NUTS: Eddy-Robust Reconstruction of Surface Ocean Nutrients via Two-Scale Modeling

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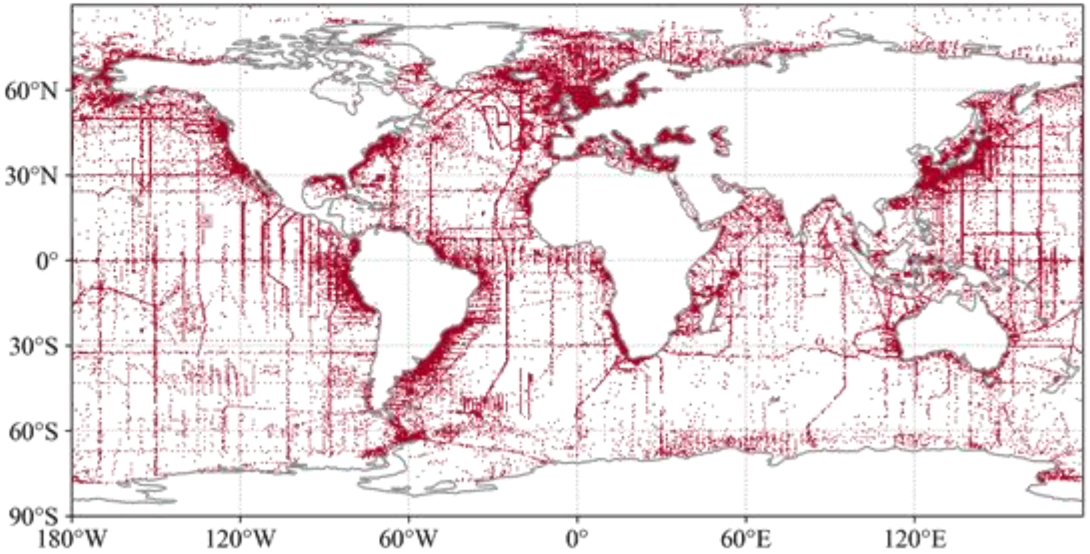
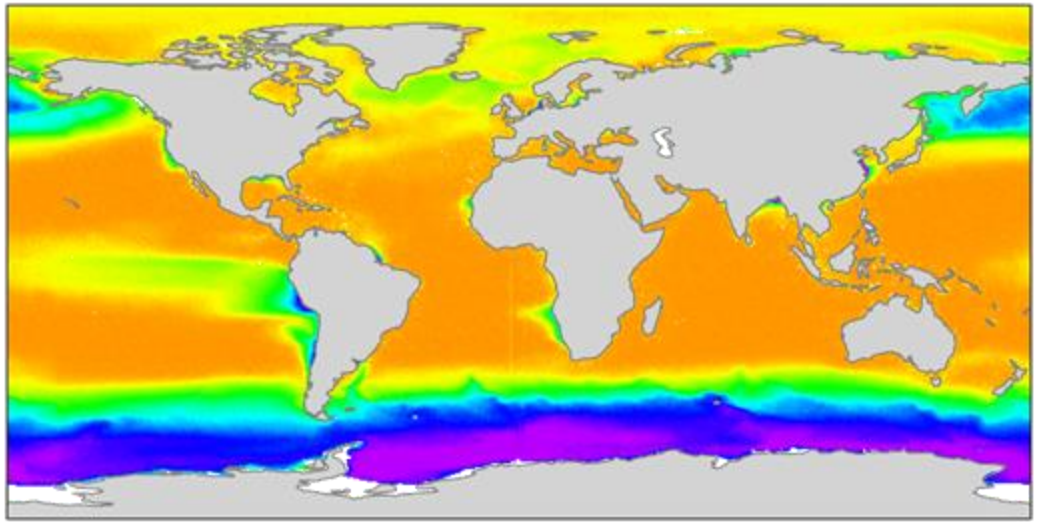
Introduction—Ocean Nutrient Reconstruction

