Machine Learning in NWP: **What I have learnt in the past year**

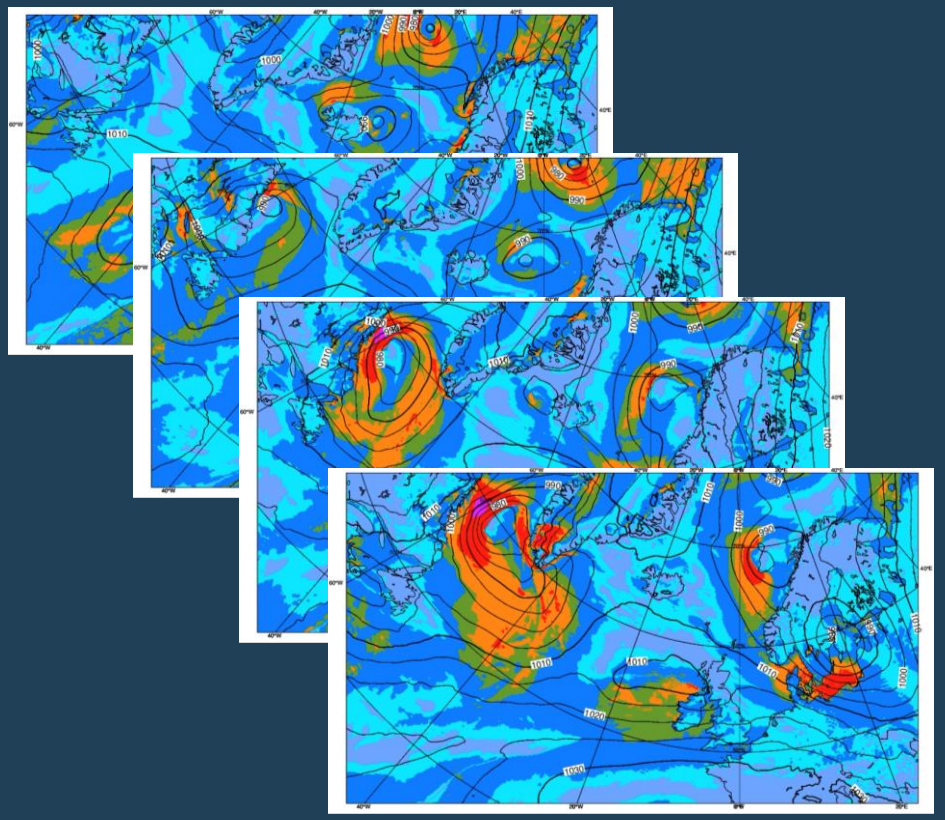
Linus Magnusson and colleagues at ECMWF

Forecasts available from ECMWF web:

- AIFS (ECMWF experimental AI model)
- FourCastNet (NVIDIA)
- PanguWeather (Huawei)
- Graphcast (Google Deepmind)
- FuXi (Fudan University, Shanghai)

All models are trained on ERA5 reanalysis (~0.25 degree resolution)

$$X(T) = X(0) + \int_0^T M(t)dt$$



In all experiments below, we have initialised all ML models from ECMWF initial conditions.

Real-time experimental forecasts available on OpenCharts

ECMWF | Charts

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Search products...

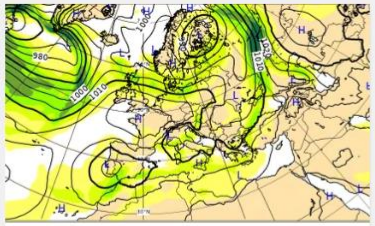
Range
- Medium (15 days)
- Extended (42 days)
- Long (Months)

Type
- Forecasts
- Verification

Component
- Surface
- Atmosphere

Product type
- High resolution forecast (HRES)
- Ensemble forecast (ENS)
- Combined (ENS + HRES)
- Extreme forecast index
- Point-based products
- Experimental: AIFS
- Experimental: Machine learning models
- Atmospheric composition

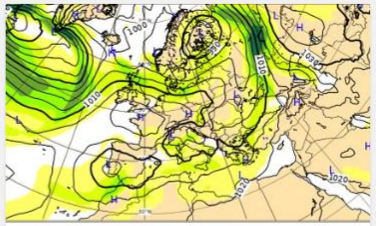
Parameters
- Wind
- Mean sea level pressure
- Temperature



Latest forecast

Experimental: AIFS (ECMWF) ML model: Mean sea level pressure and 850 hPa wind speed

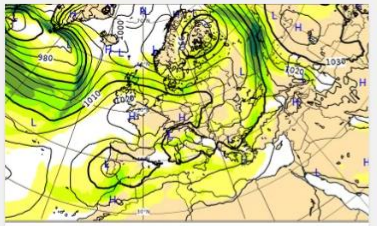
AIFS (ECMWF): a deep learning-based system developed by ECMWF. It is initialised with ECMWF HRES analysis. AIFS operates at 0.25° resolution



Latest forecast

Experimental: FourCastNet ML model: Mean sea level pressure and 850 hPa wind speed

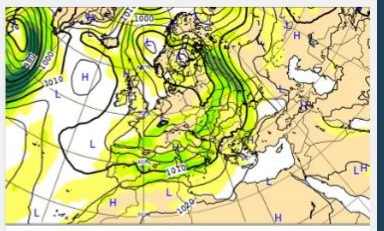
FourCastNet v2-small:a deep learning-based system developed by NVIDIA in collaboration with researchers at several US universities.It is initialised with ECMWF HRES analysis. FourCastNet operates at 0.25° resolution.



Latest forecast

Experimental: FuXi ML model: Mean sea level pressure and 850 hPa wind speed

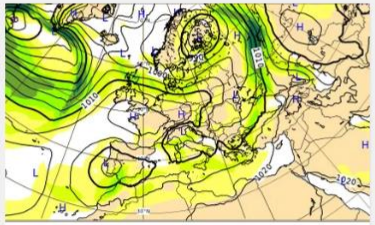
FuXi: a deep learning-based system developed by researchers at Fudan University. It is initialised with ECMWF HRES analysis. FuXi operates at 0.25deg resolution.



Latest forecast

Experimental: GraphCast ML model: Mean sea level pressure and 850 hPa wind speed

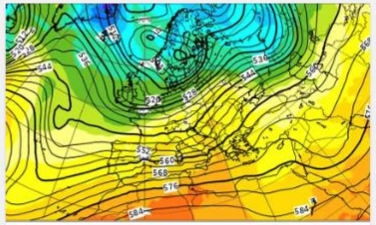
GraphCast (Google DeepMind): a deep learning-based system developed by Google DeepMind.It is initialised with ECMWF HRES analysis. GraphCast operates at 0.25° resolution.



Latest forecast

Experimental: Pangu-Weather ML model: Mean sea level pressure and 850 hPa wind speed

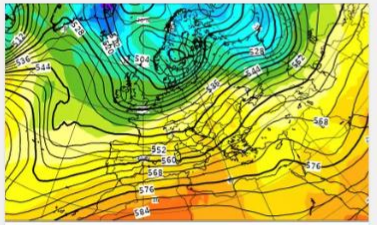
Pangu-Weather: a deep learning-based system developed by Huawei. It is initialised with ECMWF HRES analysis. Pangu-Weather operates at 0.25° resolution.



Latest forecast

Experimental: AIFS (ECMWF) ML model: 500 hPa geopotential height and 850 hPa temperature

AIFS (ECMWF): a deep learning-based system developed by ECMWF. It is initialised with ECMWF HRES analysis. AIFS operates at 0.25° resolution



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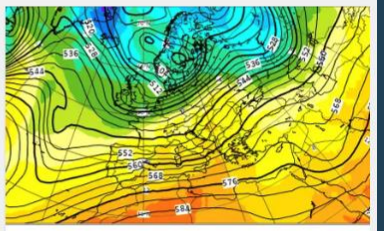


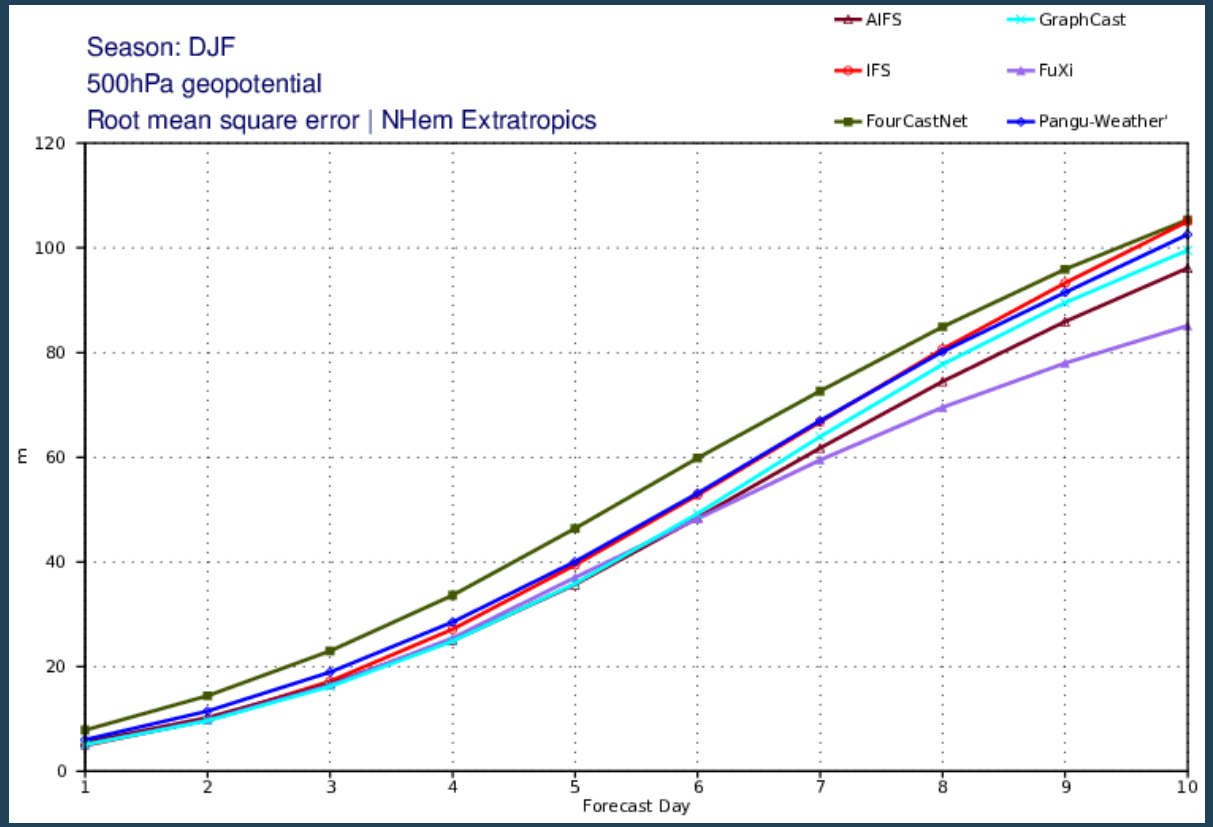
Latest forecast

Experimental: FuXi ML model: 500 hPa geopotential height and 850 hPa temperature

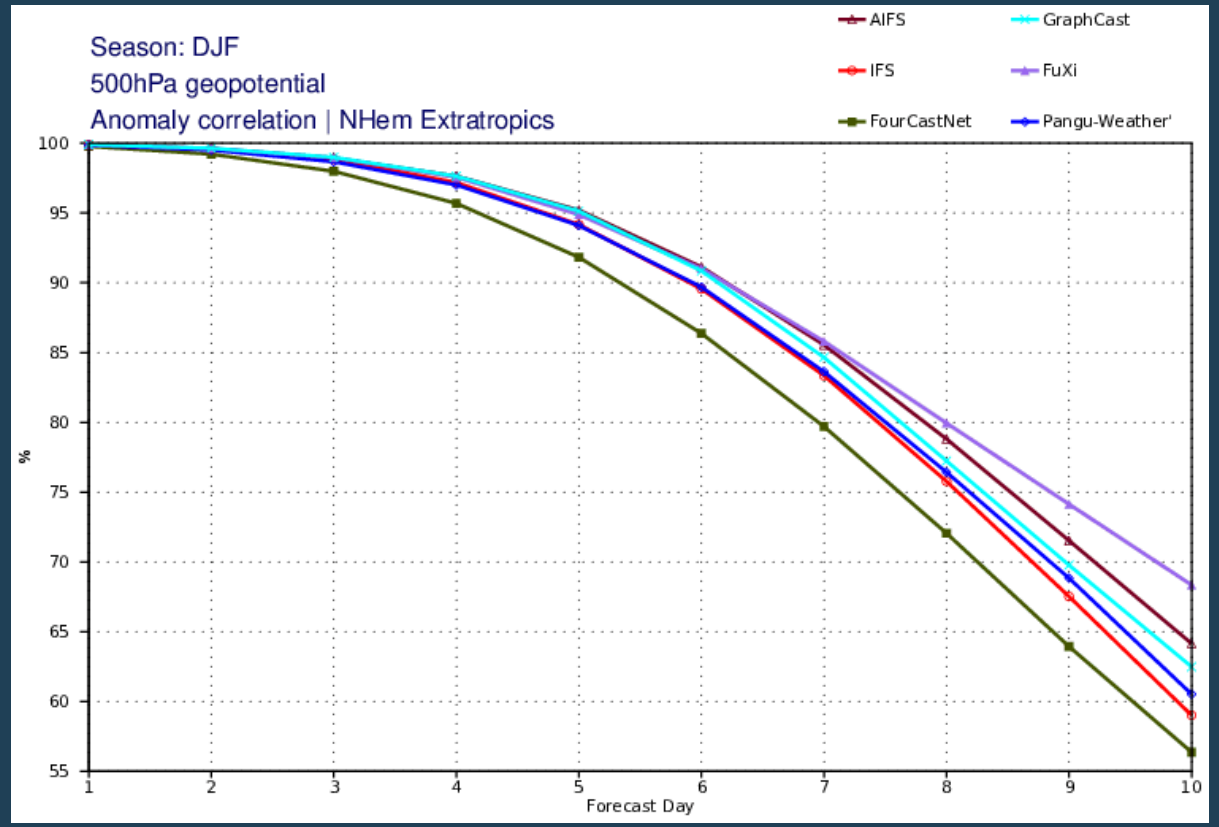
FuXi: a deep learning-based system developed by researchers at Fudan University. It is initialised with ECMWF HRES analysis. FuXi operates at 0.25deg resolution.

