Summary of online bias correction work across the centers

Bias correction inside the DA scheme
ECMWF

Online bias correction in forecast
UK Met Office, ECCC, ECMWF

Adaptive parameter tuning
DWD, ECCC, ECMWF

Spectral nudging
ECCC, CMA, ECMWF, Meteo France, UK MetOffice

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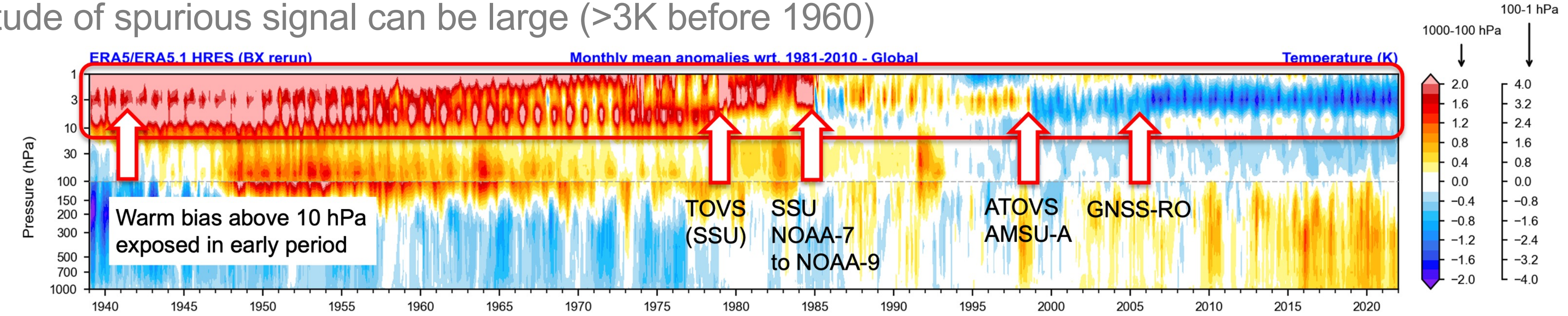
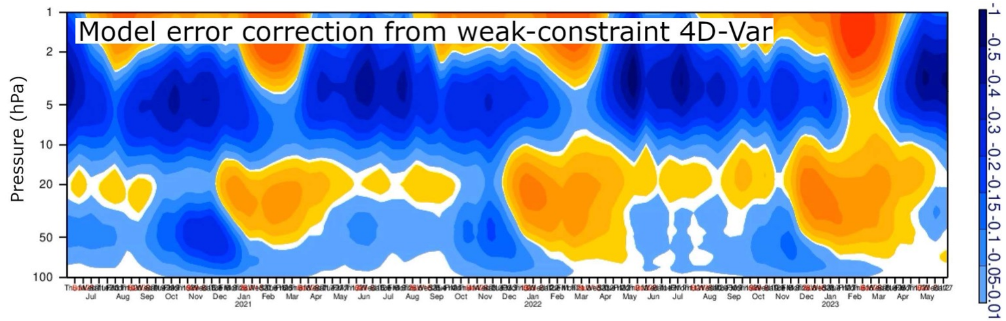
Model bias correction in ERA6 for the stratosphere

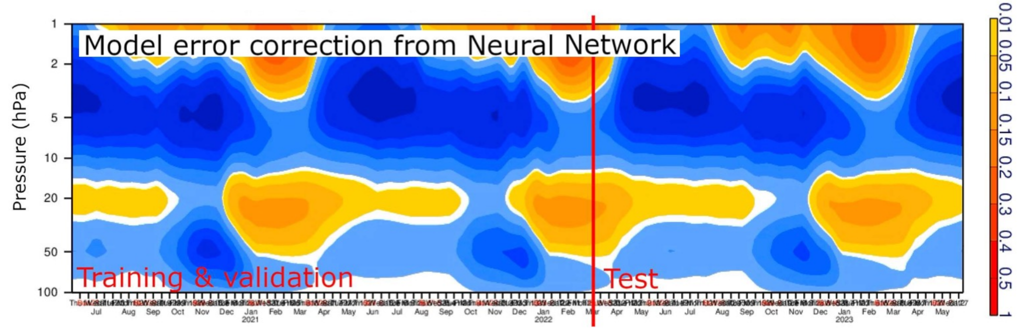
ERA5 presents artefacts in stratospheric climate trends due to model biases and ever-changing observing system. Amplitude of spurious signal can be large (>3K before 1960)



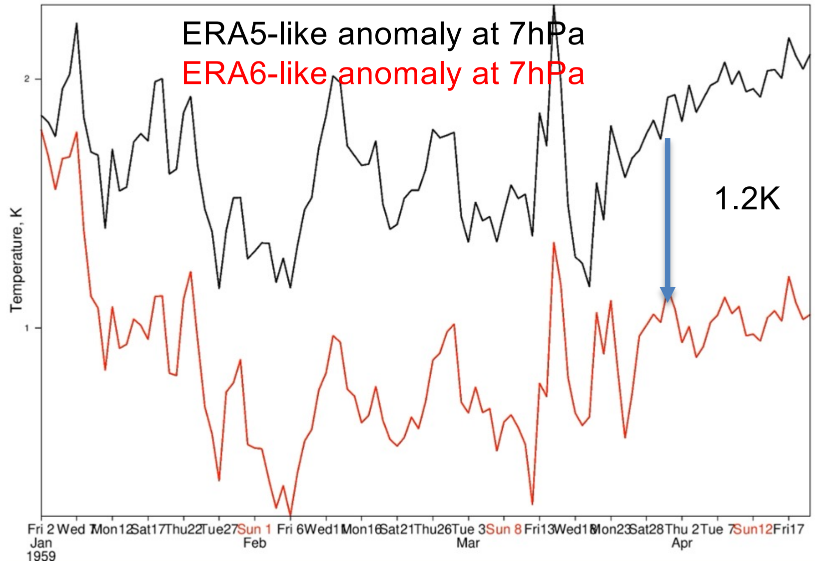
1. Weak-constraint 4D-Var estimates model biases effectively over recent periods (2021/2023)



2. This model bias correction is emulated using ML with the model first-guess as input



3. The ML correction can be applied over any reanalysis period (e.g. Jan 1959 to May 1959)

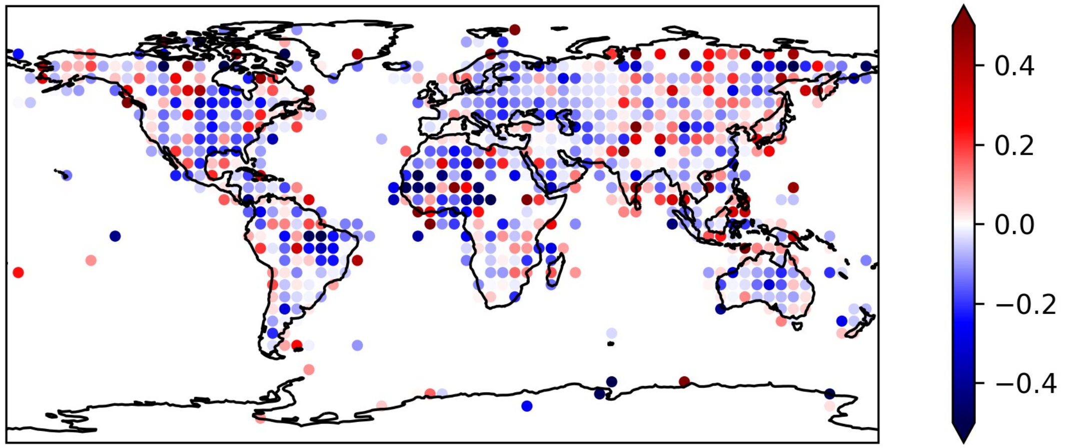


4. Emulator cools down the upper stratosphere to account for the warm bias

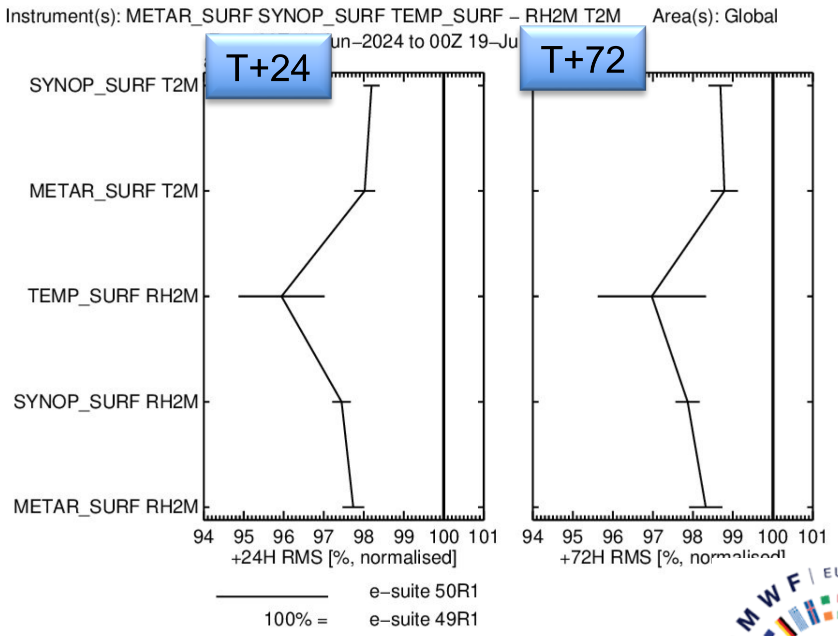
T2m assimilation: Weak constraint 4d-var in the boundary layer

- Weak constraint extended to the boundary layer (& top soil temperature level) including representation of the diurnal cycle of model error. **Operational in 2026**.

RMS of first-guess departure for T2m



RMS of forecast departure against surface data



Overall a 3% reduction in the RMS compared to CY49R1

Impacts for summer 2024

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DWD, ECMWF, ECCC

Spectral nudging
ECCC, CMA, ECMWF, Meteo France, UK MetOffice

Adaptive parameter tuning at DWD

- **IDEA:** Use time-filtered analysis increments of near-surface variables (2m T, 10m winds, 2m relative humidity) to update tunable parameters in the forecasts.

- **Recently more parameters added to tuning:** now including hydraulic diffusivity of the soil, land albedo, surface transfer resistance, and the snow cover fraction diagnosis (at low snow amounts).

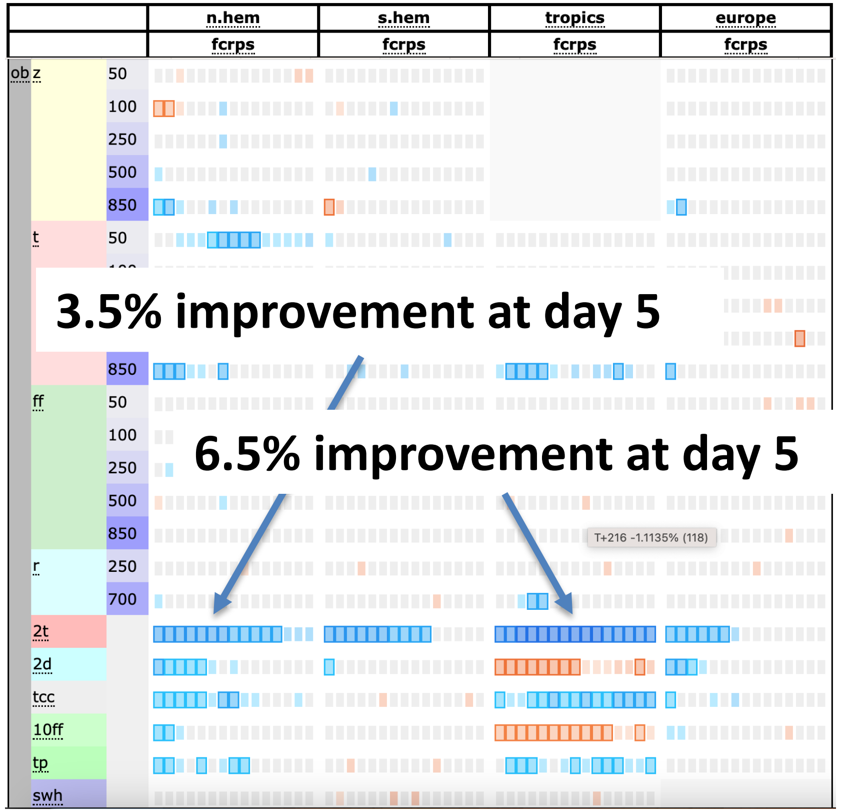
See Zängl (2023) https://doi.org/10.1002/qj.4535 for further information

Adaptive Parameter Tuning for the land model including information from analysis increments

- Following the DWD approach, we use time-filtered analysis increments of screen-level variables used to update parameters in the forecasts (*parameter-of-the-day*).

