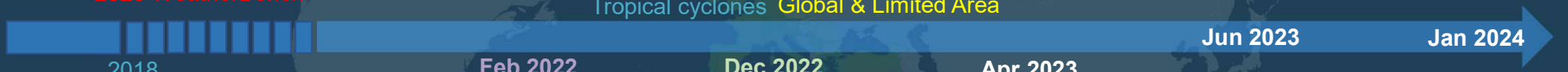
Machine Learning in NWP: **What I have learnt in the past year**

Linus Magnusson and colleagues at ECMWF

A brief history of data-driven models



2018
Exploring the idea

ECMWF's Peter Dueben and Peter Bauer publish a paper on using ERA5 at ~500km resolution to predict future z500.

2020 WeatherBench

Defining the dataset, split, headline fields and metrics

Feb 2022
Full medium-range NWP

Keisler - GraphNN 1°, competitive with GFS

NVIDIA – FourCastNet Fourier+ , 0.25°

O(10⁴) faster & more energy efficient than IFS

Nov 2022
Tropical cyclones

Huawei – PanguWeather 0.25° hourly product

"More accurate tracks" than the IFS.

Dec 2022
Extensive predictions

Deepmind – GraphCast 0.25° 6-hour

Many variables and pressure levels with comparable skill to IFS.

Jan 2023
Global & Limited Area

Microsoft – ClimaX

Forecasting various lead-times at various resolutions, both globally and regionally

Apr 2023
7-day+ scores improve

FengWu – China academia + Shanghai Met Bureau 0.25° 6-hour product

Improves on GraphCast for longer leadtimes (still deterministic)

Jun 2023
Spherical harmonics

NVIDIA – SFNO 0.25° 6-hour product

Extension of FourCastNet to Spherical harmonics, improved stability

Diffusion modelling

Alibaba – SwinRDM 0.25° 6-hour product

Sharp spatial features

Jan 2024

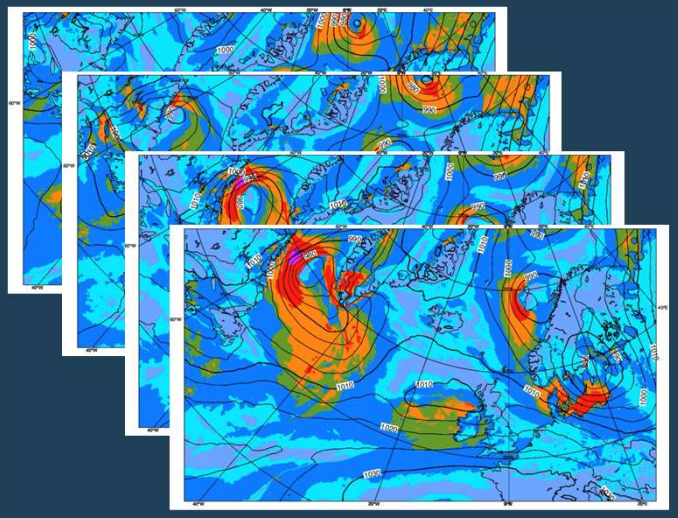
AIFS 0.25° 6-hour product

In-house developed model from ECMWF

Last months
FuXi
AtmoRep
FuXi-extreme
NeuralGCM

Forecasts available from ECMWF web:

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



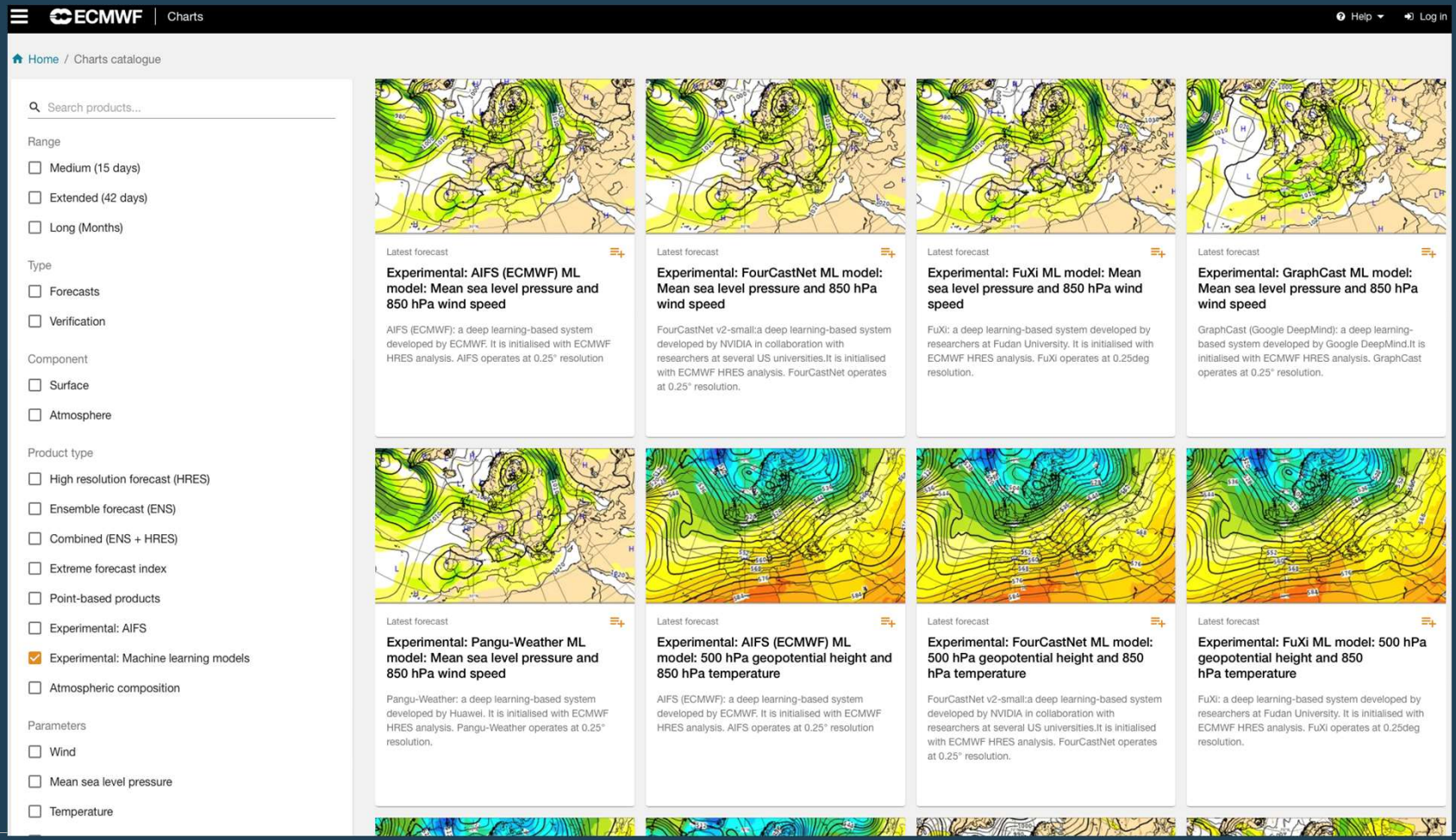
All models are trained on ERA5 reanalysis (~0.25 degree resolution), but some fine-tuned on HRES analysis

