Hybrid Physics Based - Machine Learning approaches for weather prediction based on spectral nudging

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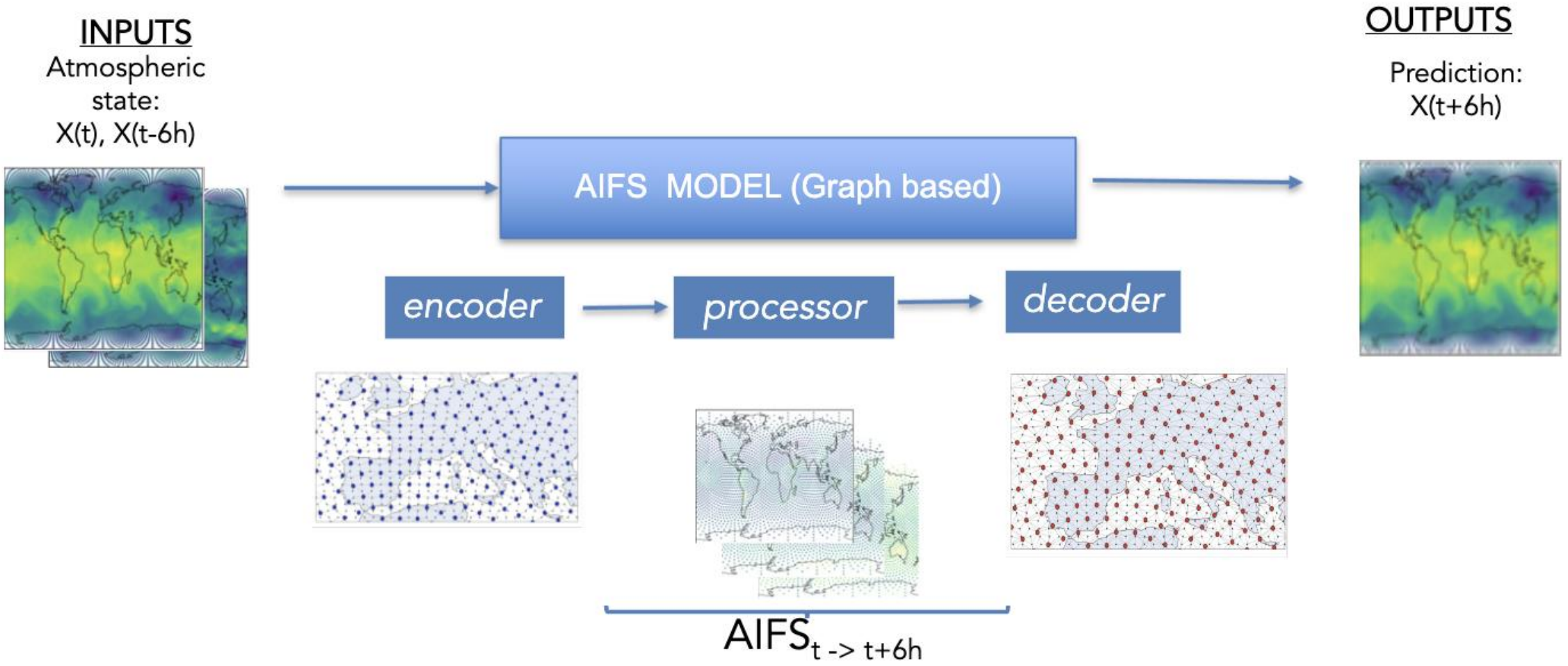
April 2026, NM Training Course

ECMWF

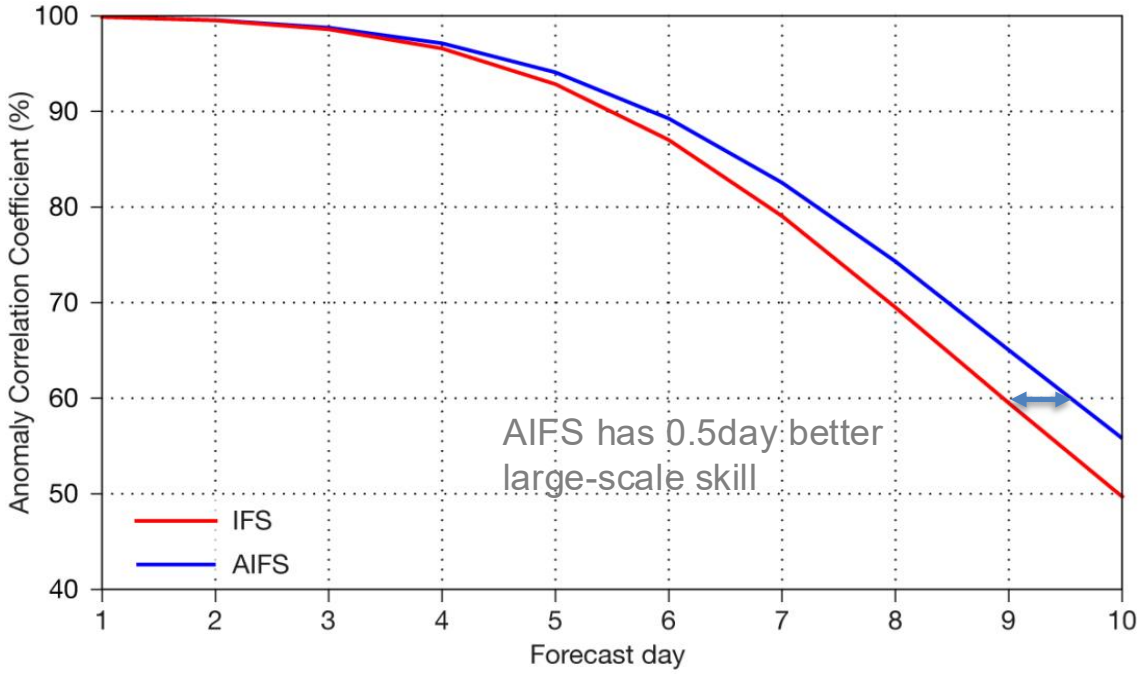
We have IFS-CF physics-based forecasts…..
and we have AIFS-Single machine learning forecasts



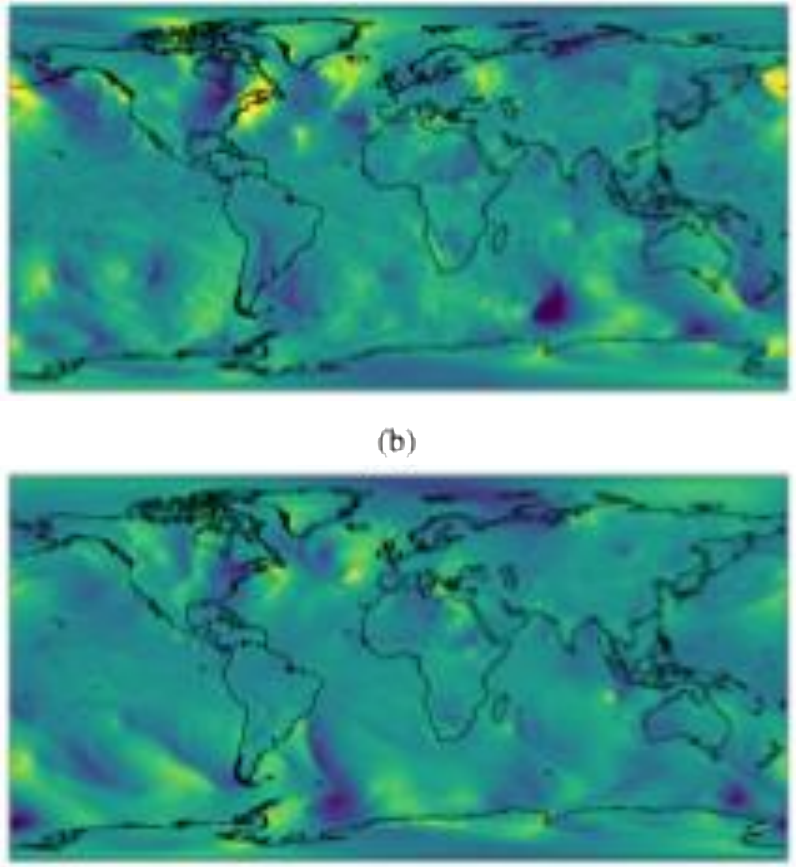
Lang et al. (2024a)
https://arxiv.org/abs/2406.01465

Strengths and weaknesses of AIFS-Single

- AIFS-Single considerably better at forecasting large scales than IFS.
- But AIFS-Single produces overly smooth smaller scales and under-estimates storm intensities.
- AIFS-Single very cheap to run but does not produce all the variables forecasters use/need.



ACC for NH Z@500hPa from Lang et al. (2024a)

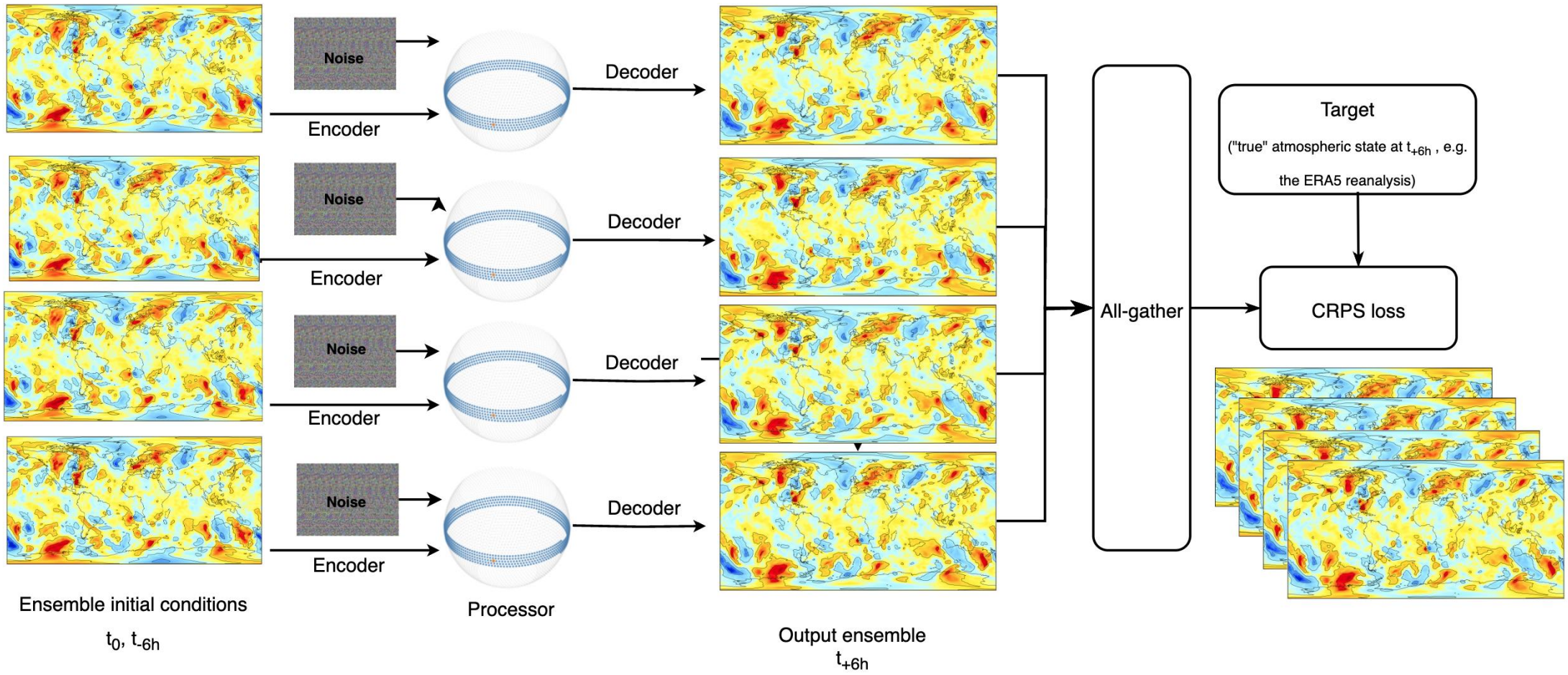


IFS-CF

AIFS-Single

Lang et al. (2024b)

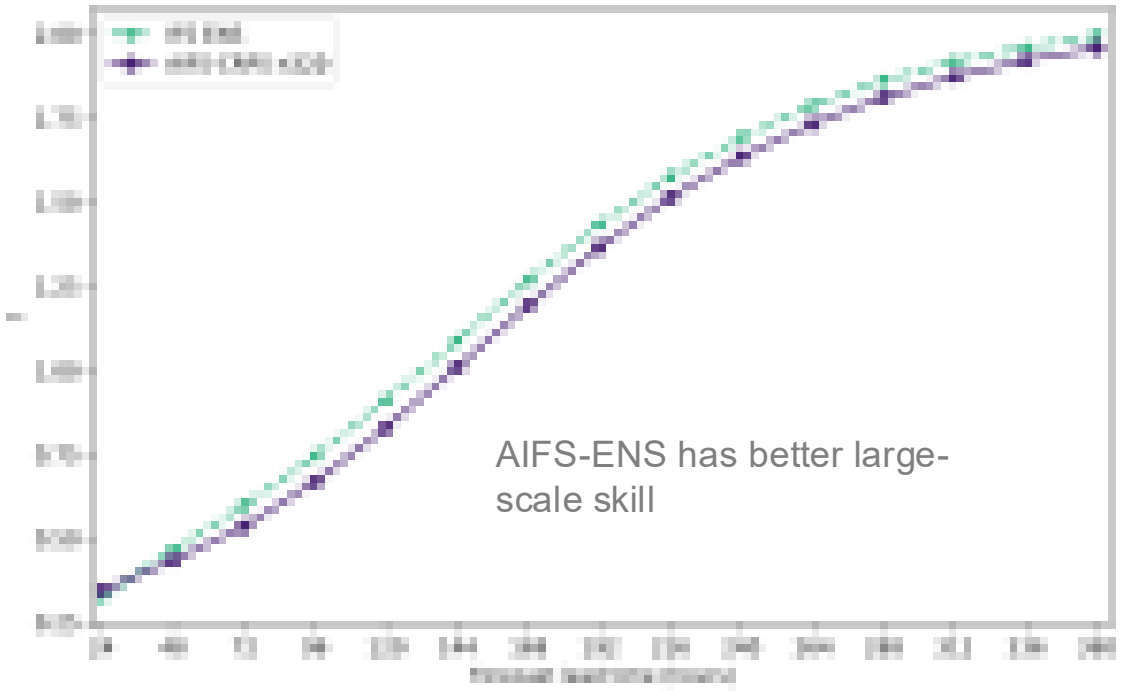
We have IFS-ENS physics-based forecasts…
and we have AIFS-ENS machine learning forecasts



