Can Artificial Intelligence Global Weather Forecasting Models Capture Extreme Events?

A Case Study of the 2022 Pakistan Floods

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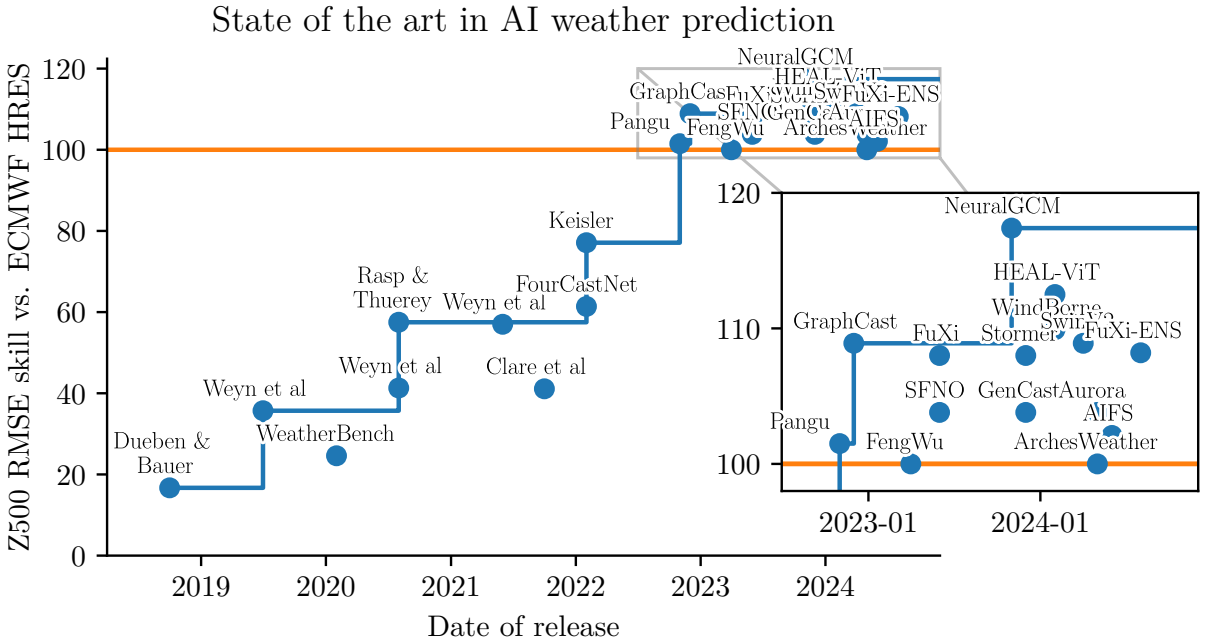
AI weather prediction (AIWP) is state of the art*

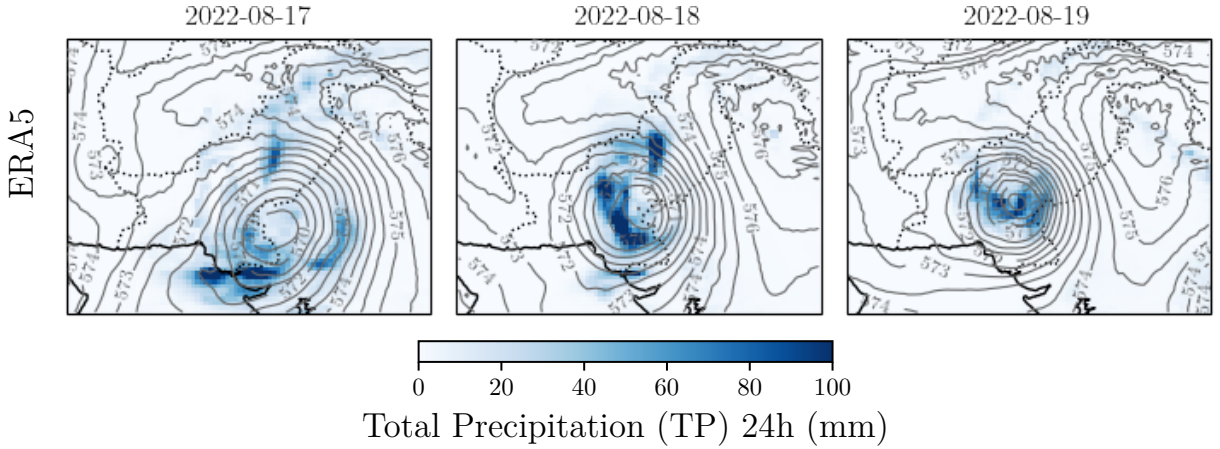
- Most benchmarks are deterministic
- Limits uncertainty quantification (UQ) and extremes performance assessment
- Probabilistic forecasts are critical for decision makers
- **Goal**: Test different perturbations (IC) + deterministic AIWP models on extremes