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

Since this summer:
Experimental AIFS ensemble with 1 degree resolution

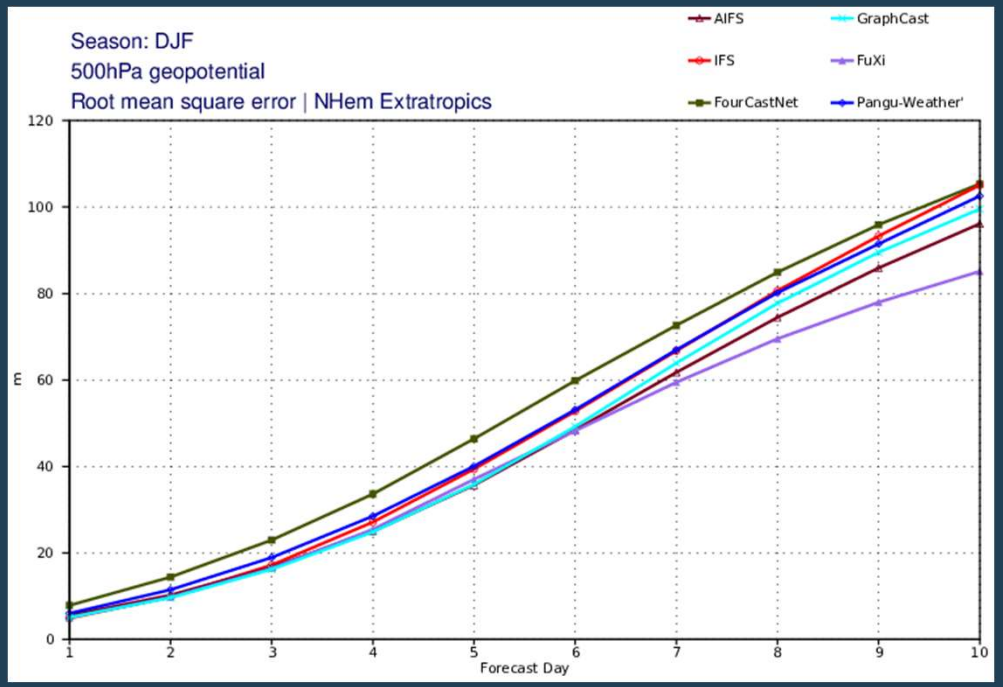
In all experiments below, we have initialised all ML models from ECMWF initial conditions.

Real-time experimental forecasts available on OpenCharts

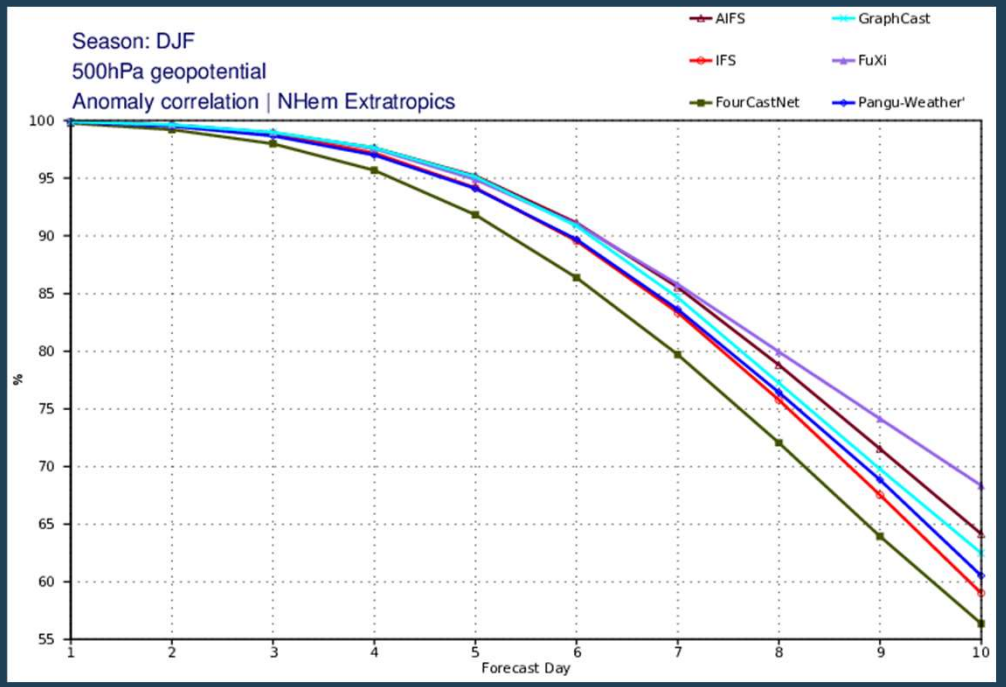


Scores from the recent winter – z500 over Northern Hemisphere (N.Hem)