(a) Observations

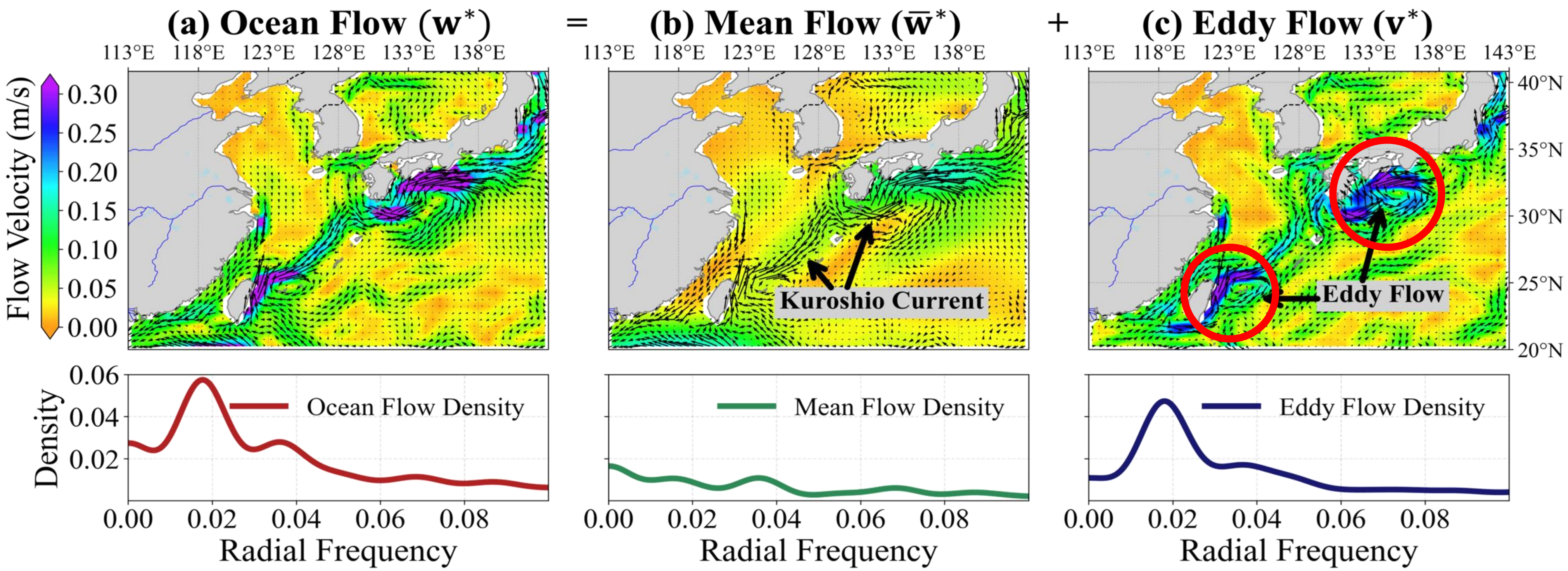


(b) Reconstruction



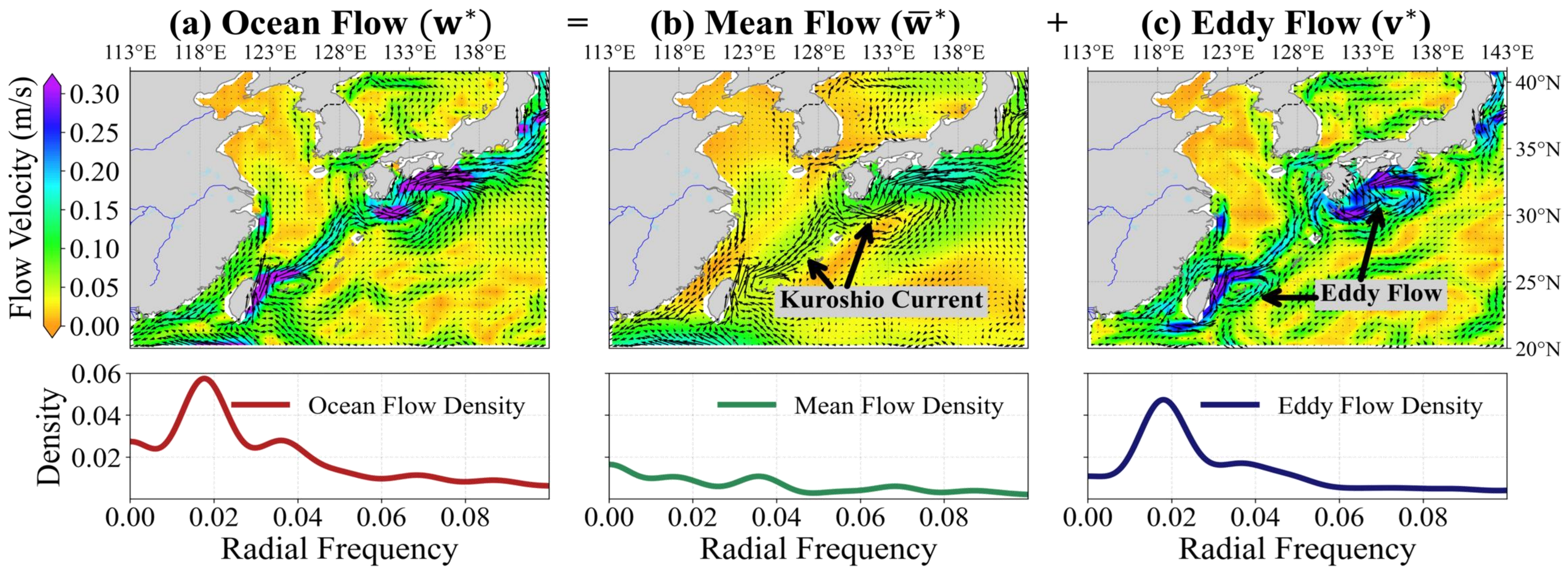
Ocean nutrient reconstruction aims to reconstruct nutrient concentration distribution based on *sparse* and *irregular* observations collected from ship-based campaigns.

