A Data-Driven Regional Model for Skillful Typhoon Prediction

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58th Typhoon Committee session, Jeju, Korea

Typhoon Committee Research Award for Young Scientists 2025

ESCAP/WMO Typhoon Committee

ESCAP Economic and Social Commission for Asia and the Pacific

WORLD METEOROLOGICAL ORGANIZATION

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Your reference	*Your letter of*	*Our reference*	*Date*
		TCS/002-2026	12 January 2026

Subject: Notification of Award – Typhoon Committee Research Award for Young Scientists 2025

Dear **Mr. Zeyi Niu**

On behalf of the ESCAP/WMO Typhoon Committee Secretariat (TCS), I am pleased to inform you that, following the review by the Young Scientist Award Selection Working Group (YSASWG), endorsement by the Advisory Working Group (AWG), and approval by the Chairperson of the ESCAP/WMO Typhoon Committee, you have been selected as the recipient of the **Typhoon Committee Research Award for Young Scientists 2025**.

- **Pioneered a feasible AI–physics integration pathway, improving typhoon track and intensity forecasts.**

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Earth and Space Science

RESEARCH ARTICLE
10.1029/2024EA003952

Key Points:

- An machine learning (ML)-driven hybrid typhoon model combing the Pangu model and Weather Research and Forecasting model using spectral nudging
- The ML-driven hybrid typhoon model outperforms ECMWF IFS in typhoon intensity forecasts
- Data assimilation can further improve the performance of the ML-driven hybrid typhoon model

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Methodology: Zeyi Niu, Wei Huang, Lin Deng, Hong Li
Resources: Yuhua Yang
Software: Zeyi Niu
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Improving Typhoon Predictions by Integrating Data-Driven Machine Learning Model With Physics Model Based on the Spectral Nudging and Data Assimilation

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Abstract The rapid advancement of data-driven machine learning (ML) models has improved typhoon track forecasts, but challenges remain, such as underestimating typhoon intensity and lacking interpretability. This study introduces an ML-driven hybrid typhoon model, where Pangu forecasts constrain the Weather Research and Forecasting (WRF) model using spectral nudging. The results indicate that track forecasts from the WRF simulation nudged by Pangu forecasts significantly outperform those from the WRF simulation using the NCEP GFS initial field and those from the ECMWF IFS for Typhoon Doksuri (2023). Besides, the typhoon intensity forecasts from Pangu-nudging are notably stronger than those from the ECMWF IFS, demonstrating that the hybrid model effectively leverages the strengths of both ML and physical models. Furthermore, this study is the first to explore the significance of data assimilation in ML-driven hybrid typhoon model. The findings reveal that after assimilating water vapor channels from the FY-4B AGRI, the errors in typhoon intensity forecasts are significantly reduced.

Plain Language Summary This study explores the use of a hybrid typhoon forecasting model that combines machine learning (ML) with traditional weather modeling to improve the accuracy of typhoon predictions. Specifically, the Pangu model's forecasts are used to constrain the WRF model through a technique called spectral nudging. The results show that this approach provides more accurate track forecasts for Typhoon Doksuri (2023) compared to traditional methods using NCEP GFS as initial field. Additionally, the model improves the prediction of typhoon intensity, which is often underestimated by current models. This study also highlights the importance of data assimilation, showing that assimilating water vapor data from the FY-4B satellite further reduces errors in intensity forecasts. This hybrid approach effectively combines the strengths of both ML and traditional physical models, offering a promising direction for improving typhoon forecasting.

1. Introduction

In recent decades, physics-based numerical weather prediction (NWP) models have achieved tremendous success in fields such as weather forecasting and climate change prediction (Kalnay, 2003; Kay et al., 2015). With the rapid development of techniques like model physical parameterization, data assimilation and ensemble forecasting (Geer & Bauer, 2011; Geer et al., 2018; Hong & Dudhia, 2012; Richardson et al., 2020; Toth & Kalnay, 1993), the performance of NWP models has been continuously improved. This gradual and incremental

Sincere thanks to WMO TCS for recognizing this series of work!

CONTENTS

01

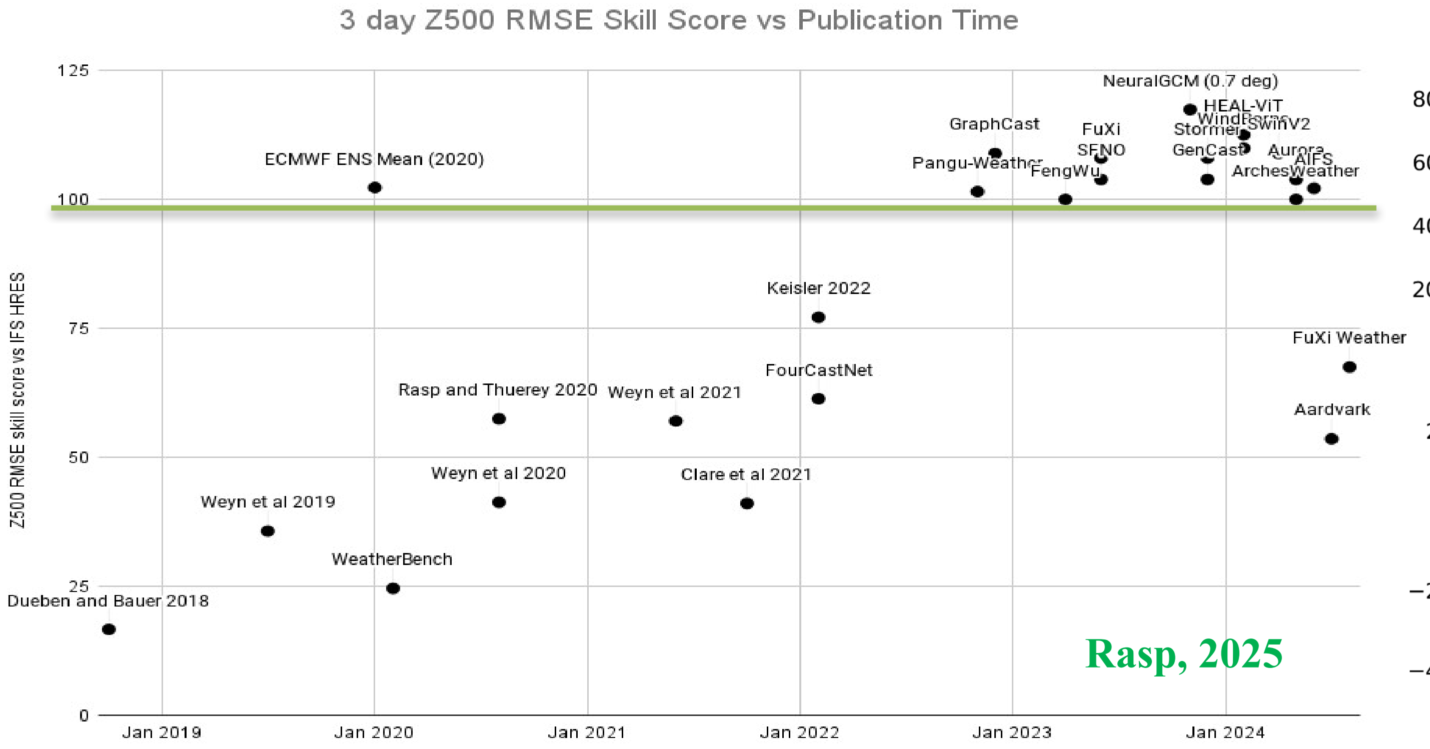
Part one

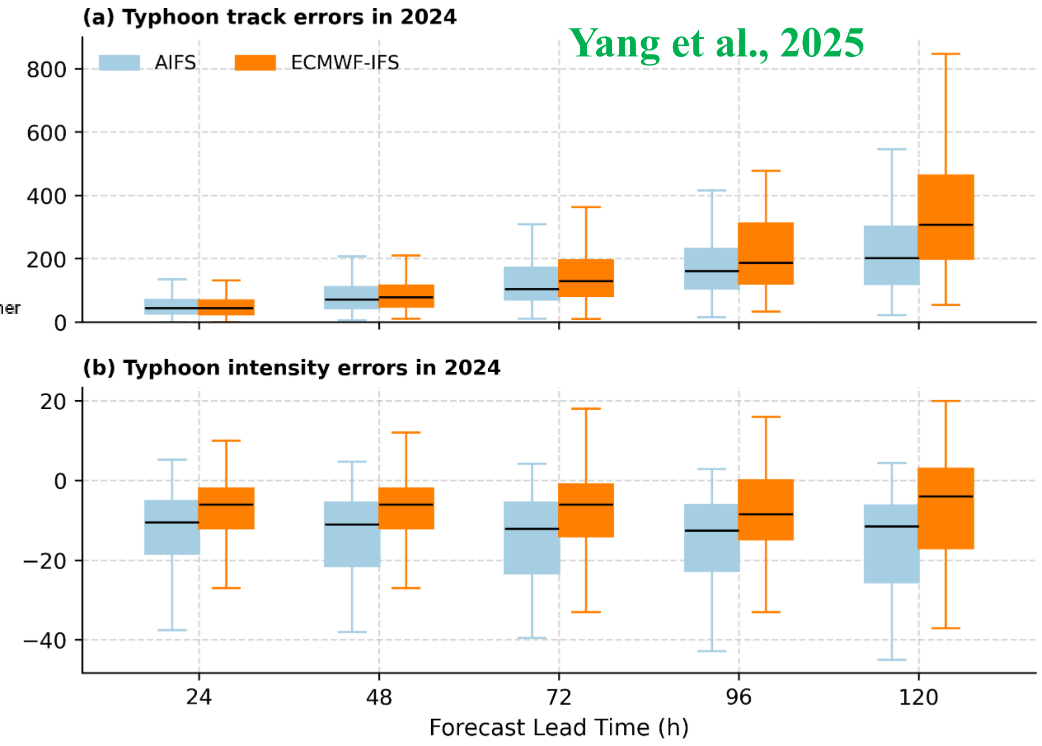
Backgrounds

Developments of AI weather prediction models (AIWP)

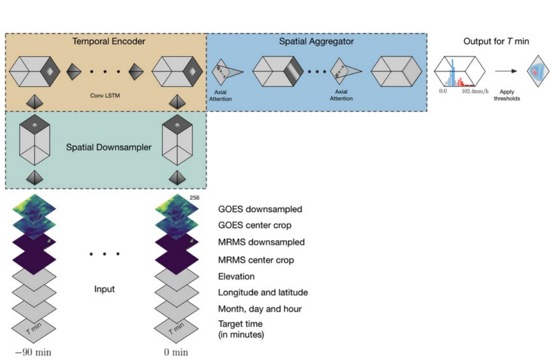
- AIWP models are becoming increasingly mature: evolving from grid-based forecasting to end-to-end and observation-to-observation prediction, and shifting from deterministic forecasts toward ensemble predictions.

- **AIWP models still show a clear underestimation in typhoon intensity forecasting.** One major reason is that these models are trained on ERA5 reanalysis dataset (~25 km resolution), whose horizontal resolution is too coarse to resolve the mesoscale structures.





