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A Lagrangian perspective on wave-driven turbulence in the ocean surface boundary layer

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Turbulent processes in the ocean surface boundary layer (OSBL) play a key role in weather and climate systems. OSBL turbulence is driven by surface waves: Wave-current interactions lead to wind-aligned vortices, called Langmuir circulation (LC), and breaking waves (BWs) are a source of near surface turbulent kinetic energy (TKE). A common description of turbulence relies on the Eulerian reference framework for which flow properties are evaluated at fixed location. However, fluid parcels move throughout the entire OSBL from the surface to the OSBL base, being exposed to physical, chemical, and biological property gradients, which controls the fate and transformation of properties in the OSBL. By following fluid parcels with the flow, the Lagrangian reference framework provides a natural alternative to the Eulerian framework. To trace fluid particle paths, we employ a large eddy simulation (LES) model of the OSBL with wave effects. LC is captured by the Craik-Leibovich vortex force, also known as the CL2 mechanism. BW effects are modeled by a surface TKE flux, constrained by wind energy input to surface waves. Unresolved subgrid-scale motion is simulated with a stochastic model that is energetically consistent with the subgrid-scale model of the LES. With LC, Lagrangian autocorrelations reveal three distinct time scales, an integral time, a dispersive mixing time scale, and a coherent structure time scale. Coherent structures due to LC result in relatively narrow peaks of Lagrangian frequency velocity spectra. With and without waves, the high-frequency spectral tail is consistent with expectation for the inertial subrange, but BW substantially increase spectral levels at high frequencies. Consistently, over short times, particle pair dispersion results agree with the Richardson-Obukhov law, and dispersion is significantly enhanced due to BWs. Over longer times, our dispersion results are consistent with Taylor dispersion. In this case, turbulent diffusivities are substantially larger with LC in the cross wind direction, but may be reduced in the along wind direction due to enhanced mixing with LC that reduces mean Eulerian shear. Our results indicate that the Lagrangian analysis framework is effective and physically intuitive to characterize OSBL turbulence.