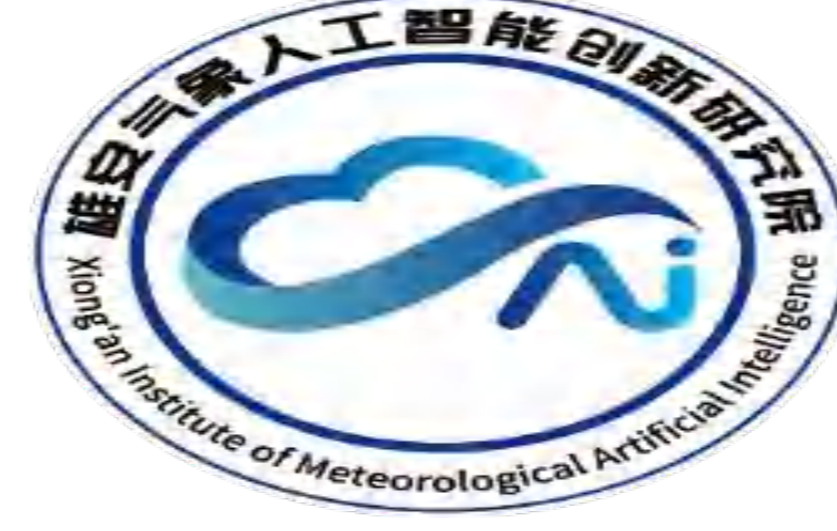
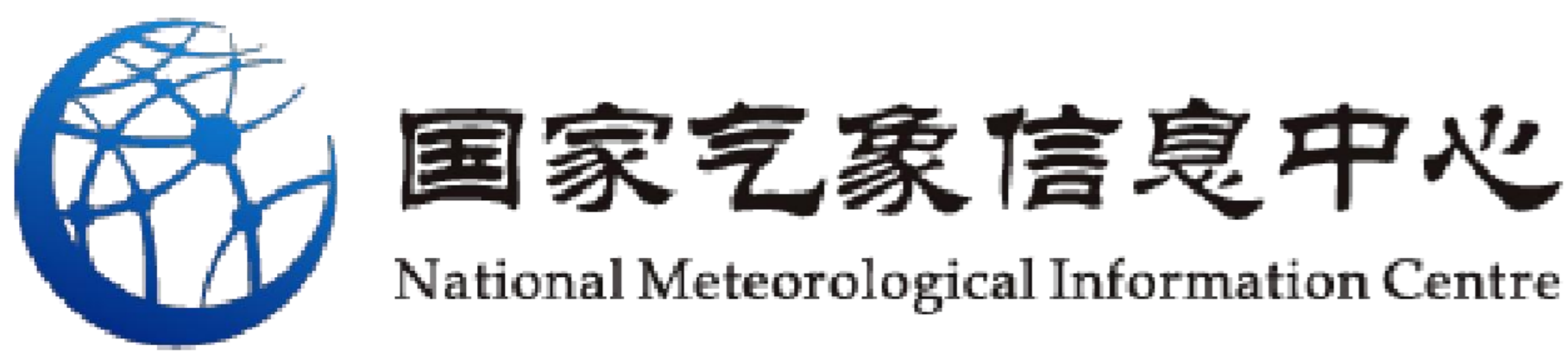


