



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

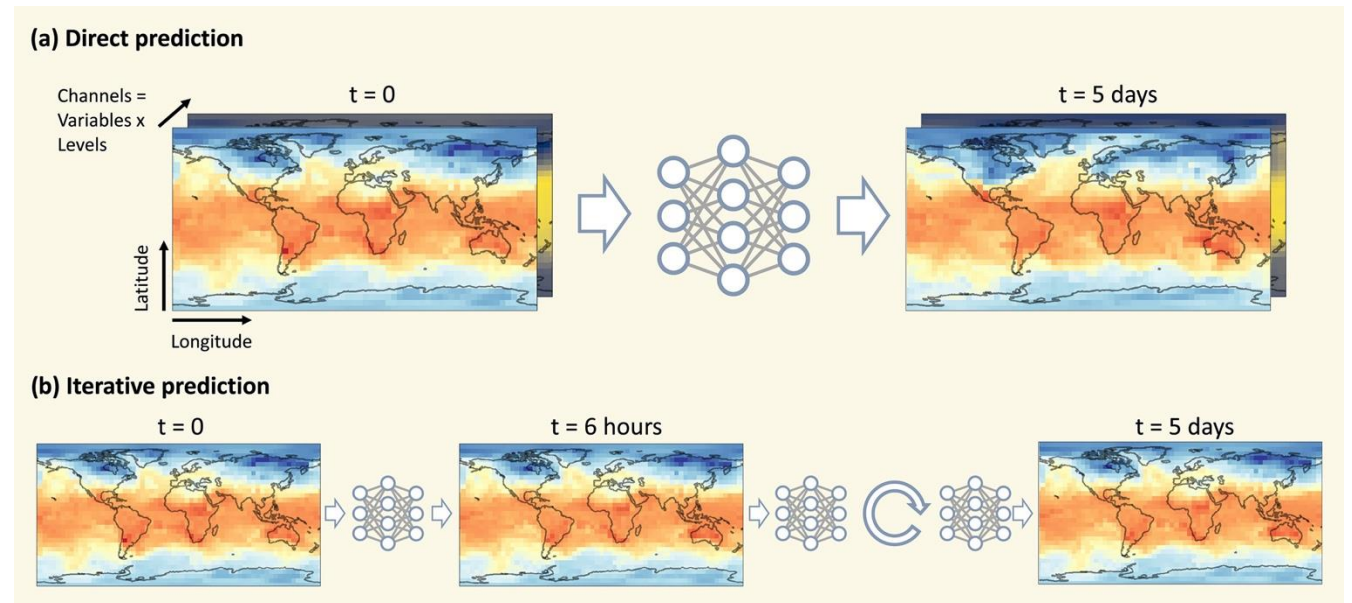
Paul Keil & Caroline Arnold 23.09.2026

HELMHOLTZAI Artificial Intelligence
Cooperation Unit



How does AI weather prediction work?

- **Numerical weather prediction**
 - Take initial state of the atmosphere
 - Update to next time step by solving complex equations
 - CFL criterion
- **AI weather prediction**
 - „Image“ to „image“ translation
 - Longer timesteps possible
 - More than 10,000 times cheaper!



Training data: Reanalysis

- **ERA5**

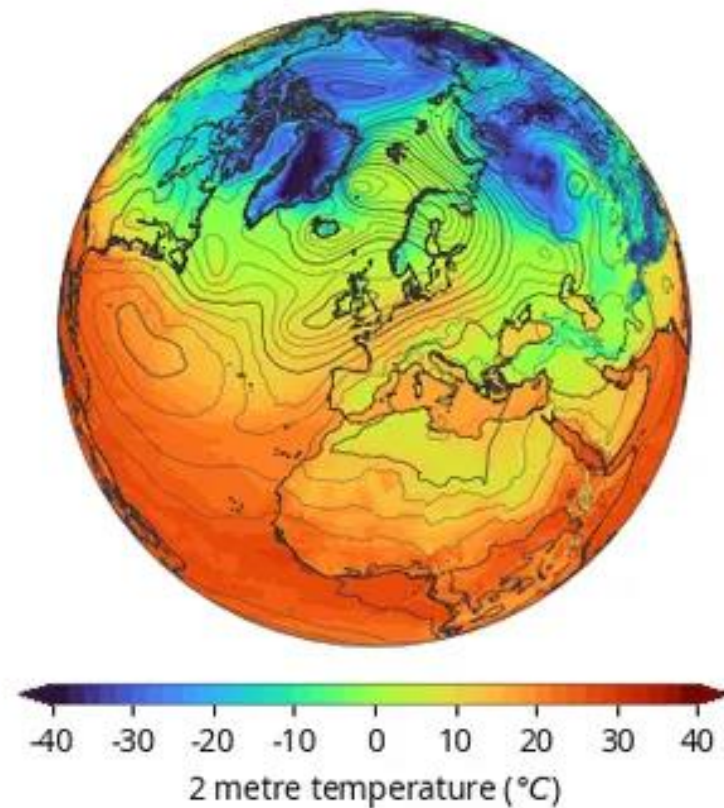
- Atmosphere, ocean-wave, land surface
- Resolution: 0.25° (25 km) / 1 h / 37 pressure levels
- Regular latitude/longitude grid
- Available 1940 – today
- Latency: 5 days
- Total dataset size: ~ TB

- **ICON-DREAM (NEW!)**

- Higher spatial resolution, shorter timespan

- **Sometimes raw observations are also used**

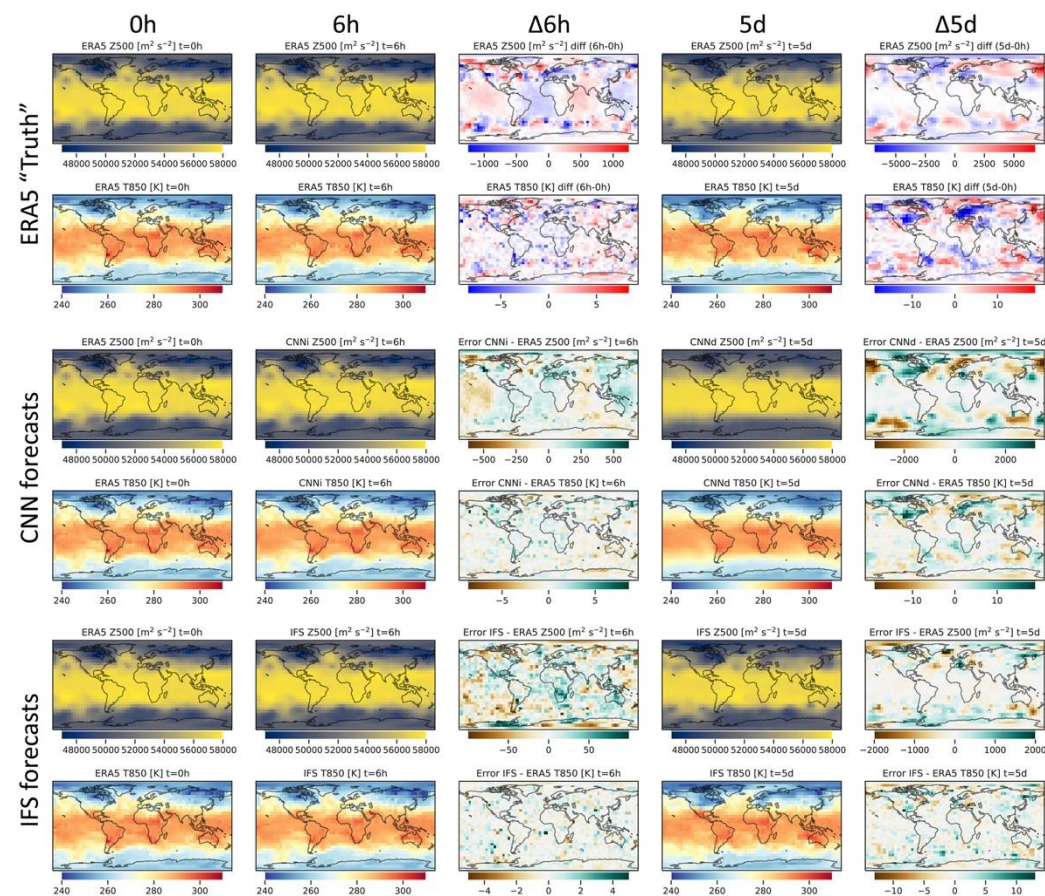
ERA5 2 metre temperature and Mean sea level pressure
1 January 2023 at 00:00 UTC

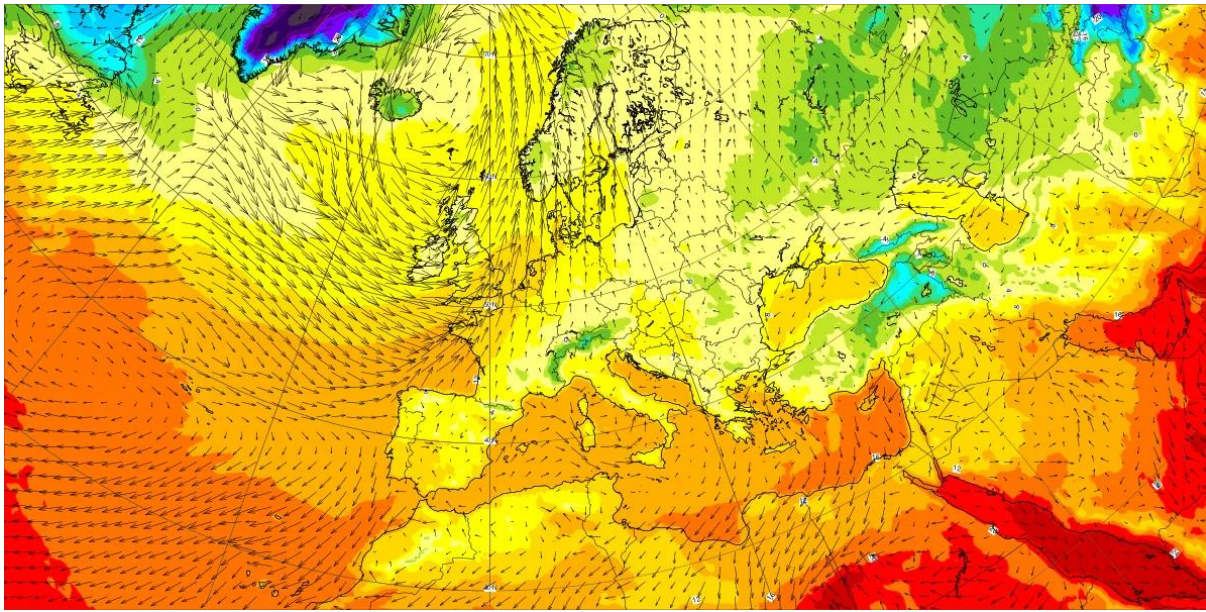


First steps: Simple Convolutional Neural Network (CNN)

