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Measurements of fluid transport by controllable vertical migrations of plankton

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Abstract

Diel vertical migration of zooplankton has been proposed to be a significant contributor to local and possibly large-scale fluid transport in the ocean. However, studies of this problem to date have been limited to order-of-magnitude estimates based on first principles and a small number of field observations. In this work, we leverage the phototactic behavior of zooplankton to stimulate controllable vertical migrations in the laboratory and to study the associated fluid transport and mixing. Building upon a previous prototype system, a laser guidance system induces vertical swimming of brine shrimp (*Artemia salina*) in a 2.1 meter tall, density-stratified water tank. A schlieren imaging system and a conductivity probe are used for measurements of the water column. Fluid transport and mixing is quantified through analysis of turbulent scales and the density profile evolution. These experiments will add to our understanding of the dynamics of active particles in stratified flows and inform the ongoing debate regarding biogenic ocean mixing.

1 Introduction

The ocean consists of large scale temperature and salinity gradients leading to a stable density stratification superimposed upon a highly varying distribution of nutrients. At the surface, nutrient concentrations are impacted by biological activity. At depth, light attenuation reduces biological activity and nutrient concentration reaches a maximum. Vertical transport mechanisms, such as upwelling, are critical for surface nutrient replenishment. In this work, vertical fluid transport by collective swimmers, such as zooplankton, is investigated as a potential mechanism affecting the chemical and physical characteristics of the water column.

Zooplankton comprise a significant portion of the ocean biomass and cluster in dense swarms throughout the ocean. Following light cues of sunrise and sunset, these dense swarms migrate to and from the surface in a process known as diel vertical migration (DVM) (Dewar et al., 2006). These migrations have been witnessed vertically over hundreds of meters in regions of high nutrient variation (Denman and Gargett, 1995). Representative plankton swimmers and *in situ* migration observations exhibit speeds around 100 m hr^{-1} (Kunze, 2006) while upwelling vertical velocities that play a crucial role in nutrient transport are notably slower on the order of 4 m hr^{-1} (Mahadevan, 2016). Additionally, field measurements have shown turbulent kinetic energy dissipation can be elevated by three to four orders of magnitude following a vertical migration (Kunze, 2006), although subsequent measurements have brought into question what levels of enhancement are representative (Rousseau et al., 2010). Overall, current knowledge lacks a quantitative understanding of the potential impacts of DVM to the physical and biogeochemical structure of the water column.

The collective nature of plankton migration presents the possibility for animals of sizes smaller than scales of relevant gradients in the ocean to produce fluid motion at scales much larger than the individuals. Despite conventional thought regarding biogenic mixing efficiency that assumes the scale of induced motion is limited by the size of an individual animal (Visser, 2007), the interaction or superposition of flows created by adjacent swimmers presents multiple potential mechanisms for larger scale transport and meaningful mixing to occur (Wilhelmus and Dabiri, 2014).

The difficulty of predicting the location and timing of a migration has made comprehensive *in situ* measurements impractical. Moreover, numerical simulation remains computationally expensive due to the large range of length and time scales necessary to capture the near-field and far-field flow concurrently. Thus, a controlled laboratory setup has been designed to examine the unique fluid dynamic interactions created by sustained collective movement in a stable stratification.

1.1 Previous Work

The phototactic response of *Artemia salina*, a representative swimmer, has been well characterized in work by Wilhelmus and Dabiri (2014). The strong attraction of *Artemia* to light in the green to blue wavelengths was used to study the upward movement of group swimmers in a meter high tank.

