

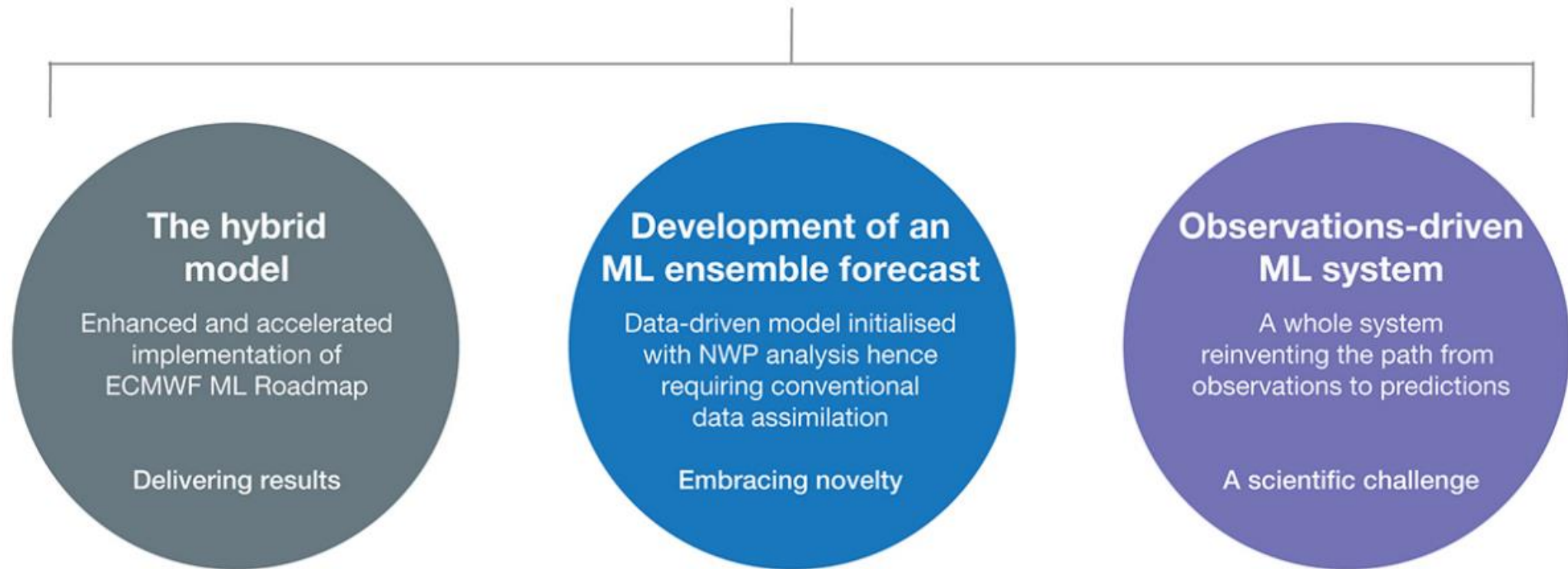
Machine learning @ ECMWF

Matthew Chantry

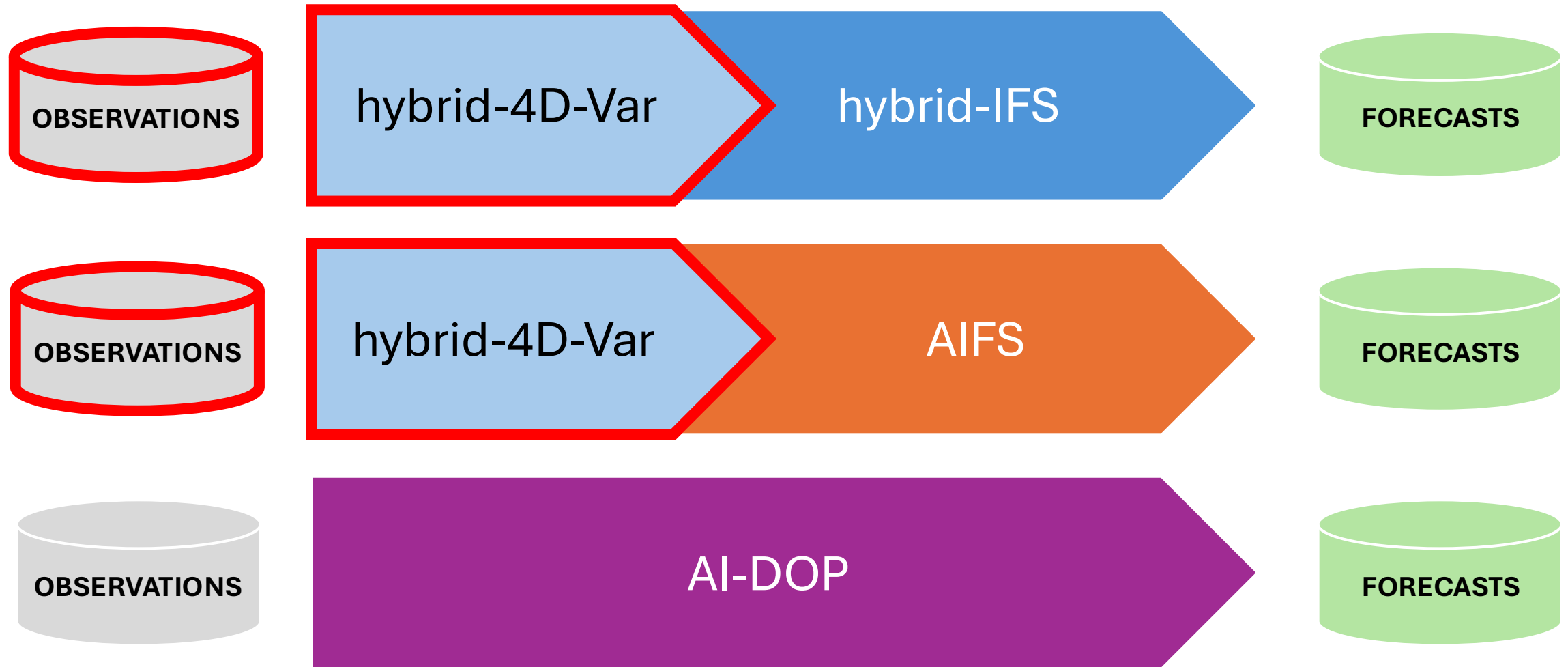
Strategic Lead for Machine Learning



Three strands of machine learning



Hybrid Data Assimilation... ML enhancing the exploitation of observations

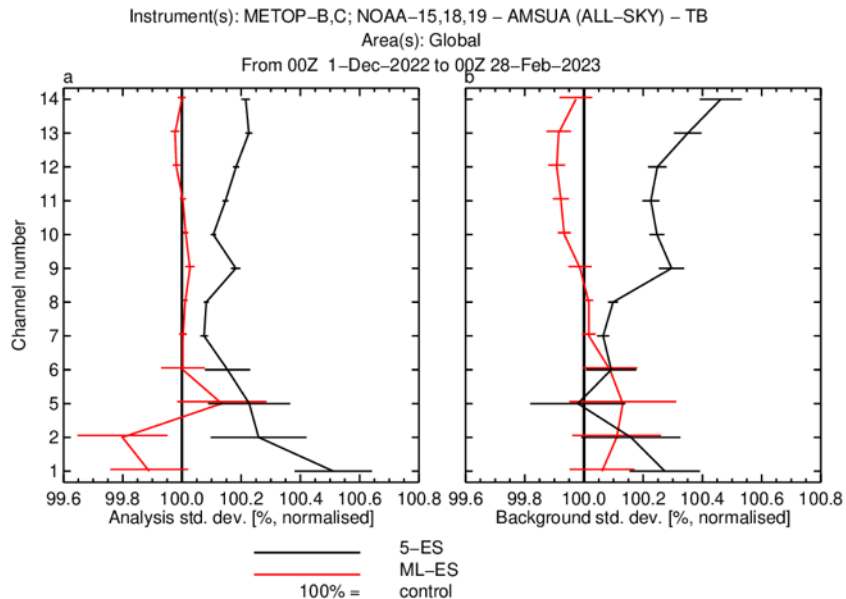
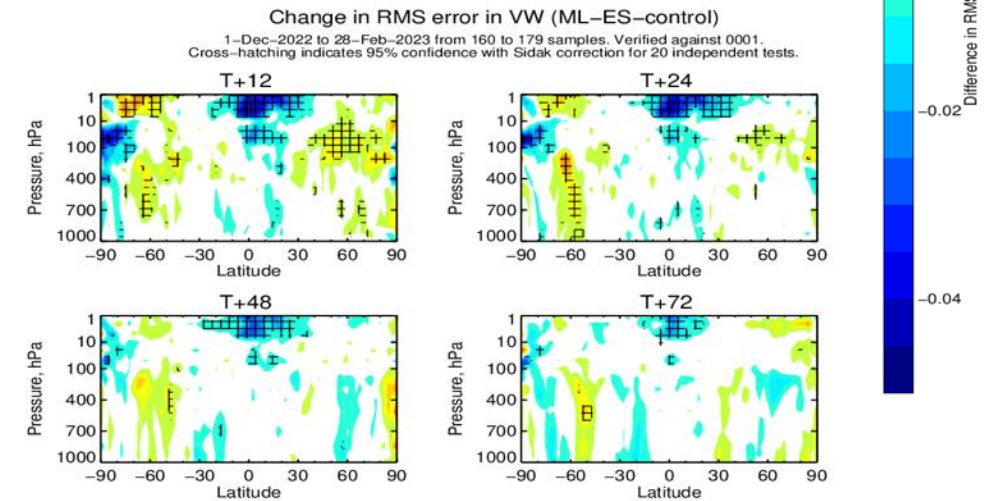
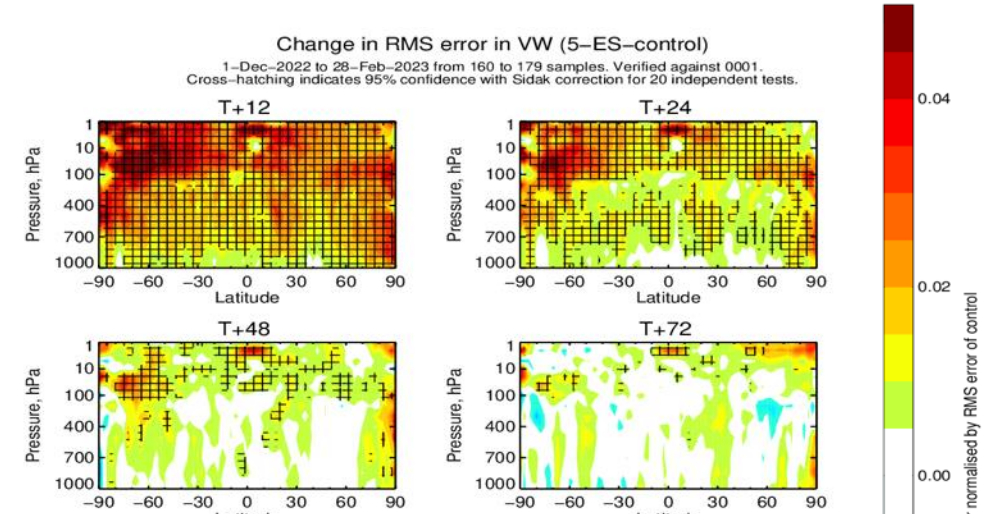


Example: EDA emulation

Emulate EDA statistics of 50 members
using ML + 5 members
Minimal degradations observed