Root-mean-square error (RMSE)



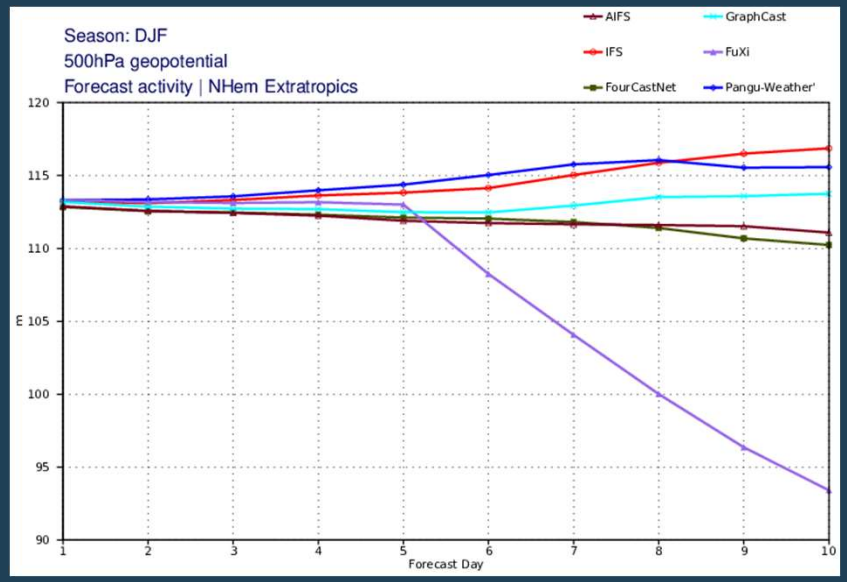
Anomaly correlation (ACC)



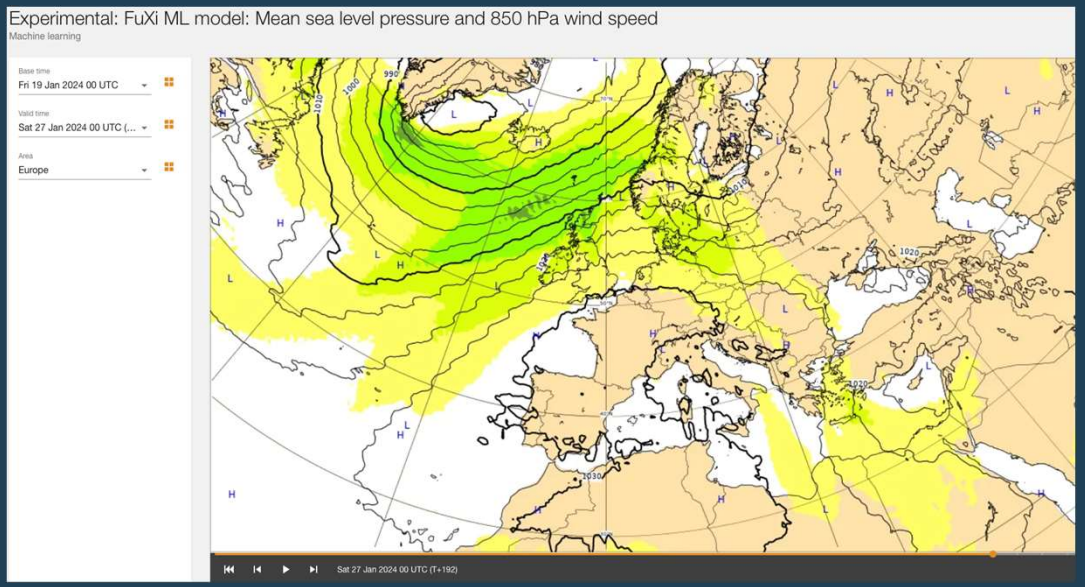
Verification plots available from OpenCharts

Scores are not telling everything!