Research Progress in Regional AI Model



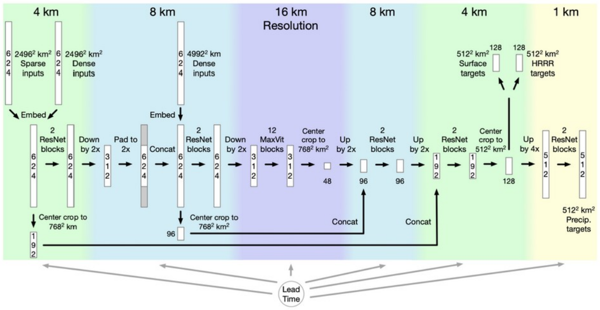
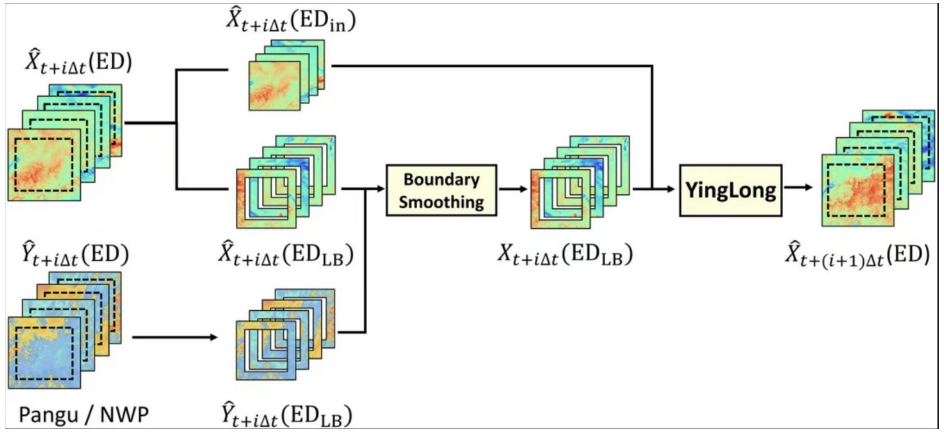


Figure 11: MetNet-3 network architecture. Rectangles denote tensors and the numbers on/under them denote their spacial sizes in pixels.



MetNet-V1 — 2020

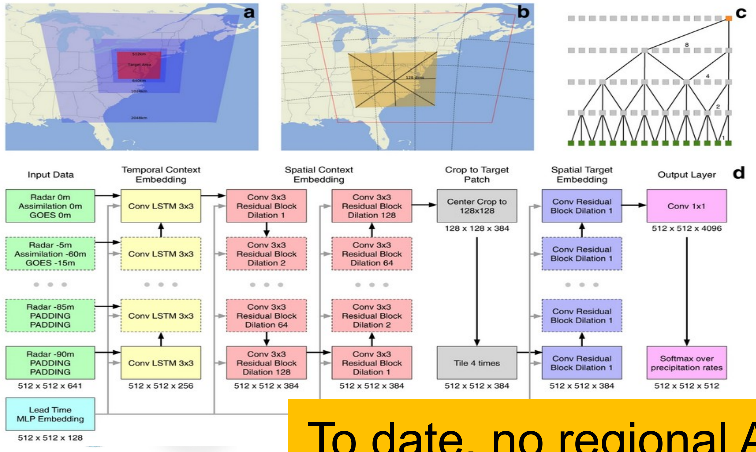
MetNet-V2 — 2021

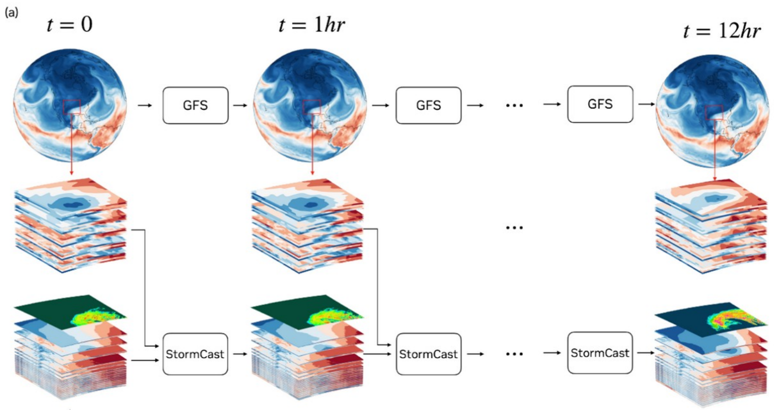
MetNet-V3 — 2023

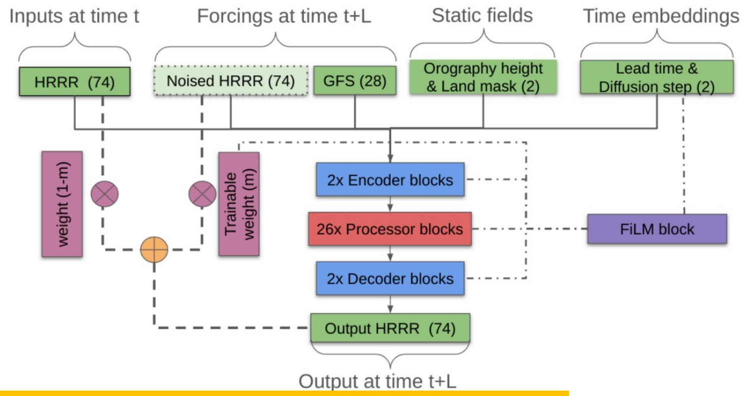
StormCast — 2024

YingLong — 2024

HRRRCast — 2025

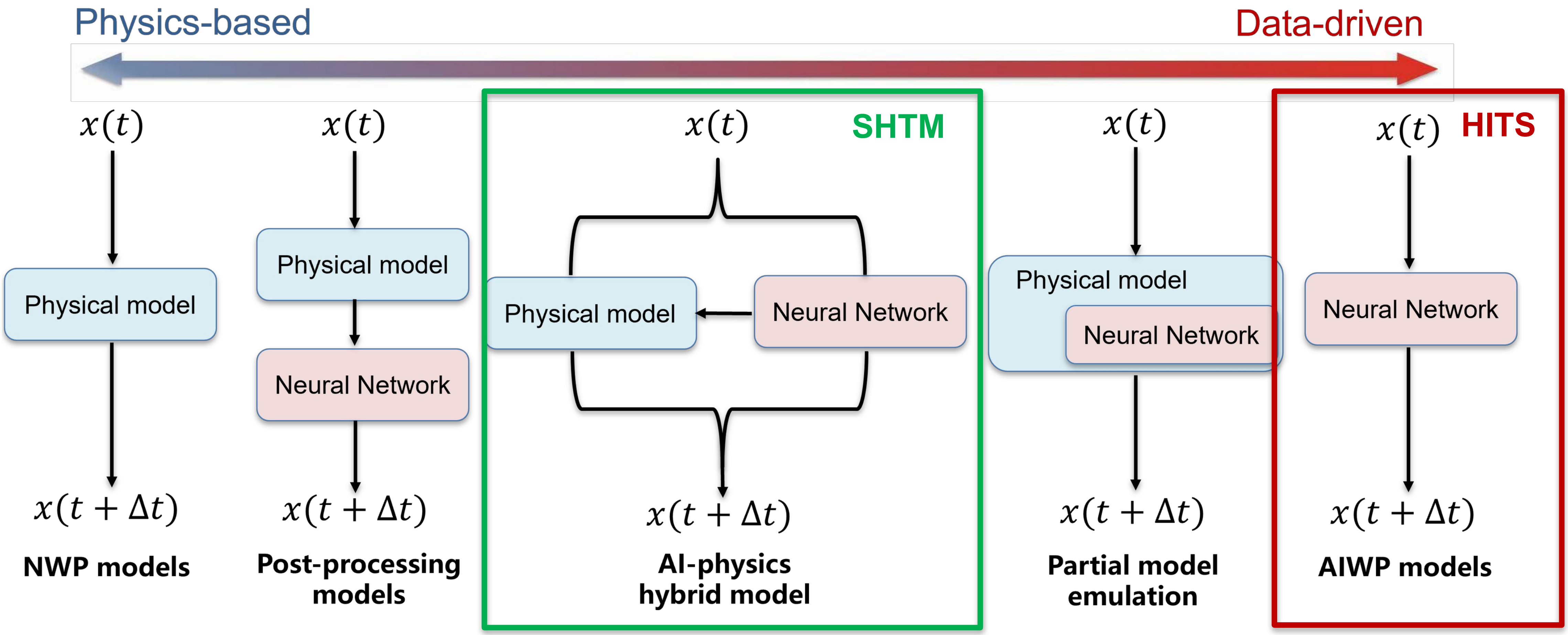






To date, no regional AI model has been specifically developed for 5-day typhoon forecasting

AI–physics blending (hybrid) paradigm



- Shanghai Typhoon Model (SHTM) ： AI-physics hybrid model
- Hybrid Intelligent Typhoon System (HITS): combining global AI model and regional AI model training based on high resolution typhoon reanalysis.

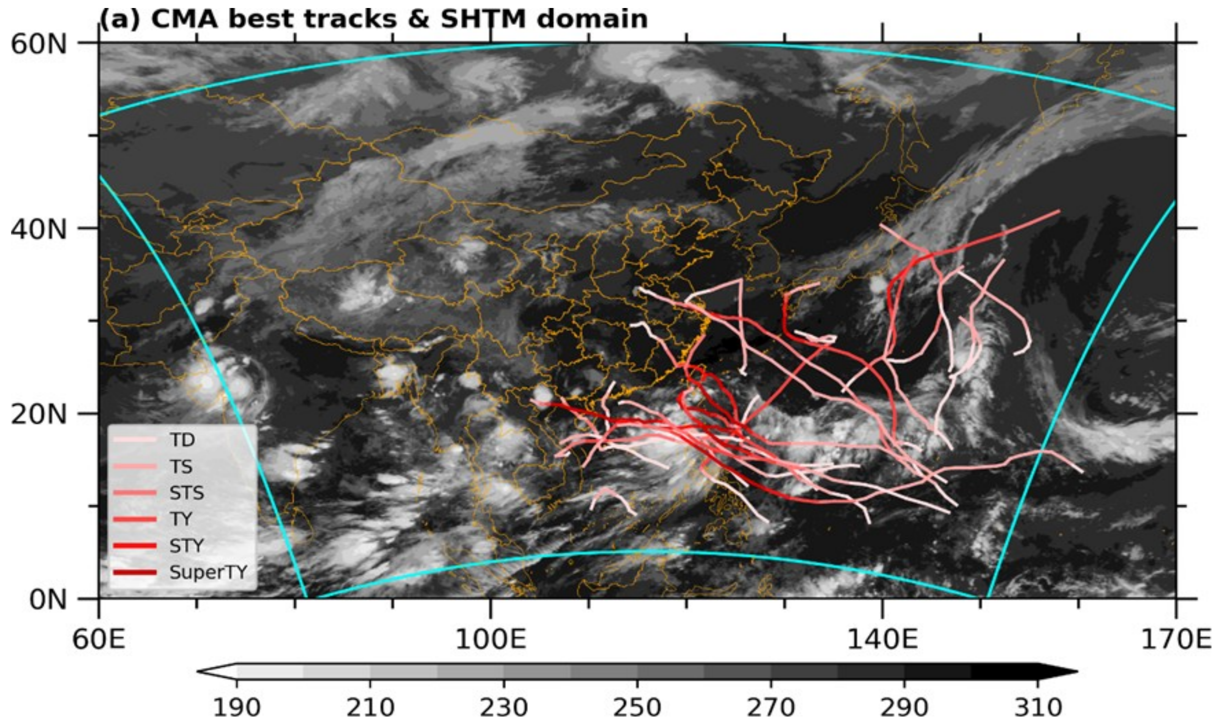
02

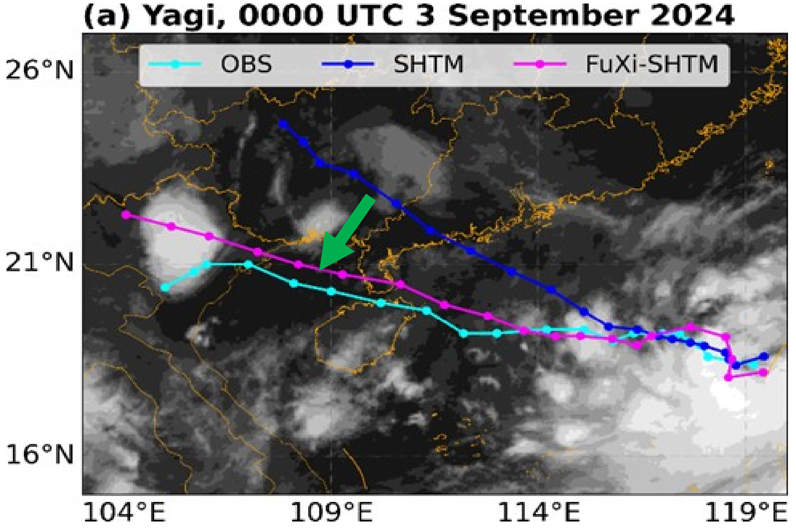
Part two

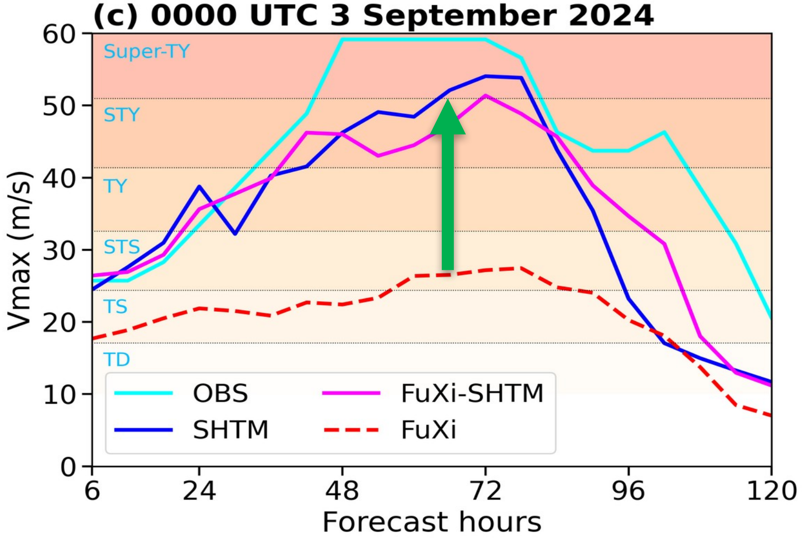
AI-physics hybrid model: Shanghai Typhoon Model