Introduction—Challenge



Two-Scale Structure of Ocean flow. Ocean flow consists of ***mean flow*** and ***eddy flow***. Small errors in the eddies propagate through time and distort nutrient reconstruction.

Introduction—Challenge



Modeling Dilemma

Filtering out the high-frequency eddies?

Stabilizes nutrients reconstruction process at the cost of removing fine-scale structures.

Retaining all flow components?

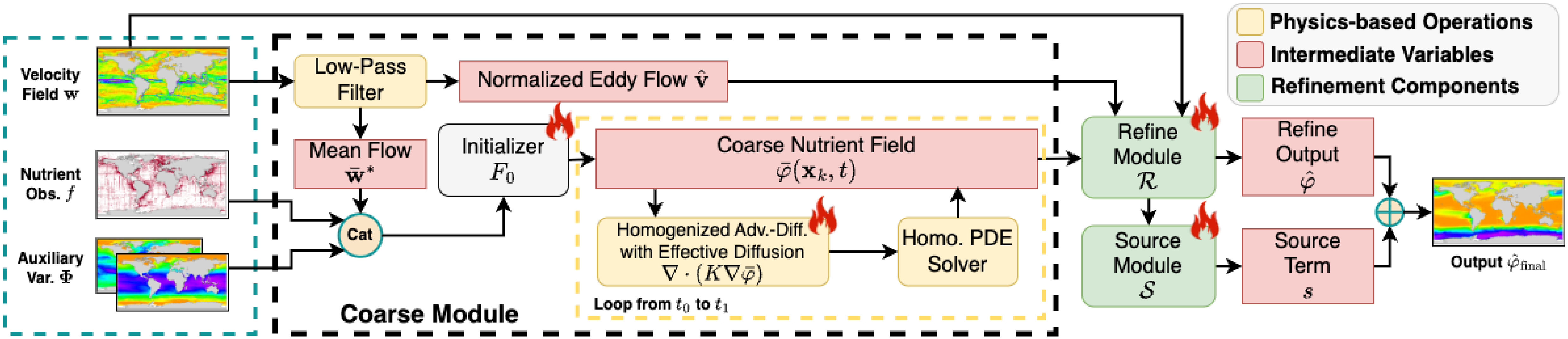
Keeps the integrity of ocean flow structures at the cost of introducing eddy-caused instabilities.