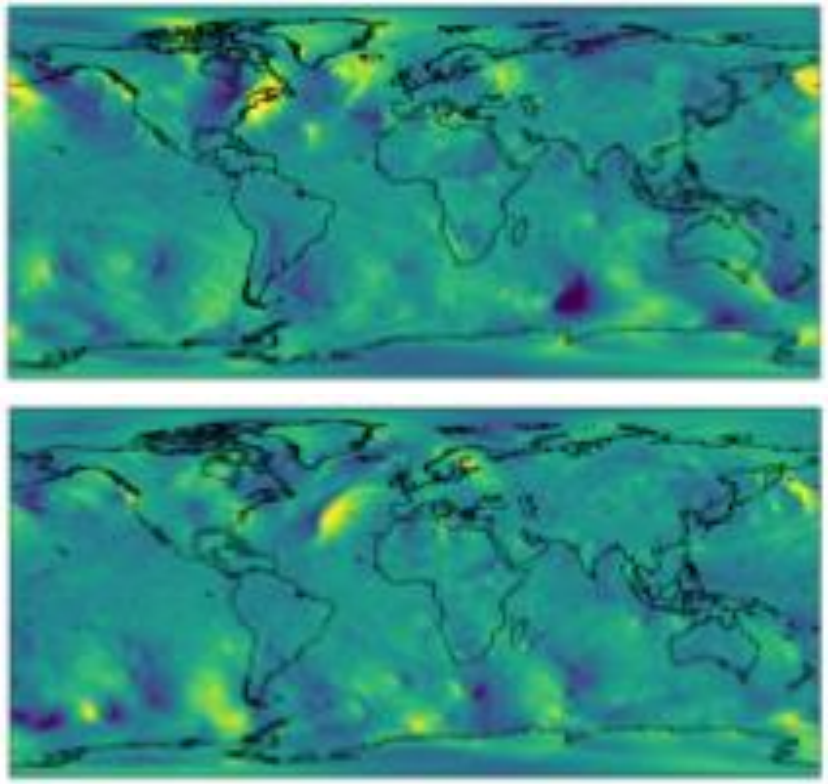
Lang et al. (2024b)
https://arxiv.org/abs/2412.15832

Strengths and weaknesses of AIFS-ENS

- AIFS-ENS also considerably better at forecasting large scales than IFS-ENS.
- AIFS-ENS does not suffer from smoothing, but still at lower resolution than IFS-ENS (N320 vs. TCo1279)
- AIFS-ENS cheap to run but does not produce all the variables forecasters use/need.



CRPS for NH T@850hPa from Lang et al. (2024b)



IFS-ENS

AIFS-ENS

Question:

Can we combine AIFS and IFS to retain AIFS's large-scale skill while preserving realistic small-scale structure and full IFS outputs?

Yes, by creating a hybrid model via spectral nudging

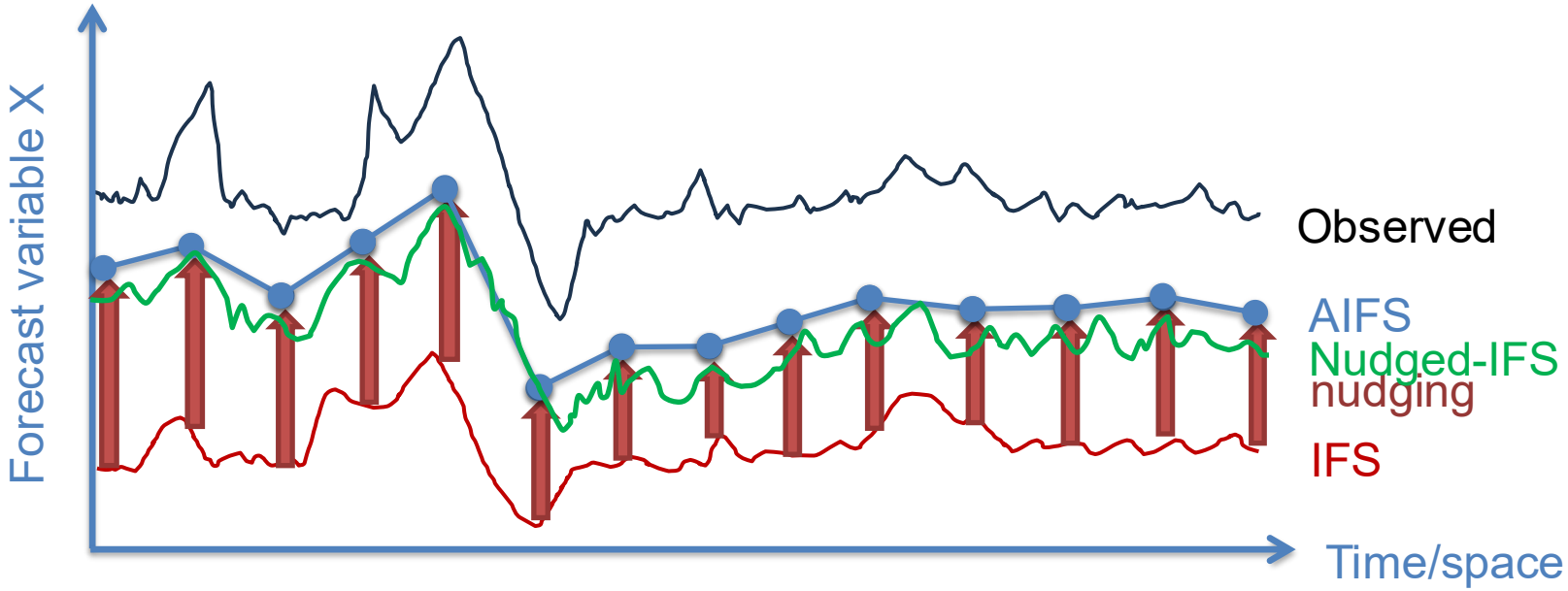


Figure courtesy:
Andreas Muller

How to do this?

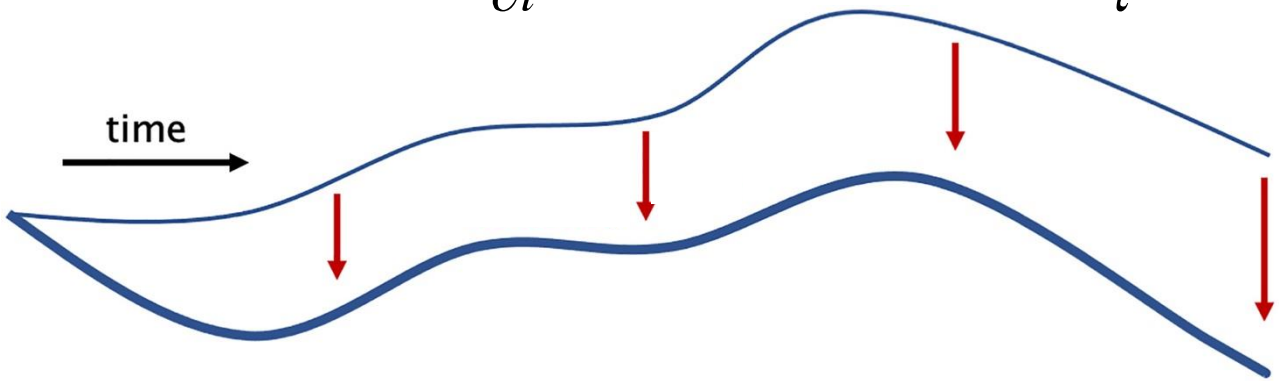
- Use spectral nudging to bespoke AIFS models that predict fields on IFS model levels.

- Take AIFS-Single and AIFS-ENS forecasts and spectrally nudge IFS-CF and IFS-ENS to them.
  Tv and VOR nudged up to total wavenumber T21 in the **troposphere**.
  Like Hussain et al. (2024) @ECCC

- **Pros:** A) Small-scales not damped.
  B) Very cheap (to develop & forecast run-time).
  C) Does not need to be developed for each cycle.
  D) Retains better physical consistency of a physics-based model

$$\frac{\partial a}{\partial t} = -\mathbf{v} \cdot \nabla a + Q_a^p - \frac{a - a_{obs}}{\tau},$$

a = {T_v ,VOR}
τ = 12 hours
a_{obs} = AIFS (wavenumbers 0-21)



IFS model state a

AIFS forecast a_{obs}

From Watt-Meyer et el. (2021)

RECALL FROM MONDAY

Spectral vs. grid-point representation in the IFS dynamical core

- **Derivatives, dissipation and semi-implicit solver** calculated in **spectral** space. Only VOR, DIV, T_v ,Φ and p_s have spectral representations.

→ The only prognostic variables that can be spectrally nudged are VOR, DIV, T_v and p_s

$$\frac{D\mathbf{V}}{Dt} + f\mathbf{k}\times\mathbf{V} + \nabla_h\Phi + R_d T_V \nabla_h \ln p = P_V + K_V,$$

$$\frac{DT}{Dt} - \frac{\kappa T_V \omega}{[1+(\delta-1)q]p} = P_T + K_T,$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla_h \cdot \left(\mathbf{V}\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0,$$

$$\frac{Dq}{Dt} = P_q,$$

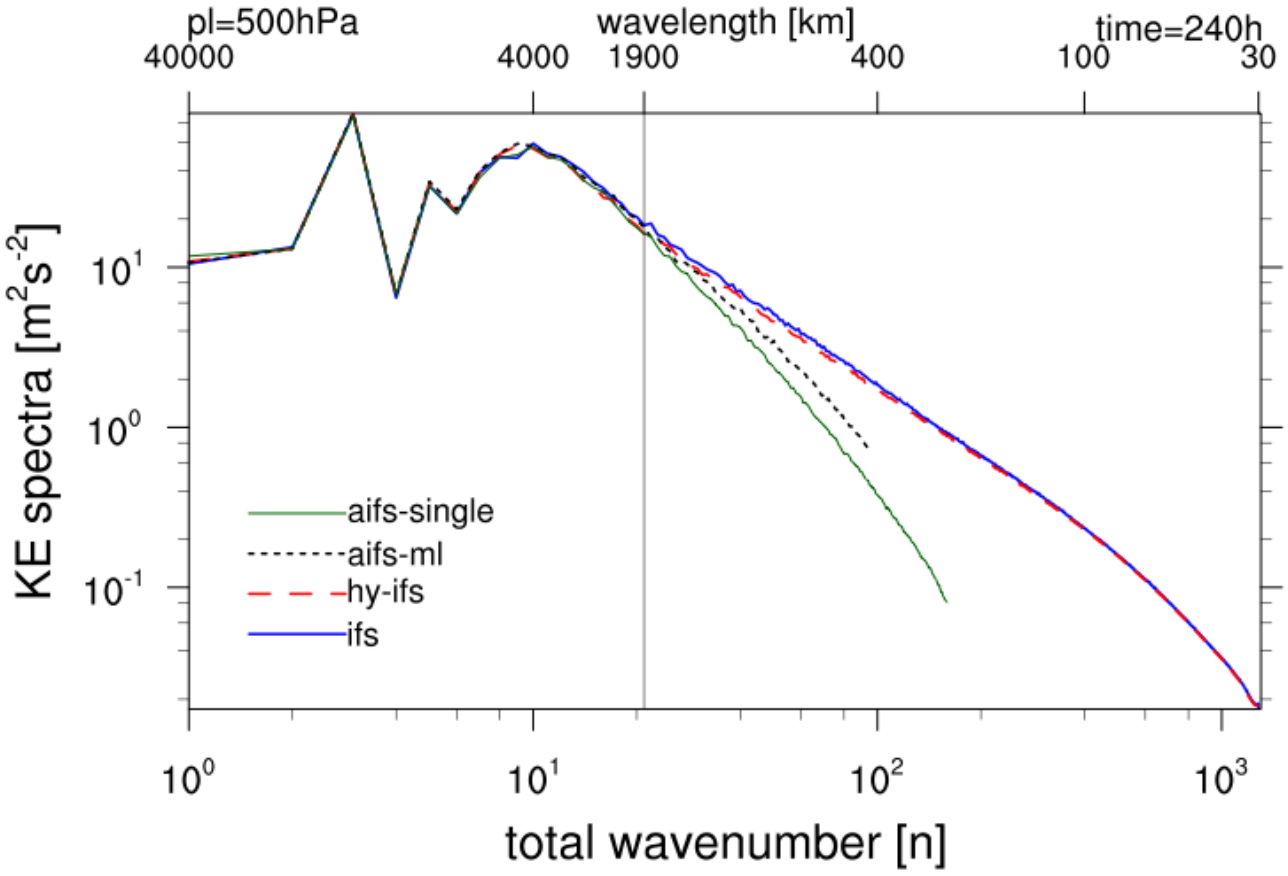
$$\frac{\partial \Phi}{\partial \eta} = -R_d T_V \frac{\partial \ln p}{\partial \eta},$$

