Ten-day artificial intelligence forecasts can match official predictions in a fraction of the time.

ARTIFICIAL INTELLIGENCE

AI is set to revolutionize weather forecasts

Cheap and fast algorithms are matching—and surpassing—the world's top models

Paul Keil & Caroline Arnold 12.03.2026

HELMHOLTZ AI Artificial Intelligence Cooperation Unit

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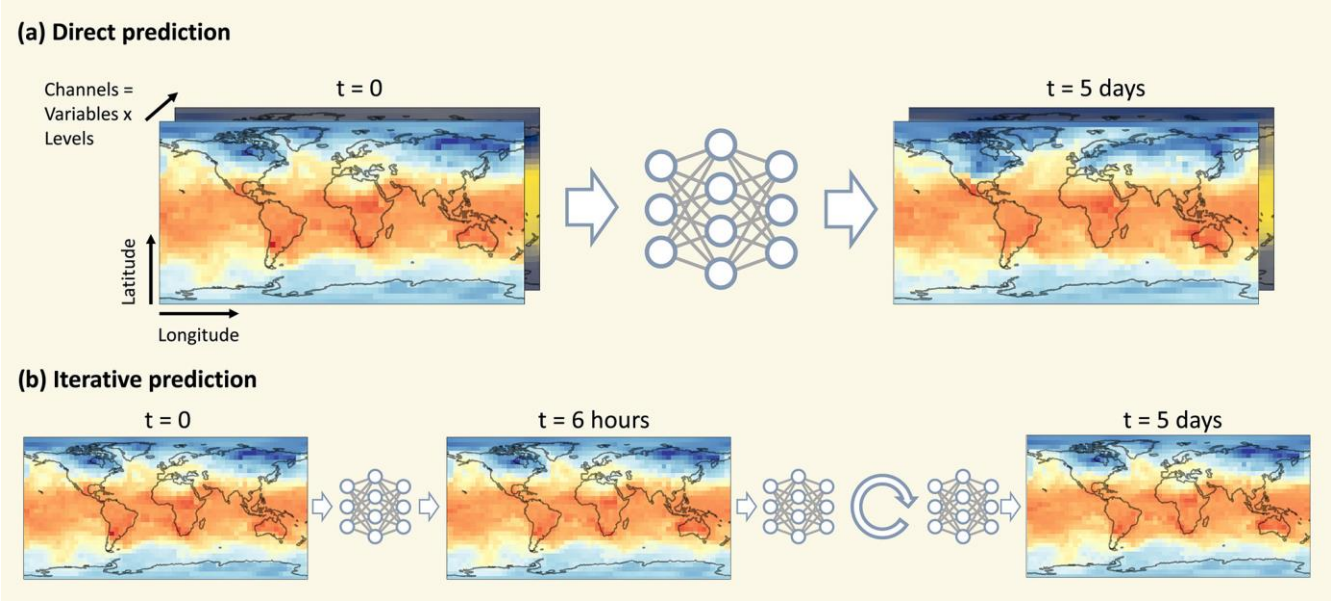
How does AI weather prediction work?

- Numerical weather prediction
  - Take initial state of the atmosphere
  - Update to next time step by solving complex equations

- AI weather prediction
  - „Image“ to „image“ translation

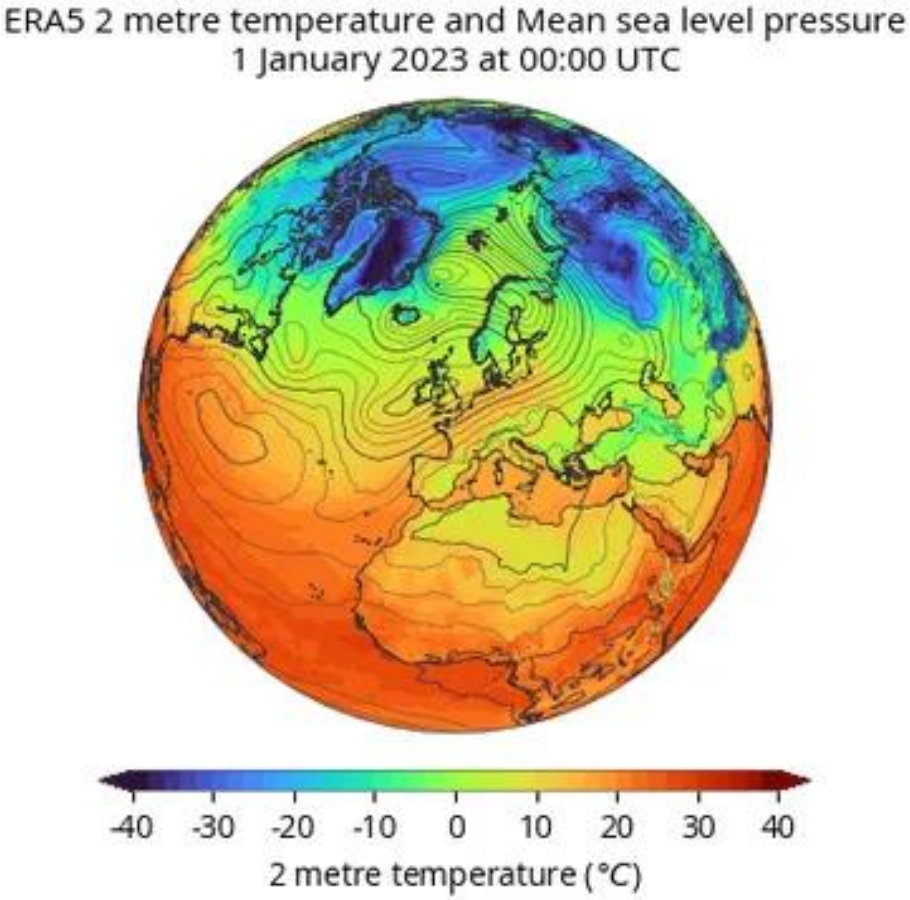


Rasp et al, WeatherBench: A Benchmark Data Set for Data-Driven Weather Forecasting, https://doi.org/10.1029/2020MS002203

Training data: ERA5 reanalysis

- Reanalysis data
- Atmosphere, ocean-wave, land surface
- Resolution: 0.25° (25 km) / 1 h / 37 pressure levels
- Regular latitude/longitude grid
- Available 1940 – today
- Latency: 5 days

- Total dataset size: ~ TB
- Recently extending to CMIP / observations

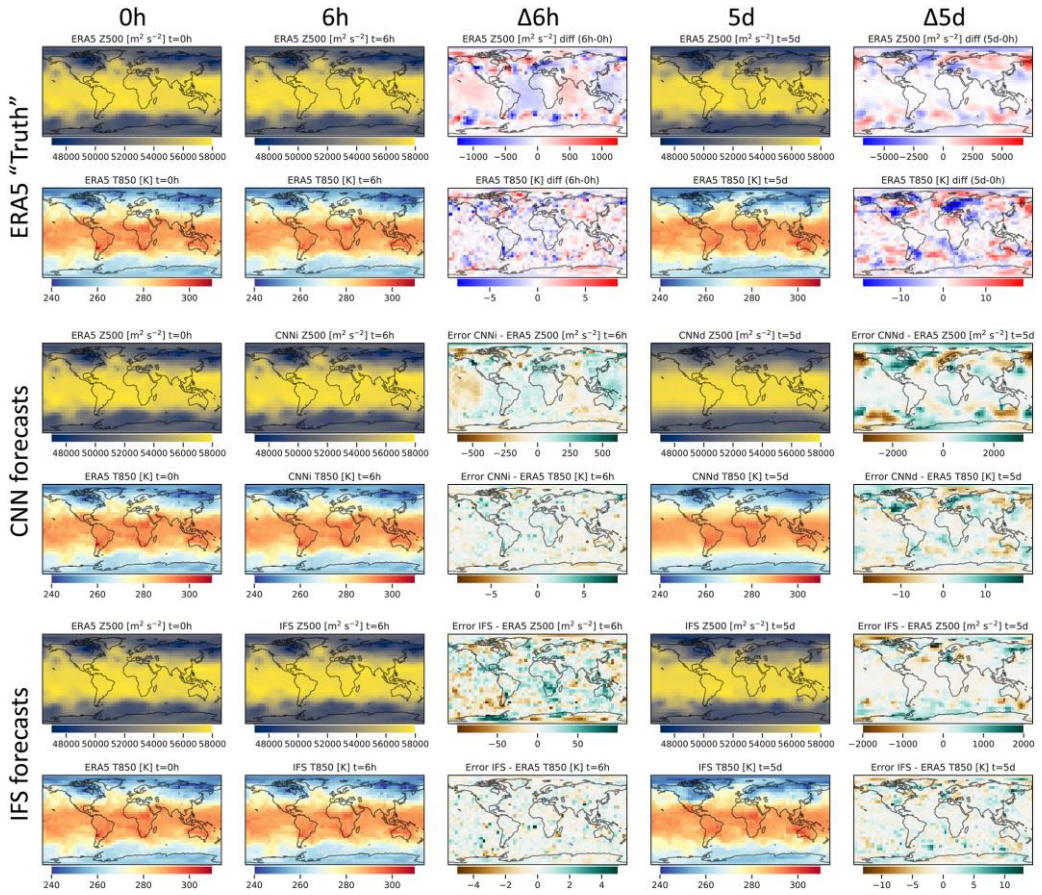


https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

First steps: Simple Convolutional Neural Network (CNN)

Rasp et al (2020)

- CNN architecture
  - 5 layers
  - 64 channels each
  - 300,000 learnable parameters
- Trained only on Z500 and T850
- Good results for up to 1.5 days, then quickly deteriorates