Adapted from [Hoyer and Rasp, 2025]

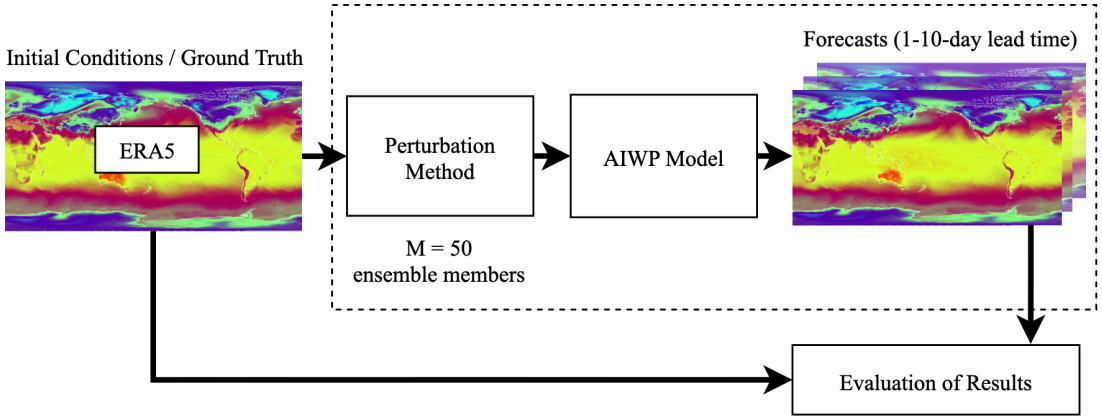
Record breaking floods in Pakistan

- Extreme monsoon rains in August 2022
- Flooding main driver was extreme precipitation [Cui et al., 2025]
- Thousands of deaths, 30M people displaced [Hong et al., 2023]