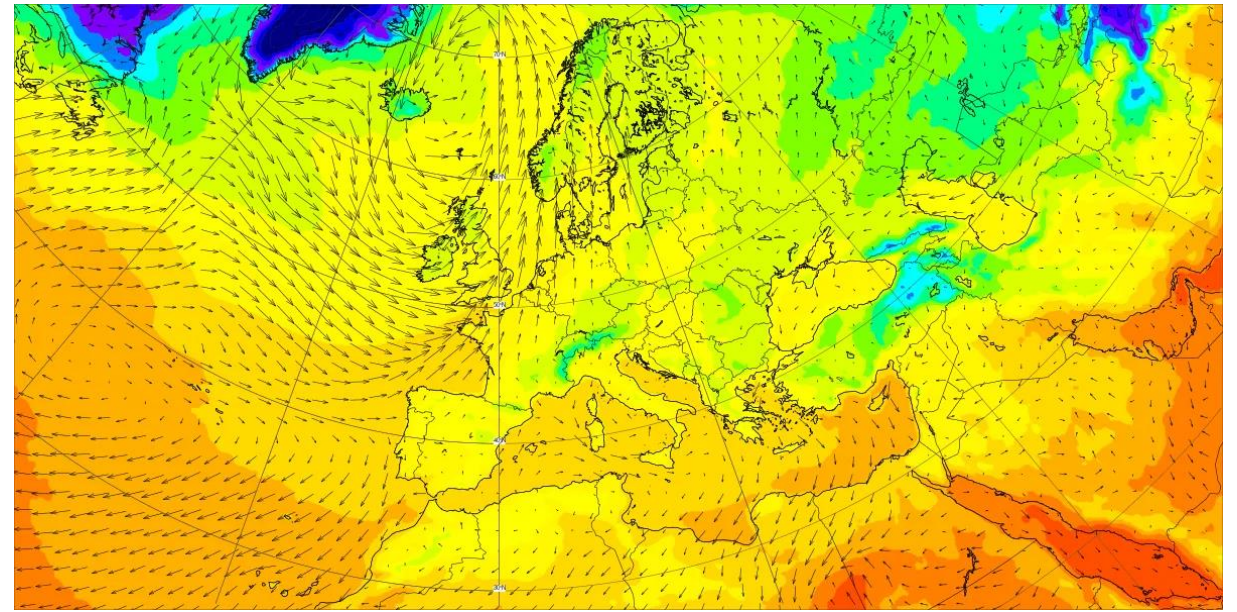
Rasp et al (2020)

- 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





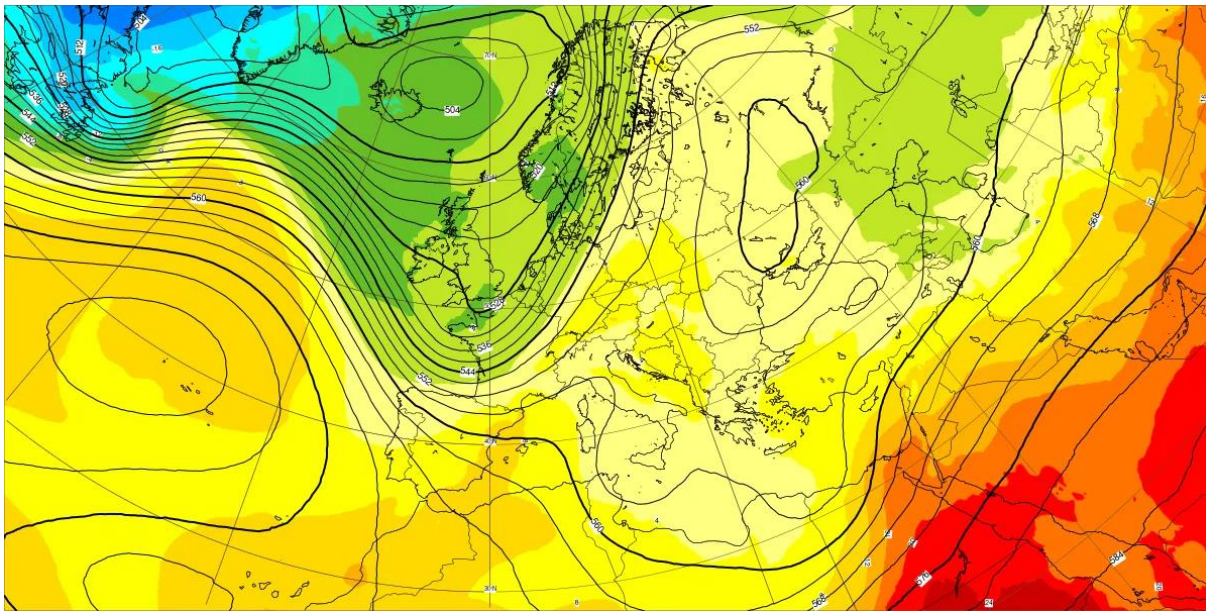
ECMWF Control (ex-HRES)



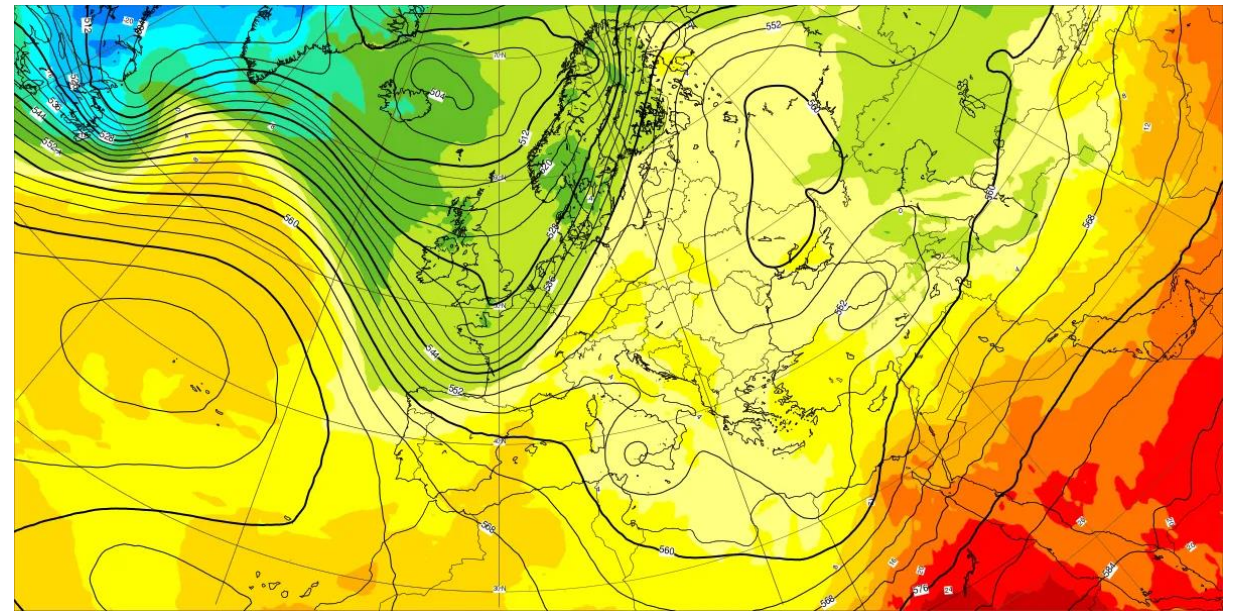
AI Forecast (Pangu, 2022)

T + 24H

**2m temperature
30 m wind**



AI Forecast (Aurora, 2025)

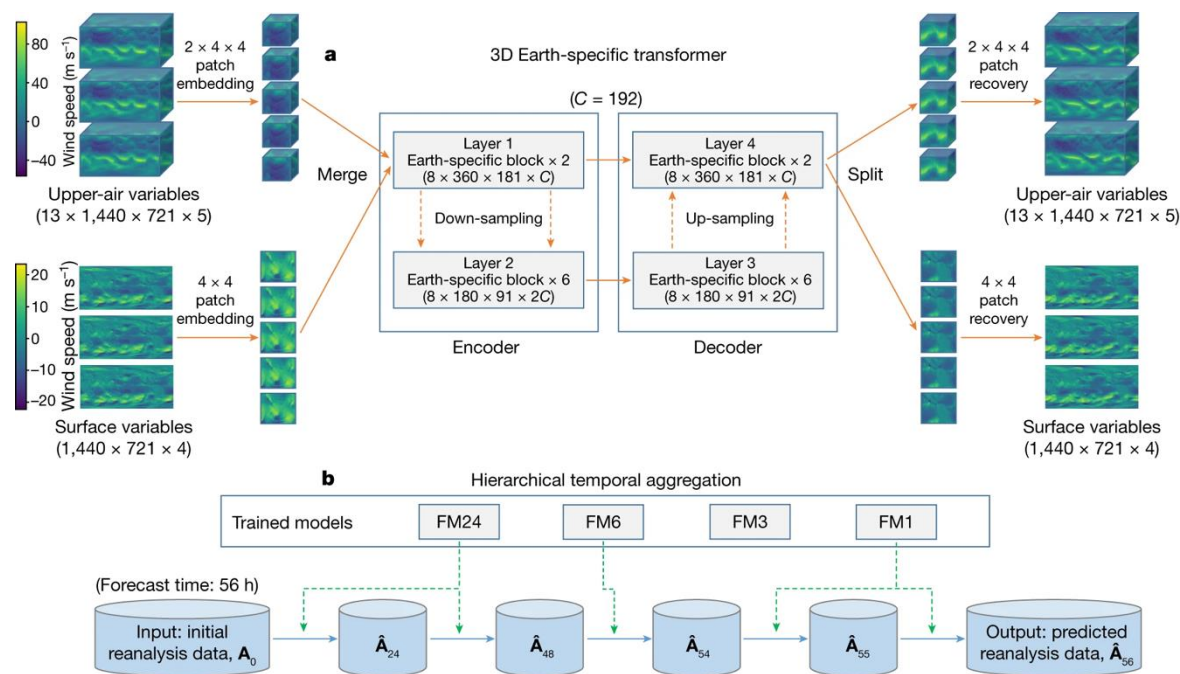


ECMWF Control (ex-HRES)