FengYuan: An End-to-End Deep Learning Model for Global Weather Forecasting

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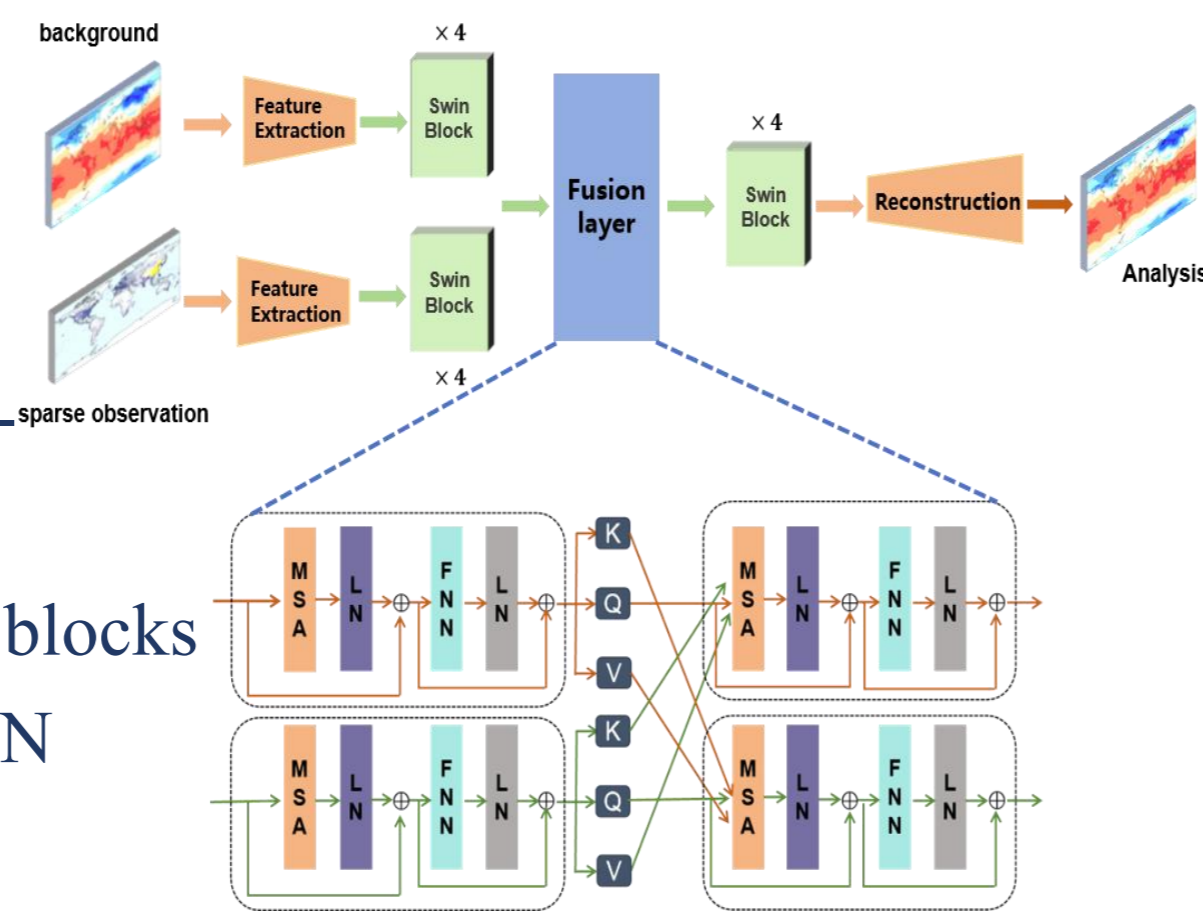
FengYuan-DA

FengYuan Data Assimilation Module (FengYuan-DA) integrates multi-source observations (satellites, surface stations) with prior background fields to generate high-precision analysis fields, overcoming single-source data dependencies.

Dual-Stream Architecture

The module operates on an encoder-fusion-decoder paradigm across four stages:

- Data Preprocessing:** Standardizes data and spatially aligns inputs.
- Feature Extraction:** Employs Swin-Transformer blocks to extract features from gridded data, and uses a CNN with an MLP for sparse observations.
- Cross-Modal Fusion:** Utilizes a dual-attention mechanism: self-attention first strengthens internal feature associations, followed by cross-attention where observation features act as queries and background fields act as keys and values.
- Reconstruction:** Fused features are processed by a decoder (Swin Block, transposed convolutions, and upsampling) to reconstruct a full-resolution analysis field.



