Numerical simulations of the effects of turbulence on size distribution of sinking particles in the surface mixing layer

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Sinking particles in the ocean contribute to material transport to the deeper ocean. For example, phytoplankton in the oceanic surface mixing layer absorb carbon by photosynthesis, and sink as particles. It is known that atmospheric CO_2 absorbed in the particles and various materials stuck to particles' surfaces are advected and transported to the deep layers in the ocean. Estimation of their amount is therefore important for quantitative evaluation of the net global carbon transport. However, sinking velocity of particles have not been well quantified. For example, the velocity is often tuned in some numerical models in order to reproduce observations. Therefore evaluation of material transport by particle sinking is not sufficient even today.

Volume and surface area of the sinking particle as well as its sinking velocity are key parameters for the transport, and all these parameters depend on particle size. Hence size distribution of the particles is the most important parameters to be understood. The particle size is known to increase through collision between particles due to Brownian motion, differential settling or flow shear effect (Burd and Jackson, 2009; Ayala et al., 2008). On the other hand, recent studies show that strong turbulence breaks larger particles and limits their sizes to about Kolmogorov's scale (Takeuchi et al., 2019).Thus turbulence has two opposite effects on the particle size, but net effects have been unquantified.

The present study is intended to quantify the net effects of turbulence on the particle size distribution in the mixing layer. For this purpose, we simulated turbulent flow field using large-eddy simulations (LESs) and tracked particles in the flow field using a modified Lagrangian cloud model (LCM, Riechelmann et al., 2012). In the LCM, not each particle but group of particles with a particular size (referred to as packet in this study) is tracked. Each packet contains the number of particles and its size, and changes its position due to the flow simulated by the LES and its own (negative) buoyancy. Packets interact (coagulate) with other packets to change the number and size of the particles. Coagulation processes considered in this study were Brownian motion, differential settling and flow shear. Effects of resolved-scale shear were represented by the simulated flow. Other processes including subgrid-scale shear effects were parameterized (Andrejczuk et al., 2010). Fragmentation of the particles by turbulence was parameterized by limiting the largest size to the local Kolmogorov's scale. When the fragmentation occurred, the number of particles in the packet was increased so as to conserve total mass of particles.

In the present study, turbulent flow was forced by constant wind stress imposed at the rigid-lid surface of an ocean on a f-plane. The model domain is cubic with periodic horizontal boundaries and free-slip bottom boundary. Turbulent flow was first simulated until the turbulence became statistically steady, and then packets of 10-12 μm in size (radius) were continuously deployed at the surface. The packets reached at the bottom were removed. To quantify the turbulent effects, we also deploy packets in the same manner at the surface of the same but motion-less ocean.

Comparison between the turbulent and motion-less experiments revealed that turbulence increased the number of larger-size particles. Enhanced collision due to turbulent shear and elongated residence time in the mixing layer due to turbulent diffusion were found to be responsible for this increase. These effects

were larger than the size-limiting effects due to turbulence. According to this size increase, the average sinking velocity of the particles passing through the bottom within unit time was increased by 30%, while surface area was decreased by 20%. These results suggest that turbulent shear increase volume transport of particles but can decrease transport via their surfaces.

Keywords: mixing layer, turbulence, sinking particle, size distribution