$$T_V = T\left[1 + \left(\frac{R}{R_d} - 1\right) q\right]$$

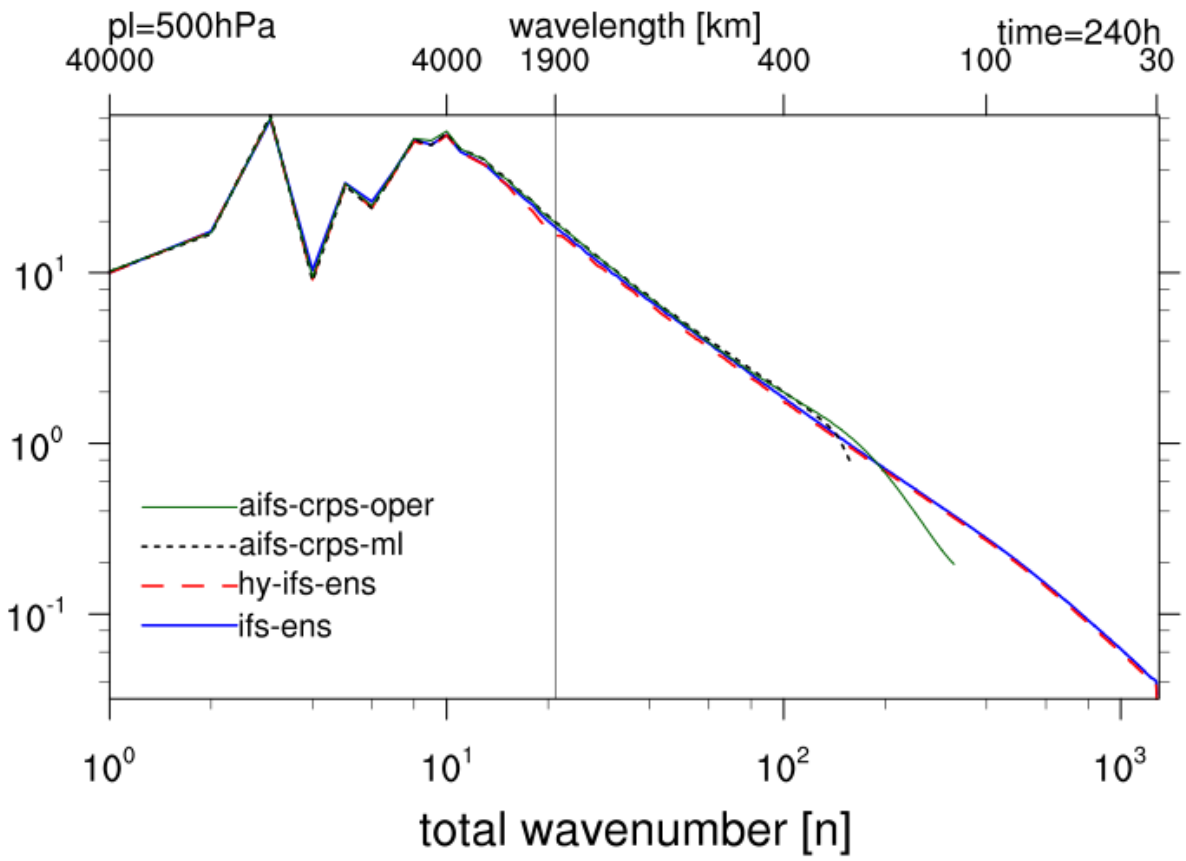
Kinetic energy spectra

- Small scales are indeed retained in the hybrid model.