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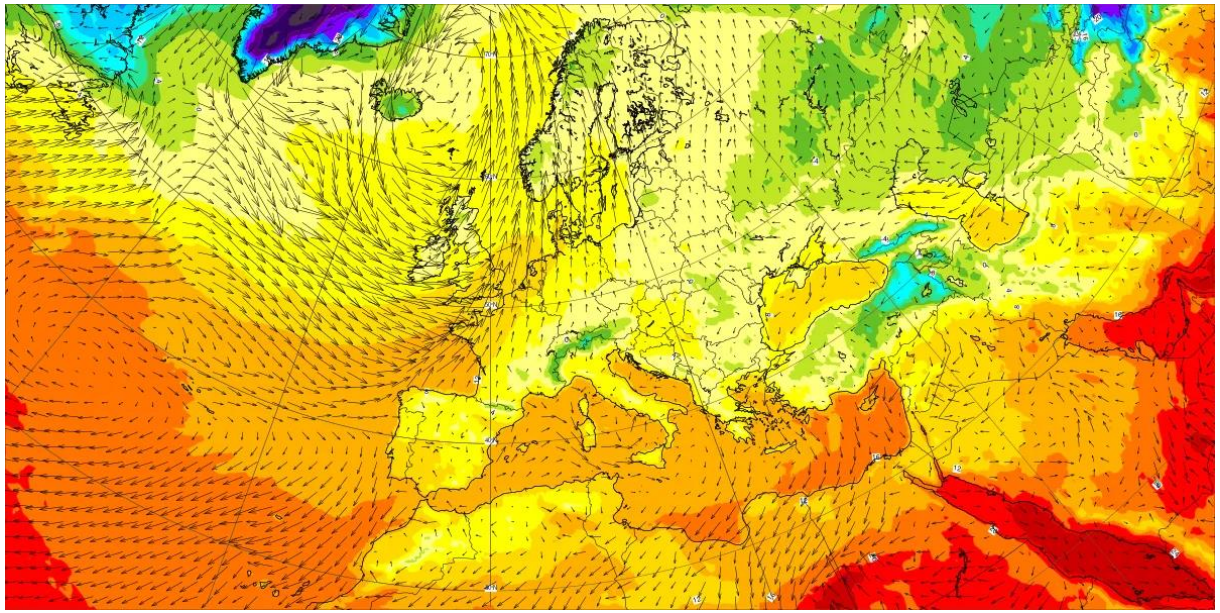
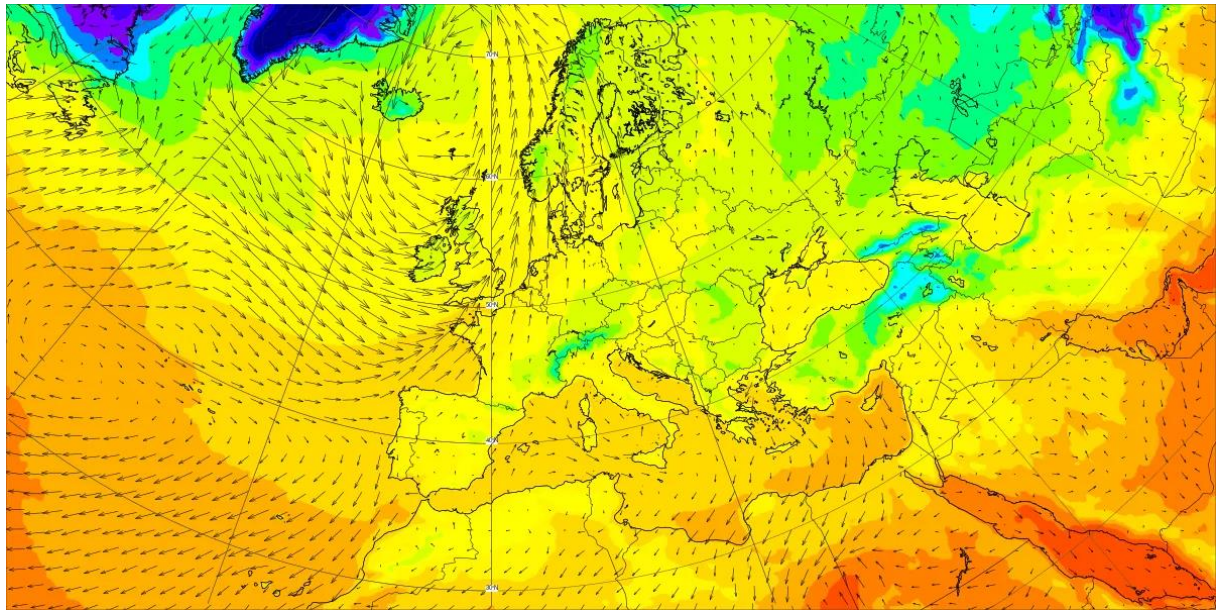


ECMWF Control (ex-HRES)



AI Forecast (Pangu, 2022)

T + 24H

2m temperature
30 m wind

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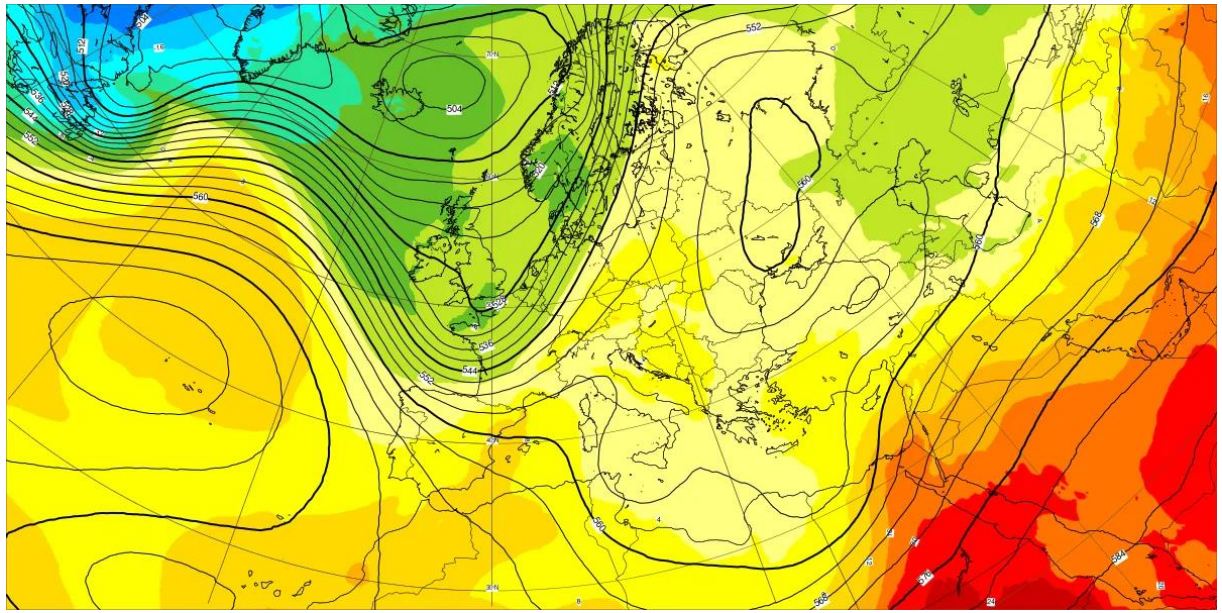
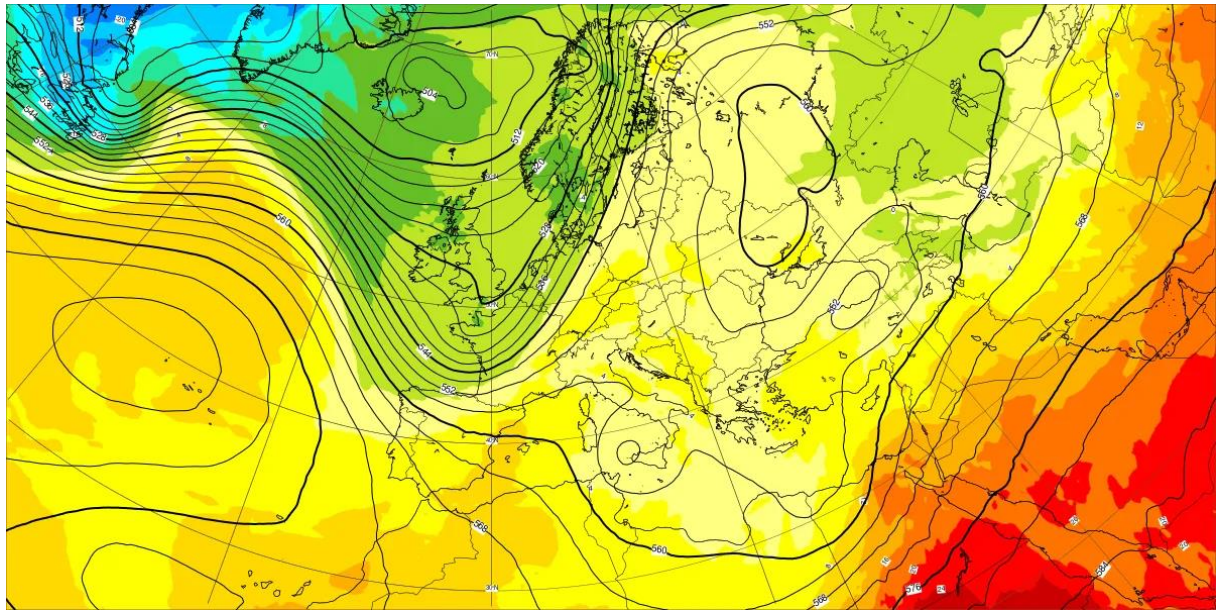


AI Forecast (Aurora, 2025)



ECMWF Control (ex-HRES)

