulence. *Journal of Physical Oceanography*, 47(7), pp.1637-1656.

Ma, B., E. D'Asaro, T. Sanford, and J. Thomson, 2020, LC–DRI Field Experiment and Data Calibration Report. Technical Report APL-UW TR 2002 March 2020. Applied Physics Laboratory, University of Washington, Seattle, WA.

Shcherbina, A.Y., D'Asaro, E.A. and Nylund, S., 2018. Observing finescale oceanic velocity structure with an autonomous Nortek acoustic Doppler current profiler. *Journal of Atmospheric and Oceanic Technology*, *35*(2), pp.411-427.

Thomson, J., Moulton, M., de Klerk, A., Talbert, J., Guerra, M., Kastner, S., Smith, M., Schwendeman, M., Zippel, S. and Nylund, S., 2019, March. A new version of the SWIFT platform for waves, currents, and turbulence in the ocean surface layer. In *2019 IEEE/OES Twelfth Current, Waves and Turbulence Measurement (CWTM)* (pp. 1-7). IEEE.