Deterministic

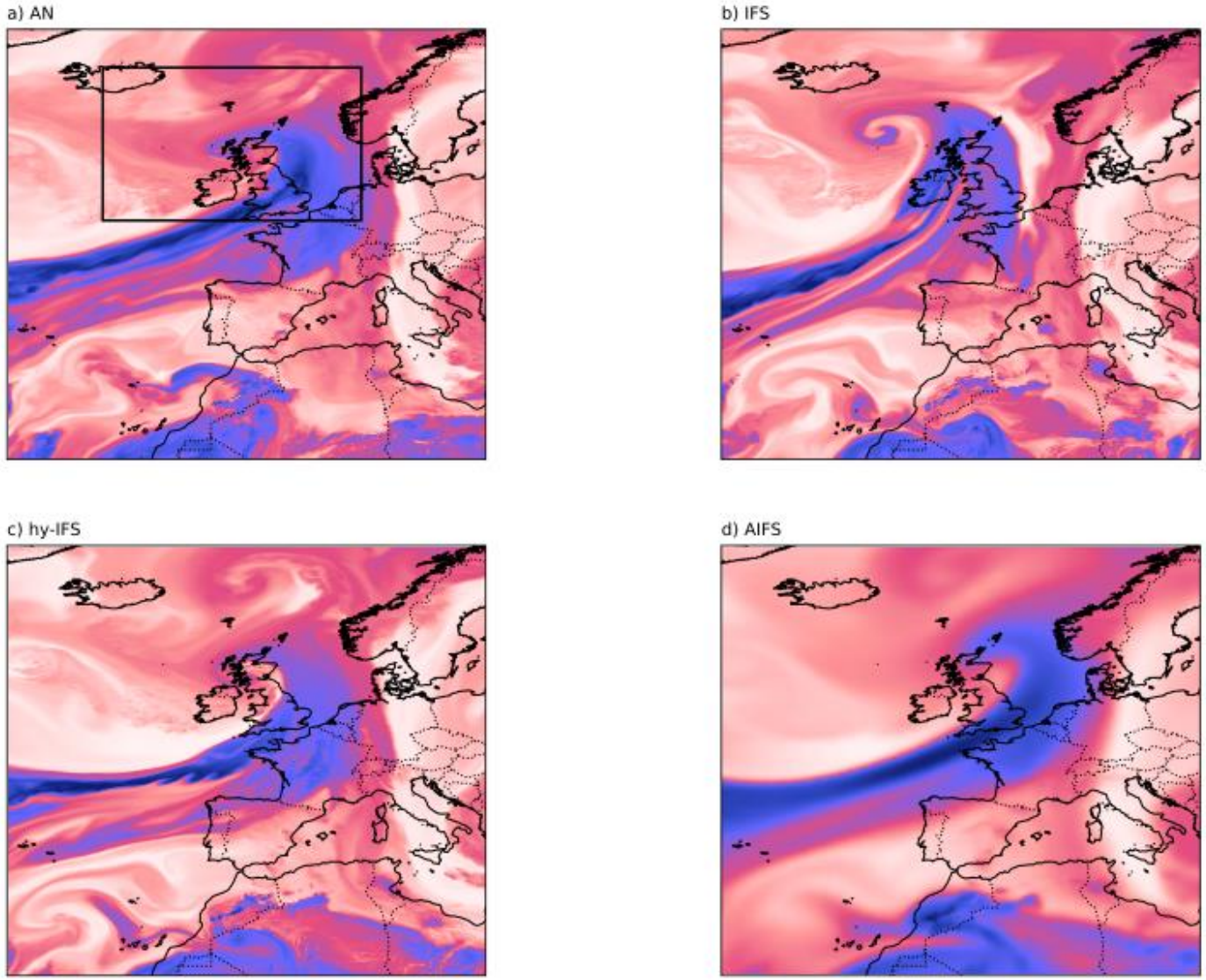


Ensemble

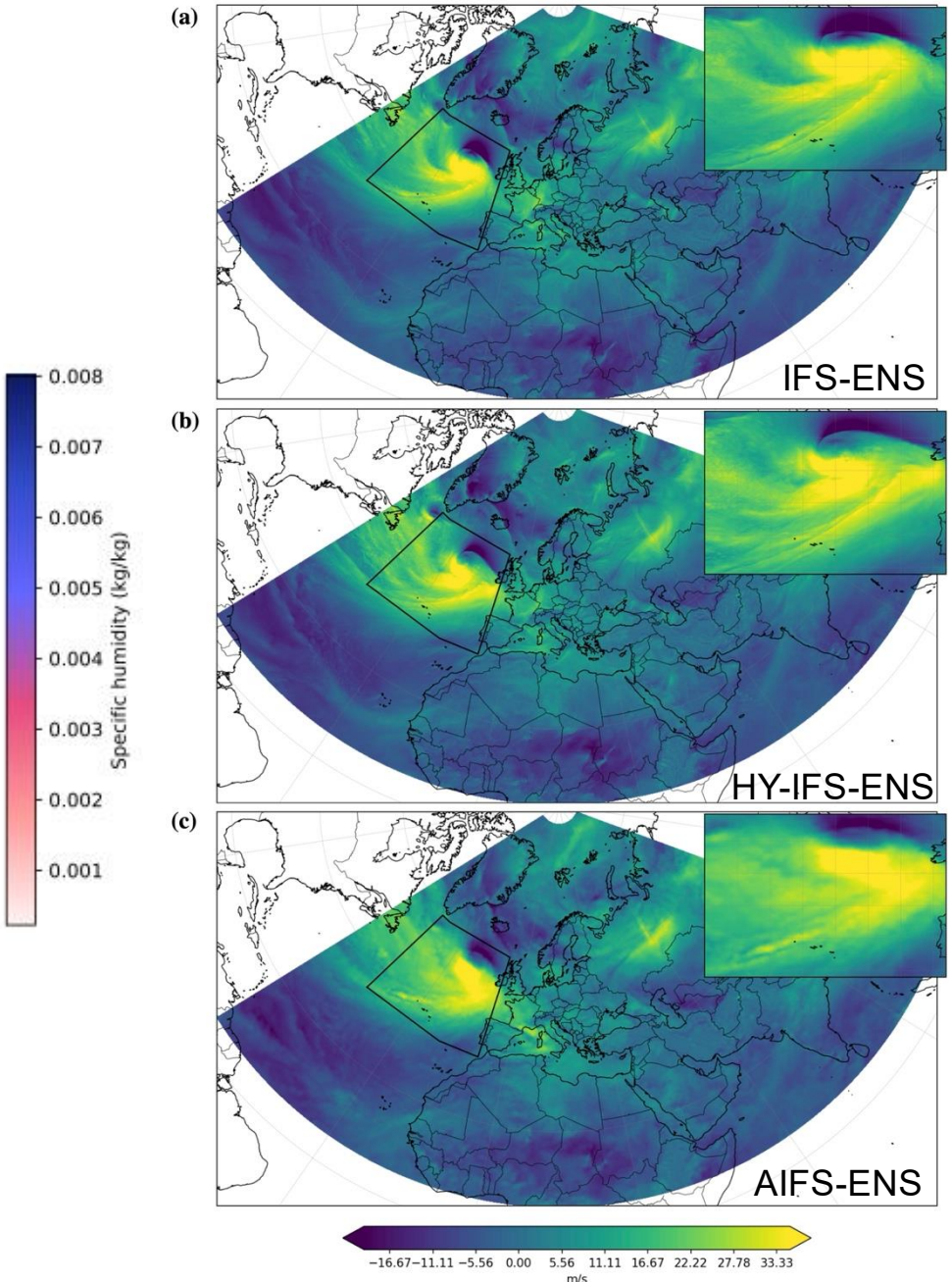


Case studies also support this

Storm Amy in deterministic setup

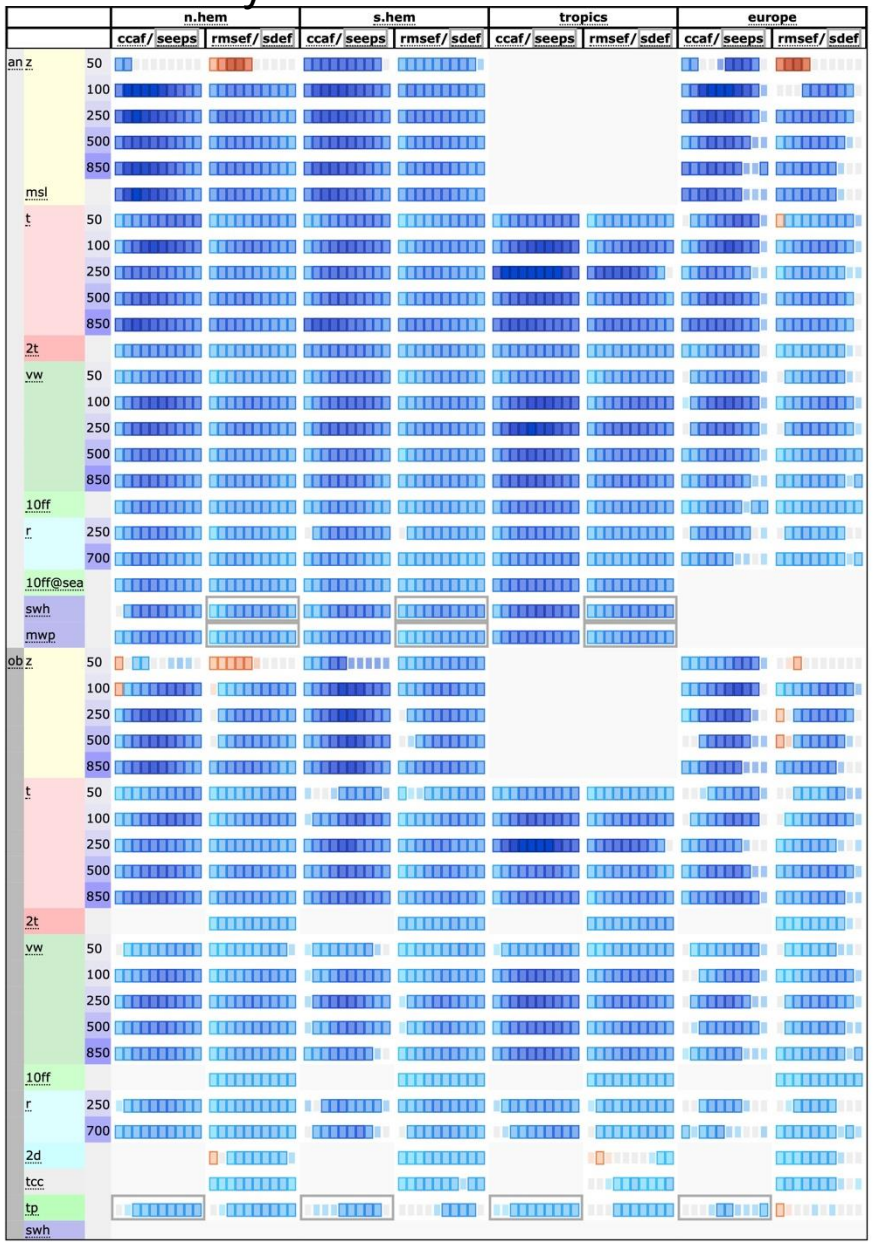


Storm Eowyn in ENS setup

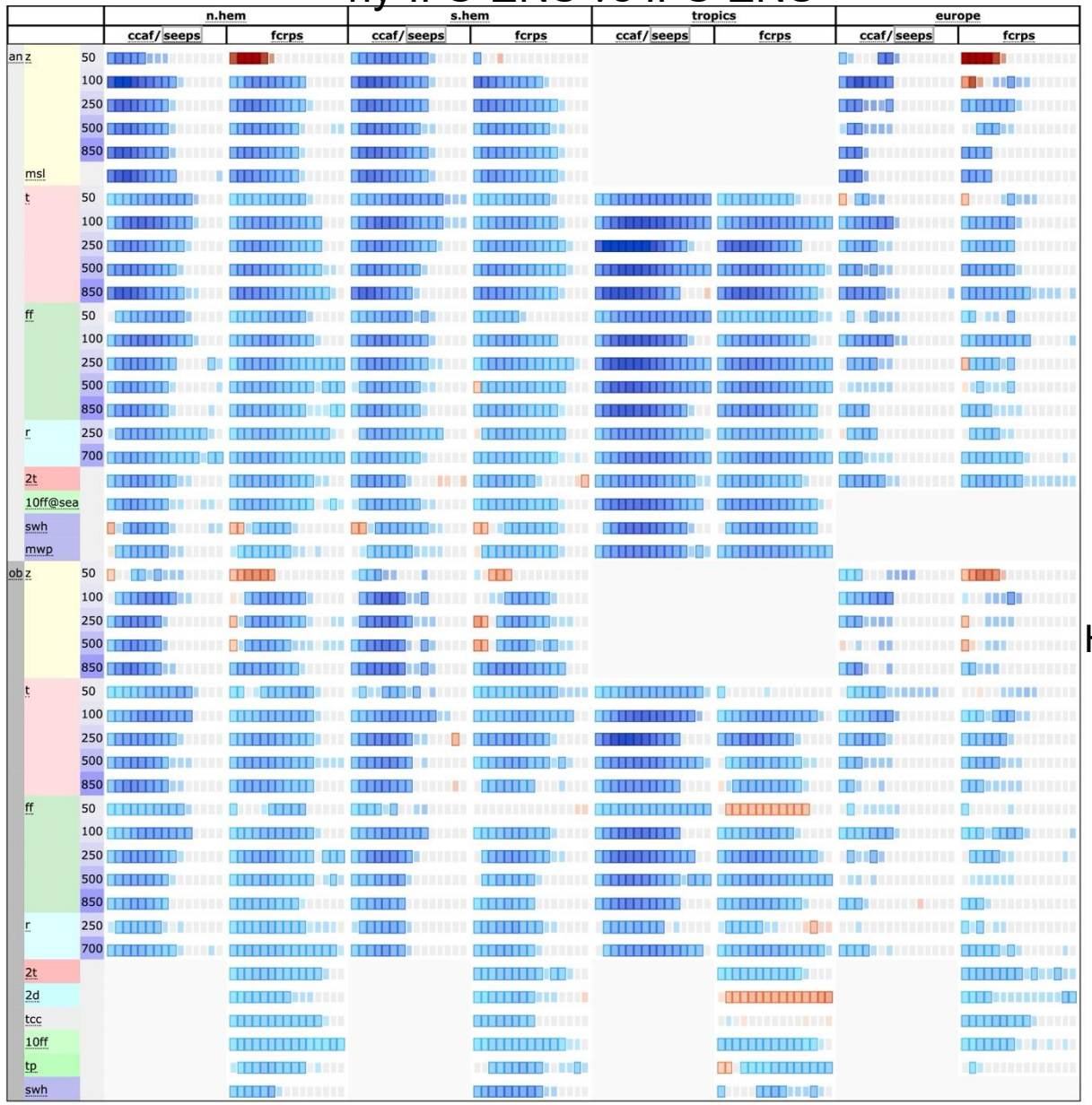


Large-scale skill improvements

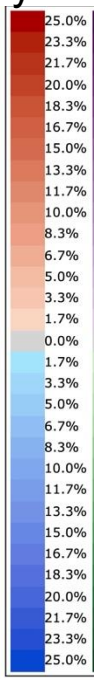
hy-IFS-CF vs IFS-CF



hy-IFS-ENS vs IFS-ENS



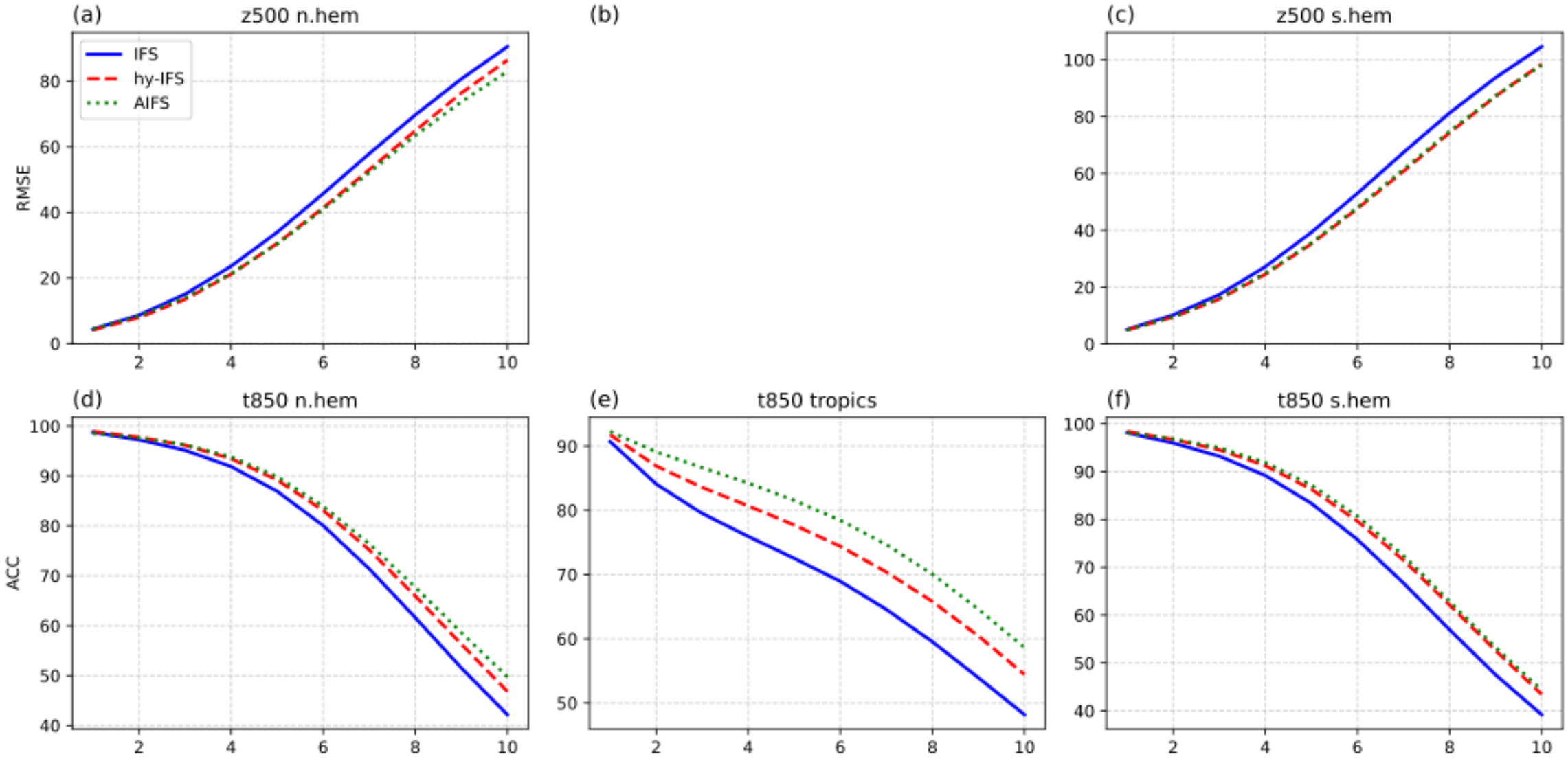
Hybrid worse



Hybrid better

Large-scale skill improvements: Control (=deterministic)

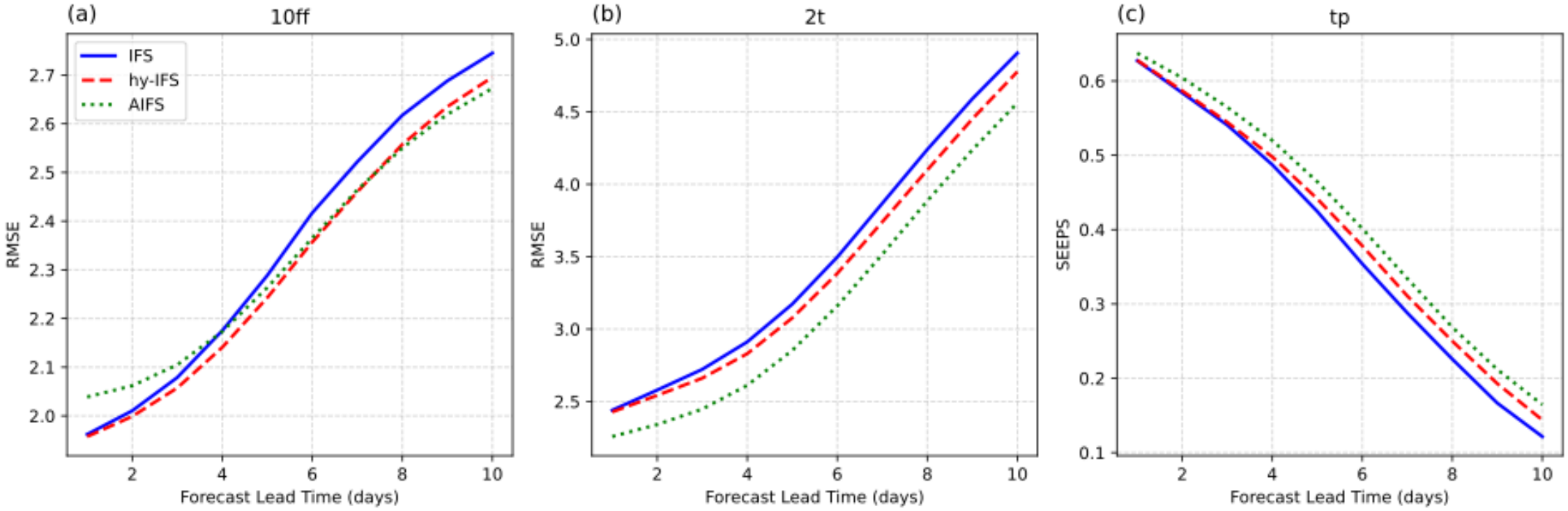
- Upper air forecast skill translated from AIFS-Single to the hybrid model almost entirely



Large-scale skill improvements: Control (=deterministic)

- Surface variable forecast skill also improved significantly, even though surface variables not directly nudged.

- Hybrid has best forecasts for 10m winds, but AIFS-Single still outperforms on 2m temperature and precipitation.



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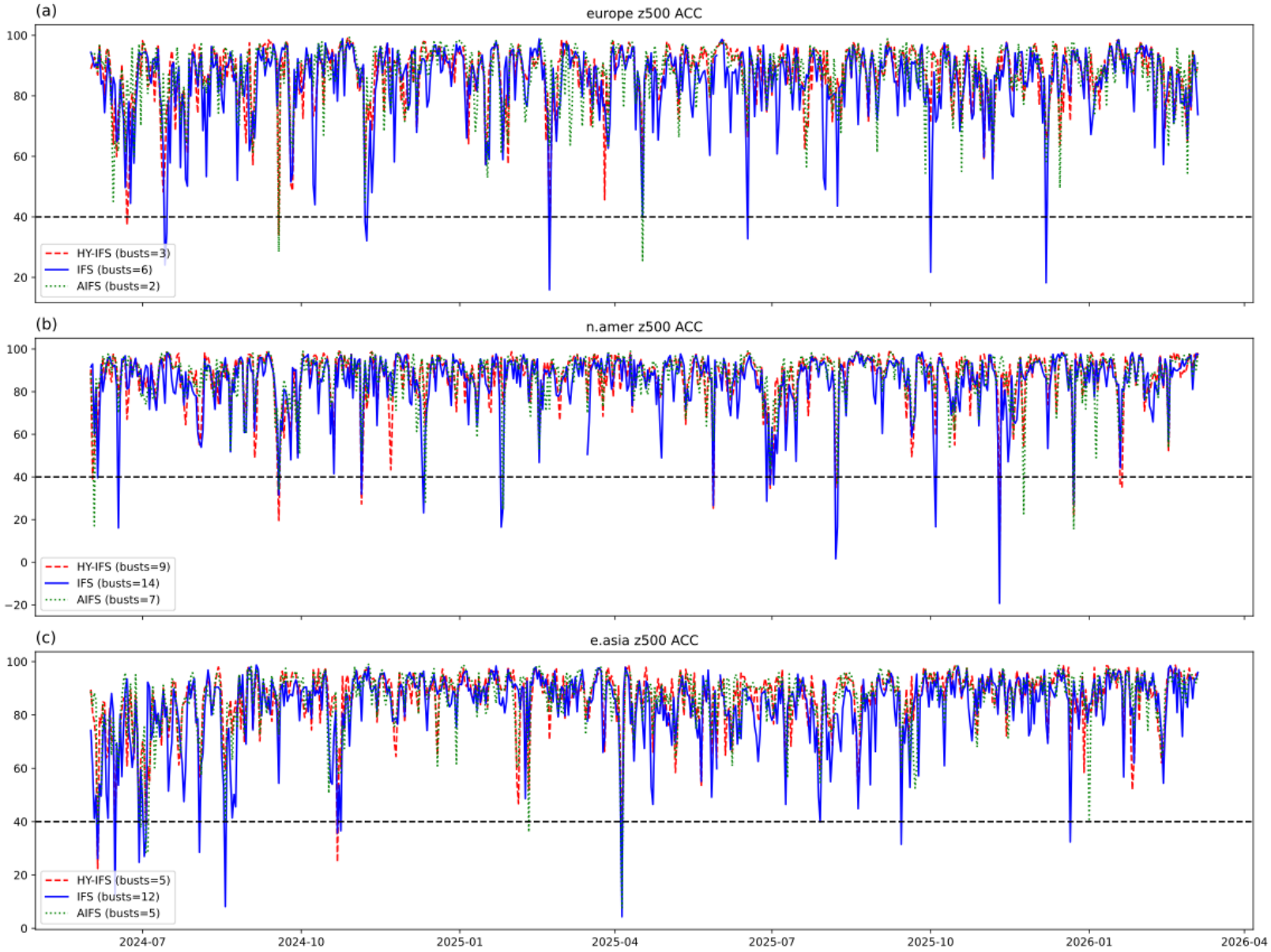
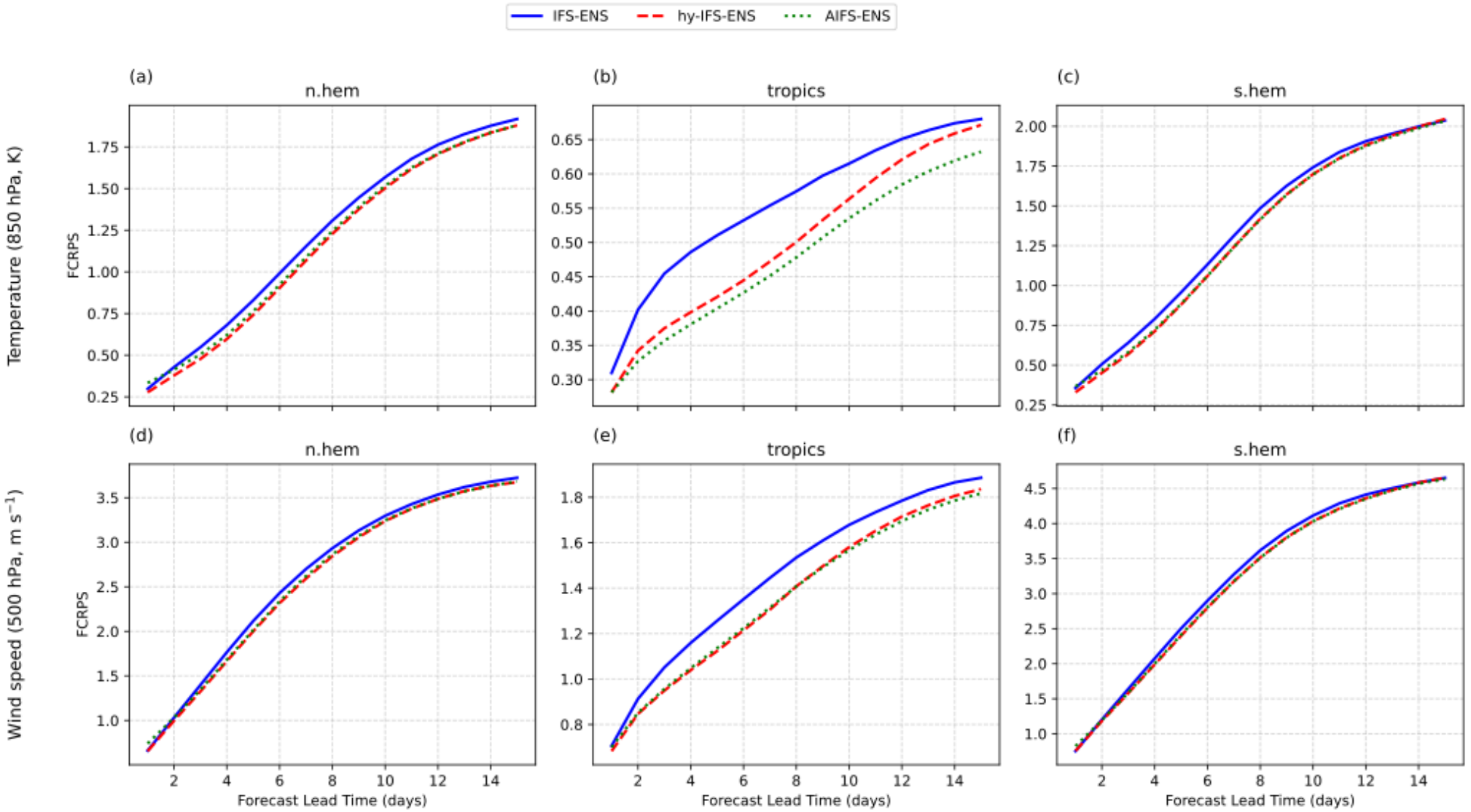