Scores from the recent winter – z500 over Northern Hemisphere (N.Hem)

Root-mean-square error (RMSE)



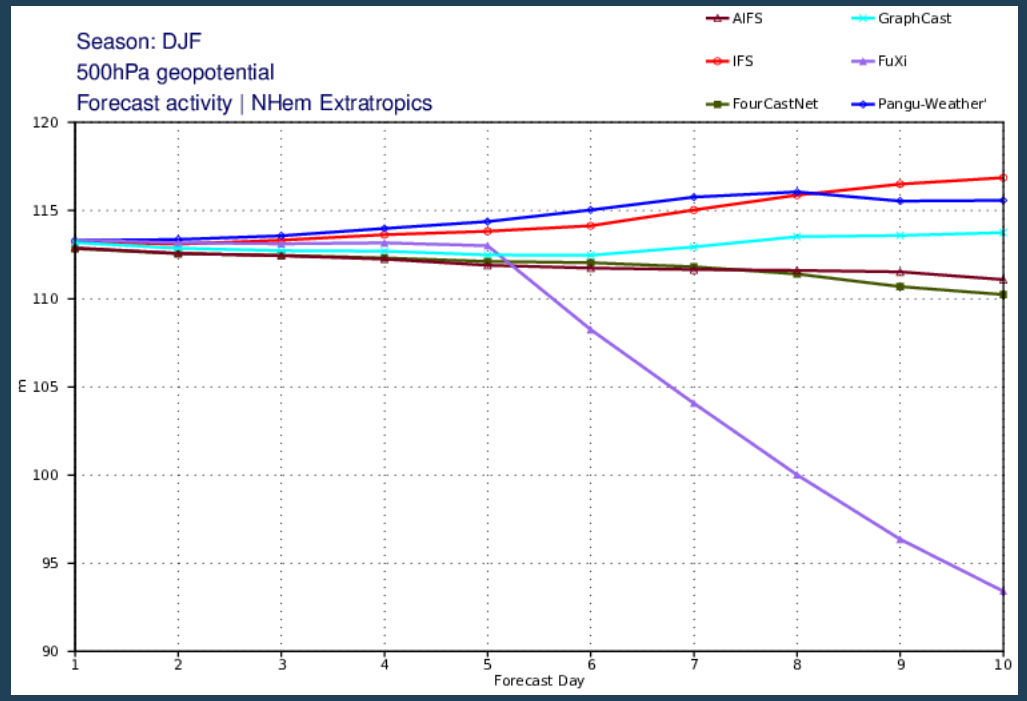
Anomaly correlation (ACC)



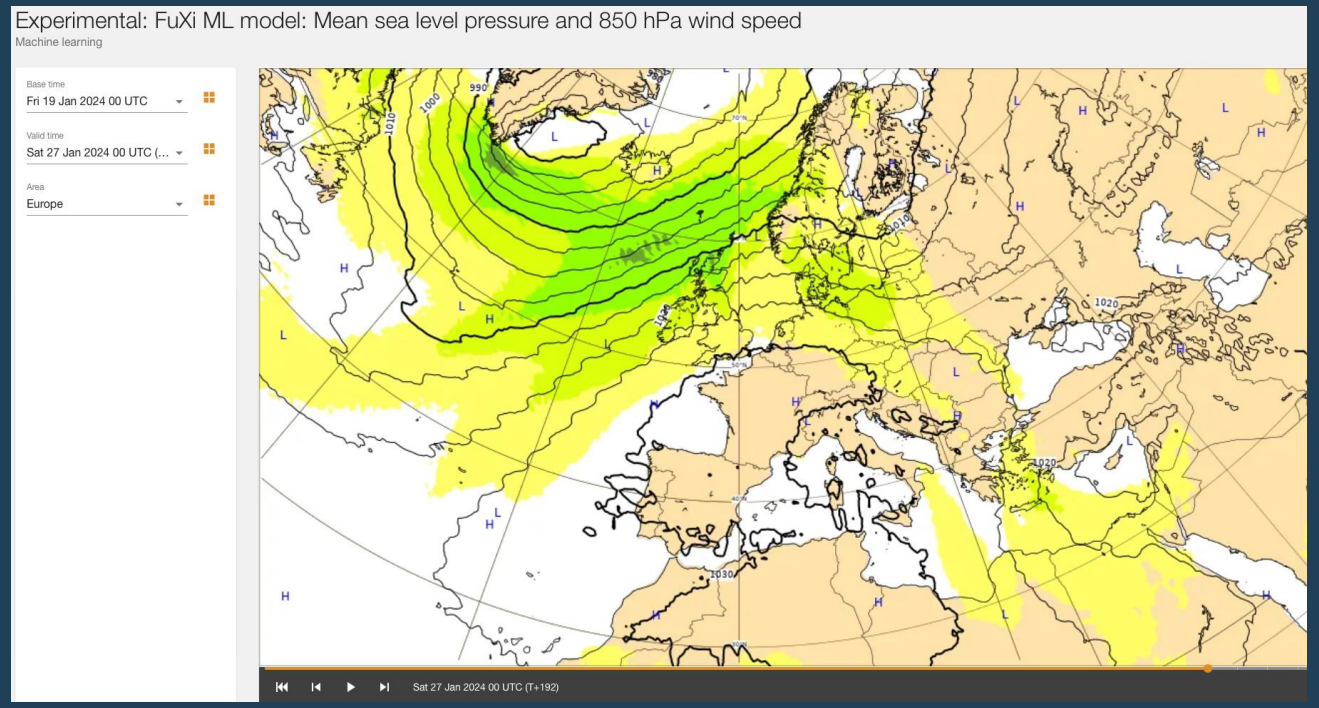
Verification plots available from OpenCharts

Scores are not telling everything!

Forecast activity (measure of smoothness)

