Physics-Informed Deep Learning for Subsurface Current Estimation in the Florida Straits: Toward Operational Resource Assessment for Ocean Current Turbines

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1.1 Background/Objectives

Ocean current turbines (OCTs) deployed in persistent, fast-flowing western boundary currents represent a promising renewable energy resource with strong potential to support coastal electrification along the southeastern United States. OCT deployment requires accurate characterization of three-dimensional currents within the upper 100–150 m, where turbines are expected to operate. Conventional methods rely on sparse ADCP observations or computationally intensive ocean circulation models, limiting rapid and spatially resolved operational assessment. Deep learning can reconstruct subsurface ocean states from surface observations, but data-only models may produce physically inconsistent currents away from the surface. This work develops a physics-informed framework that estimates three-dimensional subsurface velocities in the Florida Straits from 35 gridded surface and hydrographic input channels. The objective is to improve depth-resolved Florida Current and transport reconstruction while retaining the flexibility of data-driven learning for ocean-current-turbine resource assessment.

1.2 Approach/Activities

The proposed framework uses a Fourier neural operator (FNO) backbone to map seven surface channels and subsurface temperature and salinity fields to zonal and meridional velocities at 14 depth levels extending from the surface to 222 m. By operating in the spectral domain, the FNO captures non-local relationships between surface forcing, hydrographic structure, and subsurface circulation within a global receptive field, in contrast to the local receptive fields of conventional convolutional encoders. A data-only FNO is compared with physics-informed neural operator variants incorporating geostrophic and thermal-wind constraints as soft loss terms. The thermal-wind constraint is applied below the Ekman layer to constrain vertical shear while allowing the ageostrophic component of the flow to remain learnable. The models are trained on GLORYS12V1 data from 2011–2022, validated on 2023 data, and evaluated on an independent held-out test period covering 2024–2025. Performance is assessed using depth-dependent zonal and meridional velocity root mean square error (RMSE), Florida Current transport RMSE, and transport correlation. Validation against independent shipboard ADCP observations and cable-derived Florida Current transport measurements is planned as a necessary next step toward operational application.

1.3 Results/Lessons

On the held-out test set, the thermal-wind-constrained model (PINO-TW) achieved v- and u-component RMSE values of 0.0168 and 0.0136 m s^{-1}, representing reductions of approximately 27% and 23% relative to U-Net. PINO-TW yielded a transport RMSE of 0.334 Sv, compared with 0.369 Sv for the data-only FNO. The geostrophic constraint produced only marginal gains, suggesting that the full geostrophic relationship may be overly restrictive. The reconstructed mean power density peaked at approximately 20–30 m. These results indicate that the thermal-wind constraint improves section-integrated transport more clearly than pointwise velocity accuracy. The framework therefore shows potential for depth-resolved Florida Current resource assessment, but independent observational validation is required before operational use.