#	Adapted parameters under testing
1	Minimum stomata resistance
2	Bare soil resistance to evaporation
3	Skin conductivity (veg, soil and snow)
4	Albedo of snow under forests
5	Albedo of bare soil

Ensemble FC scores against obs, June-July



- Generally improving T2m scores. Largest impact in JJA, smaller impact in DJF season.
- Generally neutral to positive impact in other variables
- The new information generated by the parameter-of-the-day approach will not be used operationally, but rather to adjust default parameter values

Self adjusting, online, surface-atmosphere bias correction

Dominik Jacques, data assimilation group, ECCC, Dorval

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Environnement et Changement climatique Canada

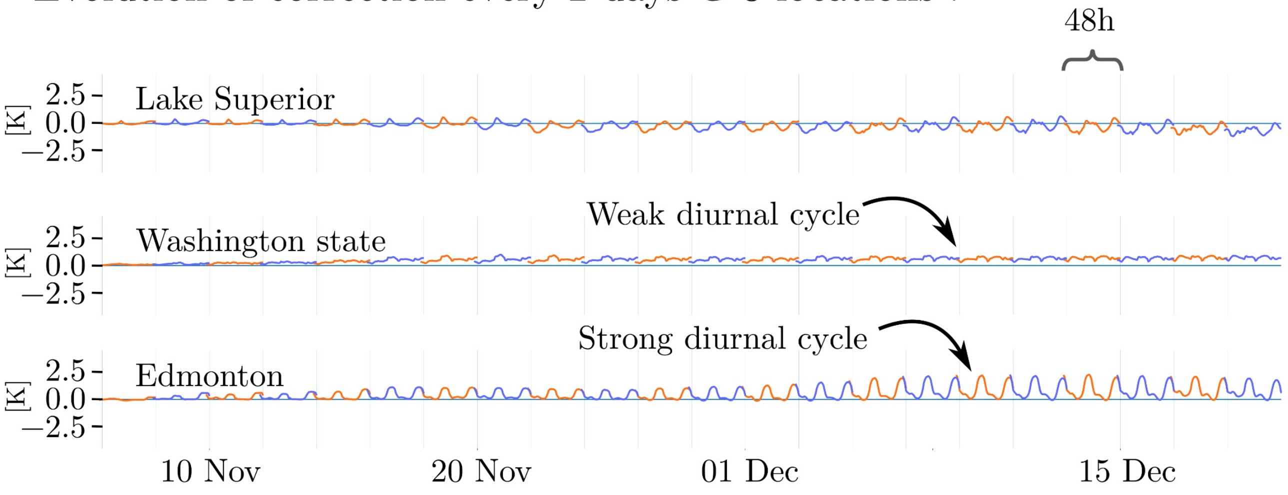
Biases of prediction systems have been addressed in many ways:

- Post-processing (e.g. MOS, UMOS and others)
- Adjustment of parameters controlling surface-atmosphere interactions (Zängl, 2023, 10.1002/qj.4535)
- Online correction of atmospheric biases using machine learning (Farchi et al. 2025, 10.1002/qj.4934)

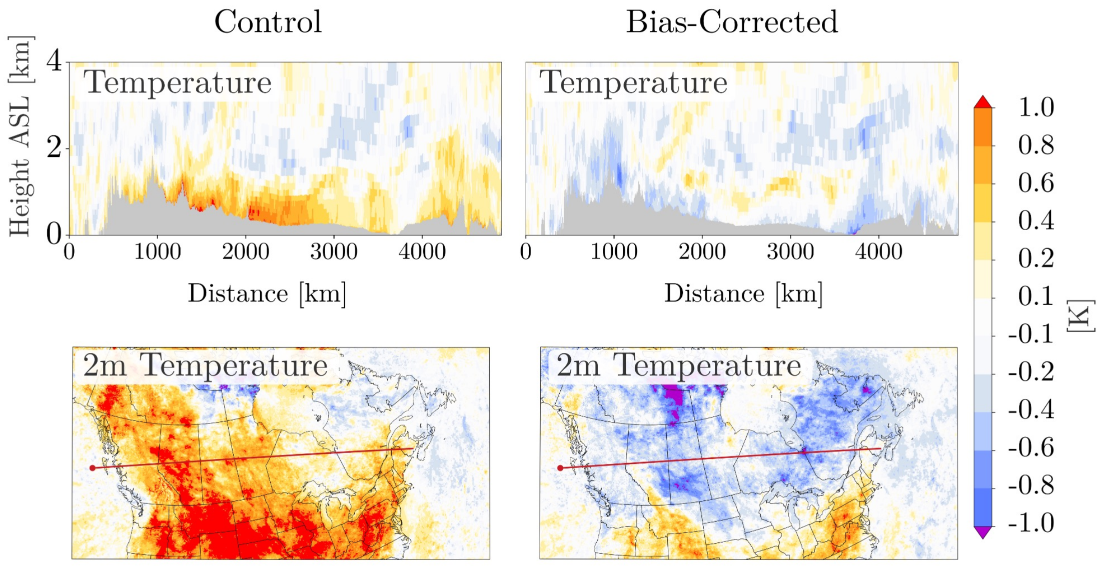
At ECCC, we are developing an approach where a correction term is added to surface temperature and moisture to compensate for the long-term (15 days +) average differences between analyses and forecasts.

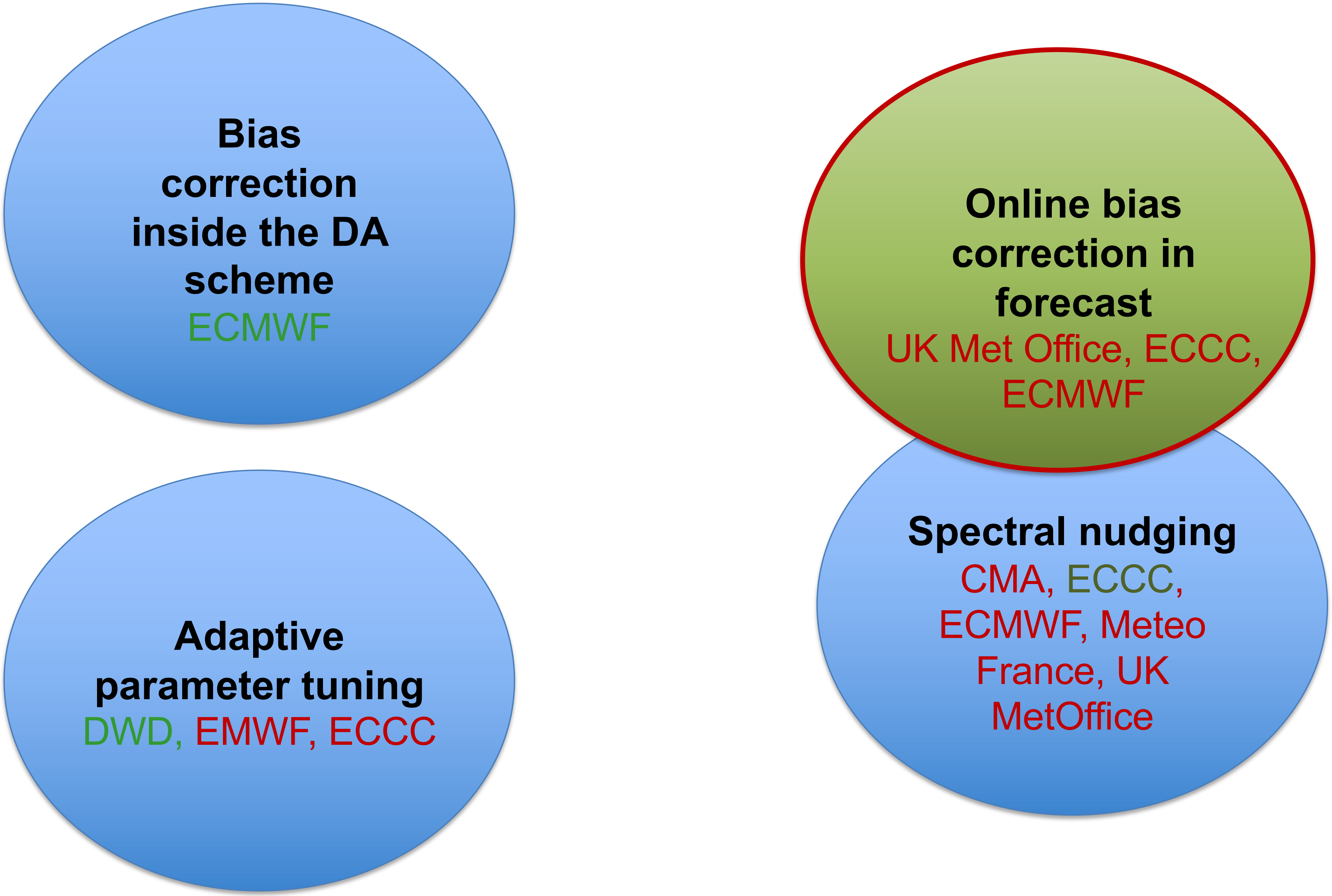
The correction is separately determined at every grid point as a function of lead time.
It it adjusted every day.

Evolution of correction every 2 days @ 3 locations :



18-day averages of Analysis - Forecast
for temperature at 24h lead time

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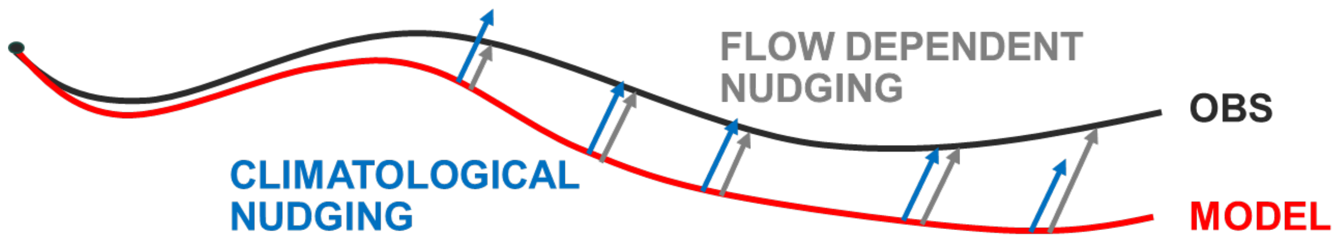
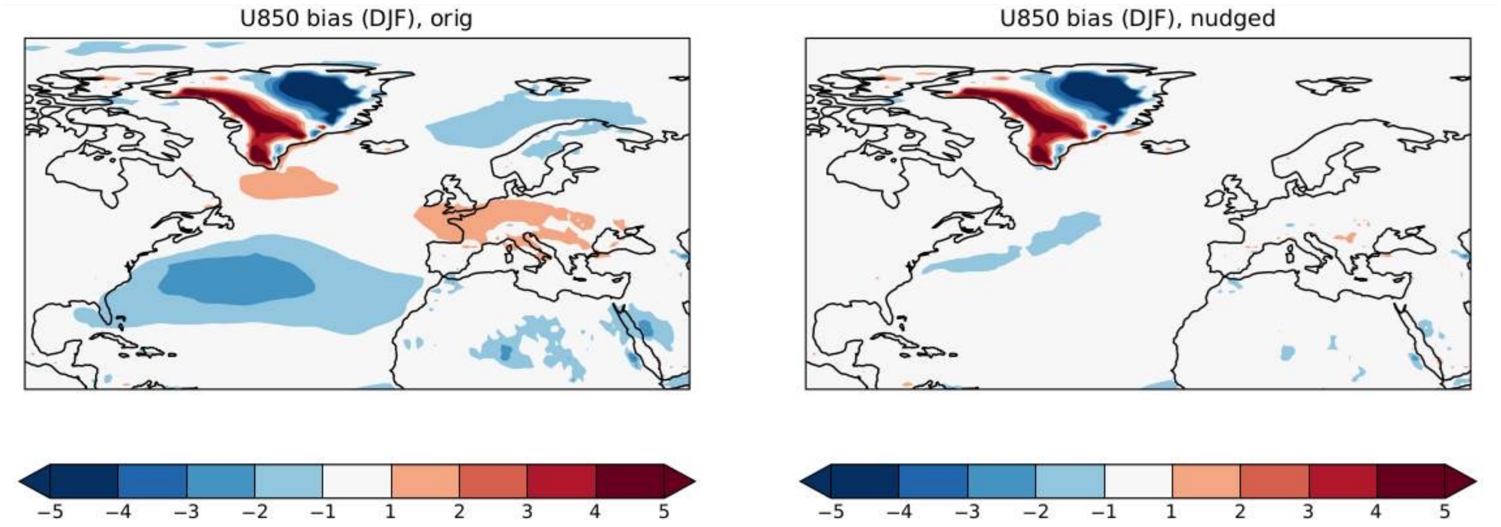
Machine learning for correcting seasonal forecast model biases

Steven Hardiman, Adam Scaife, et al.

