Sphere Fusion Forecast (SFF): A Neural Operator Based Model for Global Weather Forecasting

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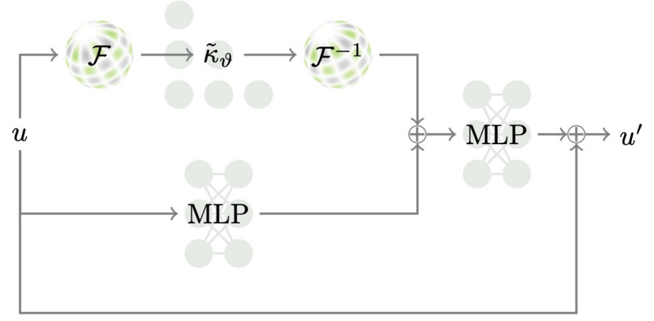
Session CL5.9
Hall X5 #X5.227

Introduction

Background

Weather forecasting is essential for various human activities, including agriculture, transportation, and disaster management. Traditional numerical weather prediction models, while effective, often encounter limitations due to the complexity of physical processes and significant computational demands. In recent years, deep learning–based neural networks have emerged as promising alternatives, offering potential improvements in efficiency and accuracy.
The Spherical Fourier Neural Operator (SFNO) model introduced the use of spherical harmonic transforms to maintain SO(3) rotational invariance, enhancing the stability of long-term forecasts and preventing early collapse.



The structure of a single SFNO block[1]

However, it still presents two critical limitations:

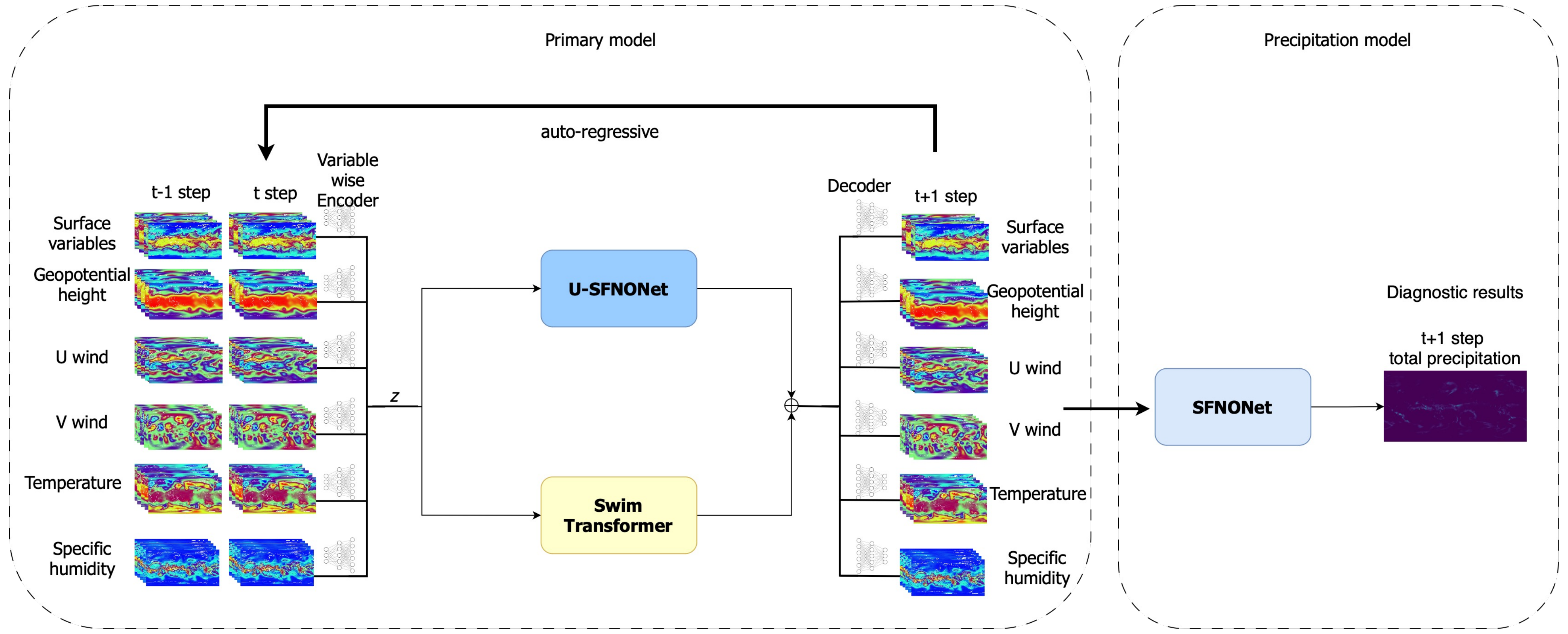
- The fixed model width limits both the model's depth and its scalability.
- Struggling to effectively capture high-frequency local features, reducing its ability to model fine-grained atmospheric variations.