Methodology

Our Scheme

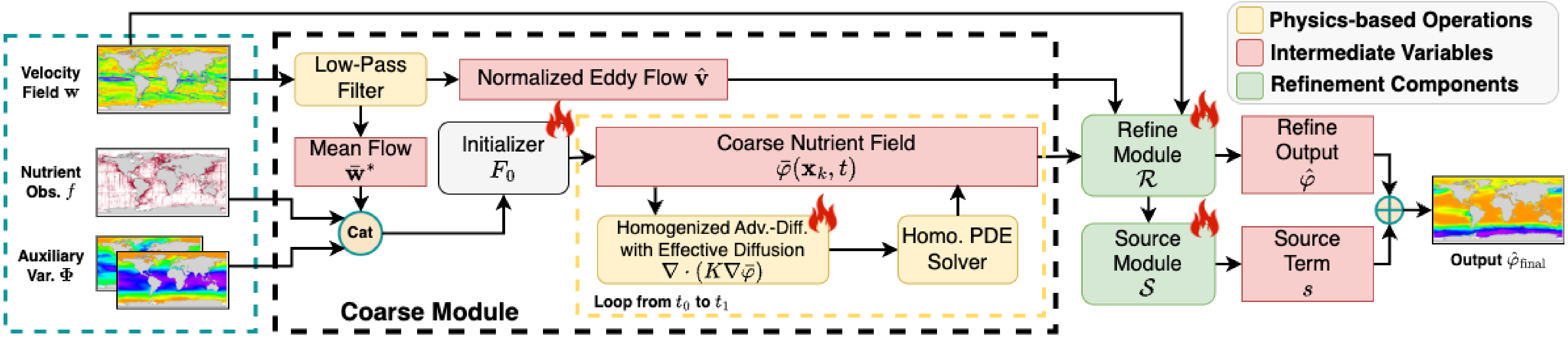
Utilizing the structured decomposition of ocean flow.

Resolves mean flow and eddy flow via coarse and refinement module, respectively.



Structure of NUTS. A coarse-to-refined architecture that approaches the reconstruction problem via two-scale modeling scheme.

Methodology—Ensuring Physical Consistency



Source Module. We introduce a learnable correction term to account for source-sink dynamics.

$$s = \mathcal{S}(\hat{\varphi}), \quad \hat{\varphi}_{\text{final}} = \hat{\varphi} + s$$

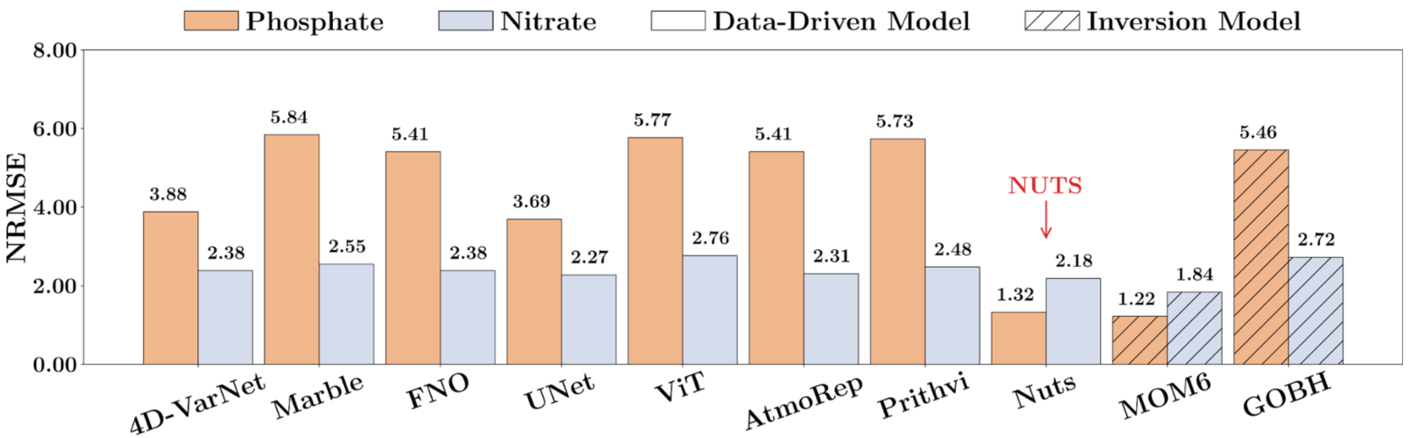
Mass Conservation Loss. We penalize the mass shift between refinement and coarse outputs, as well as the coarse outputs within a reconstruction interval. ***M*** *denote the total nutrient mass*.