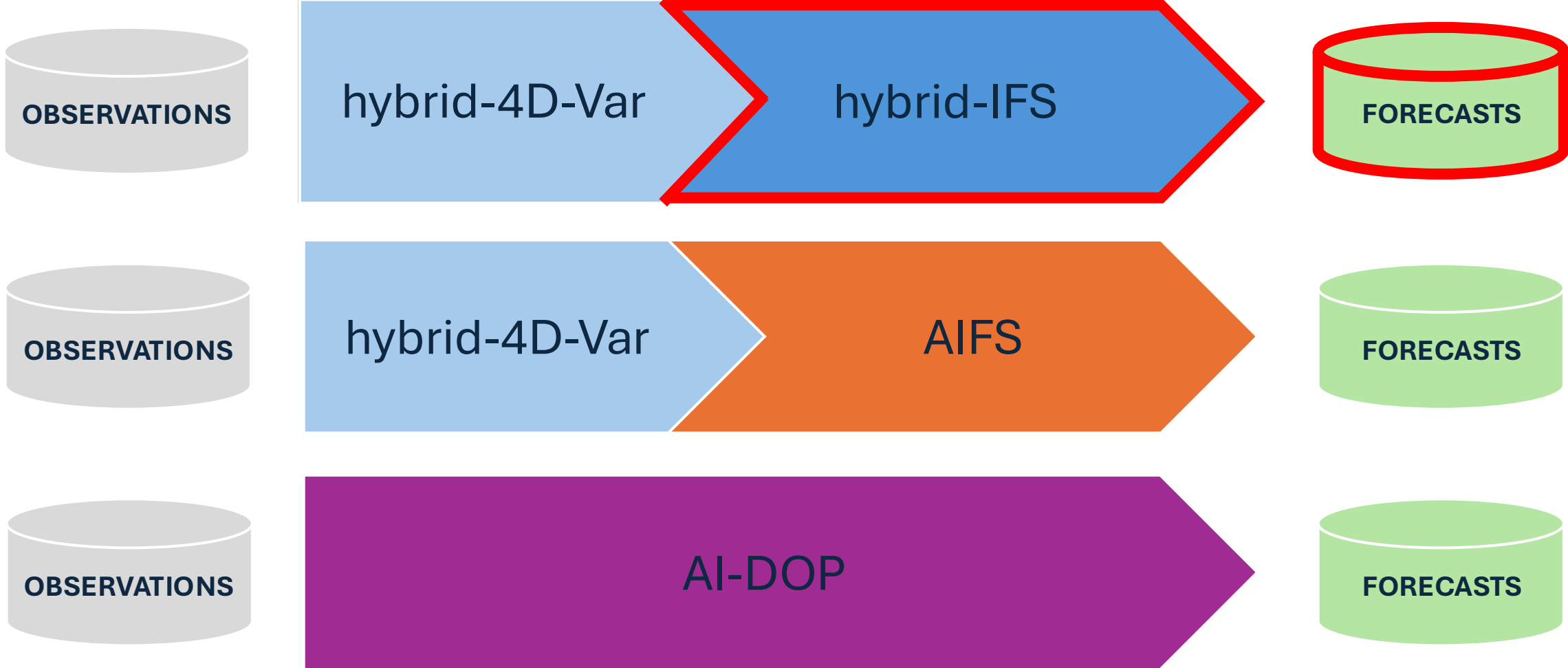
Next steps: Generate EDA perturbations

5 members

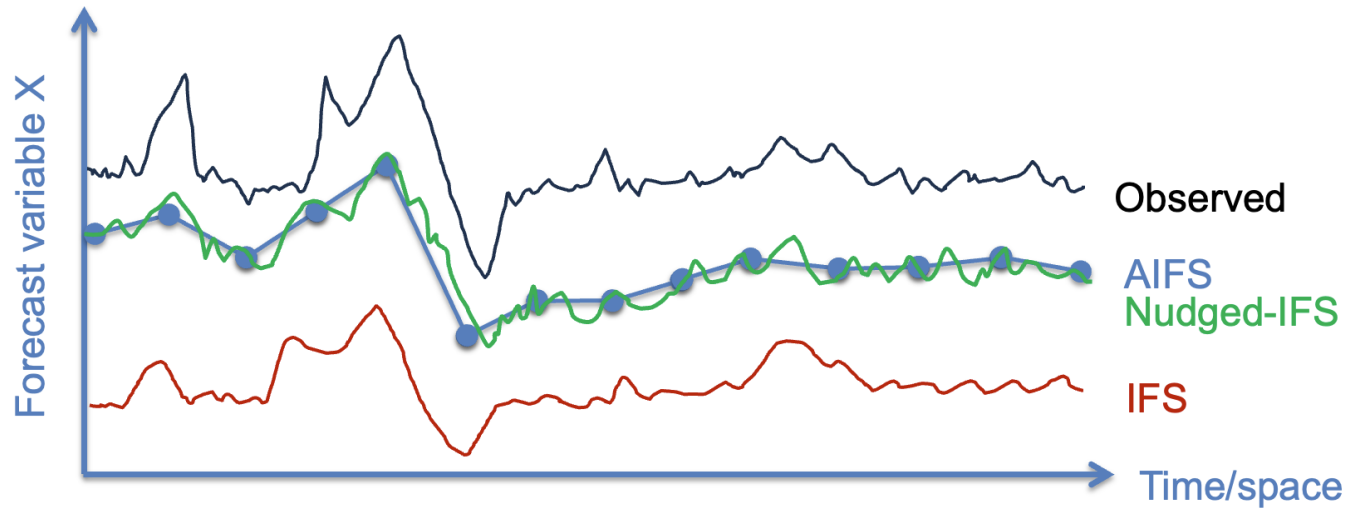


5 members + emulation

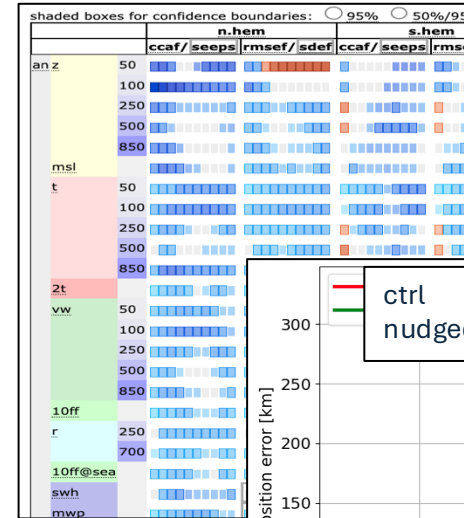
Hybrid IFS Forecast Model



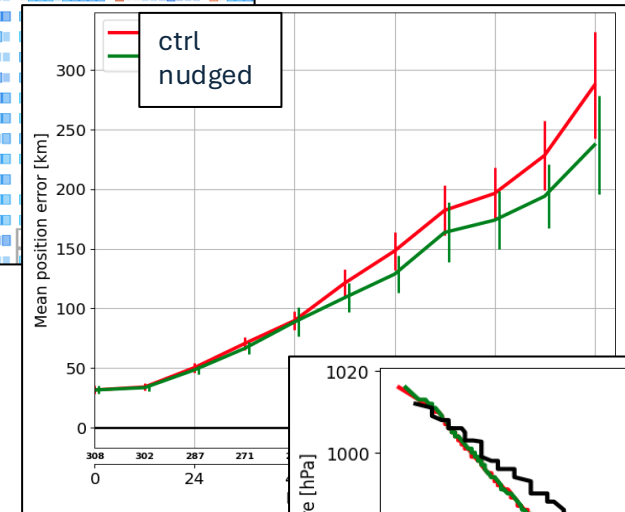
Example: Spectral Nudging



Internal real-time deterministic setup running for evaluation

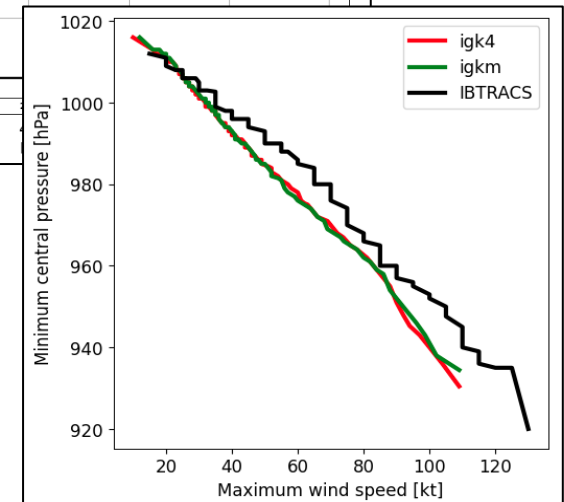


Improved large-scale scores

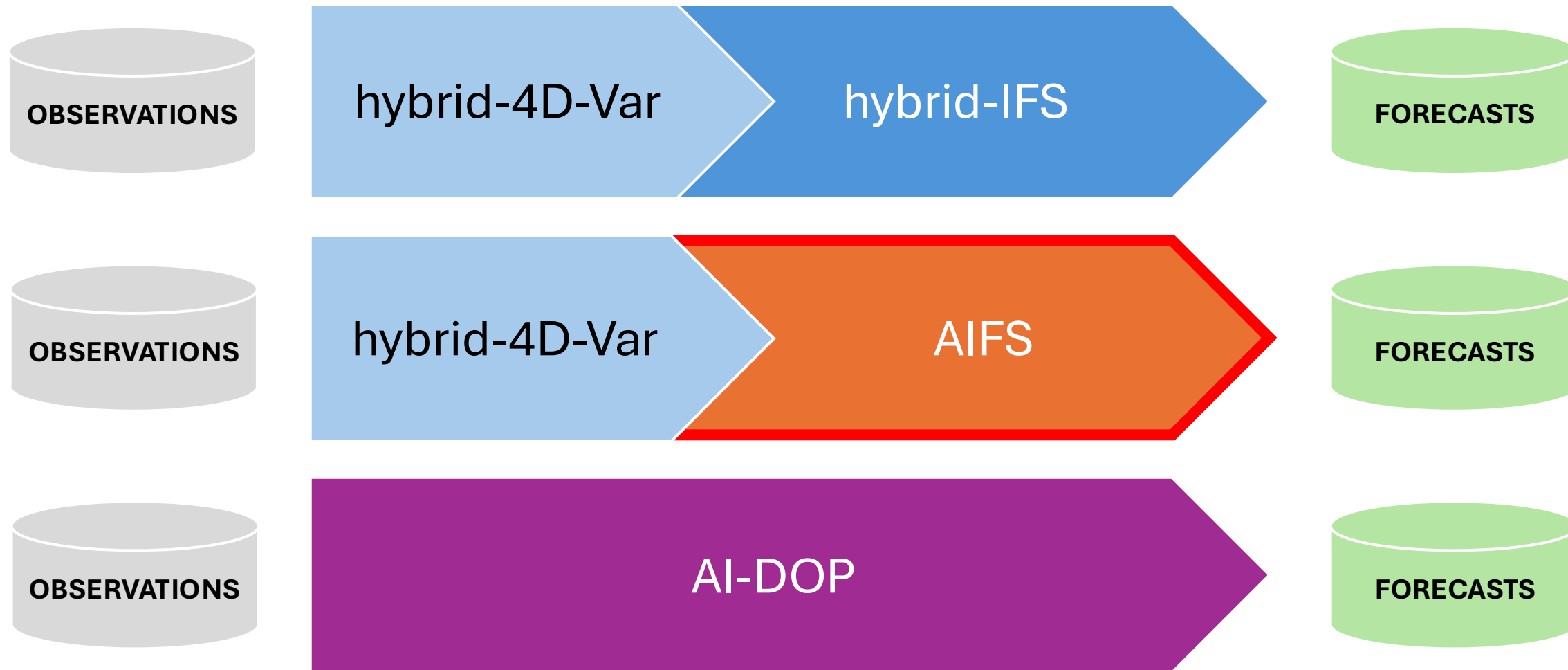


Improved TC tracks

No loss of TC intensity



AIFS Progress...



Operational Implementations of AIFS Single Forecasts

V1 - Jan 2025

- Additional variables, physical bounds on model parameters, improved stratosphere, trained within Anemoi

V1.1 – August 2025

- Fix precipitation artefacts caused by inverted soil moisture causation.

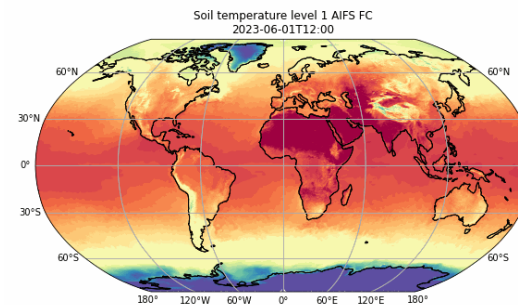
V2 – Q2 2026

- Waves, further improved stratosphere, improved skill.

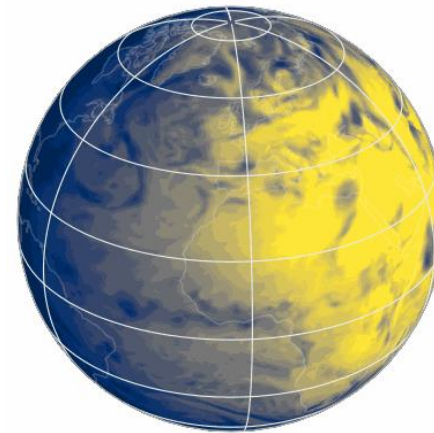
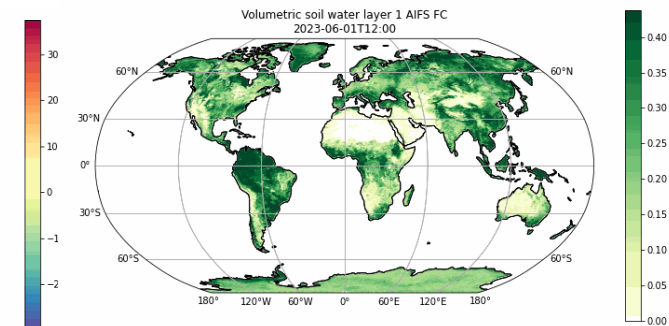
V3 - ...

- Ocean, hindcasts, hourly predictions.