- Hybrid model also has about half the amount of forecast busts (when ACC drops below 40%) than IFS.
- Hybrid model has comparable number of FC busts to AIFS-Single.

Large-scale skill improvements: Ensemble

- Upper air forecast skill translated from AIFS-ENS to hybrid ENS almost entirely.



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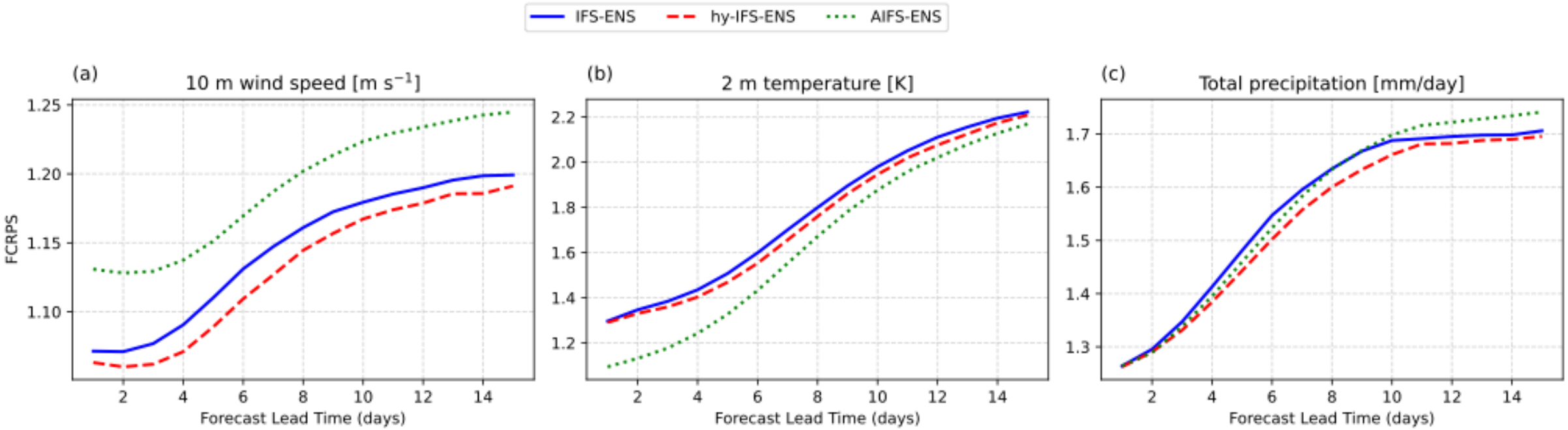
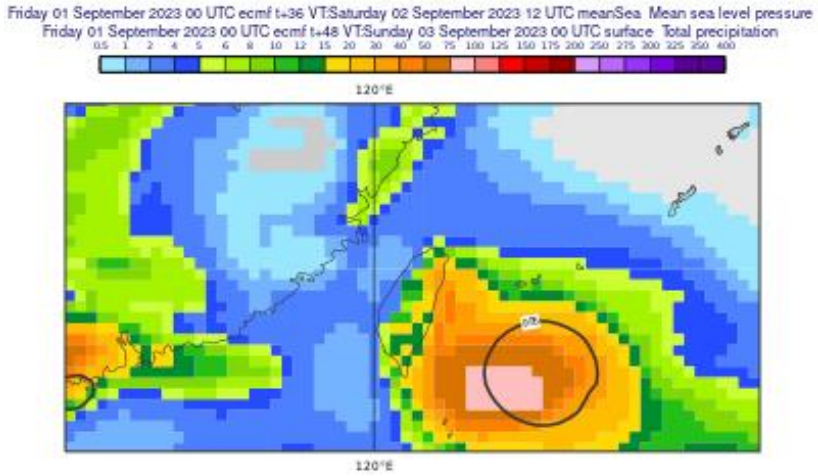
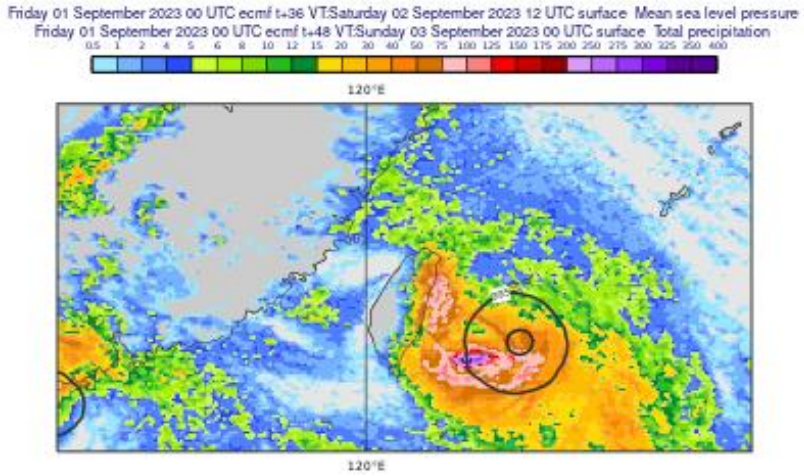


Extremes: Typhoon Haikui in 2023

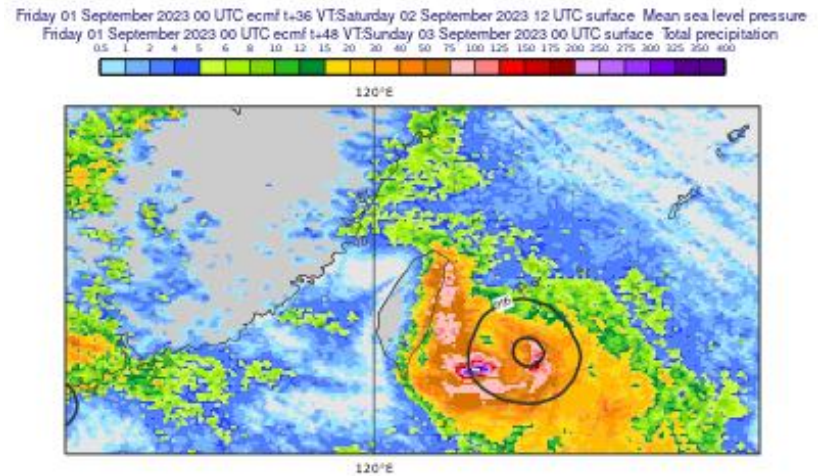
AIFS v0.2



IFS 49r1



IFS 49r1-nudged



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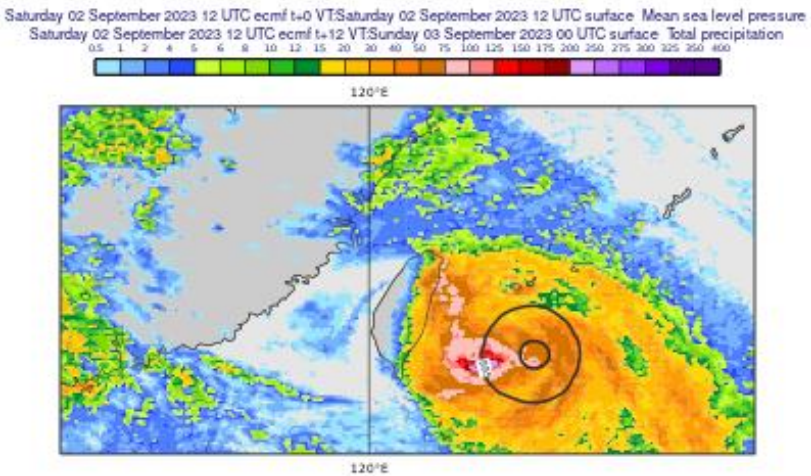

- Nudging preserves small-scale features and tropical storm intensities of a physics-based model.
- Nudged forecast predicts better track than IFS from +86h onwards.

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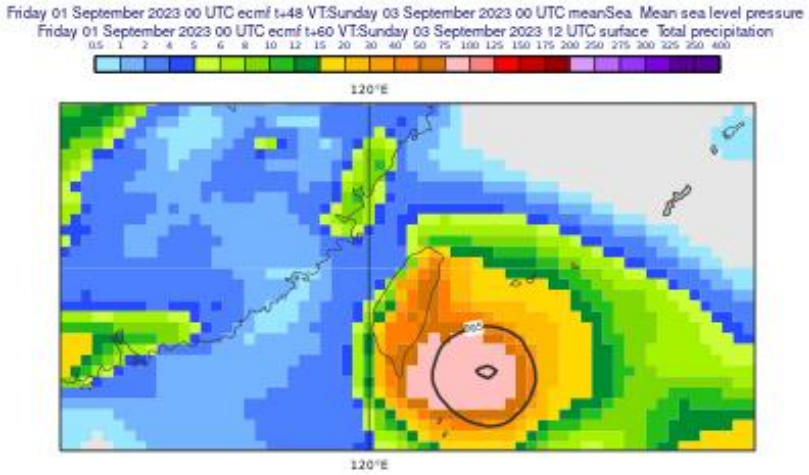

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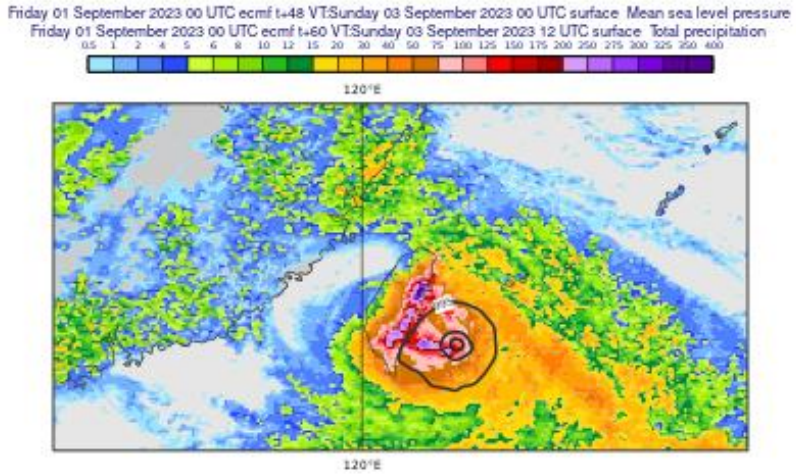