Our works

We introduce Sphere Fusion Forecast(SFF), an advanced machine learning model that employs SFNO as its core operator. SFF is capable of performing rapid autoregressive forecasting and independently diagnosing total precipitation.
Experimental results show that SFF can produce stable 25-day forecasts in less than five minutes on a single NVIDIA H20 GPU. Key evaluation metrics—such as root mean square error (RMSE) and anomaly correlation coefficient (ACC) for Z500, T2m, and T850—are comparable to those well-established IFS model and outperform the original SFNO. Moreover, in precipitation prediction, SFF demonstrates a forecast skill level on par with the IFS model.

Method

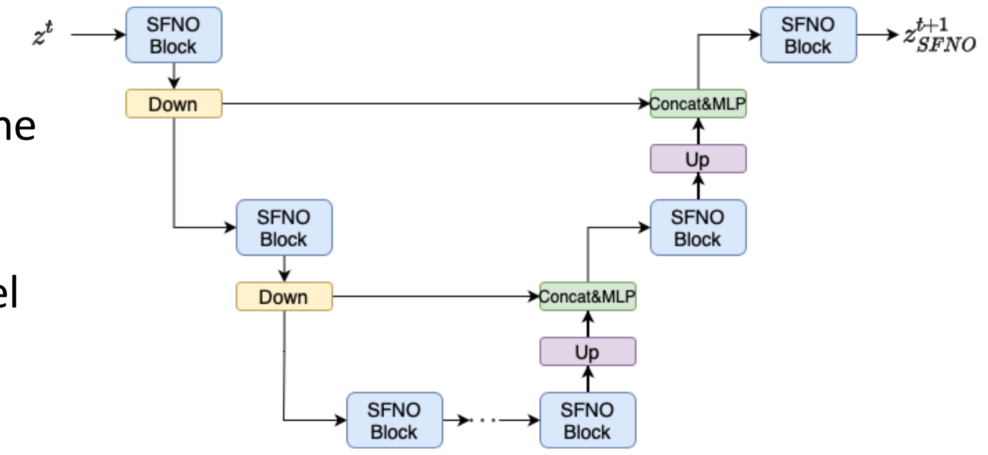
SFF model comprises two components: a primary model for autoregressive forecasting and an independent model dedicated to diagnosing precipitation.



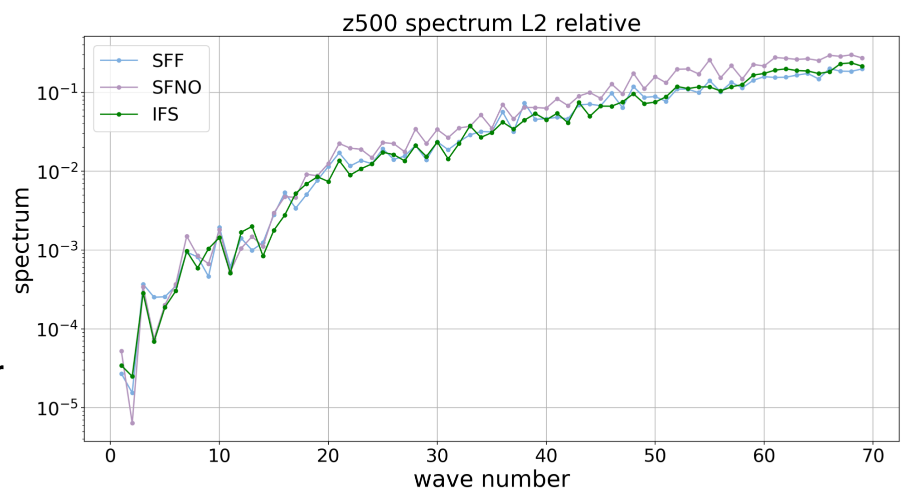
Primary model

To address the aforementioned issues, we propose the SFF primary model, which introduces two key enhancements to the original SFNO architecture:

- U-Structure Integration: By incorporating up-sampling and down-sampling operators between SFNO blocks, the model allows the initial and final stages to handle broader frequency spectra, while the middle layers focus on low-frequency information. This design enables an increase in the number of SFNO blocks or an enlargement of the embedding dimension under a limited parameter budget, thereby enhancing both parameter efficiency and forecast accuracy.
- Vision Transformer-base Residual Connection: We introduce a Vision Transformer-base architecture between the encoder and decoder as the skip connection, specialized to focus on local features. This scheme improves the model's capacity for local feature learning, producing more robust and accurate forecasts.