Development of an AI–physics hybrid model based on spectral nudging

$$\frac{\partial \xi}{\partial t} = F(\xi) + \omega(\xi^{L}_{Fuxi} - \xi^{L}_{WRF})$$



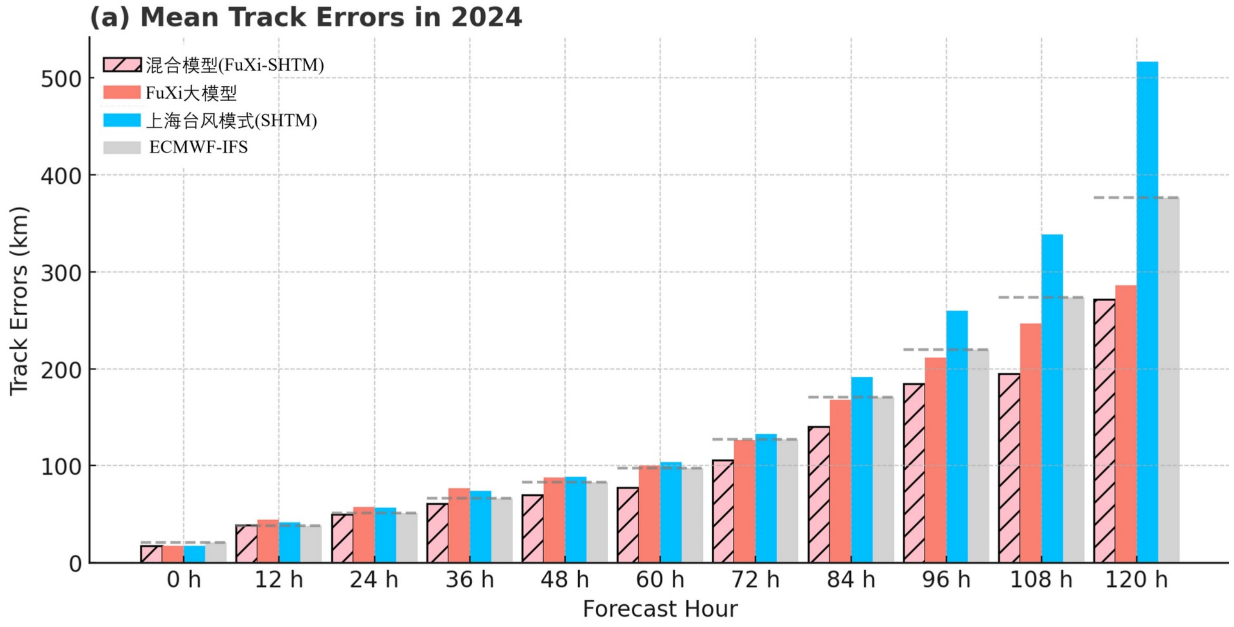




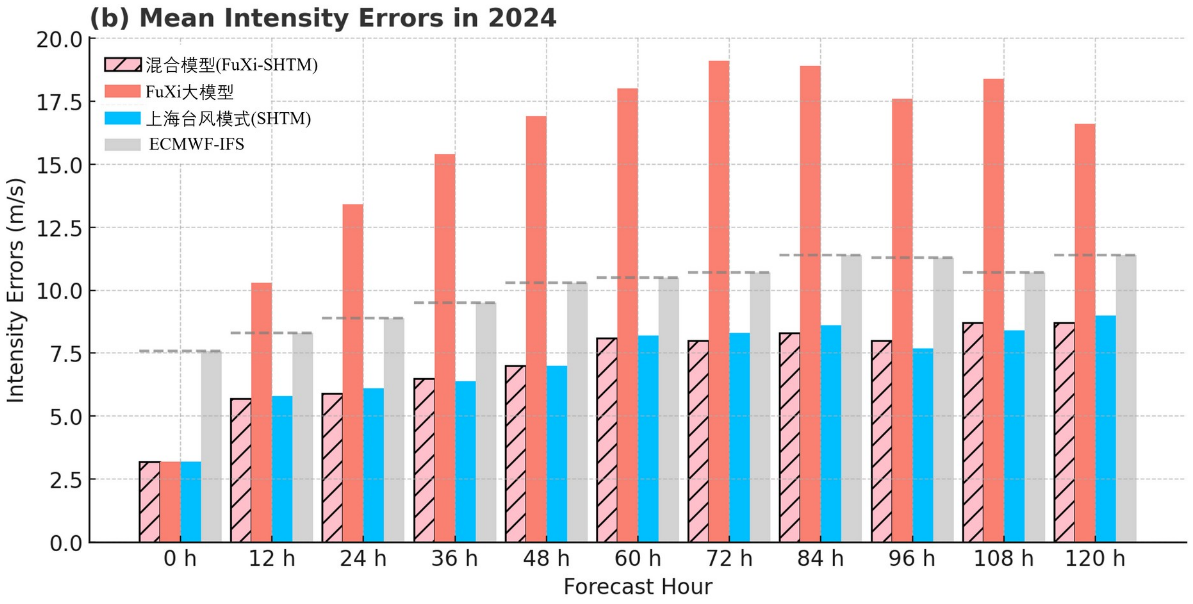
- By combining the large-scale forecast strengths of AI model (FuXi) with the SHTM's skill for meso- and small-scale features, we can achieve optimal forecasts of typhoon track and intensity.

Performance of SHTM-FuXi hybrid model in 2024 typhoon forecasting

samples 171 145 131 115 101 89 78 67 59 44 35

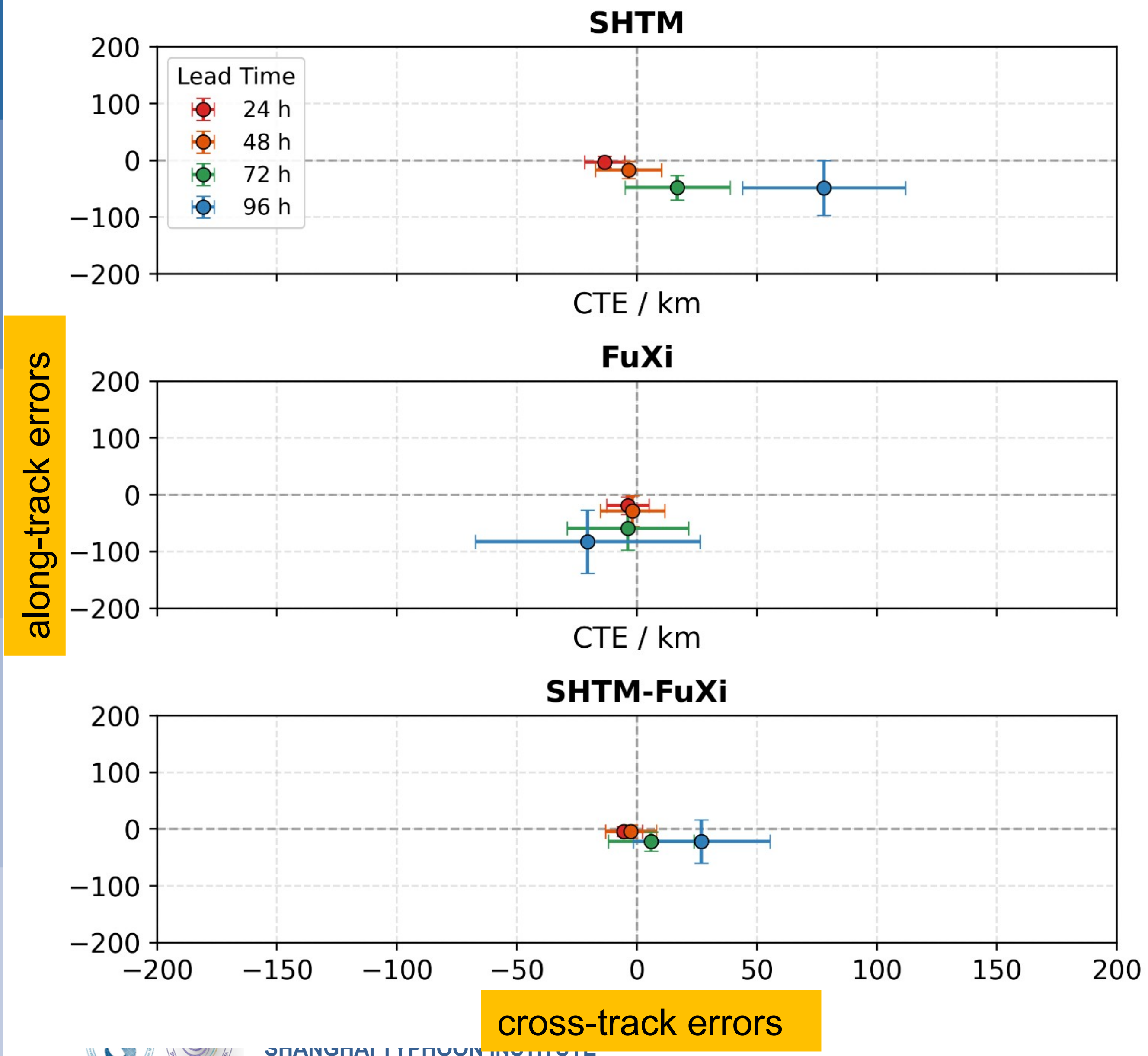


171 145 131 115 101 89 78 67 59 44 35



- The hybrid model achieves a track error within 100 km for forecasts up to 72 hours and within 200 km for forecasts up to 108 hours.
- The hybrid SHTM-FuXi model performs better than both the original SHTM and FuXi in typhoon track forecasting, showing a clear combined benefit where the two models together work better than either one alone.