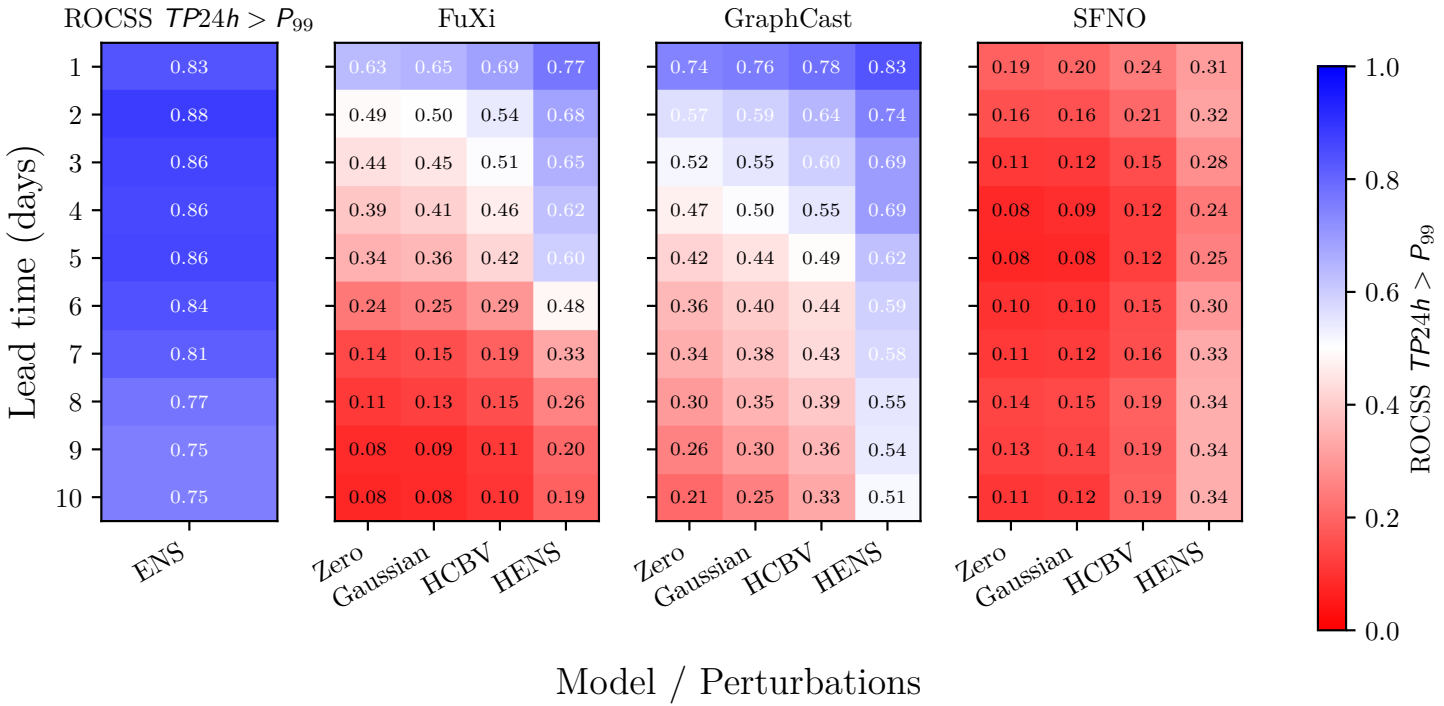
Perturb ⇒ Forecast ⇒ Evaluate

Methodology



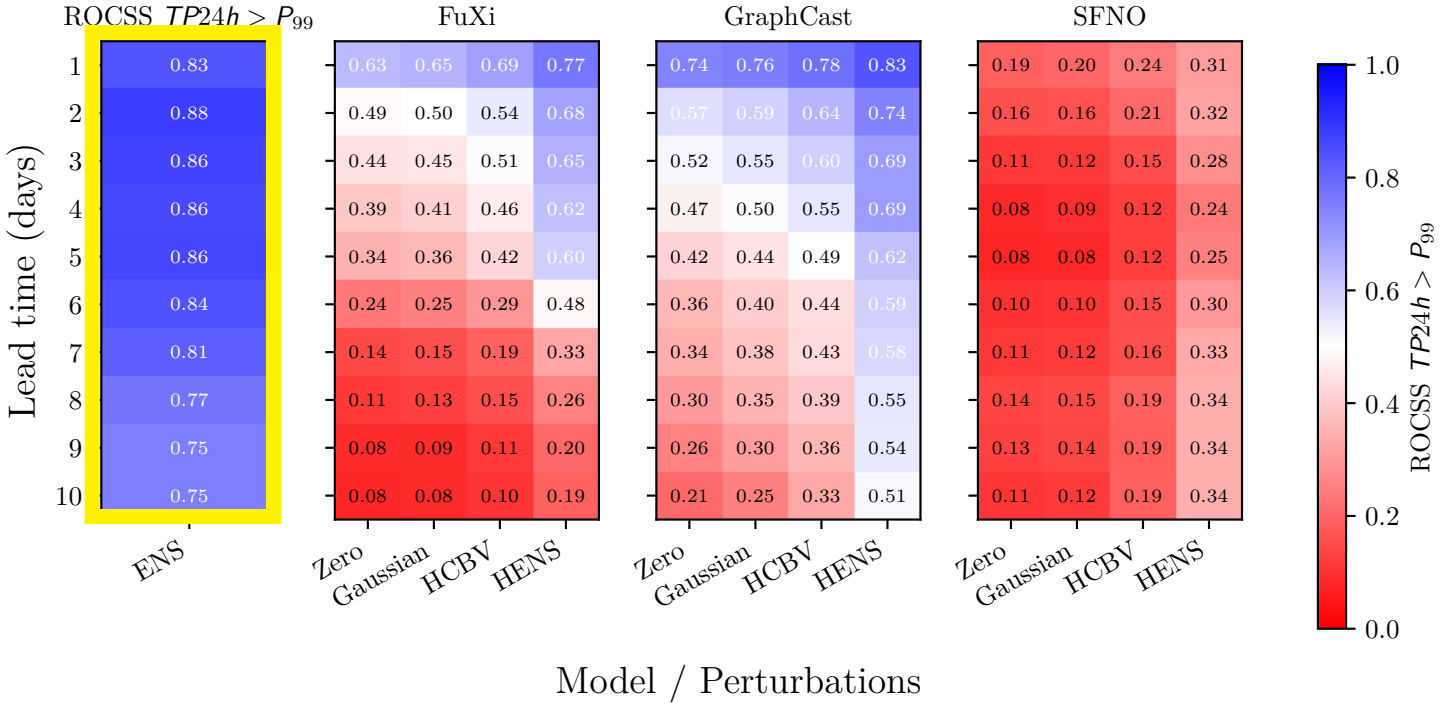
- **Data:** ERA5 [C3S, 2018] and IFS ENS [ECMWF, 2016]
- **Models:** FuXi [Chen et al., 2023], GraphCast [Lam et al., 2023] and SFNO [Bonev et al., 2023]
- **Perturbations:** Gaussian, HCBV, HENS
- **Metrics:** ROCSS, CRPS, RMSE
- **Tools:** `earth2studio` (forecasting, [Geneva and Foster, 2024]), `weatherbenchx` (evaluation, [Goo, 2025, Zhao et al., 2025])

ENS wins, GraphCast + HENS runnerup



Pakistan region, August 2022.