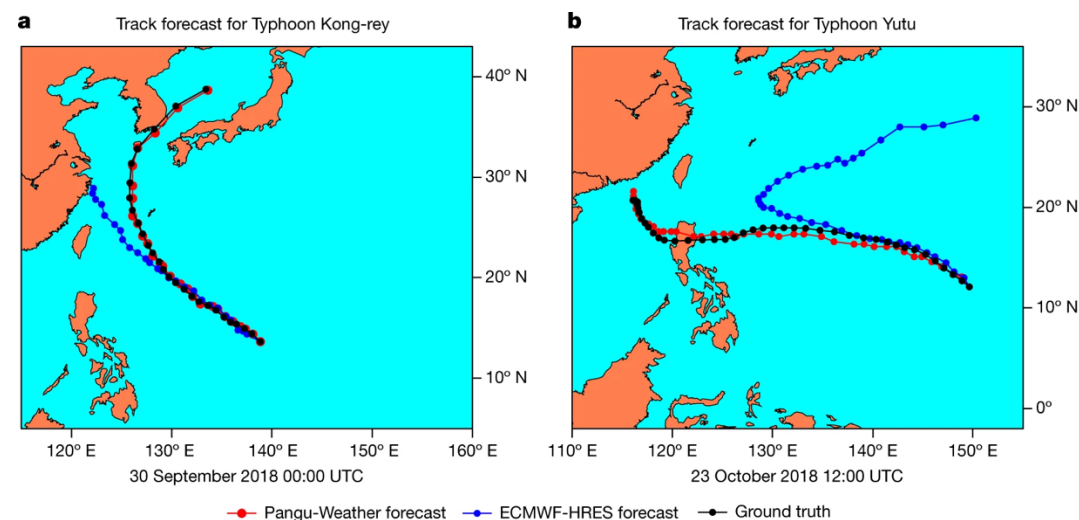
T + 48H

500 hPa geopotential height and 850 hPa temperature

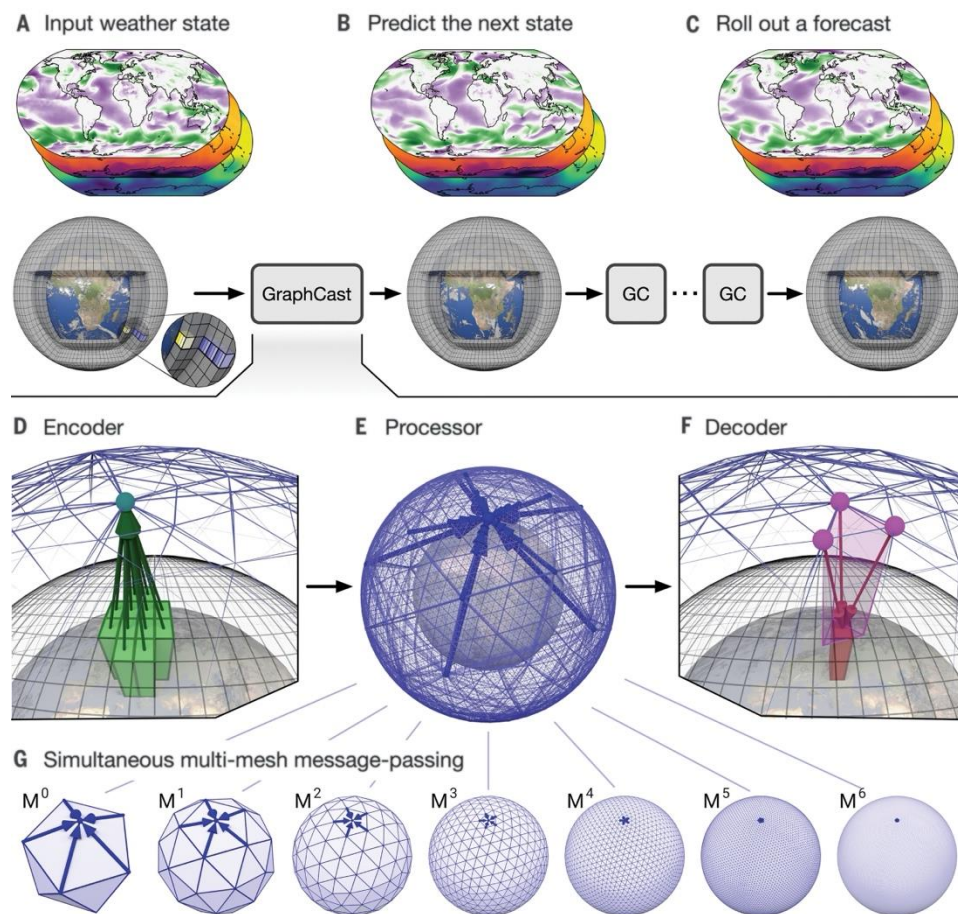
PanguWeather



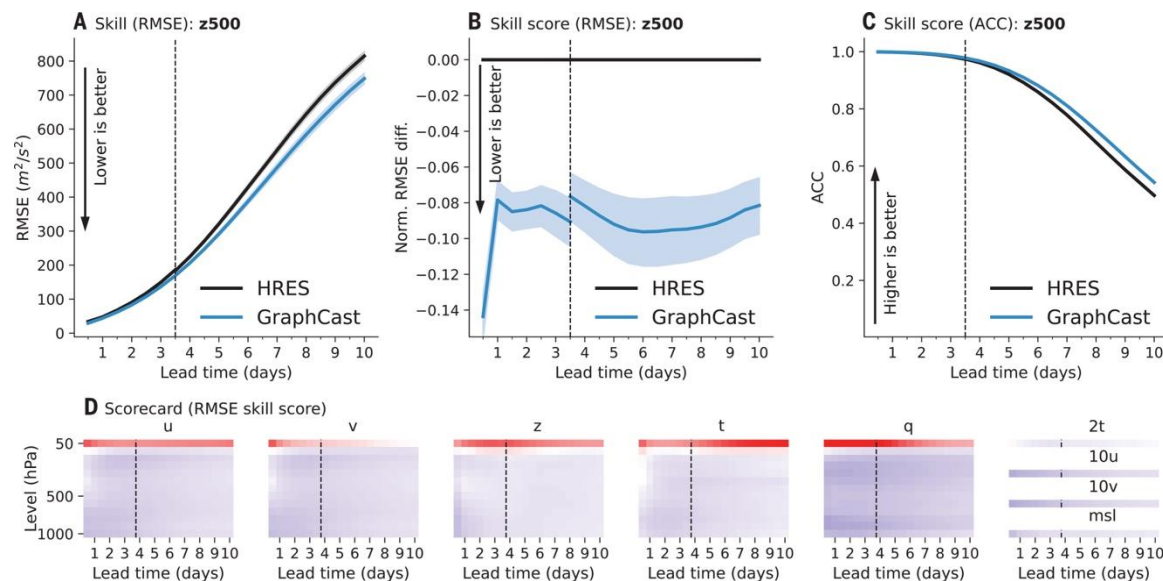
- 3D transformer
- Based on sliding window (SWIN) transformer
- Tokens with positional encoding (lat/lon)
- Trained for 4 lead times (1H, 3H, 6H, 24H)



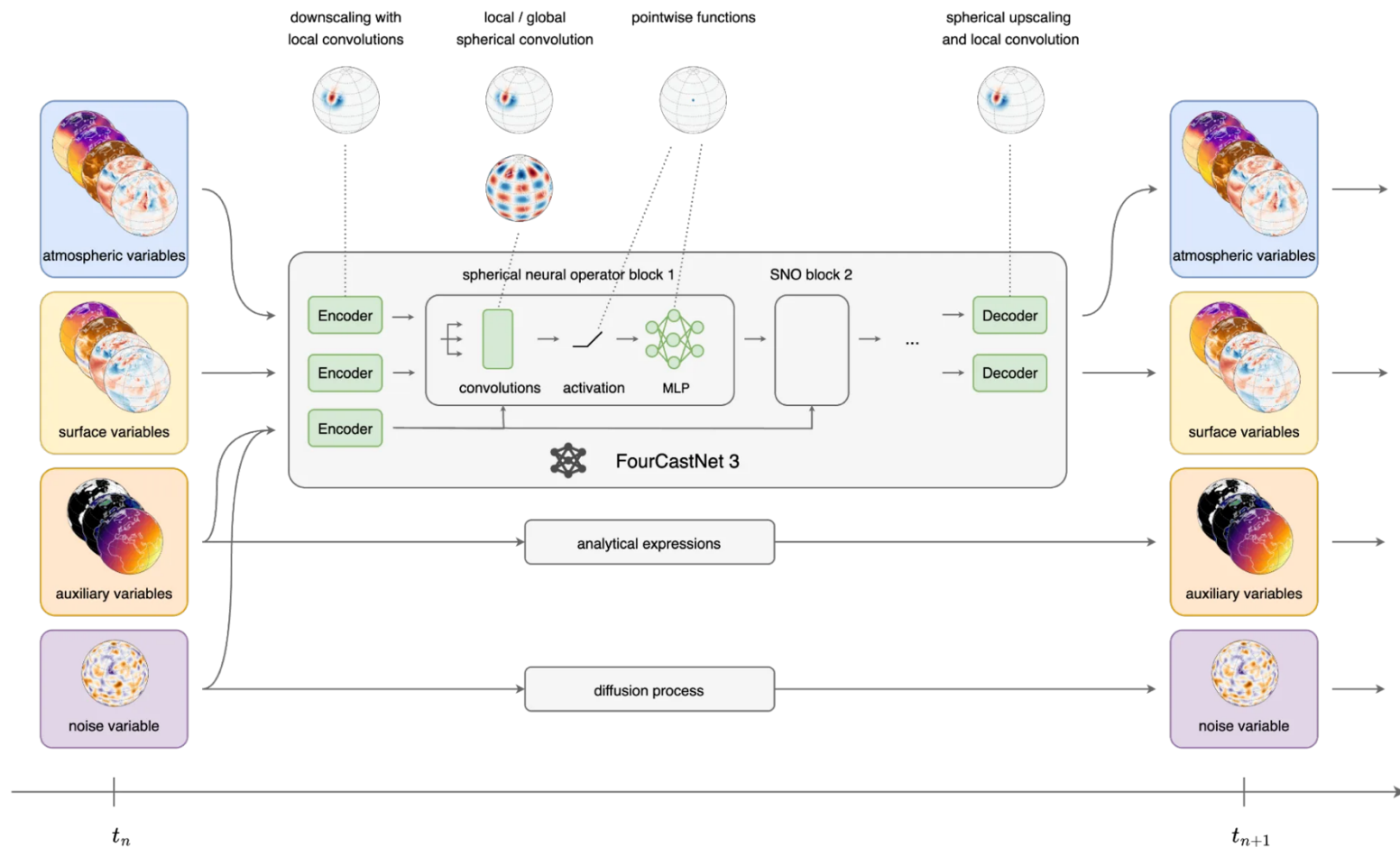
GraphCast (Deepmind)