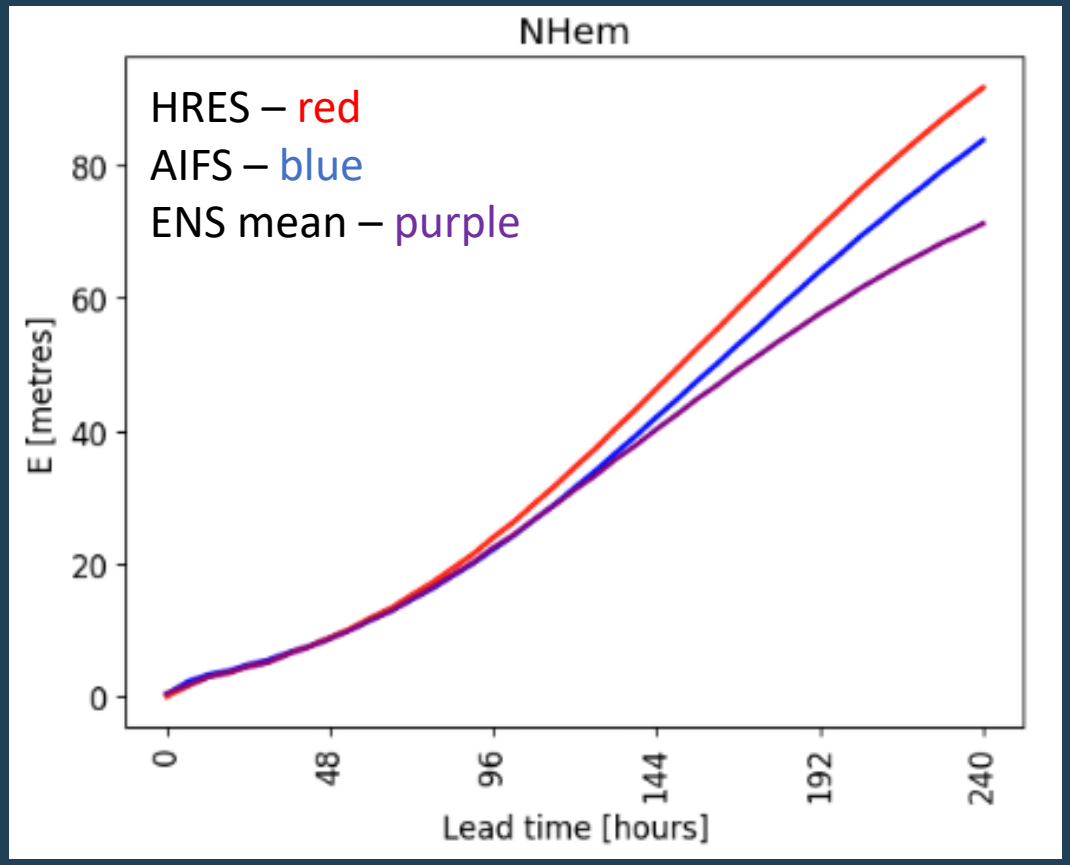


Example of MSLP and 850hPa wind speed from FuXi

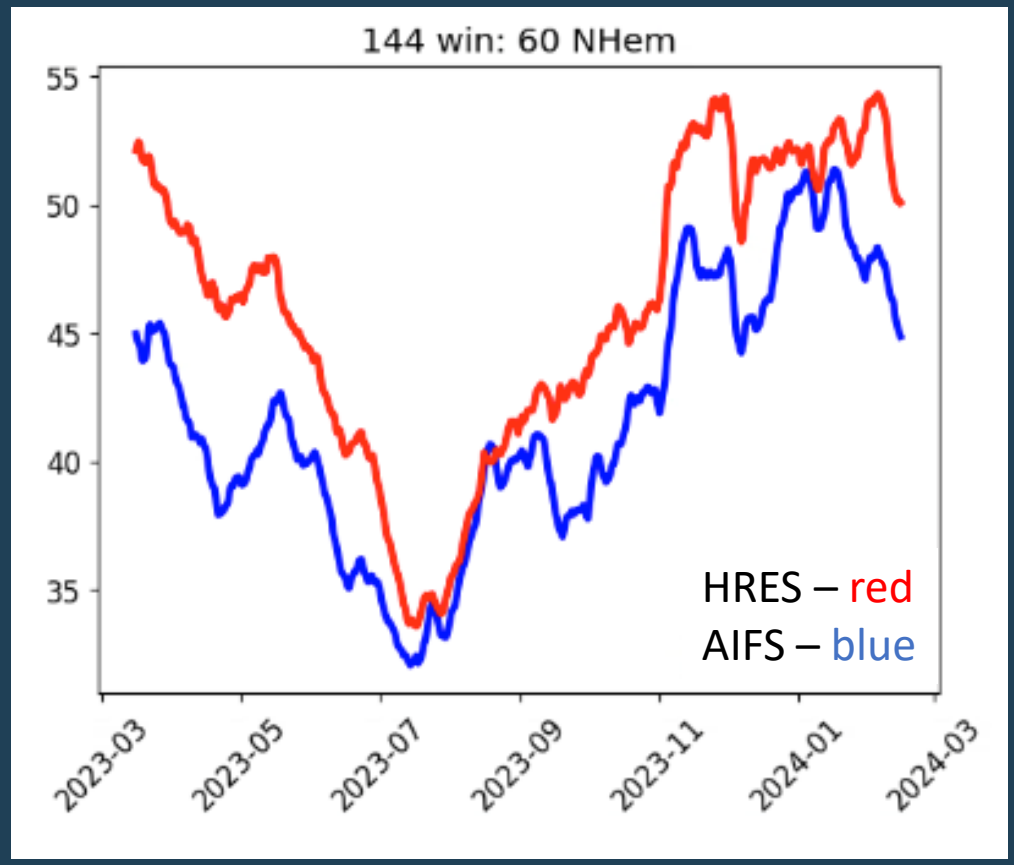


z500 RMSE for N.Hem - HRES vs AIFS, 1 March 2023 – 1 March 2024

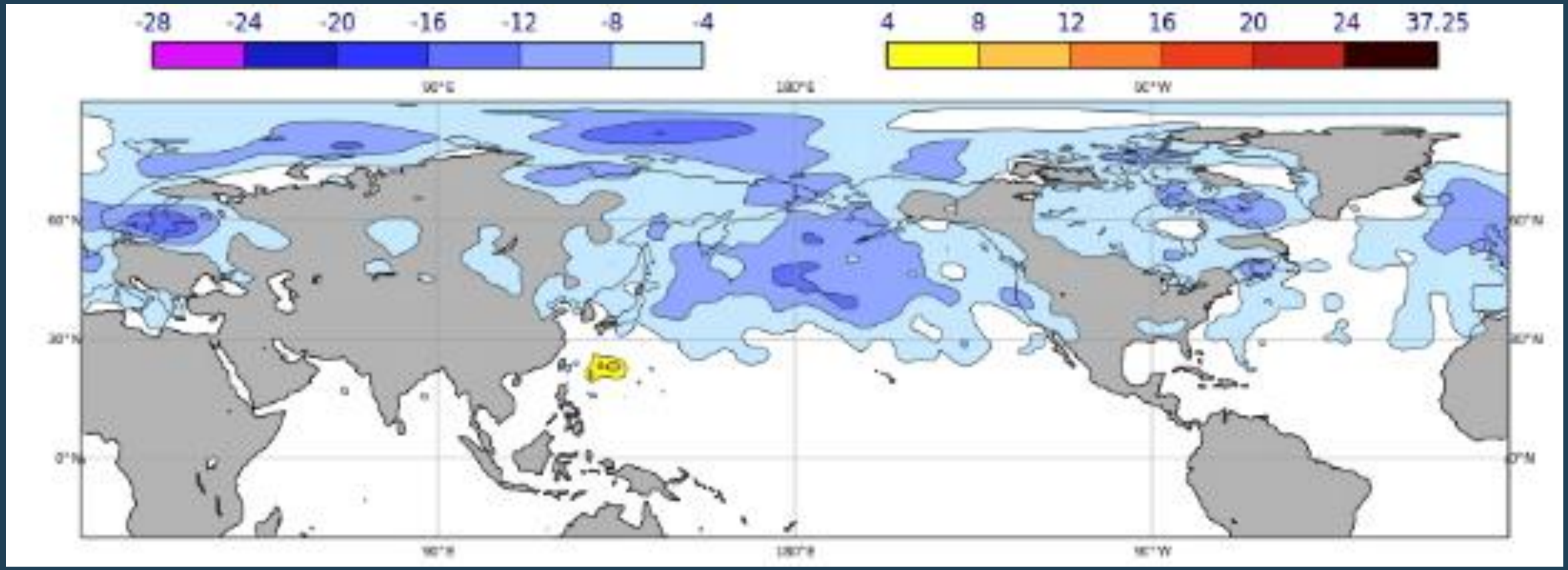
RMSE for 1 March 2023 – 1 March 2024



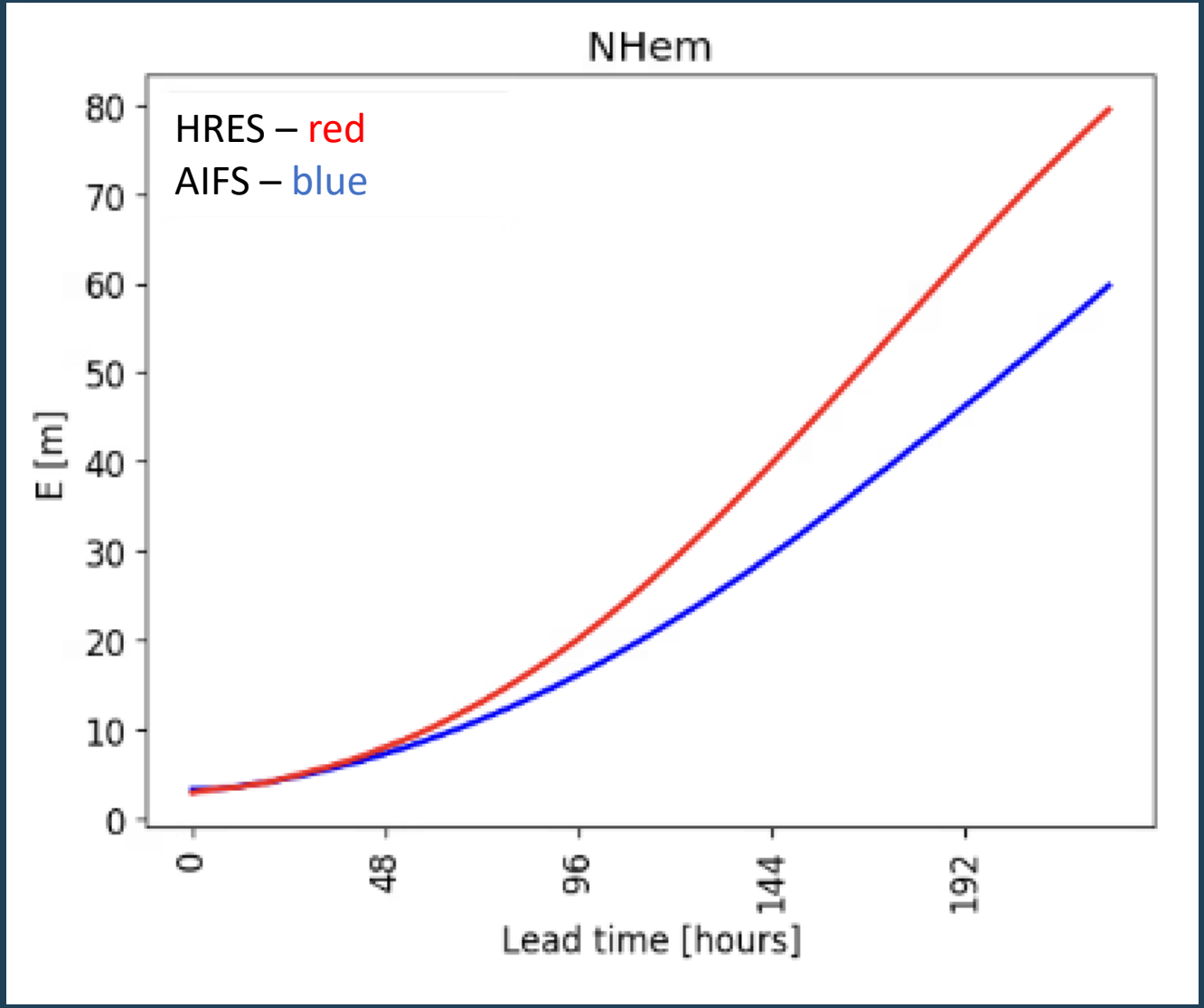
Day 6 RMSE with 30 day running mean



Difference in z500 RMSE (AIFS – HRES) Day 6



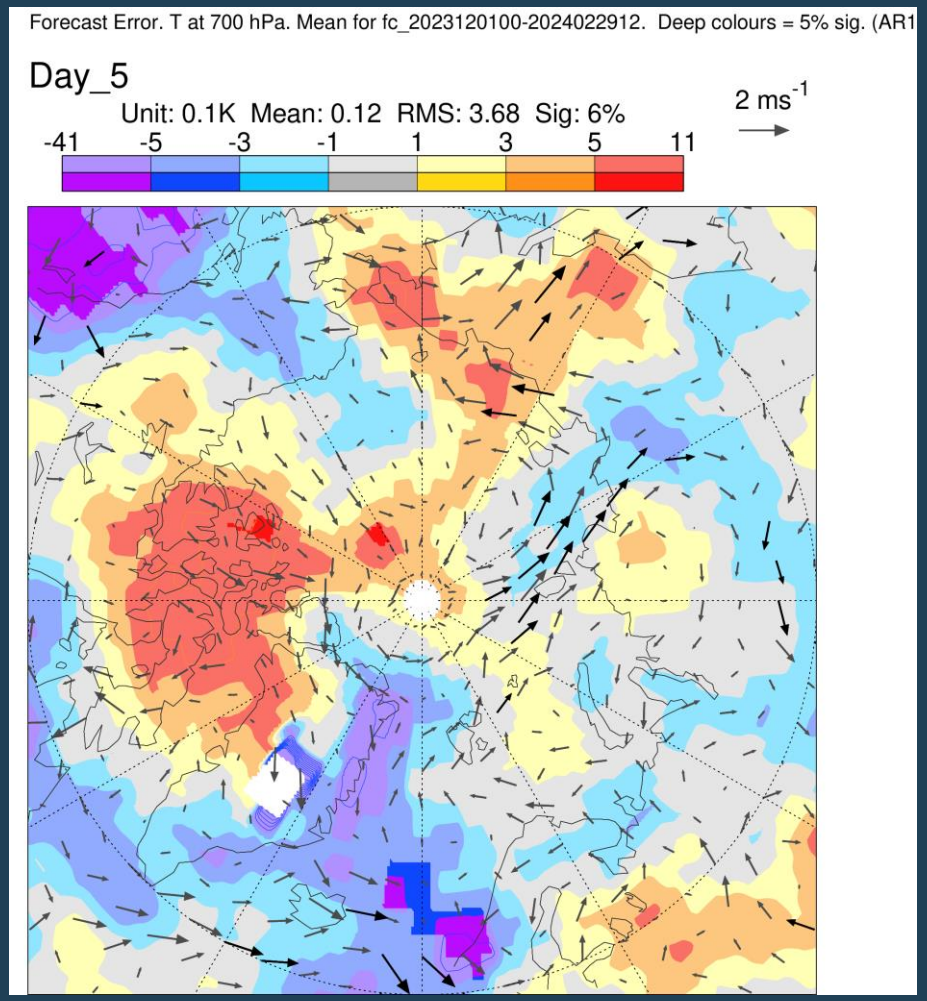
Forecast consistency*, z500, H.Nem



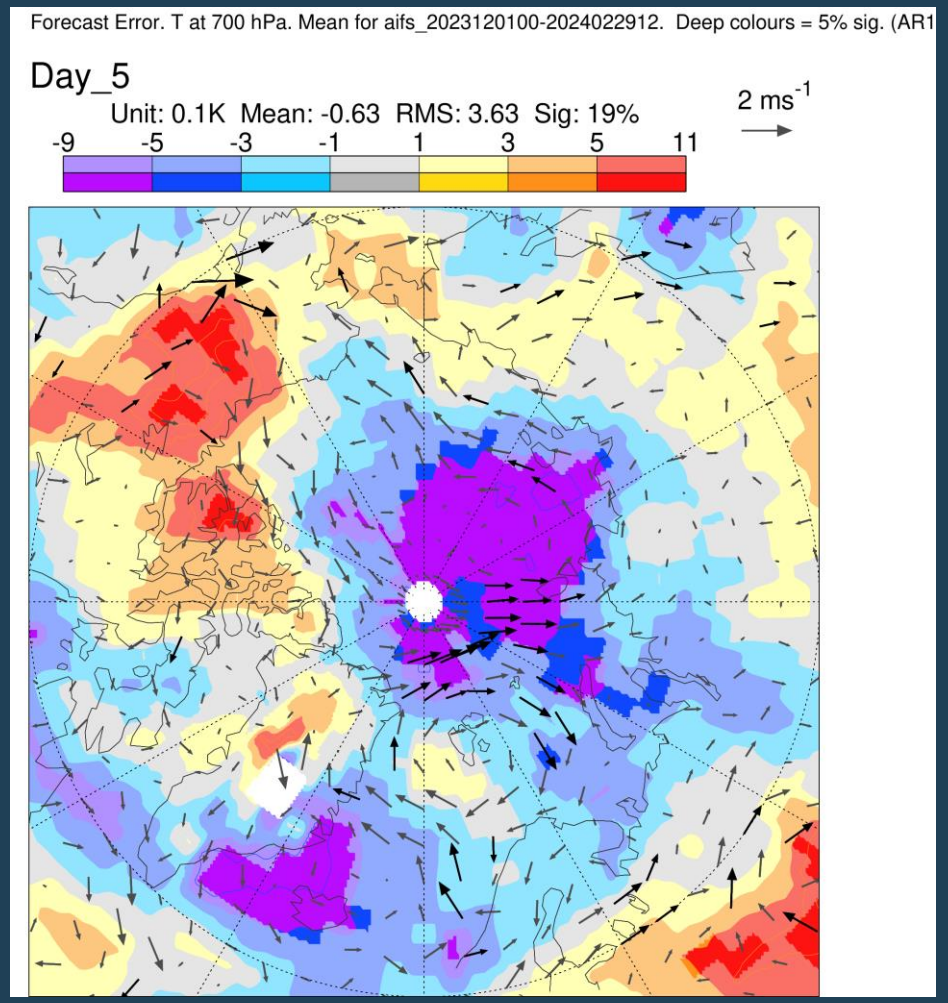
* Difference between forecasts initialised 12 hours apart, but valid at the same time

700hPa temperature bias DJF 2023/24 over Arctic

IFS



AIFS



Thanks to Mark Rodwell and Tim Hewson

Extreme weather cases

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Severe Event Catalogue

Created by Florian Pappenberger, last modified by Timothy Hewson on Nov 09, 2022

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On this space we collect material for evaluation of severe/extreme weather events. The focus is on the meteorological conditions and the forecast performance. The amount of material differs from case to case, and we are not claiming to give the full picture of the cases here. Users are welcome to contribute with material for the cases by using the comment function in the bottom of each page. To suggest a new case to evaluate, please contact us at the email address given below. If you have any initial comments and material, please include them in the mail.

Contact email address	servicedesk@ecmwf.int

(Please note that some of the links on the pages are only accessible from ECMWF.)

Navigation

List of (recent) cases

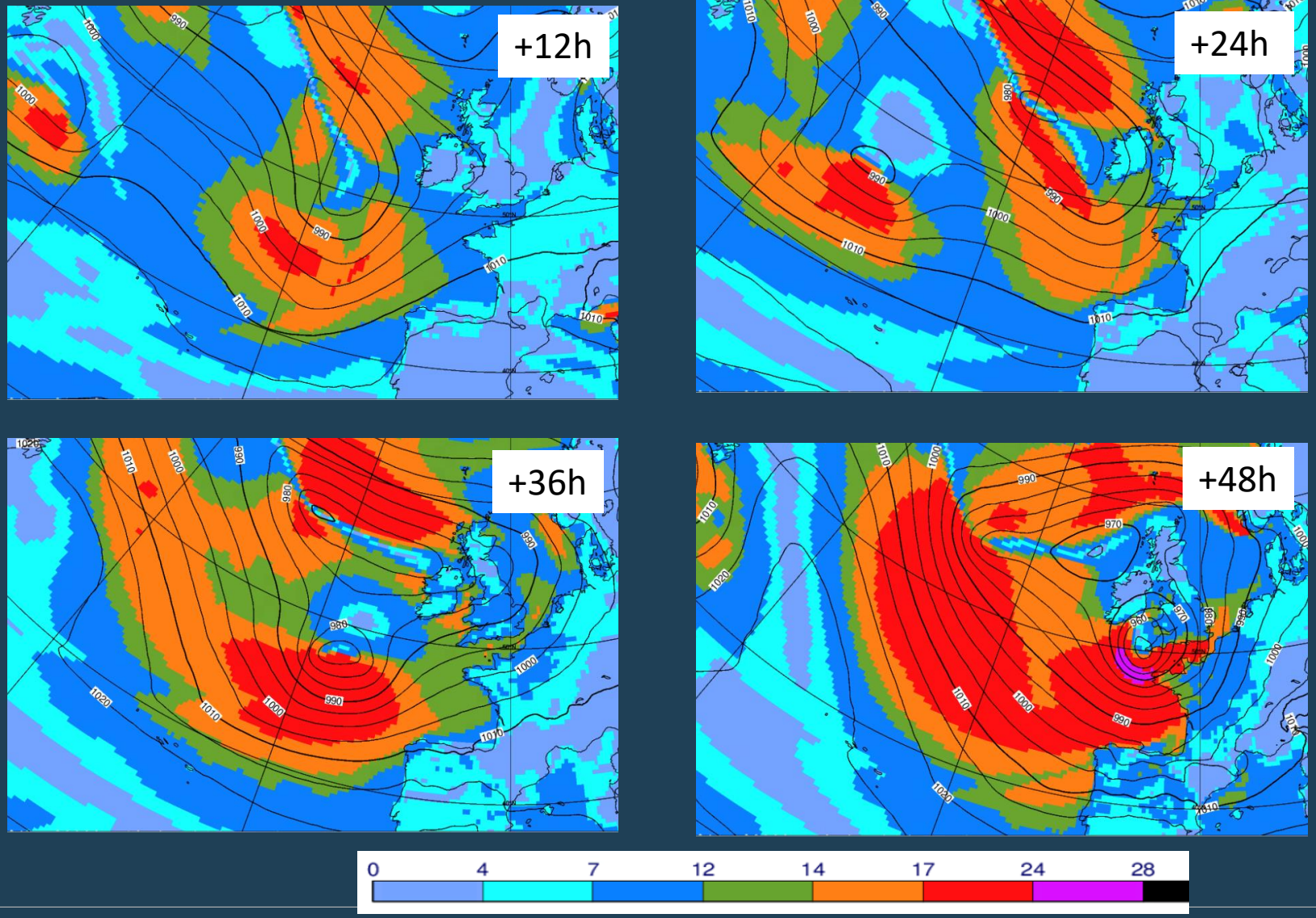
- 202404 - Snowfall / Cold - Sweden / Finland
- 202404 - Rainfall - UAE
- 202404 - Rainfall - Brazil
- 202404 - Cold -Europe

Search (for old cases enter the year and month of the event, as yyyymm)

Screenshot

AIFS cases usually included in the ECMWF severe event catalogue https://confluence.ecmwf.int/display/FCST/Severe+Event+Catalogue