ENS wins, GraphCast + HENS runnerup



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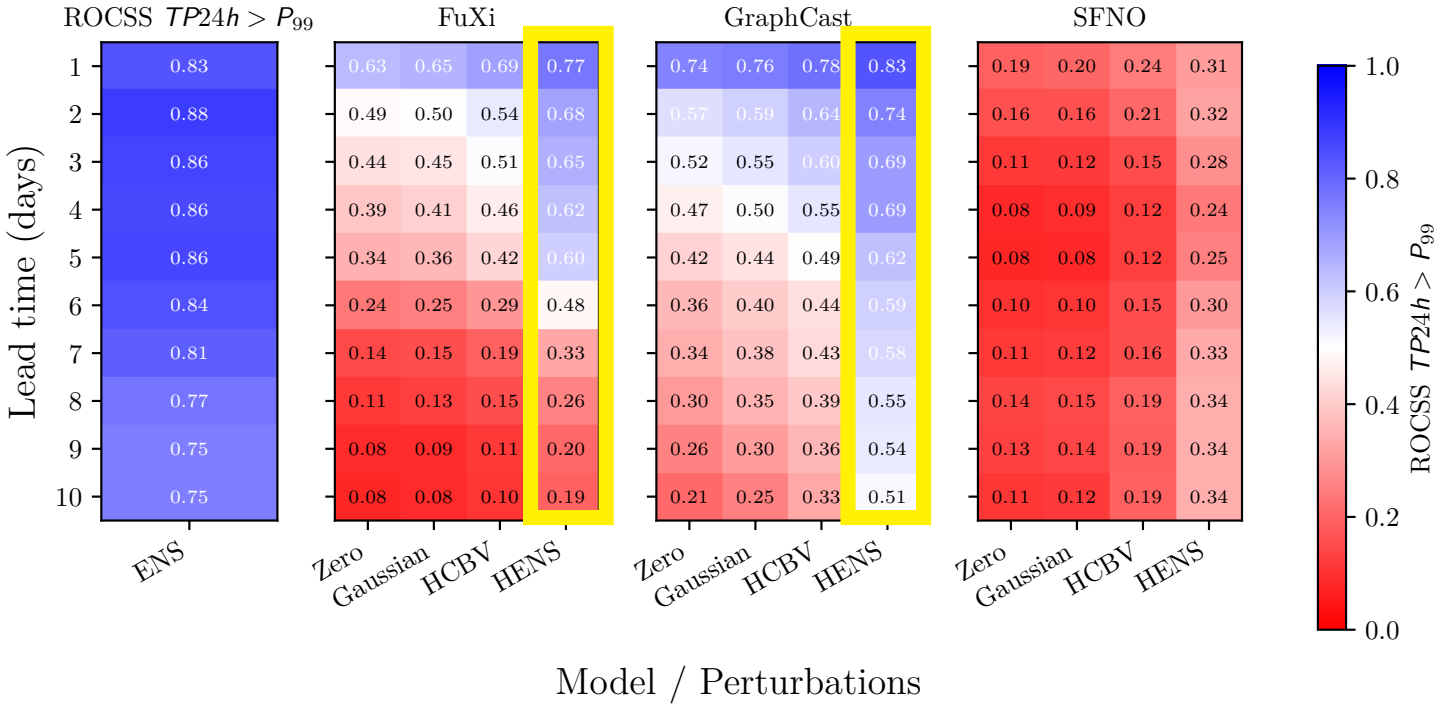