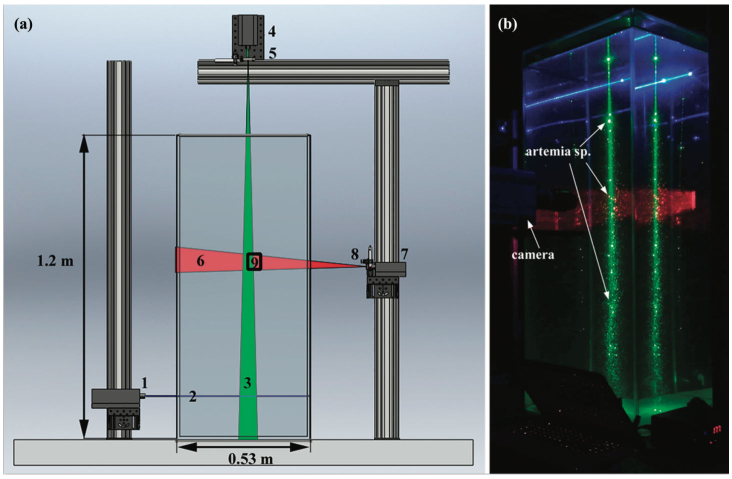

Figure 1: Experimental setup by Wilhelmus and Dabiri (2014). Laser guidance system for control of animal migrations. A 447 nm laser (1) generates a horizontal blue laser beam (2) aligned with a vertical green laser sheet (3), generated by a 532 nm laser (4), and a 25 mm focal length cylindrical lens (5), and introduced from above the tank. A vertical, red laser sheet (6) is utilized for PIV measurements. (b) Photo of the setup during a migration event, after the 447 nm laser has completed its vertical traverse of the tank. The image was captured at an angle, producing duplicate reflections of the lasers in the two visible sides of the tank.

Results from particle image velocimetry (PIV) over the course of the migration yielded energy spectra displaying energy increases at all scales, but most importantly at scales larger than the scale of the animals (figure 2). It was concluded that the large-scale fluid transport measured was a result of the animals clustering while traversing the tank. This clustering was created by the laboratory guidance method and is consistent with field observations of plankton grouping during DVM. This work has prompted further investigation into the mechanisms resulting in large scale fluid transport, the impacts over a larger domain, and the interactions with a stable density stratification.

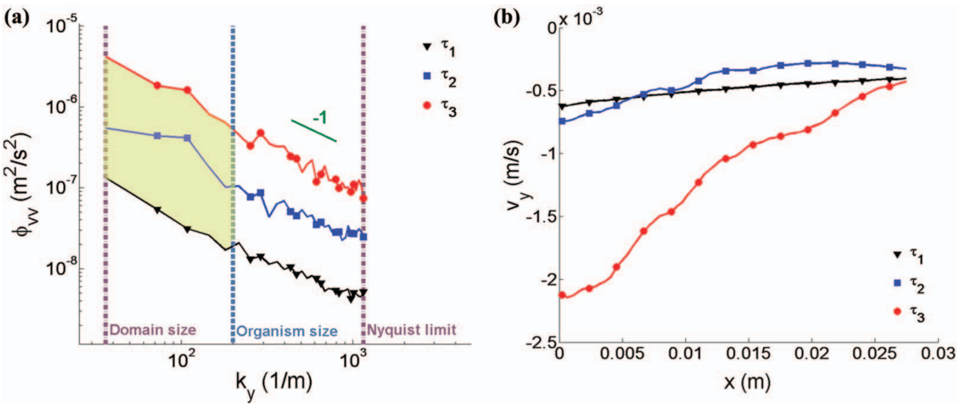

Figure 2: (a) Vertical component of the velocity spectrum tensor versus wavenumber for the three time steps corresponding to different stages of the migration. The yellow shaded region indicates increasing kinetic energy at length scales greater than the individual animal size. (b) Vertical velocity profiles at varying time steps throughout migration. (Wilhelmus and Dabiri, 2014)

2 Experimental Design

A new laboratory setup has been built to further investigate fluid transport and mixing by collective swimmers. A 2.1 m high × 0.9 m wide × 0.9 m long tank allows for full development of animal migration and sustained swimming over roughly 500 animal body lengths. The increase in scale allows for the incorporation of new measurement techniques such as a density profiler and avoids domain size limitations from boundary effects. The tank is linearly stratified in density using a double-bucket method (Economidou and Hunt, 2009) and saline water. Lasers are used to induce collective motion of the animals toward the light. A 1 W, 447 nm (blue) laser is mounted horizontally above the tank and aligned with a -50 mm focal length spherical lens and a 45° mirror to redirect the beam vertically downward in the center of the water column. A 1 W, 532 nm (green) laser is mounted horizontally beneath the tank with identical optics to redirect the beam vertically upward. The blue and green laser beams are centered and aligned throughout the height of tank. The spherical lens expands the laser beam into a narrow cone that has been optimized empirically to maximize animal response over the depth of the tank. One laser is utilized at a time to induce unidirectional swimming toward the powered laser (i.e. toward the top or bottom of the tank).