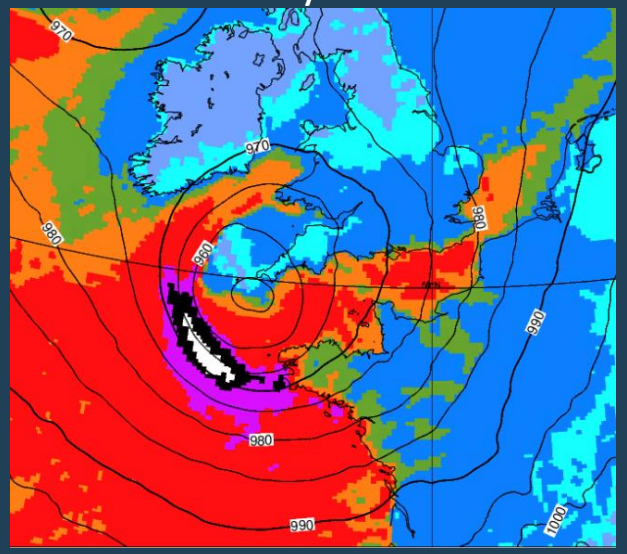
AIFS: **Storm Ciaran (forecast from 31 Oct 2023 00UTC)**



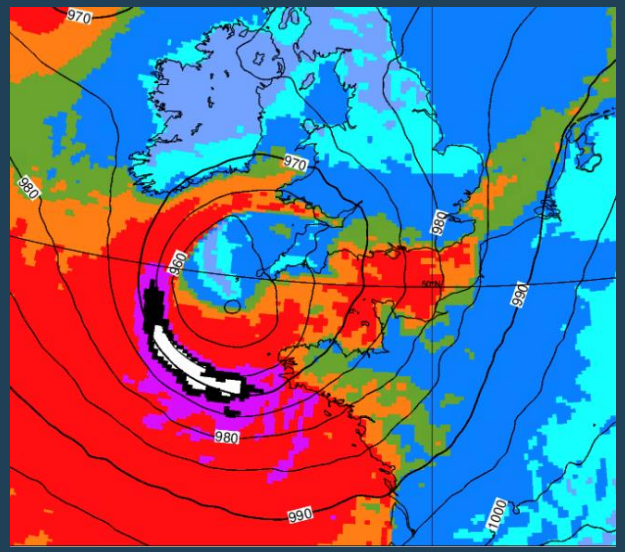
MSLP and wind speed from AIFS model

Storm Ciaran (2-day forecasts valid 2nd Oct 2023 00UTC)

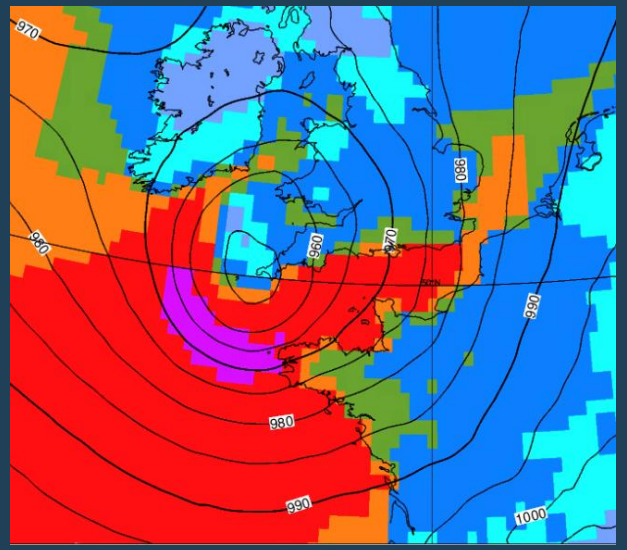
Analysis

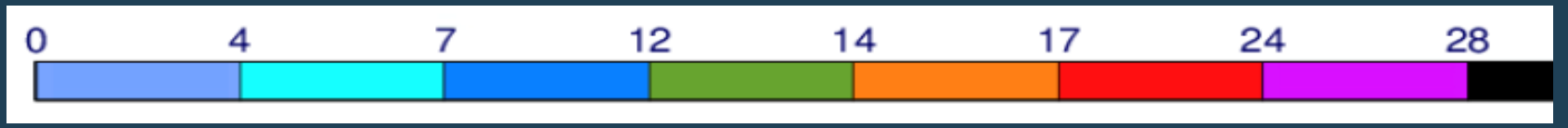


HRES



AIFS



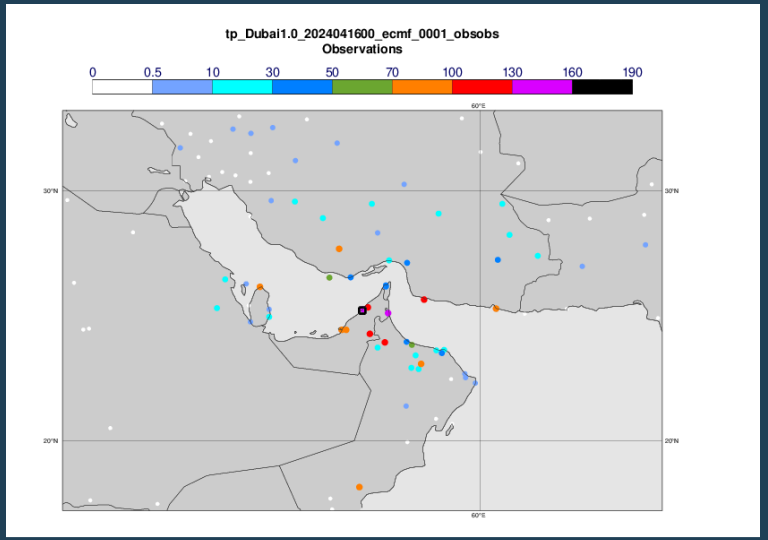


- Better position forecast in the ML models
- Similar minimum pressure 960-965hPa
- Less extreme wind speed in ML models
- See Charlton-Perez et al. (2024, Nature)

Extreme precipitation in the United Arab Emirates and Oman April 2024

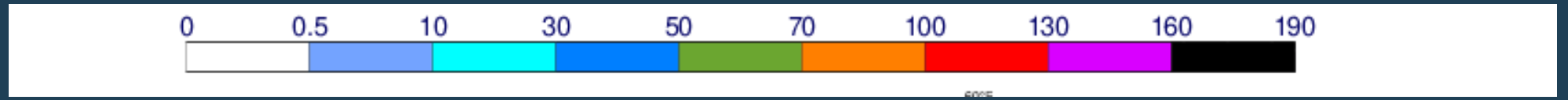
24-hour precipitation 16 April 00UTC – 17 April 00UTC

Observations



HRES (72-96h)

AIFS (72-96h)

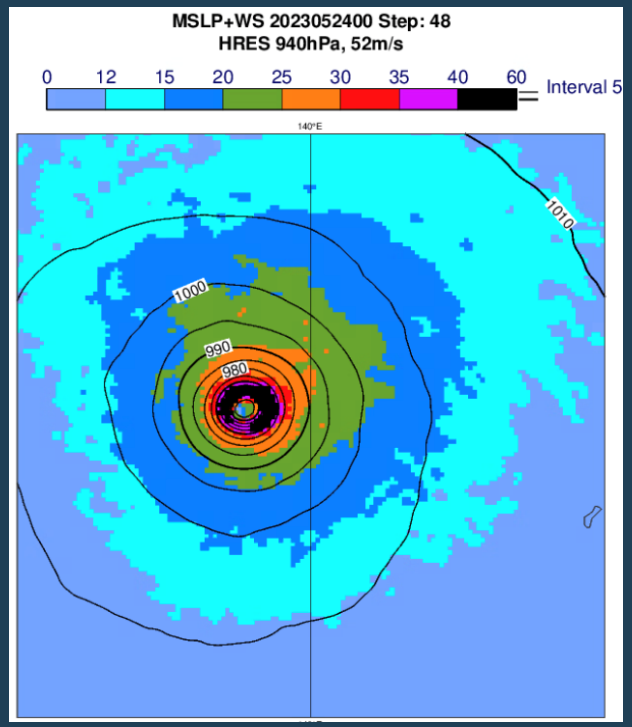


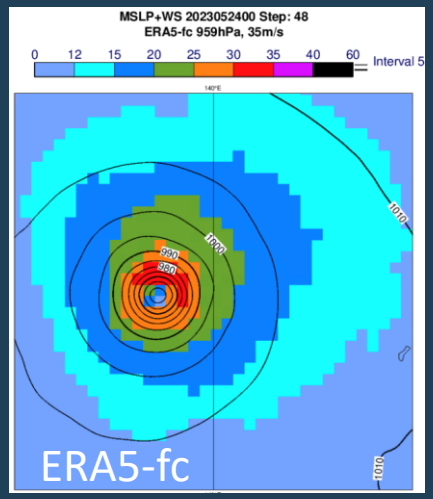
- Smooth precipitation field from AIFS (do not capture local structures)
- AIFS predicted very extreme values for this region

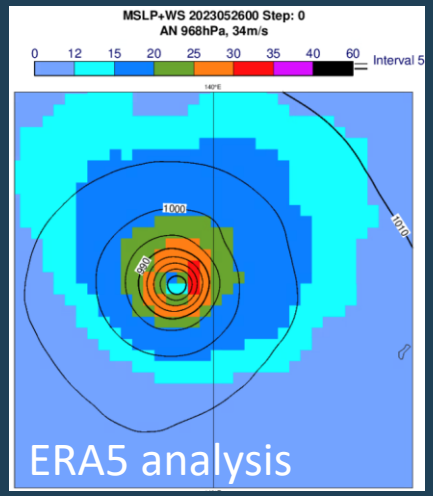
Tropical cyclone MAWAR (26 May 2023 00UTC)

Observed: 897hPa , 82 m/s

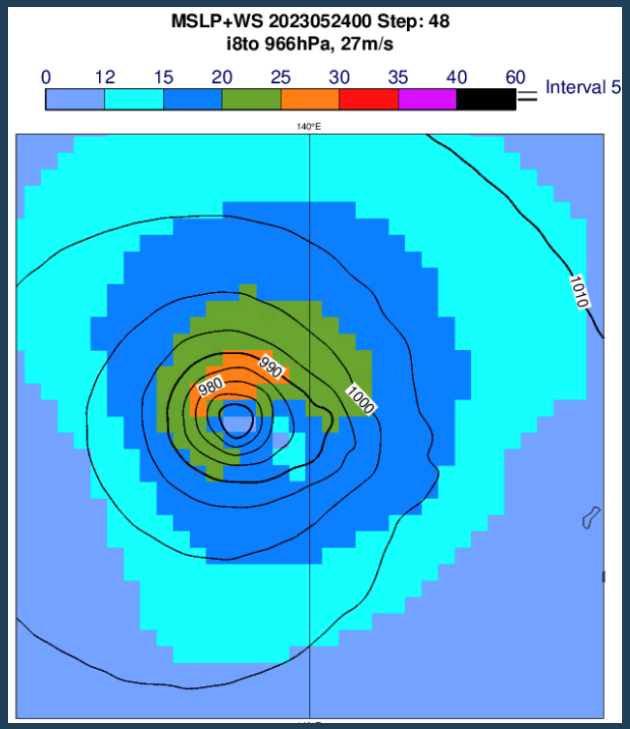
HRES (+48h)



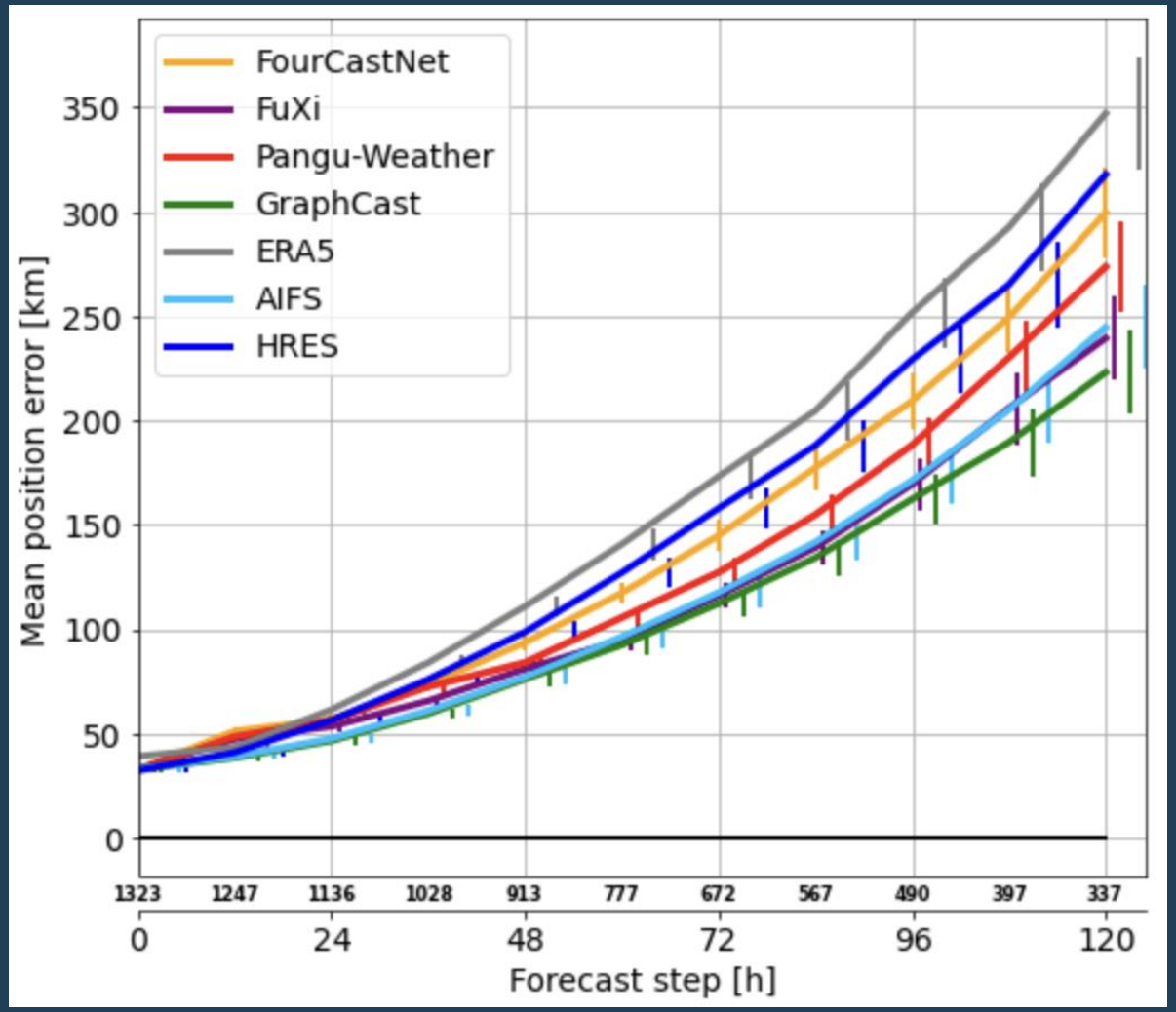




AIFS (+48h)