T + 48H

500 hPa geopotential height and 850 hPa temperature

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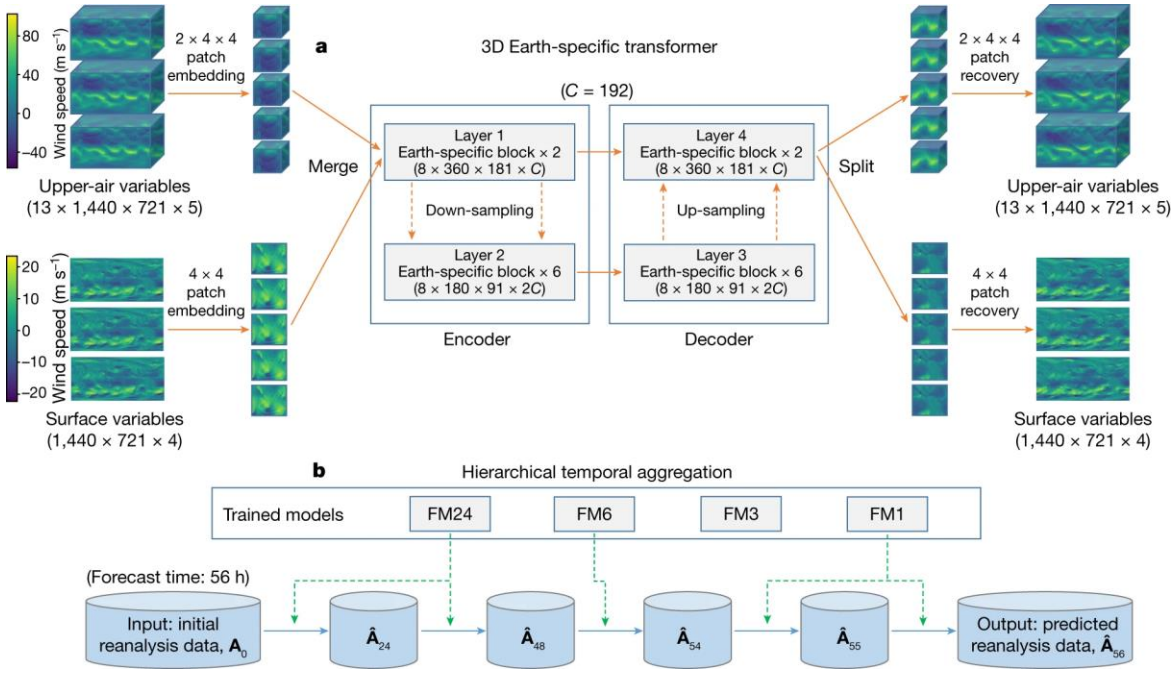
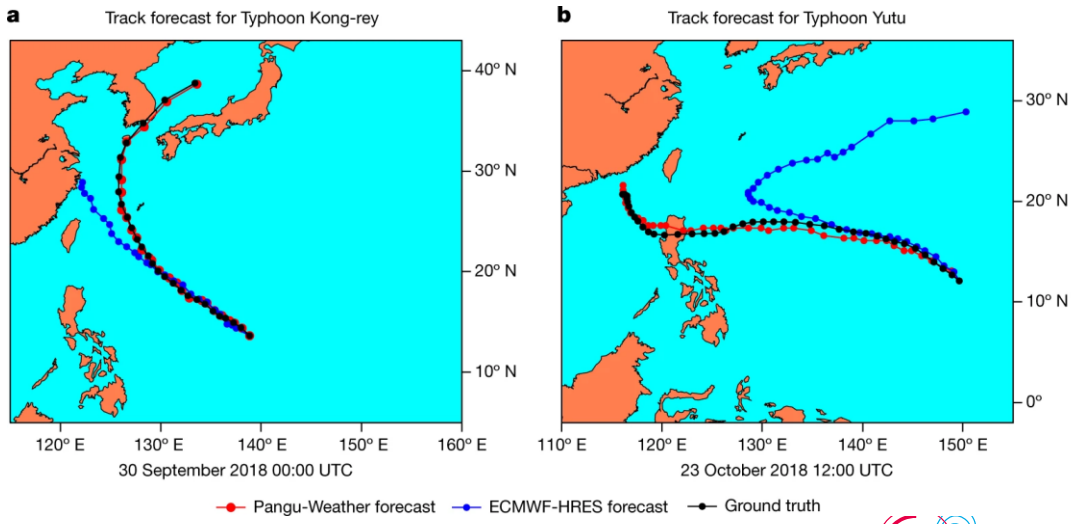
PanguWeather

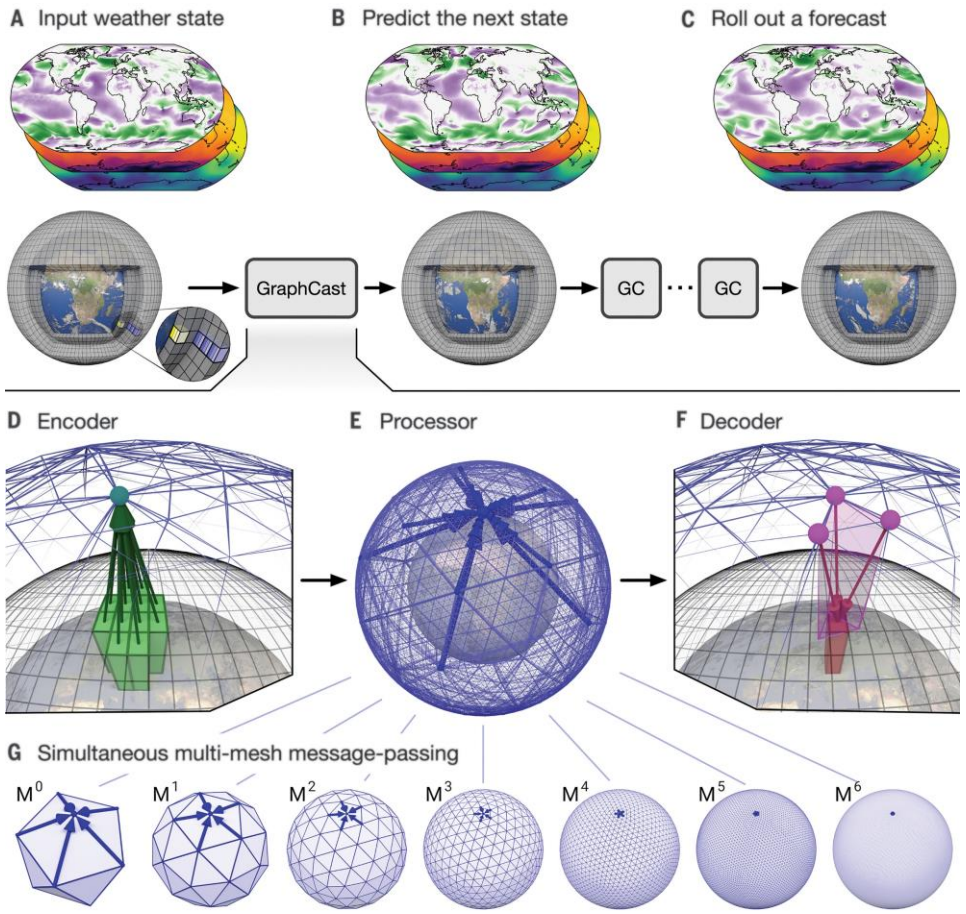


- 3D transformer
- Based on sliding window (SWIN) transformer
- Tokens with positional encoding (lat/lon)
- Trained for 4 lead times (1H, 3H, 6H, 24H)

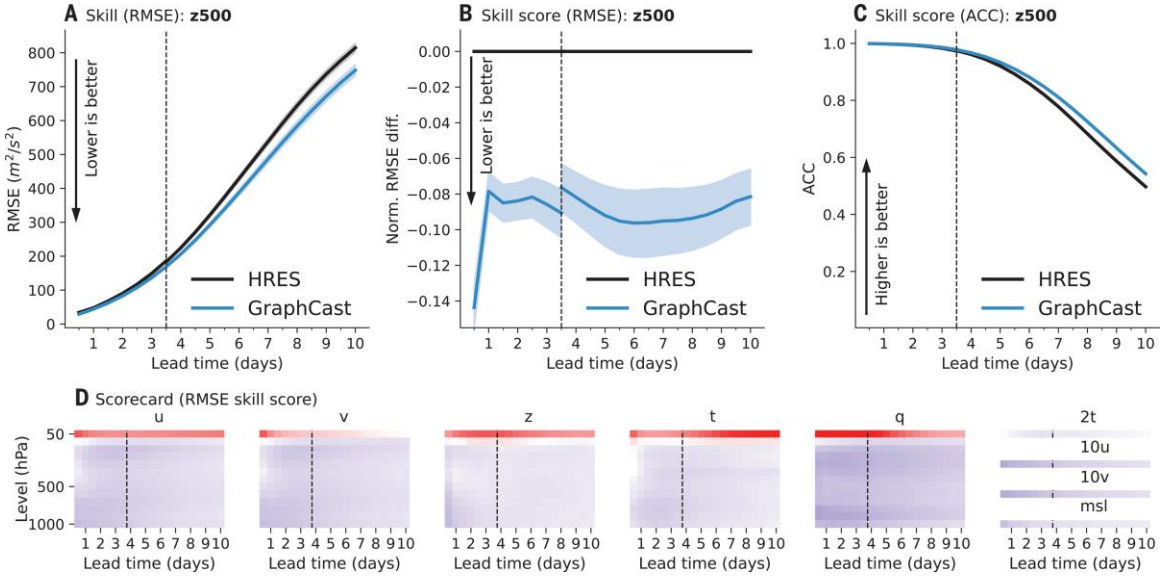


Bi, K., Xie, L., Zhang, H. *et al.* Accurate medium-range global weather forecasting with 3D neural networks. *Nature* **619**, 533–538 (2023). https://doi.org/10.1038/s41586-023-06185-3

GraphCast (Deepmind)

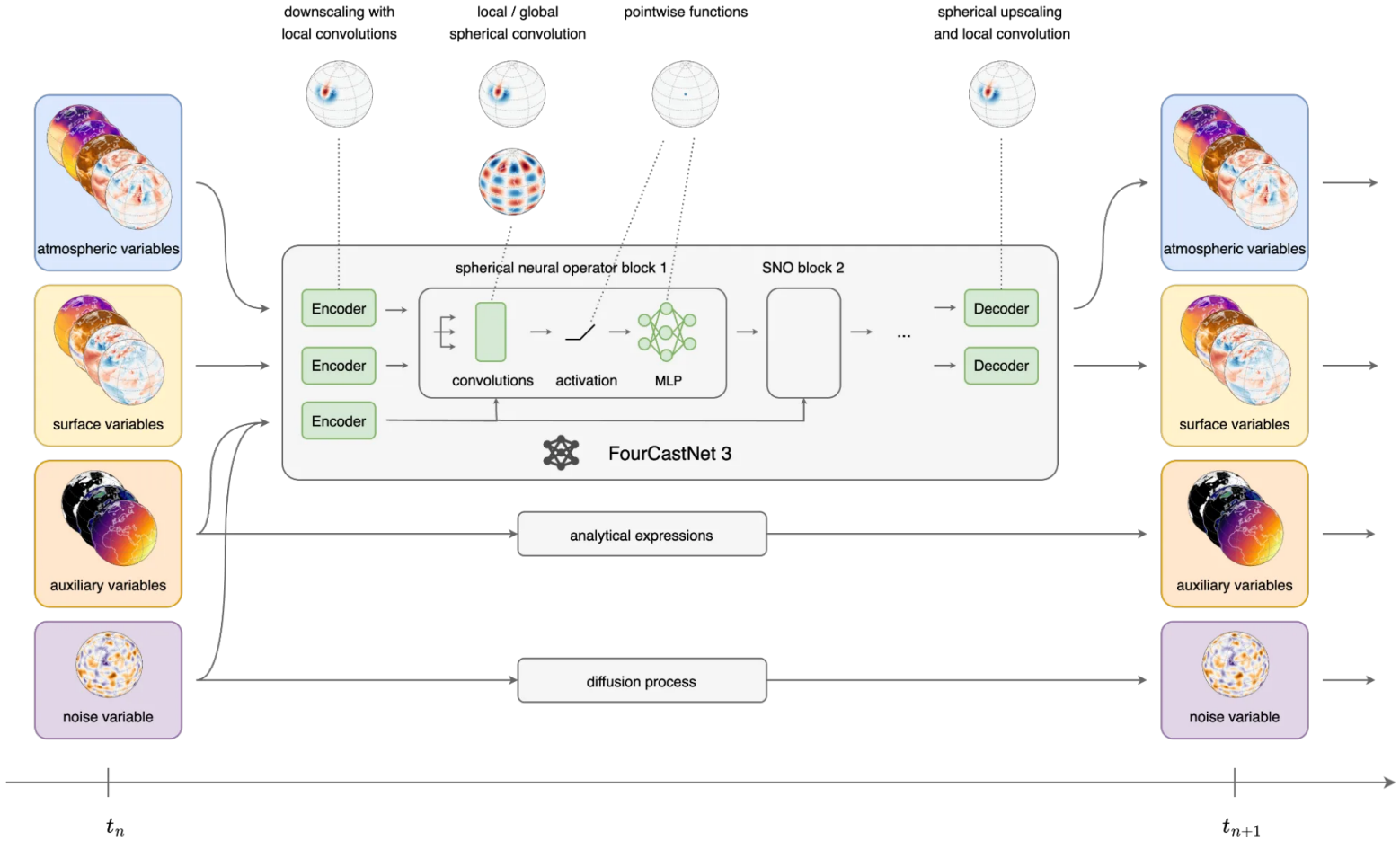


- Encode to graph representation
- Learned multi-mesh message-passing
- Decoder to lat/lon grid