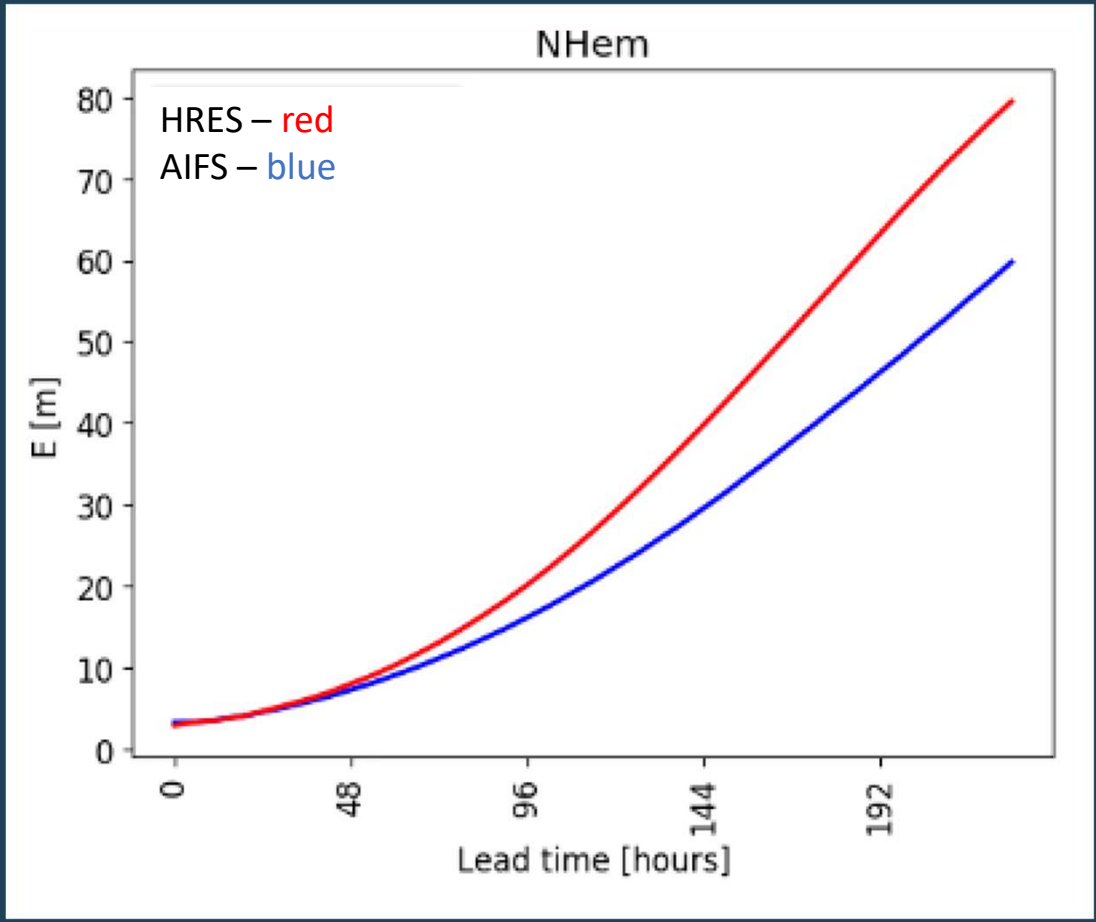
Forecast activity (measure of smoothness)