Track forecast error analysis of SHTM, FuXi, and SHTM-FuXi

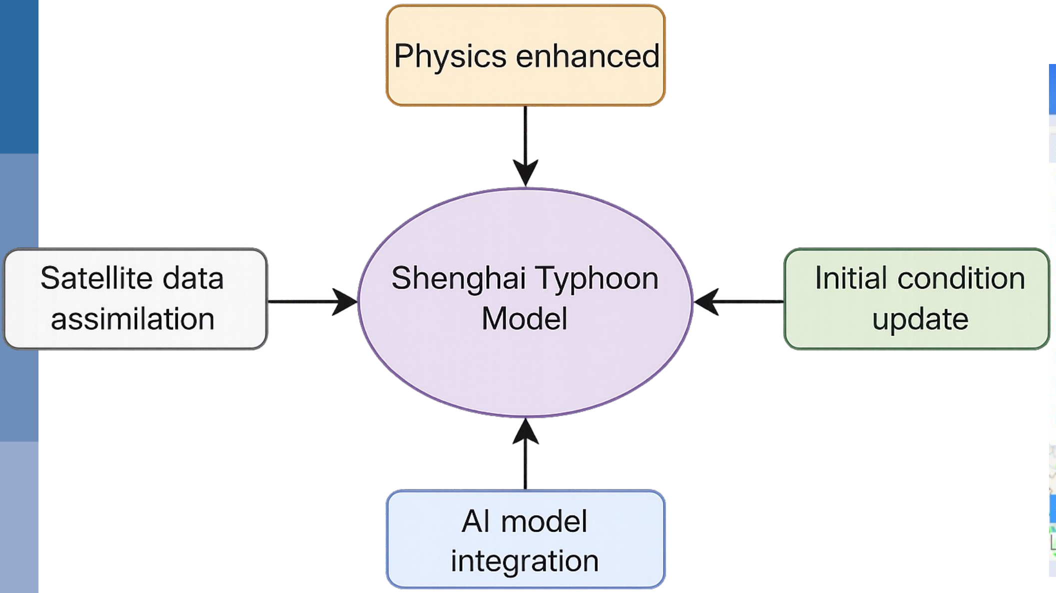


- SHTM shows a clear rightward track bias at longer lead times.

- FuXi shows a clear slow-moving bias in typhoon motion forecasts at 24–96 hours, with a slight leftward bias at 96 hours.

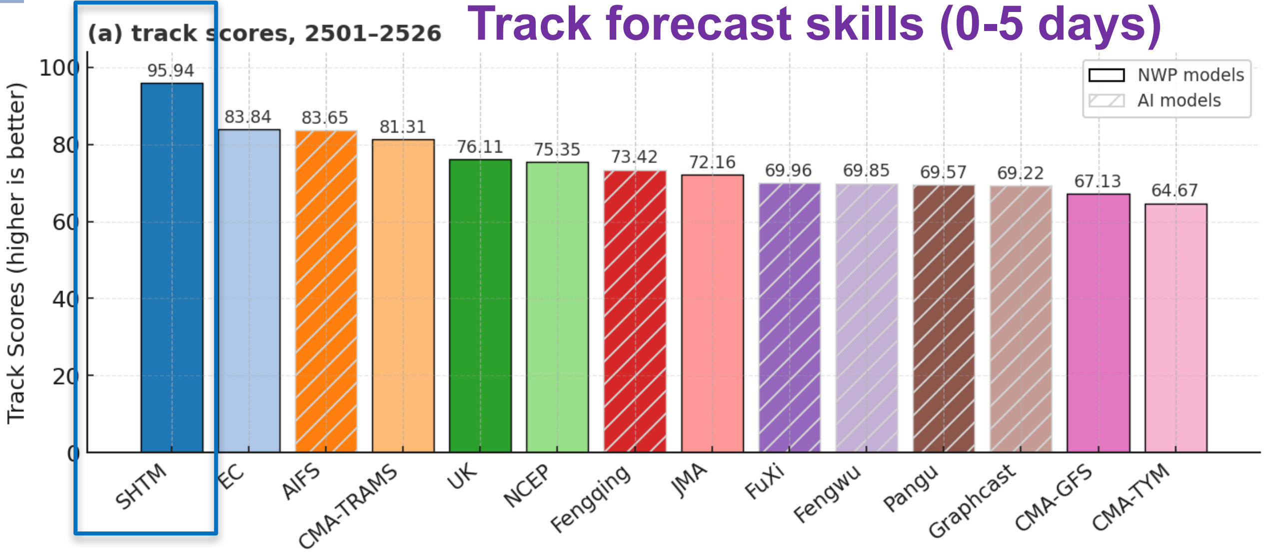
- However ， the SHTM-FuXi model only shows a slight rightward bias at 96 hours, with no evident bias in typhoon speed.

Performance of SHTM-AIFS hybrid model in 2025 typhoon forecasting

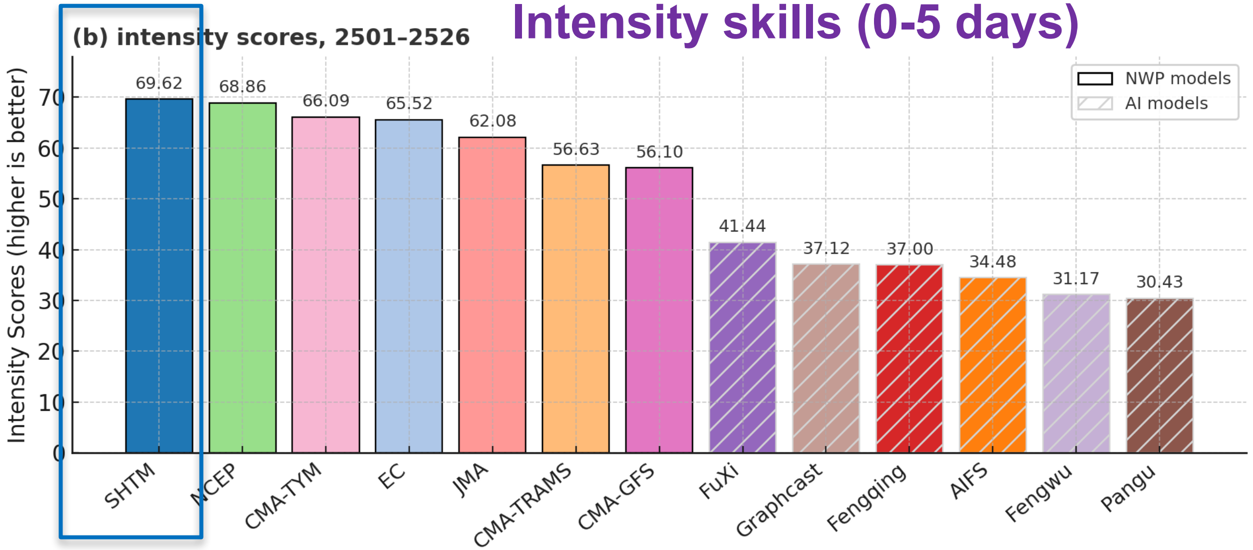


TC Forecast Demonstration Project (National Meteorological Center)

Track forecast skills (0-5 days)



Intensity skills (0-5 days)



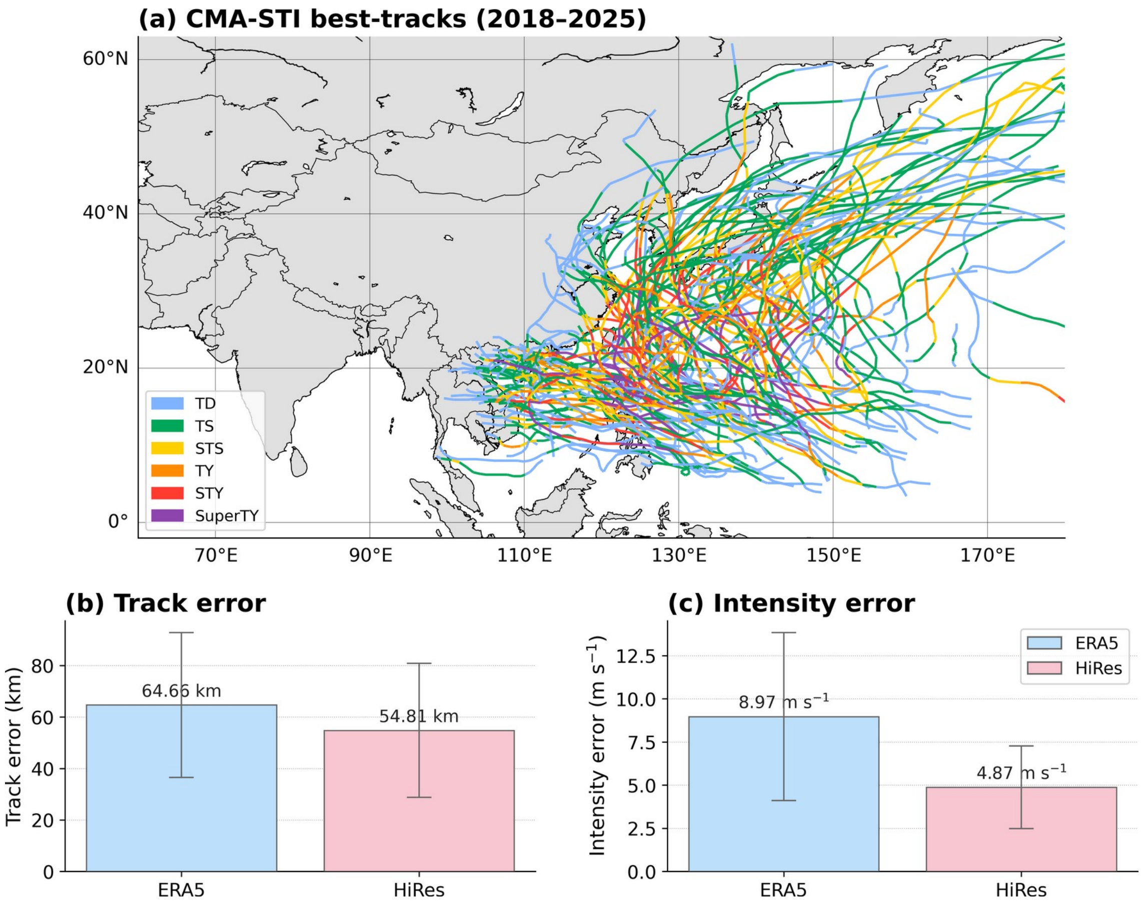
- The Shanghai Typhoon Model ranked first in both track and intensity forecast skill in 2025’s TC-FDP.

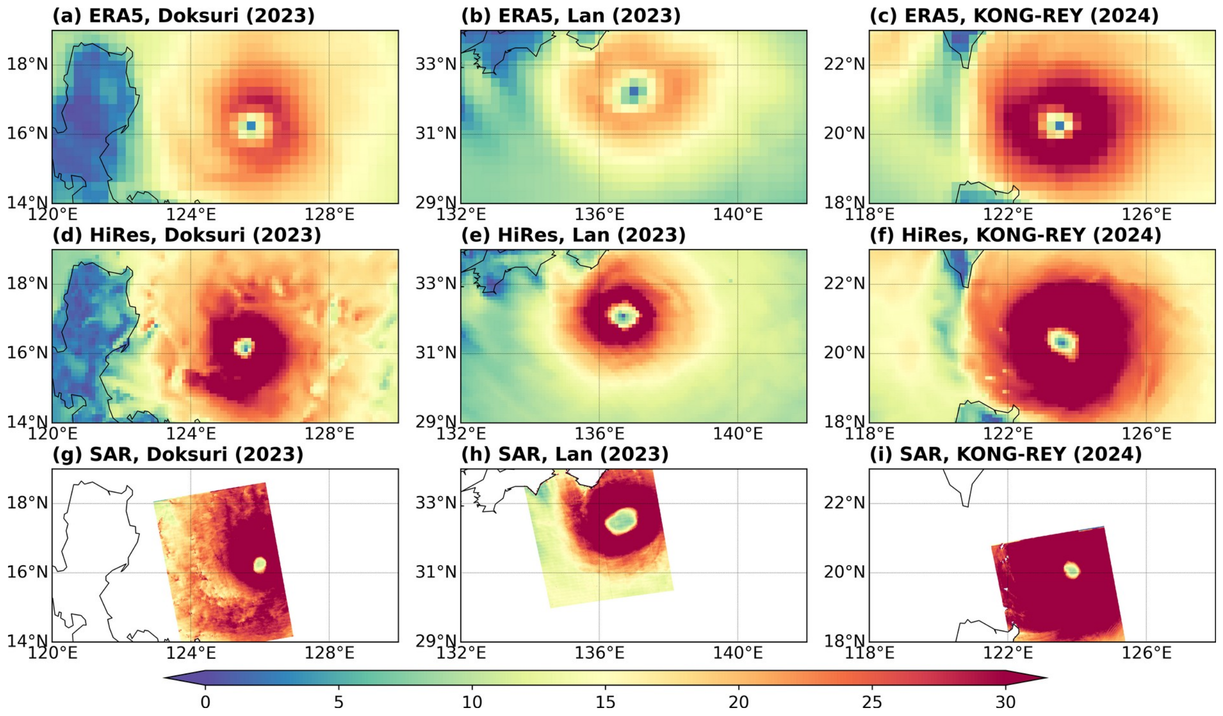
03

Part three

Data-driven regional model: HITS (海司)

