Data-Driven Stochastic Parameterization for Unresolved Ocean Dynamics

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Ocean dynamics span a vast range of spatial and temporal scales, from small turbulent fluctuations to basin-scale circulation. Fully resolving all these scales remains computationally intractable, and the representation of unresolved motions through parameterizations is therefore central to ocean climate and forecasting models. This challenge is especially acute for mesoscale and submesoscale eddies—unresolved or only partially resolved in many simulations—which critically influence large-scale currents, tracer transport, mixing, energy transfers, and intrinsic variability. This motivates the development of data-driven parameterizations that remain consistent with the physical structure of the governing equations.

In this talk, I will present a series of collaborative works on data-driven stochastic parameterization for ocean dynamics. The approach builds on the stochastic transport framework [1], where unresolved fluctuations are introduced as random perturbations of the flow map. This formulation provides a natural representation of model uncertainty while preserving key structural properties of the underlying fluid equations, and offers a physically interpretable description of unresolved energy transfers.

The unresolved stochastic component is learned from high-resolution simulations. In [1], Proper Orthogonal Decomposition (POD) was used to calibrate the dominant spatial structures of unresolved eddies in a multilayer quasi-geostrophic model, improving jet current representation and low-frequency variability in coarse simulations. Building on this approach, [2] introduced Dynamic Mode Decomposition (DMD) to move beyond a stationary covariance description by separating slowly evolving coherent components from faster decorrelating fluctuations. The resulting DMD-based formulation better captures the temporal organization of unresolved dynamics, leading to improved variability and kinetic-energy backscatter in the resolved flow.

These methods were subsequently extended and validated in [3] within NEMO, a hydrostatic primitive-equation model widely used for operational ocean simulations. In this more realistic setting, POD- and DMD-based stochastic parameterizations were combined with physical constraints, notably by projecting unresolved fluctuations along isopycnal surfaces to limit spurious diapycnal mixing. A hybrid strategy was also introduced, in which DMD learns the vertically integrated component from sea-surface height—a quantity routinely observed by satellite altimetry—while the remaining vertical fluctuations are represented through model-based noise.

Taken together, these results demonstrate that unresolved eddy effects should not be modeled as purely data-driven fluctuations decoupled from the resolved flow. Hybrid data- and model-driven parameterizations offer a more effective strategy: learning unresolved dynamical structures from data while preserving physically meaningful dependencies on the simulated state. This perspective provides a coherent route to combine stochastic parameterization and data-driven calibration within operational ocean models, enabling more reliable and uncertainty-aware simulations.

References

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