Flow-animal interactions in the ocean

<u>［課程博士・論文博士共通］</u>

博士学位論文内容要旨
Abstract

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論文題目 Title	Flow-animal interactions in the ocean （海洋における生物と流れの相互作用に関する研究）		

While marine animals are always exposed to fluid motions, interactions between animals and flows are still controversial. Due to difficulty in measurement, *in situ* observations of animal swimming simultaneously with environmental flow fields are rare. Also, it has been unclear whether animals significantly modify surrounding flow fields. While previous studies have focused on effects of environmental flow field on marine animal (or *vice versa*), in this study, field and laboratory experiments were conducted using novel technologies to investigate "two-way" interactions between flows and animals.

Filed campaigns were conducted to investigate zooplankton avoidance to water disturbance, focusing on diel vertical migration (DVM). DVM of zooplankton has been identified to contribute to vertical flux of carbon in the ocean. While most researchers have worked on mechanism and dynamics of DVM from the view point of biology and/or ecology, several studies have demonstrated that surrounding flow field modify behavior of individual zooplankton (e.g. Seuront et al. 2004). To reveal how zooplankton modify their DVM in response to fluid motions, I analyzed *in situ* data acquired by a cabled observatory that carries a plankton camera (Continuous Plankton Imaging and Classification System, CPICS) and various environmental sensors. The cabled observatory was fixed on the sea floor of 20 m depth near Habu Port at Izu-Oshima Island, Japan. The analysis period was from August 2014 to January 2015. The plankton images were classified at a taxonomic level. The zooplankton taxa were separated into three groups: "strong migrator" (Ostracoda, Mysida, etc.) that appeared only during nighttime, "moderate migrator" (Calanoida, Larvacea, etc.) that appeared at day and night but preferred night, and "non-migrator" (Radiolaria, Aulosphaera) that appeared at day and night evenly. Optical backscatter intensity measured by the turbidity sensor was frequently increased during night throughout the analyzed period, and the nighttime average was over 10-fold higher than that of daytime. Abundance of the strong migrator (individuals L^{-1}) significantly correlated with the optical backscatter intensity ($r^2 = 0.79$, $p < 0.01$), suggesting that the source of the nighttime increases in the optical backscatter intensity was the strong migrator. Hence, I will use the optical backscatter intensity as a proxy of migrator abundance. Several typhoons passed near the cabled observatory during the analysis period, resulting in increased significant wave height ($H_{1/3}$~4 m at maximum). I compared both the strong migrator abundance and the optical backscatter intensity to orbital velocity induced by the surface gravity wave and found that both were negatively correlated with orbital velocity ($r^2 = 0.32$, $p < 0.01$ and $r^2 = 0.27$, $p < 0.01$, respectively). Since most strong migrator were demersal zooplankton, given the previous studies (e.g. Seuront et al. 2004), the negative correlations suggest that strong migrator actively avoided water disturbances and stayed near the sea floor or in the deeper layers, consequently suppressing their DVM. Additional data that support the main suggestion will be shown in the main text.

To confirm reproducibility of the zooplankton response to surrounding flow field, I analyzed long-term data acquired by two ADCP mooring systems. Filed campaigns were carried out near Izu-Oshima Island and off Eilat, Israel. While the observation site near Izu-Oshima Island has a typical coastal environment in middle latitude, the one off Eilat is in a semi-enclosed gulf (the Gulf of Aqaba) in low latitude where salinity is always

>40 PSU throughout the year. Acoustic backscatters were used as a proxy of zooplankton density (Flagg & Smith 1989). Acoustic backscatters during nighttime were significantly higher than that of daytime, suggesting DVM of zooplankton. The nighttime acoustic backscatters were significantly reduced when current velocity increased at the both observational sites, despite the fact that the sites have very different environments. The consistent result from two different locations suggests the generality of the zooplankton avoidance in response to fluid disturbances.

Zooplankton generally display positive phototaxis. Both CPICS and the fluorescence/turbidity sensor carried a light source. To test how zooplankton is attracted by these optic sensors and affect the data, I have conducted tank experiments using a natural zooplankton community and a cultured community composed of nauplius larva of *Artemia salina*. The fluorescence/turbidity sensor was put in an experimental tank with a community. While zooplankton in the both communities were not attracted by the light source of the sensor under room light condition, they are significantly aggregated nearby the light source under dark condition. Altering abundance of the natural community, the effect on the turbidity signal was then tested. The turbidity signal was 1.0 FBU when the abundance was 430 individuals L^{-1}, while the average was 0.1 FBU under the control (without zooplankton). While the turbidity increased to 2.2 FBU when the density was 870 individuals L^{-1}, the turbidity did not show significant increase when the density was altered to 1300 individuals L^{-1}. Second, the effect of environmental flow on the phototactic behavior was tested using the cultured community. While the individuals of *A. salina* are attracted by the light source of the sensor, flows were generated in the tank by stirrers. The flow velocity increased up to 3 cm s^{-1}, and the turbidity data decreased as the individuals hovering around the sensor were flushed away. A significant negative correlation of turbidity against flow velocity was produced by this experiment ($r^2 = 0.40$, $p<0.01$), which was observed by the cabled observatory. Bias due to the phototactic behavior on the *in situ* data is discussed in the main text.

Finally, an experimental campaign on fish-generated turbulence was conducted. While organism-generated turbulent mixing (called biomixing) was first time mentioned by Munk (1966) and has been actively discussed for over the last decade, role of biomixing in ocean mixing is still elusive. The most controversial issue is whether organisms can generate turbulent eddies larger than their body size (Visser 2007). To test this issue, several direct observations have been carried out for low-Reynolds-number animals (i.e. zooplankton), but there is no direct observation for high-Reynolds-number animals (i.e. fish). To clarify if fishes can generate turbulent eddies large enough to mix stratified water columns, we conducted an observational experiment in a large aquarium tank containing several thousand Japanese sardines *Sardinops melanostictus*. Turbulence data were collected from inside the sardine school using a turbulence microstructure profiler. While the averaged turbulent kinetic energy dissipation rate was 6.7×10^{-6} W kg^{-1} outside the school, the averaged value inside the school was 2.3×10^{-4} W kg^{-1}: two orders of magnitude higher than typical dissipation rates in the surface mixed layer. The school displayed fast and non-continuous ‘avoidance behavior’, or fast and long-lasting ‘feeding behavior’ during the measurements. A noticeable difference between the 2 behaviors was found in turbulent shear spectra: the avoidance behavior spectra showed a power decline in comparison with the Nasmyth empirical spectrum in the inertial sub-range, but the feeding behavior spectra exhibited no power decline, even in the inertial sub-range. In the latter case, the sardine school imparted kinetic energy into scales larger than the average individual body size of 0.173 m. This result is a counter-example to a general hypothesis that swimming organisms cannot impart kinetic energy at scales larger than their individual body size. Ecological significance of the flow-animal interactions is discussed with the results from this study and previous studies.