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



FourCastNet 3 (NVIDIA)

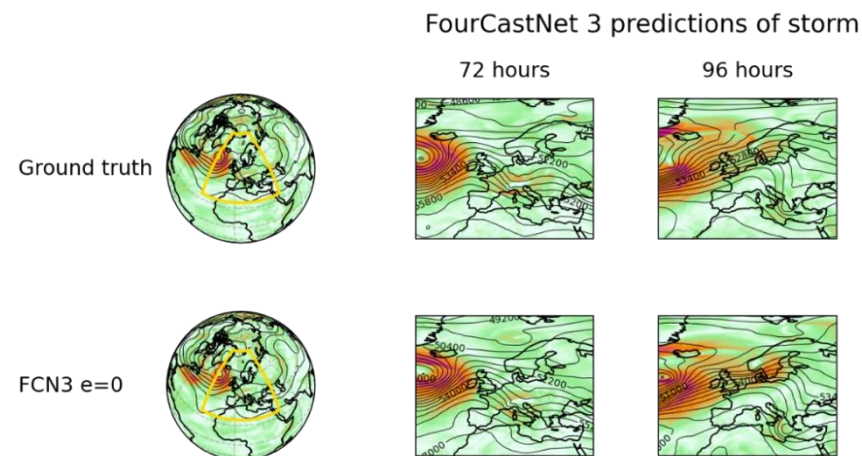


**Local spherical convolutions
+ spectral convolutions**

Noise injected for ensemble generation

Trained already as an ensemble (CRPS)

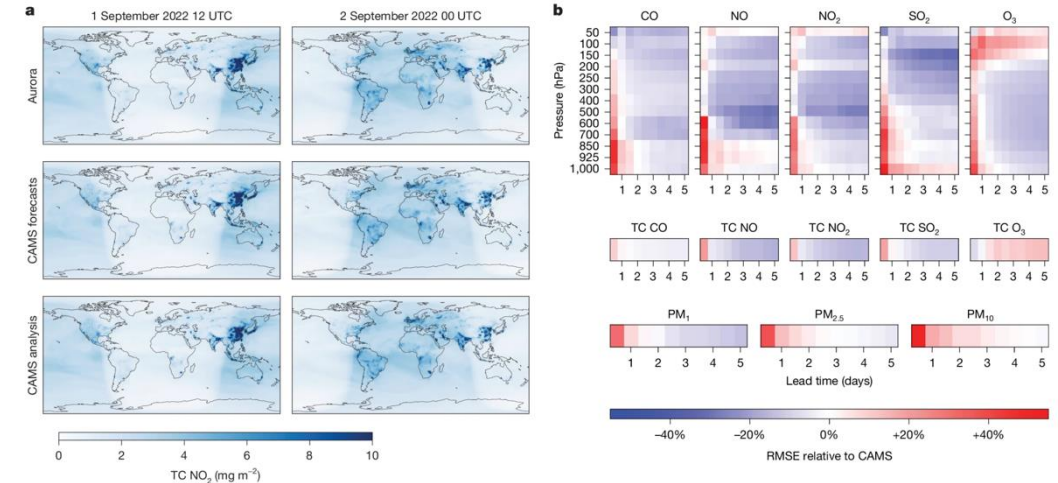
Domain decomposition for scaling



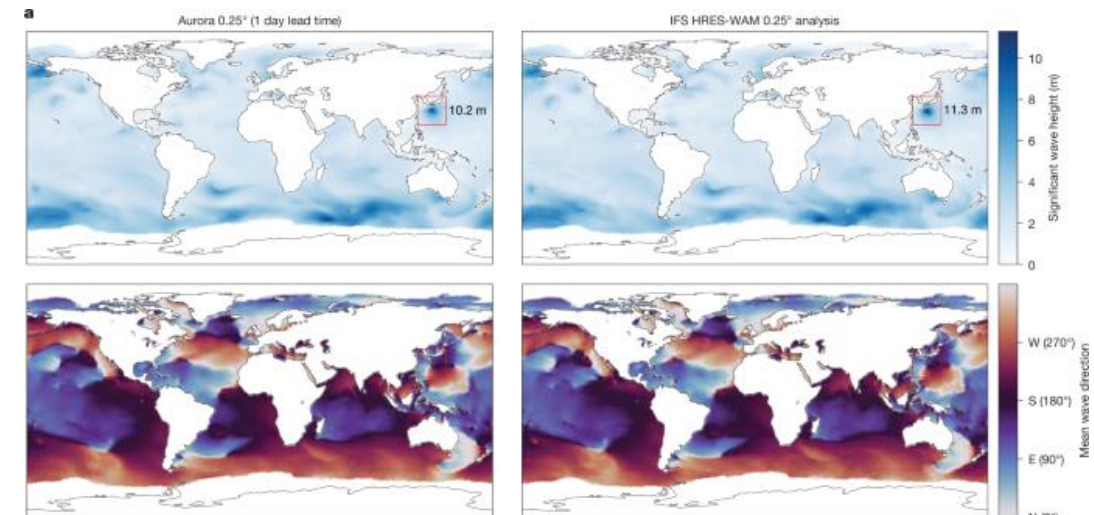
Aurora

- 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:

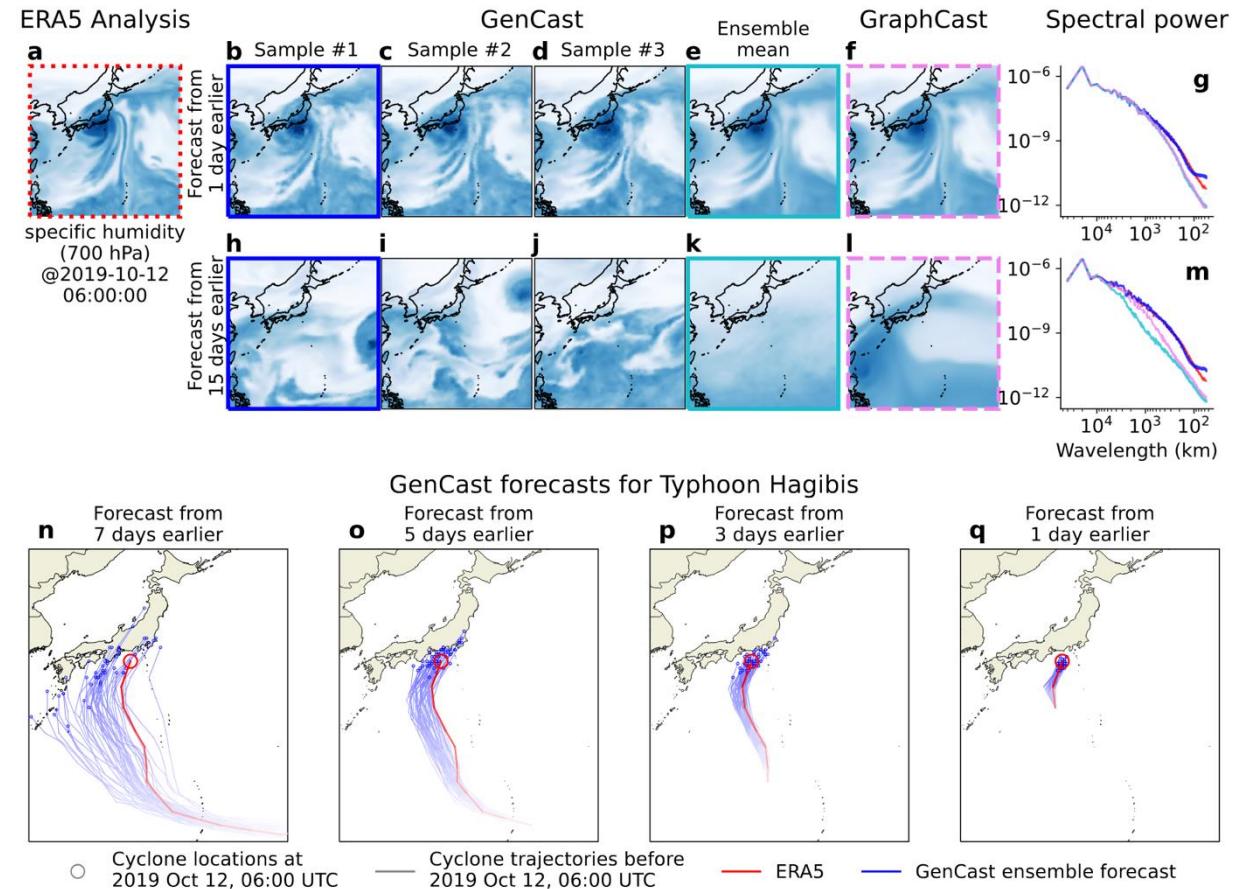


Ocean Wave Height



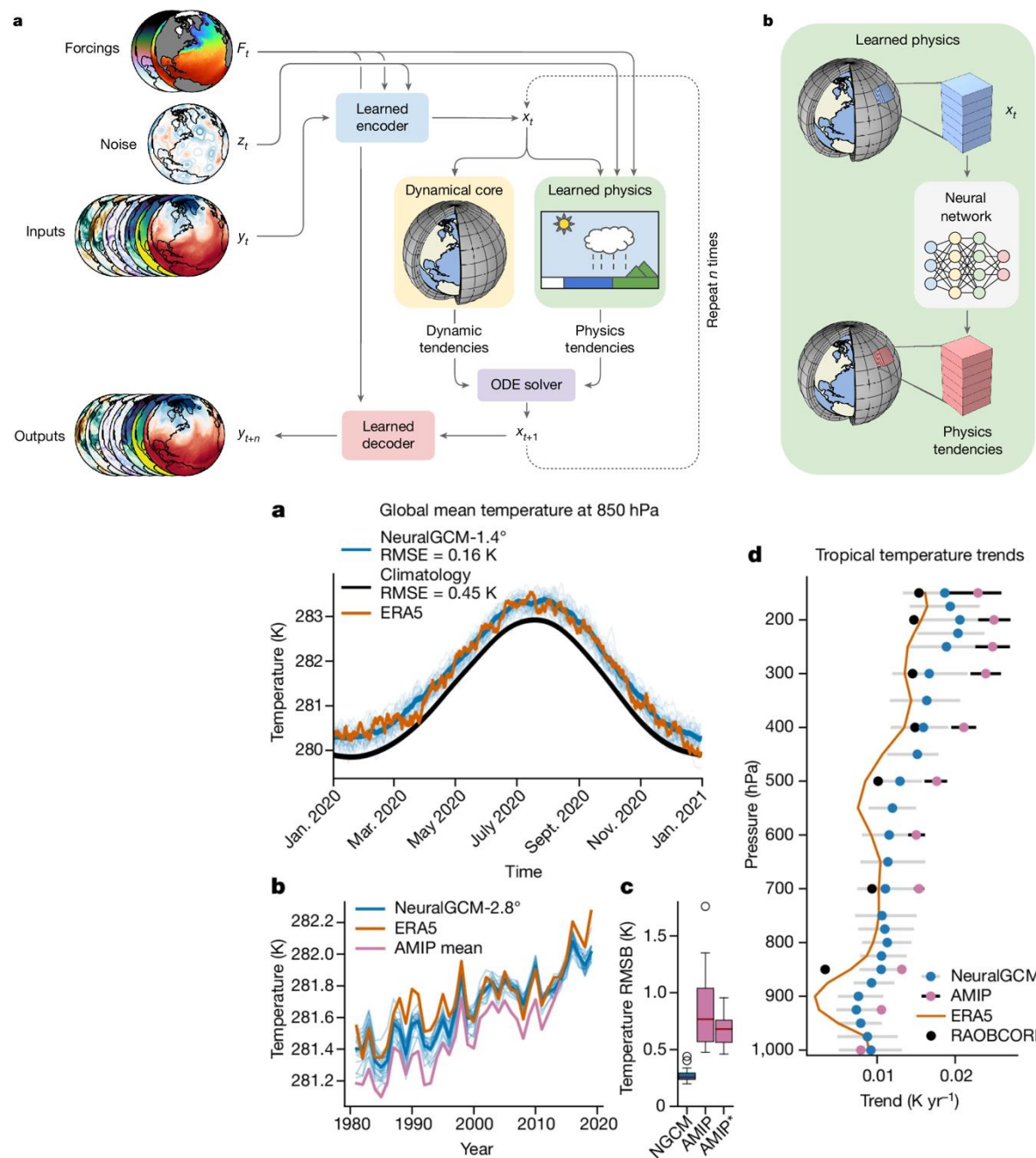
GenCast (Deepmind)

- **Diffusion Model for ensemble forecasts**
 - Non-deterministic
 - Good uncertainty quantification
 - Outperforms deterministic models for extreme events
- **More diffusion modelling tomorrow**



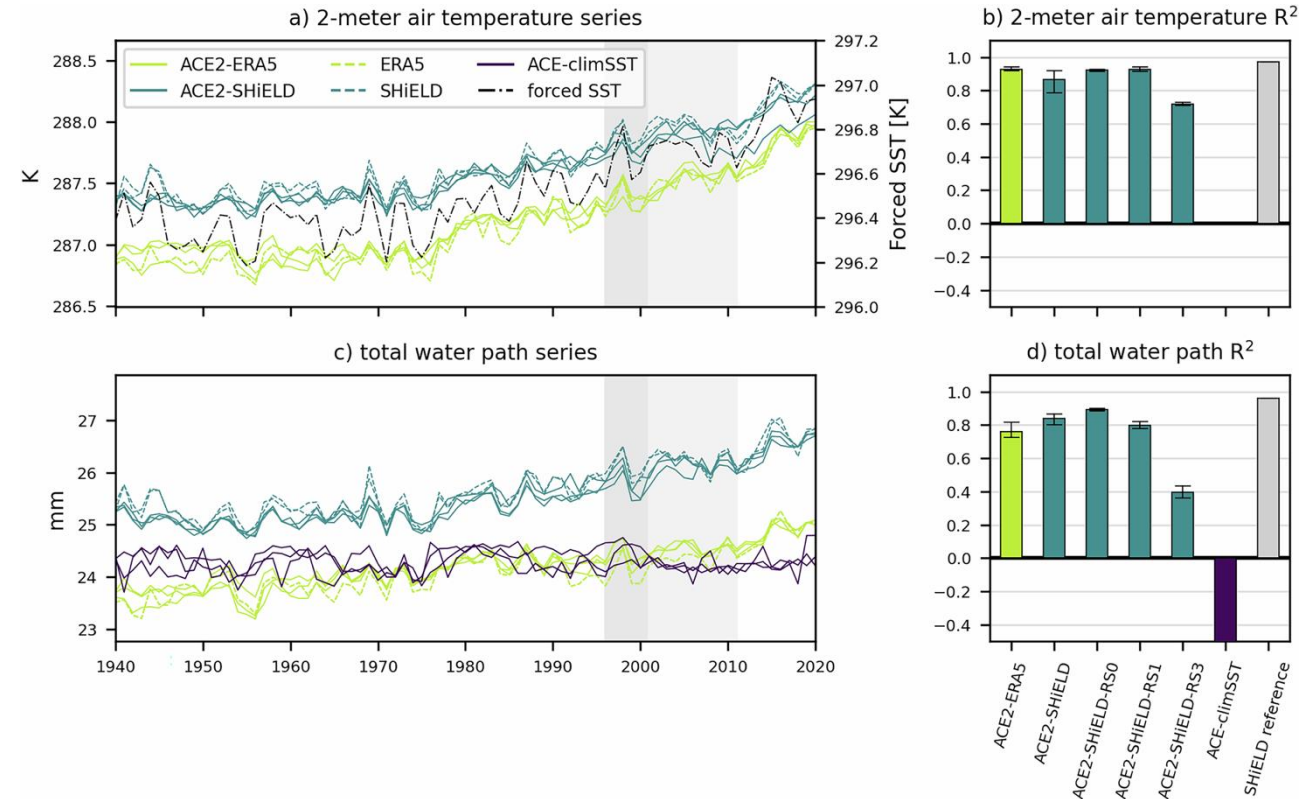
NeuralGCM

- **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**



ACE2

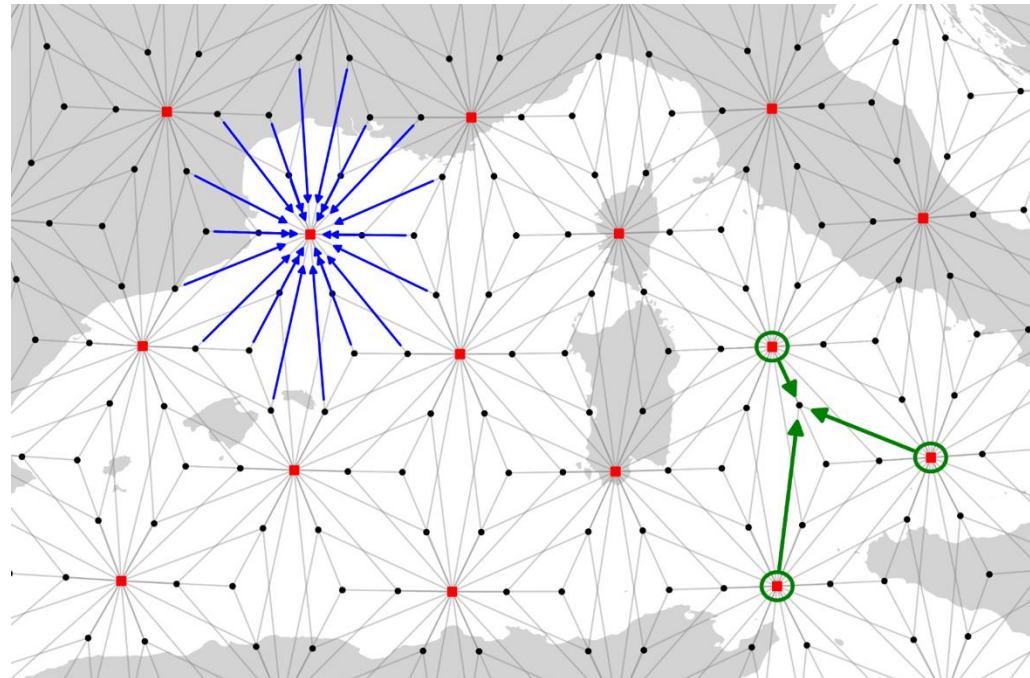
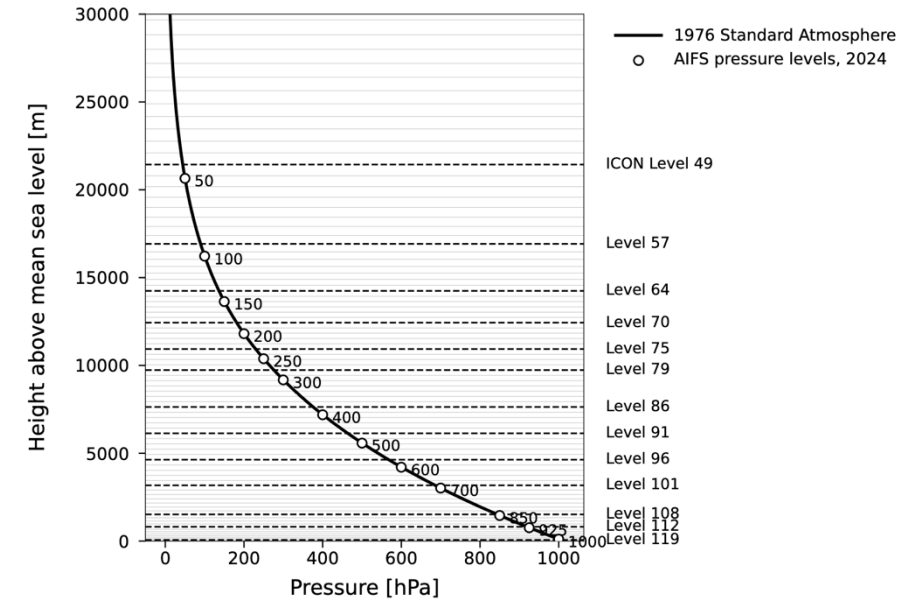
- Exactly conserves global dry air mass and moisture
- 1500 simulated years per wall clock day
- Captures variabilities, at least to some extent
- **ACE-SOM:**
 - coupled to a slab ocean
 - Generalises (to some degree) to 4xCO₂ conditions
- **SamudrACE**
 - Coupled to AI ocean model Samudr
- **AIMIP:**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



