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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The relevance of this work would not be realized without the collaborations I have had over the last couple of years. In particular, I would like to thank Jack Costello (Providence College) and Sean Colin (Roger Williams University) who opened my eyes to the vast and largely unexplained field of marine biology. They continue to be actively involved in the design of the field apparatus discussed in this thesis. Over the years we have amassed a data set that has been barely used and I look forward to our continued collaboration. Through my interactions with Jack and Sean, I have also had the opportunity to meet and work with Monty Graham (Dauphin Island Sea Lab), Mike Dawson (University of California, Merced), Houshuo Jiang (Woods Hole Oceanographic Institute), Thomas Kiørboe (National Institute of Aquatic Resources, Denmark), Hermes Mianzan (National Institute for Research and Development of Fisheries, Argentina), and Adam Benovic (Institute for Marine and Coastal Research, Croatia), who are all renowned biologists in the study of zooplankton.

Most of the animal measurements I made during my time at Caltech were conducted at Cabrillo Marine Aquarium in San Pedro, CA. Mike Schaadt, the director of the aquarium and a marine biologist, was intrigued in our early studies of jellyfish propulsion and opened up the facility for us to work. If for any reason we needed to work in the laboratory at Caltech, their aquarists would provide us with jellyfish to transport back to Pasadena. I was given space in their Jellyfish Lab and enjoyed the opportunity to share what I was doing with the staff. Mike and Kiersten Darrow would arrange to have volunteers (Stephanie, Cora Webber, and Erin Schaadt) set up tanks, take care of animals, etc. Unfortunately none of the data has been incorporated in this thesis, however I hope to include it in a future publication. In addition, Mike was the first dive buddy I had while conducting field measurements at a local site in Long Beach, CA.

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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.

I need to thank my closest friend, Tina Koo, who has known me by far the longest. She drove with me from Seattle to Pasadena when I moved to Caltech. She was there with me when I returned from my first Caltech orientation event; I had tears in my eyes because I just grasped the hopelessness of my situation. She laughed at me. To this day, she is the only person who can laugh at me during moments of anguish and get away with it. After Tina left me to my fate at Caltech, I managed to make solid friendships with some of the few women at Caltech (i.e., Emily Schaller, Emily McDowell, Joannah Metz, Carrie Hoffman, and Lydia Ruiz). I truly enjoyed our midweek ladies nights and I hope we never lose touch with each other.

Our research group was and is made up of a spectacular bunch of people. Jifeng Peng was always an inspiration to me as to how many papers he could write and publish in a short time. I cannot tell you how many times I would just drop by Lydia Ruiz's office or lab to chat about life or a misfiring q-switch. I want to thank Janna Nawroth for her humor and her uncanny ability to climb up mountains and tune out my complaints at the same time. Since both Jeff and Lydia graduated, the group has never been the same and I wish you all the best in your future endeavors.

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WELCOME

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.

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