Remi Lam *et al.* Learning skillful medium-range global weather forecasting.*Science* **382**,1416-1421(2023).DOI:10.1126/science.adi2336

FourCastNet 3 (NVIDIA)

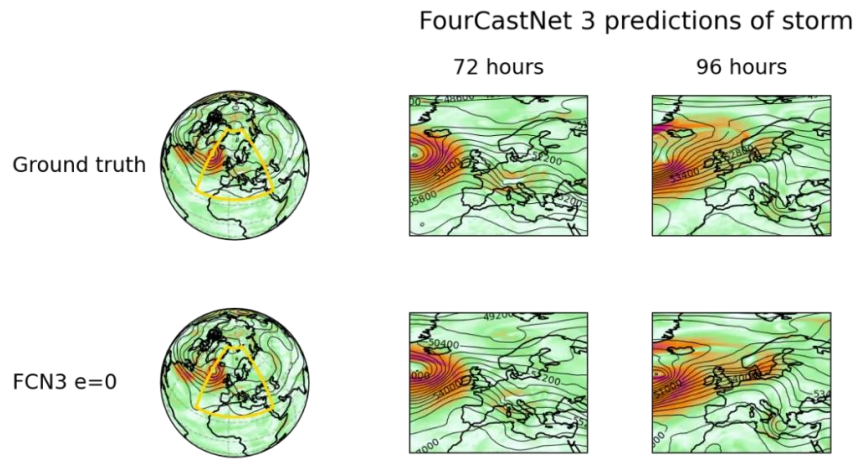


Local spherical convolutions + spectral convolutions

Noise injected for ensemble generation

Trained already as an ensemble (CRPS)

Domain decomposition for scaling



https://developer.nvidia.com/blog/fourcastnet-3-enables-fast-and-accurate-large-ensemble-weather-forecasting-with-scalable-geometric-ml/

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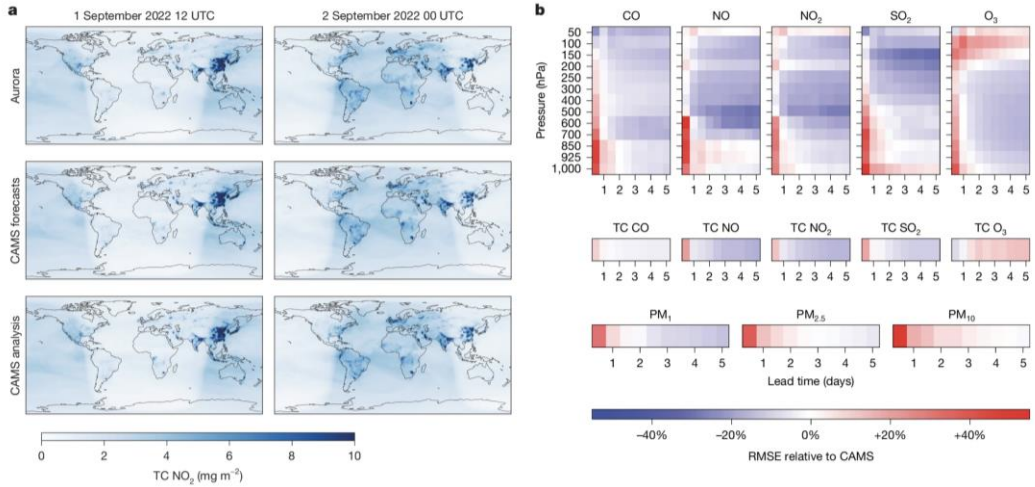
Aurora

- **A “Foundation Model” for the atmosphere**
  - Good out of the box weather forecasting skill
  - Designed to be “finetuned” to downstream tasks:
    - Atmospheric Chemistry
    - Ocean Waves
    - Cyclone tracking
    - High Resolution Forecasting

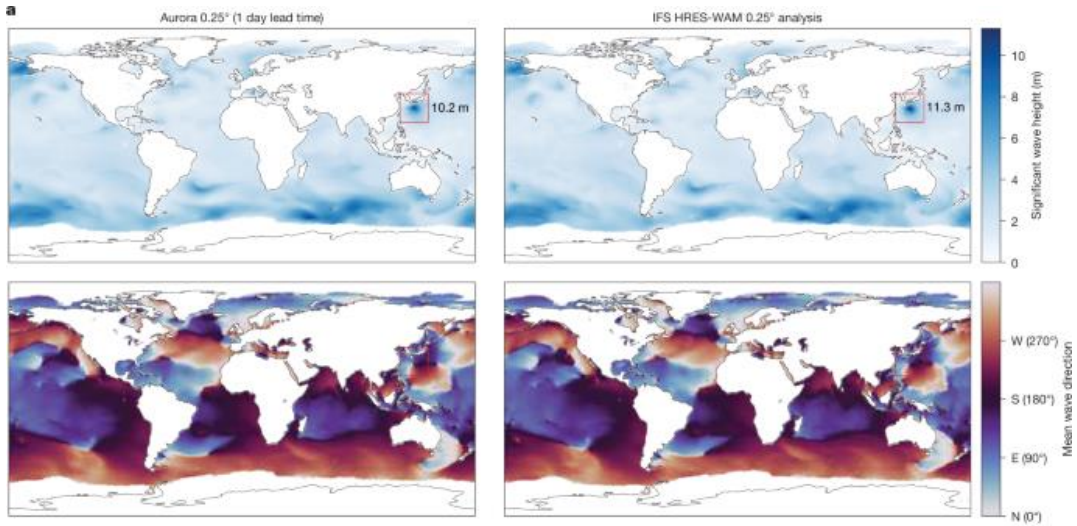
- **Potential for diverse applications with cheap computing**

- **The concept and usefulness of foundational model are currently debated!**

Chemistry:



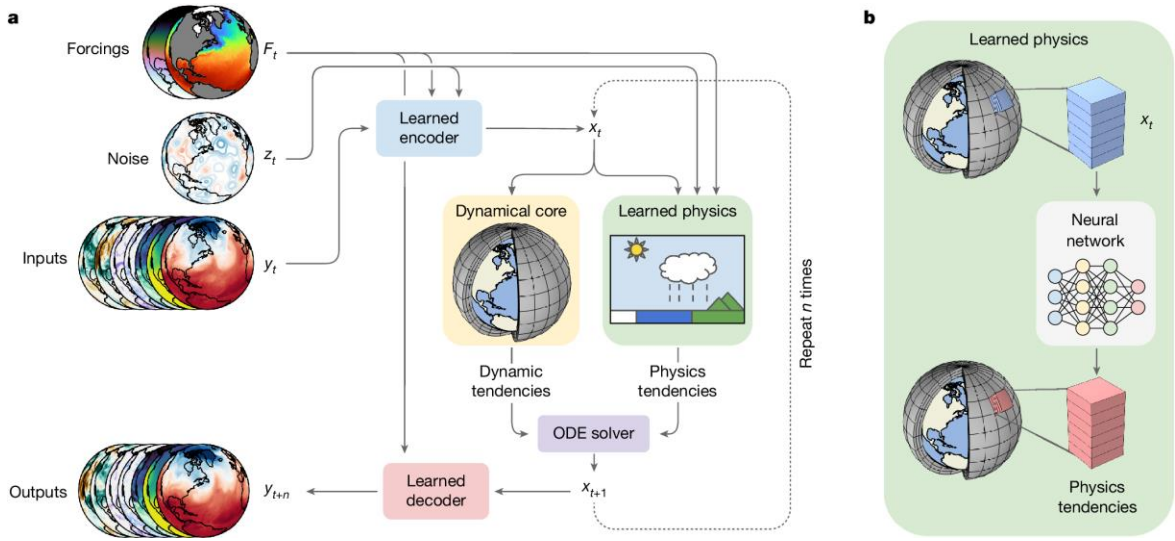
Ocean Wave Height

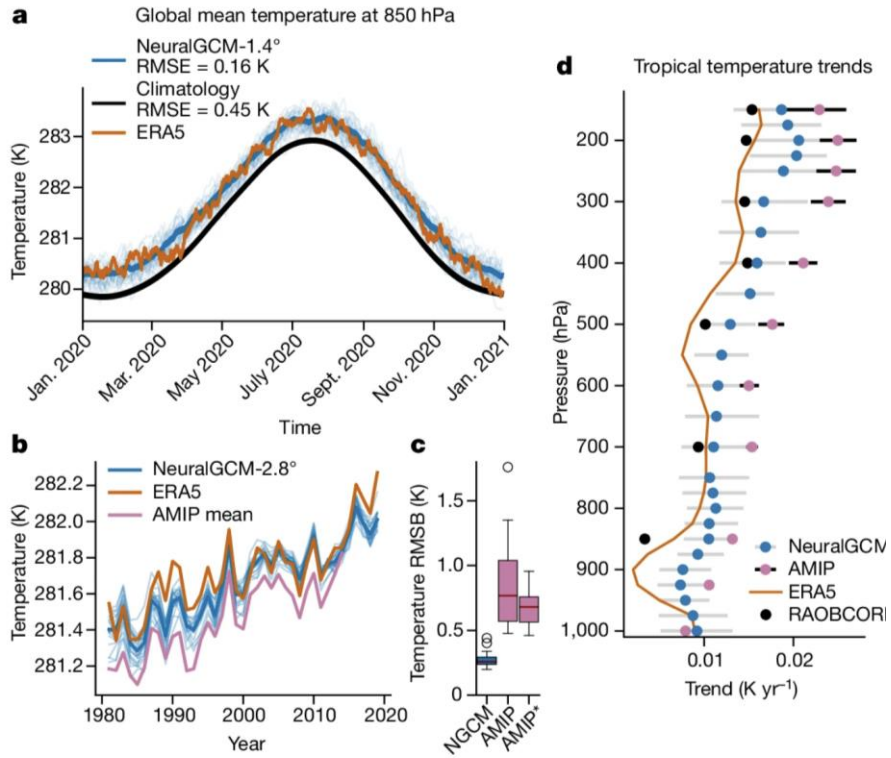


Bodnar, Cristian, et al. "A foundation model for the Earth system." *Nature* 641.8065 (2025): 1180-1187.