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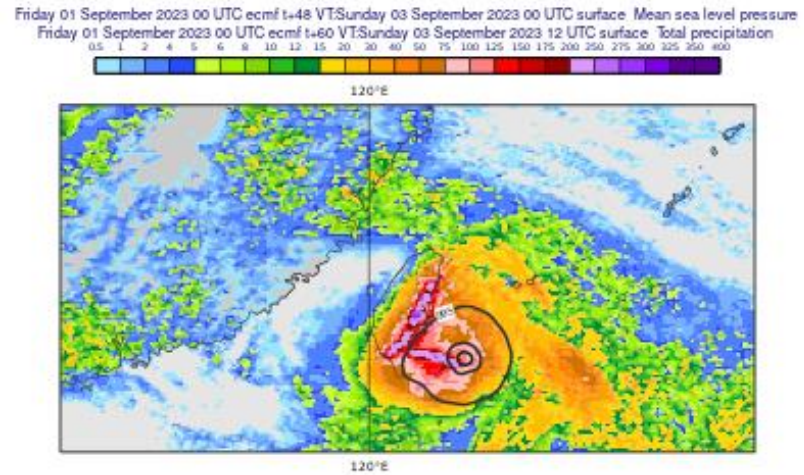

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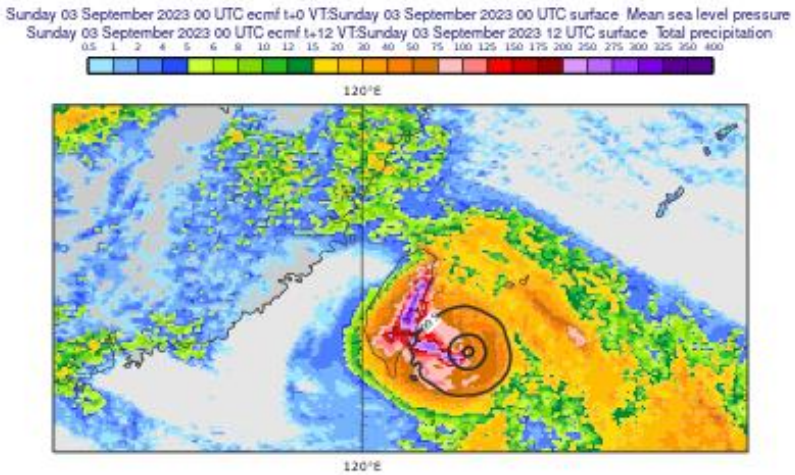

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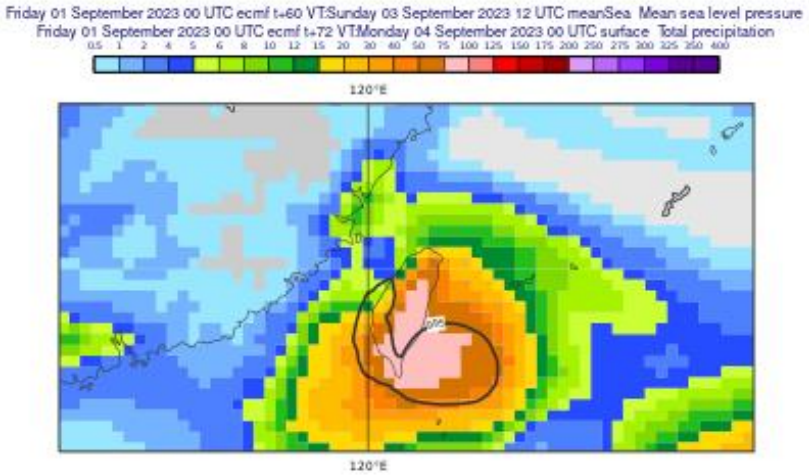

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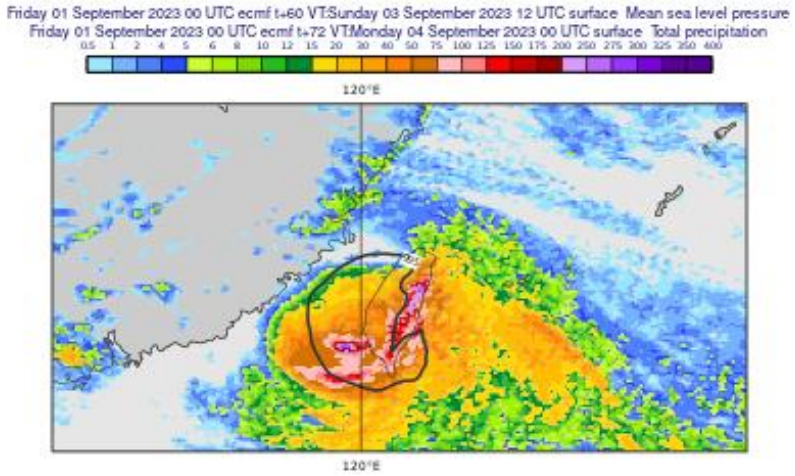

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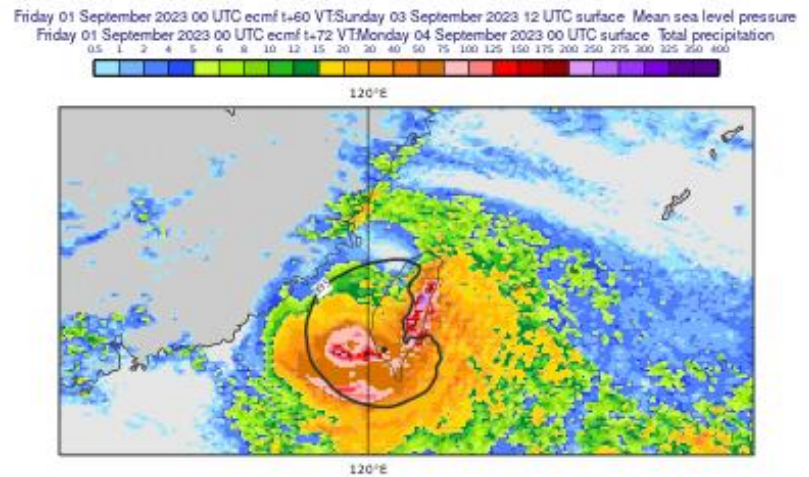

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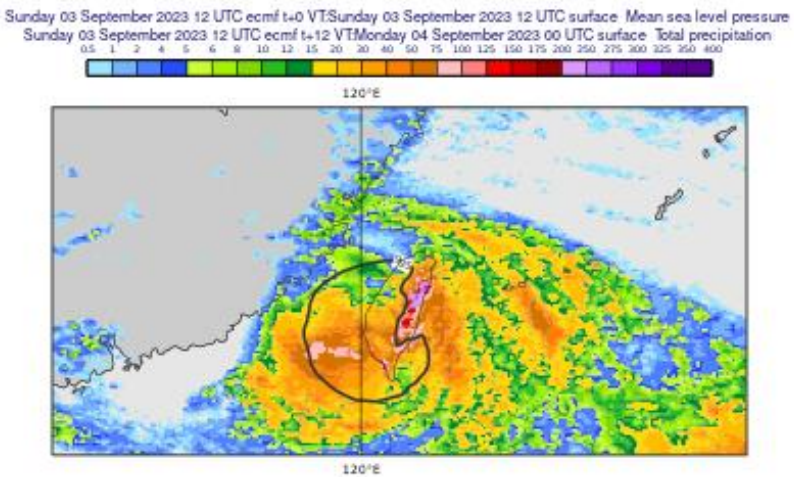

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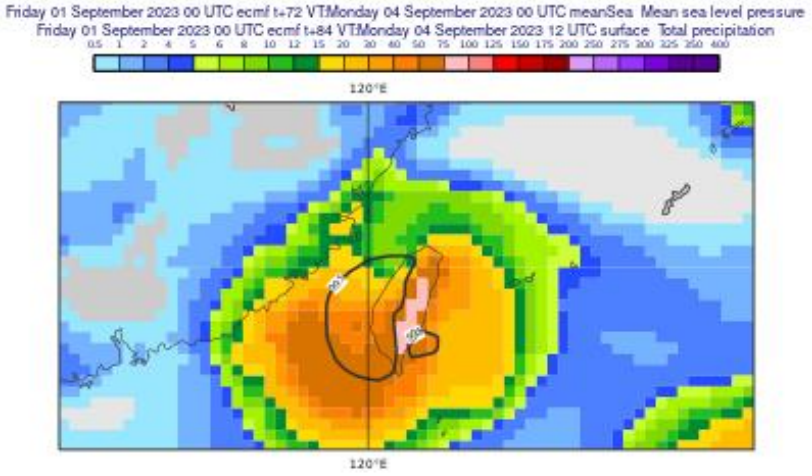

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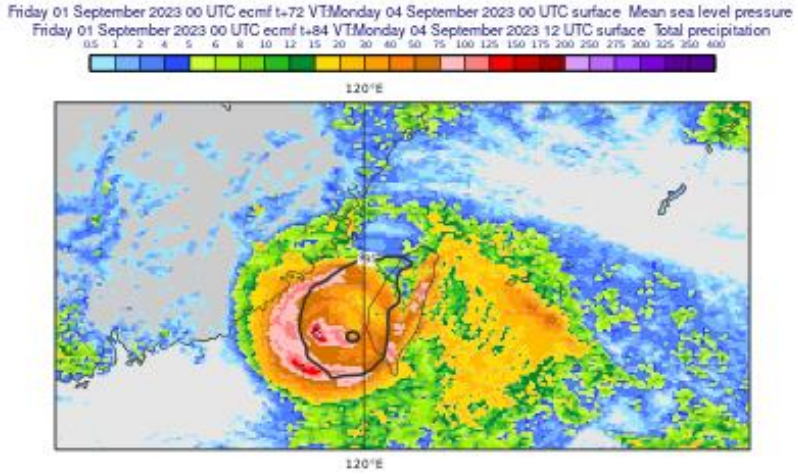

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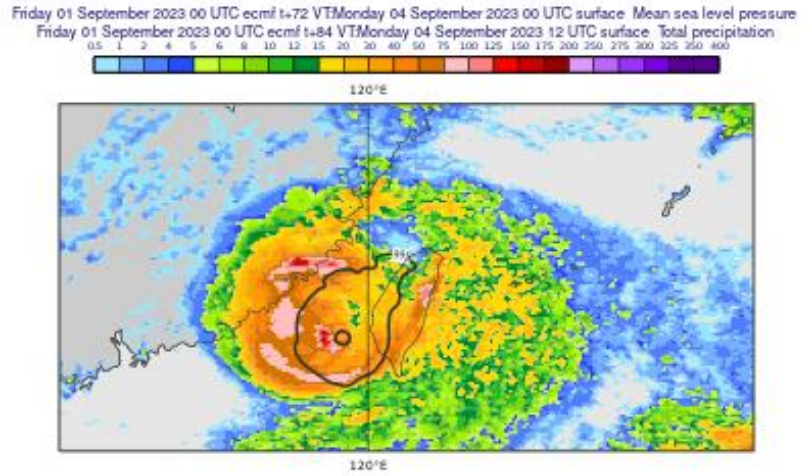

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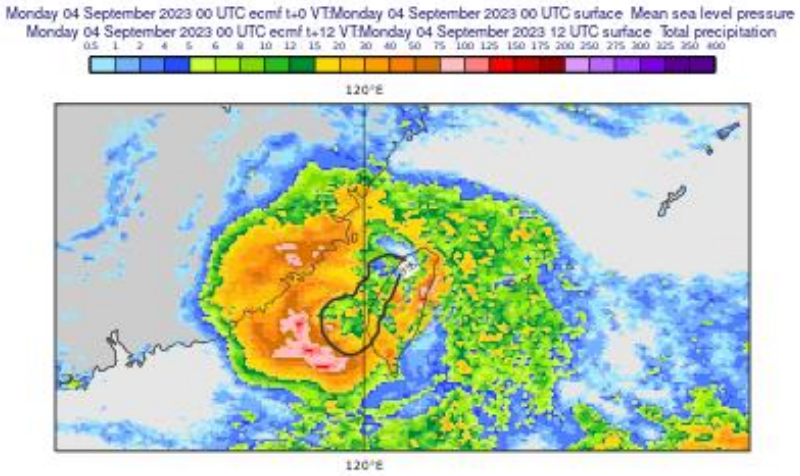

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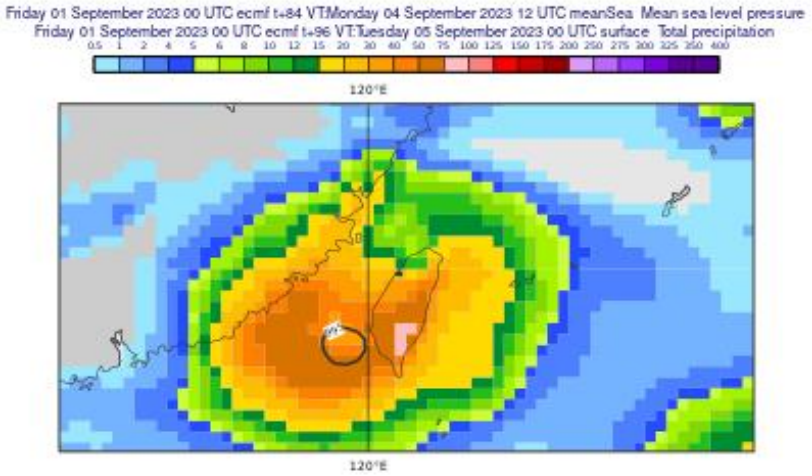

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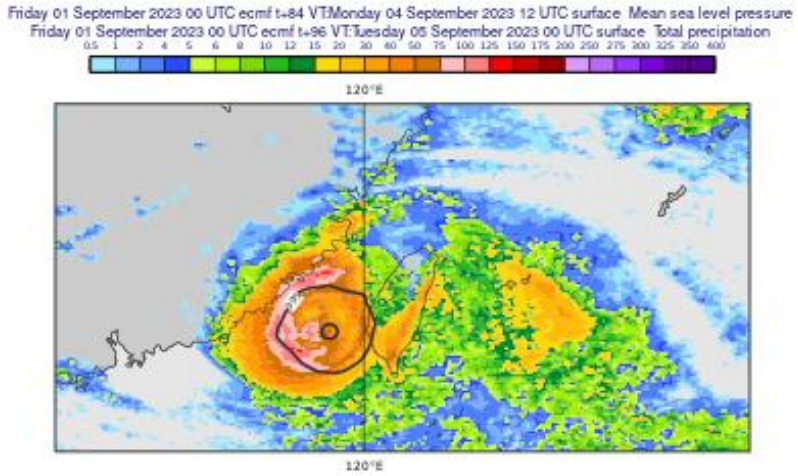