Can a neural network (NN) learn flow dependent model bias (grey arrows) due to GW and other missing processes, just from the current flow?

If so, could use it to bias-correct a future seasonal forecast in real time, where there are no observations





Running retrospective forecasts with the NN included (nudged) shows the greatest improvement in the north Atlantic sector (pictured) and a weak jet bias found in free-running retrospective forecasts (orig) is largely removed.

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- **CanESM5** is one of two models contributing to ECCC's seasonal prediction system (GPC Montreal)
- Uniquely among current prediction models, employs **atmosphere and ocean** online bias correction
- Kharin & Scinocca (2012) methodology: nudging run → annual cycle of nudging terms → tendency correction
  - ➢ Atmosphere: T,u,v,q, nudging parameters optimized as in Scinocca & Kharin (2024)
  - ➢ Ocean: temperature/salinity nudging
- Atmosphere/ocean **biases reduced** →
- Pattern of ENSO variability and associated teleconnection improved

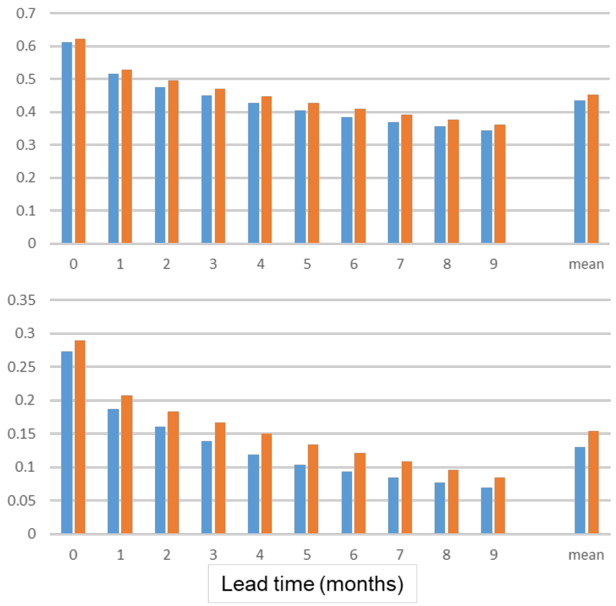
Global Mean Anomaly Correlation*

2m Temp

Precipitation

Free

Bias corrected

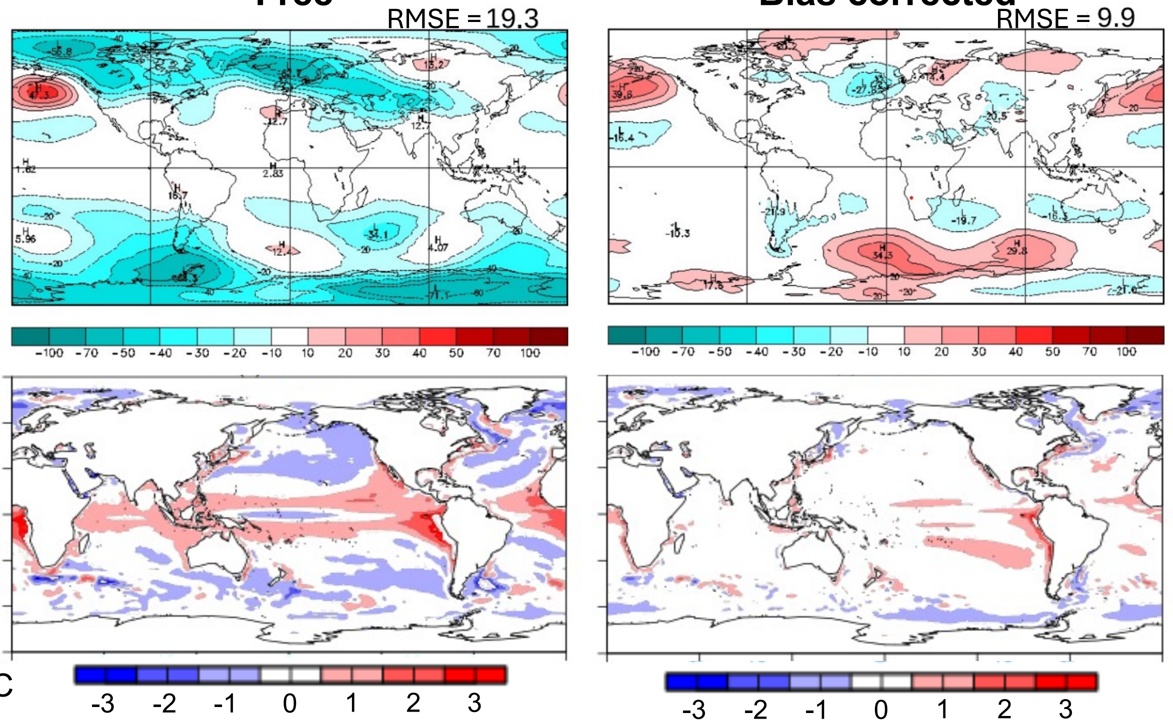


*average over all initial months

Free | **Bias corrected**

Z500 bias in AMIP runs

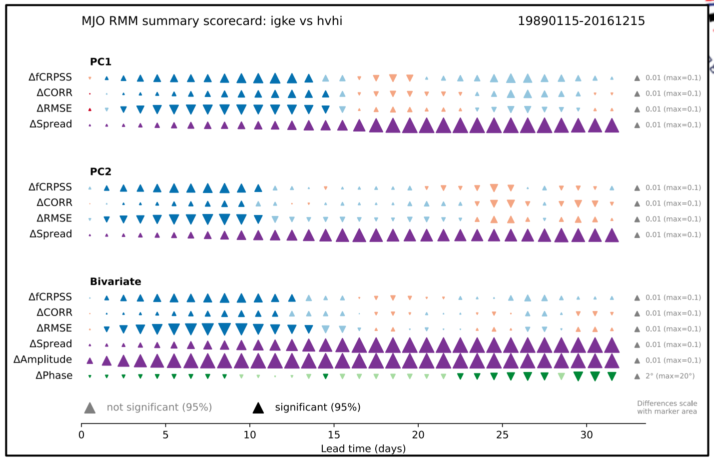
SST bias at 6-month lead

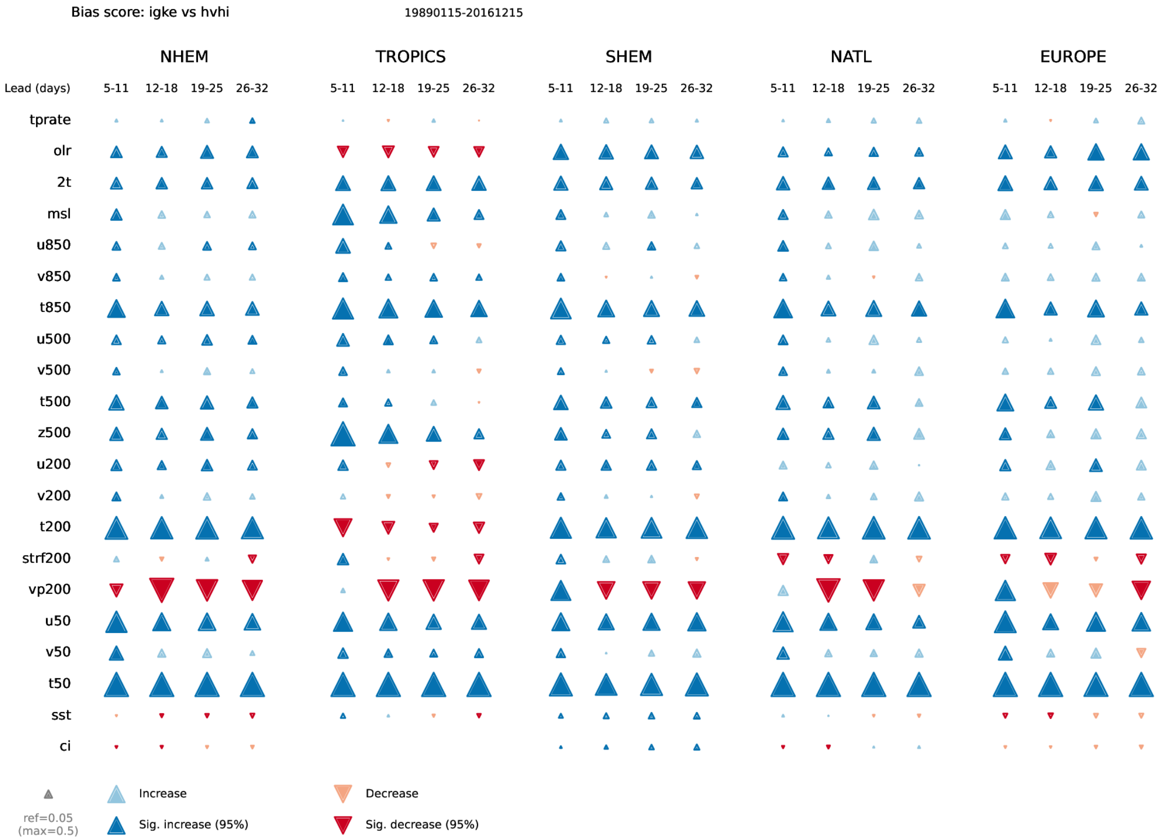


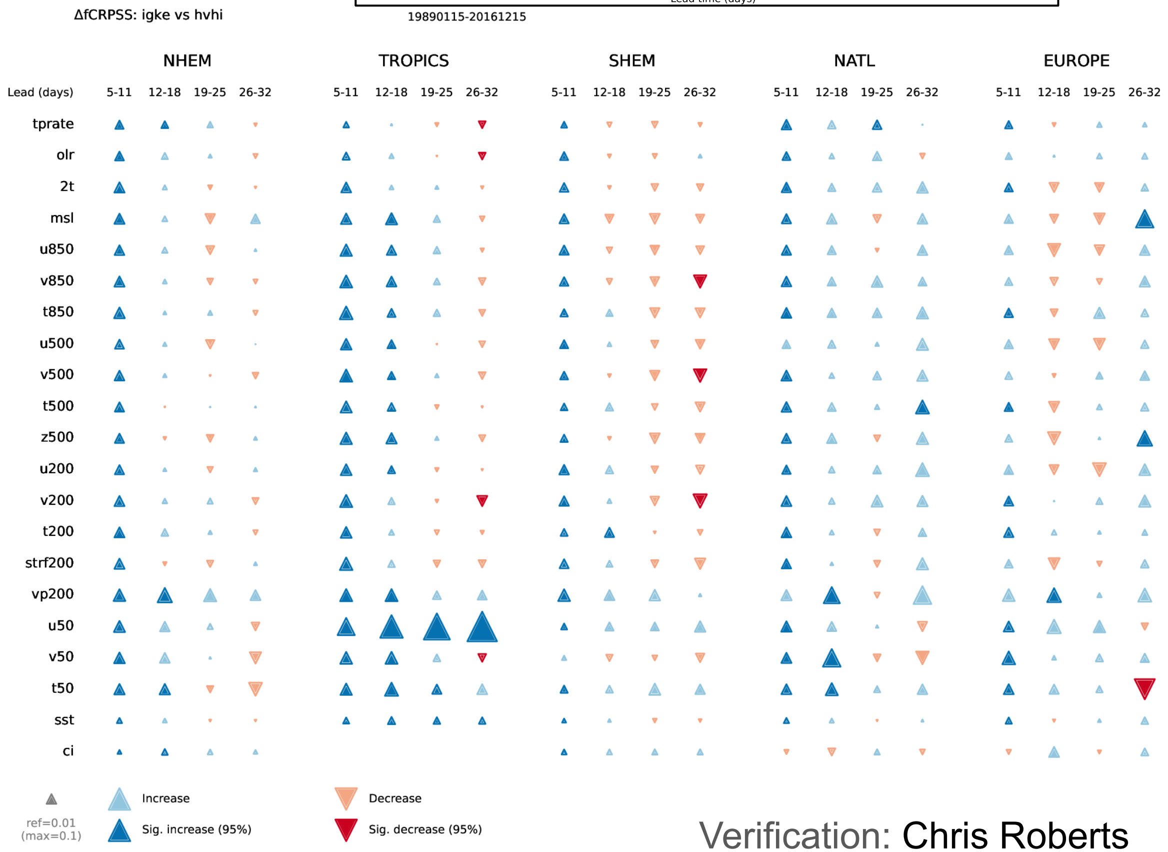
← • **Seasonal prediction skill improved** globally at all lead times, even though ENSO (Nino3.4) skill slightly degraded

Flow-dependent online bias correction: target monthly-range

- Column NN trained to predict large-scale U/V/T model error, estimated from 14 years of 6-hrly spectral nudging tendencies.
- Applying this flow-dependent NN bias correction online results in:
  - Improvements in mean biases to week 4
  - Improvements in anomalies by 1-3% to week 1 (week 2 in tropics)
  - Improvements in MJO and NINO indices
- BUT: Apart from QBO & MJO improvement, applying 6-hrly model error climatology gives similar results.







Verification: Chris Roberts

Learning the model of model error

We consider a hybrid model formulation for the IFS, where the model is parameterized by a set of parameters p:

$$\mathrm{x}_{k+1} = \mathcal{M}^{\mathrm{nn}}_{k+1:k}(\mathrm{p}, \mathrm{x}_k) = \mathcal{M}_{k+1:k}(\mathrm{x}_k) + \mathcal{F}(\mathrm{p}, \mathrm{x}_0)$$

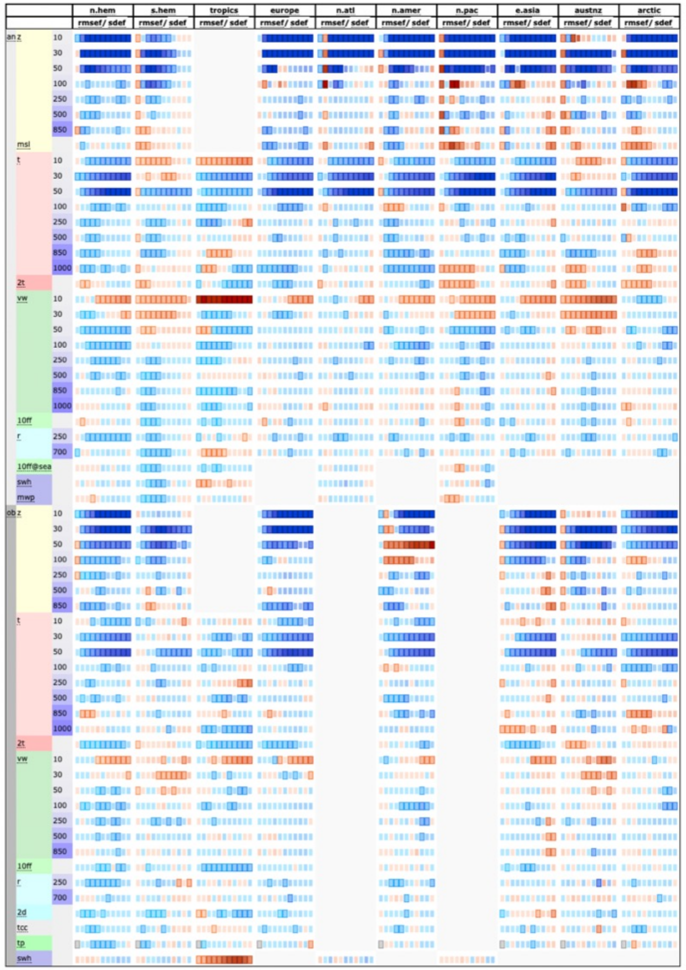
The NN is first **trained offline**, using operational analyses (as predictors) and analysis increments (as targets) at the start of each DA window

Subsequently, the NN can be further **trained online** in 4D-Var. The non-linear 4D-Var cost function takes the form:

$$\mathcal{J}^{\mathrm{nn}}(\mathrm{p}, \mathrm{x}_0) = \frac{1}{2}\left\|\mathrm{x}_0 - \mathrm{x}_0^{\mathrm{b}}\right\|^2_{\mathrm{B}^{-1}} + \frac{1}{2}\left\|\mathrm{p} - \mathrm{p}^{\mathrm{b}}\right\|^2_{\mathrm{P}^{-1}} + \frac{1}{2}\sum_{k=0}^{L}\left\|\mathrm{y}_k - \mathcal{H}_k \circ \mathcal{M}^{\mathrm{nn}}_{k:0}(\mathrm{p}, \mathrm{x}_0)\right\|^2_{\mathrm{R}_k^{-1}}.$$

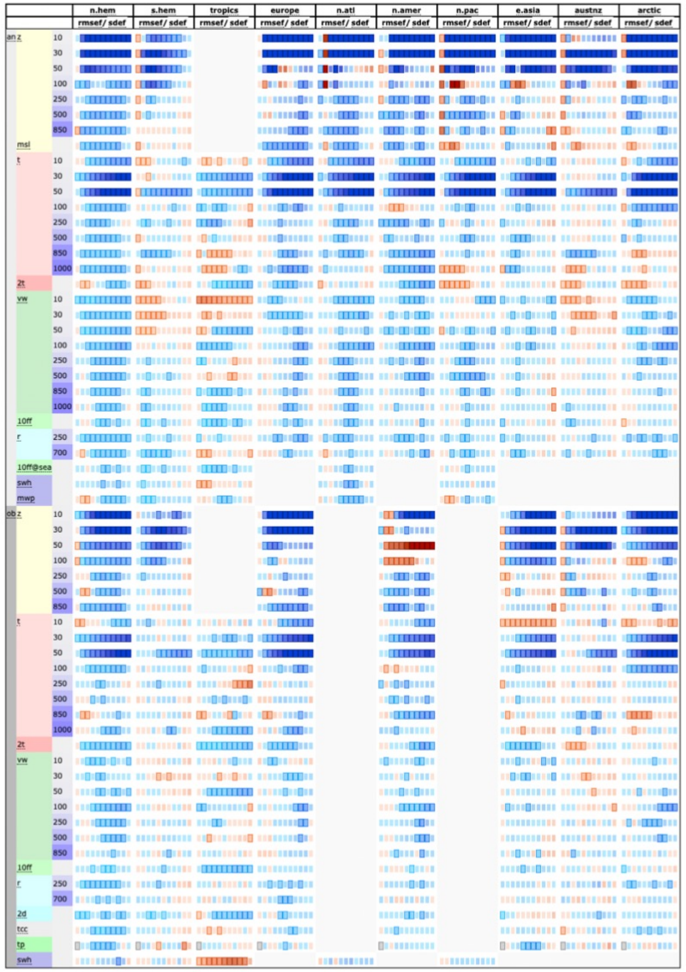
The cost function is minimized following the standard incremental 4D-Var formulation

Impact of online training on forecast scores



Bias-corrected worse

Bias-corrected better



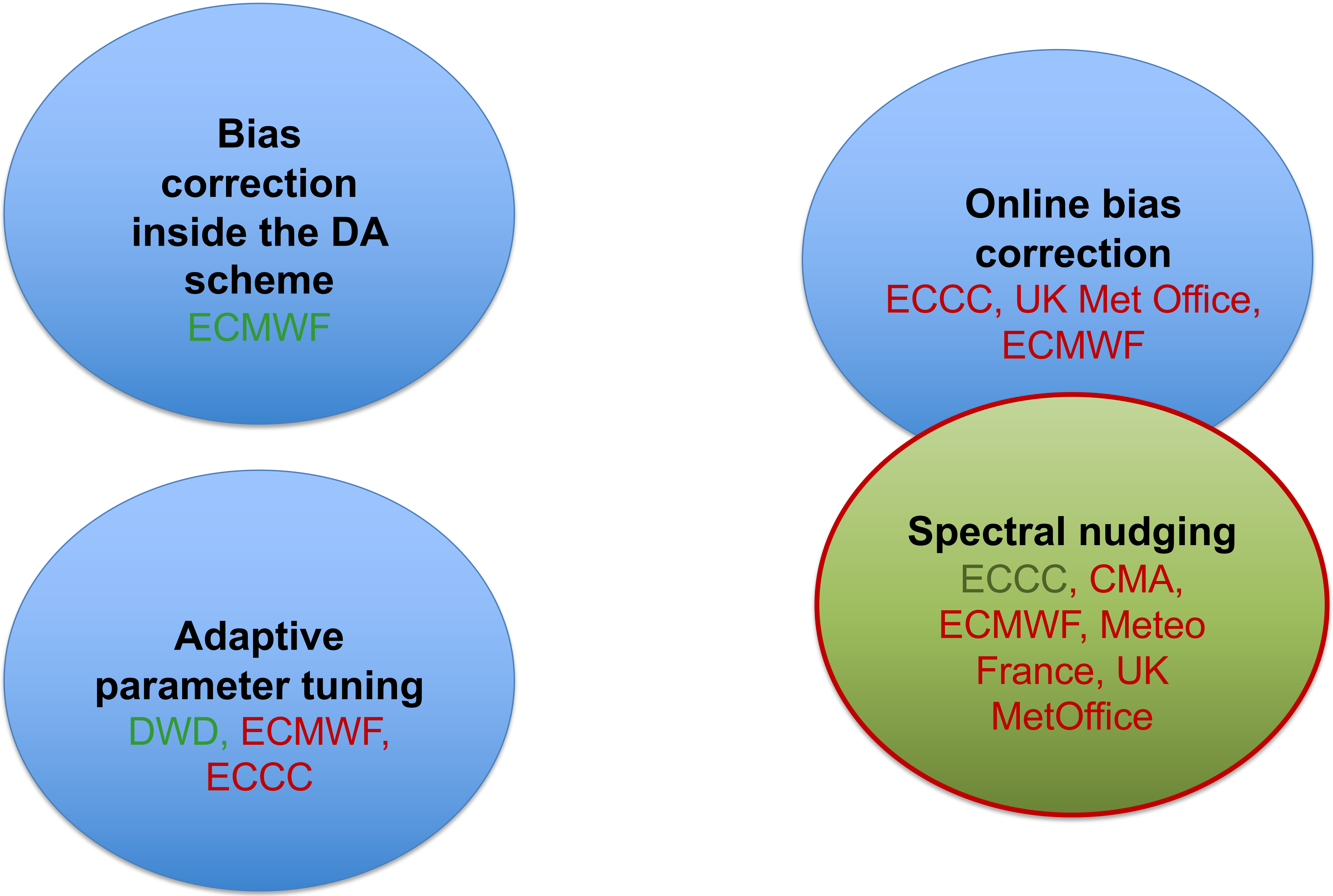
Training the NN online improves the forecast scores

Currently investigating the impact of:

- the data assimilation window length
- the spatial resolution of the NN correction
- the temporal resolution of the NN correction

Figure: Score card 2022/06/03 to 2022/07/28. 24H assimilation window with **offline** NN model error correction.