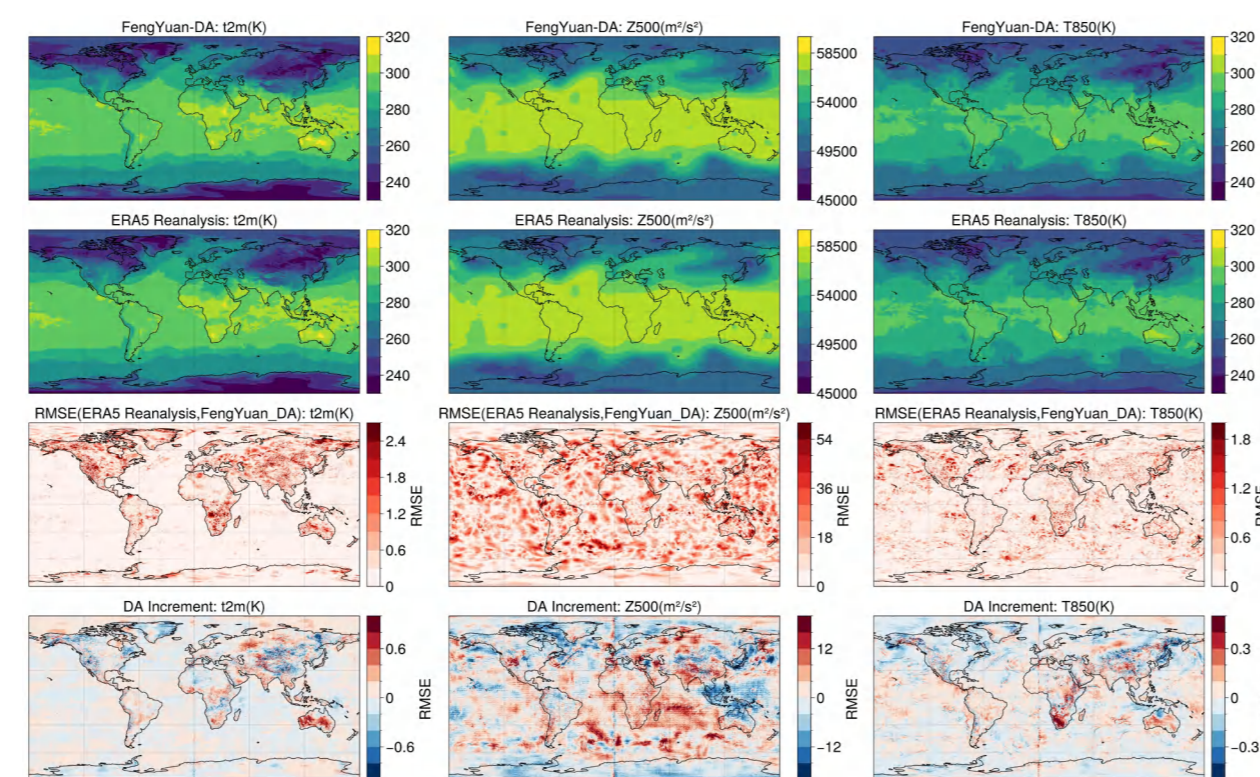
Loss Function

- Composite Loss Function:** Designed to balance spatial structure and numerical accuracy:

$$L_{total} = \lambda_{SSIM} L_{SSIM} + \lambda_{Huber} L_{Huber}$$

Results

- High Fidelity:** Analysis fields demonstrate remarkable spatial consistency with ERA5 reanalysis and genuinely low global RMSE.
- Analysis increment fields** show physically reasonable adjustments, confirming the model extracts and fuses observational signals rather than just inheriting background data.



FengYuan-End to End Forecast

FengYuan is an end-to-end global weather forecasting model that directly processes raw, multi-source observational data to generate medium-range forecasts.

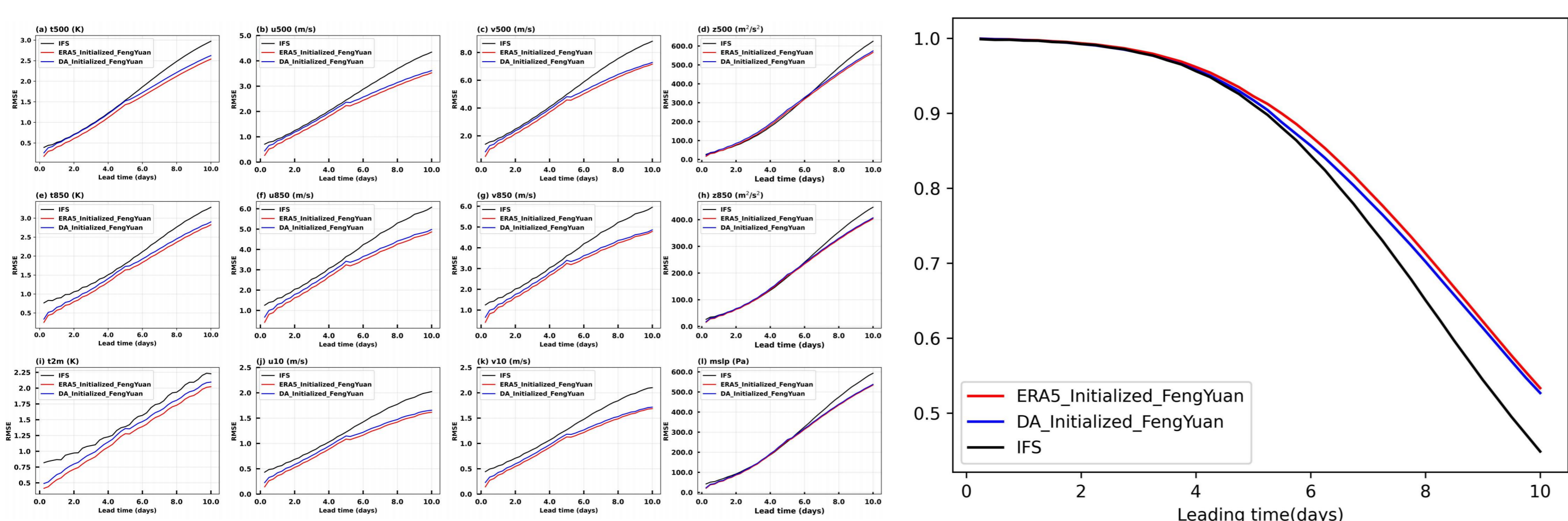
- Seamless Integration:** It couples the Data Assimilation Module (FengYuan-DA) and the Forecasting Module (FengYuan-Forecast) into a sequential workflow, that is the observations are processed by FengYuan-DA to generate analysis fields (initial states); these are fed directly into the forecasting module to predict future atmospheric states.

