

Effects of In Situ Animal-Fluid Interactions on Transport and Mixing

Thesis by

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To my family and friends who inspire me everyday.

Acknowledgments

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My brother, Ikaika, and I were very close growing up. Before I decided to commit myself to graduate school, I was an internationally ranked figure skater (and an alternate for the US Olympic team in 2002), and my ice dancing partner was my brother. We trained together, traveled the world together, and shared dreams together. I think the toughest decision I have ever made was to forego my involvement in figure skating to focus on graduate school. I was not giving up my dream of one day making it to the Olympics, I was giving up the dream that I shared with my younger brother and best friend. After a few short-lived ice dancing partnerships, Ikaika is now an accomplished ice dancing coach. In writing this thesis, I hope he can appreciate my decision to focus my efforts on academia.

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Abstract

Traditional studies of animal-fluid interactions have led to the understanding of factors that affect the distribution, ecology and energetics of swimming organisms. These interactions are commonly investigated by using quantitative flow measurement techniques, which include digital particle image velocimetry. Due to limitations in quantitative flow measurements in the natural environment, animal measurements are conducted in laboratories. Laboratory measurement techniques have been shown to have an altering impact on animal behavior and resulting flow fields. Hence, it is reasonable to question conclusions made about the impact of background flows in the natural environment from measurements conducted in the laboratory. Therefore, an apparatus that will enable the quantitative measurement of flows surrounding a swimming animal in the field is needed to accurately address the effect of background flows on animal swimming and fluid transport.

We describe the development of a self-contained underwater velocimetry apparatus that achieves the goal of real-time, quantitative field measurements of aquatic animal-fluid interactions. Using this apparatus, we obtain measurements of flow fields surrounding animals in the field and analyze the effect of background flows on swimming animals. Using a dynamical systems technique called Lagrangian coherent structures to quantitatively compare laboratory and field-generated flows, we find that background flow structures alter fluid transport by swimming jellyfish. From these studies, we define a biologically-relevant metric for animal feeding that is based entirely on the volume of fluid that interacts with the swimming animal. The ability to quantify background flows and their influence on animal-fluid interactions will allow us to broaden our concept of animal-fluid interactions to include the effects swimming animals have on their surrounding environment. This represents a paradigm shift in the analysis of animal-fluid interactions.

Recent studies have provided heated debate about whether biologically-generated (or biogenic) mixing can have an impact in the ocean. Arguments for biogenic mixing lacked an efficient mechanism for fluid transport in viscous and stratified flow environments. We present an effective mechanism for biogenic mixing called drift, which is active during swimming, and results in permanent displacement of fluid in the direction of the animal's motion (in unstratified flow). We show that unlike mechanisms that rely on turbulent mixing generated by wake structures, drift is enhanced as viscous effects are increased. While drift has been observed in jellyfish and copepods, to understand its relevance in the global ocean, the effects of stratification need to be considered. By conducting simulations of moving bodies in stratified flow, we show that at buoyancy frequencies on the order of the mean ocean, fluid transport due to drift remains a powerful mechanism through which swimming animals may provide a significant contribution to mixing in the oceans.

Contents

1	Introduction	1
1.1	Background	1
1.2	Research Objectives	3
1.3	Organization of Thesis	3
2	Development of Field Measurement Technique	5
2.1	Introduction	5
2.2	Experimental Methods	7
2.2.1	Components of the Field Apparatus	10
2.2.2	Additional Considerations for Field Data	12
2.3	Computational Methods	16
2.4	Results	17
2.5	Potential Applications for Field Apparatus	24
3	Effect of Background Turbulence on Animal-Fluid Transport	26
3.1	Introduction	26
3.2	Methods	28
3.2.1	Experimental Methods	28
3.2.2	Lagrangian Method	30
3.3	Results	33
3.3.1	Capture Efficiency Measurements	33
3.3.2	Flow Visualization and Digital Particle Image Velocimetry	34