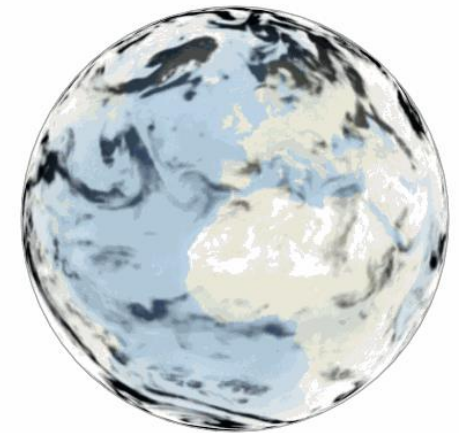
Soil temperature



Soil moisture

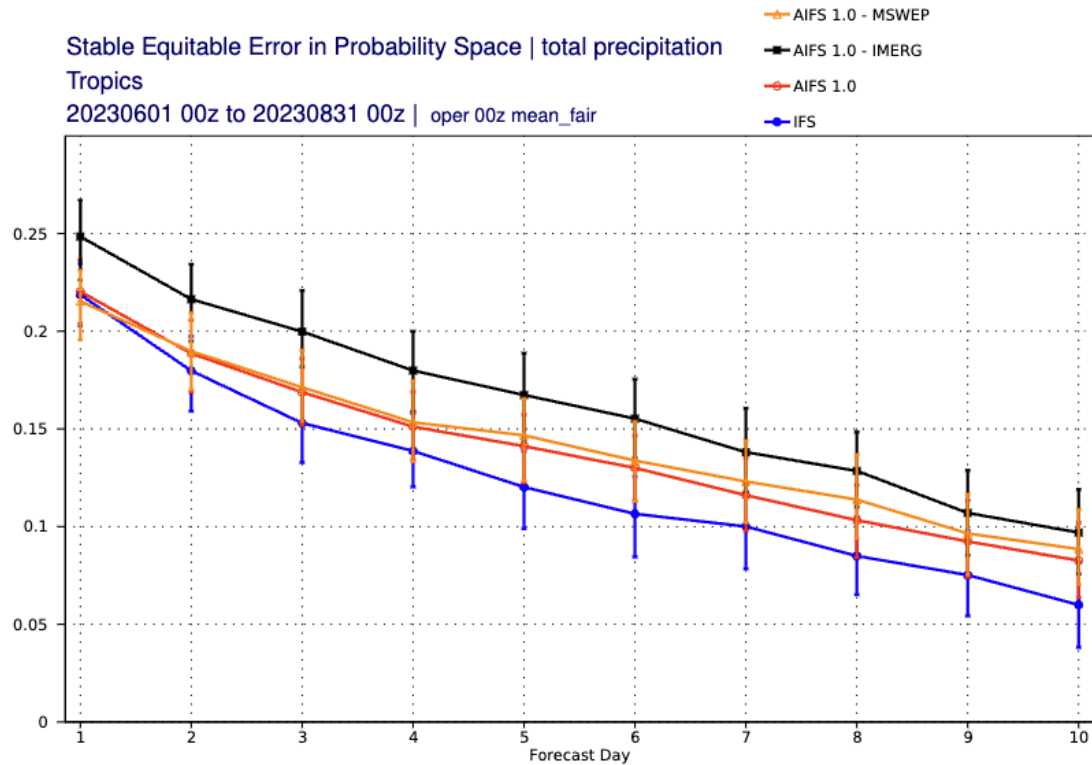


Surface Solar Radiation

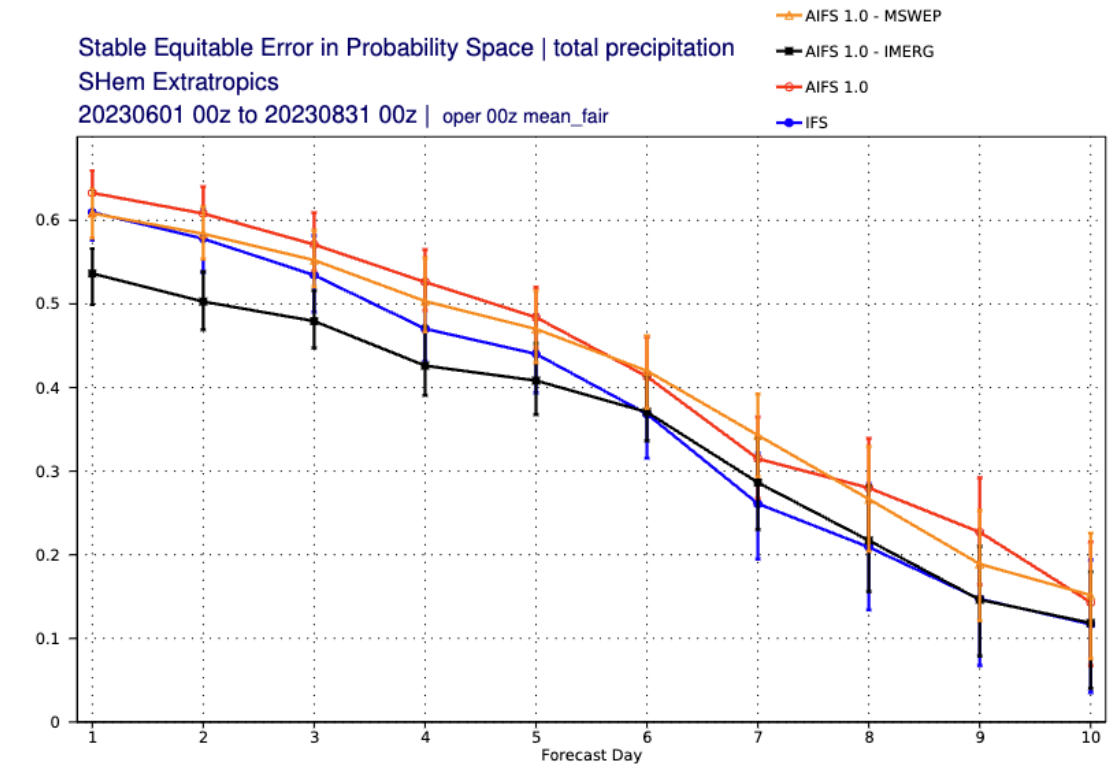


Cloud Cover

Alternate precipitation data sources

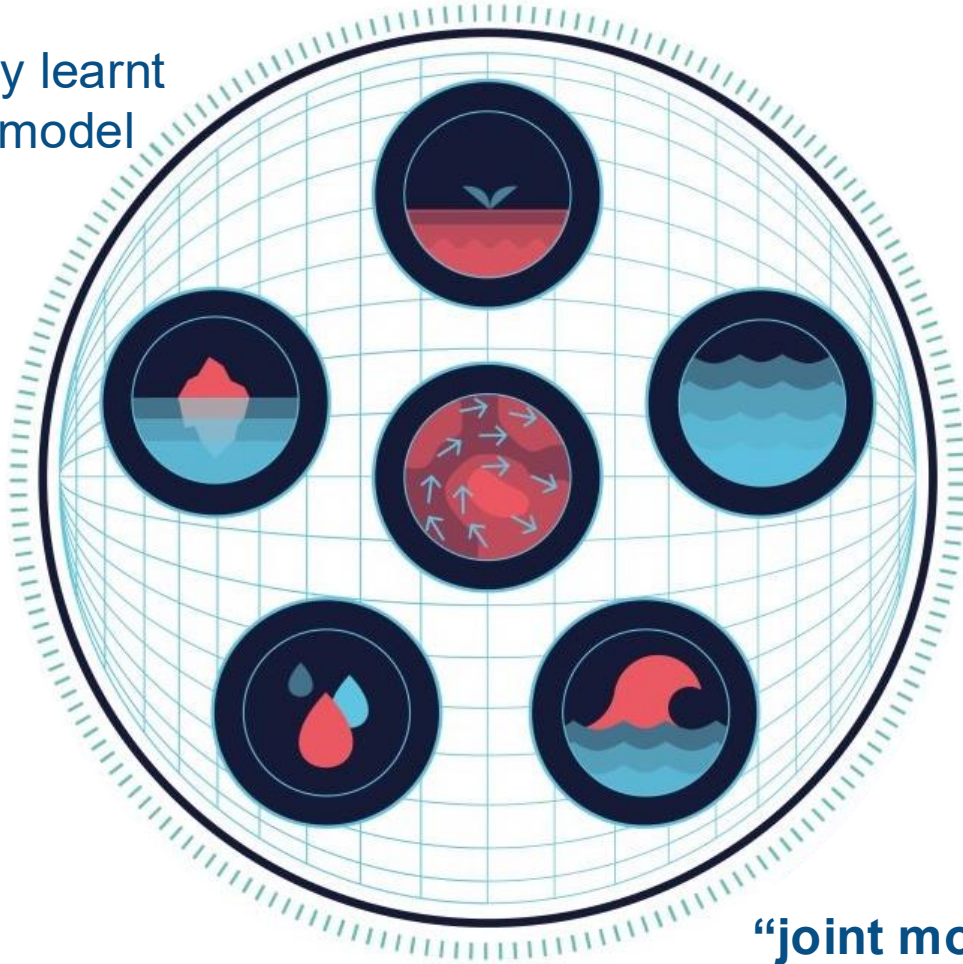


- Tropical precipitation skill can be significantly improved with use of satellite precipitation products.
- Southern hem extratropics significantly degraded when using these products.
- Next steps, utilising both datasets together in training.

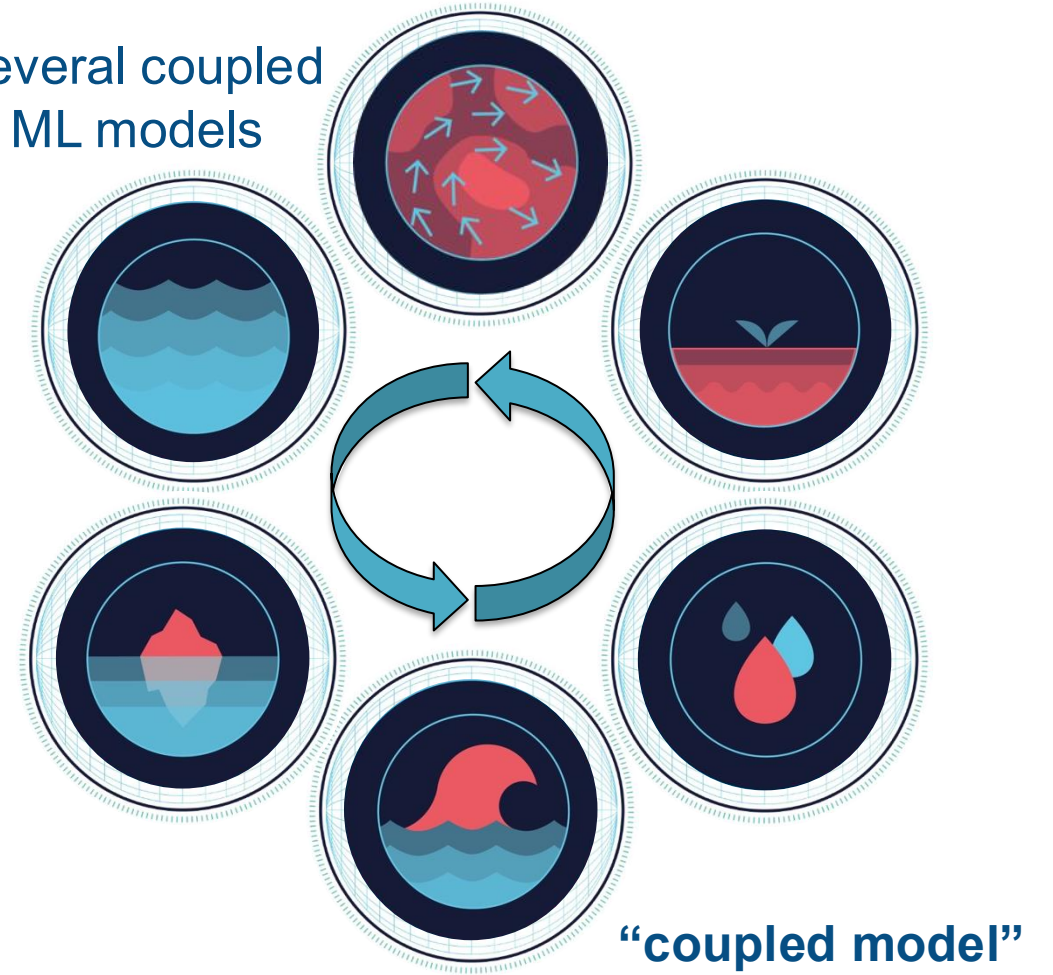


Coupling AI Earth System Models

Jointly learnt
ML model



Several coupled
ML models

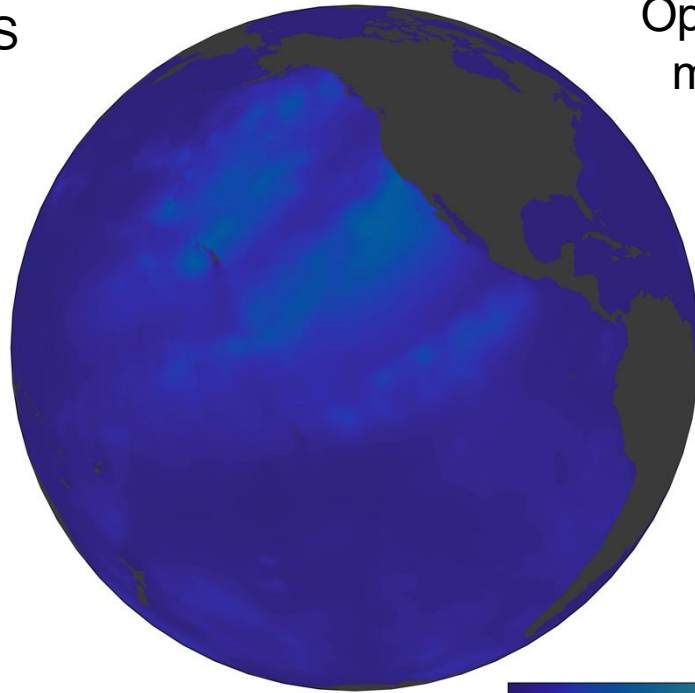


Contributions to AIFS Single 2.0: Wave Component going operational

Significant Wave Height Forecast for waves with periods $21 \leq T < 25s$

2024-12-20 00:00

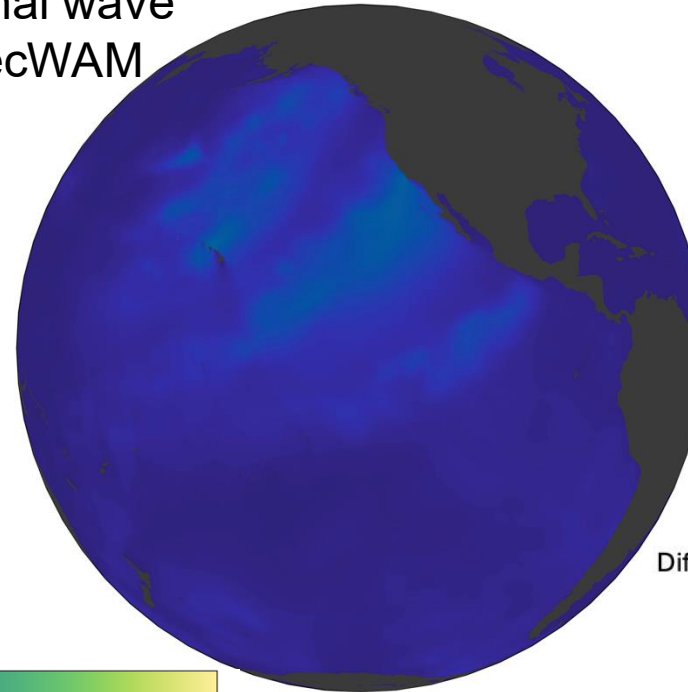
AIFS



0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
Surface wave height (m)

