

**Probabilistic Regional Ocean Predictions:  
Stochastic Fields and Optimal Planning**

by

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Submitted to the Department of Mechanical Engineering and  
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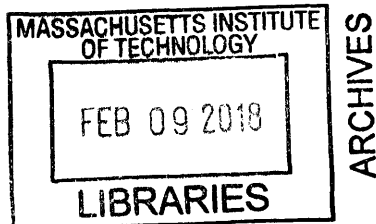
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## Abstract

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

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