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A Physics-Guided ControlNet Framework for Global Ocean Chlorophyll Forecasting

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Seasonal prediction of marine phytoplankton biomass is essential for ecosystem management and climate adaptation, as phytoplankton forms the foundation of marine food webs and directly affects fisheries productivity. While Earth System Models (ESMs) provide reliable chlorophyll predictions, their computational demands limit operational applications. We present a deep learning framework that incorporates ocean transport dynamics into neural network predictions for monthly chlorophyll forecasting at global scales.

Our approach employs a ControlNet architecture where the control branch receives physically advected chlorophyll fields rather than raw ocean currents. By applying a simple advection operation to past chlorophyll data before neural processing, we test whether explicitly accounting for ocean transport improves the network's ability to predict future chlorophyll patterns. This provides a method for incorporating physical knowledge into deep learning architectures for ocean prediction.

The framework is trained on CMIP6 historical simulations and GFDL-ECDA ocean reanalysis data, then validated against satellite observations including MODIS/SeaWiFS chlorophyll, NOAA SST, and CMEMS ocean currents. All data are processed as monthly anomalies at $1^\circ \times 1^\circ$ resolution with log-transformed chlorophyll values. We conduct ablation studies comparing three configurations: physics-guided control with advected chlorophyll, standard control with raw flow fields, and no control branch.

This work examines how simple physical constraints can be integrated into deep learning architectures for Earth system prediction. By separating physical transport from biological processes in the neural network design, we evaluate whether such hybrid approaches can benefit operational ocean forecasting. Results from ongoing experiments will help assess the potential of physics-guided neural networks for marine ecosystem prediction.

Keywords: Physics-guided neural networks, Ocean biogeochemistry, Chlorophyll forecasting, ControlNet, Physical advection