Probabilistic Regional Ocean Predictions: Stochastic Fields and Optimal Planning

by

Deepak Narayanan Subramani

B.Tech, Indian Institute of Technology Madras (2012)
M.Tech, Indian Institute of Technology Madras (2012)
S.M., Massachusetts Institute of Technology (2014)

Submitted to the Department of Mechanical Engineering and
Center for Computational Engineering
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Mechanical Engineering and Computation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2018

Signature redacted

Author ....
Department of Mechanical Engineering and
Center for Computational Engineering
November 30, 2017

Signature redacted

Certified by ....
Pierre F.J. Lermusiaux
Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Accepted by ....
Nicolas Hadjiconstantinou
Co–Director, Computational Science and Engineering

Signature redacted

Accepted by ....
Rohan Abayaratne
Chairman, Department Committee on Graduate Theses

Probabilistic Regional Ocean Predictions: Stochastic Fields and Optimal Planning

by

Deepak Narayanan Subramani

Submitted to the Department of Mechanical Engineering and Center for Computational Engineering on November 30, 2017, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering and Computation

Abstract

The coastal ocean is a prime example of multiscale nonlinear fluid dynamics. Ocean fields in such regions are complex, with multiple spatial and temporal scales and nonstationary heterogeneous statistics. Due to the limited measurements, there are multiple sources of uncertainties, including the initial conditions, boundary conditions, forcing, parameters, and even the model parameterizations and equations themselves. To reduce uncertainties and allow long-duration measurements, the energy consumption of ocean observing platforms need to be optimized. Predicting the distributions of reachable regions, time-optimal paths, and risk-optimal paths in uncertain, strong and dynamic flows is also essential for their optimal and safe operations. Motivated by the above needs, the objectives of this thesis are to develop and apply the theory, schemes, and computational systems for: (i) *Dynamically Orthogonal ocean primitive-equations with a nonlinear free-surface, in order to quantify uncertainties and predict probabilities for four-dimensional (time and 3-d in space) coastal ocean states, respecting their nonlinear governing equations and non-Gaussian statistics*; (ii) *Stochastic Dynamically Orthogonal level-set optimization to rigorously incorporate realistic ocean flow forecasts and plan energy-optimal paths of autonomous agents in coastal regions*; (iii) *Probabilistic predictions of reachability, time-optimal paths and risk-optimal paths in uncertain, strong and dynamic flows.*

For the first objective, we further develop and implement our Dynamically Orthogonal (DO) numerical schemes for idealized and realistic ocean primitive equations with a nonlinear free-surface. The theoretical extensions necessary for the free-surface are completed. DO schemes are researched and DO terms, functions, and operations are implemented, focusing on: state variable choices; DO norms; DO condition for flows with a dynamic free-surface; diagnostic DO equations for pressure, barotropic velocities and density terms; non-polynomial nonlinearities; semi-implicit time-stepping schemes; and re-orthonormalization consistent with leap-frog time marching. We apply the new DO schemes, as well as their theoretical extensions and efficient serial implementation to forecast idealized-to-realistic stochastic coastal ocean dynamics. For the realistic simulations, probabilistic predictions for the Middle Atlantic Bight region, Northwest Atlantic, and northern Indian ocean are showcased.

For the second objective, we integrate data-driven ocean modeling with our stochastic DO level-set optimization to compute and study energy-optimal paths, speeds, and headings for ocean vehicles in the Middle Atlantic Bight region. We compute the energy-optimal paths from among exact time-optimal paths. For ocean currents, we utilize a data-assimilative multiscale re-analysis, combining observations with implicit two-way nested multi-resolution primitive-equation simulations of the tidal-to-mesoscale dynamics in the region. We solve the reduced-order stochastic DO level-set partial differential equations (PDEs) to compute the joint probability of minimum arrival-time, vehicle-speed time-series, and total energy utilized. For each arrival time, we then select the vehicle-speed time-series that minimize the total energy utilization from the marginal probability of vehicle-speed and total energy. The corresponding energy-optimal path and headings be obtained through a particle backtracking equation. For the missions considered, we analyze the effects of the regional tidal currents, strong wind events, coastal jets, shelfbreak front, and other local circulations on the energy-optimal paths.