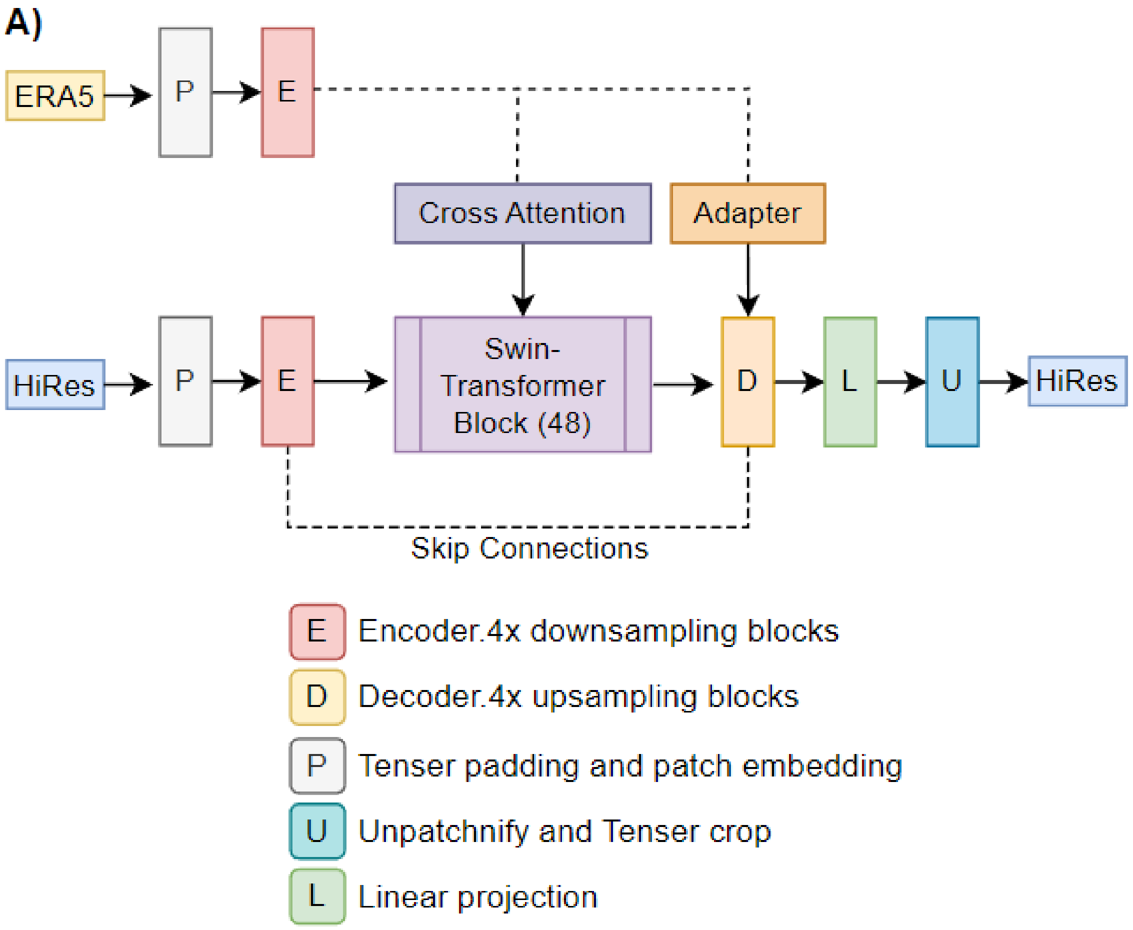
What is training dataset?
High resolution typhoon reanalysis (HiRes)

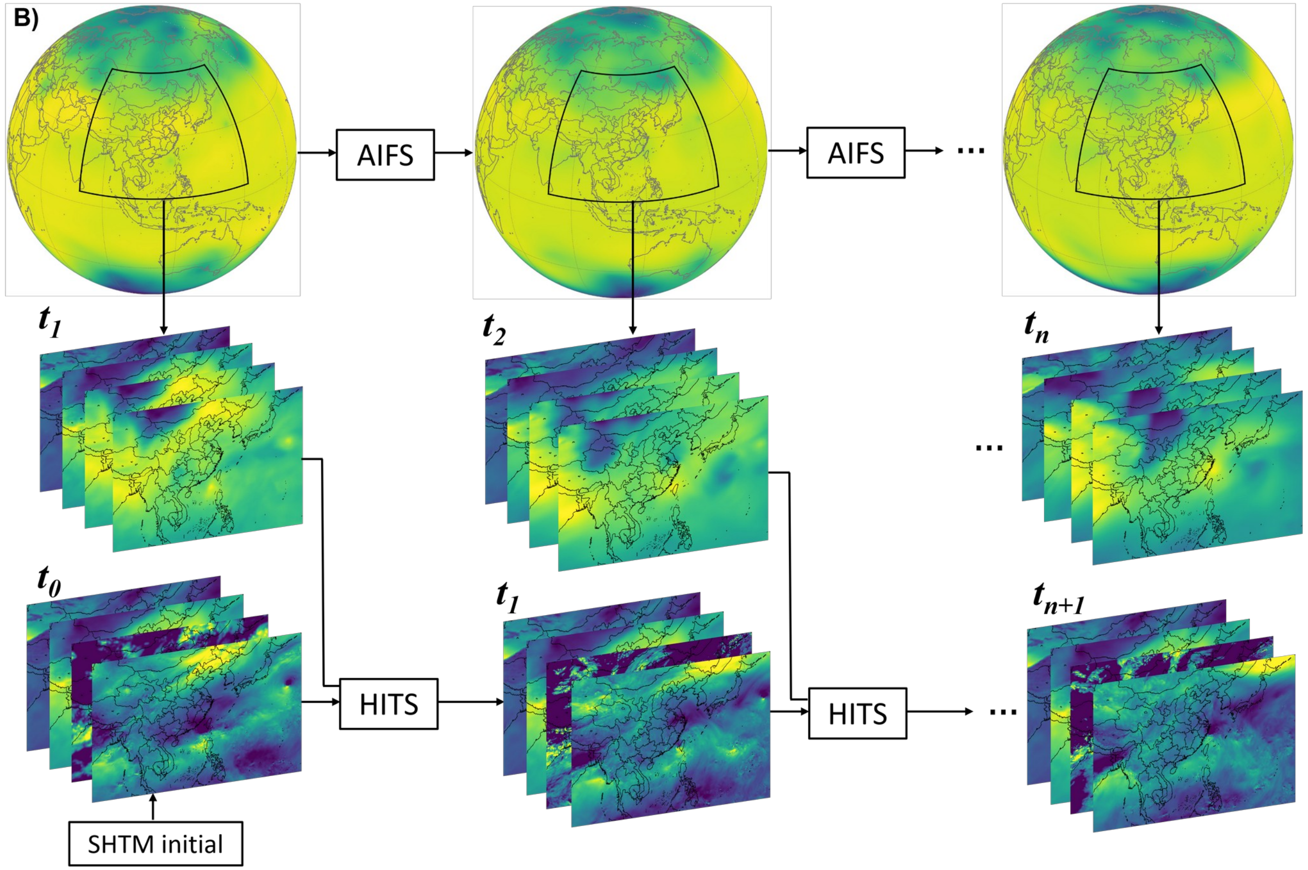




- From the statistical results of typhoon track and intensity, the track and intensity errors of HiRes are smaller than those of ERA5. In particular, the intensity error is reduced by about half.

Architecture of Hybrid Intelligent Typhoon System (HITS)





- Application of the nudging concept to regional AI models to explore the optimal paradigm for regional AI-based typhoon forecasting.

Experiment designs

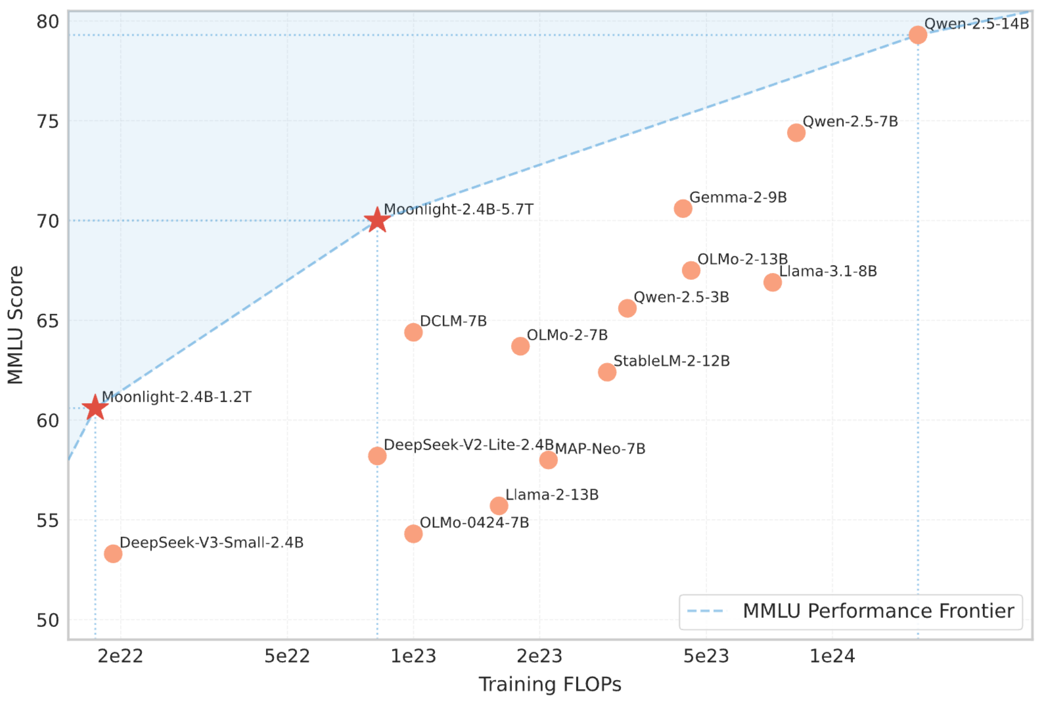
Models	Descriptions
ISTM	**Downscaling** of AIFS forecast fields (two-stage approach using Transformer and Diffusion). (Niu et al., 2025)
CTL	U-Transformer-based autoregressive forecast trained by HiRes **(without boundary conditions)**.
HITS	U-Transformer-based autoregressive forecast trained on HiRes, with AIFS forecast fields incorporated through cross-attention as a dynamical constraint. **(autoregressive forecast+downscaling)**
HITS-LPIPS	The HITS model incorporates **a multi-scale perceptual** LPIPS scheme into its training loss.

