Towards Probabilistic Dynamically-Orthogonal Primitive Equation Forecasts for the Gulf of Mexico

by

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Department of Mechanical Engineering
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Abstract

Forecasting circulation in the Gulf of Mexico requires an explicit treatment of uncertainty associated with the Loop Current and its eddies, whose geometry and timing can fluctuate irregularly and lead to chaotic deterministic forecasts. Building on the dynamically orthogonal (DO) methodology for evolving low-rank stochastic representations and on efficient DO numerical schemes for geophysical fluid flows, this thesis develops and assesses massive probabilistic Primitive Equation (PE) hindcasts for the Gulf using the Dynamically Orthogonal Primitive Equations (DO–PE) framework as implemented for realistic ocean dynamics in previous MIT-MSEAS studies. The workflow extracts a time-dependent stochastic subspace from a balanced MIT MSEAS PE ensemble via singular-value decomposition, represents the initial non-Gaussian coefficient cloud with Gaussian mixture models, and subsequently evolves the DO–PE mean, modes, and coefficients under dynamics, numerics, and forcings consistent with the MIT MSEAS PE modeling system.

A 12-day hindcast simulation experiment spanning 28 May–8 June 2015 quantifies skill and convergence across truncations, with weak-type tests (means, standard deviations, kernel-density marginals) and strong-type tests against matched full-order realizations started from identical initial states. Consistent patterns emerge. Uncertainty concentrates along the Loop Current jet, the Yucatán inflow, and eddy peripheries. For weak convergence, as the retained dynamic modes increase from 15 to 60, standard-deviation maps sharpen and expand coherently along these dynamically active features, and the statistics indicate convergence with the normalized RMSEs for both mean and standard deviation fields decreasing in a largely monotonic fashion. At depth and for sea-surface height, late-time mean-error behavior can become mildly non-monotonic, indicating sensitivity to mode allocation among variables. In strong-convergence experiments, DO–PE reconstructions initialized at coefficient quantiles closely track the corresponding full-order trajectories: pathwise misfits remain modest, organize along shear zones, and their RMSE time series lie below persistence and within the envelopes implied by the weak-type spread, reinforcing that truncation primarily filters small-scale content while preserving trajectory-level evolution over the 10–12-day window.

Together, these results demonstrate a practical, reproducible pipeline for massive probabilistic forecasting in the Gulf of Mexico that respects PE dynamics while quantifying and localizing forecast uncertainty in flow-dependent ways (details, configuration, and figures in Chapters 3–4). This thesis also introduces dynamic web pages for the interactive visualization of DO–PE output, facilitating the inspection of mean fields, modes, and standard deviations over time in Chapter 5.

Thesis Supervisor: Pierre F.J. Lermusiaux
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