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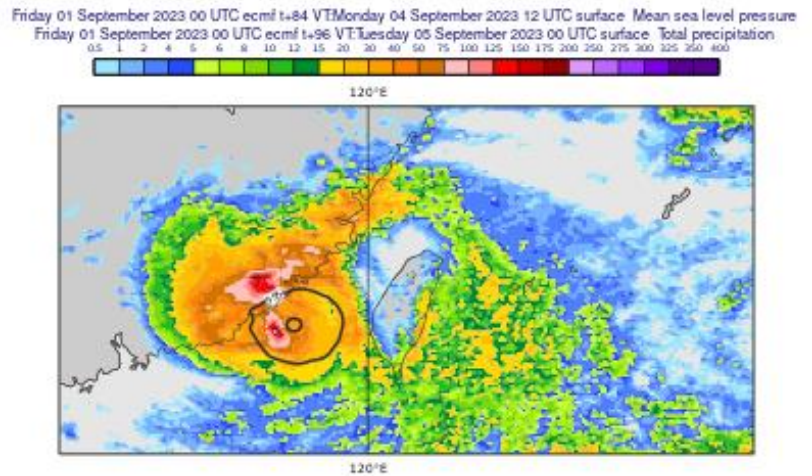

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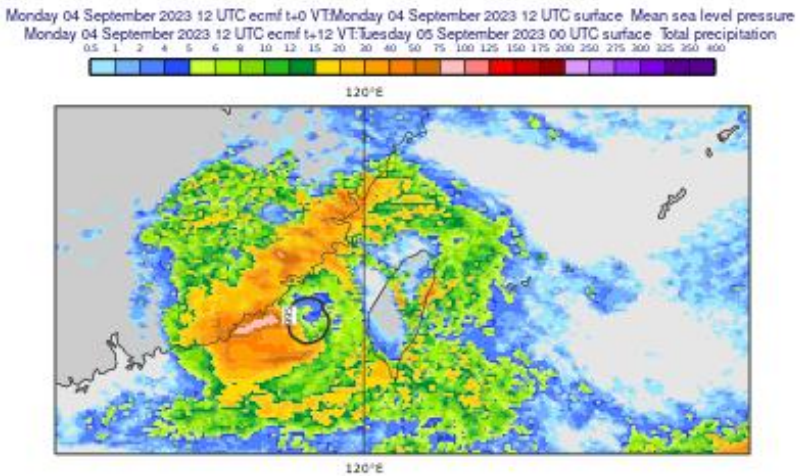

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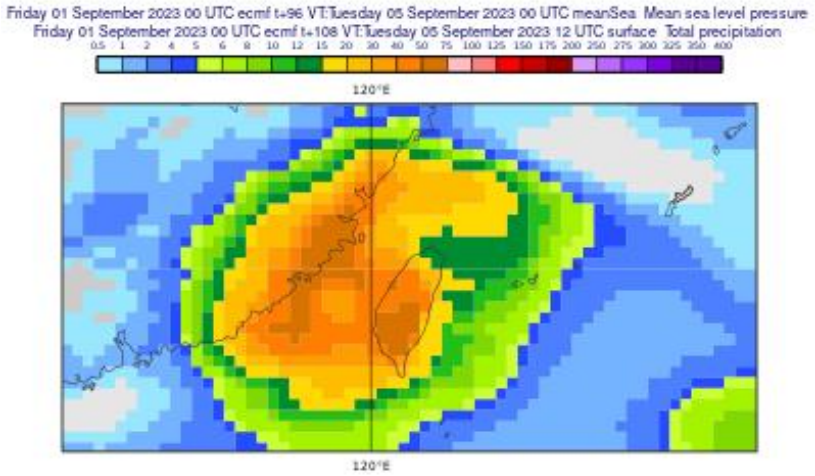

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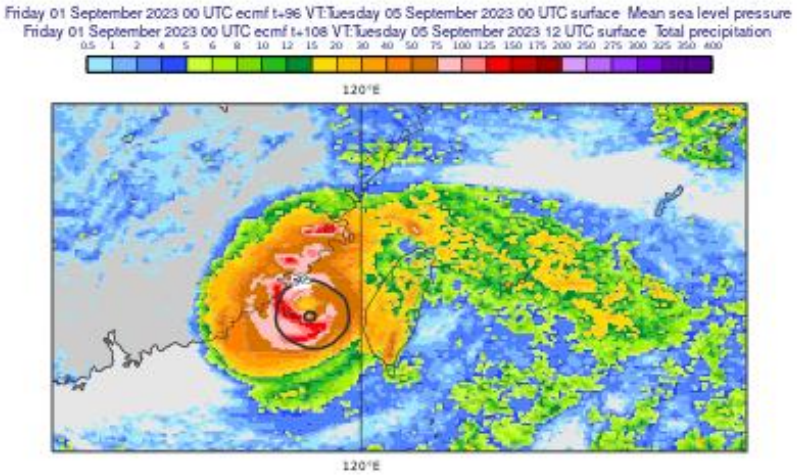

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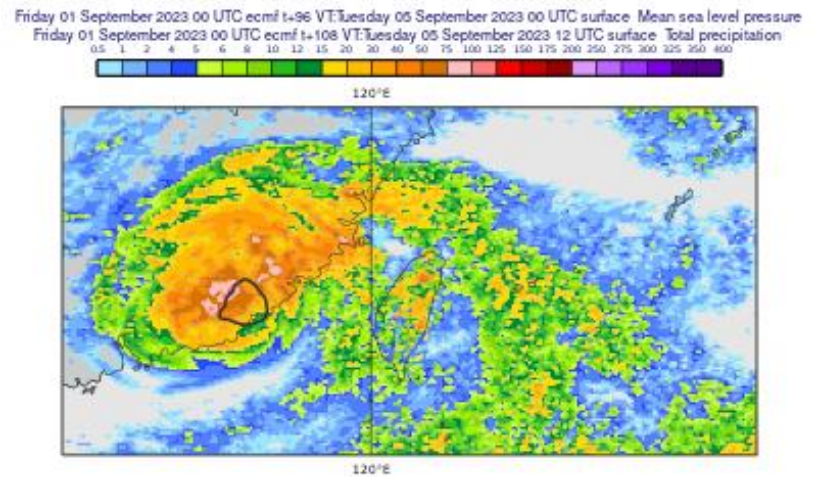

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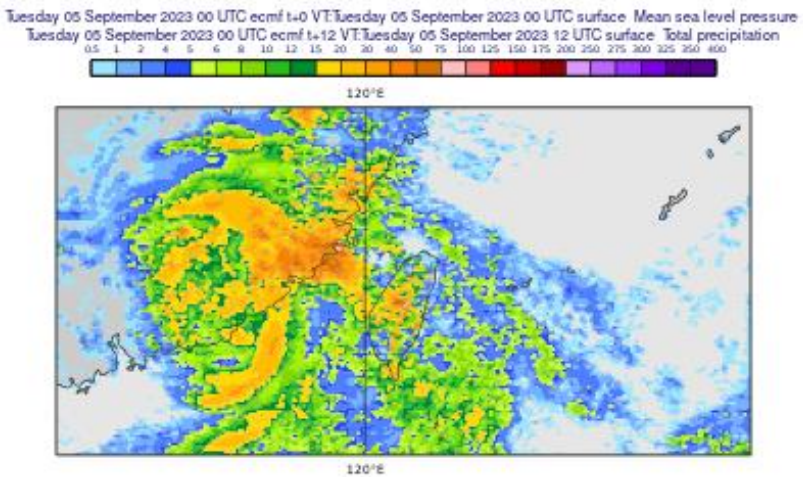

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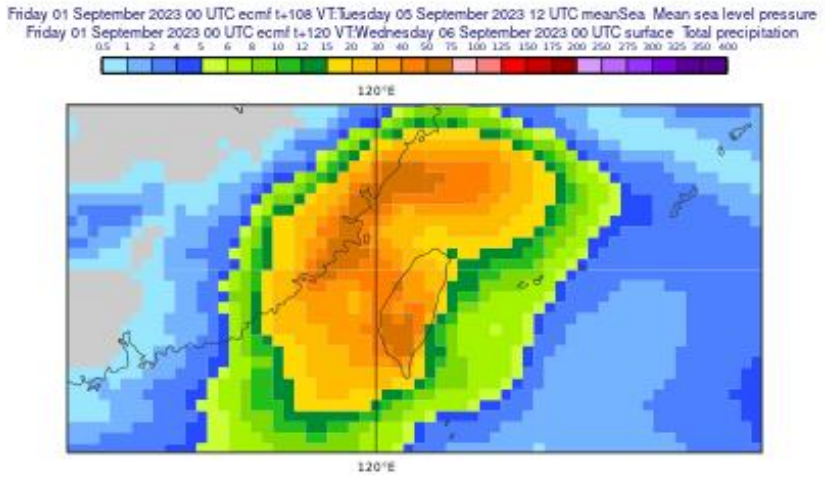

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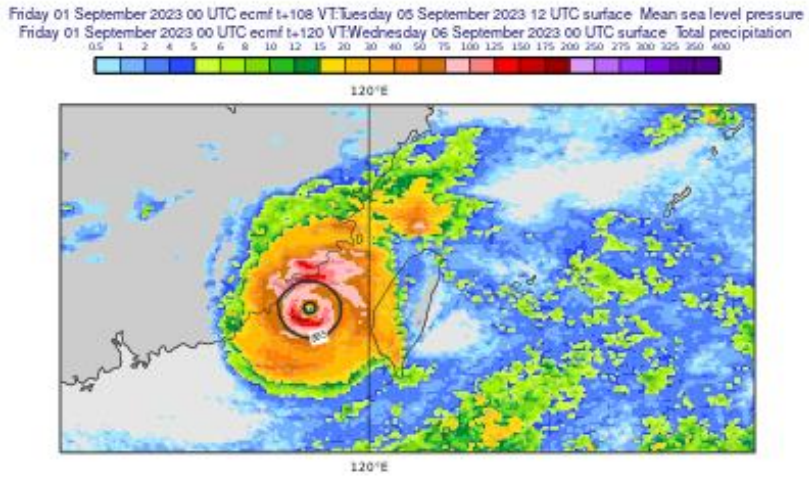

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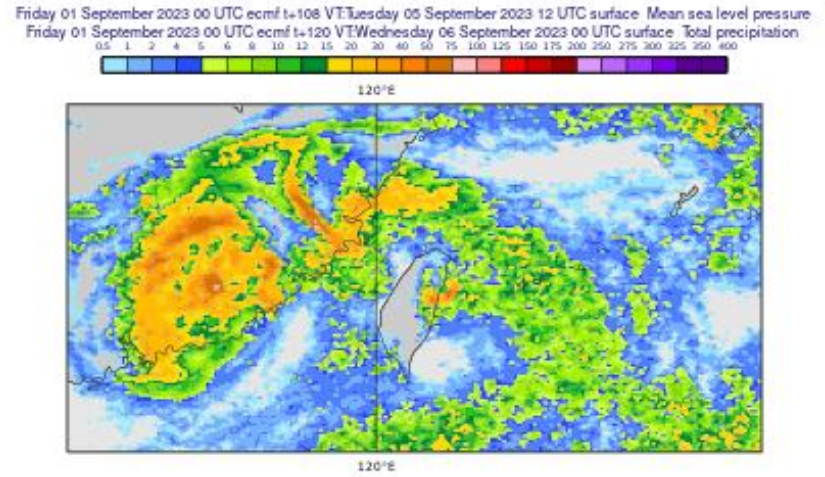

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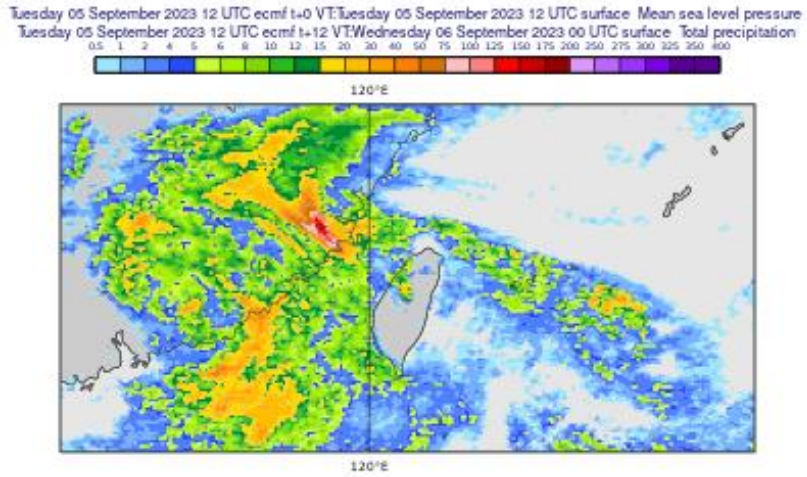


- Nudging preserves small-scale features and tropical storm intensities of a physics-based model.
- Nudged forecast predicts better track than IFS from +86h onwards.

Tropical cyclones statistics at TCo1279 for 2024-2025: CF

- Tropical cyclone track errors improved up to 50 km by day-5.
- TC intensity and pressure wind-relationship similar to IFS and thus closer to observed.