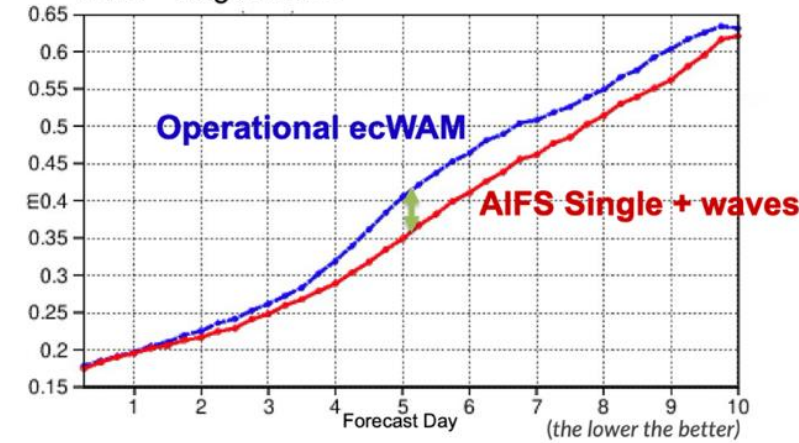
2024-12-20 00:00

Operational wave
model ecWAM

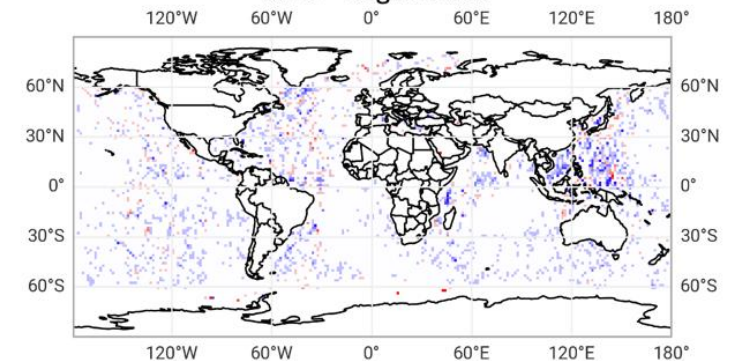


Northern Hemisphere Significant Wave Height

Standard deviation of forecast error
June – August 2023



Difference (%) in RMSE of Significant Wave Height Forecasts (48 to 72h)
June – August 2023



- Builds on Destination Earth earth system components
- Represent 10 wave fields in next version of AIFS Single 2.0

Operational Implementation of AIFS CRPS Ensemble

AIFS ENS: CRPS optimisation

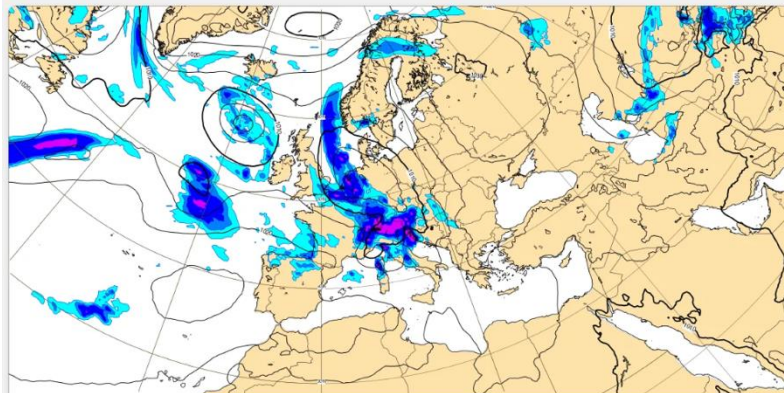
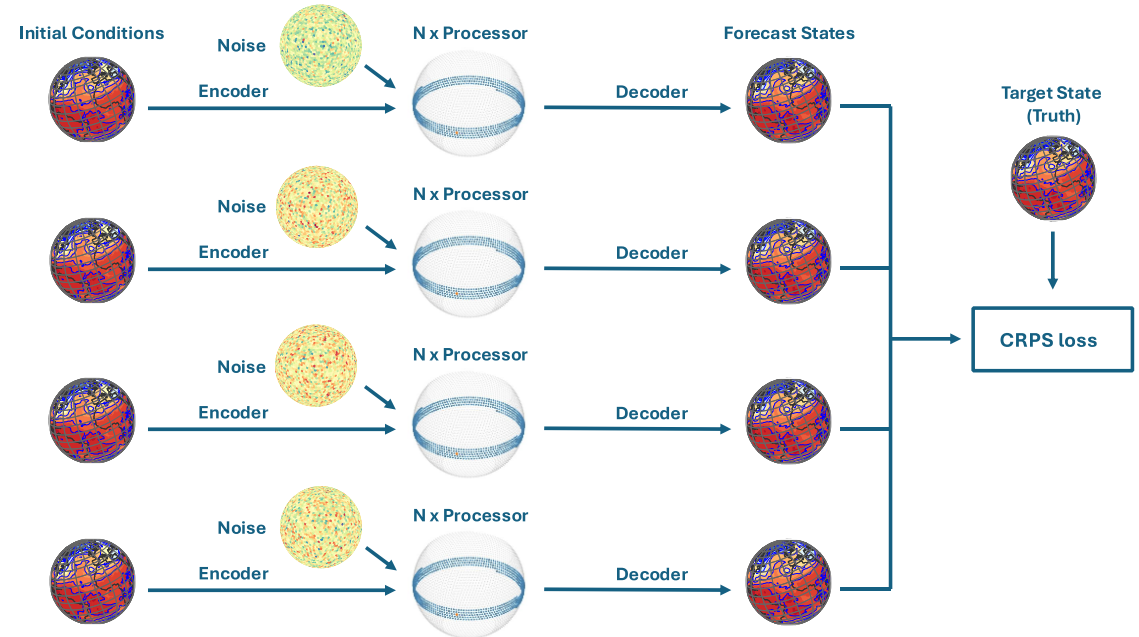
Probabilistic training of AIFS:

$$\text{afCRPS}_\alpha := \alpha \text{fCRPS} + (1 - \alpha) \text{CRPS}$$

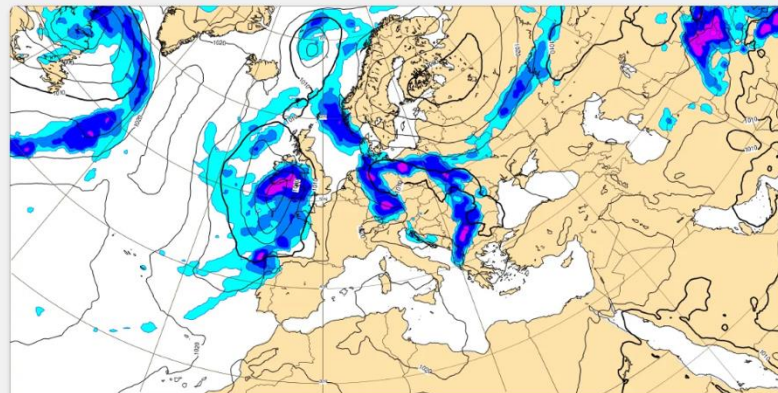
$$= \frac{1}{M} \sum_{j=1}^M |x_j - y| - \frac{M-1+\alpha}{2M^2(M-1)} \sum_{j=1}^M \sum_{k=1}^M |x_j - x_k|$$

$$= \frac{1}{M} \sum_{j=1}^M |x_j - y| - \frac{1-\epsilon}{2M(M-1)} \sum_{j=1}^M \sum_{k=1}^M |x_j - x_k|$$

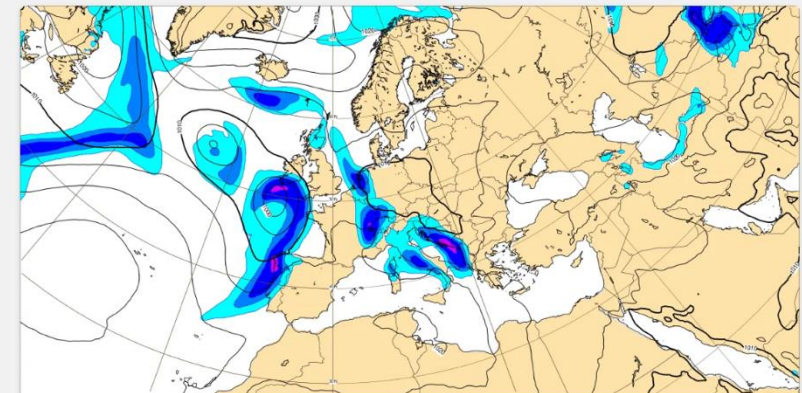
AIFS-CRPS runs with a 6h timestep



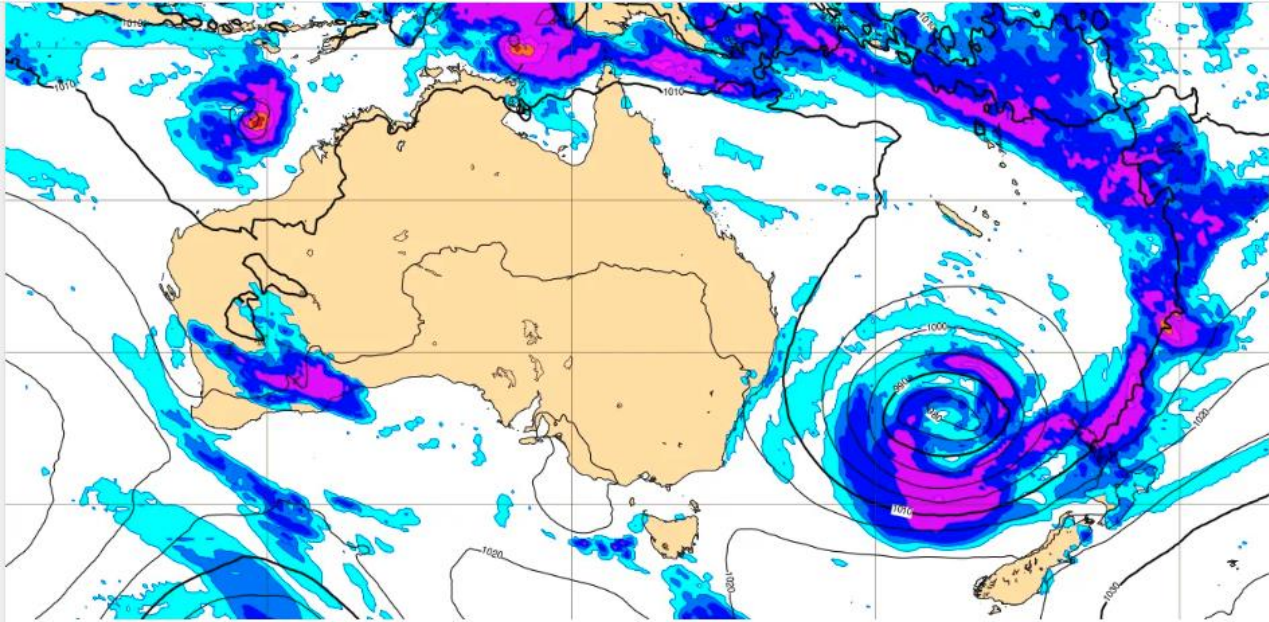
Rain and mean sea level pressure



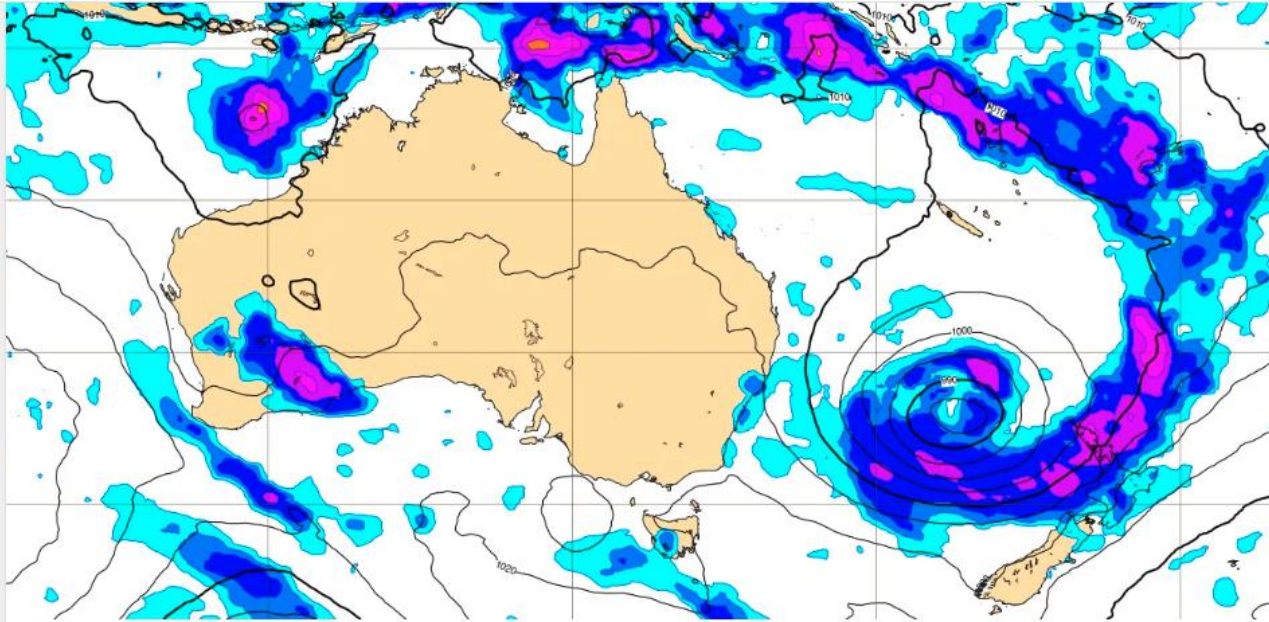
AIFS CRPS : Rain and mean sea level pressure