For the third objective, we develop and apply stochastic level-set PDEs that govern the stochastic time-optimal reachability fronts and paths for vehicles in uncertain, strong, and dynamic flow fields. To solve these equations efficiently, we again employ their dynamically orthogonal reduced-order projections. We develop the theory and schemes for risk-optimal planning by combining decision theory with our stochastic time-optimal planning equations. The risk-optimal planning proceeds in three steps: *(i)* obtain predictions of the probability distribution of environmental flows, *(ii)* obtain predictions of the distribution of exact time-optimal paths for the forecast flow distribution, and *(iii)* compute and minimize the risk of following these uncertain time-optimal paths. We utilize the new equations to complete stochastic reachability, time-optimal and risk-optimal path planning in varied stochastic quasi-geostrophic flows. The effects of the flow uncertainty on the reachability fronts and time-optimal paths is explained. The risks of following each exact time-optimal path is evaluated and risk-optimal paths are computed for different risk tolerance measures. Key properties of the risk-optimal planning are finally discussed.

Theoretically, the present methodologies are PDE-based and compute stochastic ocean fields, and optimal path predictions without heuristics. Computationally, they are several orders of magnitude faster than direct Monte Carlo.

Such technologies have several commercial and societal applications. Specifically, the probabilistic ocean predictions can be input to a technical decision aide for a sustainable fisheries co-management program in India, which has the potential to provide environment friendly livelihoods to millions of marginal fishermen. The risk-optimal path planning equations can be employed in real-time for efficient ship routing to reduce greenhouse gas emissions and save operational costs.

Thesis Supervisor: Pierre F.J. Lermusiaux
Title: Professor of Mechanical Engineering

Acknowledgments

I would like to start by thanking my advisor Prof. Pierre Lermusiaux. I still remember that day–March 27, 2012–when he first replied to my email inquiring about opportunities to work with the MSEAS group. The journey since has been very productive and I got to do almost all the things that I wanted initially. Pierre has been a kind mentor both academically and personally. He has (mostly) put up with and supported my crazy ideas. I am grateful for the long research meetings early on in my grad student life, especially around my qualifier exam which coincided with his sabbatical year. Academically, I learnt a lot of computational engineering, stochastics, debugging strategies, ocean sciences and research management from him. Personally, he has supported me through difficult times. Among the many incidents, I would like to highlight two. First was when I had a surgery just two months after coming to MIT. He visited me daily, drove me back from the hospital, and presented me with the book *The Perfect Storm: A True Story of Men Against the Sea* when I was in the hospital. This book played a great role in shaping my research interests. Second was when I lost my dad in my third year. It was a tough time for me and I had to go away for six weeks. He was available through Skype for meetings when I was in India. I am also thankful to Pierre and our MSEAS group for all the fun we have had. Our trips to conferences–AGU Ocean Sciences Meeting 2015 and Fall Meeting 2016–were memorable. One fun fact is that we derived a key result in this thesis in the New Orleans airport!

I thank Pat Haley for the support and help in navigating through the MSEAS softwares. His expertise in writing robust code has helped my thesis work a lot. He provided all the ocean fields for the energy-optimal path planning work reported here. He helped in the initial coding of the dynamically orthogonal primitive equations and later in checking and debugging. The all-nighters we shared along with other MSEAS members before the ONR reviews, talks and real-time sea exercises are unforgettable. Thanks to Pat's calming smile, presence and insights, the most intense of situations became manageable. Hats off to the passion and dedication that Pat Haley brings to his work. I am extremely fortunate to have worked with and learned from Pat.

I thank my Ph.D committee members–Prof. Nicholas Patrikalakis, Dr. Glen Gawarkiewicz, and Prof. Avijit Gangopadhyay for their valuable comments and suggestions during the several meetings that we have had. I thank them for their time and knowledge sharing. Their questions and suggestions helped refine my research and presentation. I am also grateful for the career advice and encouragement they have provided me.

We, at the MSEAS group, are grateful to the Office of Naval Research for research support under grants N00014-09-1-0676 (Science of Autonomy - A-MISSION), N00014-14-1-0476 (Science of Autonomy - LEARNS), N00014-14-1-0725 (Bays-DA), N00014-15-1-2616 (NASCar-OPS) and DARPA (POINT BBN) to MIT. We thank the MIT Tata Center for my Tata fellowship support during the years 2015-2017. My graduate education and research at MIT was made possible by these generous grants and fellowship. We specially thank Drs. Robert Stoner, Diane Rigos and Chintan Vaishnav at the MIT Tata Center for their support, guidance and encouragement.

The MSEAS SW06-AWACS-06 ocean reanalyses employed in chapter 4 were made possible by research support to MIT from ONR under grant N00014-11-1-0701 (MURIIODA) and the National Science Foundation under grant OCE-1061160. We thank all of our SW06 and AWACS-06 colleagues, especially G. Gawarkiewicz, P. Abbot, and T. Duda for their ocean data and M. Taylor and J. Hare for their NMFS survey data. We also thank J. Evans, S. Glenn, and J. Wilkin for their real-time WRF atmospheric fluxes and the FNMOC teams for their own products.