NeuralGCM

- Dynamical Core and Learned Parameterisations
- Fully Differentiable written in JAX
- The Parameterisations are learned „online“ while coupled to the rest of the model
- (Kind of) stable long term simulations
- Somewhat realistic Climate for AMIP timeframe (1979-2021) when using SSTs as boundary condition
- Robust features of climate warming at +1K and +2K

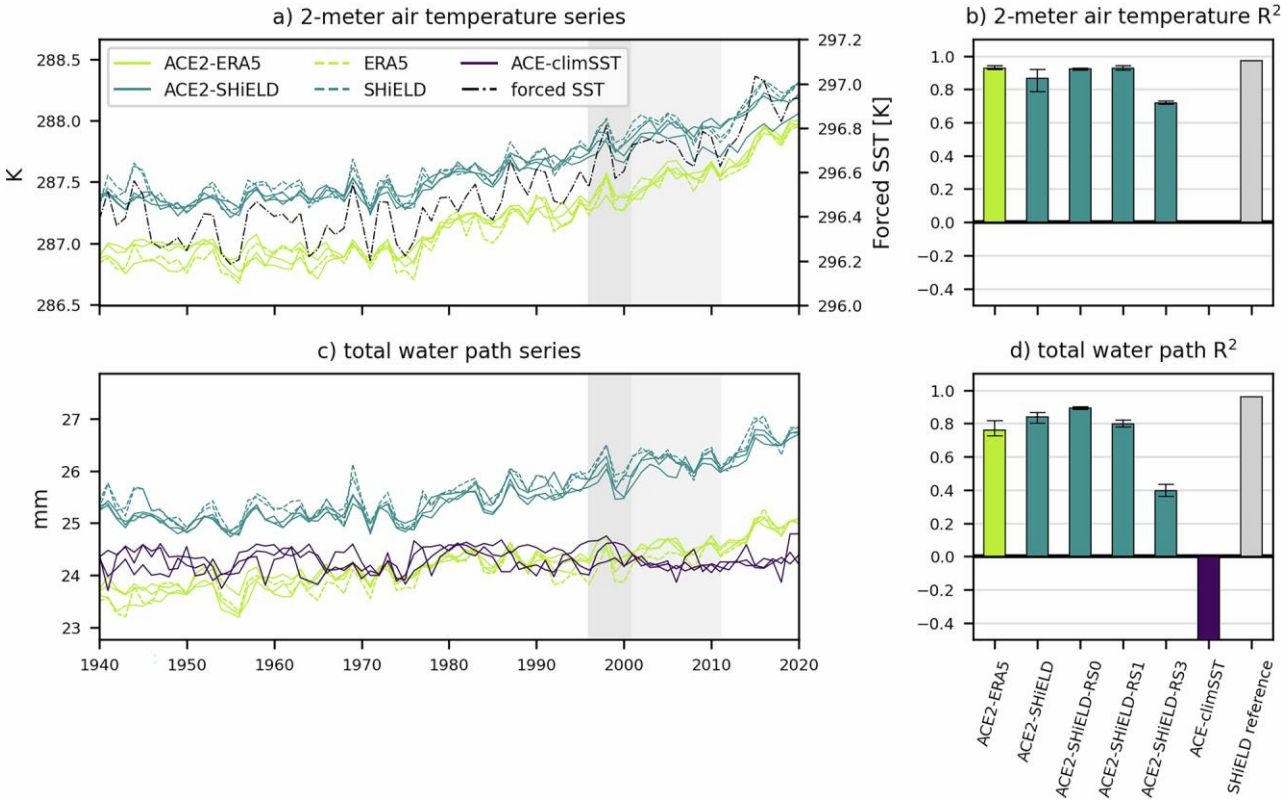




Kochkov, Dmitrii, et al. "Neural general circulation models for weather and climate." *Nature* 632.8027 (2024): 1060-1066.

ACE2

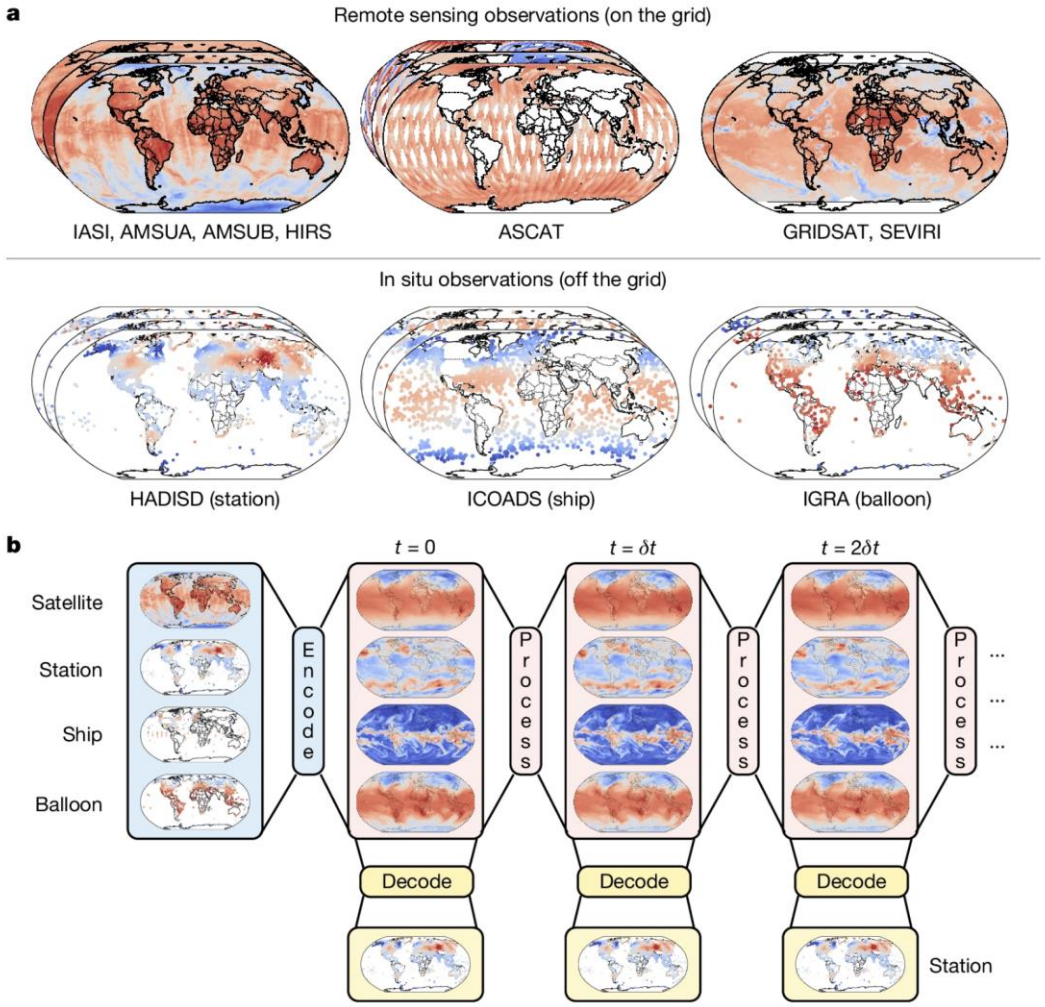
- **Exactly conserves global dry air mass and moisture**
- **1500 simulated years per wall clock day**
- **Captures variabilities, at least to some extent**
- **ACE-SOM:**
  - coupled to a slab ocean
  - Generalises (to some degree) to 4xCO2 conditions
- **SamudrACE**
  - Coupled to AI ocean model Samudr
- **AIMIP: https://github.com/ai2cm/AIMIP**



Watt-Meyer, Oliver, et al. "ACE2: accurately learning subseasonal to decadal atmospheric variability and forced responses." *npj Climate and Atmospheric Science* 8.1 (2025): 205.

Many More:

- AI-DOP: ECMWF's new model trained only on observations: https://arxiv.org/abs/2407.15586
- Aardvark: End-to-End weather prediction, including data assimilation: https://www.nature.com/articles/s41586-025-08897-0
- GenCast: Google's Diffusion Model: https://arxiv.org/abs/2312.15796
- ArchesWeather: Efficient small Model https://arxiv.org/abs/2405.14527
- FGN: https://arxiv.org/abs/2506.10772
- WeatherGenerator: https://weathergenerator.eu/
- AICON? DWD?
- …



Aardvark Model Structure

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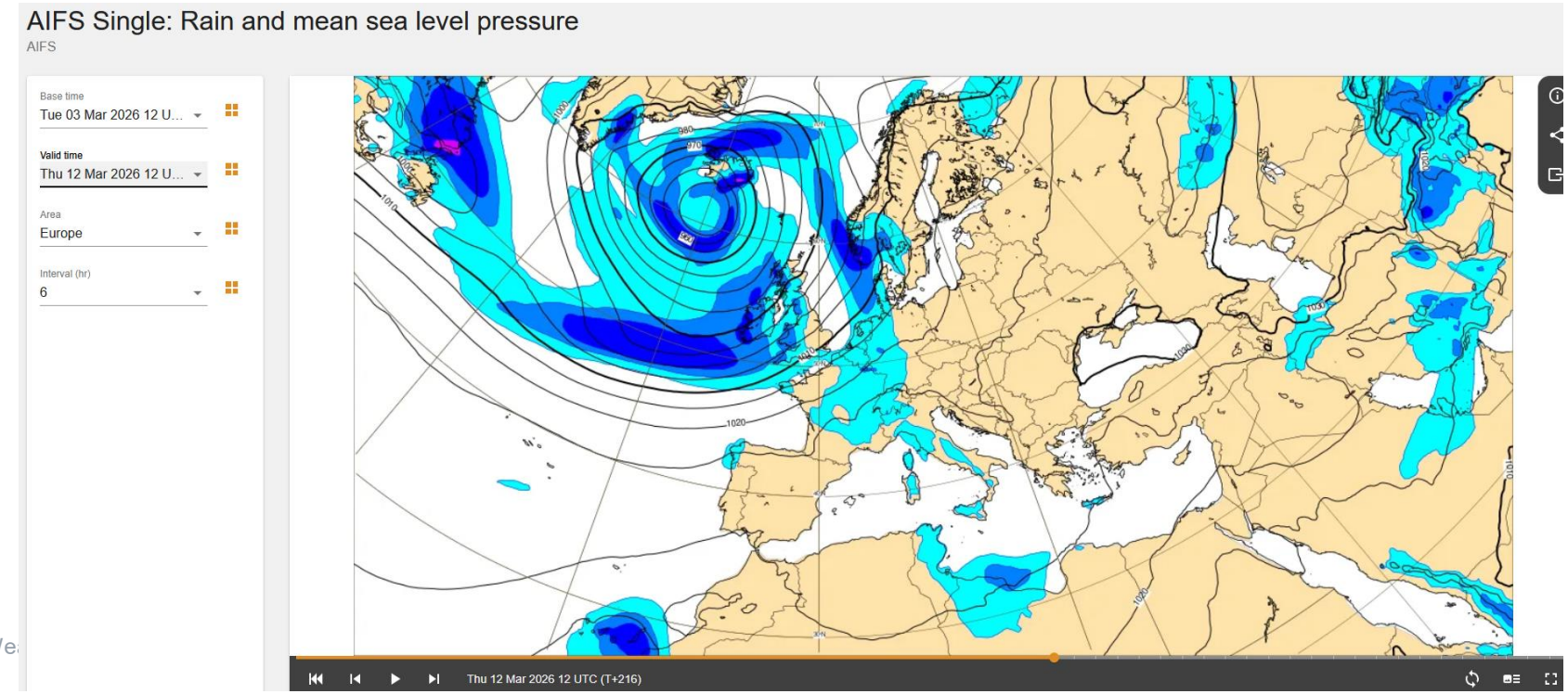
Operational AI weather models