Figure: Score card 2022/06/03 to 2022/07/28. 24H assimilation window with **online** NN model error correction.



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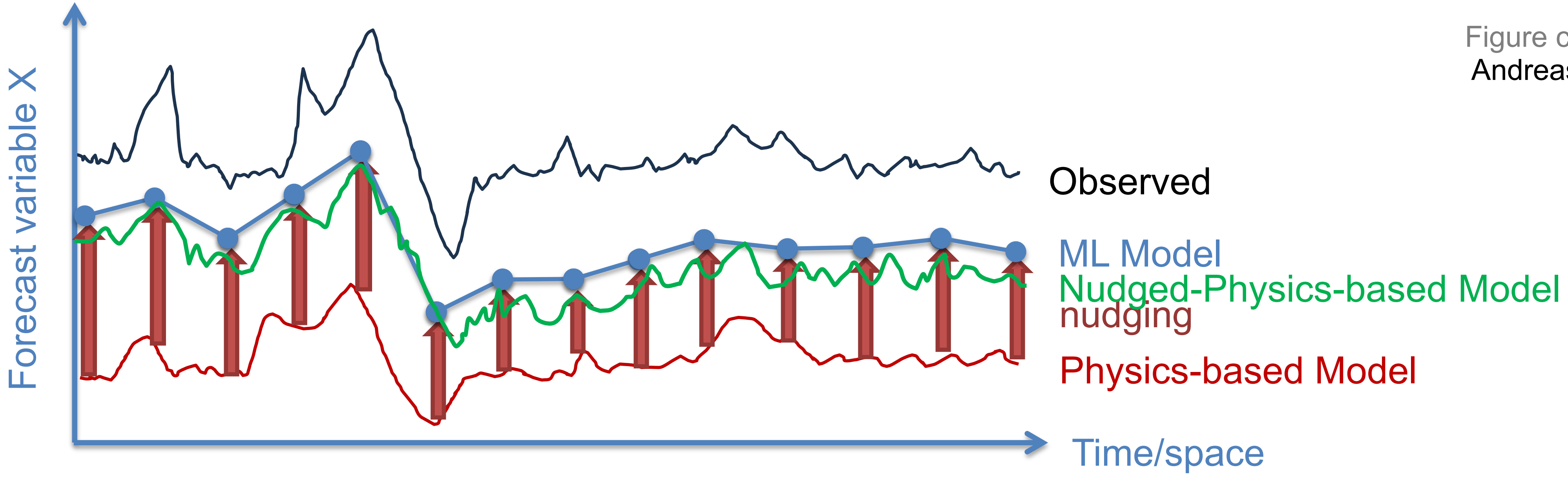

Figure courtesy:
Andreas Muller

Global Spectral Nudging

- Spectrally nudging Global Environmental Multiscale (GEM; physical model)-predicted large scales (> 2500 km) towards GEML (the ML model at ECCC) leads to:
  - Substantial reduction in RMSE compared to the operational GEM-based system (half-day improvements on the global scale)
  - Guaranteed physical consistency between fields
  - A complete set of meteorologically important variables already available with GEM
- Mesoscales develop unperturbed without showing any sign of smoothing.
  - Tropical cyclone intensities are unaffected by nudging while the position errors are reduced.

> A well-designed fusion of MLWP and NWP approaches can mitigate their individual limitations while providing a better meteorological guidance

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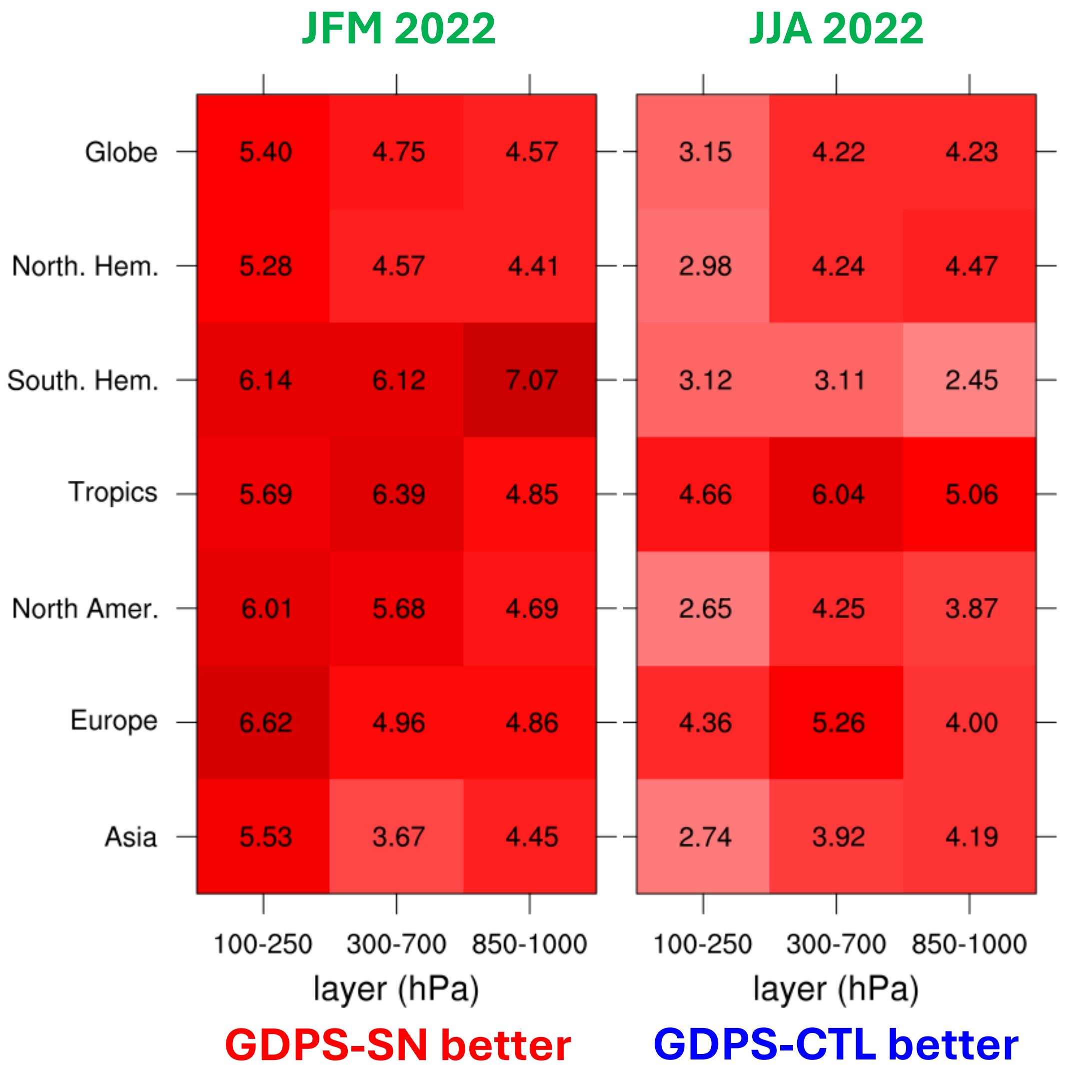
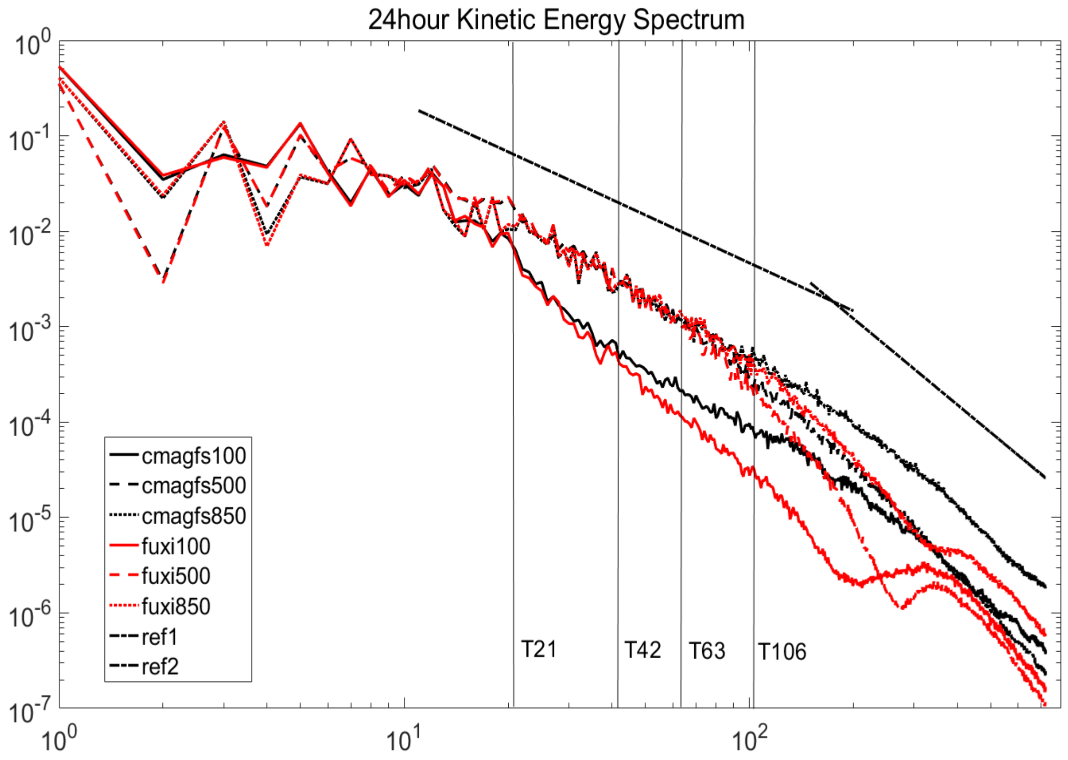
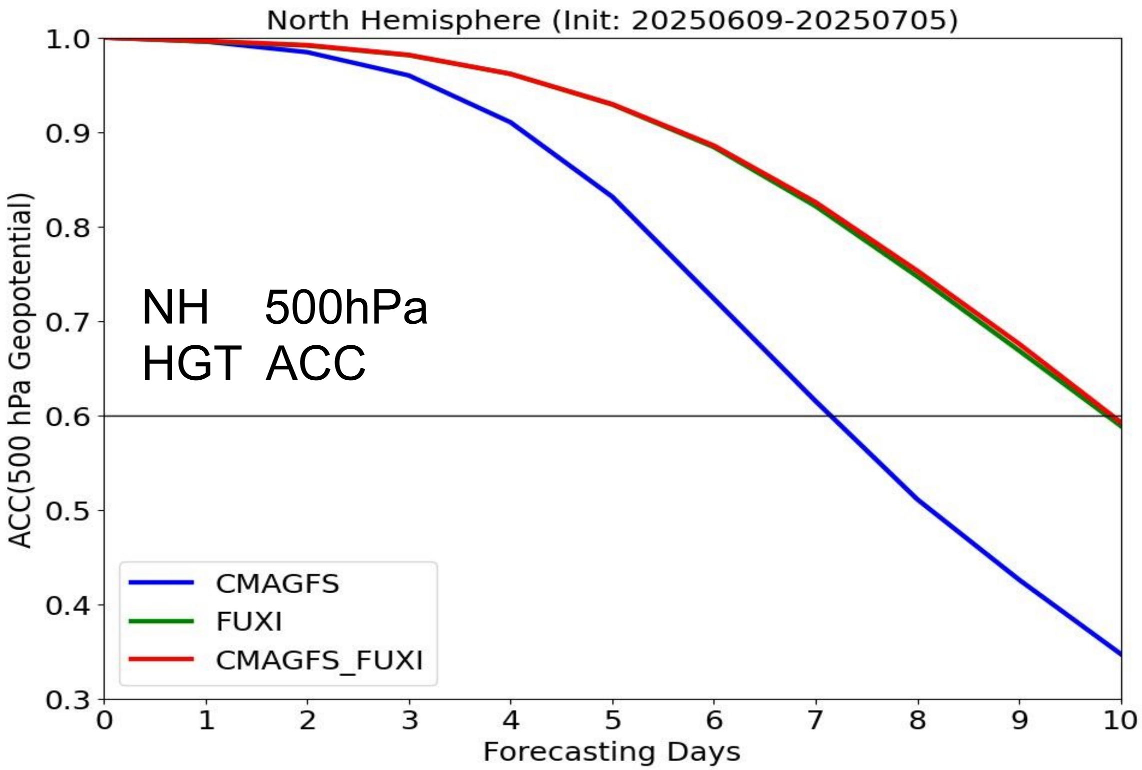