AICON

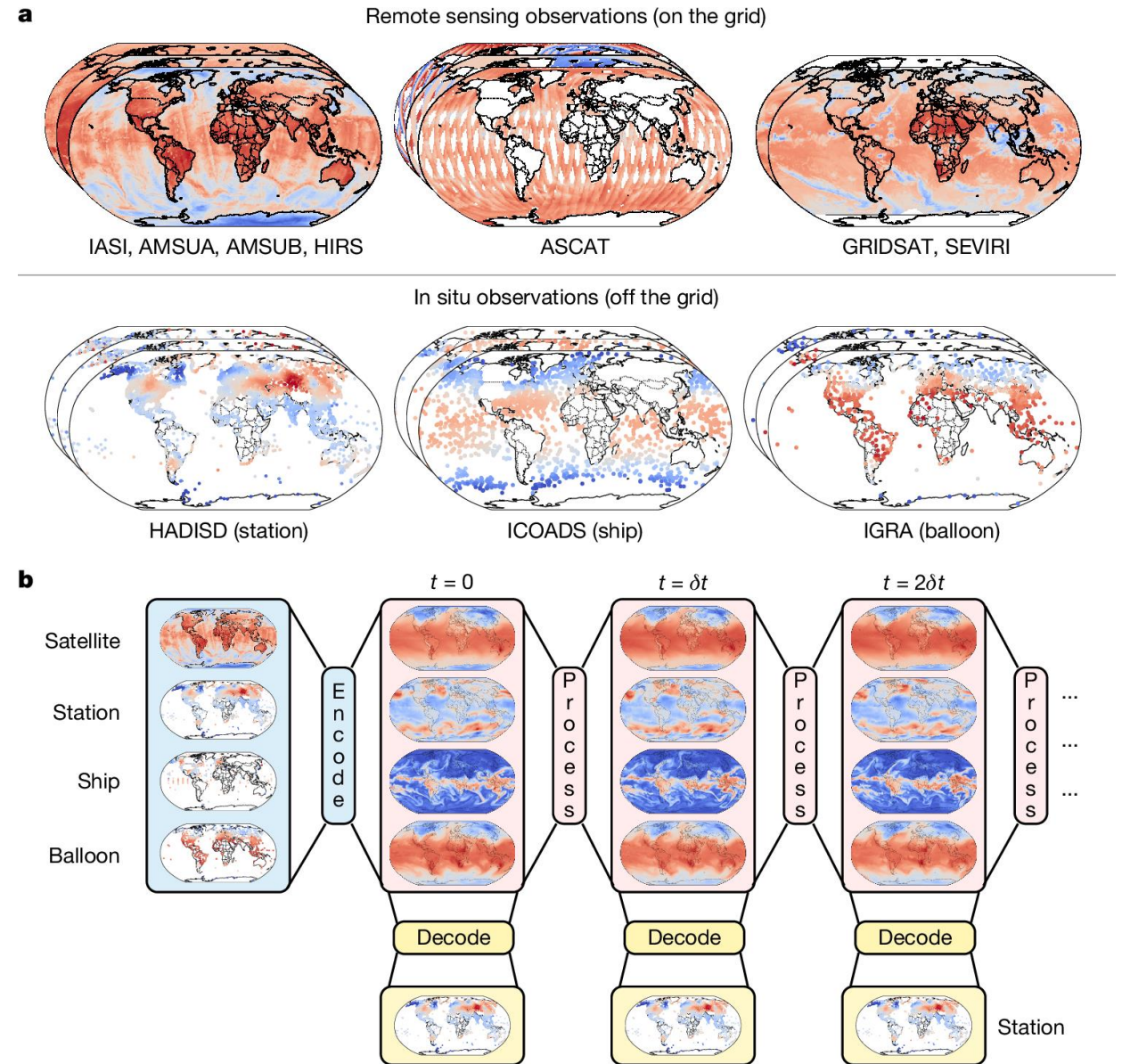
- Recently published model from DWD
- Graph neural network with attention
- Trained on ICON-DREAM reanalysis!
- Terrain-following vertical coordinate
- Preserve fine-scale structures by not training auto-regressively

Goecke, Tobias, et al. "AICON: An operational global machine learning weather forecasting model." *arXiv preprint arXiv:2608.24651* (2026).



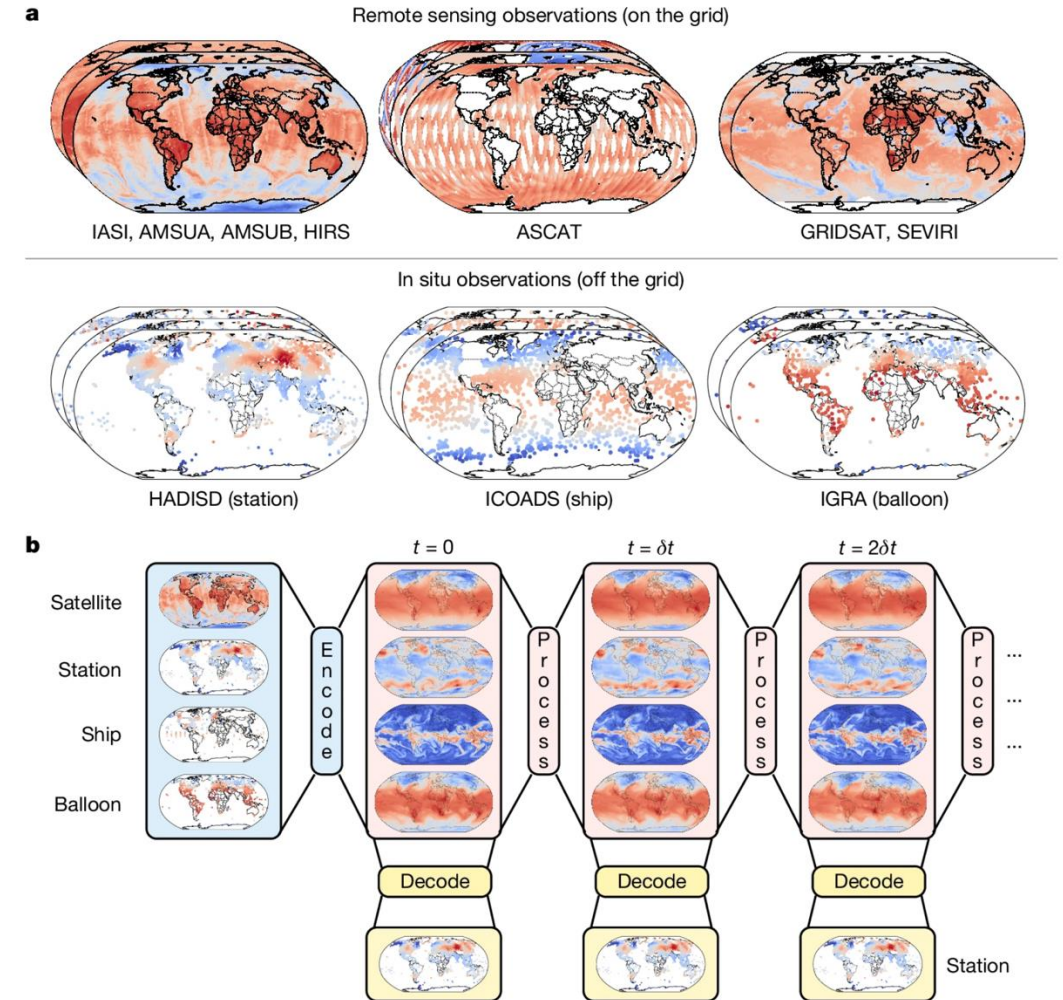
Aardvark

- **"End-to-End" weather prediction**
 - Includes data assimilation
 - Replaces entire NWP pipeline
- **Learns from unstructured observations**
 - "Neural Process" architecture for encoder and decoder handles unstructured data
 - Allows to decode to point locations
- **Grid forecasts on lower resolution than competitors**



Many More:

- **AI-DOP:** ECMWF's new model trained only on observations: <https://arxiv.org/abs/2407.15586>
- **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/>
- **WeatherNext3:** <https://deepmind.google/science/weathernext/>
- ...



