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Investigation of a Transformer-Based Fourier Neural Network for FDSD Index Prediction in Ilam Province

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Extended Abstract

Introduction: Dust storms are considered one of the most significant extreme climate phenomena in arid and semi-arid regions, with widespread consequences for health, the environment, and natural resource management. Despite extensive research efforts, accurately predicting the occurrence and intensity of dust storms remains a substantial scientific challenge due to the nonlinear, multiscale, and highly dynamic interactions among atmospheric, land surface, and climatic factors. Traditional numerical and statistical models often struggle to capture such complex relationships, leading to considerable uncertainties in forecasts. In this context, recent advances in deep learning have opened new avenues for modeling complex environmental phenomena. Deep learning models, particularly those capable of learning long-term temporal dependencies and spatial patterns, offer promising tools for improving dust storm prediction. This research, which aims to evaluate the capabilities of novel deep learning models for predicting dust storms, investigated the performance of two individual models—Autoformer and Fourier Neural Operator (FNO)—as well as a hybrid framework based on the combination of these two models across several temporal configurations.

Materials and Methods: This research aims to improve the accuracy of dust storm forecasting by evaluating the predictive performance of advanced deep learning models under different temporal input structures. Two modern architectures were selected for this purpose: the Autoformer model, known for its ability to capture long-term temporal dependencies in time series data, and the Fourier Neural Operator (FNO), which is specifically designed to learn complex spatial-spectral patterns through frequency-domain representations. In addition to assessing these models individually, a hybrid FNO-Autoformer framework was developed to combine their complementary strengths. The dust storm intensity index, representing the severity and frequency of dust events, was selected as the target variable. Ilam Province was chosen as the case study area due to its high exposure to dust storm activity and its climatic vulnerability. To investigate the influence of temporal input structure on model performance, four distinct temporal configurations were designed, ranging from short-term to long-term forecasting horizons. These configurations included time lags from one season up to one year, enabling a comprehensive analysis of how prediction horizon affects model accuracy. Following appropriate pre-processing, the data were divided into training (80%) and testing (20%) sets. Model performance was evaluated using the following statistical metrics: Nash–Sutcliffe efficiency (NS), root mean square error (RMSE), mean absolute error (MAE), and correlation coefficient (R).

Results: The results of this study revealed that the Autoformer model exhibited the weakest performance in predicting the FDSD index across all temporal configurations and was associated with relatively high error in reproducing extreme variations in dust storms. Although the FNO model performed better than Autoformer in

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extracting spatio-temporal patterns, as a standalone model it still did not achieve acceptable forecasting accuracy and showed no significant difference from Autoformer. In contrast, the hybrid FNO-Autoformer model, by integrating the strengths of FNO in learning spatio-spectral patterns and the capability of Autoformer in modeling long-term temporal dependencies, demonstrably provided the best performance across all evaluation metrics. High values of the NS index, a significant reduction in RMSE and MAE errors, and an increase in the correlation coefficient confirmed the clear superiority of this hybrid framework over the individual models. The results also indicated that short-term temporal configurations, particularly forecasts with a one-season lag, achieved the highest accuracy, and that the models' forecasting accuracy decreased with increasing time lag. This finding highlights the sensitivity of data-driven models to the temporal structure of inputs and the importance of selecting an optimal prediction horizon in dust storm modeling.

Discussion and conclusion: Overall, the findings of this research emphasize the crucial role of hybrid spatio-temporal frameworks in predicting extreme climate events and demonstrate that integrating Fourier Neural Operators with transformer-based models can represent an effective step toward developing more accurate forecasting systems and reducing uncertainty in dust hazard management. The study also highlights the strong influence of temporal input configuration on forecasting outcomes, suggesting that careful consideration of time lag selection is essential for optimizing model performance. From a practical perspective, improved dust storm prediction can contribute to more effective early warning systems, risk mitigation strategies, and sustainable environmental management. Moreover, the successful integration of spectral neural operators with transformer-based architectures represents a promising direction for future research in climate hazard modeling. Such hybrid approaches have the potential to reduce predictive uncertainty, support decision-making processes, and enhance resilience to extreme climatic events in vulnerable regions.

Keywords: Dust, Data-driven models, Hybrid models, FNO.