2.1 Experimental parameters

The collective animal motion is controlled by various parameters of the laboratory setup. The number density within the clustered migration is controlled by the width of the beam which is determined by the focal length of the spherical lens and the distance from the laser source to the water column. The light stimulus is held at a constant power at a fixed location (the top or bottom of the tank) throughout the migration to allow the animals to swim at their natural speed. The stratification of the tank is tunable and chosen to be within a naturally representative range with a buoyancy frequency of approximately $10^{-1}s^{-1}$.

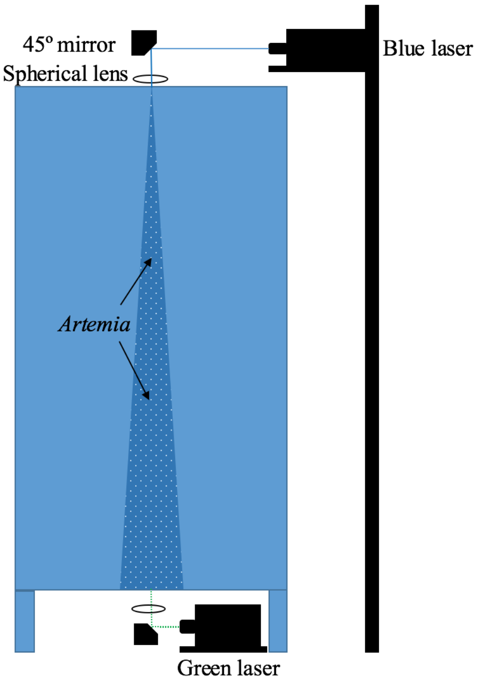

Figure 3: Laser guidance setup described in section 2. A cone of light is formed from the laser and spherical lens, identical optics above and below.

2.2 Measurement Techniques

This research aims to explore the mechanisms of fluid transport and the resultant large scale impacts by collective swimming. To achieve this, measurement techniques are utilized to image the near-field flows and record the density profile over the depth of the tank. The laboratory setup is equipped with multiple measurement devices and the capacity for future complementary techniques to be added.

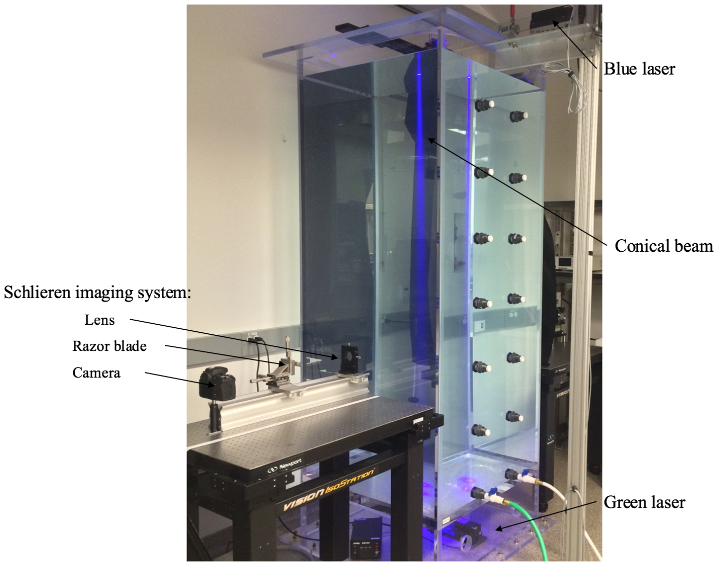

Figure 4: 2.1 m tall, 470 gallon capacity tank with blue laser powered on.

Schlieren Imaging System

A near-field visualization of density gradients is obtained with a schlieren imaging setup with a field of view of 5 cm (approximately 10 animal lengths). A 75 W Xenon arc lamp is used to illuminate the field. The light passes through a condenser lens and horizontal slit and then is collimated via a 250 mm focal length plano-convex doublet lens. The resultant 5 cm diameter parallel beam travels through the width of the tank situated 1 m above the tank base. The collimated beam is distorted by the varying indices of refraction of the perturbed density field in the path of the light. The beam then passes through a 400 mm focal length plano-convex doublet lens that converges the beam to a focal point. A precision aligner is utilized to position a horizontal razor blade at the focal point of the beam. The razor blade, when properly positioned, reduces the intensity of the beam. For a uniform density test region, the beam is simply half as bright. For a varying density flow, the deflected rays do not coincide with the focal point and are either blocked by the razor blade or pass through without any reduction in intensity, depending on the density gradients experienced. The resultant image yields a measure of the first derivative of density in the razor-normal direction (Settles, 2001). The total light distortion over the path length yields an image with regions of higher and lower illumination corresponding to regions of the highest positive and negative fluid density gradients, respectively, in the direction normal to the razor blade.