3.3.3	Lagrangian Analysis of Flow	37
3.3.4	Analysis of In Situ Fluid Interactions	44
3.4	Discussion	46
4	Viscosity-Enhanced Mechanism for Biogenic Ocean Mixing	53
4.1	Introduction	53
4.2	Methods	56
4.2.1	Defining a Biologically Relevant Mixing Efficiency	56
4.2.2	Experimental Measurements of Mixing Efficiency	56
4.2.3	Numerical Simulations of Fluid Transport due to Moving Bodies	58
4.3	Results	59
4.4	Discussion	65
5	Effects of Stratification on Biogenic Ocean Mixing via Drift	69
5.1	Introduction	69
5.2	Computational Methods	71
5.2.1	Theoretical Simulations of Fluid Particle Displacements	71
5.2.2	Simulating a Stratified Fluid	73
5.3	Results	75
5.4	Discussion	83
6	Summary and Recommendations	90
6.1	Further Development of SCUVA	90
6.1.1	Capturing Three-Dimensional Flow Fields	90
6.1.2	Correcting Flow Fields with Onboard Accelerometry	91
6.2	Determining R_f of Swimming Animals Using Available Quantitative Data	93
6.3	Effects of Animal Morphology and Swimming Modes on Fluid Transport	94
6.4	Effects of Multiple-Animal Interactions on Drift	97
	Appendix A Axisymmetric Assumption for Jellyfish-Generated Flows	99

Appendix B SCUVA Design Iterations	102
B.1 SCUVA Senior	102
B.2 SCUVA Junior with <i>Wickedlaser</i> Housing	106
B.3 SCUVA Junior with <i>Laserglow</i> Housing	107
B.4 SCUVA Autoclave with <i>Laserglow</i> Housing	112
Appendix C Previous Research and Publications	114

List of Figures

2.1	Velocity field corrections and adjustments during post-processing of data for the kinetic energy computation.	9
2.2	SCUVA shown with laser arm extended and laser sheet activated.	10
2.3	Selected images from a swimming pool demonstration of SCUVA.	13
2.4	Series of images captured by SCUVA during a single <i>Aurelia labiata</i> swimming cycle.	19
2.5	Series of uncorrected velocity fields during a single <i>Aurelia labiata</i> swimming cycle.	20
2.6	Series of corrected velocity fields during a single <i>Aurelia labiata</i> swimming cycle.	21
2.7	Comparison of kinetic energy integration areas and corresponding fluid energy values.	22
2.8	Comparison of Huntley and Zhou’s predicted animal energy expenditure with SCUVA’s computed fluid energy over a single <i>Aurelia labiata</i> swimming cycle.	23
3.1	Behavior of fluid particles near LCS curves.	32
3.2	Laboratory-generated prey tracks in the presence of <i>Aequorea victoria</i>	35
3.3	Effect of prey type on capture efficiency of <i>Aequorea victoria</i>	37
3.4	Visualization of flow around laboratory-swimming <i>Aequorea victoria</i> using fluorescent dye.	38
3.5	Velocity vectors from DPIV analysis around laboratory- and field-swimming <i>Aequorea victoria</i>	39
3.6	Magnitude of total shear rate around laboratory- and field-swimming <i>Aequorea victoria</i>	40
3.7	FTLE field of fluid motions induced by laboratory-swimming <i>Aequorea victoria</i> , extracted LCS curves and behavior of particles near LCS ($ T = 60$ frames).	41

3.8	Extraction of LCS from the FTLE field induced by laboratory-swimming <i>Aequorea victoria</i>	43
3.9	The effect of integration time on FTLE fields induced by laboratory-swimming <i>Aequorea victoria</i>	44
3.10	FTLE field of fluid motions induced by laboratory-swimming <i>Aequorea victoria</i> , extracted LCS curves and behavior of particles near LCS ($ T = 30$ frames).	45
3.11	Identification of LCS from FTLE ridges in the flow surrounding a field-swimming <i>Aequorea victoria</i>	50
3.12	Time series of FTLE fields and position of ambient attracting LCS relative to an LCS curve bound on <i>Aequorea victoria</i> while swimming in the natural field setting.	51
3.13	FTLE field of fluid motions induced by field-swimming <i>Aequorea victoria</i> , extracted LCS curves and behavior of particles near LCS ($ T = 30$ frames).	52
4.1	Diagram indicating mixing along interfacial regions due to the drift mechanism.	55
4.2	Post-processing steps used to analyze PLIF images.	58
4.3	Theoretical added-mass coefficients as a function of the length-to-diameter ratio for two- and three-dimensional bodies.	59
4.4	Qualitative field measurements of fluid drift induced by swimming <i>Mastigias sp.</i> in Ongeim'l Tketau (OTM), Palau.	60
4.5	Numerical simulations of induced vertical drift of initially horizontal layers in the presence of fluid viscosity.	61
4.6	In situ measurement of fluid velocity induced by swimming <i>Mastigias sp.</i>	62
4.7	In situ measurement of changing density field induced by swimming <i>Mastigias sp.</i>	63
4.8	Density fields obtained from PLIF measurements before and after <i>Mastigias sp.</i> swims through fluorescent dye.	64
5.1	Simulated streamlines of flow over a sphere in potential and Stokes flow.	73

