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Temporal modeling of turbulence via echo state networks

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Abstract

The primary goal of machine learning (ML) application in turbulence is to utilize the immense available data to model it without solving the underlying nonlinear equations of motion. Thus, the most desirable outcome is to model turbulence in a closed-loop scenario over time. Ideally, the aim is to accurately reconstruct the future state of the flow (prediction), but reconstructing the dynamics of the flow is also highly valuable (modeling). In this study, the aim was to model, or potentially predict, turbulence using Echo State Networks (ESN). ESNs are one of the most fundamental machine learning algorithms, featuring a simple structure and efficient training, and have proven to be well-suited for modeling time series due to their recurrent connections. Three different turbulent flows—unsteady von Kármán vortex street (KVS), flow behind cylinder arrays (CA), and Rayleigh-Bénard Convection (RBC)—were selected to draw comprehensive conclusions about the feasibility of temporal modeling/prediction of turbulence across flows with increasing complexity. For each case, the data was reduced via Proper Orthogonal Decomposition (POD), and only the time coefficients of the POD modes were used to train the network and predict the flow using the ESN. The results indicate that the ESN is capable of modeling the wake flows in KVS and CA. Furthermore, the ESN successfully captures the interaction and synchronization of various vortices present in the flow for the CA case. However, the optimal set of hyperparameters varies for different flow dynamics. Perhaps the most evident trend is the increase in the optimal leaking rate for faster flow dynamics. Finally, for the RBC, the ESN successfully models the complex flow dynamics and reconstructs dynamics that are indistinguishable from the ground truth. This extends beyond velocity values, encompassing secondary aspects of flow dynamics, such as spatial and temporal derivatives, as well as vortices.

Keywords: Echo state networks, Temporal modeling, Turbulence, Rayleigh-Bénard convection, Wake flows