Multi-Source Observational Data (DA Input)

Dataset	Sources	Time	Variable
GDAS Dataset	Global surface stations, radiosondes, aircraft, ships, buoys, and atmospheric motion vectors	Jan 1, 2016 – Dec 31, 2022	Wind Pressure Temperature Humidity Geopotential
China National Surface Dataset (V3.0)	National stations in China	Jan 1, 2016 – Dec 31, 2022	Wind Pressure Temperature Humidity
China National Upper-air Dataset (V2.1)	L-band sounding systems	Jan 1, 2016 – Dec 31, 2022	Wind Pressure Temperature Humidity

- Uses ERA5 as a reference to remove outliers.
- Interpolation: Discrete raw observations are interpolated both horizontally onto a $0.25^\circ \times 0.25^\circ$ grid and vertically onto 13 standard pressure levels (1000 to 50 hPa)

- ERA5 Reanalysis Data (Forecasting Training):** ECMWF ERA5 reanalysis data at a 0.25° spatial and 6-hour temporal resolution, comprising 70 variables in total (5 pressure-level variables across 13 levels and 5 surface-level variables).
- High Computational Efficiency:** Executing one complete end-to-end forecast cycle requires approximately 280 seconds on a single A800 GPU.
- Operational Superiority:** When initialized with its own FengYuan-DA analysis fields, the complete system achieves forecast accuracy very close to the ERA5 reanalysis-driven version.
- Beating Benchmarks:** The integrated end-to-end model outperforms the ECMWF's Integrated Forecasting System (IFS) throughout the 10-day forecast period.

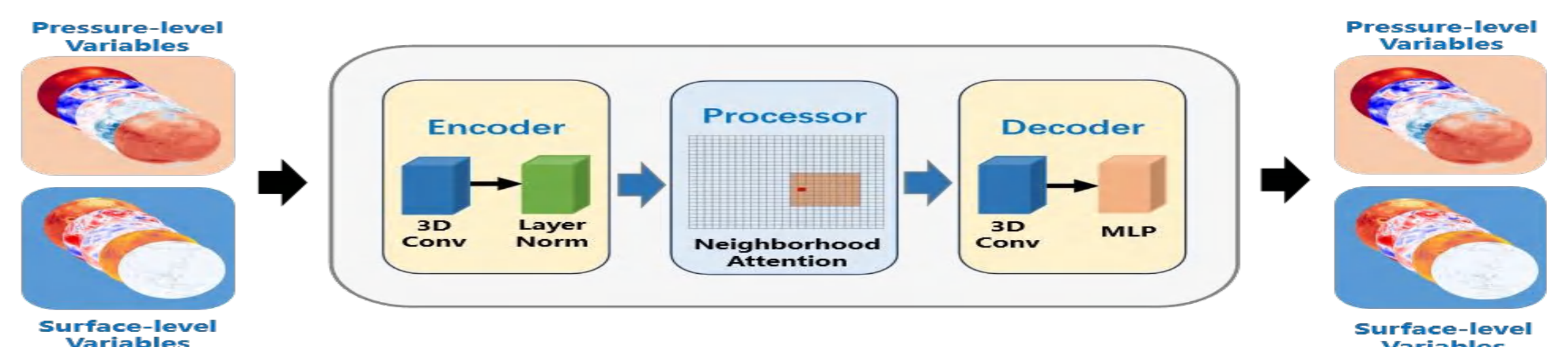


FengYuan-Forecast

FengYuan Forecasting Module (FengYuan-Forecasting) takes two time steps of atmospheric states (X_{t-1}, X_t) at 6-hour intervals to predict the next state (X_{t+1}) autoregressively.