Fractional RMSE changes (%) based on comparisons against radiosonde observations aggregated over all variables and all lead times. For details, please check: https://doi.org/10.1175/WAF-D-24-0139.1

Online Bias Correction of Large-Scale Circulation in CMA-GFS

Using spectral nudging methods, develop a hybrid system that combine the advantages of large-scale simulation of ML model (FUXI) and the fine-scale simulation of physical model (CMA-GFS)





Nudged variables: Pi, Th, U, V
Truncation wave number: T42
Relaxation time: 6hour
Vertical range: 600-200hPa

Currently, FUXI is initialized with ERA5 data

Future work:

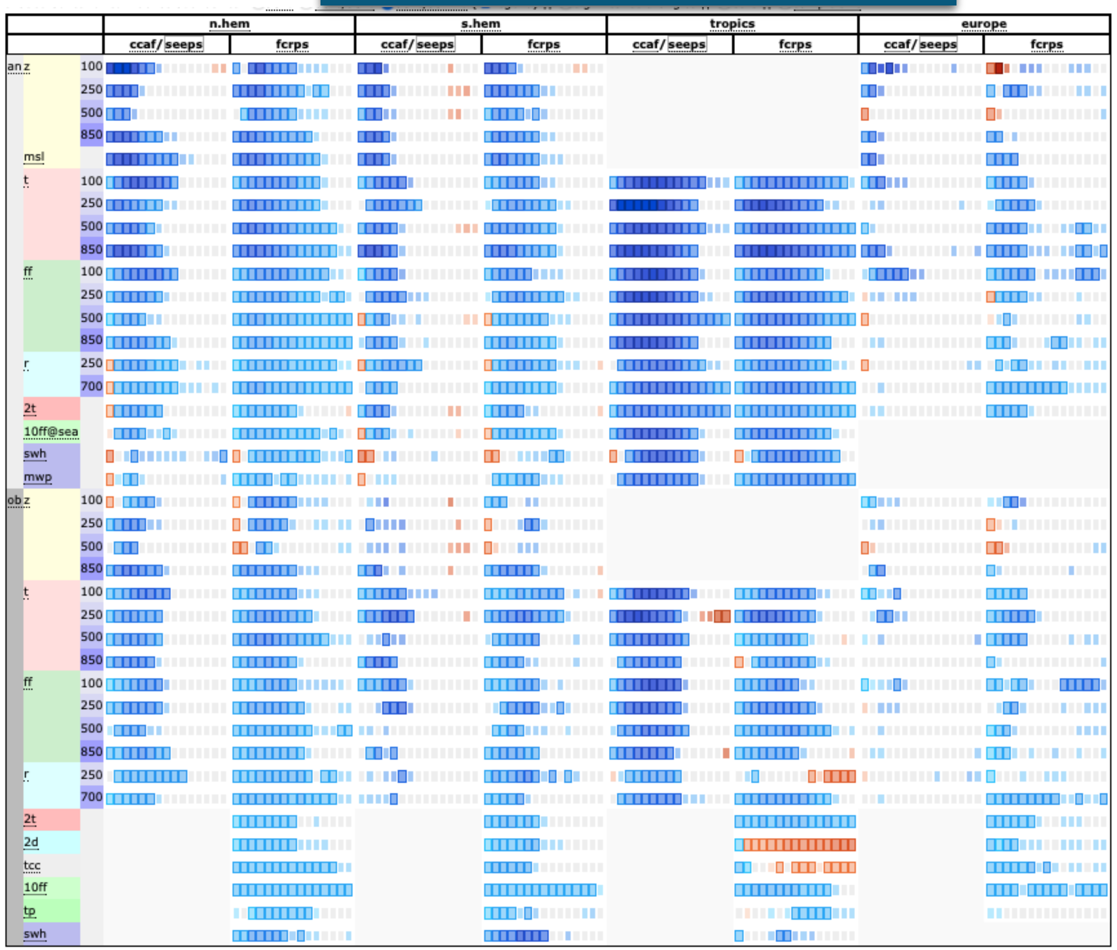
Fine-tune FUXI using CMA-GFS analysis
Establish the cycle experiment system

Nudging IFS to AIFS on large scales: CF & PF

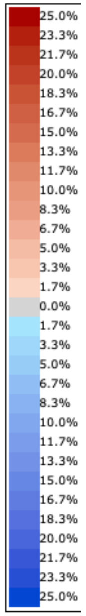
- ECMWF adopted the same approach as ECCC, nudging Tv & VO at T21.
- Dedicated AIFS model that predicts on 137 model levels trained for nudging: Both AIFS-Single for deterministic and AIFS-CRPS for ensemble

CF: 2024 (580 dates)

PF: July-Sept 2024 (175 dates)



nudged worse



nudged better

Nudging IFS to AIFS on large scales: CF & PF

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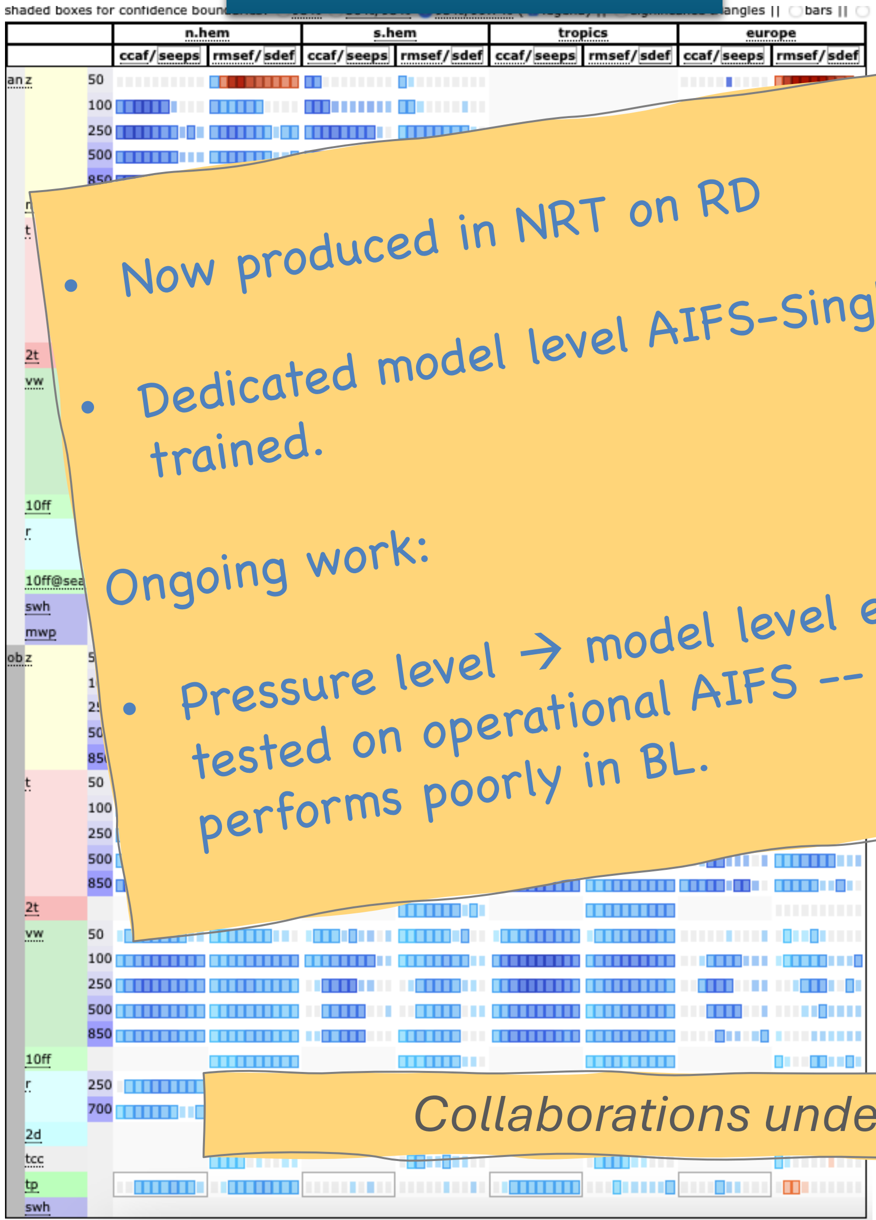
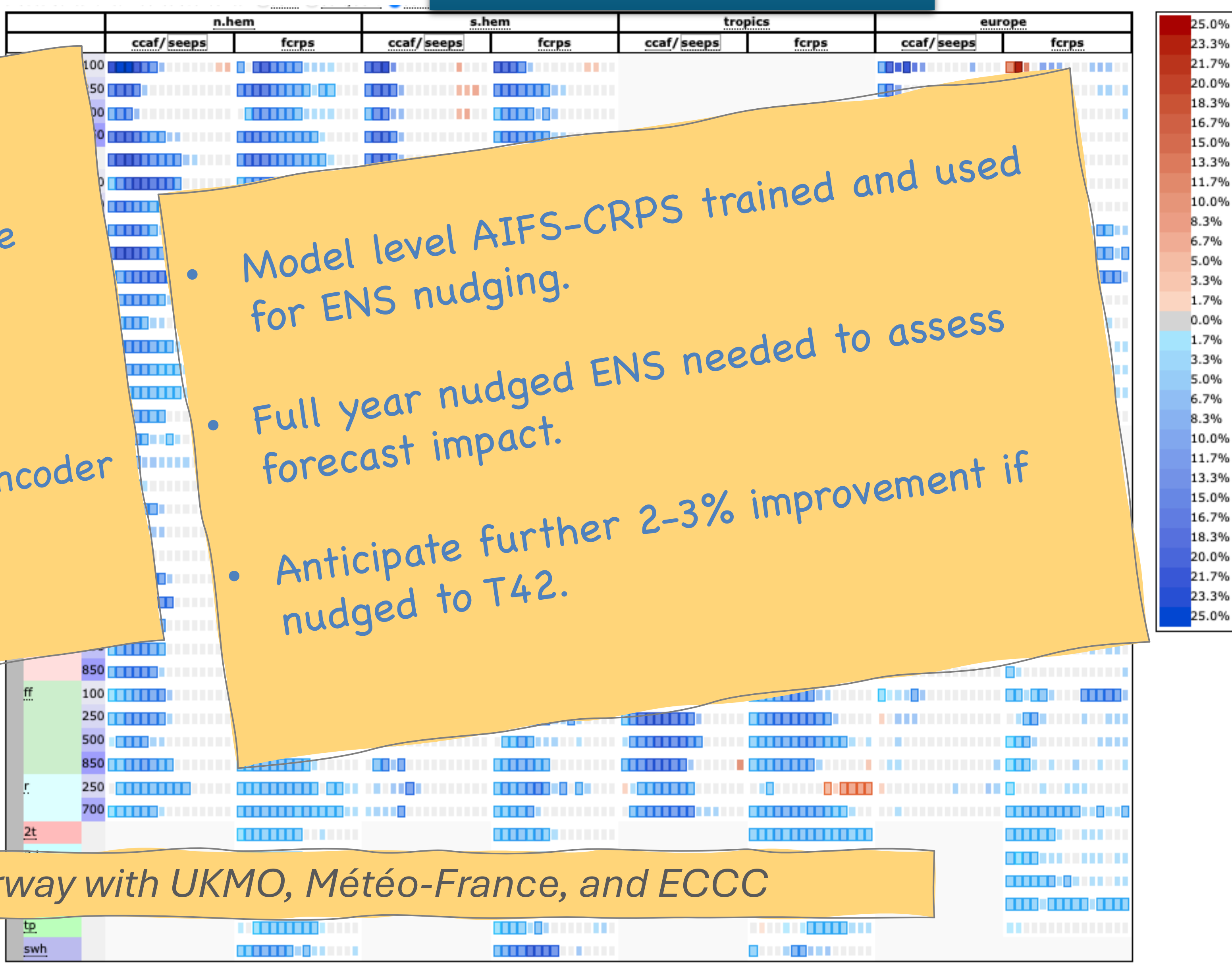


- Now produced in NRT on RD
- Dedicated model level AIFS-Single trained.