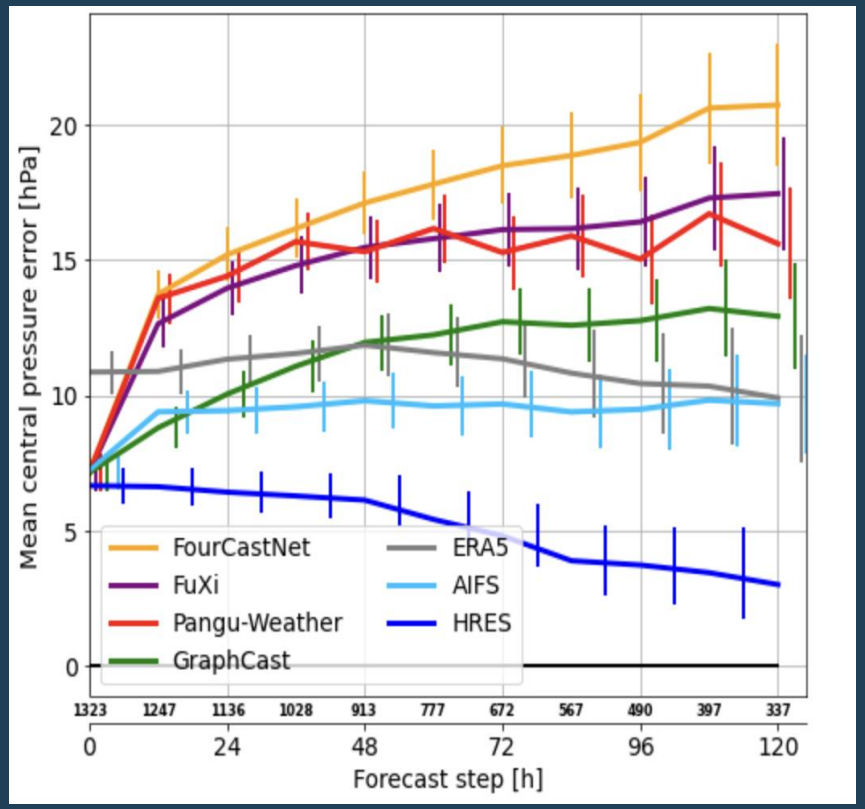
Tropical Cyclone track error (2022-2023)



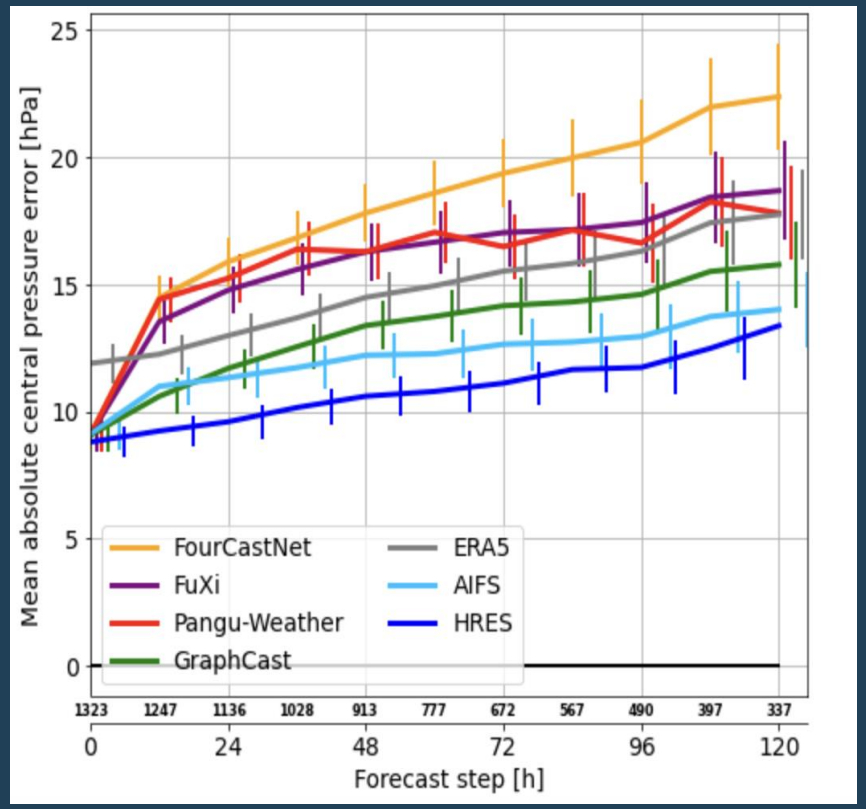
Thanks to Michael Meier-Gerber

Tropical cyclone intensity (central pressure)

Bias

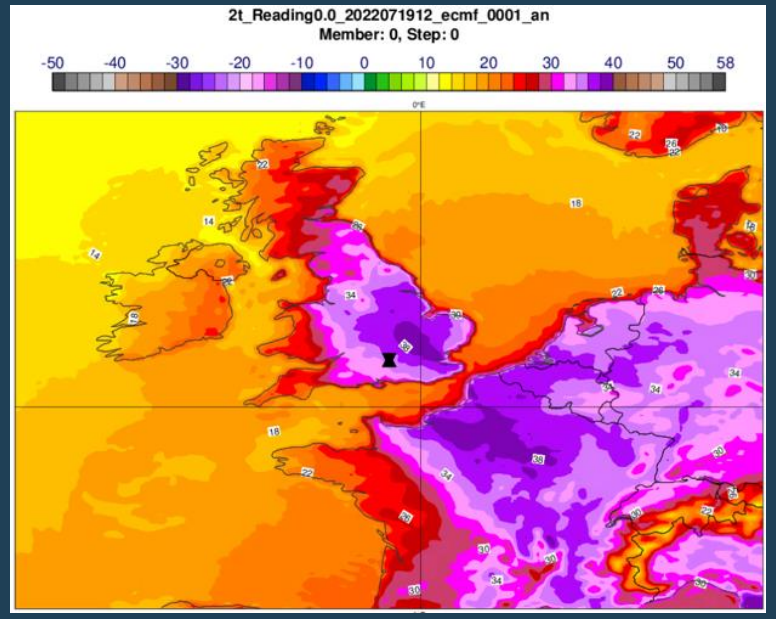


Mean abs. error

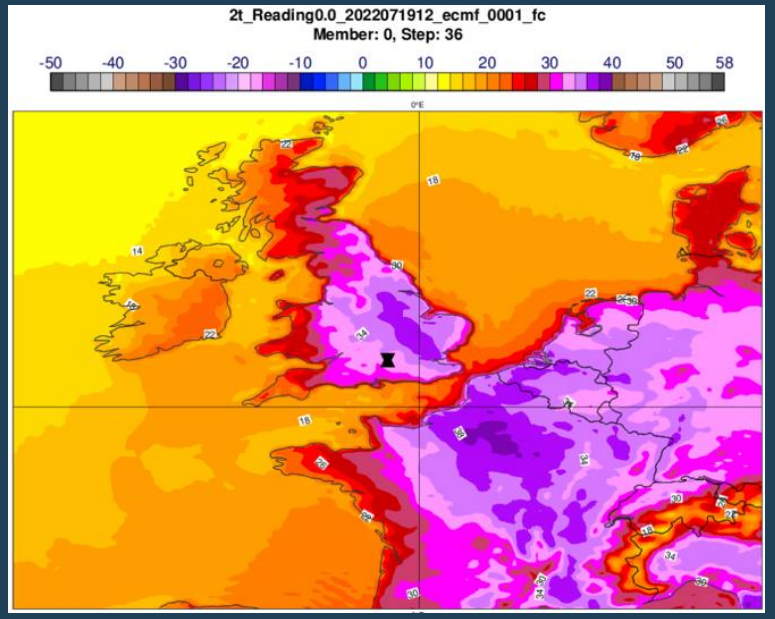


UK heatwave July 2022 (1.5 temperature day forecast)

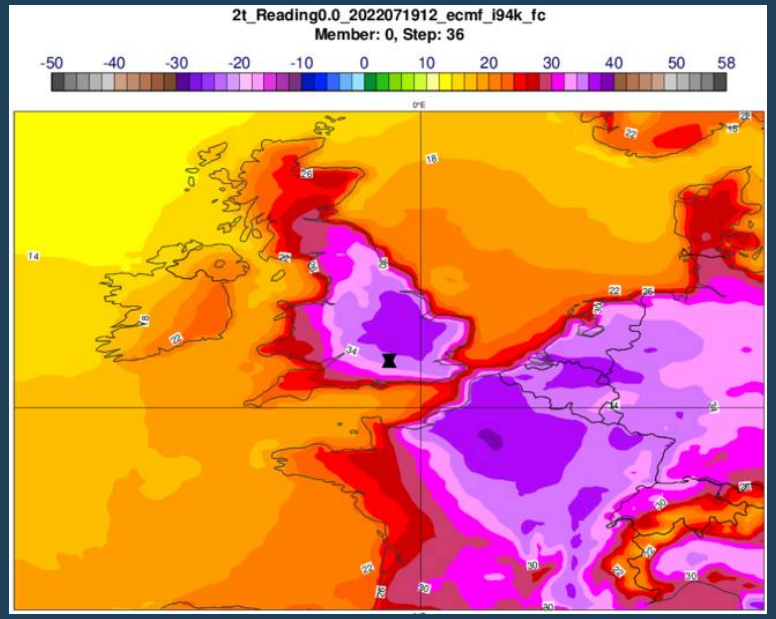
Analysis



HRES

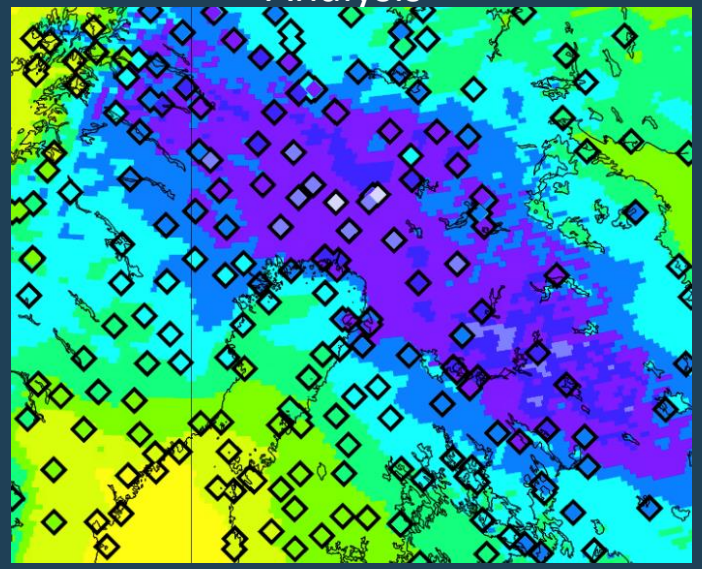


AIFS

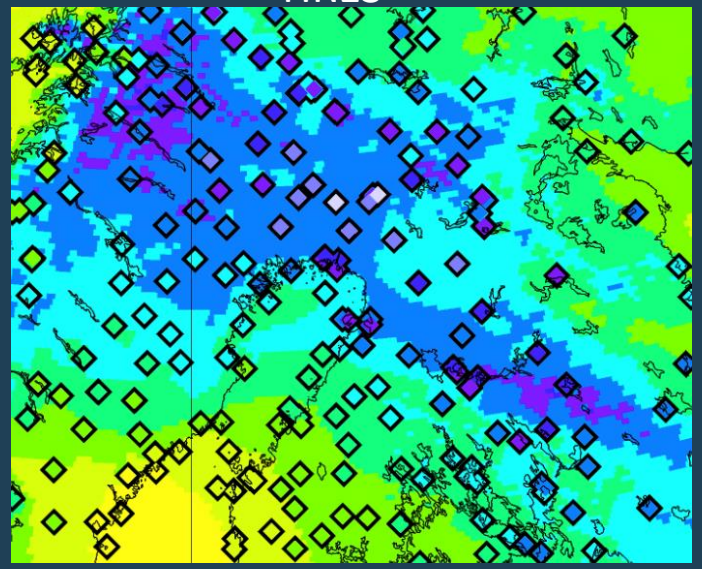


Cold weather in N. Europe (2-day temperature forecasts valid 18 Jan 2024 00UTC)