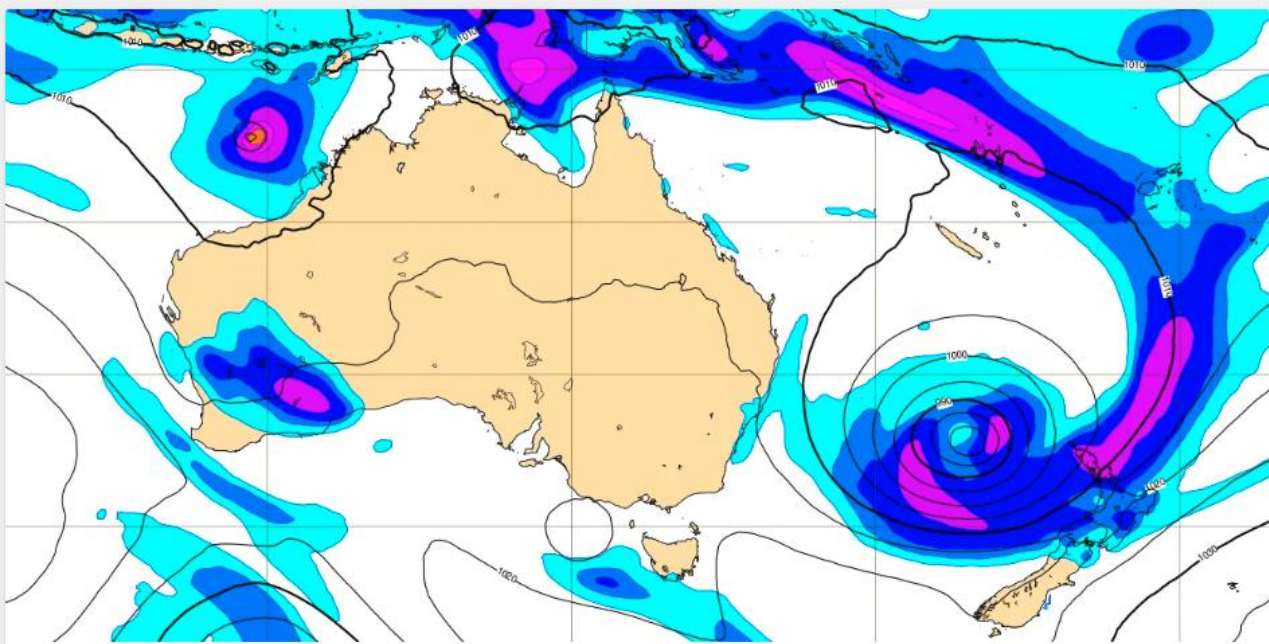
AIFS Single: Rain and mean sea level pressure



Rain and mean sea level pressure



AIFS CRPS Control: Rain and mean sea level pressure



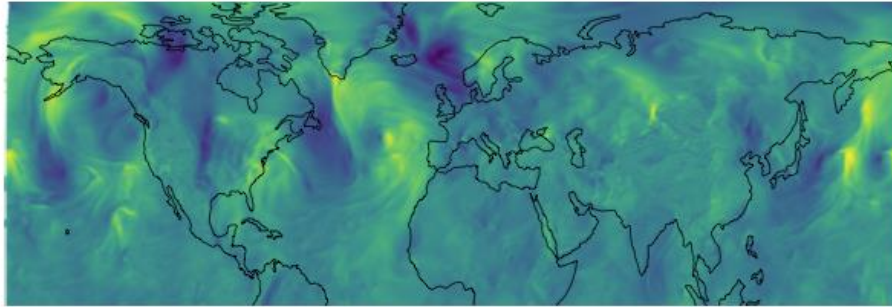
AIFS Single: Rain and mean sea level pressure



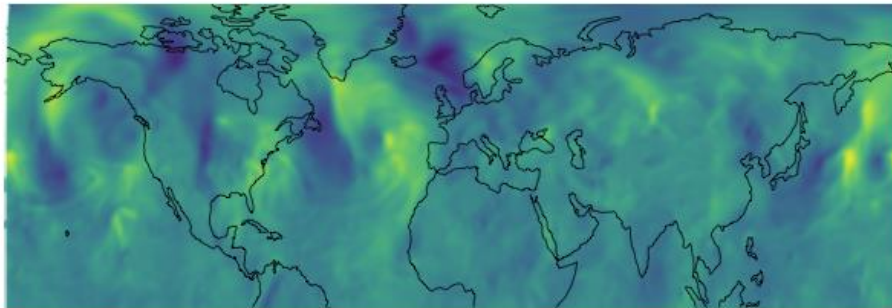
Training to minimise the probabilistic CRPS instead of the MSE produces a field with greater intensity and more energy at small scales.

AIFS ENS v2 Multi-Scale Loss: improves physical realism of predictions

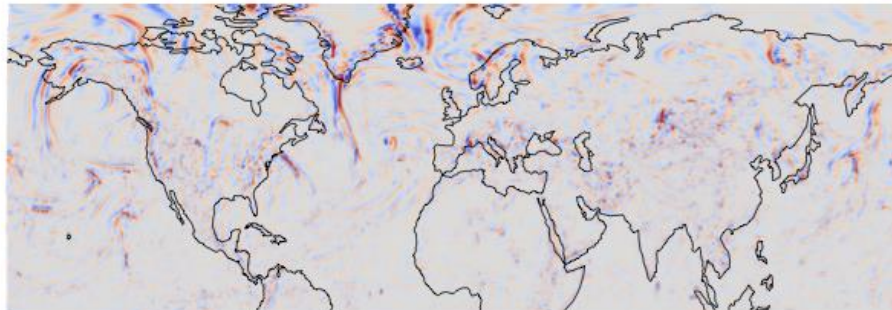
(a) target



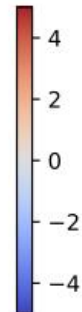
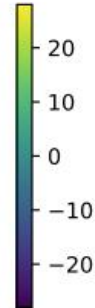
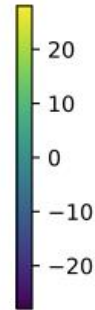
(b) target, scale 1



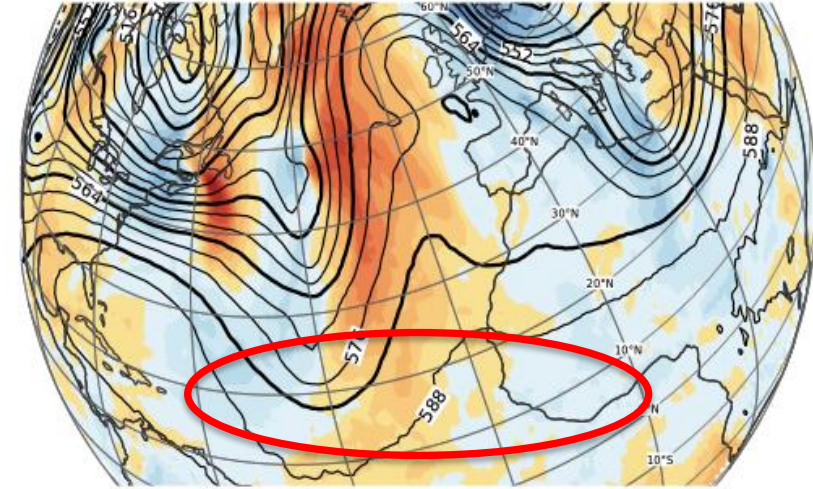
(c) target, scale 2



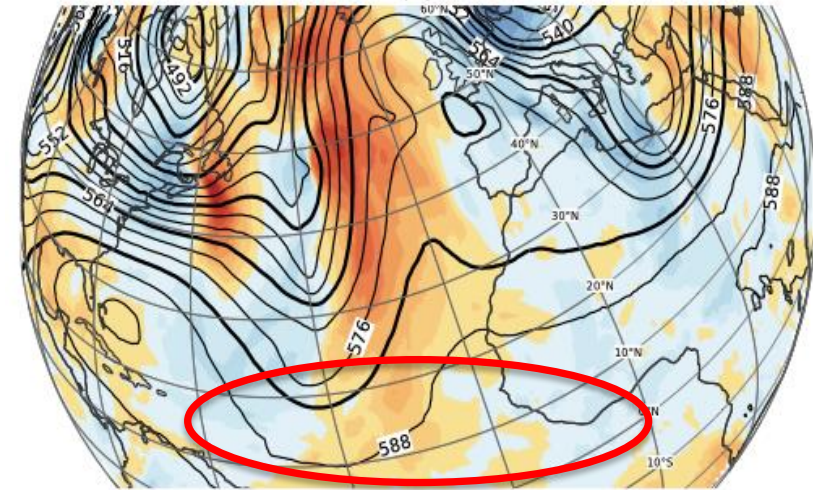
ERA5 v-component of wind (in m s^{-1}) at 850 hPa, full field (a), field after filtering (b) and difference between filtered and full field (c).



(a)



(b)



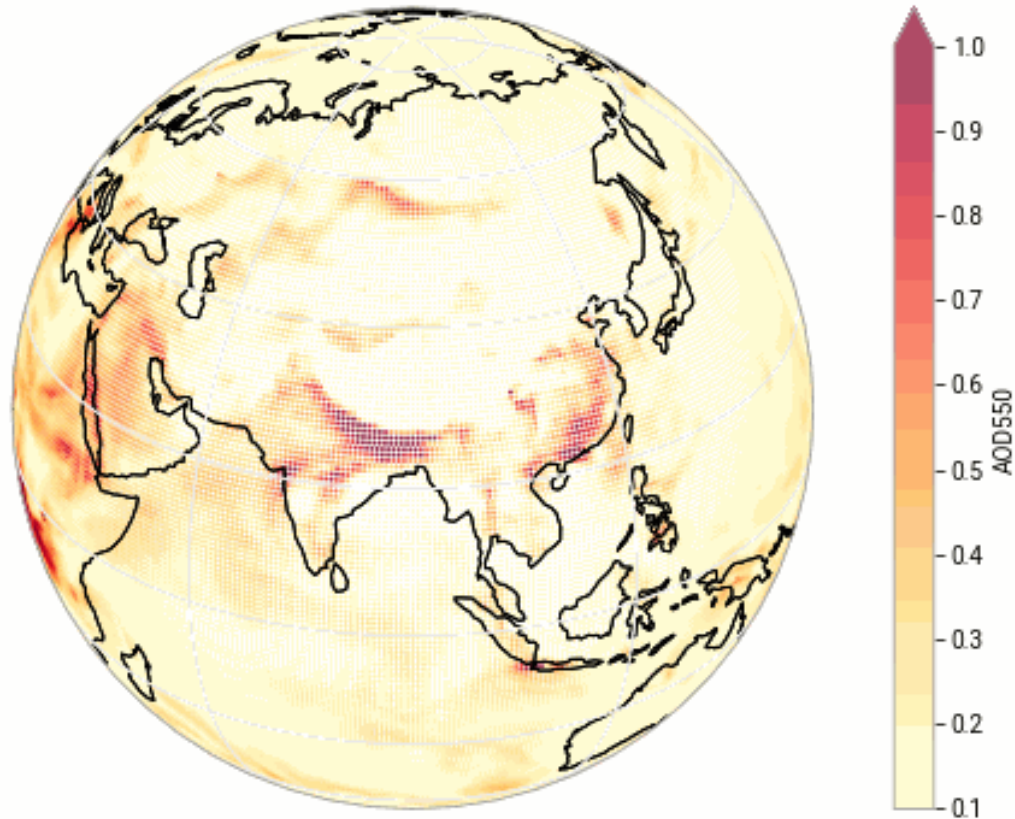
Geopotential at 500 hPa (dam, contours) and v-component of wind at 850 hPa (shaded) of (a) the scale-unaware loss experiment, (b) the multi-scale loss experiment

Shown are 24 h forecasts of member 1, initialised on 2019-01-01 00 UTC (a, b) and verifying analysis on 2019-01-02 00 UTC (c).

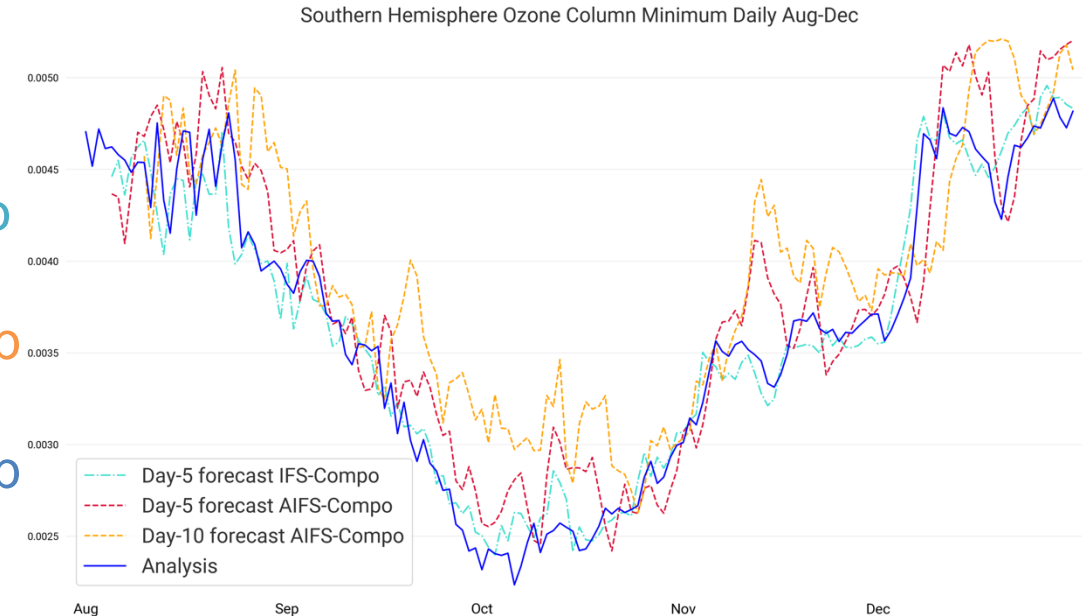
Extending AIFS to Atmospheric Composition (CAMS)