$$\mathcal{L}_{\text{cons.}} = \int_{t_0}^{t_1} \left|M[\bar{\varphi}](\tau) - M[\bar{\varphi}](t_0)\right|^2 + \left|M[\hat{\varphi}](\tau) - M[\bar{\varphi}](t_0)\right|^2 d\tau$$

Experiments—Main Results

Methods	Params	MOM6 (Daily)						WOD (Monthy)	
		Phosphate			Nitrate			Phosphate	Nitrate
		0.1%	1%	10%	0.1%	1%	10%	–	–
Kriging(Exp.)	–	0.535$_{\pm 0.022}$	0.262$_{\pm 0.015}$	0.184$_{\pm 0.023}$	0.642$_{\pm 0.020}$	0.368$_{\pm 0.025}$	0.256$_{\pm 0.019}$	1.275$_{\pm 0.130}$	1.495$_{\pm 0.091}$
Kriging(Sph.)	–	0.537$_{\pm 0.019}$	0.276$_{\pm 0.022}$	0.192$_{\pm 0.020}$	0.649$_{\pm 0.017}$	0.399$_{\pm 0.018}$	0.272$_{\pm 0.021}$	1.270$_{\pm 0.086}$	1.517$_{\pm 0.057}$
4D-VarNet	0.3M	0.151$_{\pm 0.008}$	0.154$_{\pm 0.012}$	0.156$_{\pm 0.010}$	0.168$_{\pm 0.006}$	0.170$_{\pm 0.007}$	0.161$_{\pm 0.008}$	0.187$_{\pm 0.008}$	0.203$_{\pm 0.009}$
Marble	0.6M	0.397$_{\pm 0.051}$	0.227$_{\pm 0.044}$	0.232$_{\pm 0.069}$	0.441$_{\pm 0.078}$	0.222$_{\pm 0.044}$	0.297$_{\pm 0.047}$	0.363$_{\pm 0.058}$	0.326$_{\pm 0.056}$
FNO	4.8M	0.251$_{\pm 0.015}$	0.227$_{\pm 0.016}$	0.229$_{\pm 0.014}$	0.261$_{\pm 0.012}$	0.256$_{\pm 0.013}$	0.257$_{\pm 0.014}$	0.244$_{\pm 0.015}$	0.276$_{\pm 0.017}$
U-Net	31.0M	0.151$_{\pm 0.008}$	0.148$_{\pm 0.013}$	0.149$_{\pm 0.011}$	0.169$_{\pm 0.007}$	0.166$_{\pm 0.012}$	0.167$_{\pm 0.013}$	0.174$_{\pm 0.012}$	0.187$_{\pm 0.008}$
ViT	77.7M	0.257$_{\pm 0.032}$	0.242$_{\pm 0.044}$	0.359$_{\pm 0.048}$	0.311$_{\pm 0.046}$	0.256$_{\pm 0.044}$	0.256$_{\pm 0.052}$	0.263$_{\pm 0.034}$	0.260$_{\pm 0.002}$
AtmoRep	0.7B	0.196$_{\pm 0.010}$	0.194$_{\pm 0.011}$	0.192$_{\pm 0.010}$	0.190$_{\pm 0.009}$	0.219$_{\pm 0.011}$	0.218$_{\pm 0.013}$	0.206$_{\pm 0.013}$	0.260$_{\pm 0.013}$
Prithvi	2.3B	0.216$_{\pm 0.055}$	0.197$_{\pm 0.043}$	0.208$_{\pm 0.054}$	0.279$_{\pm 0.049}$	0.274$_{\pm 0.057}$	0.275$_{\pm 0.036}$	0.222$_{\pm 0.042}$	0.338$_{\pm 0.046}$
NUTS	**125.6M**	0.014$_{\pm 0.002}$	0.015$_{\pm 0.001}$	0.022$_{\pm 0.002}$	0.143$_{\pm 0.003}$	0.136$_{\pm 0.003}$	0.142$_{\pm 0.004}$	0.035$_{\pm 0.002}$	0.151$_{\pm 0.003}$
Promotion	–	**90.7%**	**89.9%**	**85.2%**	**14.9%**	**18.1%**	**11.8%**	**79.9%**	**19.3%**