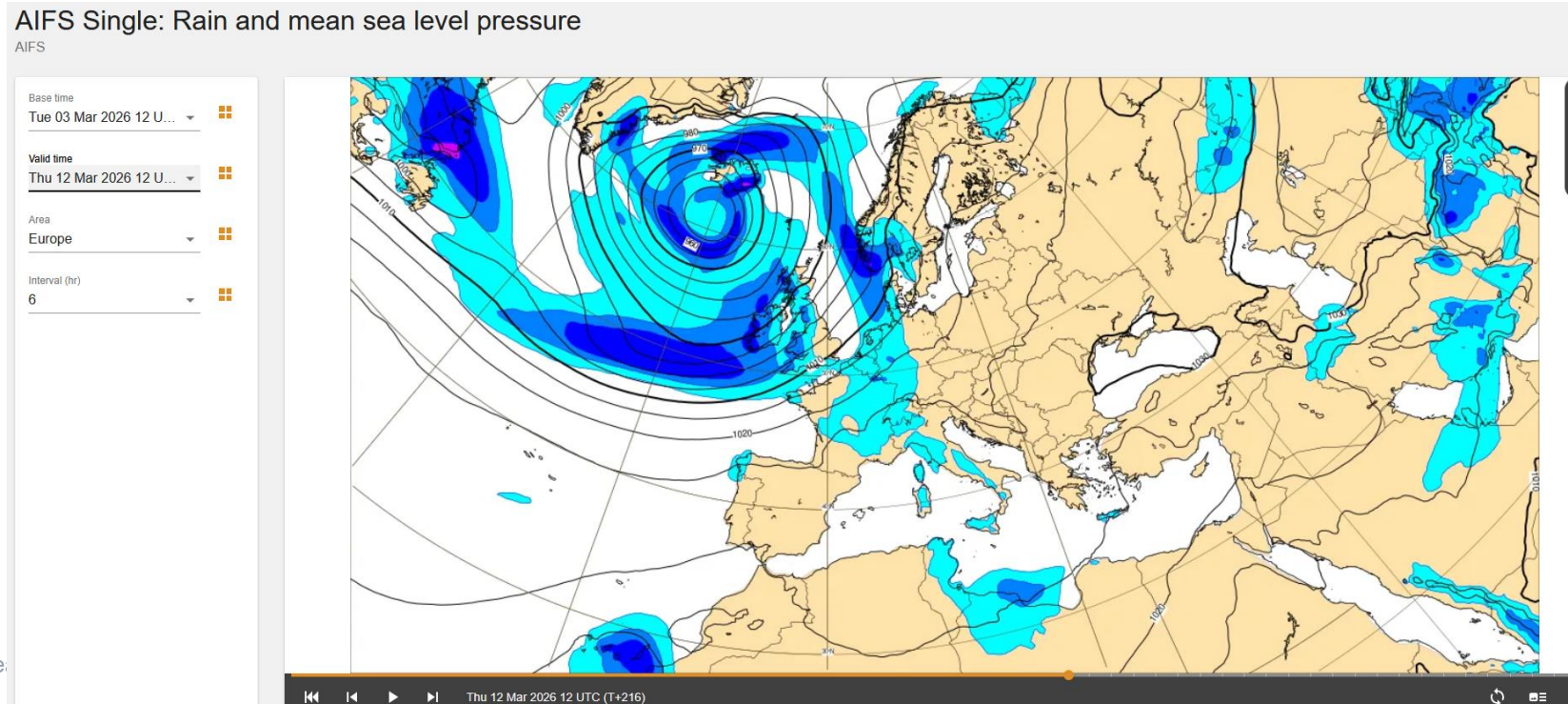
Aardvark Model Structure

Operational AI weather models

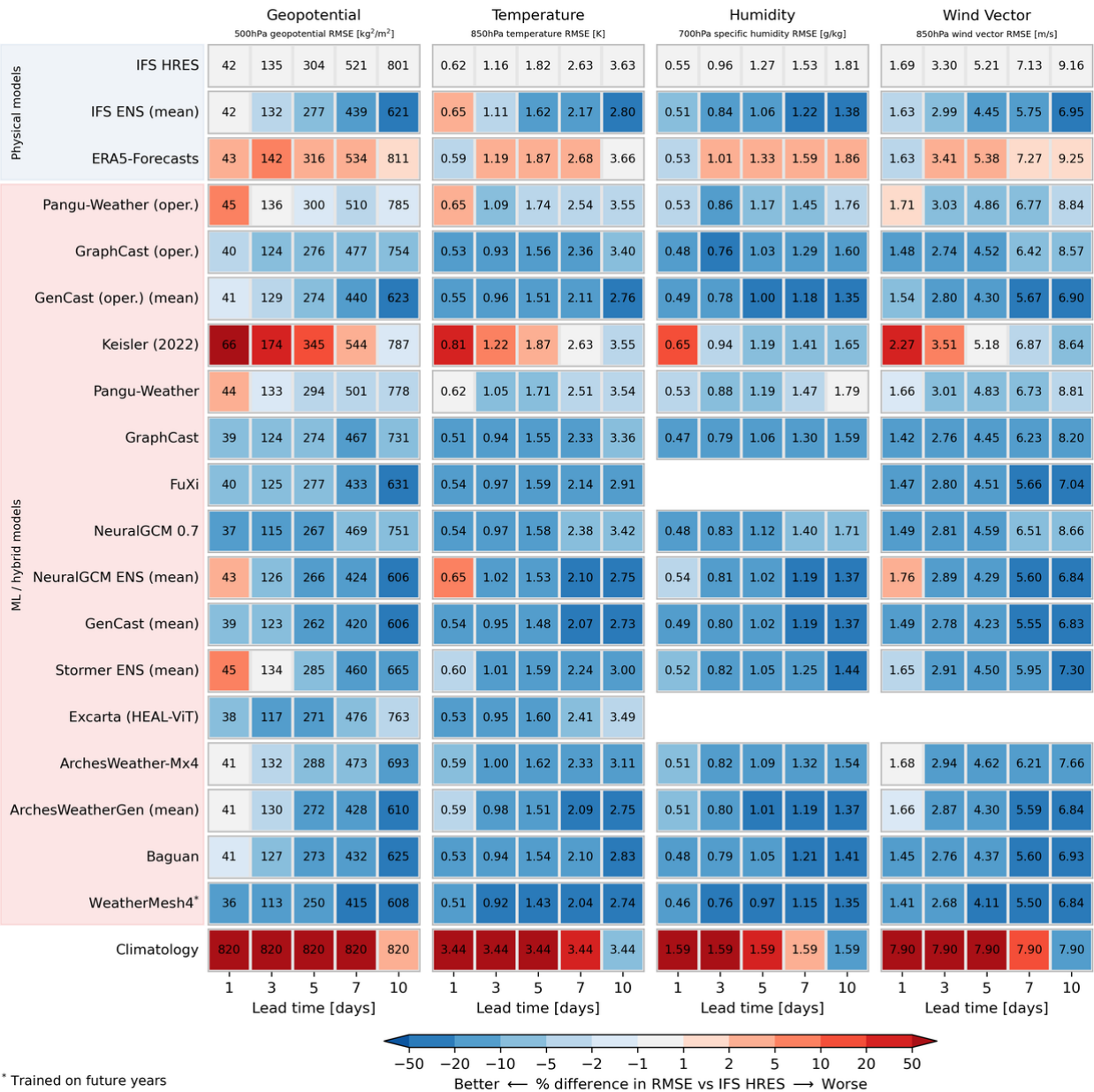
- Training data (ERA5) with 5 day delay cannot be used for operational mode
- Operational models work with the same initialization data as the IFS forecasts

AI products at ECMWF:

https://charts.ecmwf.int/catalogue/packages/ai_models/



How to evaluate AI weather models



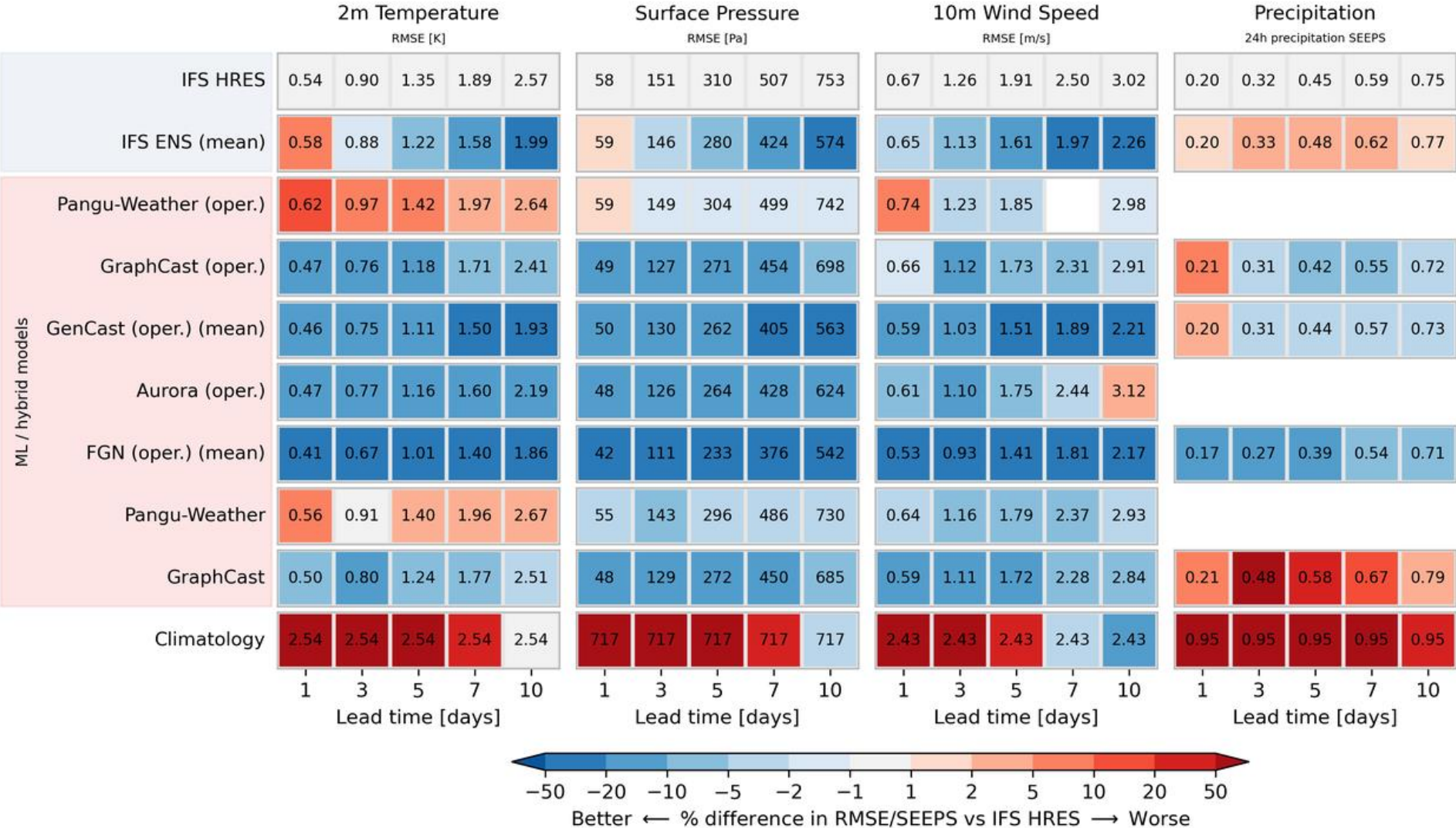
WeatherBenchX framework

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

Operational models evaluated against IFS, all others against ERA5

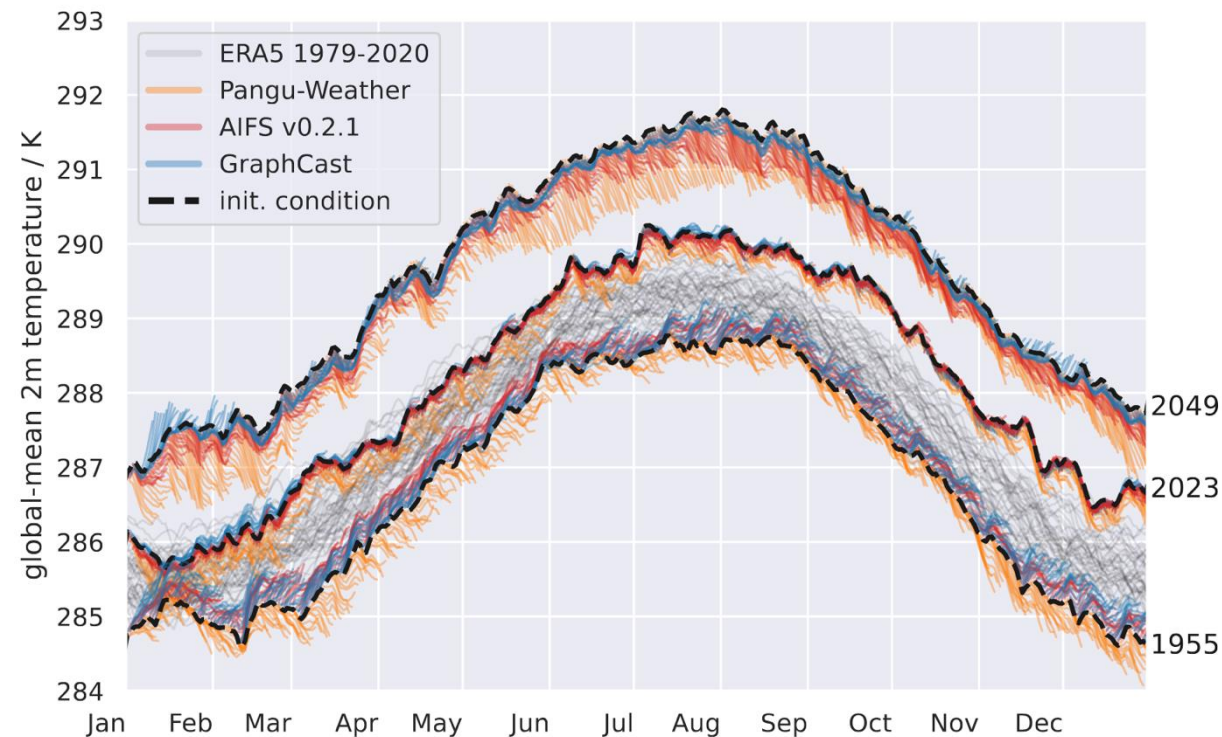
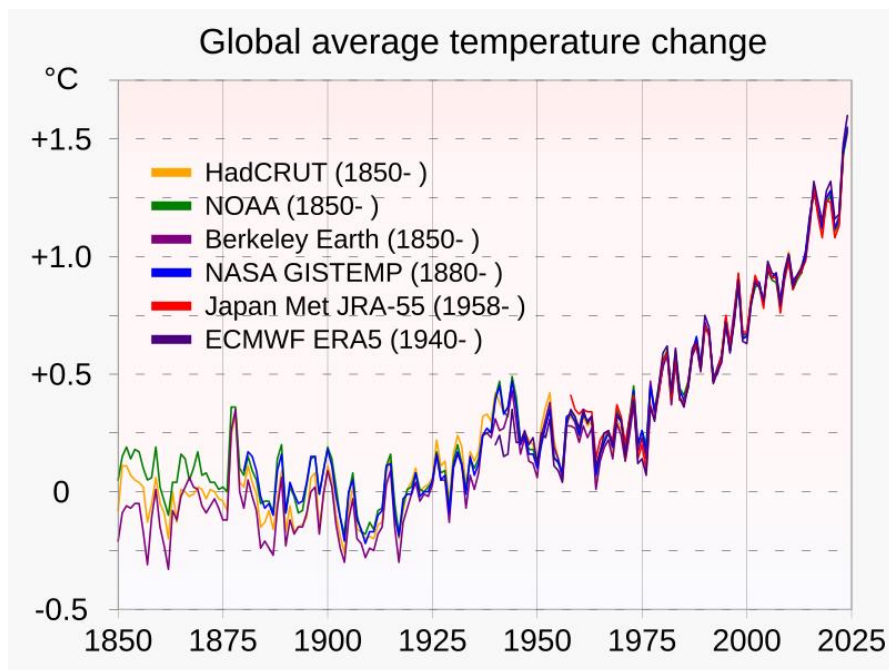
There are probabilistic score cards too.

Challenges in AI weather prediction: Precipitation



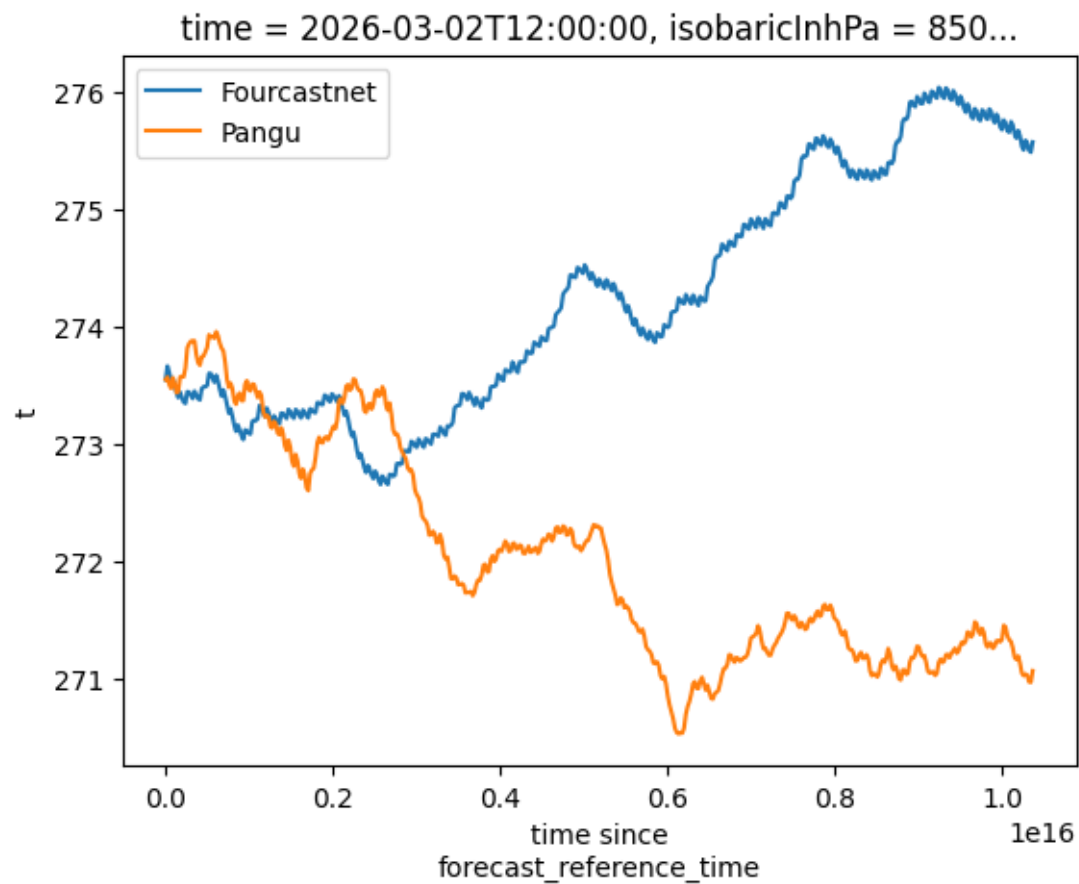
Challenges in AI weather prediction: Climate Drift

Warming climate: data drift



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

T850 global average up to 120 days ahead



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 x 16 @ 1 km : 16 km
- HRES training data is HUGE and limited to few years
- Potential Solutions:
 - Witte et al, Field Space Attention:
<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>

Questions and Feedback