Prototype AIFS Compo showing
Aerosol Optical Depth

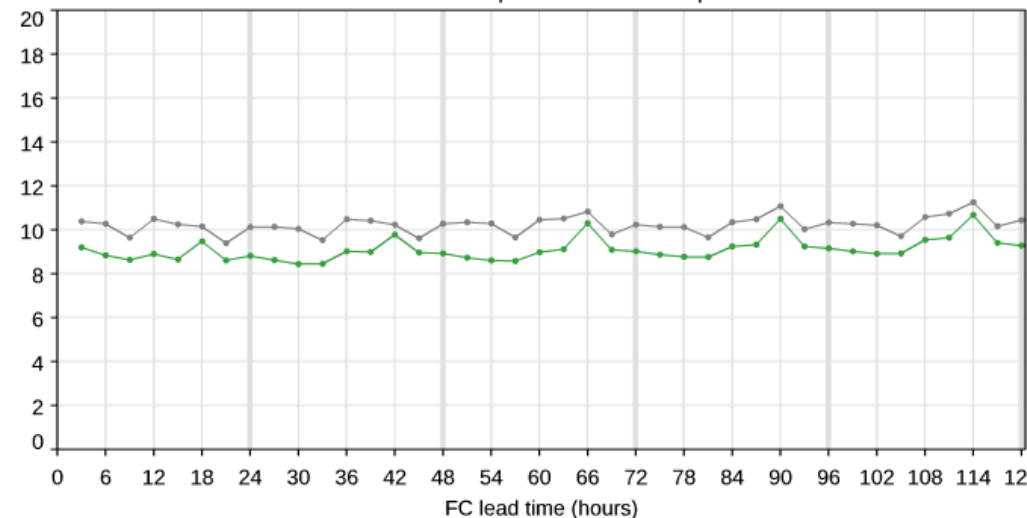
Total Aerosol Optical Depth at 550nm AIFS FC
2022-09-01T12:00



Analysis
IFS-Compo
5day
AIFS-Comp
5-day
AIFS-Comp
10-day

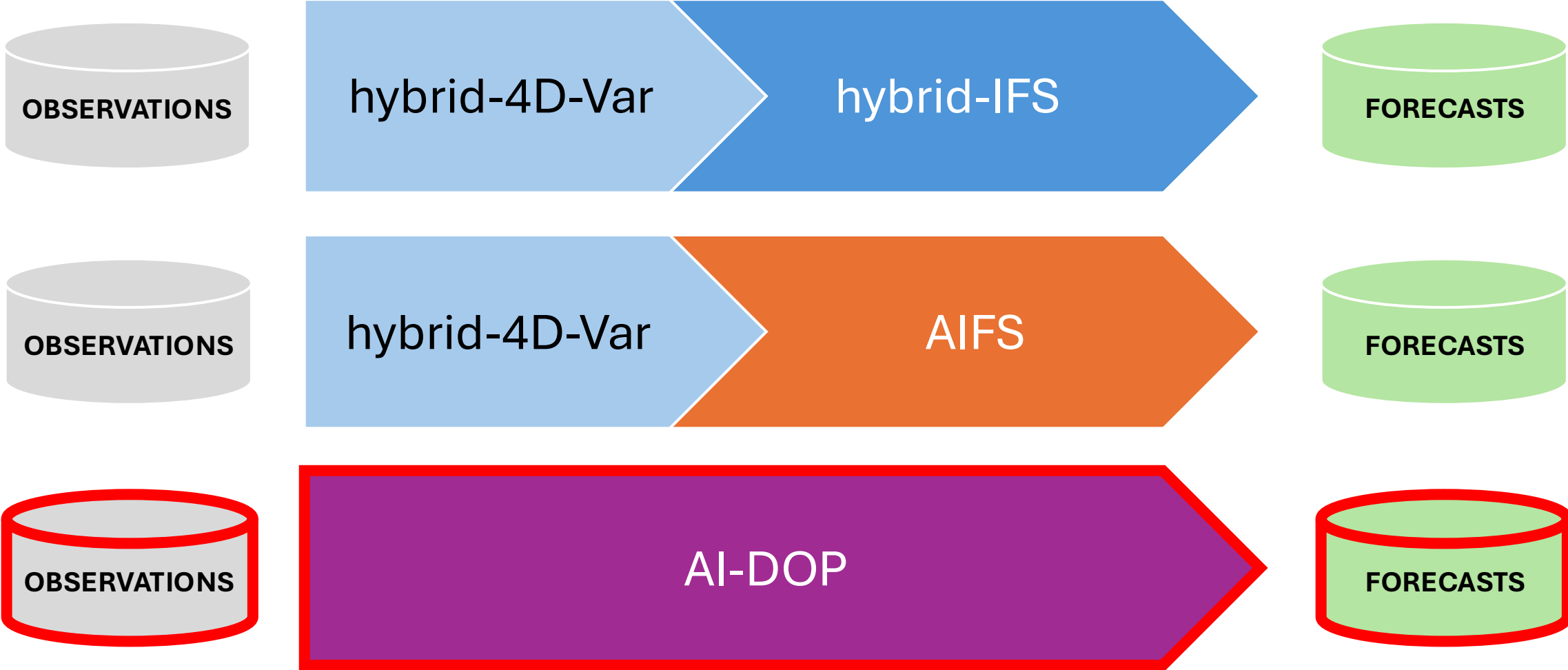


PM2.5 (ug/m3) RMS error. Model versus AirNow.
1074 sites globally. Jun - Aug 2024. 00Z. Ver0D 12.15.6.



RMSE against
observations

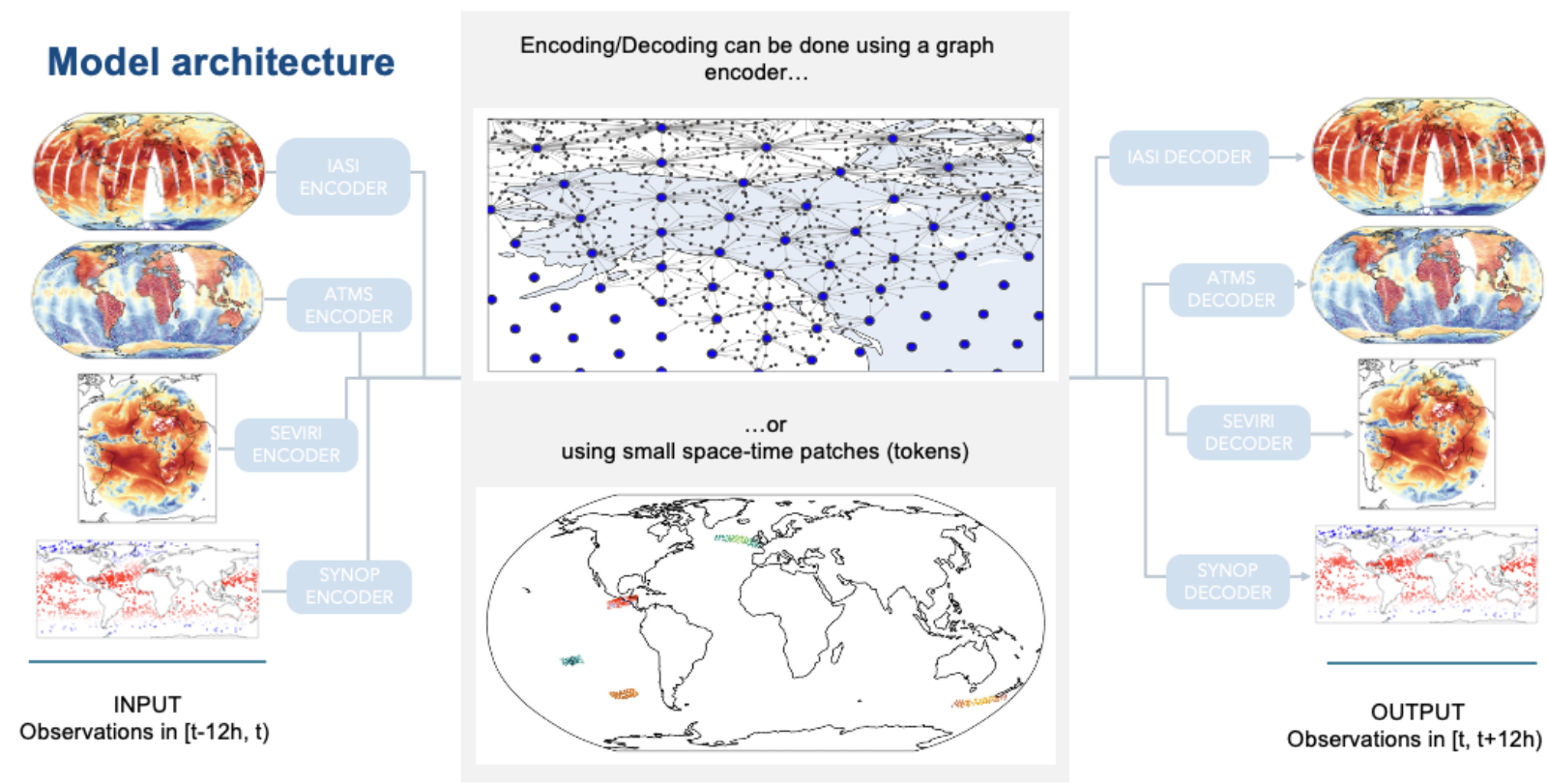
Direct Observation Prediction AI-DOP



AI-DOP uses observations to learn a physical model of the atmosphere...

Graph / Transformer NN prototype design

Observation training



Microwave sounders

- ATMS
- AMSU-A
- SSMIS
- AMSR-2

Infrared sounders

- IASI + AVHRR vis
- CrIS
- SEVIRI

Scatterometer

- ASCAT

Radio occultation

- GPSRO

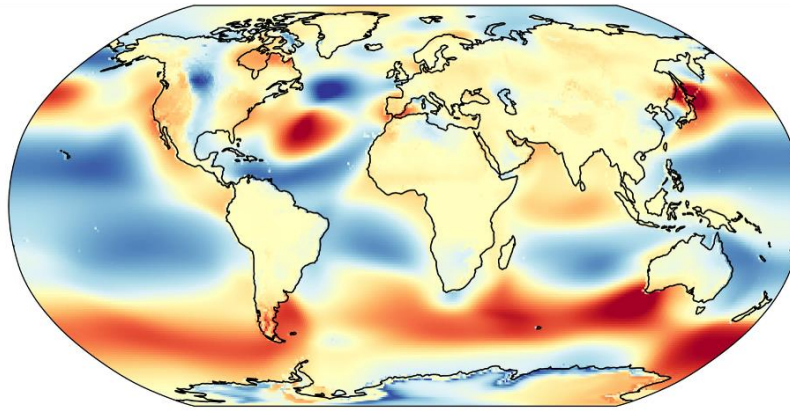
Radar altimeter

- RALT

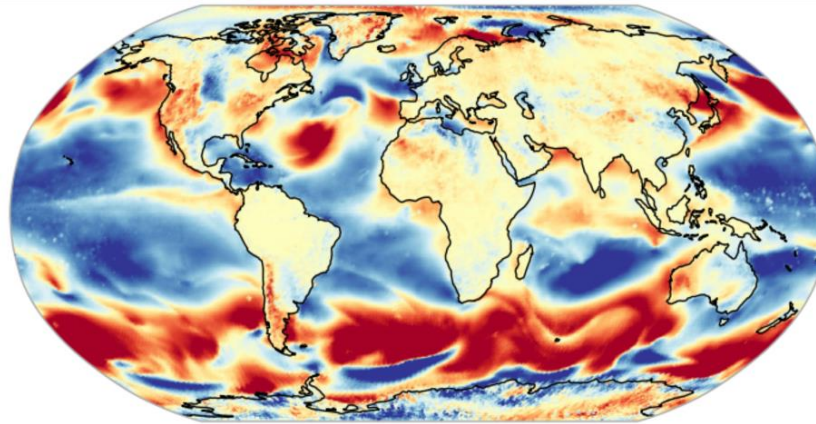
Conventional

- Surface stations (including buoys)
- Radiosondes
- Aircraft
- Snow depth
- NEXRAD Precipitation