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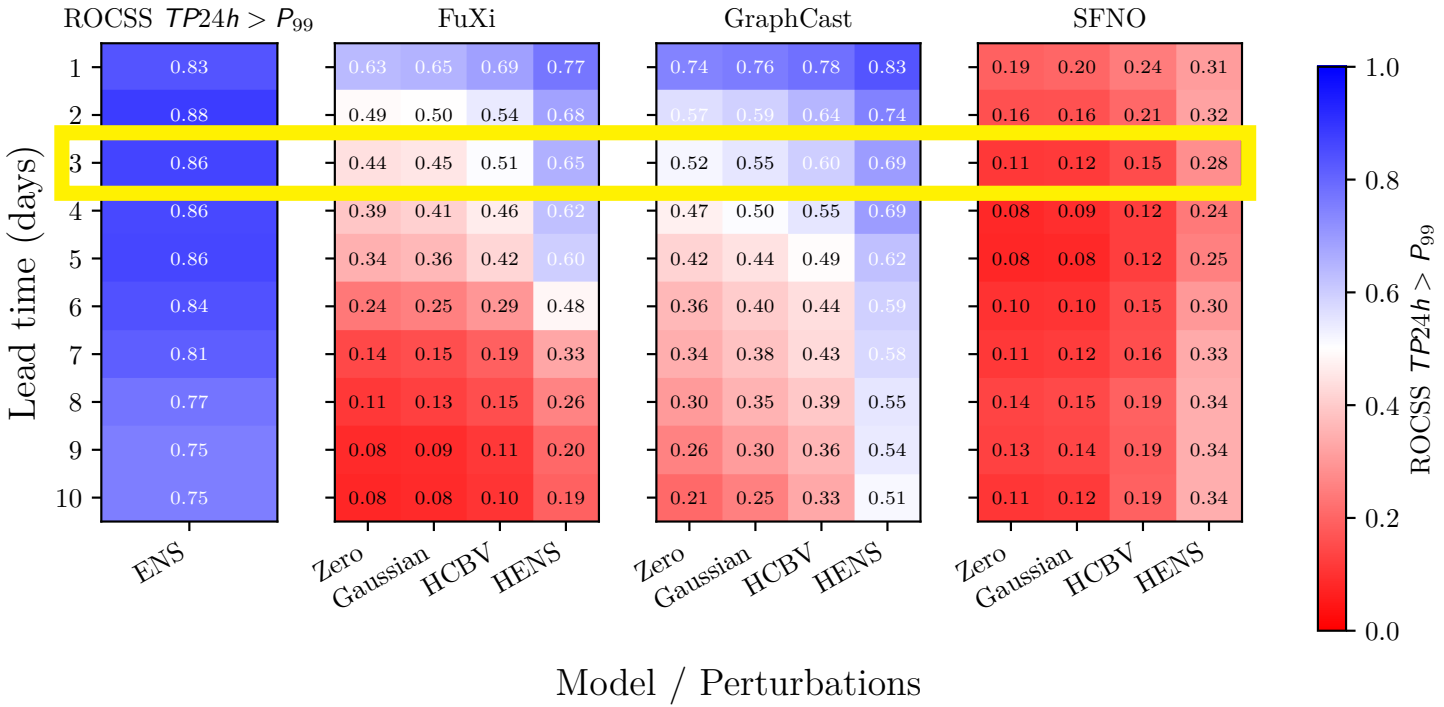
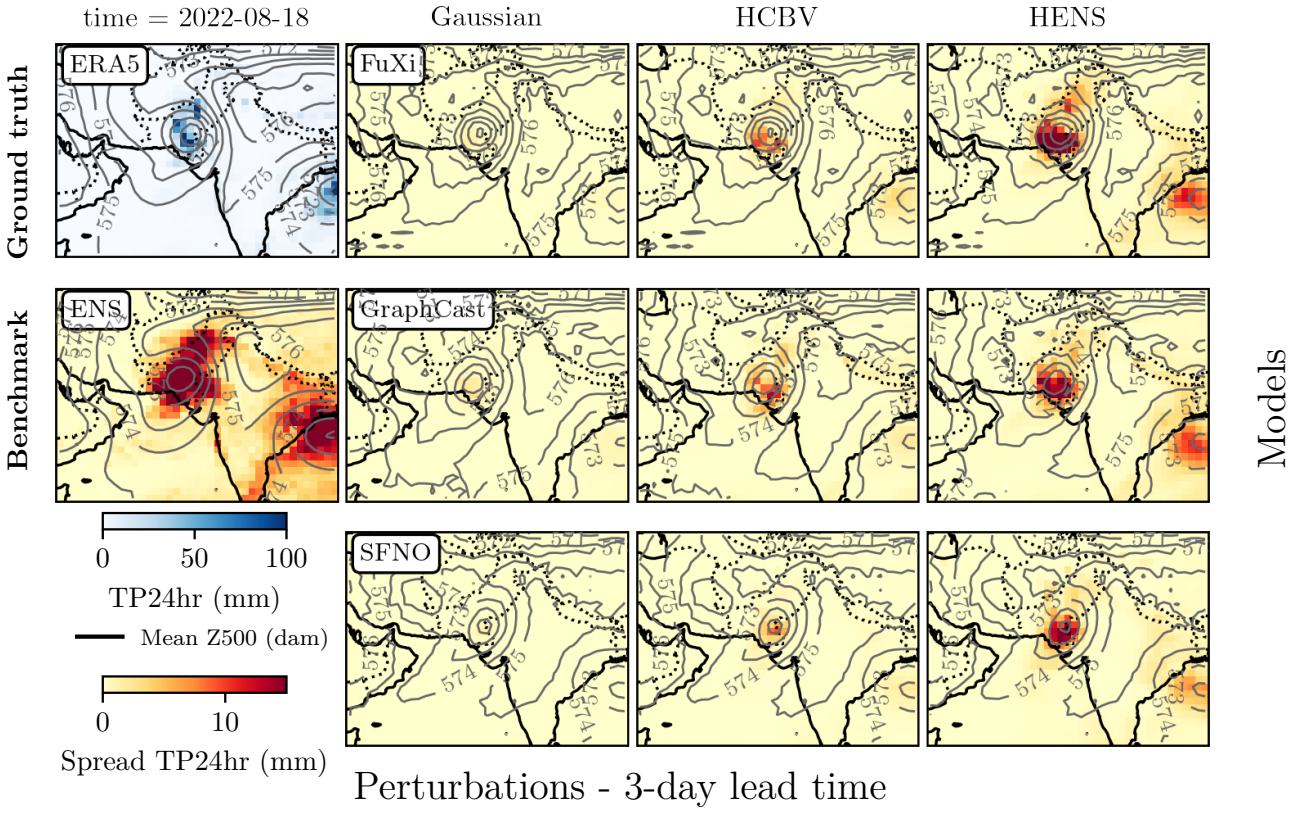