- Training data (ERA5) with 5 day delay cannot be used for operational mode
- Operational models work with the same initialization data as the IFS forecasts

AI products at ECMWF: https://charts.ecmwf.int/catalogue/packages/ai_models/



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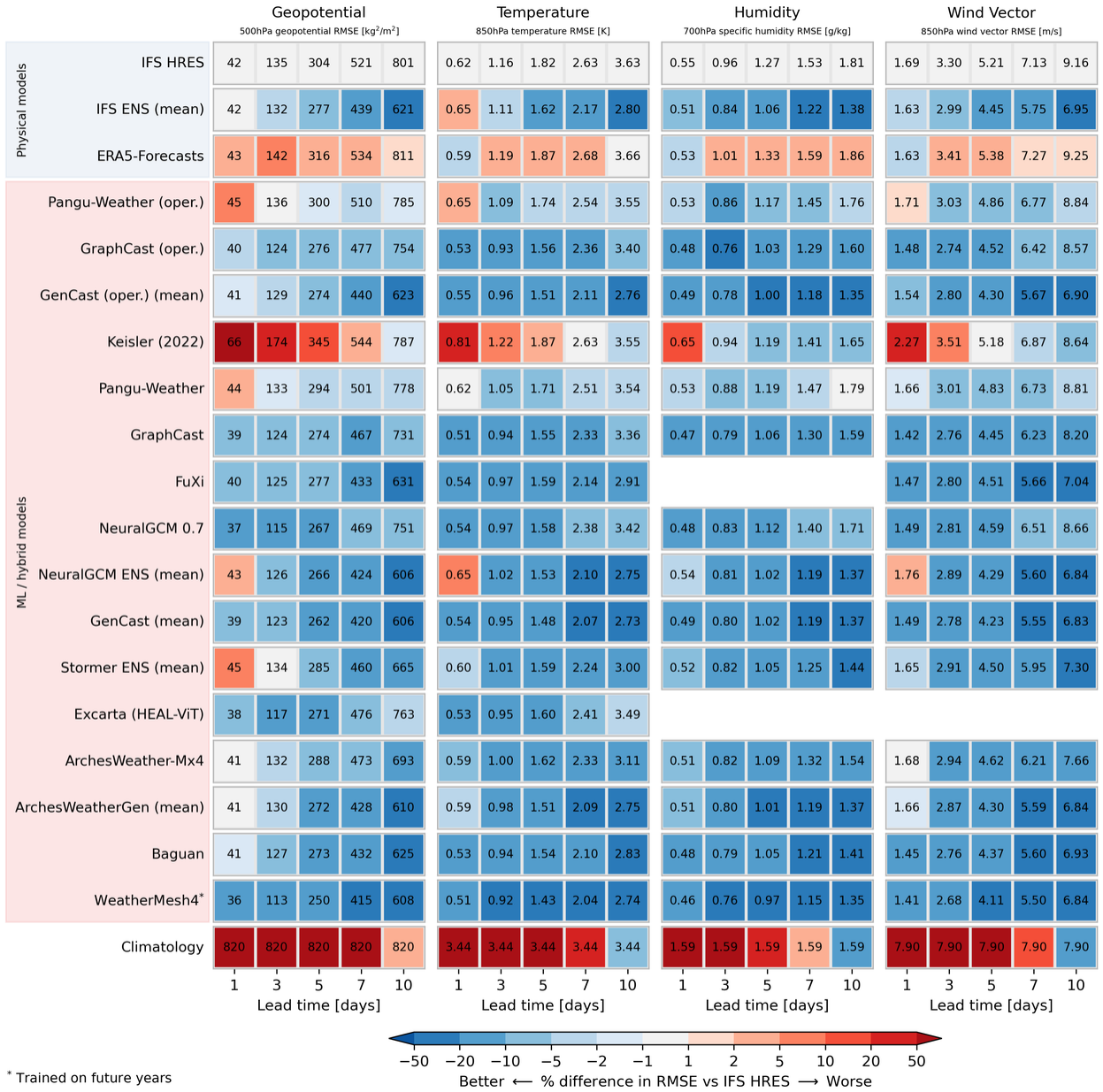
How to evaluate AI weather models



* Trained on future years

WeatherBenchX framework

https://sites.research.google/weatherbench/

Operational models evaluated agains IFS, all others against ERA5

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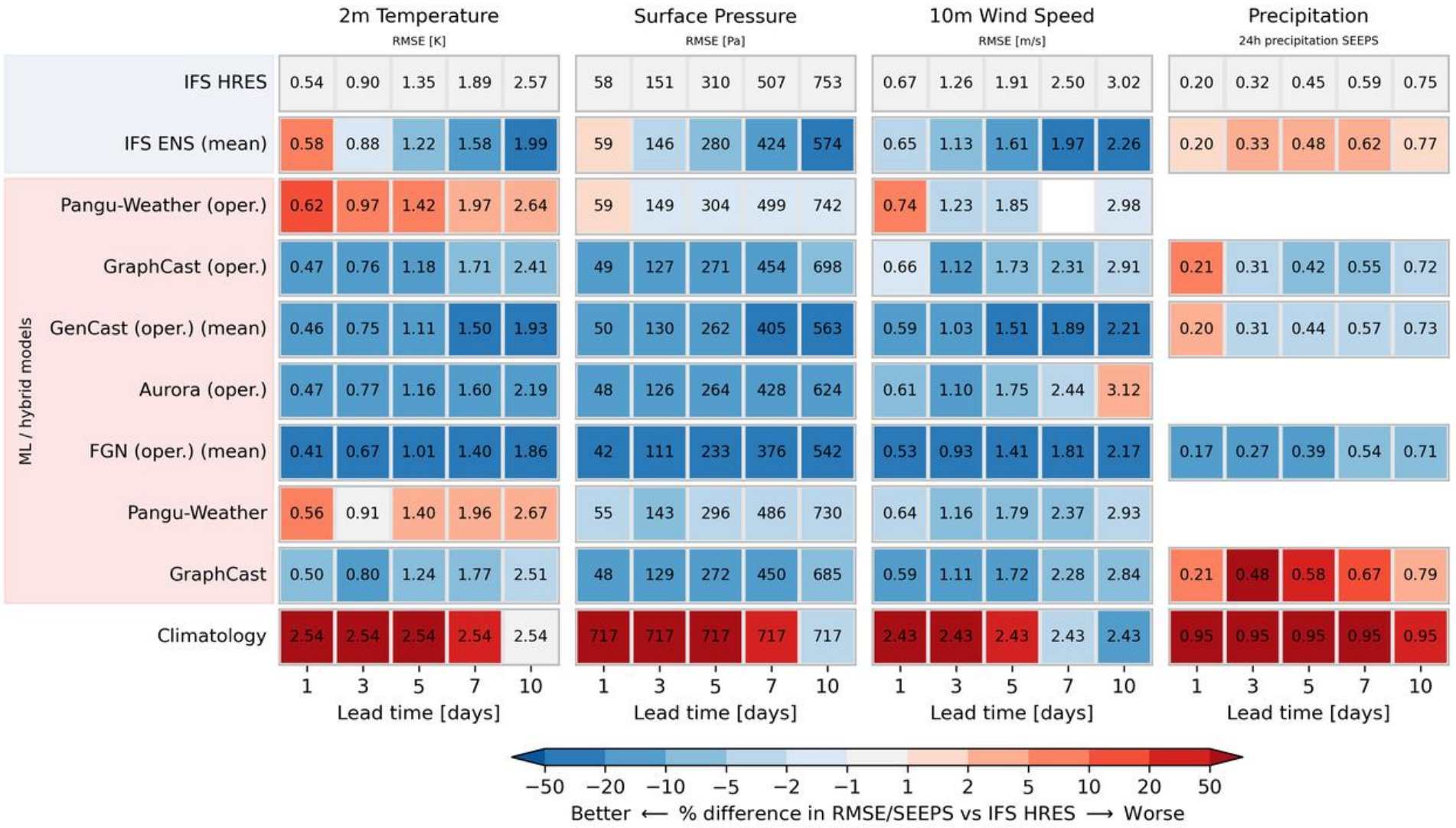
Challenges in AI weather prediction: Precipitation