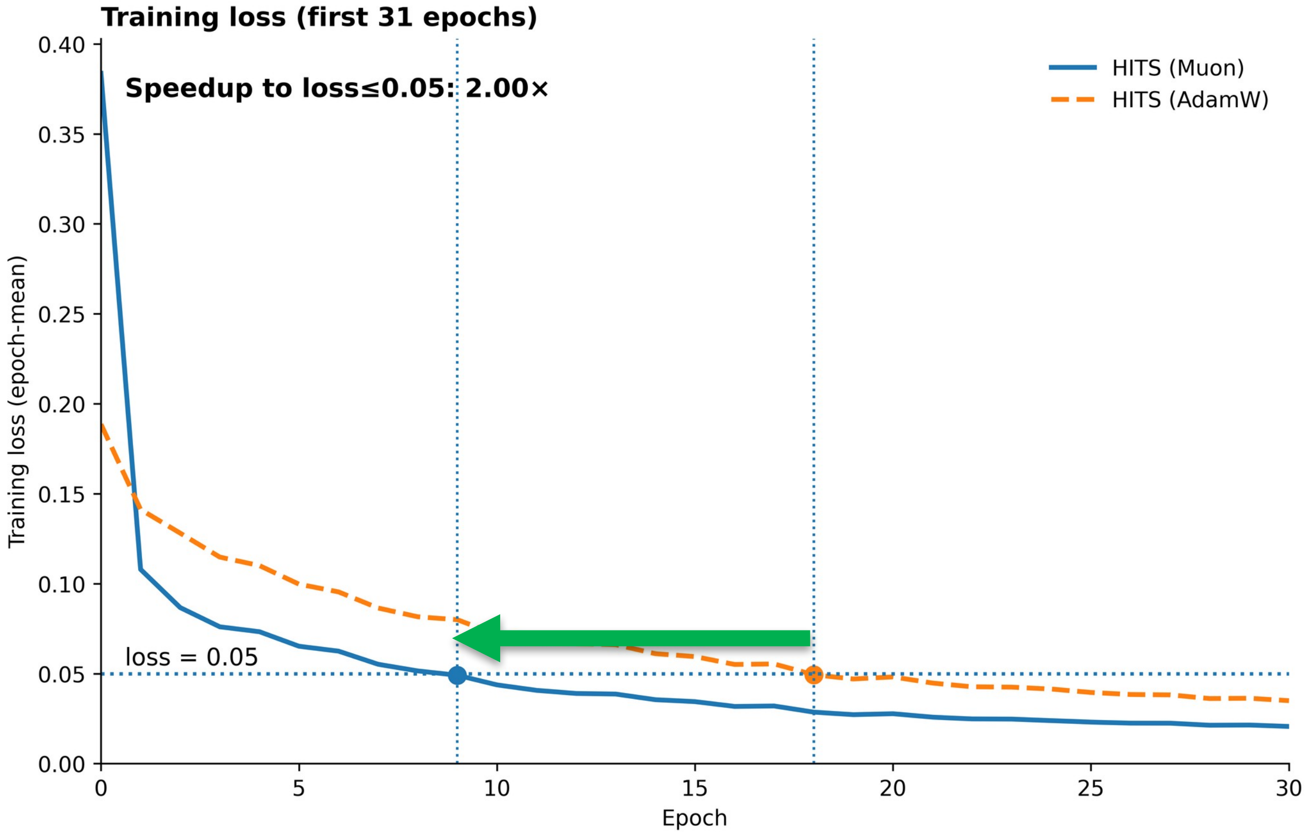
I/O setups for HITS

- **5-day forecasts of atmospheric variables at 6-hour intervals.**

	Input		Output
Training I/O	HiRes[t-6h, t]	ERA5[t+6h]	HiRes[t+6h]
Testing I/O	SHTM analysis[t-6h, t]	AIFS[t+6h]	HITS[t+6h]
Domain	80° E-152° E, 5° N-57° N		
Horizontal resolutions	0.1° × 0.1°	0.25° × 0.25°	0.1° × 0.1°
Pressure level variables	z250, z500, z850, z925	z500, z850	z250, z500, z850, z925
	t250, t500, t850, t925	t500, t850	t250, t500, t850, t925
	u250, u500, u850, u925	u500, u850	u250, u500, u850, u925
	v250, v500, v850, v925	v500, v850	v250, v500, v850, v925
	qv250, qv500, qv850, qv925	Total column water vapor	qv250, qv500, qv850, qv925
Single level variable	Mean sea level pressure		Mean sea level pressure
	2m temperature		2m temperature
	10m u-component of wind		10m u-component of wind
	10m v-component of wind		10m v-component of wind
	Maximum radar reflectivity	-	Maximum radar reflectivity
Static variable	Orography	-	-

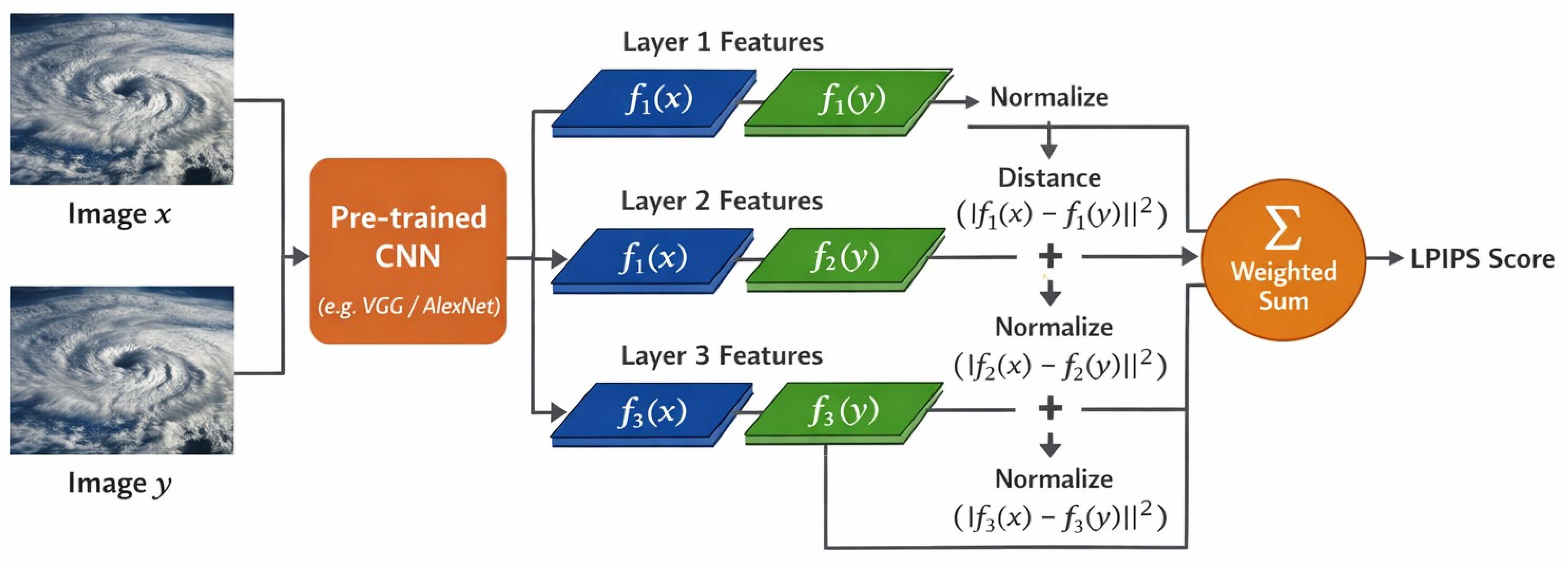
Muon optimizer





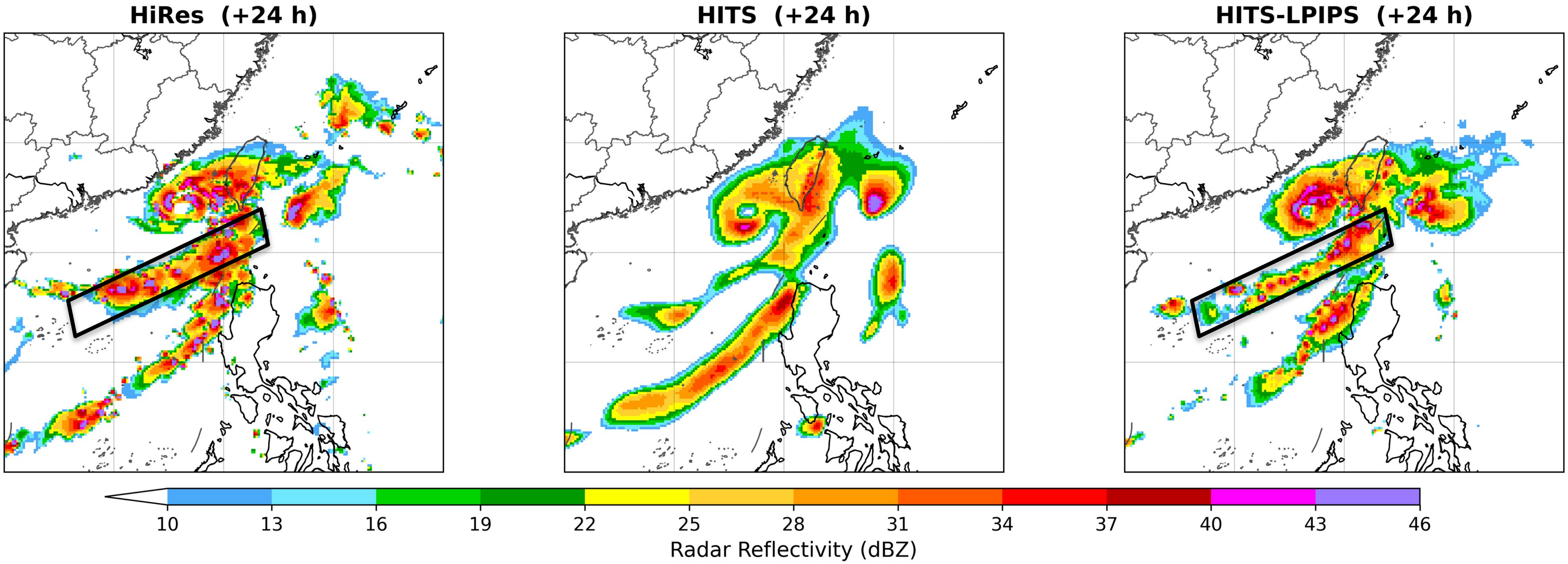
- Performance of the Moonlight model optimized with Muon on the MMLU benchmark, where it performs very well compared with similar models.
- It shows that when the training loss of HITS reaches 0.05, Muon converges about twice as fast as AdamW. In addition, Muon is able to reduce the loss to a lower level.

Learned Perceptual Image Patch Similarity (LPIPS)



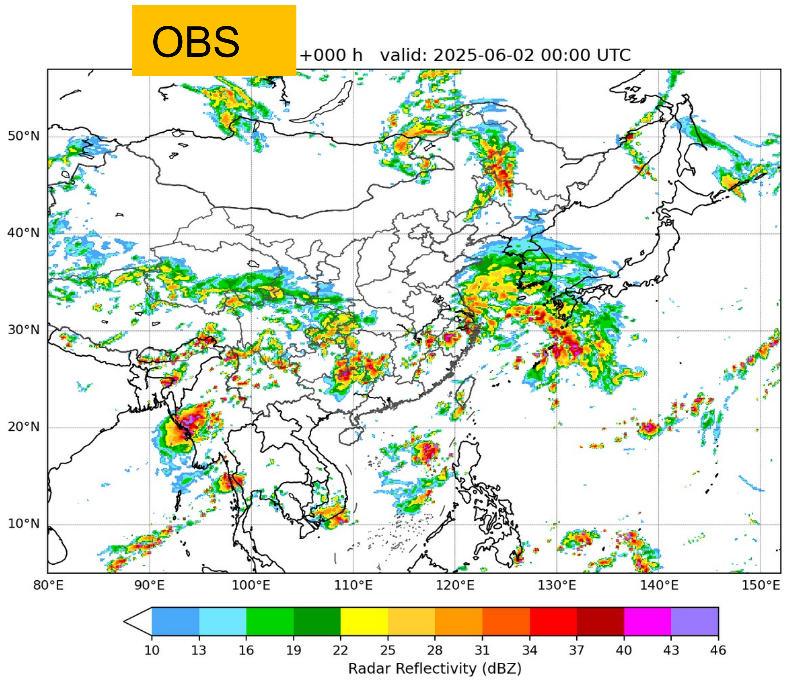
- The main purpose of LPIPS is to separate different spatial scales and **compute the loss at each scale**.
- In this way, it can better represent the mesoscale structures of typhoons **(loss=L1+0.1*LPIPS).**