Pakistan region, August 2022.

FuXi + HENS is closest to ENS spread

- AIWP does not reproduce ENS spread
- Gaussian is underdispersive



Conclusion & Outlook

- Input perturbations (HENS) improve forecasts but still below ENS for precipitation extremes, in this case
- Deterministic performance is maintained, but to different degrees for the perturbations
- Extremes remain a key challenge
- Future work, compare approaches for extremes (also warm extremes):
  - Multi-model ensembles
  - Checkpoint ensembles
  - Probabilistic AIWP
  - Explainability methods

Thank you!

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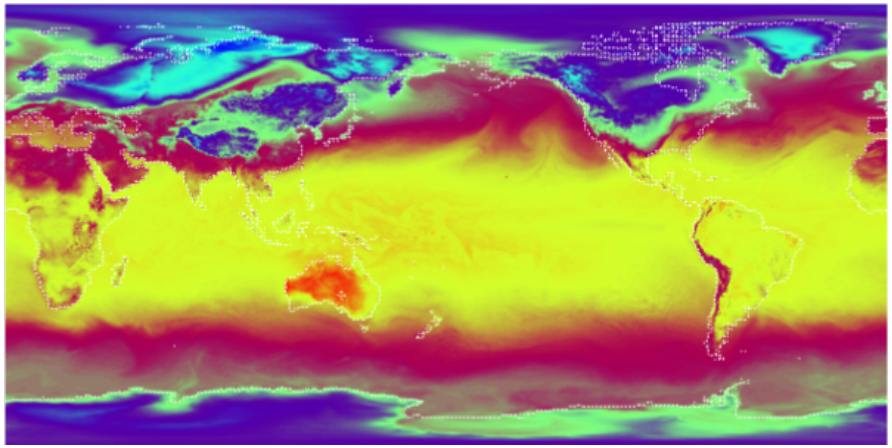
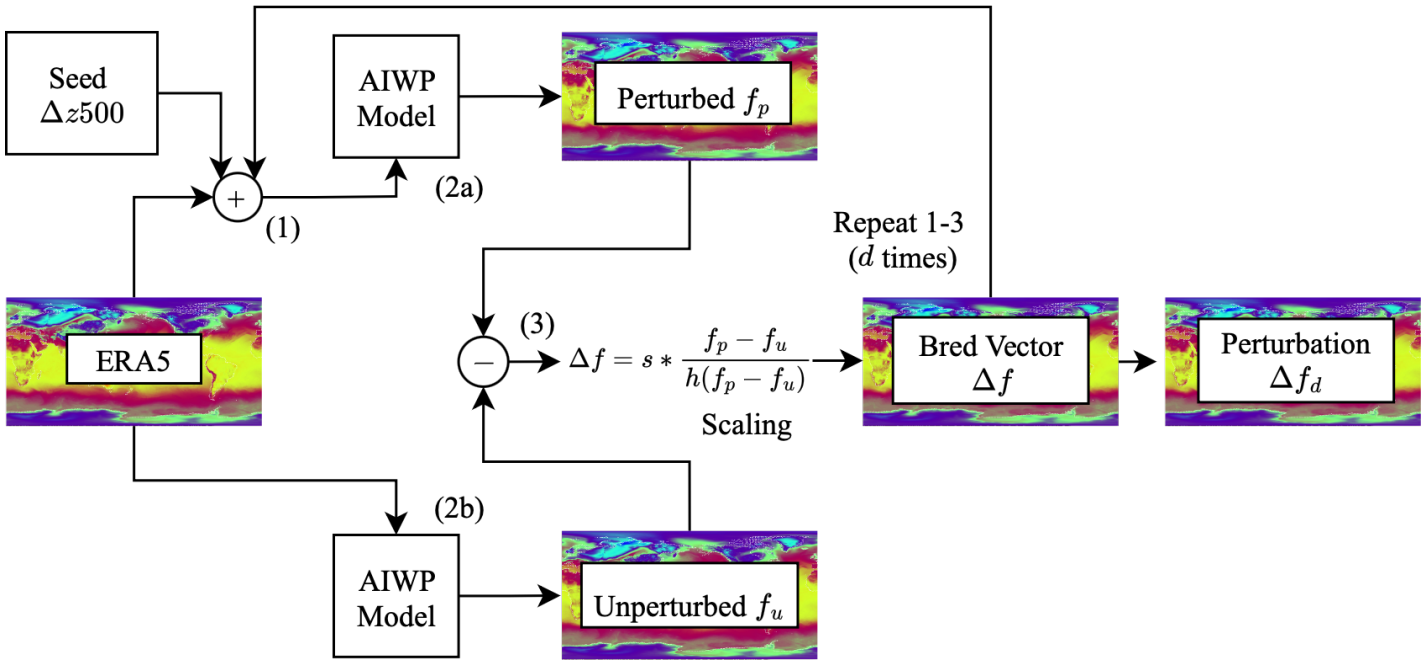
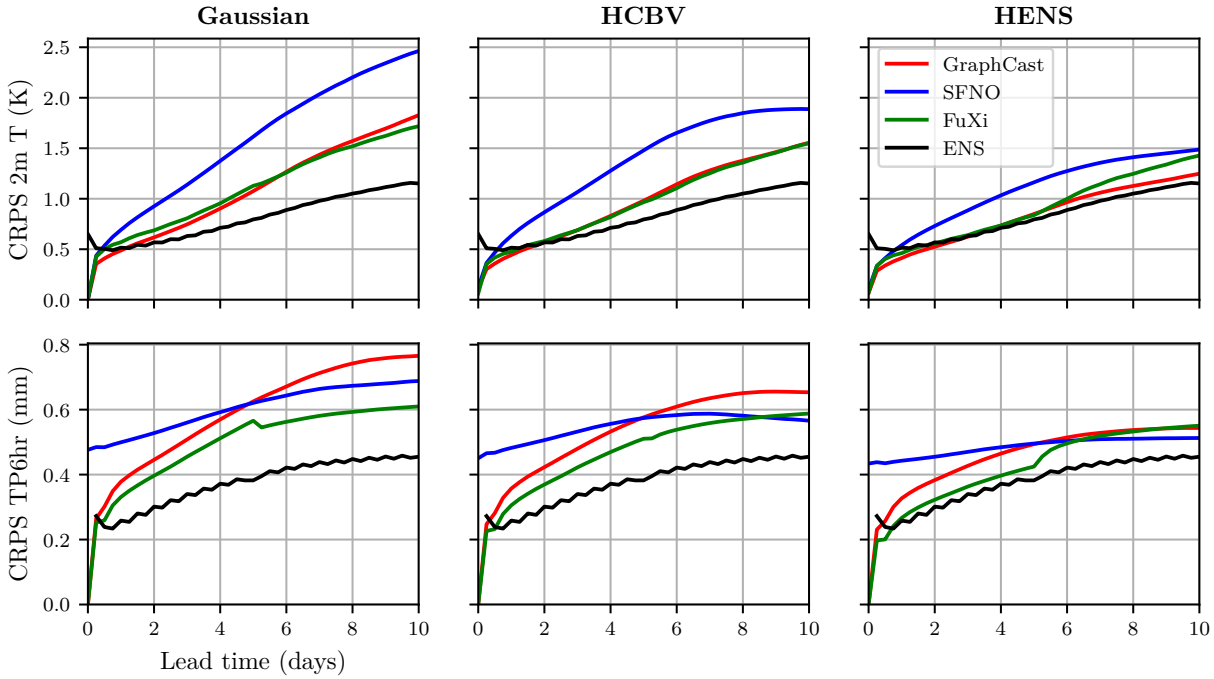


