Wave resolving numerical simulation of non-breaking wave-induced mixing

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Recent studies suggest that non breaking surface waves induce vertical mixing in the ocean surface layer. Langmuir circulations (LCs), generated by the interaction between surface waves and wind-driven shear flow, are one example of the processes that cause mixing without wave breaking. Some laboratory and numerical experiments, on the other hand, showed the mixing caused only by the non-breaking wave without wind-induced shear (hereafter referred as the non-breaking wave-induced mixing). Dai et al. (2010) observed that initially stratified water in their windless laboratory tank was homogenized under the monochromatic surface waves with wave steepness ak = 0.08 ~ 0.21. Savelyev et al. (2012) conducted windless laboratory experiments and identified an elongated streaky structure at the water surface in the presence of surface waves. Wave resolving numerical simulations showed that counterrotating streamwise vortex pairs like LCs (Tsai et al.,2015, 2017, Fujiwara et al.,2020) and elongated surface streaks (Tsai et al.,2015,2017) were formed even without wind stress at the surface. These numerical studies suggested that the structures can be formed by the CL2 instability mechanism, the interaction between surface waves and the sheard current as in LCs, but the current is produced by the wave viscous attenuation (Tsai et al.,2017, Fujiwara et al.,2020). However, there remain several issues to be resolved. For example, the numerical experiments used steeper waves (ak = 0.25; Tsai et al.,2015,2017) than the laboratory experiments (ak = 0.08 ~ 0.21; Dai et al.,2010) and larger viscosity than that of water (Fujiwara et al.,2020). The magnitude of mixing caused by this vortex structure was not evaluated in the studies. Furthermore, the velocity characteristics are different from those of LCs. Thus, the condition, magnitude, and mechanism of non-breaking wave-induced mixing need to be clarified.

The purpose of this study is to examine whether the non-breaking surface waves with relatively small steepness can induce the mixing in the water with molecular viscosity and to evaluate how strong it is. To this aim, we conduct the numerical experiments under the similar condition as the laboratory experiment by Dai et al. (2010). A sigma-coordinate free-surface nonhydrostatic model similar to Tsai and Hung (2007) and Yang and Shen (2011) was used. We considered a surface wave with a wavelength of λ = 75cm and an amplitude of 1cm (ak = 0.08) propagating on the surface of homogeneous water with an average depth of 20cm. The length and width of the computational domain are λ and $\lambda/2$ respectively with periodic boundary condition in both directions. No tangential stress at the surface was imposed. Initial surface elevation and velocity were set as those of the third-order Stokes wave. To visualize motion of water, a passive tracer with a linear vertical profile was distributed in the initial field. The domain was discretized with $256\times128\times64$ grid points. The simulated wave kept propagating until at least 100 wave periods with less deformation from the stokes wave (except for the wave viscous attenuation).

Simulated velocity field showed that convergent (divergent) zones of the spanwise velocity at the surface and divergent (convergent) zones at depth correspond with the zones of downward (upward) velocity and acceleration (deceleration) of the streamwise (downwave) velocity. Tracer distribution at the surface was also characterized by elongated streaks. These features can be explained by the formation of streamwise vortices near the water surface. The vertical diffusivity estimated from the tracer distribution was $O(10^{-5})$m

^{2}/s, with its maximum at about 2cm depth and becoming almost zero at and below about 6cm depth.

Magnitude of the estimated diffusivity is similar to that of Dai et al. (2010). More detailed analysis about the mechanism of this mixing and dependences of vertical diffusivity on wave parameters and stratification will be presented.

Keywords: ocean surface mixing, streamwise vortex pairs, wave viscous attenuation