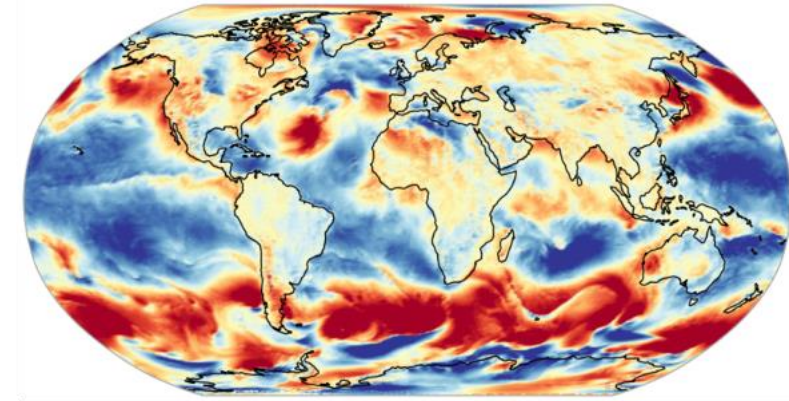
Rapid progress in DOP development



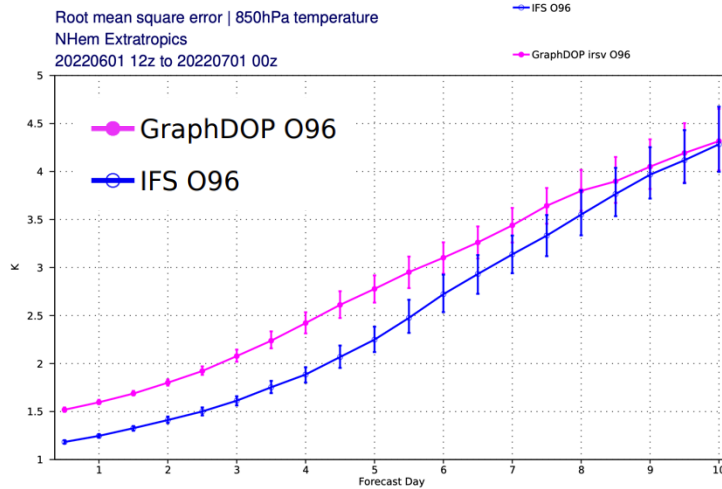
preSAC 2024



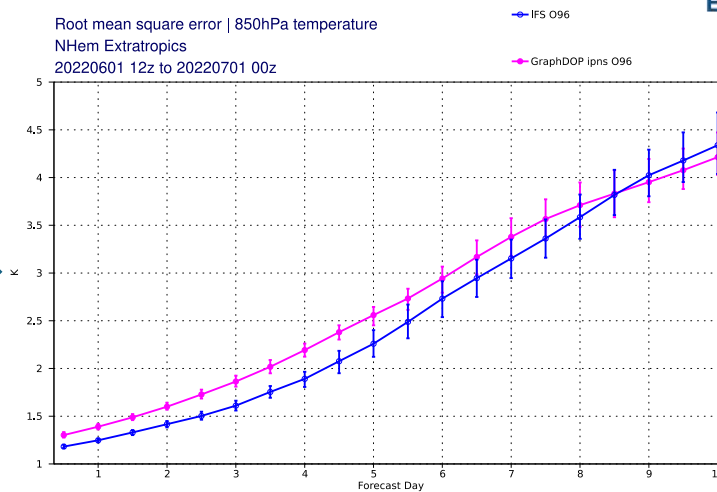
preSAC 2025



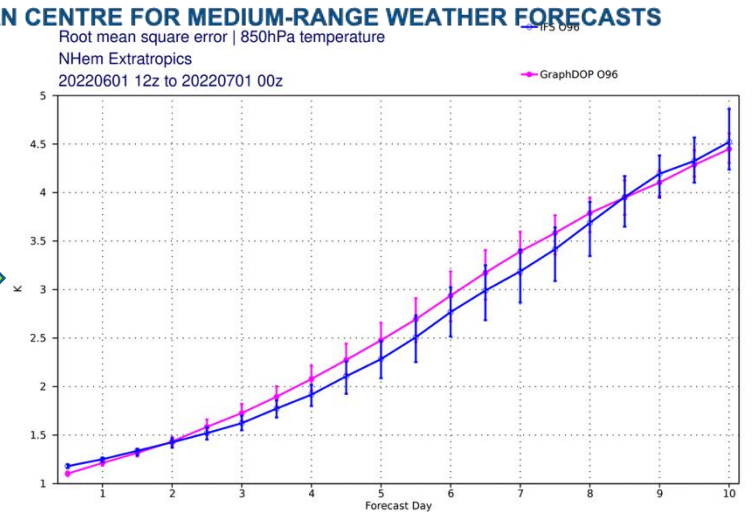
IFS analysis



May 2025



June 2025

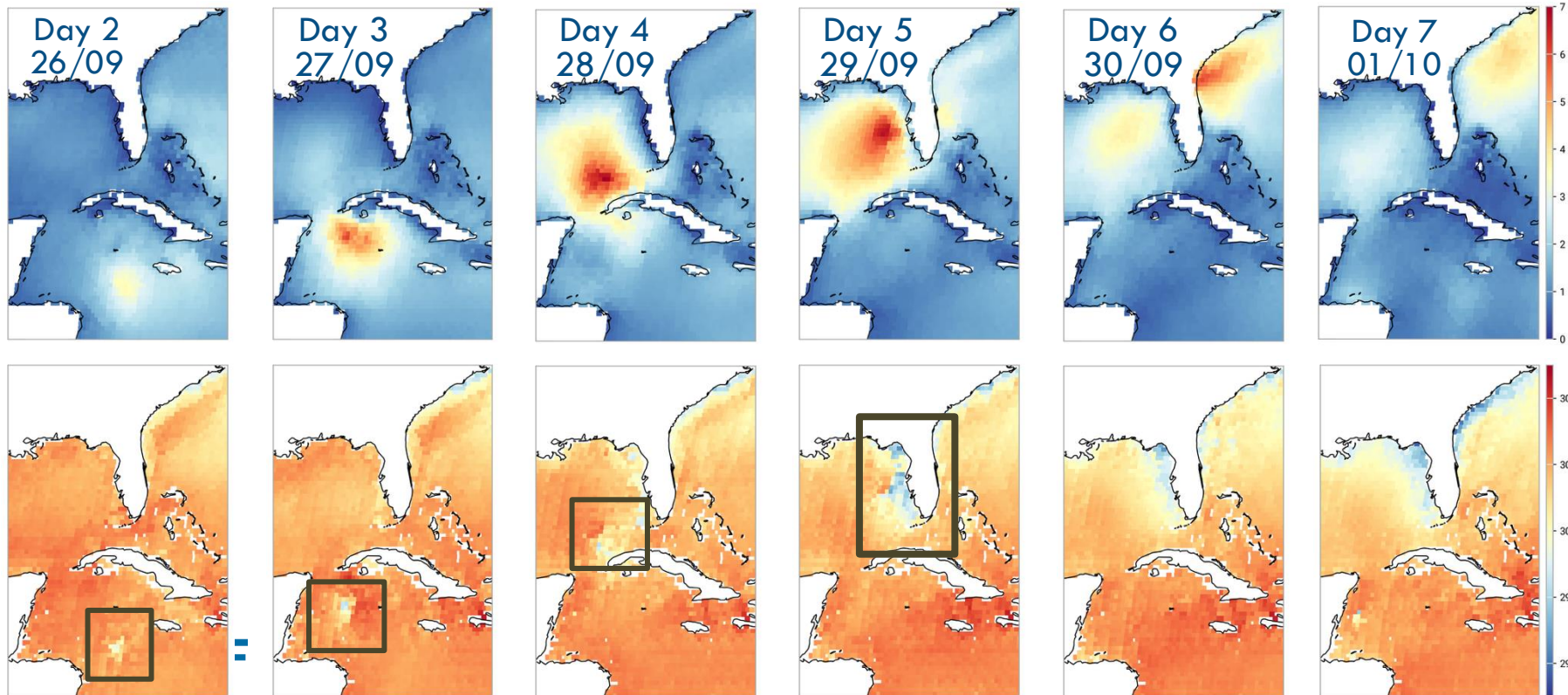


August 2025

AI-DOP forecasts are intrinsically coupled across the observable Earth system

By simultaneously learning from atmosphere, ocean and land observations, AI-DOP can produce forecasts of the complete (observable) Earth system without the need for any explicit coupling between components

Forecast initialized 24/09/2022 09-21



Significant wave height

Cold wake in Sea surface Temperature!

Anemoi

Developed and used by meteorological centers across Europe.

AEMET, DMI, DWD, FMI, GeoSphere, KNMI, MET Norway, Meteo Swiss, **Meteo France**, RMI, SMHI, Met Office & ECMWF

Global and regional modelling in the same framework.

Recent additions:

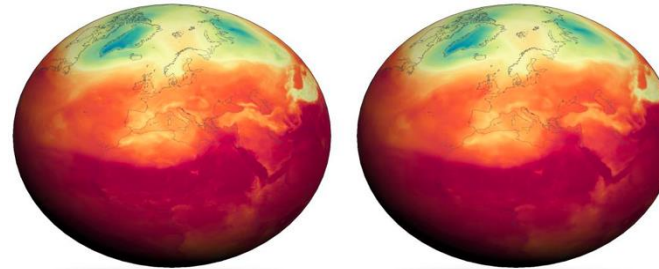
- Ensemble forecasting (2 methods)
- Temporal interpolation
- Improved HPC performance
- Training on multiple regional domains.

Ongoing:

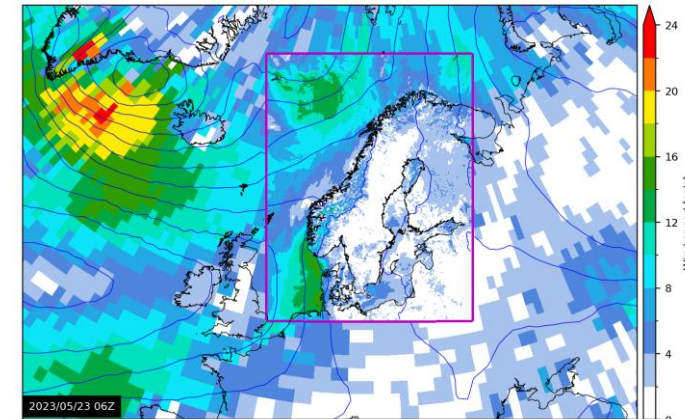
- Observations – AI-DOP in Anemoi



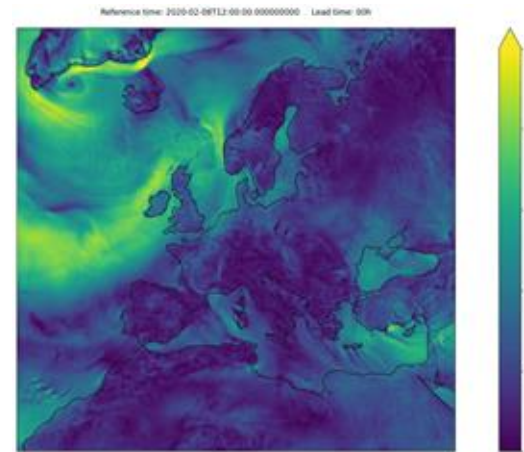
Pooling of resources to develop multiple bespoke forecast models.



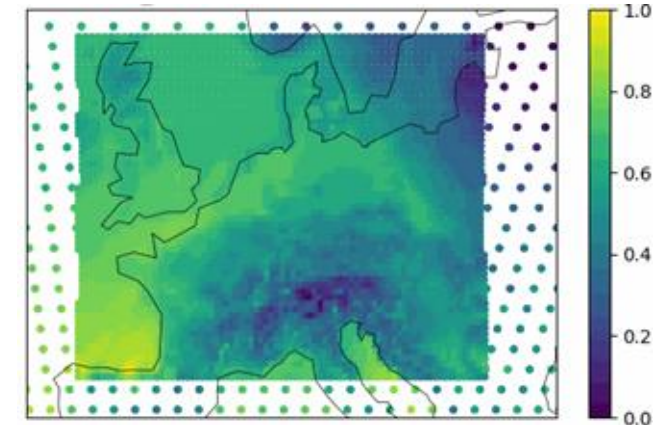
DWD's AICON – Now NWP operational



MET Norway's stretched-grid Bris

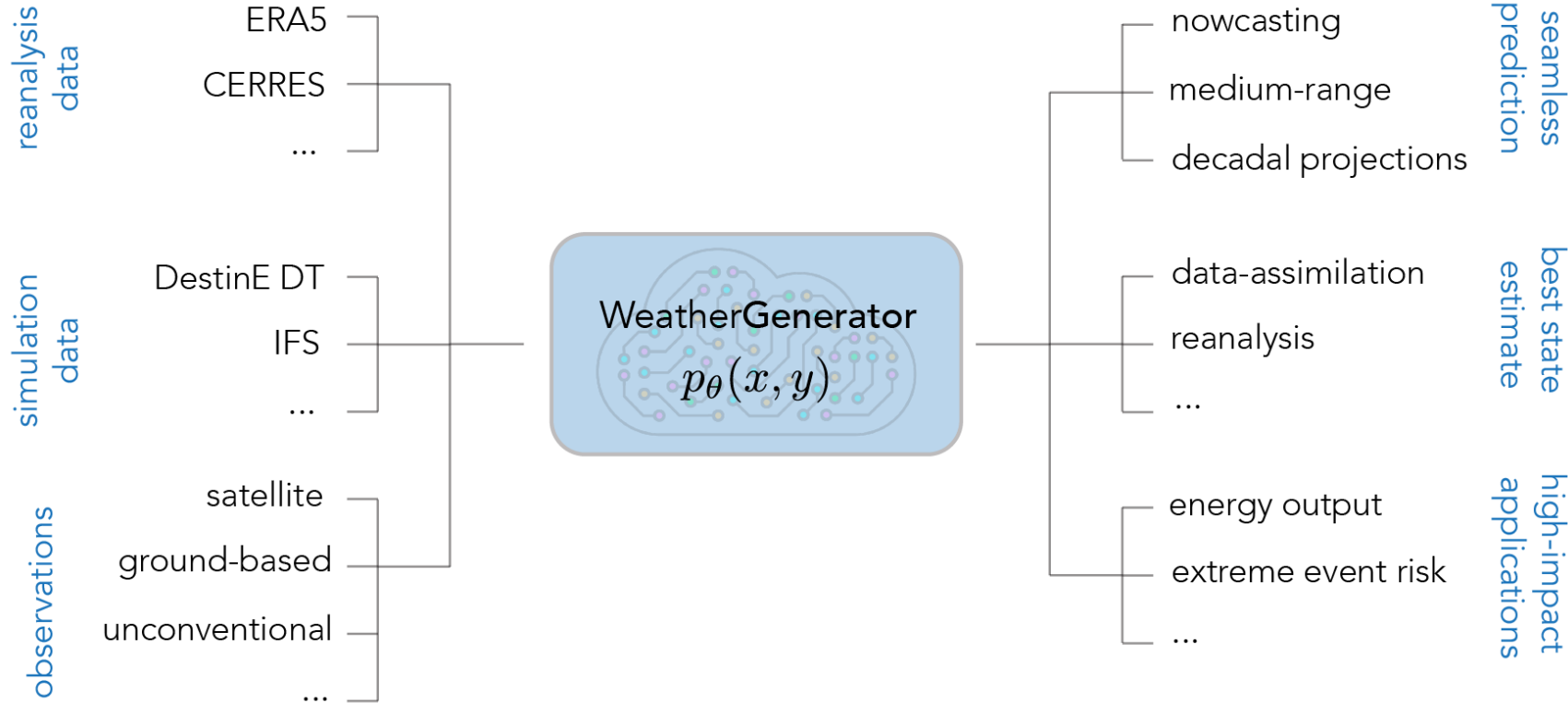
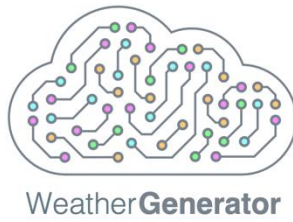