Perturbations

Perturbations: Gaussian, *HCBV, HENS* $\Downarrow$ *s* is different



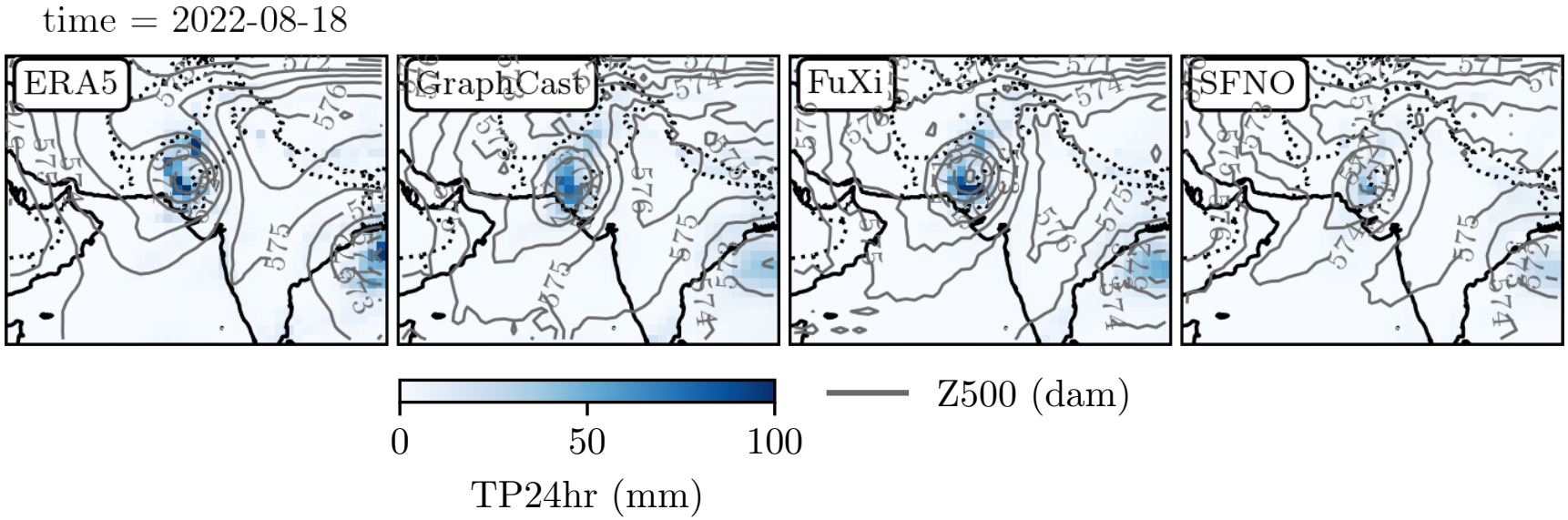
HENS narrows the gap to ENS



Global, August 2022

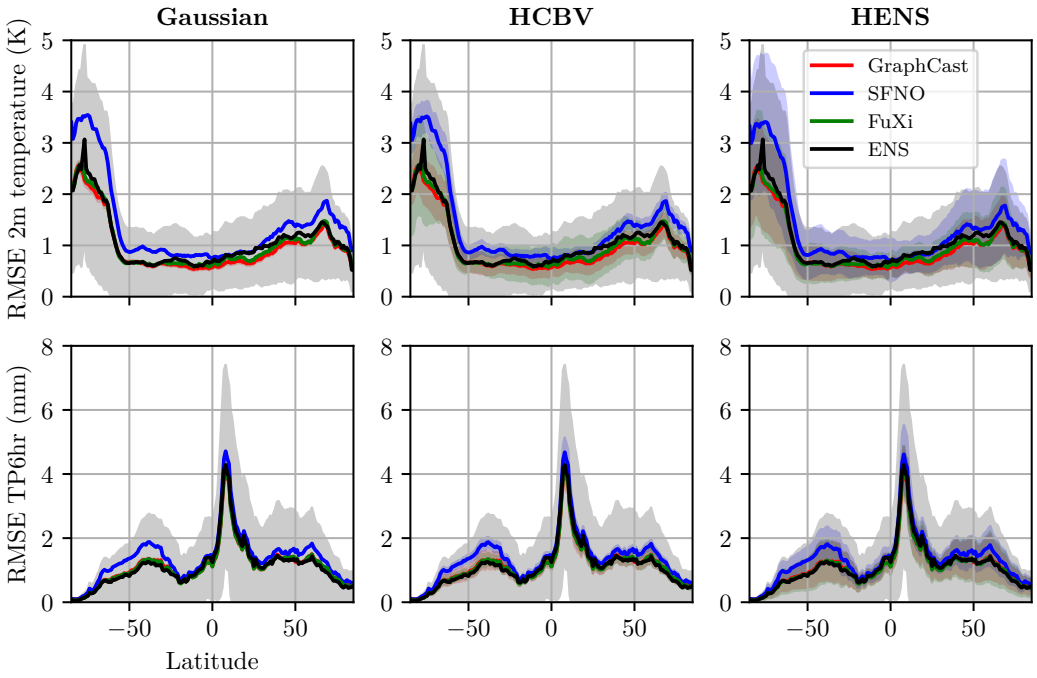
Fraunhofer HHI

Deterministic AIWP forecasts



3 day lead time, August 2022

Global metrics (by latitude)



3 day lead time, August 2022

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