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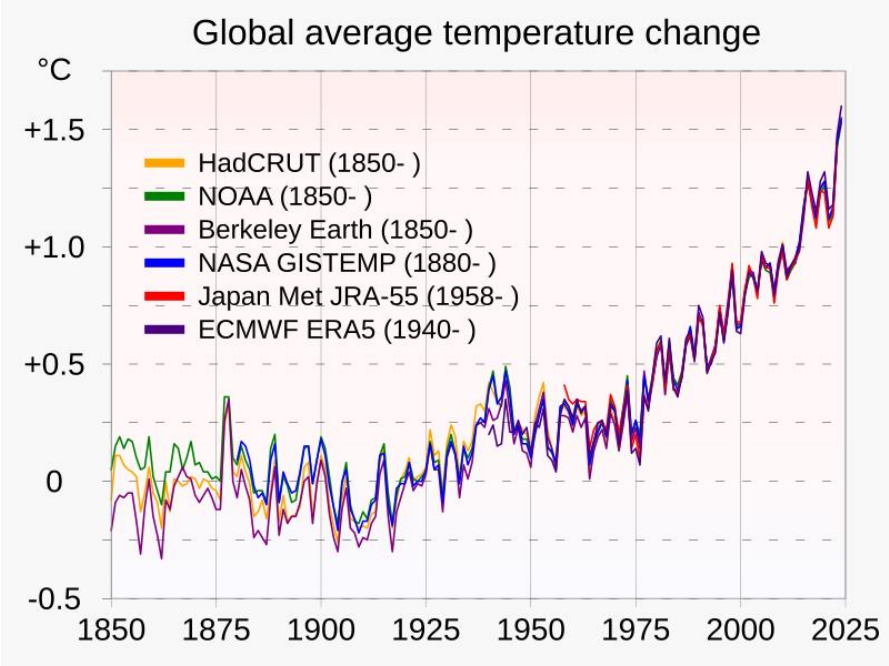
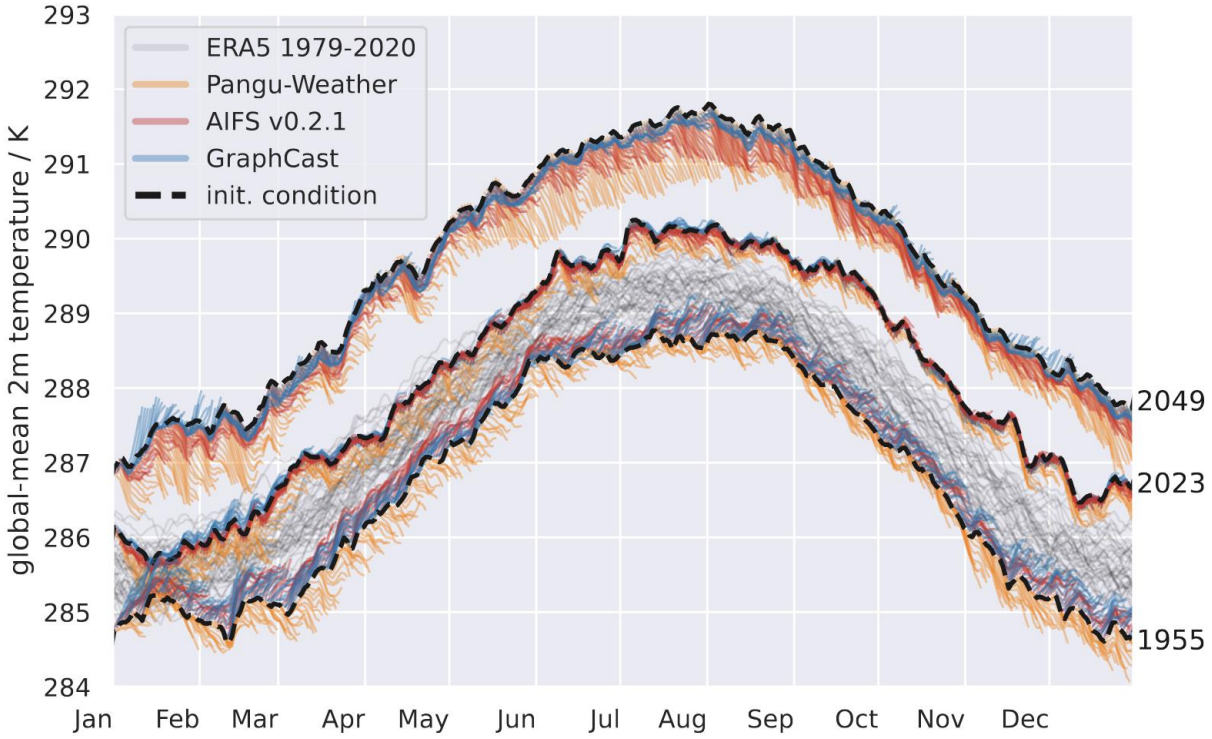
Challenges in AI weather prediction: Climate Drift

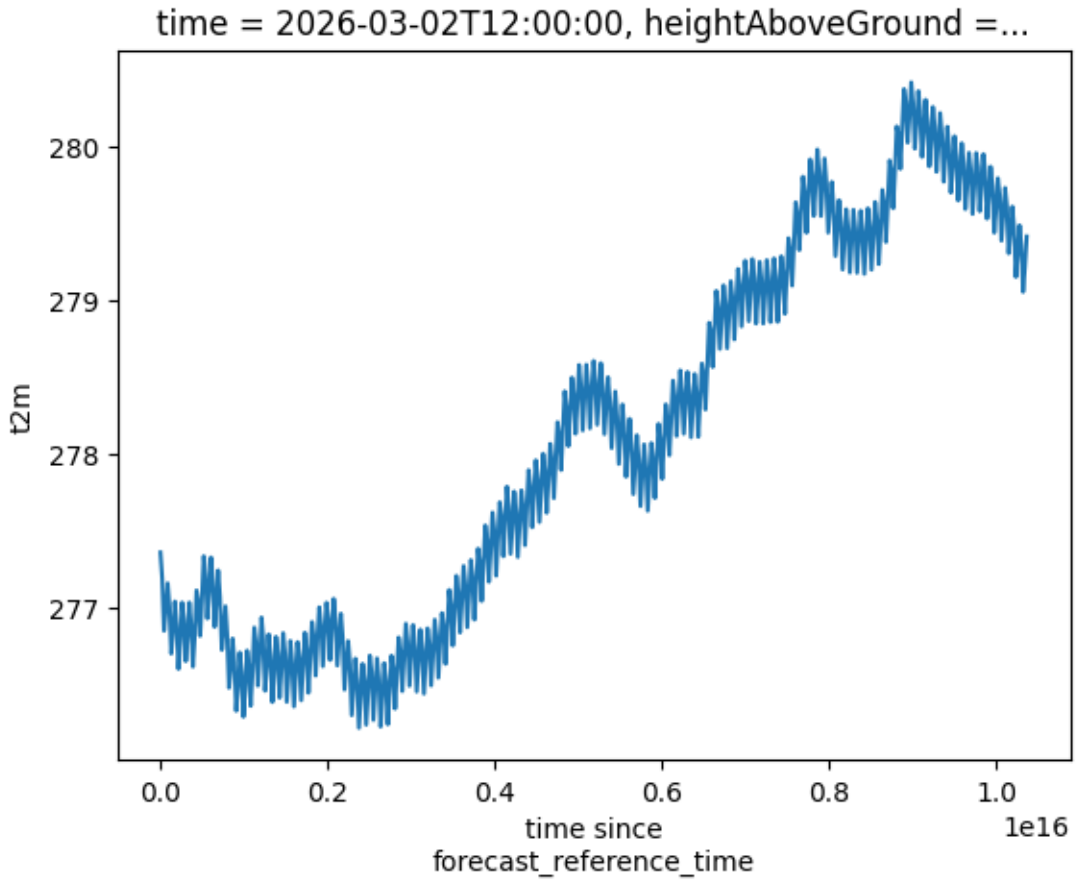
Warming climate: data drift





Rackow, Thomas, et al. "Robustness of AI-based weather forecasts in a changing climate." *arXiv preprint arXiv:2409.18529* (2024).

Global averaged 2m temperature (Fourcastnet) – up to 120 days ahead



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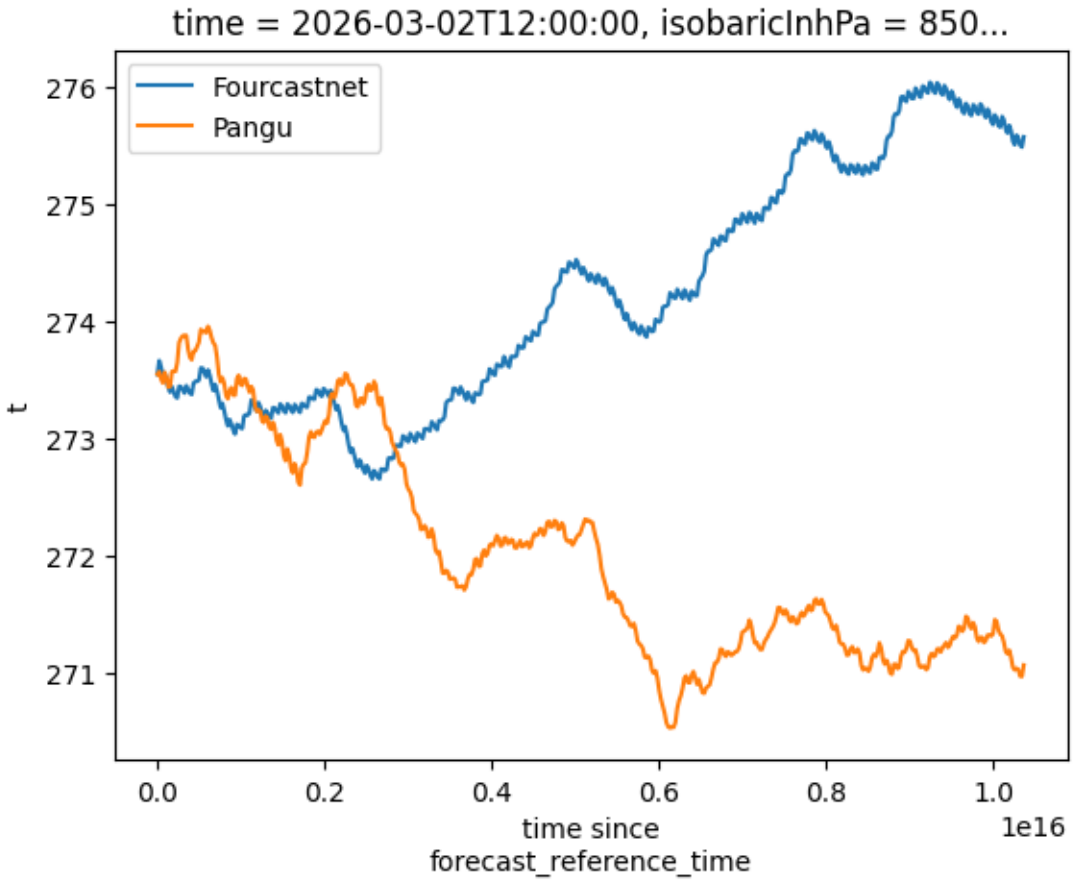
T850 global average up to 120 days ahead



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Challenges in AI weather prediction: Resolution

Wind Speed Simulated by IFS on 4km grid
https://www.youtube.com/watch?v=LBqWxNjpL2Y