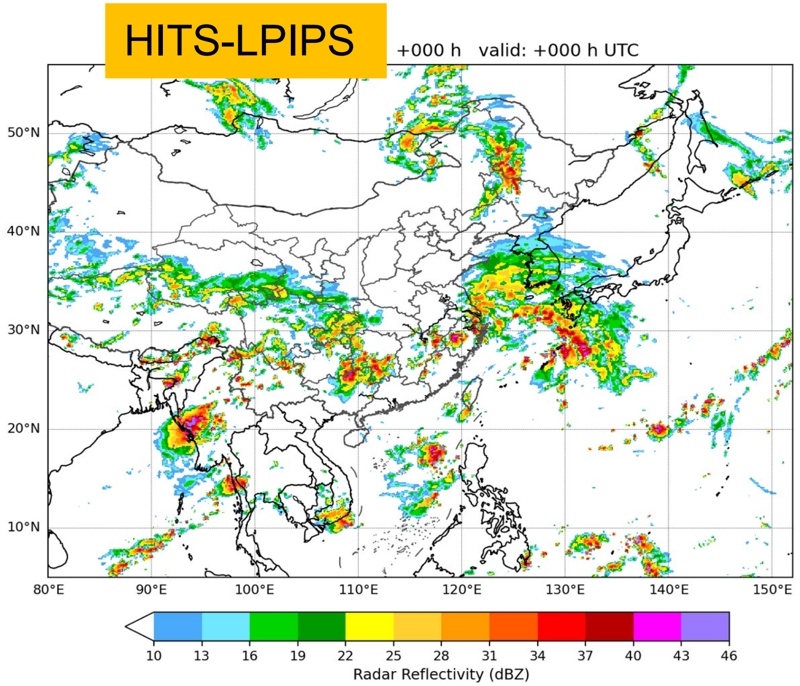
HITS-LPIPS ： Typhoon Danas （ 2025 ）



- It shows that the typhoon structure in the HITS is overly smooth, while HITS-LPIPS shows strong skill in predicting the convective cells within the outer spiral rainbands.

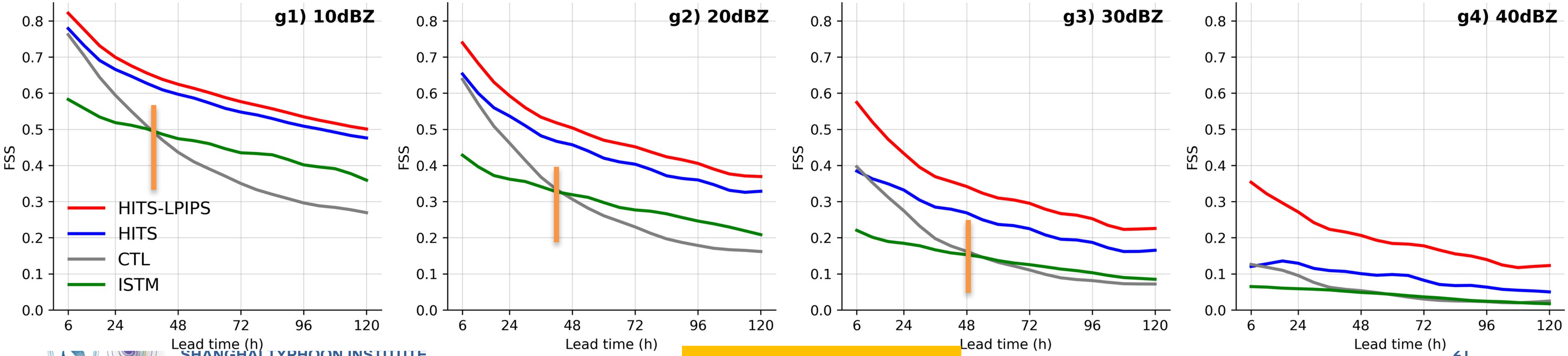
Precipitation skills for ISTM, CTL, HITS, and HITS-LPIPS





- Before 48 hours, ISTM performs worse than CTL because short-range forecasts are mainly controlled by the initial field.
- After 48 hours, ISTM performs better than CTL as the large-scale background becomes more important, and HITS benefits by combining the strengths of both.

July to November 2025

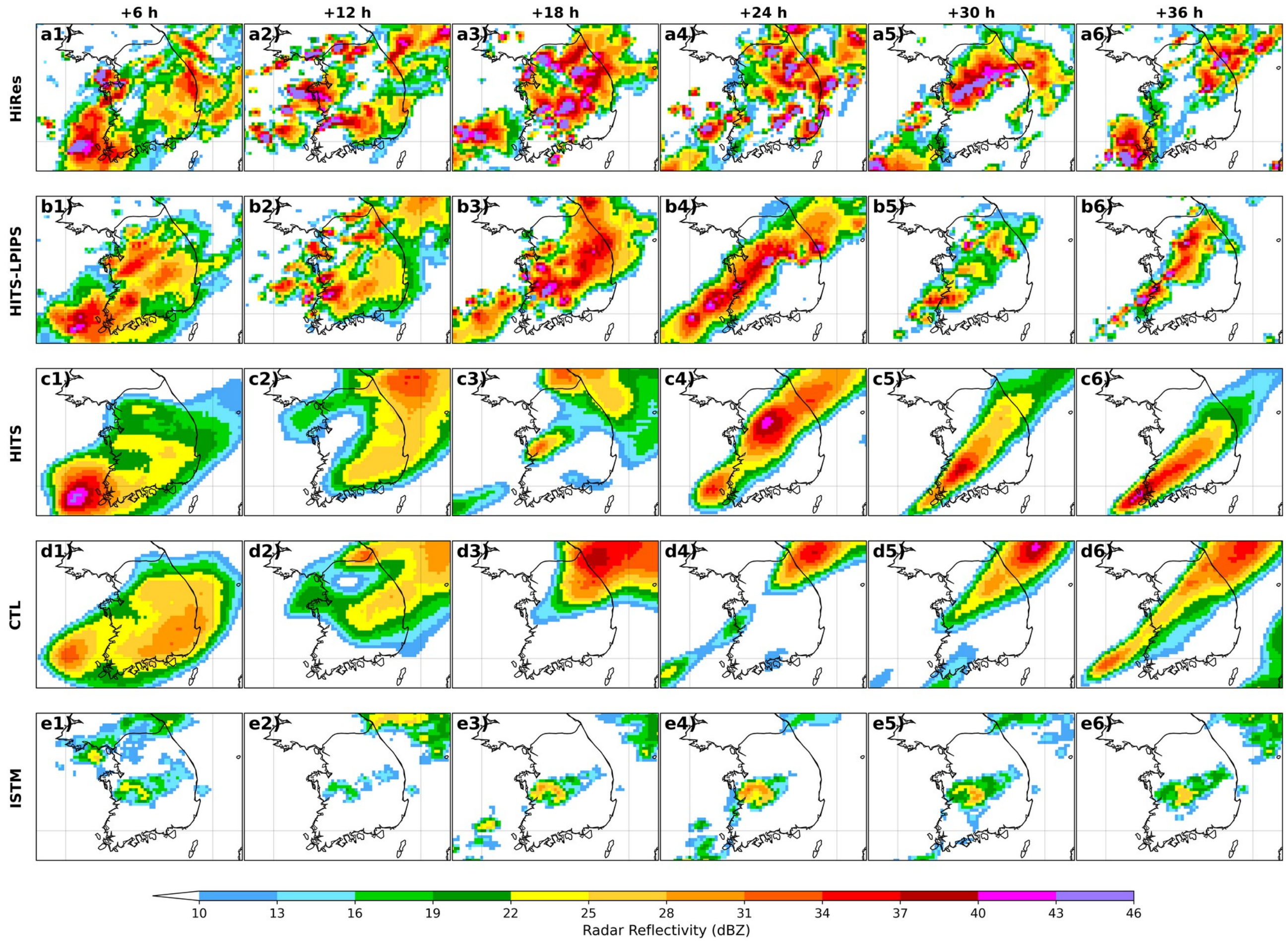


Fractions Skill Score

July 16 Korea Heavy Rainfall in 2025

From the afternoon of July 16 to early morning on July 17, 2025 (local time), heavy rain fell in the Seoul area and the central-western parts of South Korea. In some places, rainfall was over 100 mm in one hour. The rain caused rivers to overflow, and many farmlands and roads were flooded.

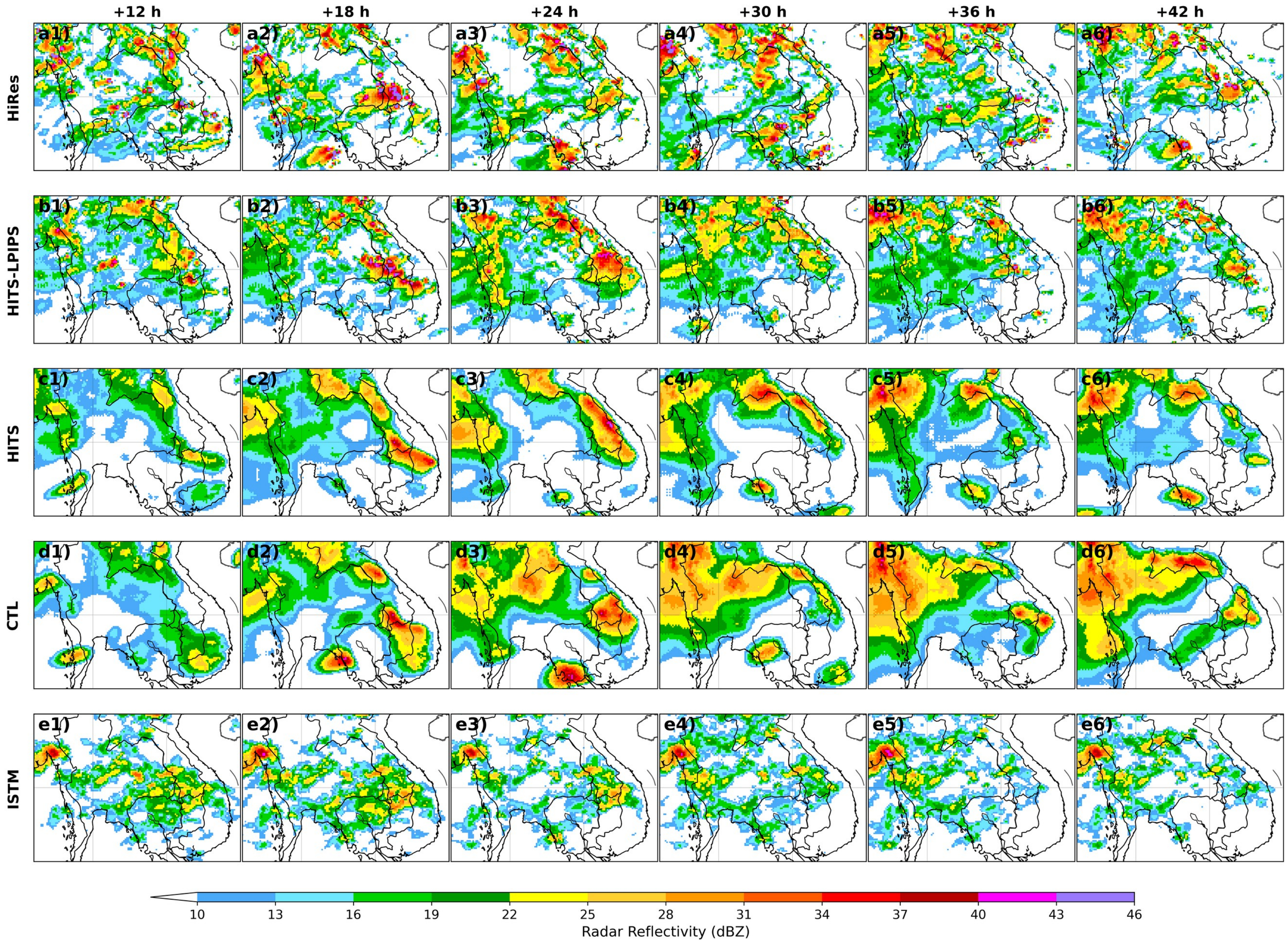
Initial time: 2025-0716-0000 UTC



- It shows that HITS-LPIPS gives the best forecast of rainfall location and intensity within the first 24 hours. However, after 30 hours, all models show weak skill in capturing the rainfall.