Ongoing work:

- Pressure level → model level encoder tested on operational AIFS -- performs poorly in BL.

PF: July-Sept 2024 (175 dates)



- Model level AIFS-CRPS trained and used for ENS nudging.
- Full year nudged ENS needed to assess forecast impact.
- Anticipate further 2-3% improvement if nudged to T42.

Collaborations underway with UKMO, Météo-France, and ECCC

Online bias correction at Météo-France

Strategy

- Nudging ARPEGE towards AIFS forecasts to benefit from AIFS improved forecast capability at large scales
- While still benefiting from the current physical system wealth of diagnostics used by end-users.

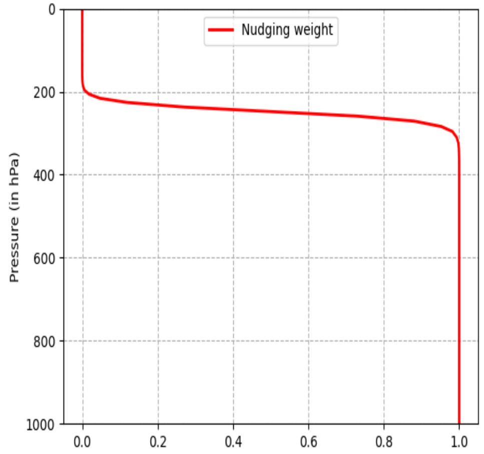
AIFS

- **Version trained by ECMWF** (thanks to M. Clare, I. Polichtchouk, M. Chantry) on ERA5 and finetune on IFS, initialized with our in-home ARPEGE analyses.
- **Horizontal resolution:** 1° - O96 (TL191)
- **AIFS prognostic variables**
  - u,v,q,T,w on **77 the lowest IFS levels** (instead of 137)
  - sp, t2m, td2m, u850, v850, T500, Z500, skt, tcw, msl, 10u, 10v
- **Constant fields**
  - Orography, standard deviation of orography, slope, land-sea mask

Nudging configuration

- **Only scales above T21c2.2 are nudged**
- **No nudging above ~200 hPa**
- **Nudged variables**
  - Virtual temperature and vorticity
- Nudging starts after a 6-hour lead time

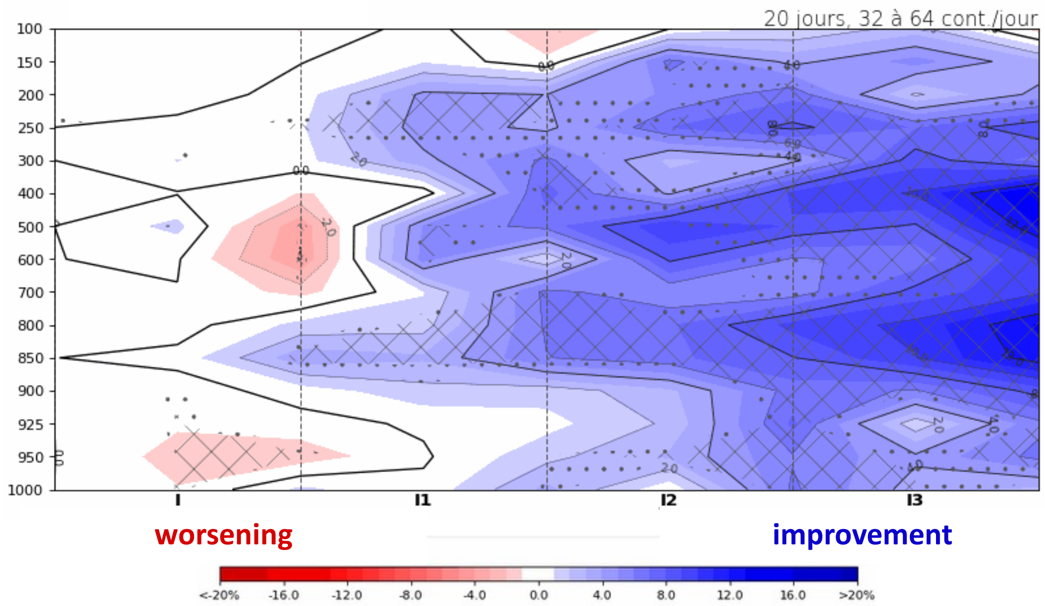
➢ A large number of postprocessing operations needed



Courtesy V. Chabot, E. Arbogast

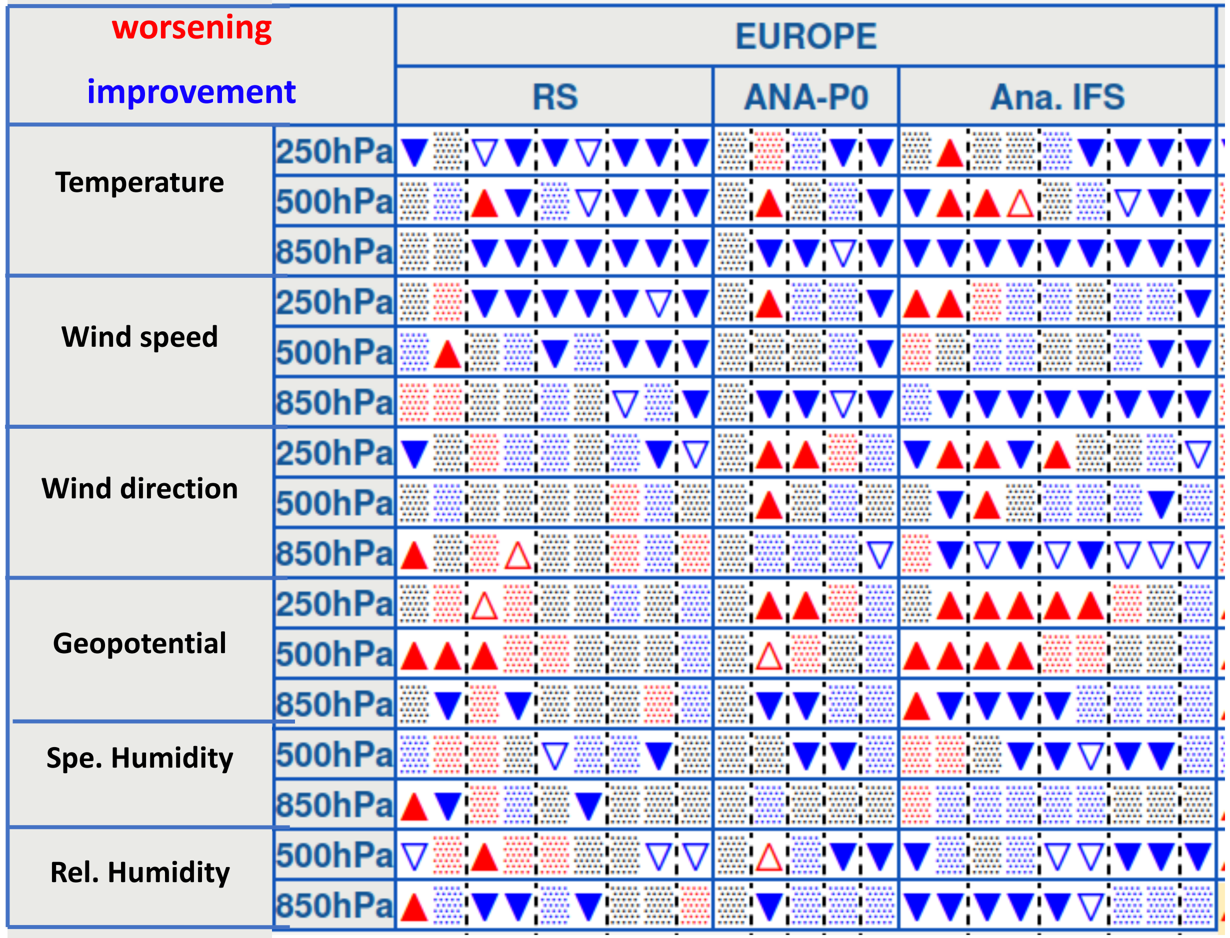
Online bias correction at Météo-France

Impact of nudging ARPEGE towards AIFS EUROPE



Temperature RMSE change between the AIFS-nudged system and the reference system (cy48t1). RMSEs are computed in reference to the radiosounding observation network as a function of lead time

Score card over a European domain



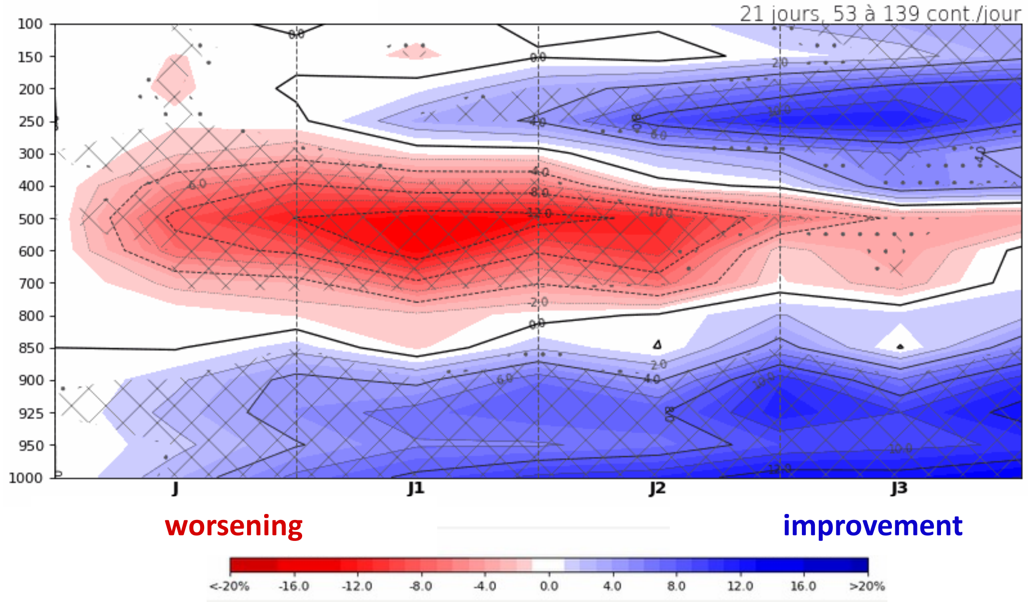
Score change between the AIFS-nudged system and the reference system (cy48t1). Scores are computed in reference to radiosoundings (RS), in-home analyses (ANA-P0) and ECMWF analyses (Ana. IFS), and presented as a function of lead time

Courtesy V. Chabot

Online bias correction at Météo-France

Difficulties over mountainous areas

Impact of nudging ARPEGE towards AIFS
ASIA



Temperature RMSE change between the AIFS-nudged system and the reference system (cy48t1). RMSEs are computed in reference to the radiosounding observation network as a function of lead time

Perspectives

- Further quantify and understand the impact of nudging
- **Finetune AIFS on our own analyses** to reduce post-processing operations and improve consistencty with ARPEGE orography

