LABORATORY STUDIES OF OCEAN MIXING BY MICROORGANISMS

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Summary Laser induced fluorescence measurements were conducted to quantify the mixing by an aggregation of *Artemia salina* swimming vertically within a stratified water column. The displacement of the center of mass of a fluorescently labelled layer was followed over time to determine the resulting fluid stirring. An increase of fluid potential energy was observed. Comparison of events with and without animal motion indicate that vertical swimming of a swarm of microorganisms results in measurable mixing, despite buoyancy forces and diffusion.

INTRODUCTION

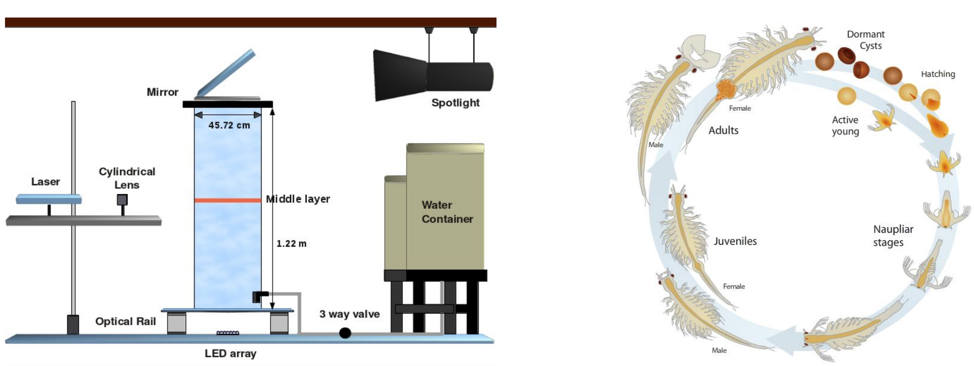
Ocean mixing plays a major role in nutrient and energy transport and is an important input to climate models. It is well known that winds and tides are the main drivers of this process. However, it has been suggested that the overall energy input required to mantain global ocean circulation exceeds the contributions from winds and tides [5]. Dating back to the suggestion of Munk [4], there has been ongoing discussion about the role swimming animals have in ocean mixing.

Kunze et al reported measurements showing elevated kinetic energy dissipation rates in the vicinity of migrating krill aggregations [3]. However, as argued by Visser [6], for animals whose body length is below the Ozmidov buoyancy length scale, turbulent wake mixing efficiency is low and energy is mainly dissipated by fluid viscosity. Recent studies of jellyfish swimming by Katija and Dabiri have shown that induced drift is the governing mechanism of mixing by swimming animals [2]. Their results demonstrate that this mixing mechanism is enhanced by fluid viscosity and is equally effective for small organisms.

Further analysis by Dabiri [1], addresses the relevance of induced drift during vertical migration of swarms. His results suggest that vertical motion is necessary to generate overturning and posterior mixing in scales larger than the length of an individual. Moreover, his numerical study shows that the amount of mixing may be sensitive to the adopted migration pattern. Following this research line, we are interested in quantifying the mixing by a controlled biomass in a water column ressembling physical conditions in the ocean.

EXPERIMENTAL SETUP

A schematic diagram of the experimental apparatus is shown in Figure 1. It consists primarily of an acrylic cylinder with 45 cm internal diameter and 1.22 m length, and an optical system to visualize the vertical displacement of the fluid. A water column with a density gradient representing the ocean was produced by introducing layers of fluid with different salinity levels through a 0.95 cm flexible tube connected to a plastic container. *Artemia salina*, a species of brine shrimp, was used as a model organism due to its resilience and phototactic behavior. Decapsuled eggs were acquired at the Cabrillo Marine Aquarium (San Pedro, CA) and hatched in the laboratory.



(a) (b)

Figure 1: (a) Experimental setup, (b) Life cycle of *Artemia salina* (*http : //www.bridgerlandaudubon.org*)

Tests were conducted by introducing the organisms at the bottom of the container. A custom LED array (465 nm), positioned as shown in Figure 1, was used to group the animals and inhibit any upward motion. Vertical migration was triggered by swtiching the luminescent signal from the bottom to the top by turning on a spotlight. Laser induced fluorescence measurements were done to analyze the resulting fluid motion, as indicated by the displacement of the fluorescently labelled middle layer. High definition videos were obtained with a Sony HDR-HC7 camera oriented perpendicular to the illuminated plane.

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RESULTS

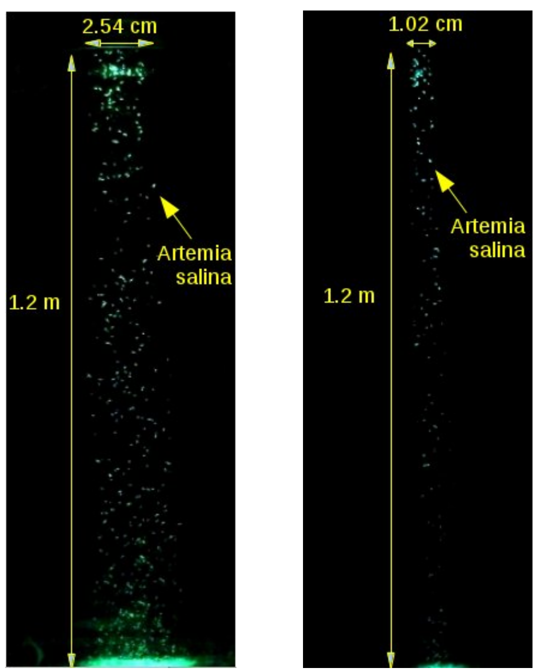
Prior to quantifying the mixing, tests were conducted to analyze the phototactic response of the animals within our setup. Figure 2 shows snapshots showing the organisms as they swim upwards within light beams of different diameters. The swimming speed and animal spacing of the organisms are shown in Table 1. The corresponding Reynolds number is 224, using the animal's body length. It was observed that the motion of the animals was vertical and confined within the light beams for both cases. Most importantly, a reduction in the beam's diameter resulted in an immediate drop in the number density of organisms.

	Case 1	**Case 2**
Beam diameter	10.16 cm	5.08 cm
Animal Spacing	2.54 cm	1.02 cm
Swimming Speed	0.02 m/s	0.02 m/s

Table 1: Experimental variables

ONGOING AND FUTURE WORK

Measurements of the density gradient and buoyancy frequency are being performed in order to confirm that our laboratory model is consistent with parameters observed in the ocean. It has been visualized that the vertical displacement of each organism produces the entrainment of fluid from one layer to the other, which generates overturning and may induce mixing. The motion of the middle layer's centroid will be followed over time in order to compute the change in fluid potential energy. Comparison of the data and a control test, in which only buoyancy forces and diffusion will be present, will show if the vertical motion of the organisms results in enhanced mixing.



(a) (b)

Figure 2: Snapshots taken from different experiments with the light coming from the top: a) 2.54 cm beam diameter, b) 1.02 cm beam diameter

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