I thank all my MSEAS labmates, past and present. Tapovan Lolla has been a constant source of inspiration. I always turned to him for advice on navigating grad school. I fondly remember the several discussions we had about research, classes, career, current affairs, badminton and several other things. Tapovan shared my interest for good food and we may have explored almost all the restaurants in Cambridge and Boston during the time he and I were in MIT together.

Jing Lin has been my office mate for the past five years. He has patiently answered all of my questions. His contribution to numerical re-orthonormalization has helped a great deal in the results obtained in this thesis.

Matt Ueckermann and Akash Phadnis helped me in my first year to understand DO numerics. Jen Landry was my point of reference for American culture, clothing styles and she introduced me to Settlers of Catan. She taught me that "I'm up for it" and "I'm down for it" both mean the same thing–who would have guessed that!

Chinmay Kulkarni and Abhinav Gupta are trusted colleagues to whom I turn to for assured support during crunch situations. They never say no and are always ready to help swiftly and accurately. Chinmay's timely help on board the R/V Discovery in running our path planning software cannot be acknowledged enough. He came in during the last moment and yet helped a great deal, a testament to his character and ability as a team player. Abhinav helped to create initial conditions for the DO-PE simulations and in obtaining the Mutual Information plots presented in this thesis. Chinmay, Abhinav, Johnathan (JVo), and Corbin helped me move on a snowy February night. Thanks a lot guys! These four along with Florian and John also made my last two years at MIT fun by sharing my interest for good food after Tapovan graduated. The number of visits to restaurants around Cambridge and Boston to eat Viatnamese Pho, Thai food and Pizza with these guys are memories that I will cherish forever.

Many thanks to Quantum Wei, who as a UROP BS thesis student, helped in coding the first version of the DO level-set equations with uncertain currents presented in chapter 5. Many thanks to Arkopal Dutt for his help in obtaining the DO flow fields for the stochastic flow past a circular island test case in chapter 5. Many thanks to Sudip Jana, Chris Mirabito and Wael Hajj Ali for their contributions in setting up the deterministic versions of the several realistic simulations presented in chapter 3. I also thank Sydney Sroka for her help.

I thank my friends outside MSEAS who made my stay at MIT sane. Thanks to Jaichander Swaminathan for being a great roommate for several years. He taught me a lot about spoken Sanskrit, and helped me appreciate the nuances of Sanatana Dharma by condensing tough root texts. I could always turn to him for a quick objective summary of any matter of current affairs. Most importantly, he was always there during tough times and his help can never be over acknowledged. I would like to thank Yashovardhan Chati, Ashwin Raghavan, Ujwal Radakrishna and Jai for the help in running cultural and linguistic student bodies at MIT. I also thank Kishor Nayar, Suhrid Deshmukh, Suvinay Subramaniam and many other acquaintances from the greater IIT family at MIT for the several treks, camps, dinners, temple trips and fun times. I thank Ketan Nayak and Piyush Chaunsali for their advice regarding career and life in general. I applied to MIT only because Ketan had laid out a path and shown that it is possible.

Navigating the administrative work at MIT is impossible without the ever helpful staff and administrators. I thank Leslie Regan, Joan Kravit, Una Sheehan and Amy Shea-Slattery at the ME graduate office, and Kate Nelson and the late Barbara Lechner at the CDO/CCE office for all their help and support. I thank Marcia Munger for always getting me reimbursements on time. I thank all the MIT Tata Center staff–Gail Monahan, Jazy Ma, Ben Miller–for their help with all matters related to India visits, reimbursements, and scheduling. I thank the Tata Trusts staff in India–Dickie Daruwala, Alamin Nomanbhoy, Darayes Shaw and their colleagues–for booking all my itineraries and accommodating last minute changes.

Last but not the least, this thesis and my graduate education would be impossible without the support of my family. It was my late father, Dr. N. S. Mani's dream that I pursue a Ph.D. He has nurtured in me a scientific spirit right from my childhood. My mother Sudha and sister Priyanka have supported me in all my decisions, especially after the demise of my father. Thanks a lot *Amma* and Priyanka. This thesis is dedicated to you two and the loving memory of *Appa*. I am grateful to my wife, Dr. Anusha Narayanan, who bravely chose to share her life with me. She hit the pause button on her career in India to come live with me for the past one year. I could not have finished this thesis if not for her home cooked meals.