The structure of U-SFNONet



Relative L2 error of the forecast results at different wavenumbers

Precipitation model

Considering the discontinuous occurrence and development of precipitation, SFF employs an independent precipitation model which can be easier to learn the physical processes of precipitation. Furthermore, to improve the detection and prediction accuracy of heavy rainfall, we leverage classification weighting and extending the effective lead time of precipitation forecasts through joint training.

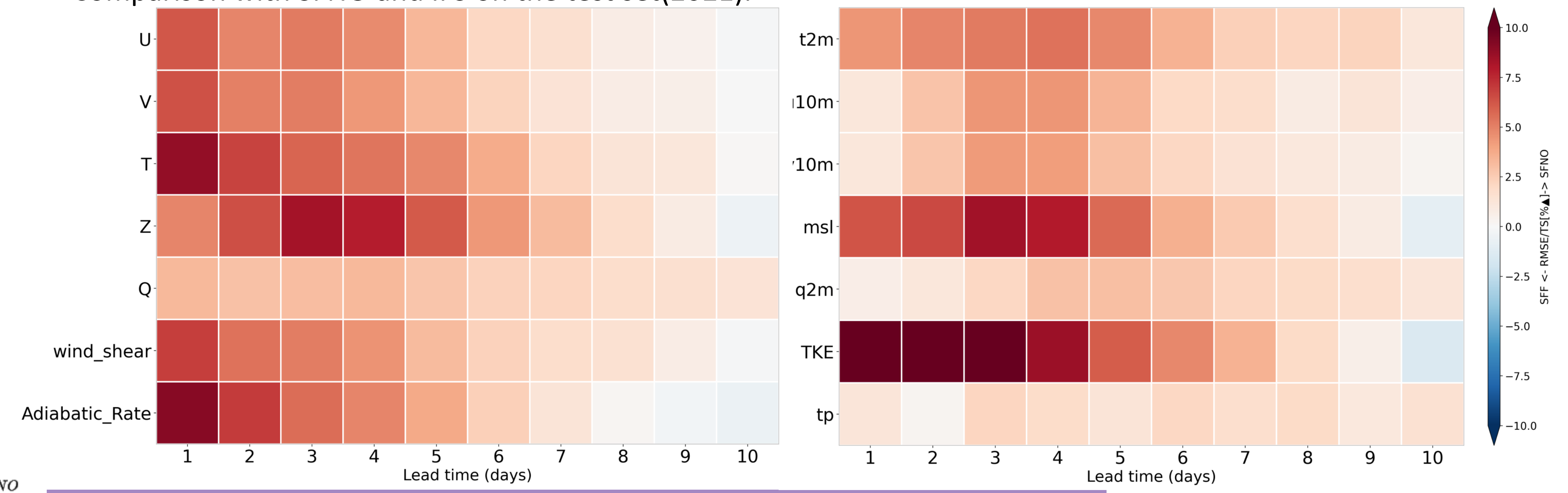
Experiments

Setting

Models are trained on the ERA5 dataset at a 0.25° spatial resolution, aiming to predict atmospheric variables of 6 hours into the future. We utilize 43 years of ERA5 data (1979–2021): 1979 to 2019 for training, 2020 for validation, hyperparameter tuning, and model selection, while 2021 serves as an out-of-sample test set. Both models are trained for 40 epochs in the first stage and 4 epochs in the multi-step finetuning stage.

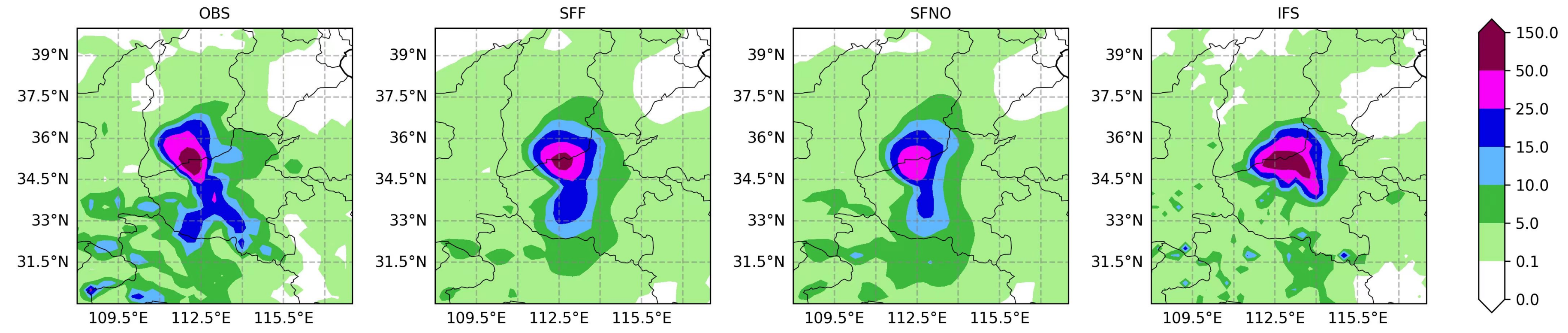
Statistical results of atmospheric variables

Comparison with SFNO and IFS on the test set(2021).