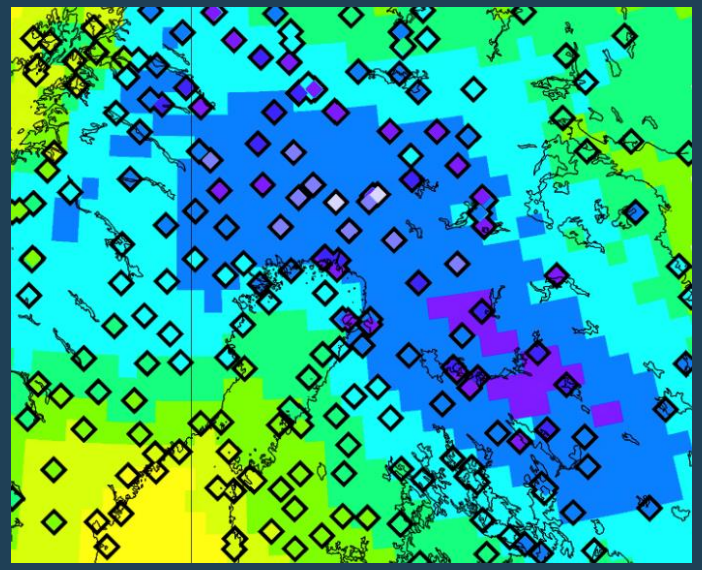
Analysis



HRES



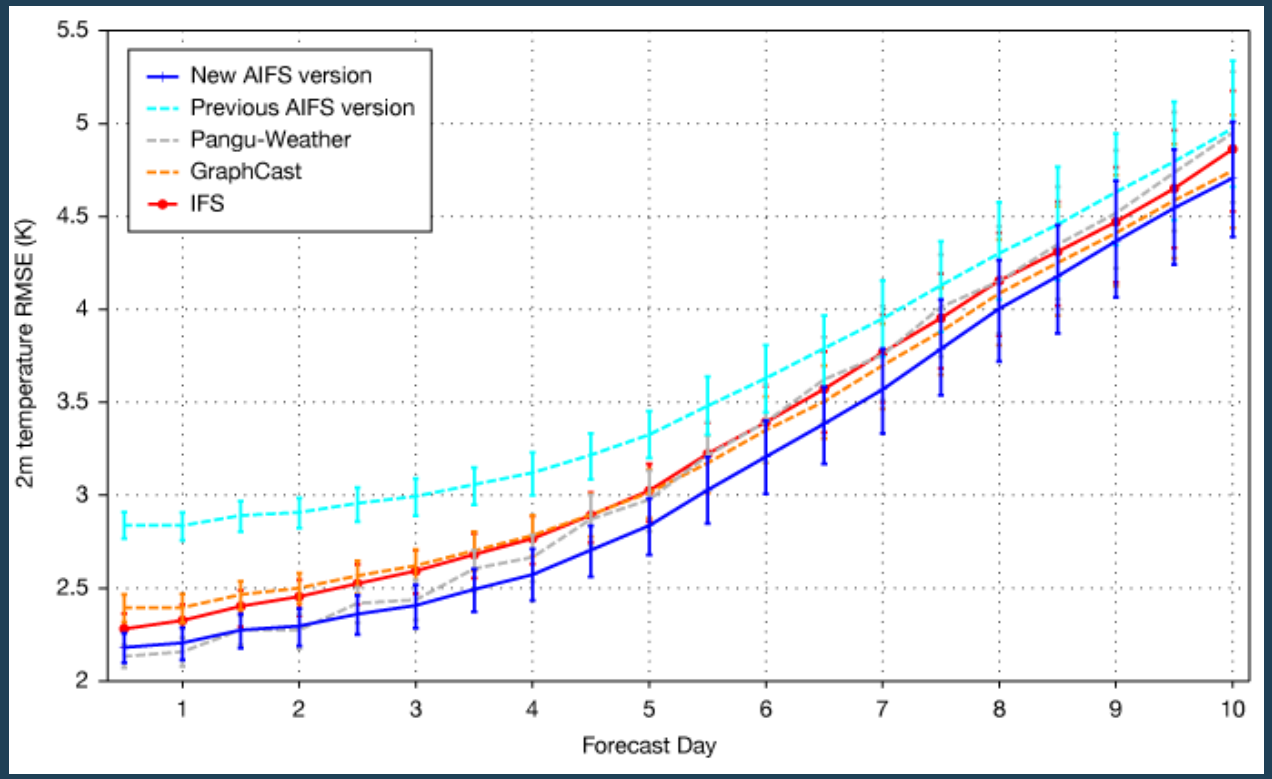
AIFS

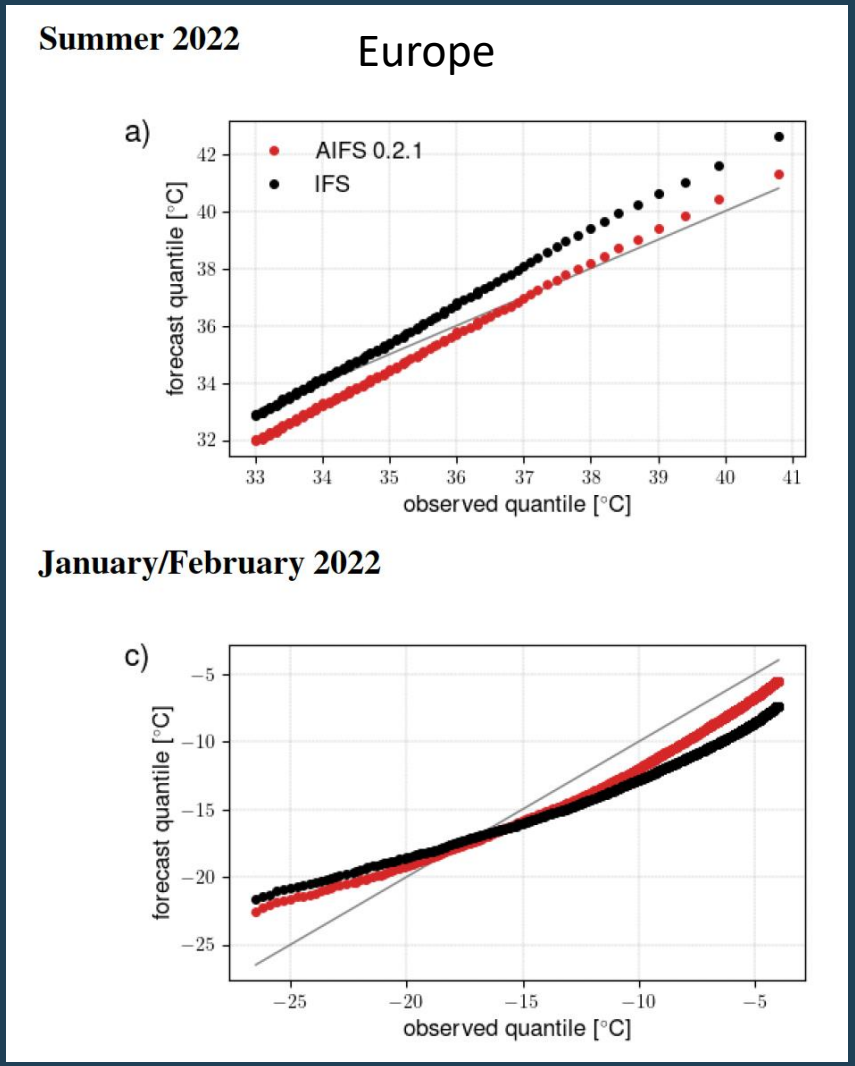


(Observations as diamonds)

Root-mean-square errors for 2-metre temperature over N.Hem (against observations)

Thanks to Zied





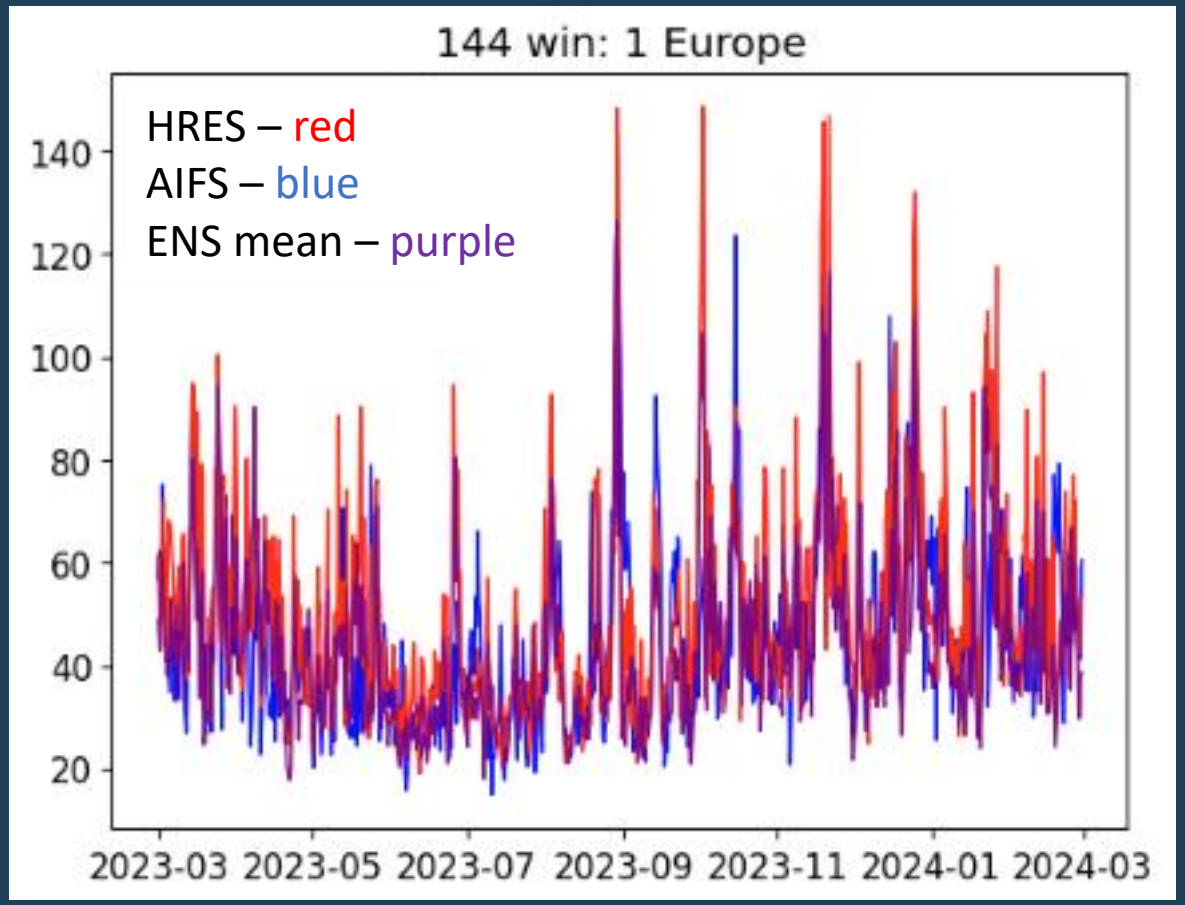
Summary

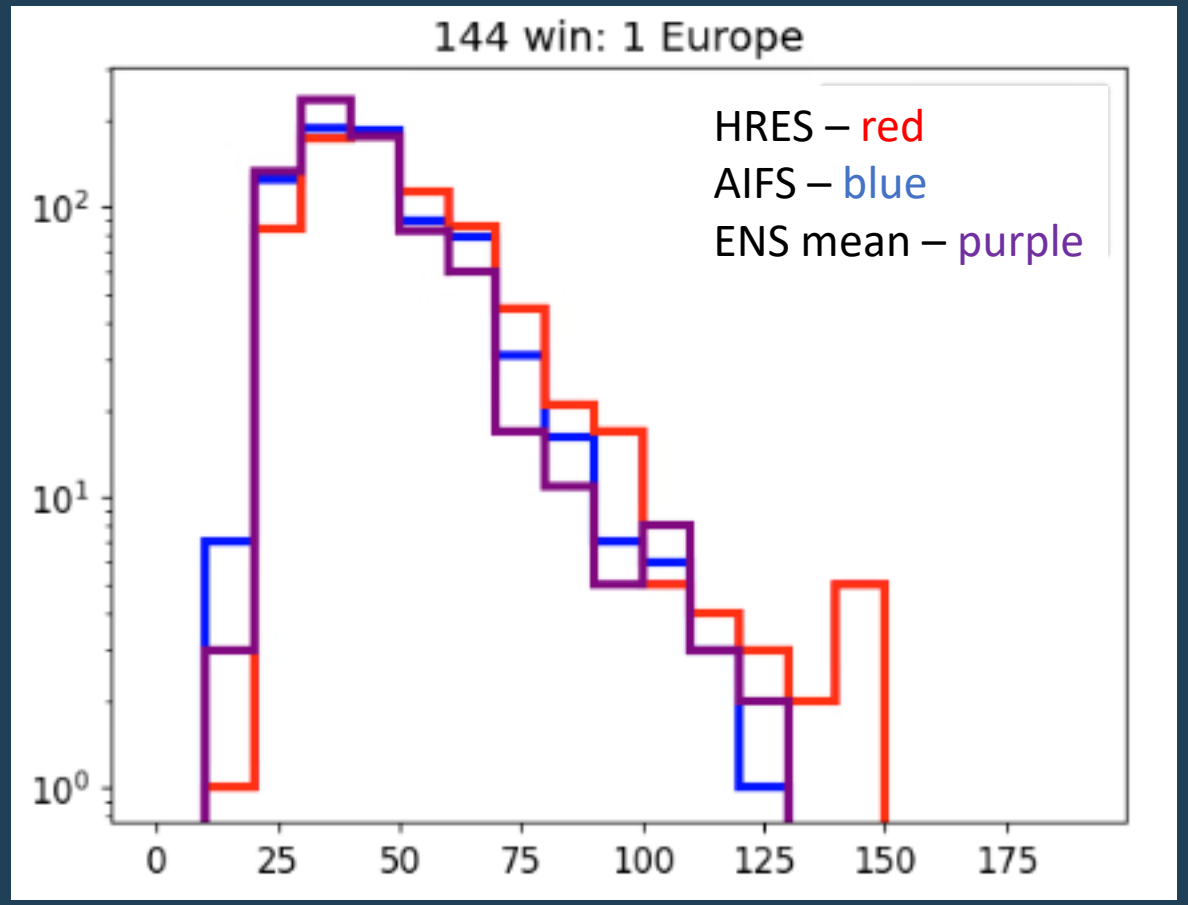
- Superior RMSE for z500 for AIFS compared to HRES
  - Mainly superior over ocean(?)
  - AIFS more consistent from forecast for forecast (less jumpy)
- AIFS predicts well large-scale features of extremes
  - Lacking mesoscale structures
- Very impressive tropical cyclone track scores for ML models

- Smooth fields of e.g precipitation (might help scores due to less “double penalties”)
- Too weak tropical cyclones
- Does AIFS lack some of the chaotic nature?

- Currently not directly impact parameters like predicting clouds (and some models missing precipitation)
- Ensemble systems under development

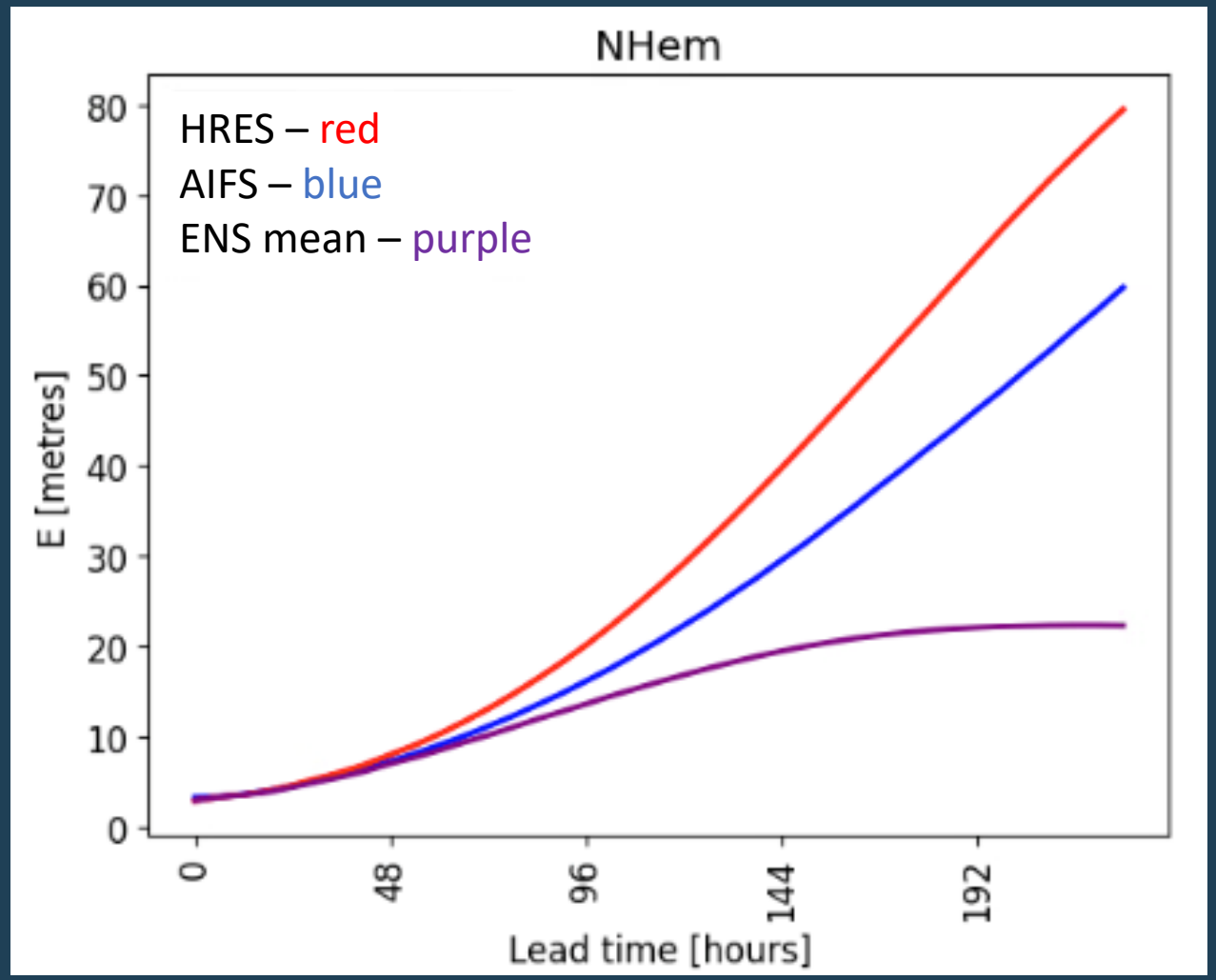
Day-to-day z500 RMSE for Europe





Less forecast busts in AIFS compared to HRES (and also ensemble mean)