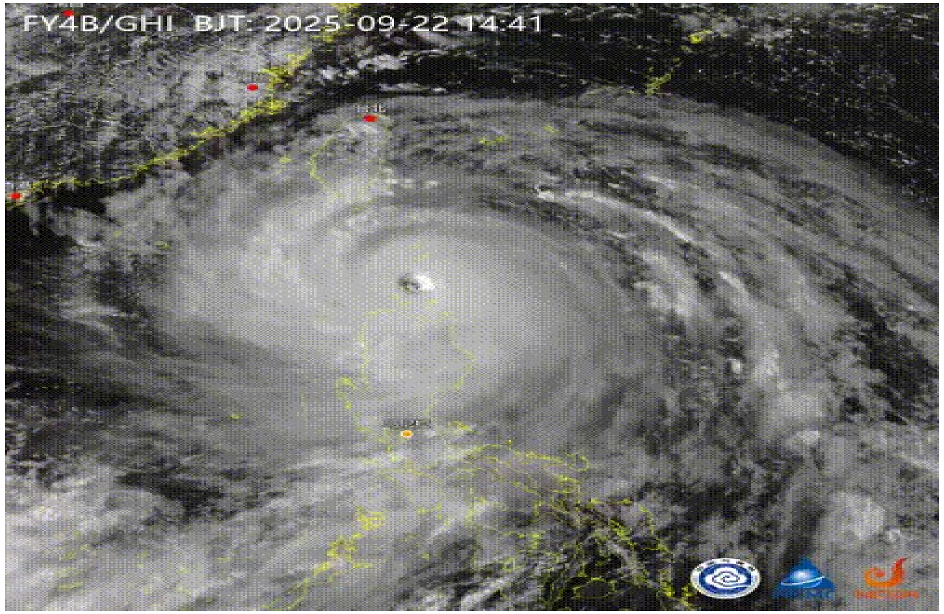
A rainfall case in Thailand

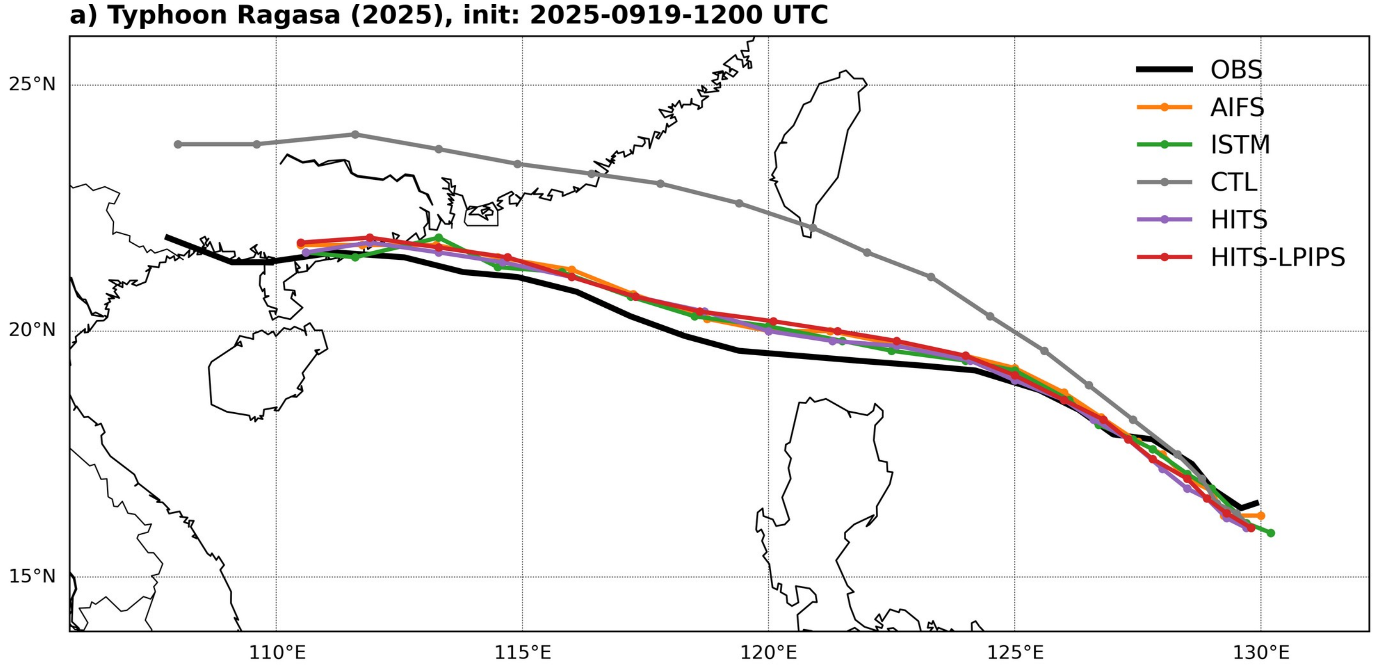
Initial time: 2025-0726-0000 UTC

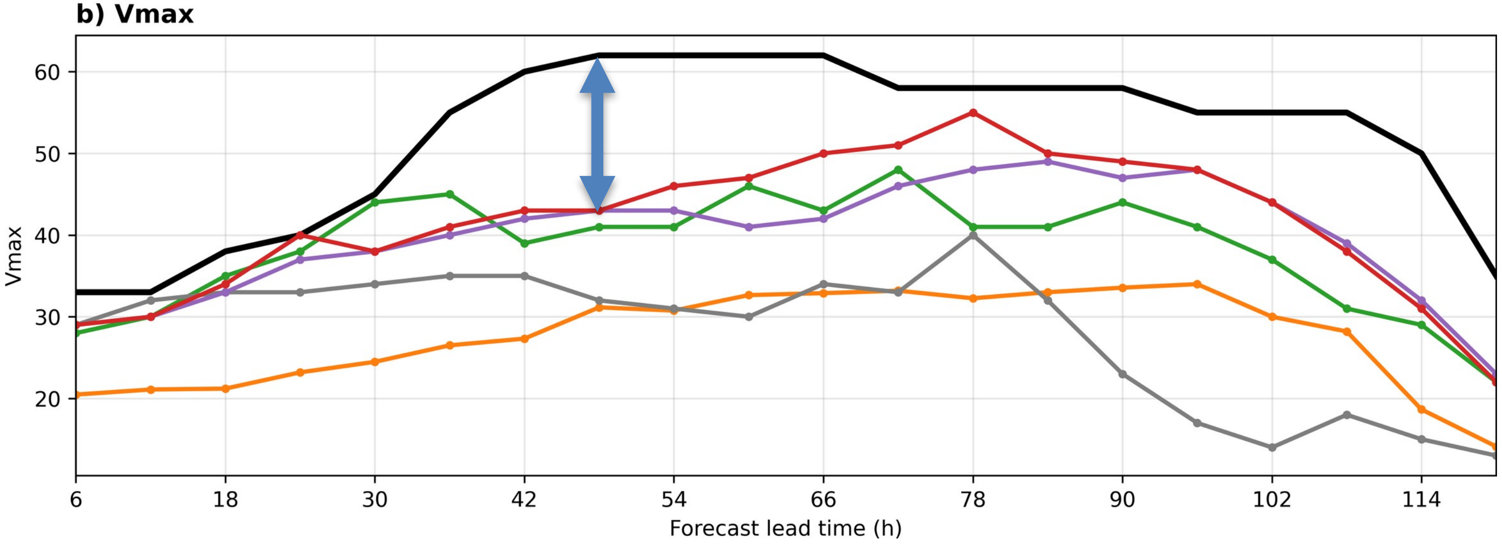


- HITS-LPIPS has a better ability to capture rainfall details compared with ISTM
- The HITS model is relatively smooth, while CTL tends to predict rainfall that is too strong and covers a larger area

Super Typhoon Ragasa (2025)

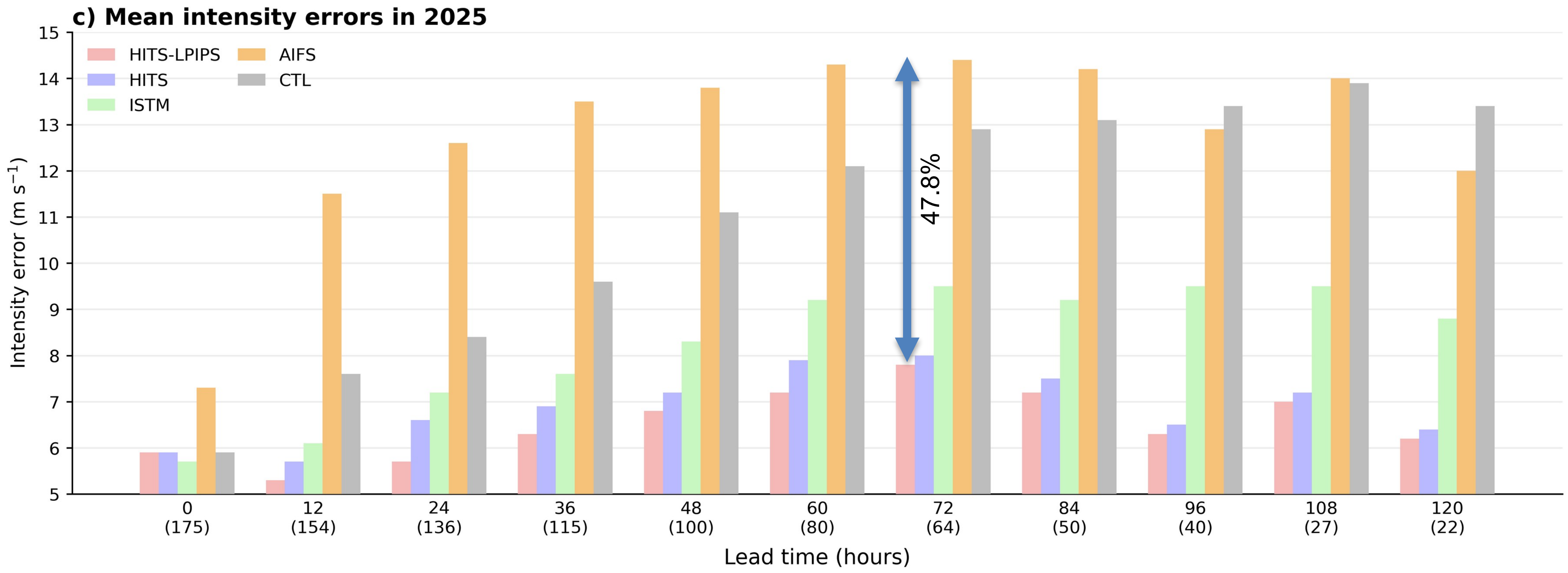






- Except for CTL, the different experiments produce very similar track forecasts.
- Although HITS-LPIPS gives the strongest intensity prediction, it still underestimates super typhoon intensity by about 10–15 m/s, indicating that the HiRes (9 km) simulation is also relatively weak.

Mean intensity forecast errors for typhoons in 2025



Intensity errors: HITS-LPIPS<HITS<ISTM<AIFS

ISTM: downscaling model based on AIFS

HITS: An autoregressive forecasting model based on constraints from AIFS and high-resolution initial fields.

Conclusion and Future

- The hybrid model SHTM and the data-driven model HITS both show strong forecast skill for typhoon track and intensity
- However, at present, both SHTM and HITS still underestimate the intensity of super typhoons
- High-quality datasets produced by traditional NWP models and data assimilation systems are the key foundation for future AI forecasting

- Conduct localized experiments and pilot applications in Korea, Thailand, and Cambodia...
- Strengthen joint monitoring and early warning information sharing for typhoons and heavy rainfall events.
- We can provide high-resolution regional reanalysis datasets as well as the HITS model under the framework of MAZU and MAZU-TC.