5.2	Comparison of mean particle displacement as the time step dt is decreased using Eulerian and Runge-Kutta particle advection.	74
5.3	Diagram depicting the stratified fluid simulations.	75
5.4	Comparison of mean particle displacement in stratified ($N = 1 \text{ s}^{-1}$), potential flow normalized by the mean particle displacement in unstratified flow.	76
5.5	Diagram showing the partial drift volume in a finite control volume.	77
5.6	Initial conditions for the flow simulations used to correct the partial drift volume. . .	78
5.7	The variation of partial drift volume ratio (V_{DP}/V_B) of a sphere in potential flow. . .	78
5.8	Displacement of fluid particles by a moving sphere in potential flow for stratified and unstratified flow conditions.	79
5.9	Displacement of fluid particles by a moving sphere in Stokes flow for stratified and unstratified flow conditions.	80
5.10	Mean displacement of fluid particles by a moving sphere in potential flow for stratified and unstratified flow conditions.	82
5.11	Mean displacement of fluid particles by a moving sphere in Stokes flow for stratified and unstratified flow conditions.	82
5.12	Comparison of normalized fluid particle mean displacement in potential and Stokes flow for unstratified and stratified conditions.	83
5.13	Diagram depicting the diffused drift volume.	85
5.14	Physical properties of Ongeim'l Tketau (OTM) measured from five CTD profiles. . . .	88
6.1	Current design of SCUVA incorporates two video camera housings that allows for the capture of three-dimensional particle trajectories.	92
6.2	Effect of animal morphology on fluid drift.	95
6.3	Effect of animal swimming mode on fluid transport and drift.	96
A.1	Analyzing the axisymmetric assumption using a representative DPIV data set of flow surrounding laboratory-swimming <i>Aurelia labiata</i>	101

B.1	First-generation design of SCUVA with components, acrylic underwater housings, and arm shown in the laser-stowed position.	102
B.2	Dimensions of the underwater camera housing for the first-generation design of SCUVA.	103
B.3	Dimensions of the underwater laser housing for the first-generation design of SCUVA.	104
B.4	Dimensions of the attached laser and camera housings for the first-generation design of SCUVA.	105
B.5	First-generation design of SCUVA in the laboratory and during testing at the Caltech pool.	106
B.6	Second-generation design of SCUVA in the laboratory and in the field.	106
B.7	Diagram showing a third-generation design of SCUVA using a small commercial video camera housing and two different laser configurations.	107
B.8	Diagram showing components of the Hercules laser housing.	108
B.9	Dimensions of the Hercules laser housing.	109
B.10	Dimensions of the Orion laser housing.	110
B.11	Dimensions of a third-generation design of SCUVA using a small commercial video camera housing.	111
B.12	Third-generation design of SCUVA using a small commercial video camera housing.	111
B.13	Diagram showing a third-generation design of SCUVA using a large commercial video camera housing and two different laser configurations.	112
B.14	Dimensions of a third-generation design of SCUVA using a large commercial video camera housing.	113
B.15	Third-generation design of SCUVA using a large commercial video camera housing.	113

List of Tables

3.1	Summary of prey capture efficiency measurements for <i>Aequorea victoria</i>	34
3.2	Summary of relevant fluid and LCS parameters from laboratory- and field-swimming <i>Aequorea victoria</i>	36
4.1	Summary of reported flux Richardson numbers of physical ocean mixing processes compared to biogenic mixing by an individual <i>Mastigias sp.</i>	63
5.1	Results summary of a moving sphere in simulated potential and Stokes flow at various stratification levels.	84