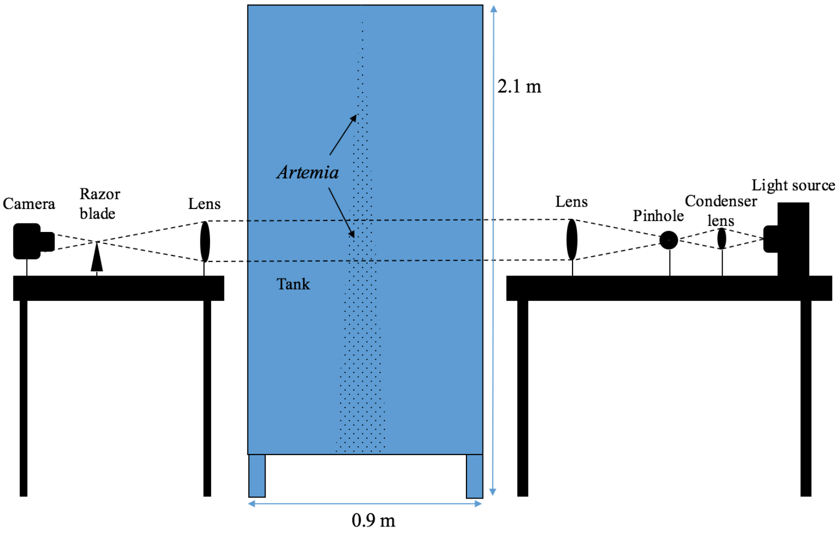

Figure 5: Schlieren imaging system described in section 2.2.

With the above setup, the three-dimensional density field cannot be quantified as only the resultant total deflection is visualized from an unknown complex density field over the path. This technique yields a qualitative visualization of the density variations illustrating the coherent structures formed by the swimming animals and perturbations to the stable stratification. Schlieren imaging yields a near-field visualization of imposed flow structures for analysis of the mechanisms for mixing to occur and perspective on the impact of group swimming. This analysis indicates the dynamics of restratification and the vertical distance over which fluid is being displaced.

Conductivity-Temperature-Density Profiler

Complementary to the near-field density gradient visualization, a large-scale understanding of water column dynamics is gained with a density profile. A conductivity-temperature-density (CTD) probe is traversed through the tank in close proximity to the centered laser beam column where migration occurs. A density profile is recorded over the depth of the tank through one or many migrations. The profile evolution allows for analysis of large scale impacts upon the stratification by collective swimming including a quantification of the overall density perturbation and assessment of the degree of irreversible mixing. Time series extending post migration inform whether a new equilibrium stratification develops or the column returns to the original stratification. The traversing probe allows for approximately millimeter resolution to capture local variations along with data at the scale of the tank.

Chemical Indicators

Current studies are focused on impacts to the stable density stratification in the water column. However, diel vertical migration of plankton has potentially important impacts on chemical concentrations in the ocean. This is particularly relevant in regions where plankton migrate through high gradients in nutrient concentration which are prevalent in the ocean. In addition to the instrumentation for density visualization and direct measurement, chemical indicators, such as by Koweek et al. (2016), can be used to quantify resultant transport by collective swimming.

Particle Image Velocimetry

Previous work has utilized PIV effectively for analysis of the scales of structures created by plankton swimming. PIV has proven powerful for gathering quantitative data regarding flow velocities and turbulence statistics, but is limited in its domain size and restriction to a 2D planar field. Moreover, correlation of the velocity vectors to local density variation is unfeasible. While both PIV and schlieren have the capacity for analysis of scales in the flow, the schlieren setup allows insight into density effects rather than induced velocities. PIV is a potential future measurement technique to complement the current constructed setup.

3 Future Work

Development of the experimental setup and reproducible animal control allows for a variety of analyses of the impacts of collective swimming upon the stratified water column. A local scale characterization of fluid movement and density perturbations via schlieren imaging provides visualization of the mechanisms leading to mixing of the water column. The tank-scale density profile gives a comprehensive representation of large scale impacts of collective swimming.

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