Courtesy V. Chabot

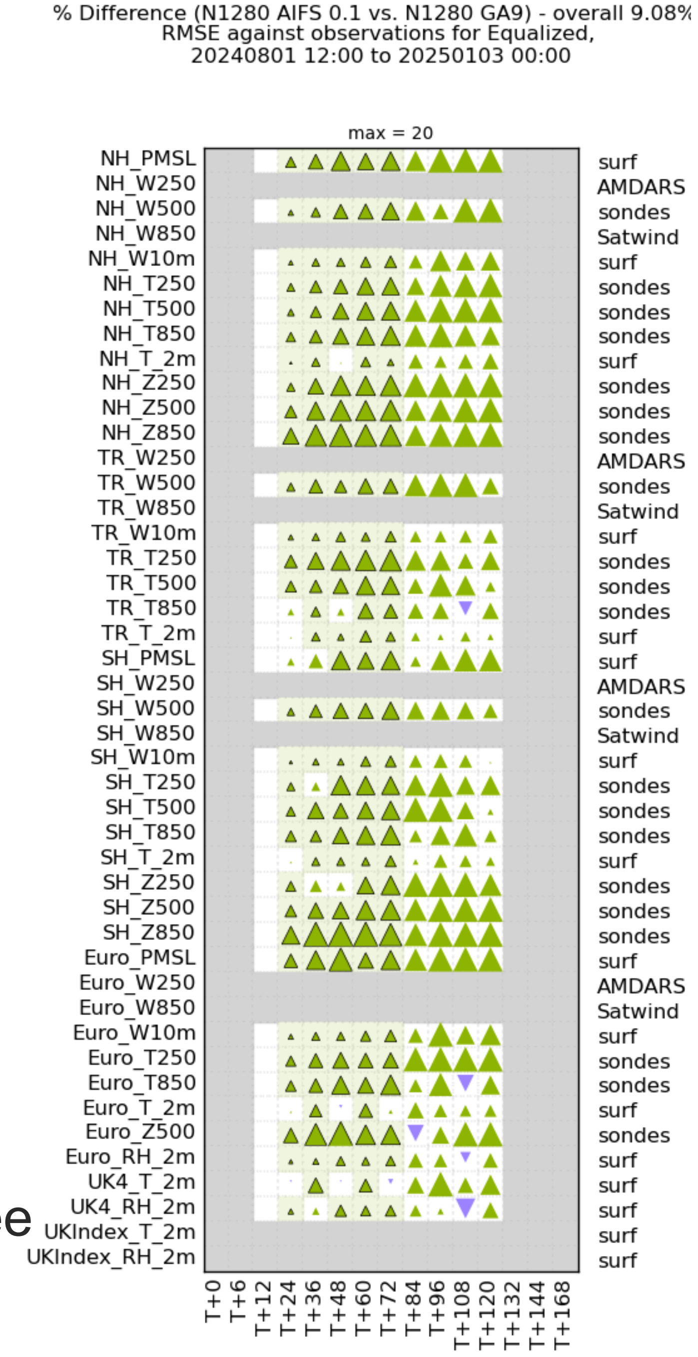
Met Office

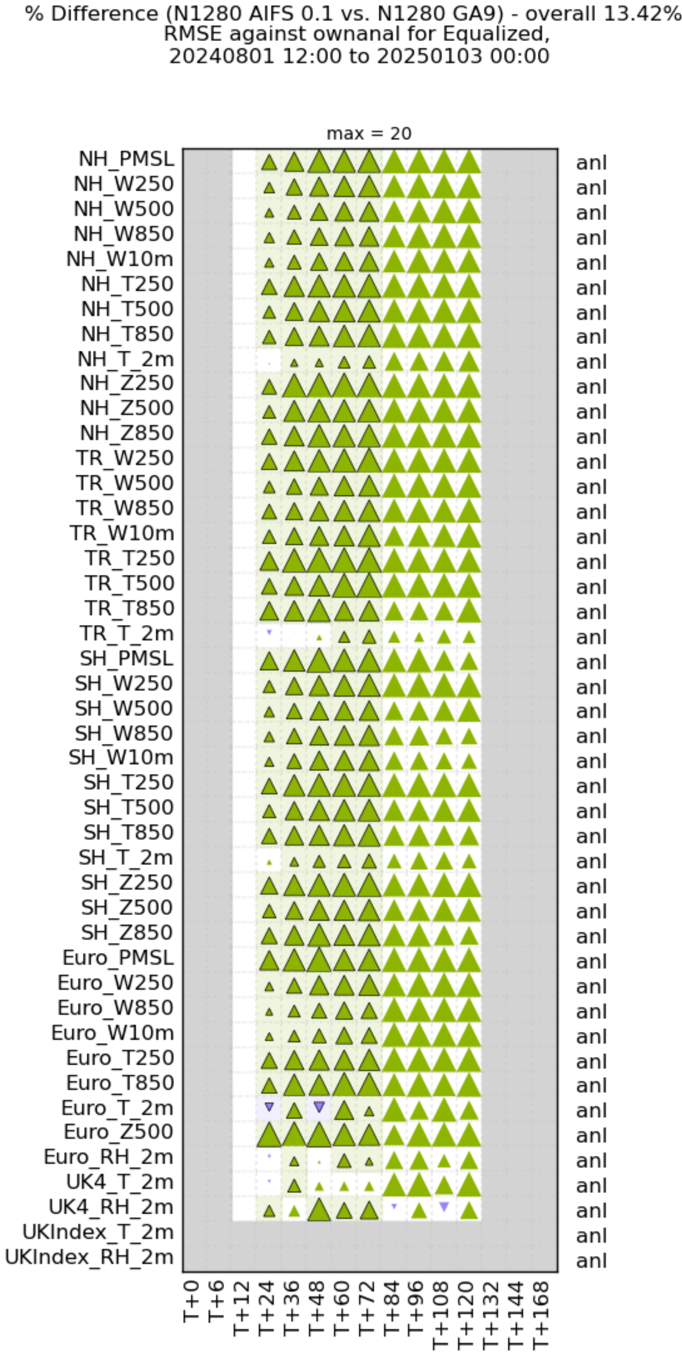
Set-up

- Nudge UM to ml-AIFS between 300m and 30 km.
- Use filter scale of ~600km
- Apply nudging every 3rd time step to save cost.

Verification

- 9-13% improvement in NWP index, vs observations or analysis
- GAL9 vs GA6 was 2.5-4.5% improvement, so this is perhaps comparable to ~20 years of traditional model development!
- Tallies with what ECCC and ECMWF see

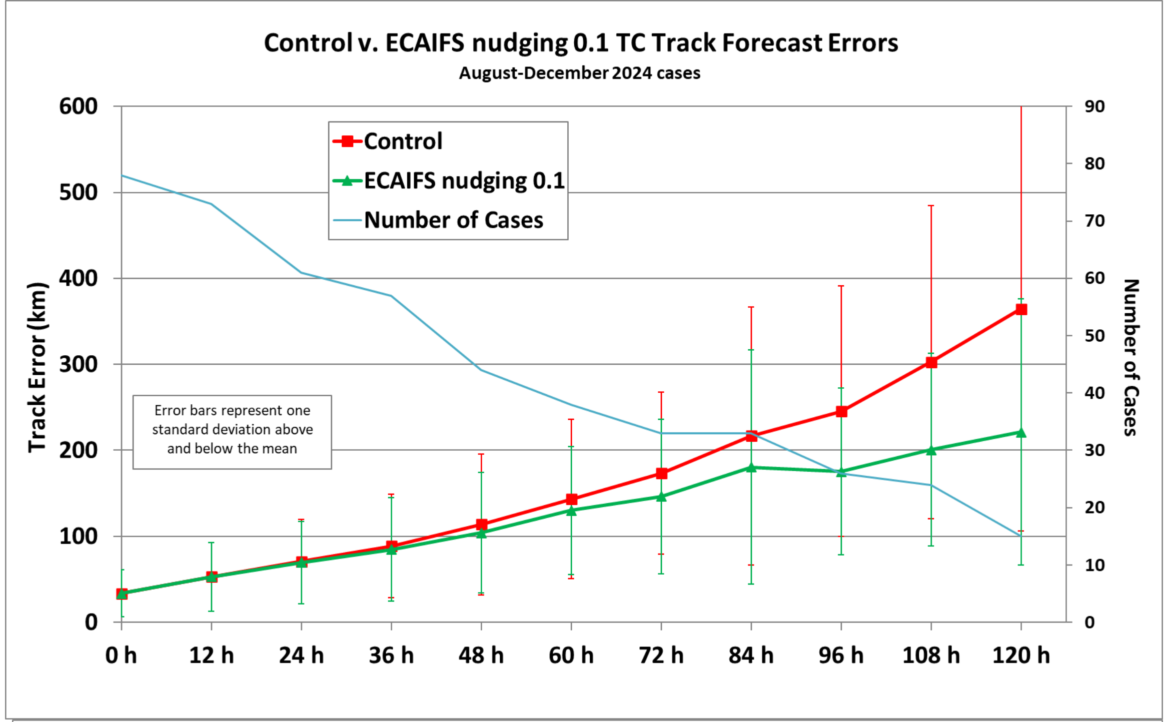


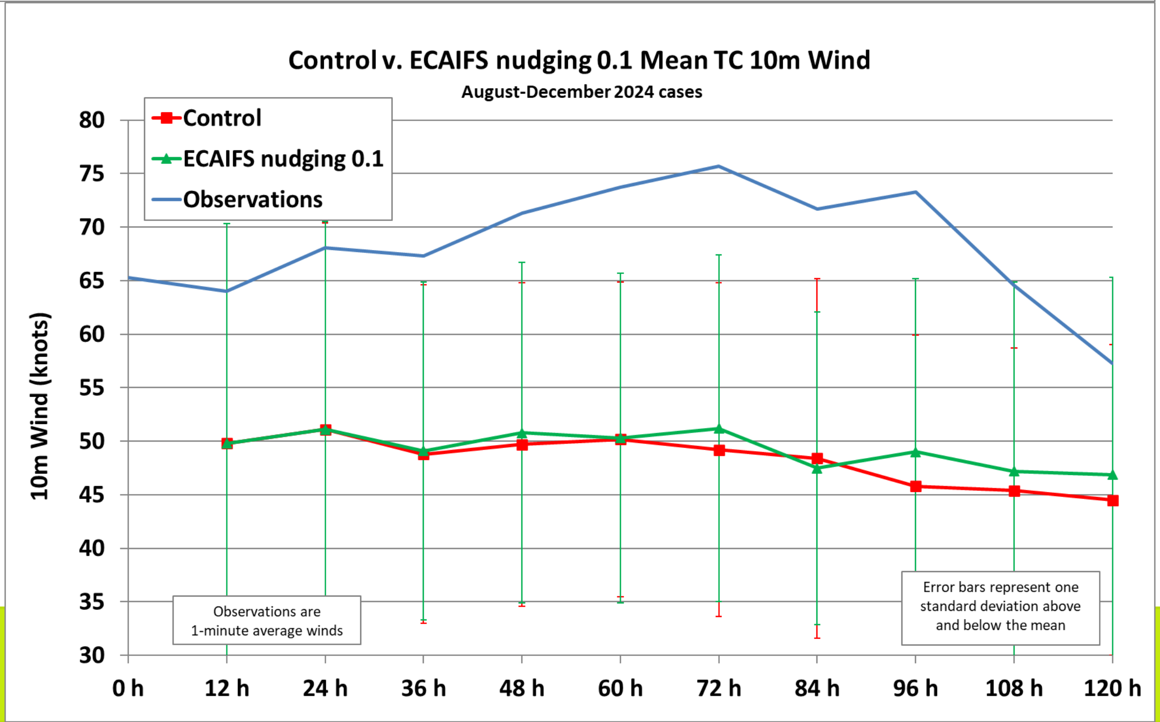


Met Office

Tropical cyclones

- Significant improvement in TC tracks
- Day 5 track errors reduced from ~375km to ~225km
- No change to intensity, as measured by central pressure, vorticity, 10m wind-speed, …
- If anything, nudged runs are slightly better!





Julian Heming