Encoder-Processor-Decoder Architecture

- Encoder:** Utilizes 3D convolutions to compress multi-modal meteorological variables from the latitude-longitude model space into a latent space.
- Processor:** Employs Swin-Transformer blocks embedded with neighborhood attention mechanisms to capture spatial dependencies and influence from surrounding information.
- Decoder:** Maps the latent feature representations back to the original latitude-longitude space using 3D convolutions and a Multi-Layer Perceptron (MLP).

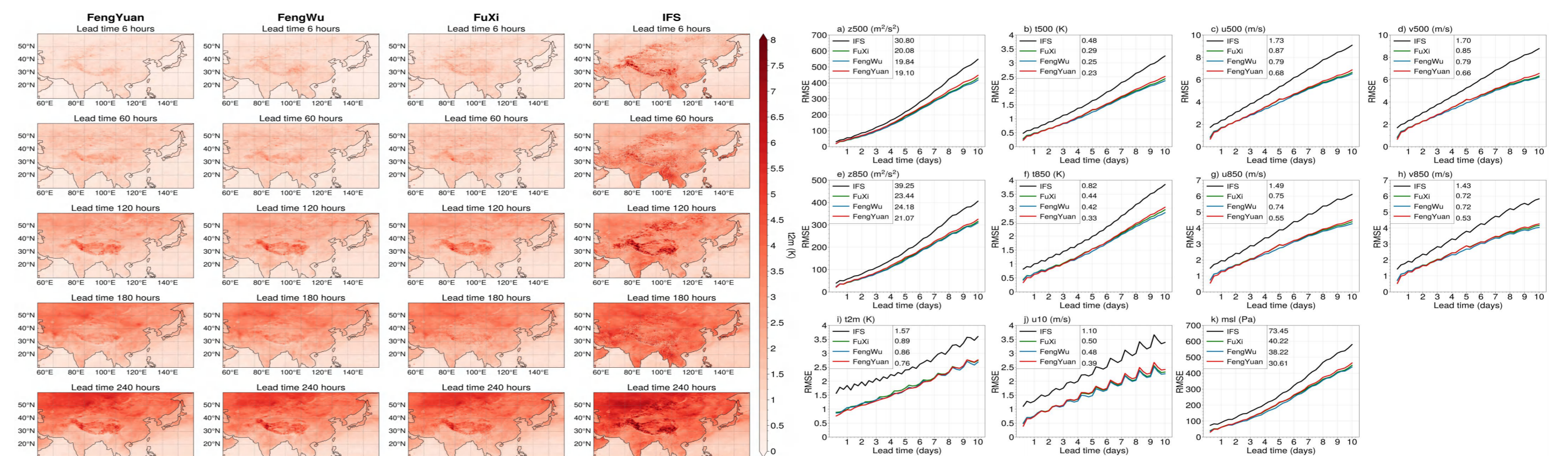


Training Strategy

- Two-Stage Process:** Stage 1 trains a single-step forecasting model; Stage 2 applies a 12-step progressive fine-tuning approach.
- Optimization:** Minimizes forecasting errors using a pressure-level weighted mean absolute error (MAE) loss function, with weights linearly increasing from high to low pressure levels.

Results

- Competitive Edge:** Demonstrates 10-day forecast performance significantly outperforms ECMWF's IFS.
- Superior Initialization:** FengYuan achieves the lowest RMSE at the initial 6-hour forecast.
- Local Advantage:** Performance advantages are notably more pronounced over East Asia compared to global metrics, specifically for low-level and near-surface variables.



Conclusion & Future Work

Conclusions

FengYuan generates medium-range forecasts directly from multi-source observations. It performs comparably to state-of-the-art AI models and consistently outperforms ECMWF's IFS over the 10-day period. FengYuan-DA produces analysis fields comparable to ERA5 by effectively extracting observational signals.

Challenges & Future Work

FengYuan forecast accuracy degrades for active regions beyond 5 days, and refinements to its data quality control are required to handle observational errors and missing data in sparse regions.

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