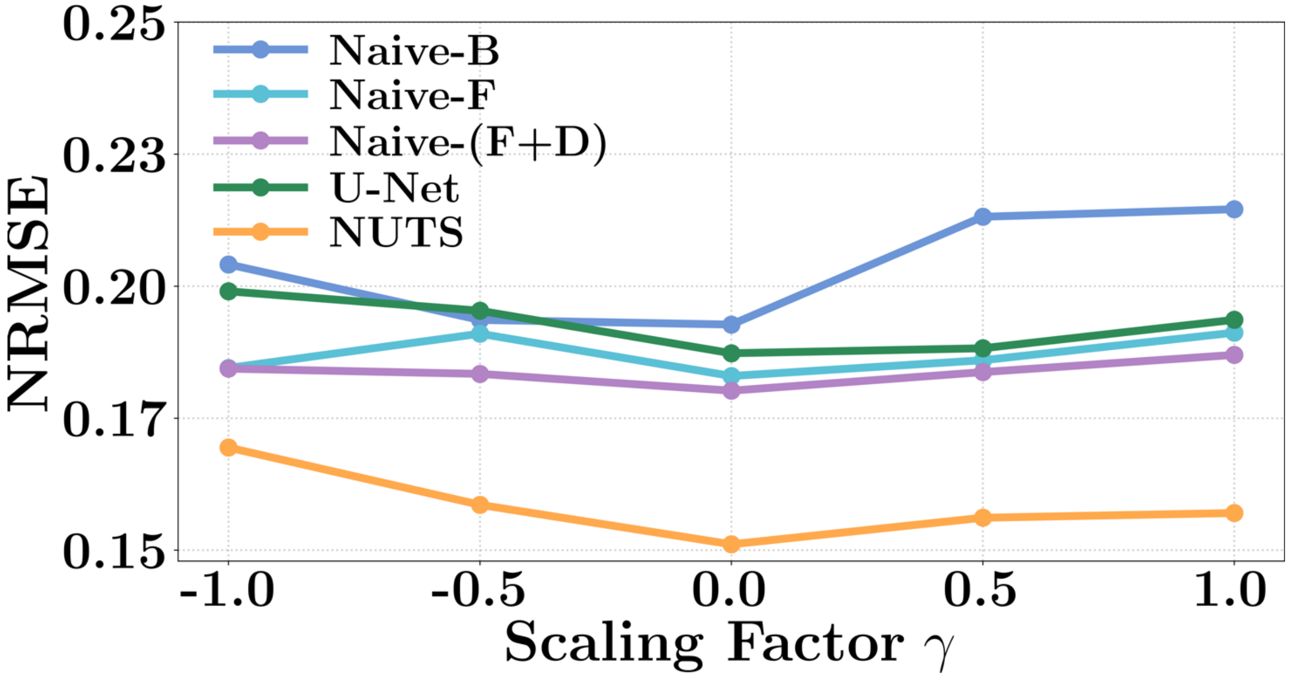
*On simulation datasets, our NUTS reduces NRMSE by **79.9%** for phosphate and **19.3%** for nitrate compared to the best data-driven baseline.*



On real observation dataset, our NUTS outperforms data-driven baselines while matching the performance of inversion models.

Experiments—Component Analysis

We introduced additional perturbations to the ocean flow, the magnitude of which is set to γ times that of the eddy flow.



Variants	Params Count	Low-pass Filter	Effective Diffusion	Refine Module
Naive-B	131.9M	×	×	×
Naive-F	131.9M	✓	×	×
Naive-(F+D)	131.7M	✓	✓	×
NUTS	125.6M	✓	✓	✓

NUTS achieves both **accuracy and robustness** under varying perturbation levels γ.

Conclusion and Broader Impact

Combining coarse advection-diffusion dynamics and data-driven refinement enables NUTS to conduct precise ocean nutrient reconstruction, achieving SOTA performance on simulated and real observation datasets.

Methods	MOM6		WOD	
	Temp.	Sal.	Temp.	Sal.
U-Net	0.148	0.021	0.111	0.009
ViT	0.225	0.023	0.143	0.017
NUTS	0.129	0.017	0.084	0.008
Promotion	**12.8%**	**19.0%**	**24.3%**	**11.1%**

Extensibility of NUTS.
NUTS is extensible to reconstructing passive tracers governed by the advection-diffusion equation.

Thank You

Github Link: https://github.com/Leamonz/NUTS