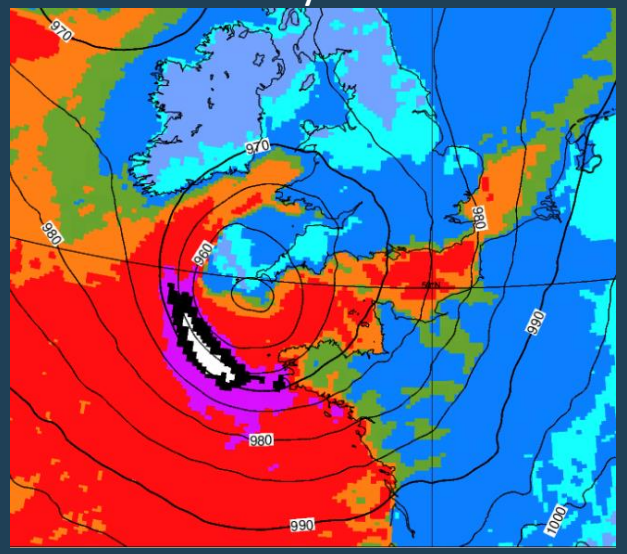
Jumpiness (difference between consecutive forecasts)



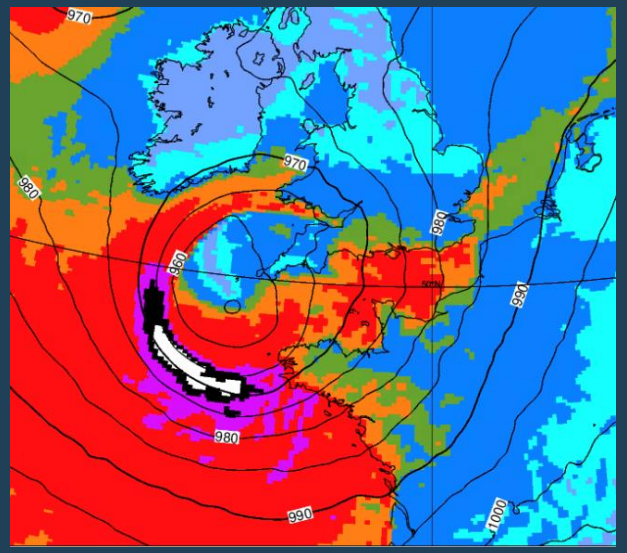
AIFS less ”jumpy” than HRES, not necessarily a good thing for a deterministic forecast

Storm Ciaran (2-day forecasts valid 2nd Oct 2023 00UTC)

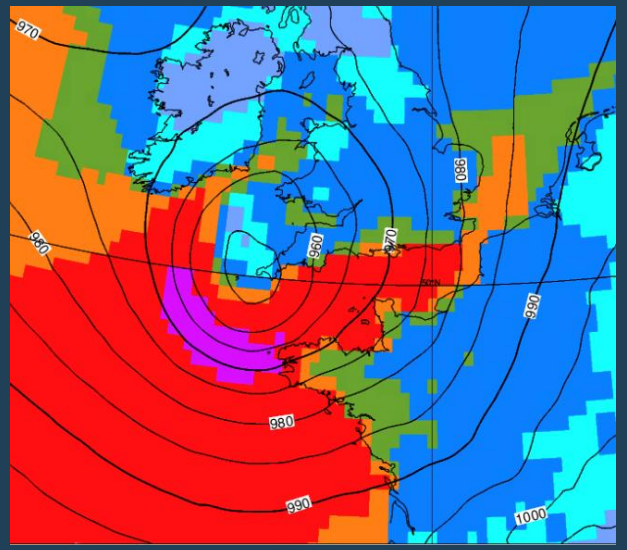
Analysis



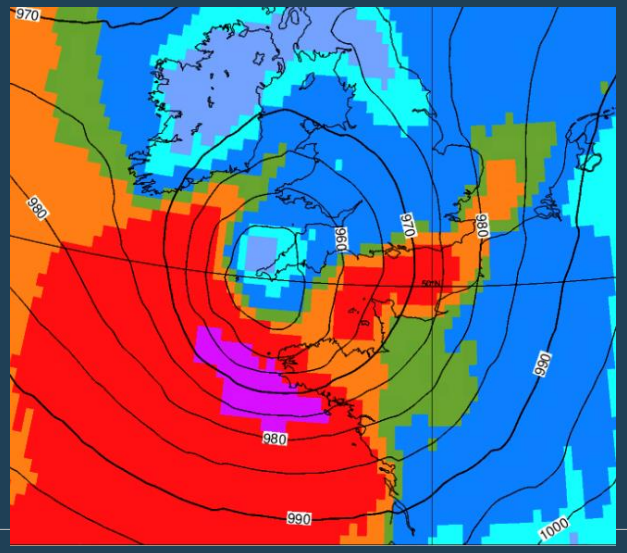
HRES



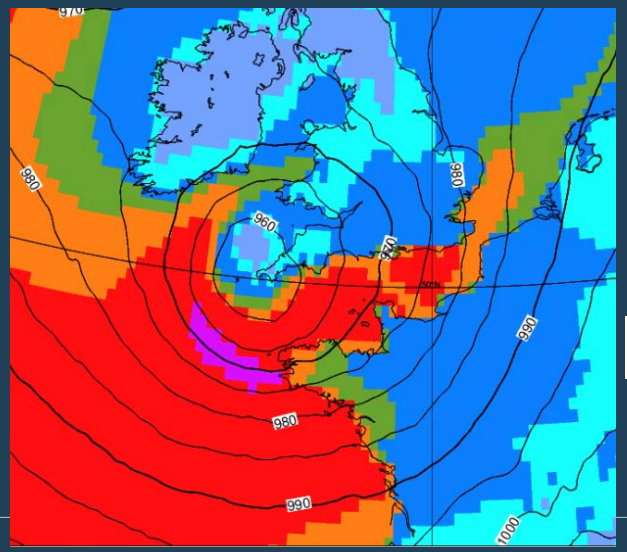
AIFS



PanguWeather



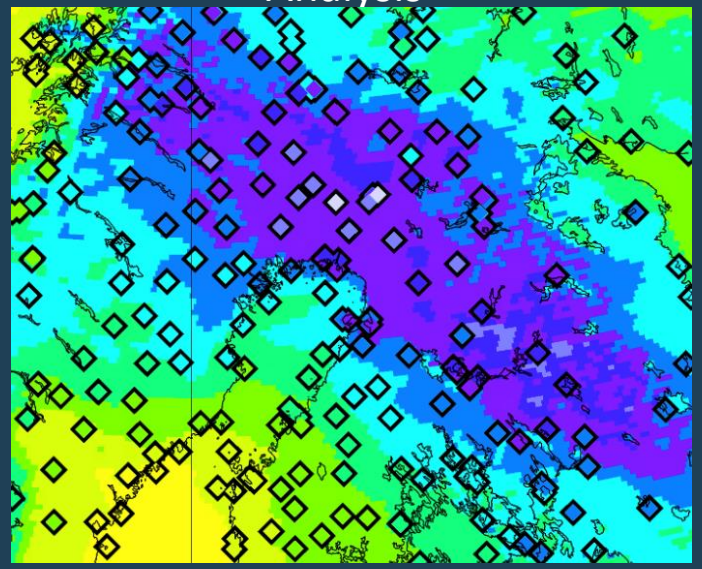
Graphcast



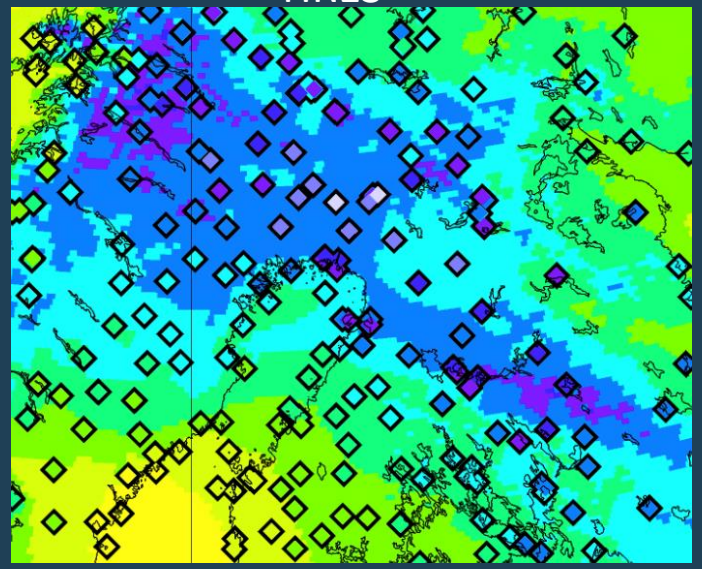
- Better position forecast in the ML models
- Similar minimum pressure 960-965hPa
- Less extreme wind speed in ML models

Cold weather in N. Europe (2-day forecasts valid 18 Jan 2024 00UTC)