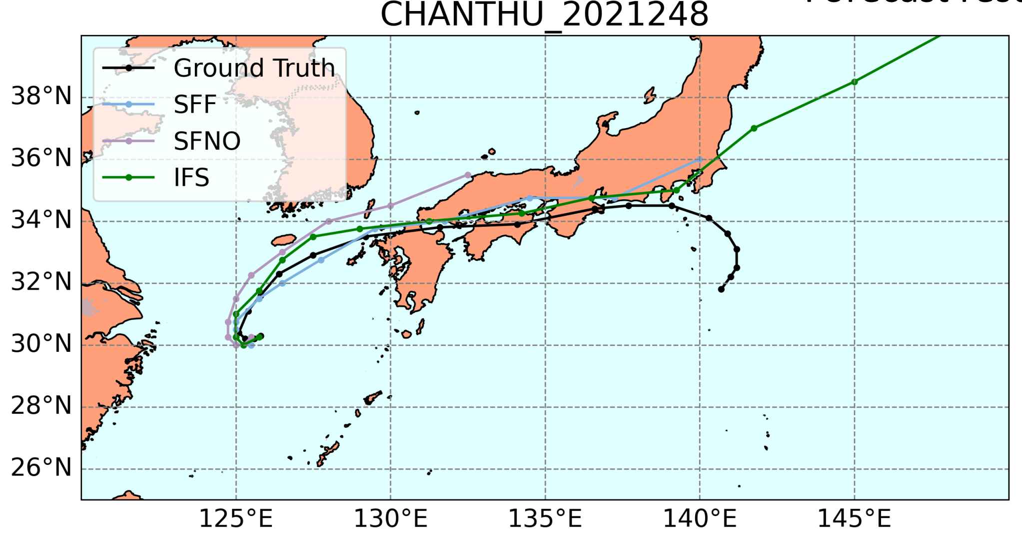


Example of extreme weather

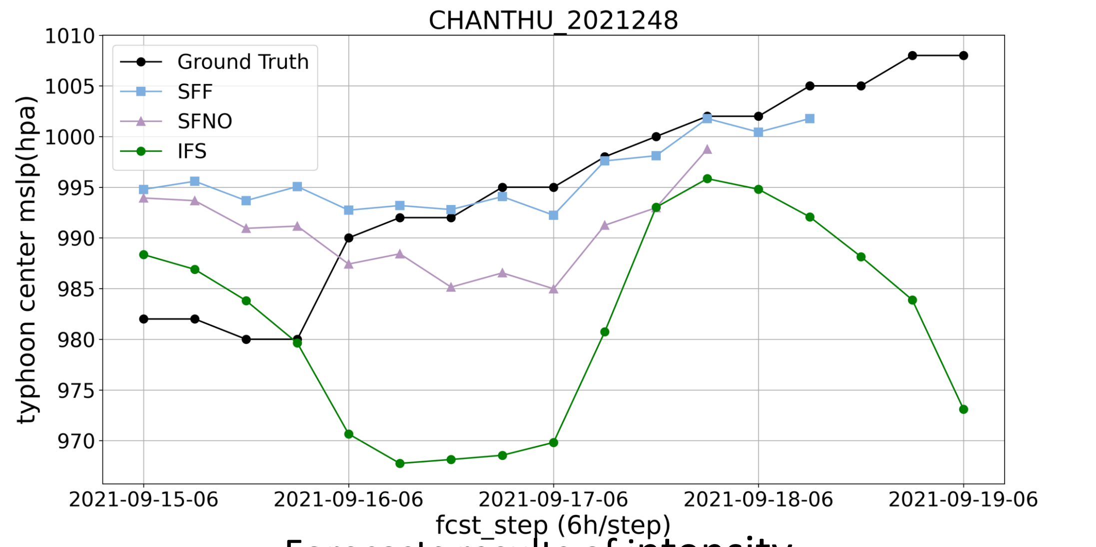
Comparison with SFNO in forecasting performance for extreme-weather case—the convection in Henan, CHINA on 21 July 2021 and Typhoon CHANTHU on 15 September 2021. In both cases, the models start forecasting at 00:00 on the current day and perform autoregressive forecasts for 4 days.



Forecast result of TP



Forecast results of track



Forecasts results of intensity

Reference

1. Bonev, Boris, et al. "Spherical fourier neural operators: Learning stable dynamics on the sphere." International conference on machine learning. PMLR, 2023.