RMI's CERRA LAM model



KNMI's stretched-grid CERRA model

Weather Generator

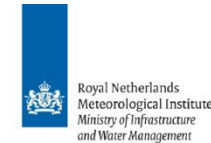


Horizon Research project started Feb 2025

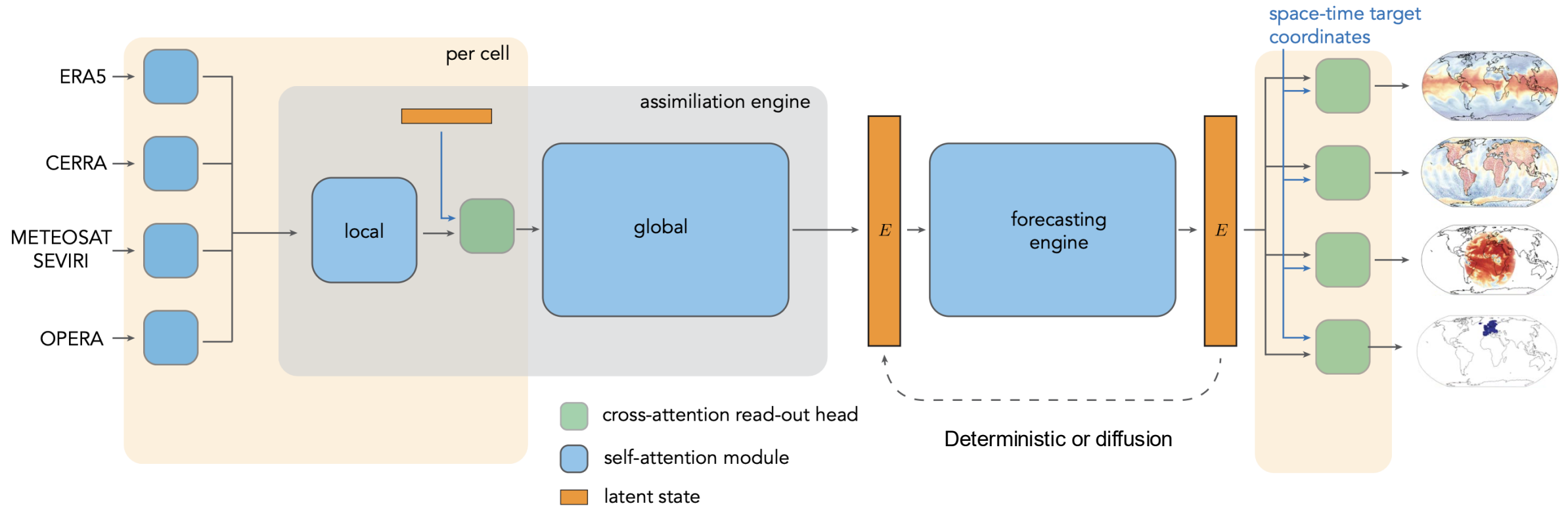
Exploring the next generation of ML models. Single foundation models across time, space and task

Benefiting from and feeding back into Anemoi

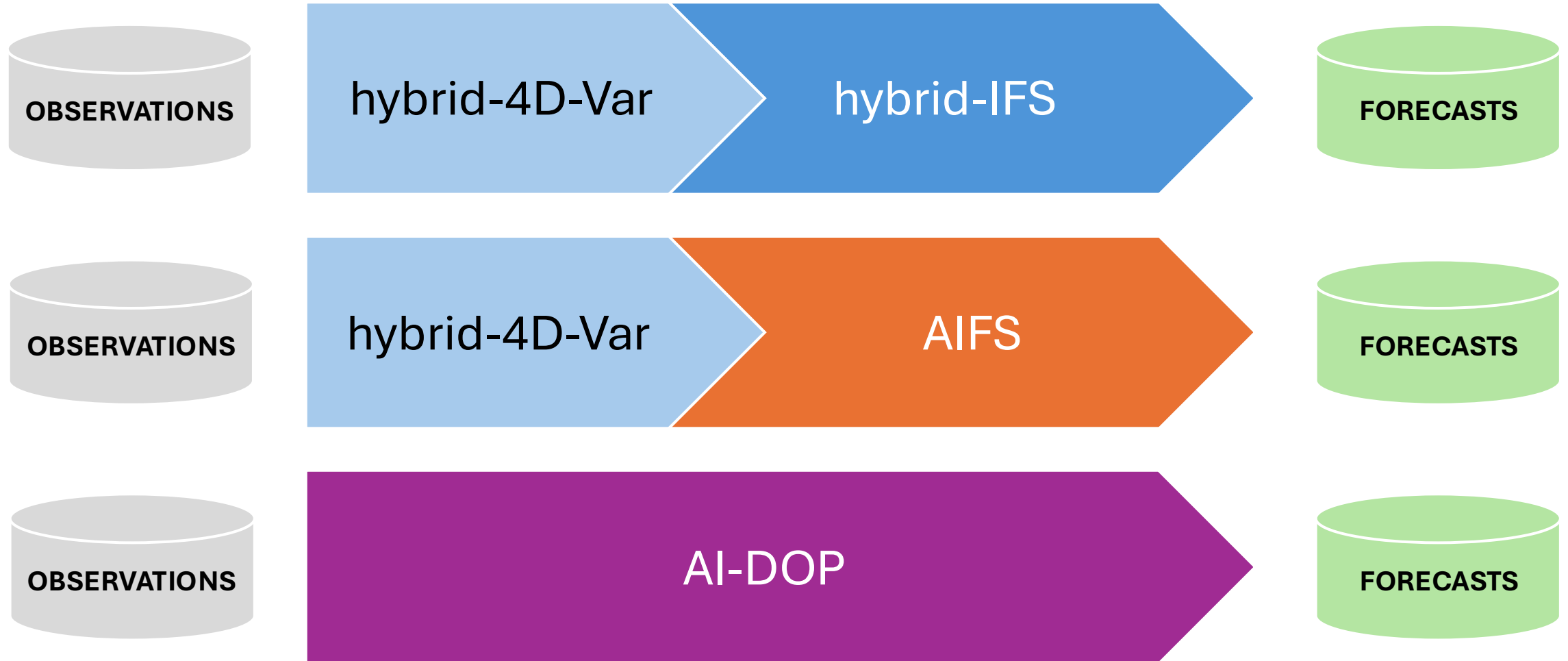
<https://www.ecmwf.int/en/about/media-centre/news/2024/weathergenerator-project-aims-recast-machine-learning-earth-system>



WeatherGenerator: latent-space rollout



...where are these exciting ML threads headed?

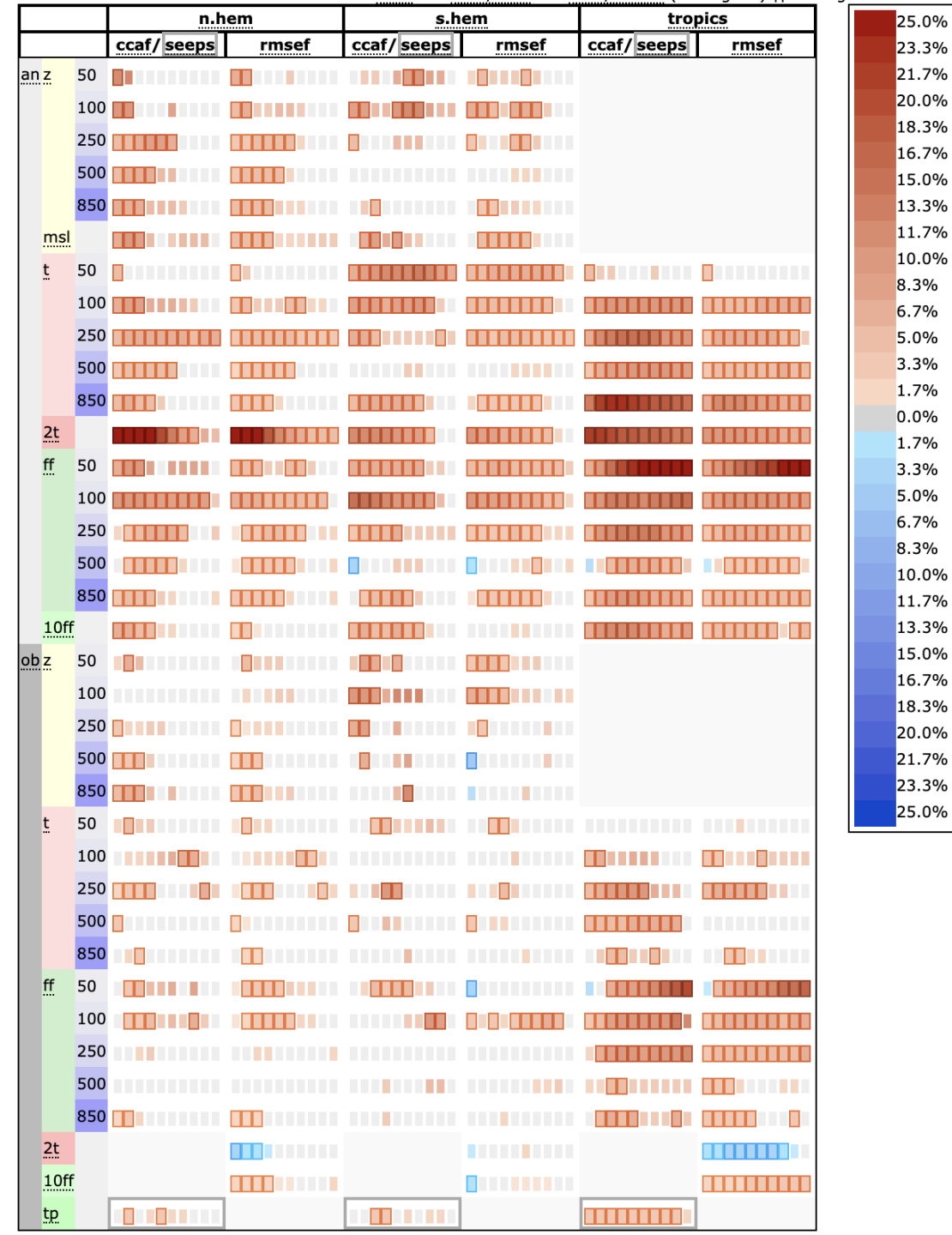


IFS+AIFS interactions add R2O complexity

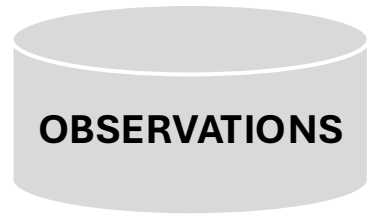
Scorecard of AIFS Single 1.1 initialised with 50r1 e-suite vs 49r1

Improvements to IFS analysis significantly change climatology of the AIFS and degrade skill

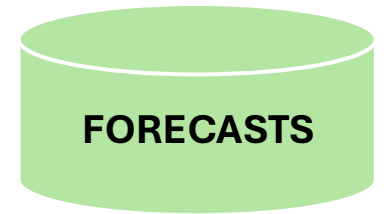
Solution – fine-tune AIFS for 50r1 initialisation
Adds complexity to already complex IFS implementation



...converge to a single end-to-end ML system

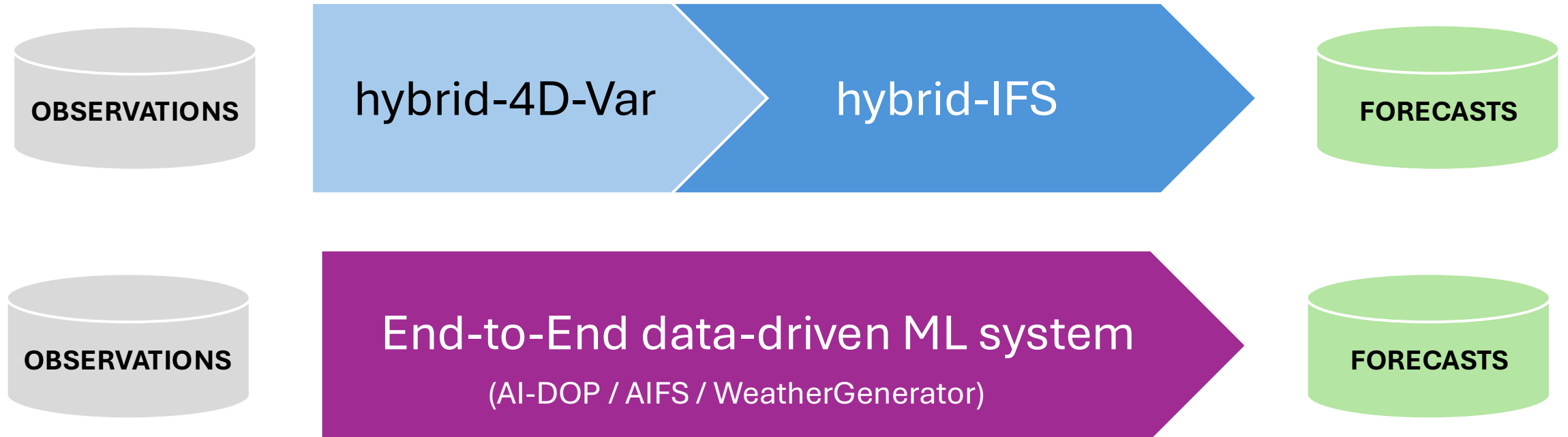


End-to-End data-driven ML system
(AI-DOP / AIFS / WeatherGenerator)



...running in parallel with an ML augmented physics-based system

We will exploit synergies between the physics-based and data-driven systems, but avoid hard dependencies, allowing us to be agile and flexible to exploit future science, HPC technology and observation opportunities in both areas.



Summary

- Rapid deployment of ML across existing ECMWF workflow to augment our physics-based DA/FC systems
- Operational AIFS Single and ENS, extension to full Earth system and sub-seasonal forecasts
- AI-DOP rapidly improving and demonstrating end-to-end ML forecasting of the full Earth system
- Convergence towards sustainable future equilibrium of dual physics-based and ML FC capability to remain agile
- Highly active and productive collaboration with Member States

Questions?