A Wave Resolving Simulation for Upper Ocean Turbulence Driven by Wave-Current Interaction

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Turbulence in the upper ocean sets bulk properties of the upper ocean. For example, turbulence deepens the surface mixed layer (ML) and entrains low-temperature water below the layer to determine the ML depth and sea surface temperature (SST), which are key parameters for large-scale ocean and climate processes. Quantitative evaluation and parameterization of the upper ocean turbulence thus have crucial importance on the large-scale studies.

Recent studies revealed that turbulence induced by the surface wave has larger impact on the ML deepening than ever considered. Good example is drastic deepening of the ML and significant decrease in SST simulated in the summer Southern Ocean if parameterized wave-induced mixing is included in the simulation (e.g., Li et al. 2016). Among three types of wave-induced turbulence, surface wave breaking, Langmuir turbulence (LT) and nonbreaking-wave induced turbulence (NBWT), the latter two are considered to have significant impacts on the ML deepening. LT is associated with Langmuir circulations (LCs), the secondary circulations driven by the surface waves interacted with the wind-driven currents (e.g., Leibovich 1980). Previous theoretical studies (Craik and Leibovich 1976) showed that the interaction can be represented solely by the vortex force, vortex tilting by the Stokes drift (the Lagrangian velocity due to the surface wave) in the wave-filtered momentum equation. Many simulations with this vortex force representation have been performed so far (e.g., Skyllingstad and Denbo 1995). However, this theoretically-derived representation has not been validated by field or numerical experiments. As a consequence, there are controversial discussions about the validity of the representation and hence the simulation results with the representaion (e.g., Mellor 2016 and Ardhuin et al. 2017). NBWT on the other hand is suggested to be caused without winds (e.g., Qiao et al. 2004; Babanin 2006), but no detailed mechanism was proposed for the turbulence generation. As a result, some people consider that NBWT is the same as LT, even though LT is dependent on winds while NBWT is not. Thus, mechanism of the wave-induced turbulence is not clearly understood.

The present study is intended to clarify dynamics involved in the wave-induced turbulence. To this aim, we developed a new numerical model in which surface waves are explicity and accurately simulated. This wave-resolving simulation provides an unique opportunity to investigate how the surface waves drive / induce turbulence. We used this model to simulate LC at first (Fujiwara et al. 2018). A wave-tank simulation was performed in which a monochromatic surface wave propagated in the surface wind direction. We found that LCs were successfully reproduced through the wave-current interaction (see attached figure). Vorticity analysis showed that the interaction is well represented by the vortex force. We also performed the simulation without the surface wind, and found that NBWT was certainly generated. The virtual wave stress was found to be a key for NBWT generation in our simulation, which induced velocity shear near the surface that interacted with the surface wave as was found in the LC simulation. The wave-resolving simulation also provided an alternative Eulerian view of the vortex force that was originally viewed from the Lagrangian frame (Stokes drift), that is, rectified vortex tilting/shrinking/streatching by orbital motions of the surface waves.

Keywords: Upper Ocean Turbulence, Surface Wave - Current Interaction, Langmuir Circulation, Non-Breaking Wave Turbulence