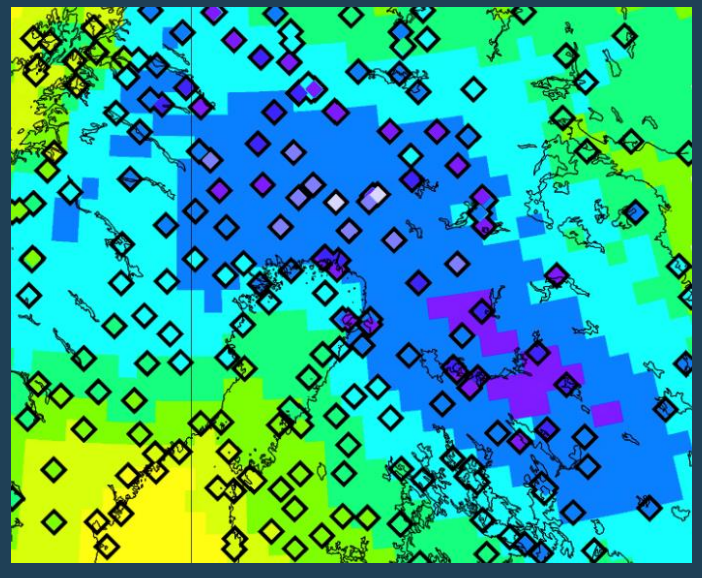
Analysis



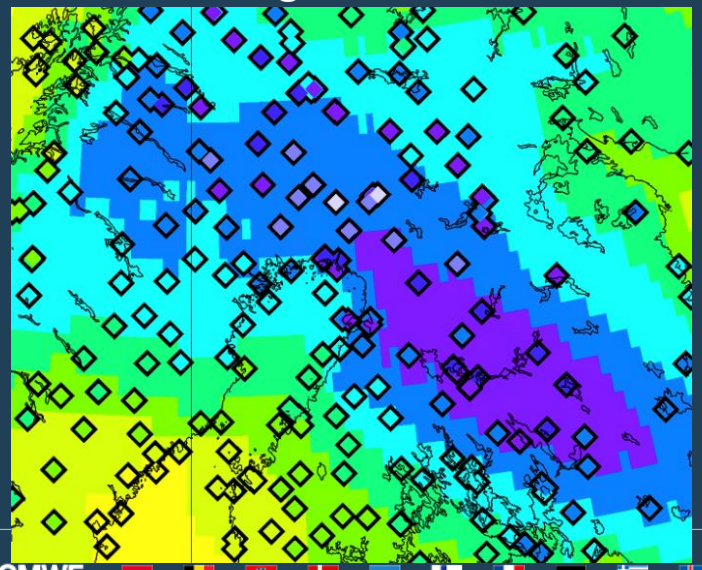
HRES



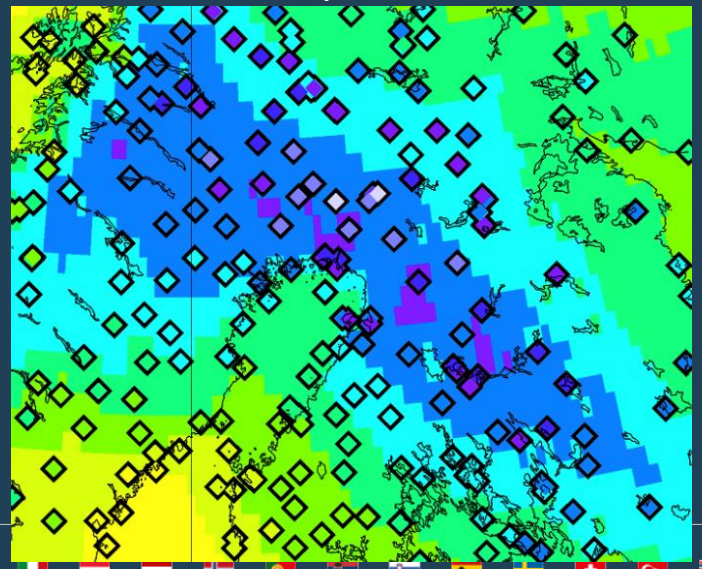
AIFS



PanguWeather



Graphcast

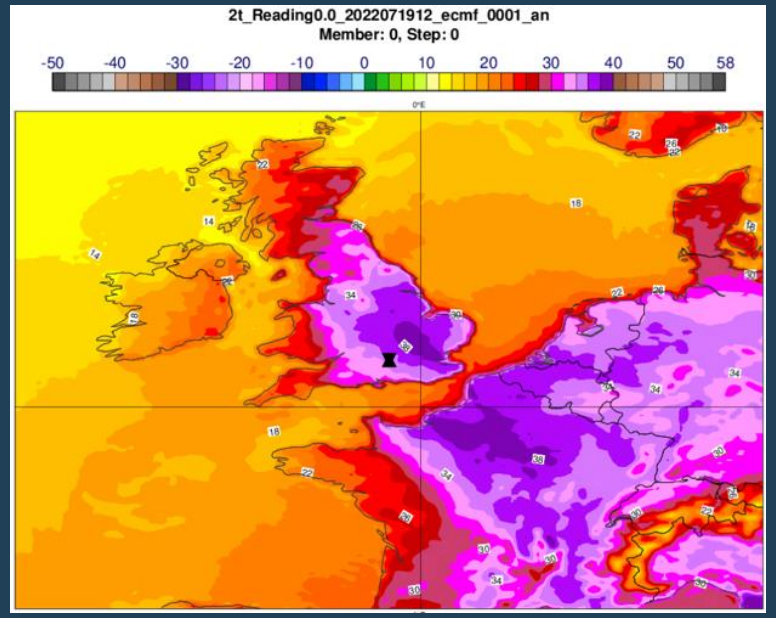


-36 -28. -20 -12 -4 4 12 20

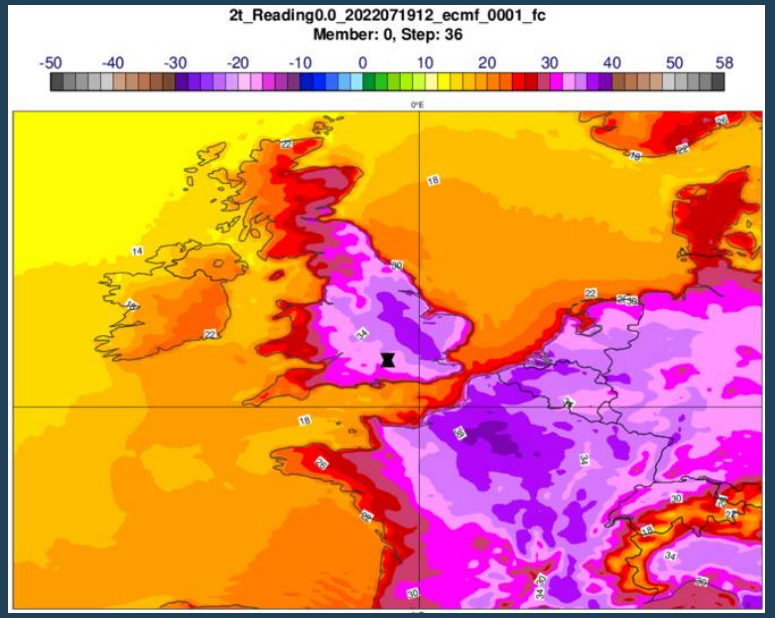
(Observations as diamonds)

UK heatwave July 2022

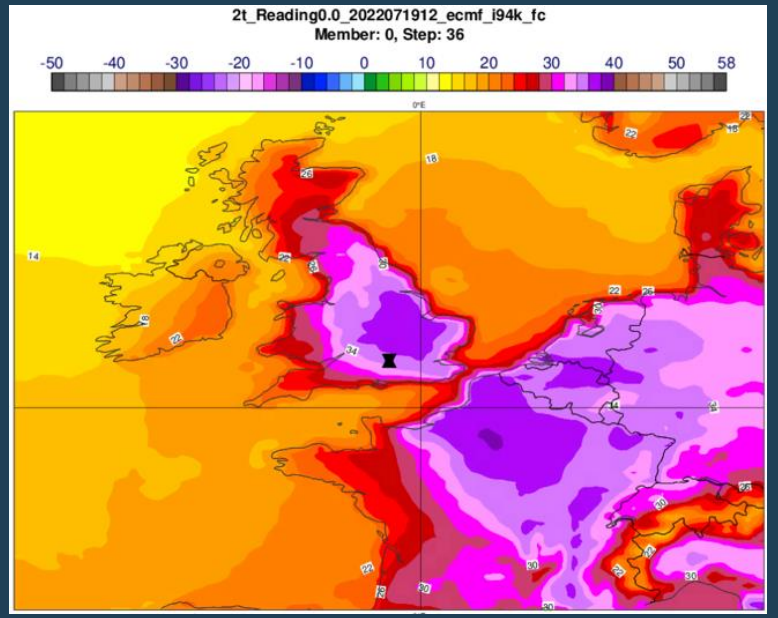
Analysis

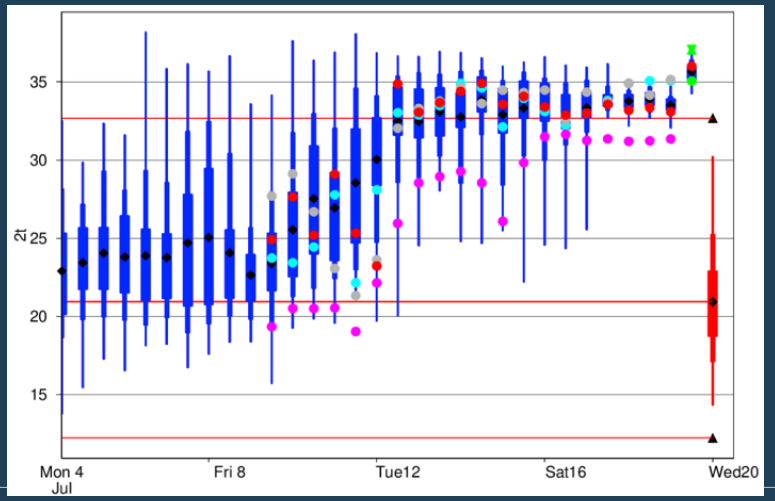


HRES



AIFS

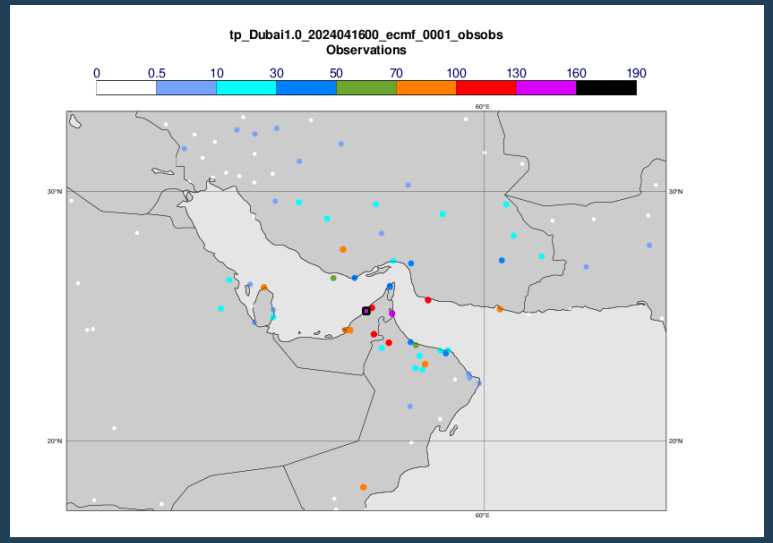




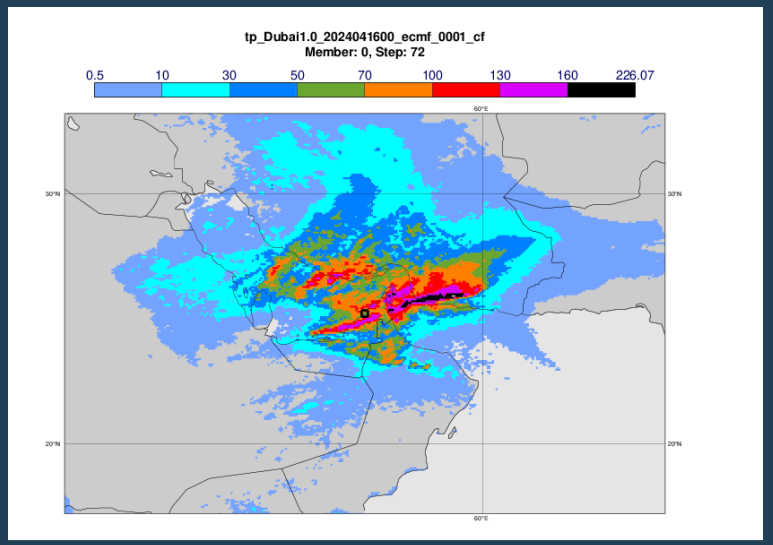
observations – green hourglass, ECMWF analysis – green dot, ECMWF HRES – red dot, AIFS – cyan dot, PanguWeather – grey dot, Fourcastnet – purple dot, ECMWF ensemble – blue box-and-whisker, ECMWF model climate – red box-and-whisker

Extreme precipitation in the United Arab Emirates and Oman April 2024

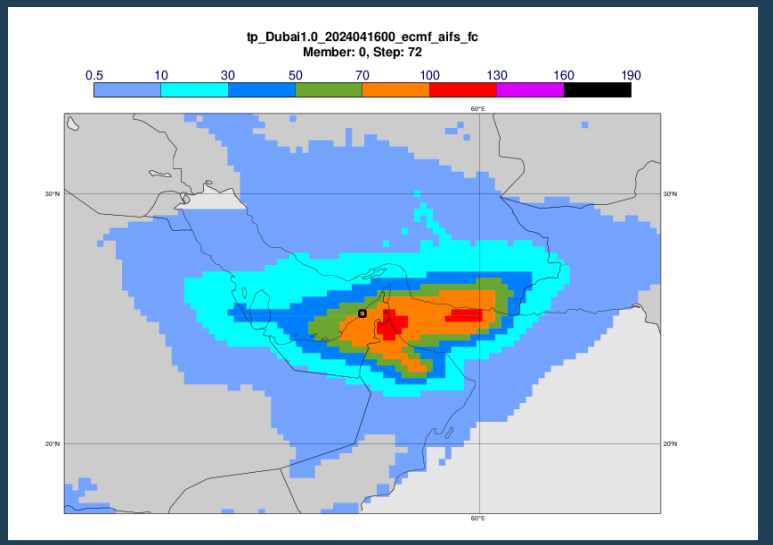
Observations



HRES



AIFS

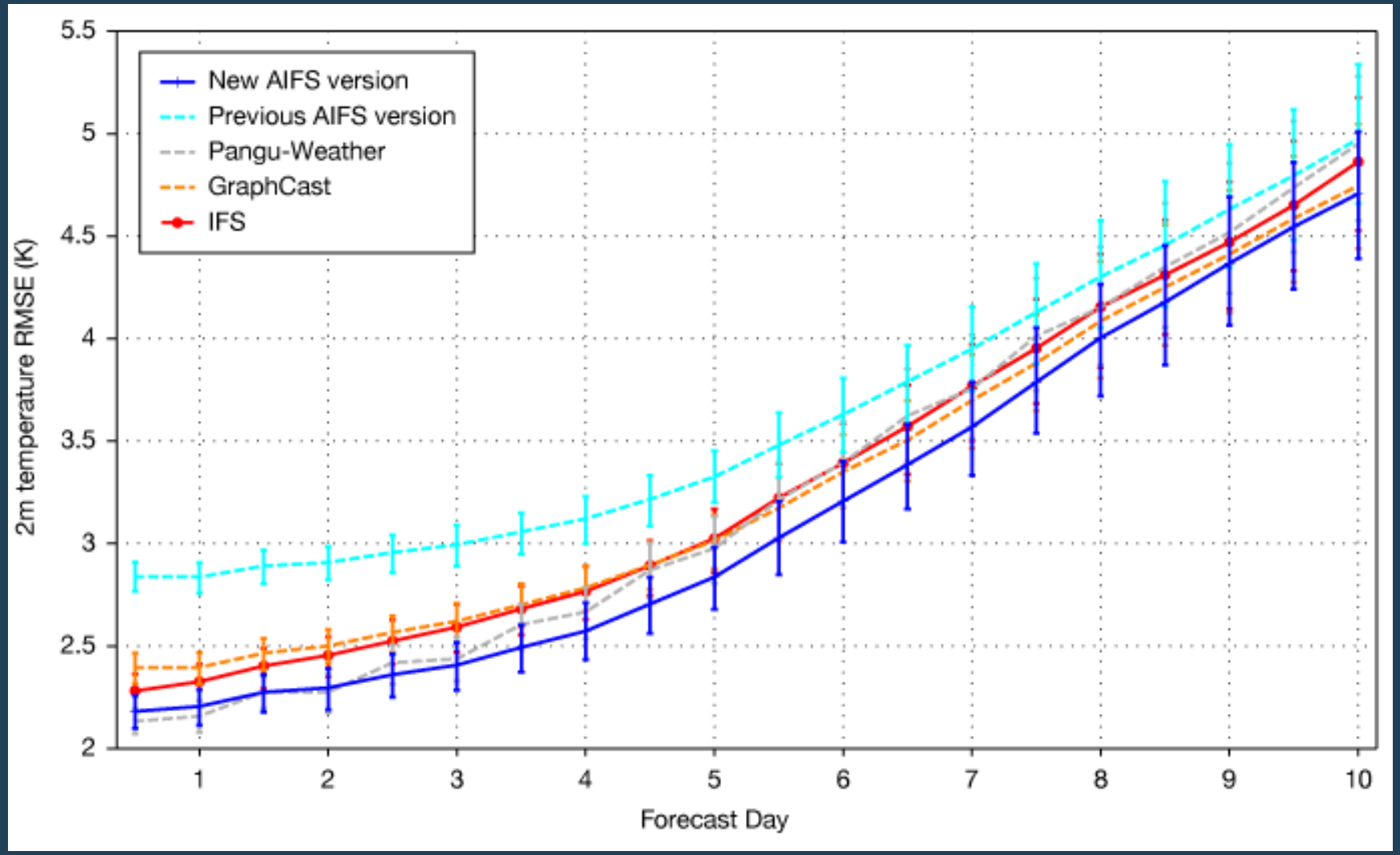


Observation - green hourglass
Analysis - green dot
ENS control–red
DestinE4.4km - purple dot
ENS - blue box-and-whisker
AIFS - pcyan dot

Model climate – cyan box-and-whisker

Ensemble mean as black diamonds. Triangle marks the maximum in the model climate based on 1800 forecasts.

Root-mean-square errors for 2-metre temperature over N.Hem (against observations)



What the forecasts are showing: **Tropical cyclone MAWAR (26 May 2023 00UTC)**