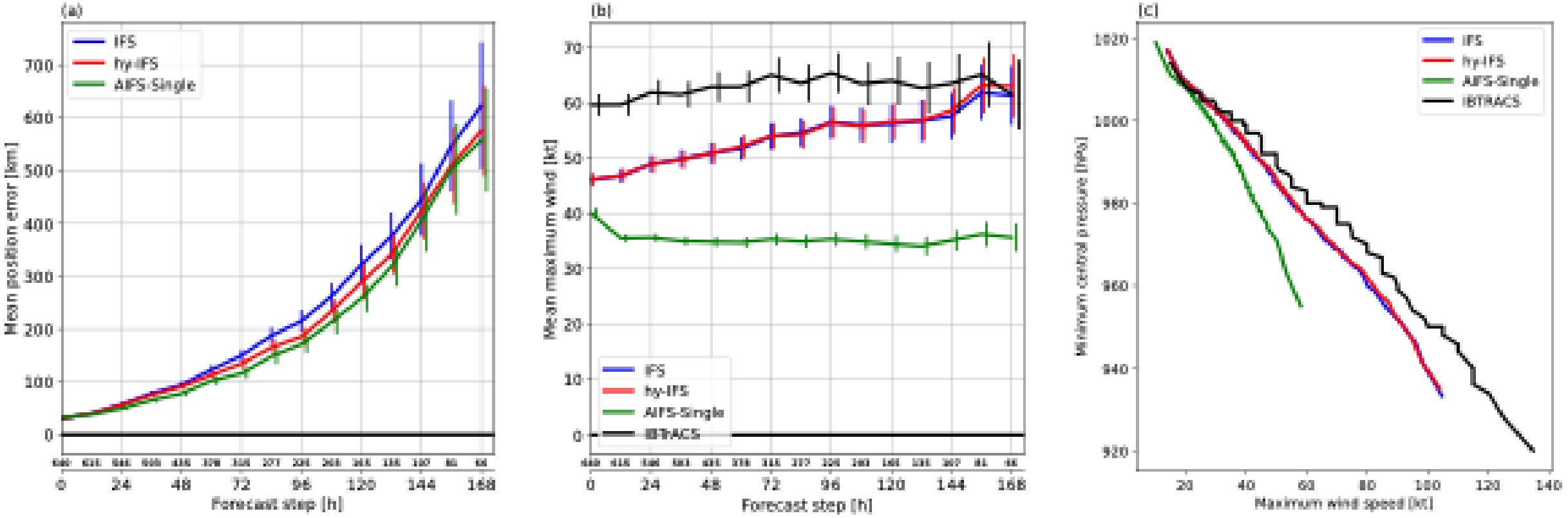
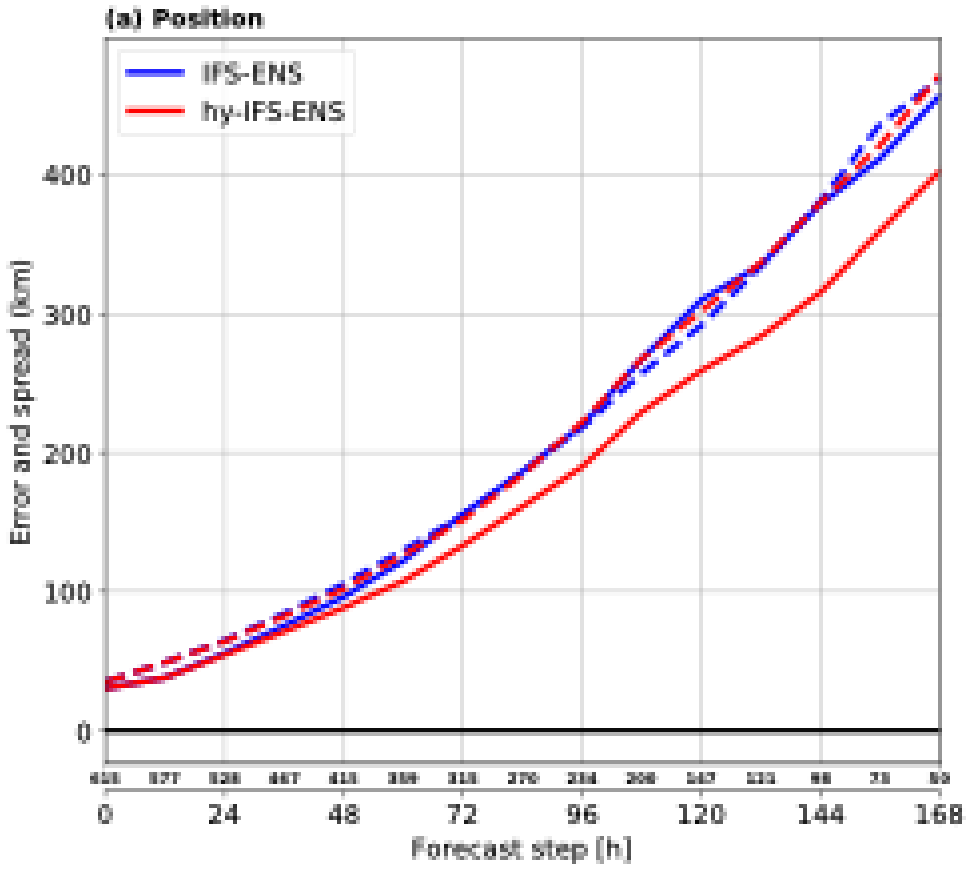
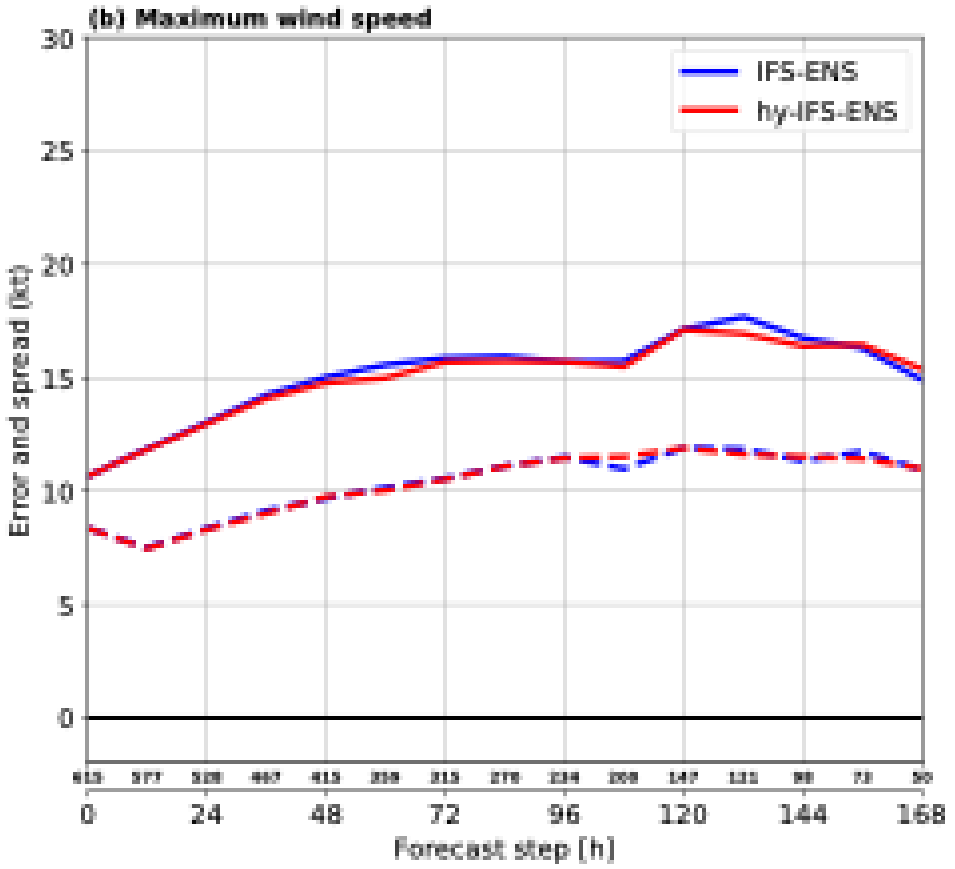


Figure courtesy: Michael Maier-Gerber

Tropical cyclones statistics at TCo1279 for 2024-2025: ENS

- Tropical cyclone track errors improved up to 50 km by day-5.
- TC intensity (maximum wind and minimum pressure) same as in IFS-ENS

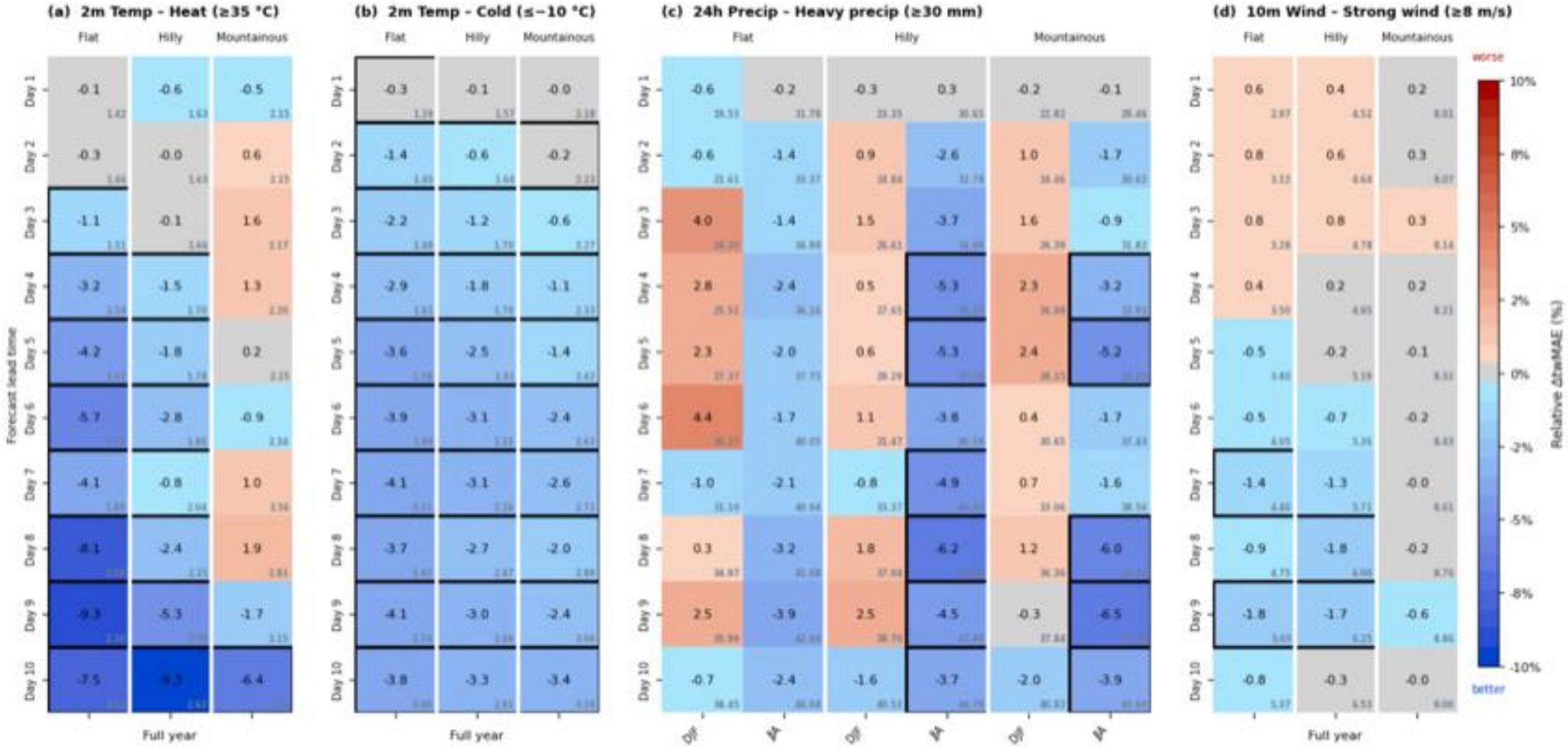




Polichtchouk et al. (2026, ArXiv)

Other extreme Northern Hemisphere events 2024-2025: CF

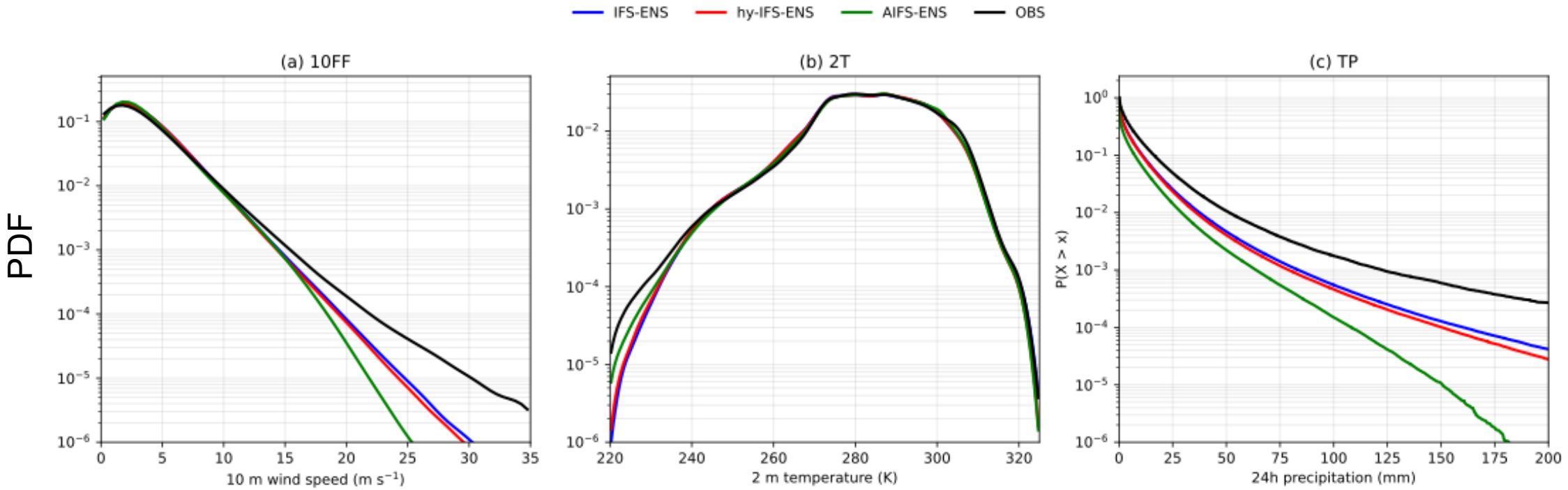
- Some indication of slightly improved temperature and wind extremes, and precip extremes in JJA in hilly and mountaneous areas.



Other extreme Northern Hemisphere events 2024-2025: ENS

- Tails of 10m wind, 2m temperature and total precipitation are very similar in hybrid and IFS-ENS.

- AIFS-ENS suffers from insufficient resolution.



Polichtchouk et al. (2026, ArXiV)

Summary

- Hybrid system can conceptually be viewed as online bias correction, where IFS takes advantage of better large-scale flow representation of AIFS.

- Combining AIFS and IFS via spectral nudging for deterministic and ensemble forecasts improves:
  - Large-scale skill score metrics everywhere in the troposphere
  - Tropical cyclone tracks
  - Northern Hemisphere extreme event prediction

- The benefit of hybrid system over pure machine learned forecasts are
  - All forecast products are identical to those in IFS.
  - Resolution of physics-based model retained, including the small scales.
  - More physically consistent

- Hybrid system easy to integrate to operational workflow and can be applied at any resolution without having to re-tune.

ECMWF