Increase spatial / temporal resolution

- From 25 km to 1 km would be challenging for the transformer architecture (globally)
- Constant patch size: Higher resolution – smaller receptive field
  - 16 x 16 @ 25 km : 400 km
  - 16 x16 @ 1 km : 16 km
- HRES training data is HUGE and limited to few years
- Potential Solutions:
  - Witte et al, Field Space Attention (what you just saw): https://arxiv.org/abs/2512.20350
  - Brenowitz, Noah D., et al. "Climate in a bottle: https://arxiv.org/abs/2505.06474

How to run an AI weather forecast

Requirements

- Trained model weights
- Initialisation data, e.g. from ERA5 or IFS
- GPU (although some work on CPU)

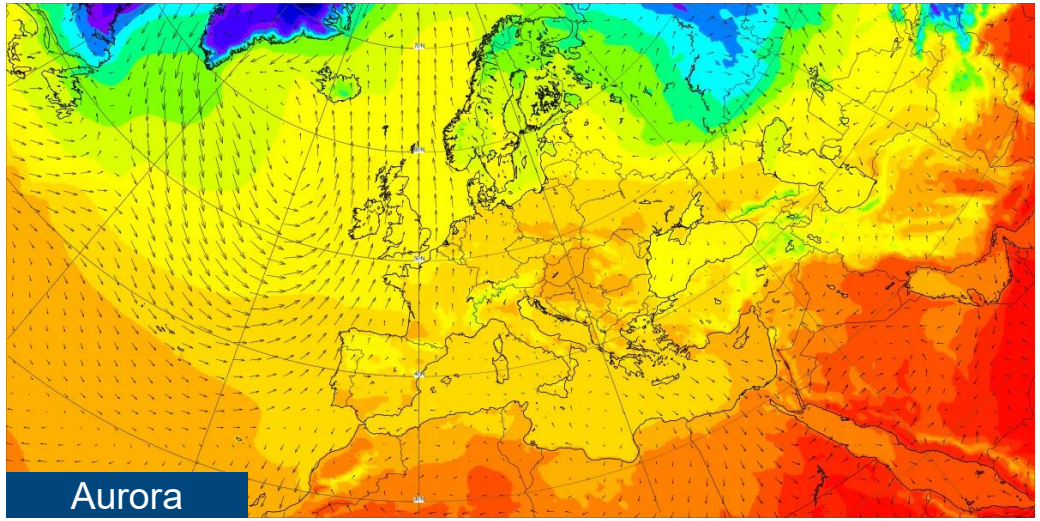
Useful libraries

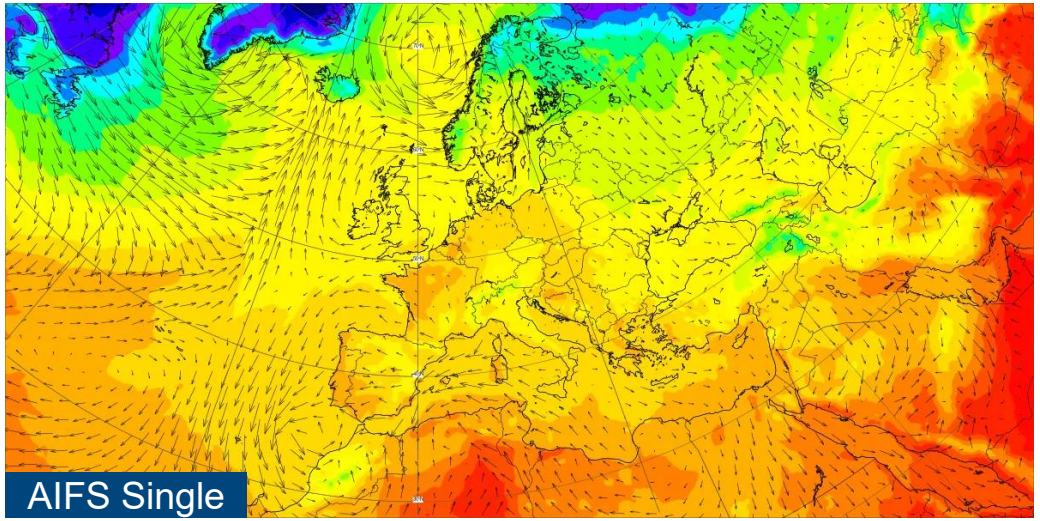
- ECMWF-LAB: ai-models
  https://github.com/ecmwf-lab/ai-models
- Anemoi: ECMWF framework for training/inference

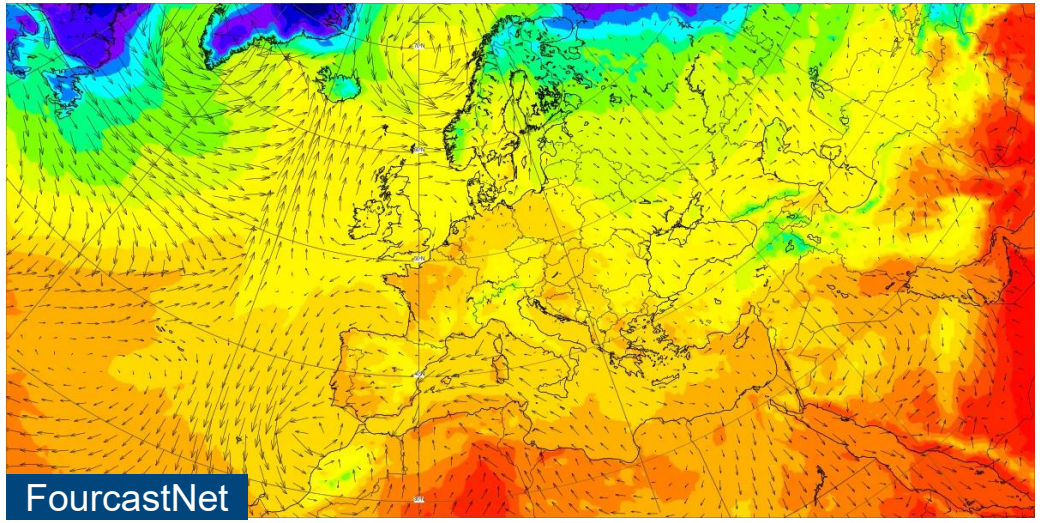
- Full model emulator, e.g. ACE:
  https://github.com/ai2cm/ace

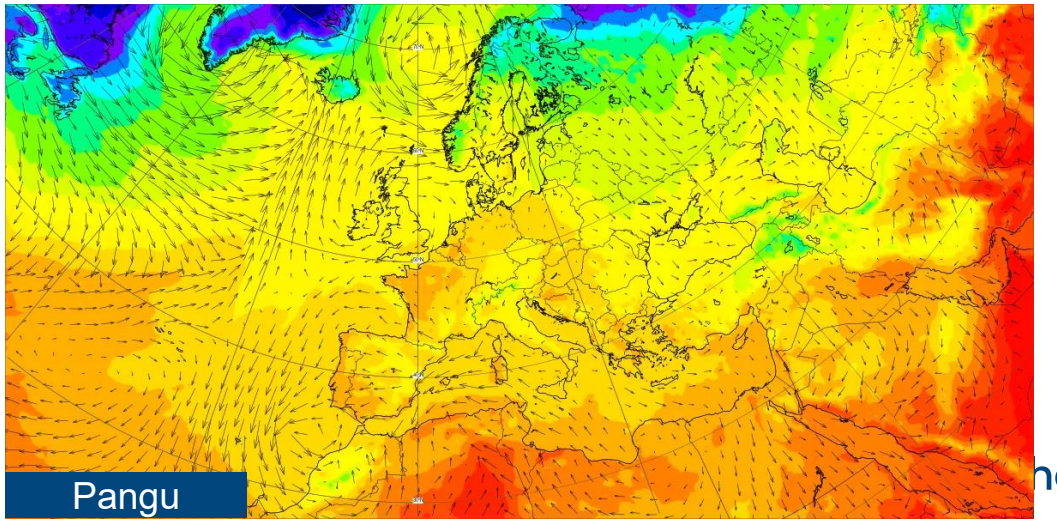
Some results of AI weather models …

Today‘s weather, forecasts initialised March 3

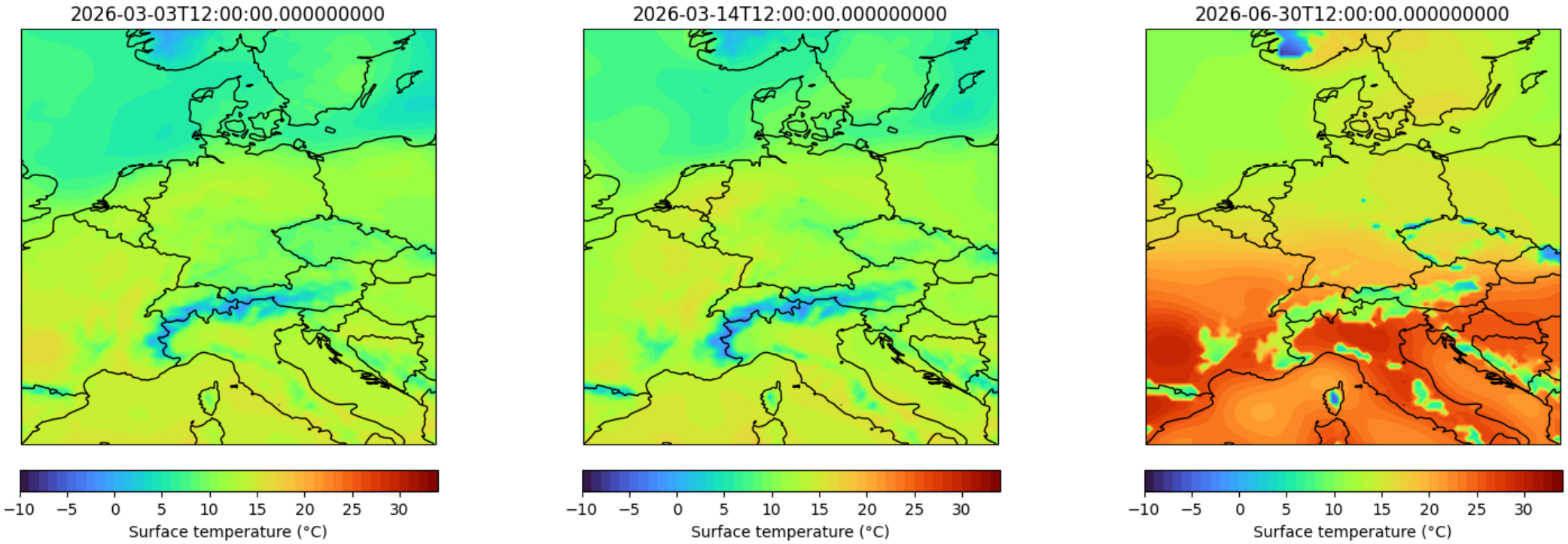








Fourcastnet initialised on 2026-03-02



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Questions and Feedback