Example of MSLP and 850hPa wind speed from FuXi

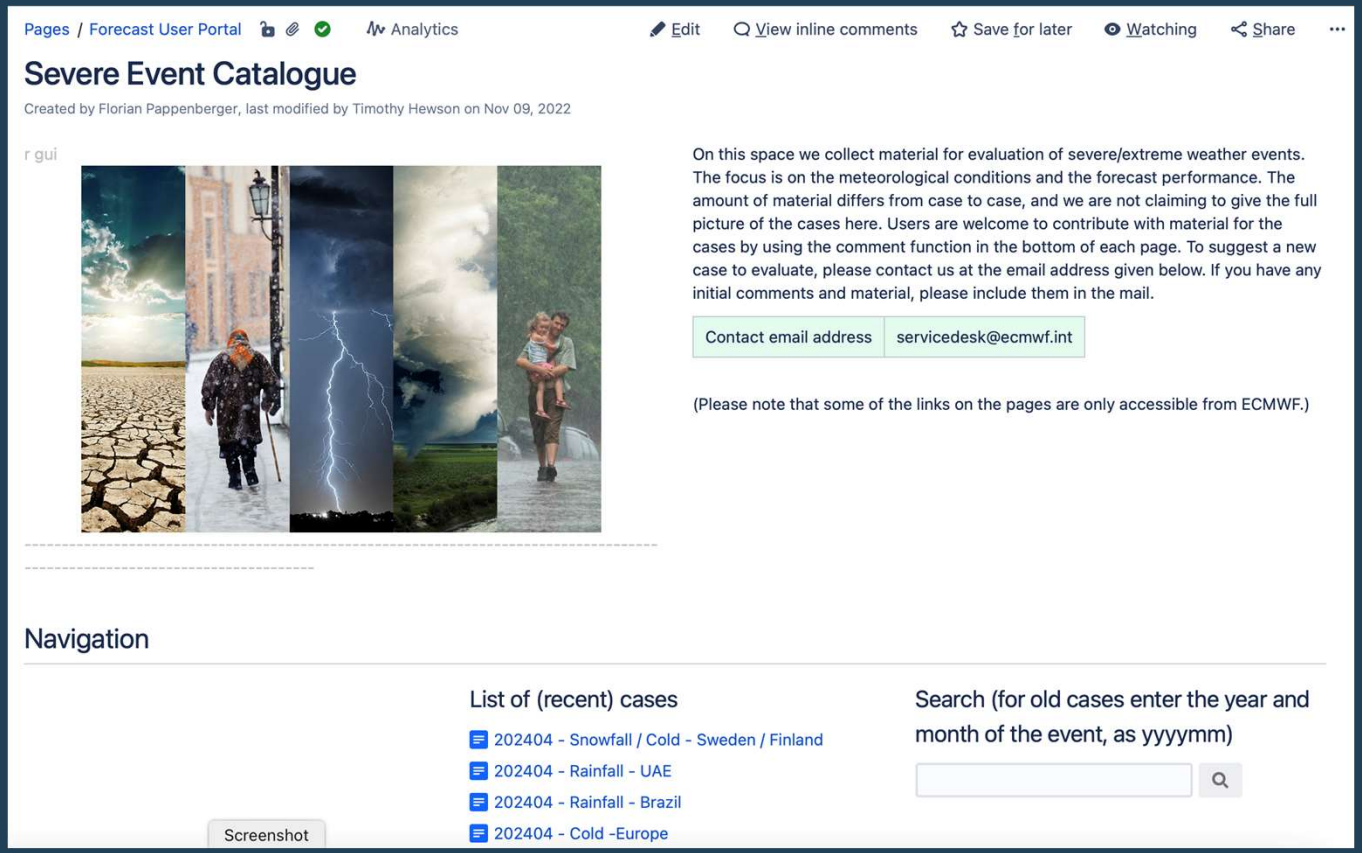


Forecast consistency*, z500, H.Nem



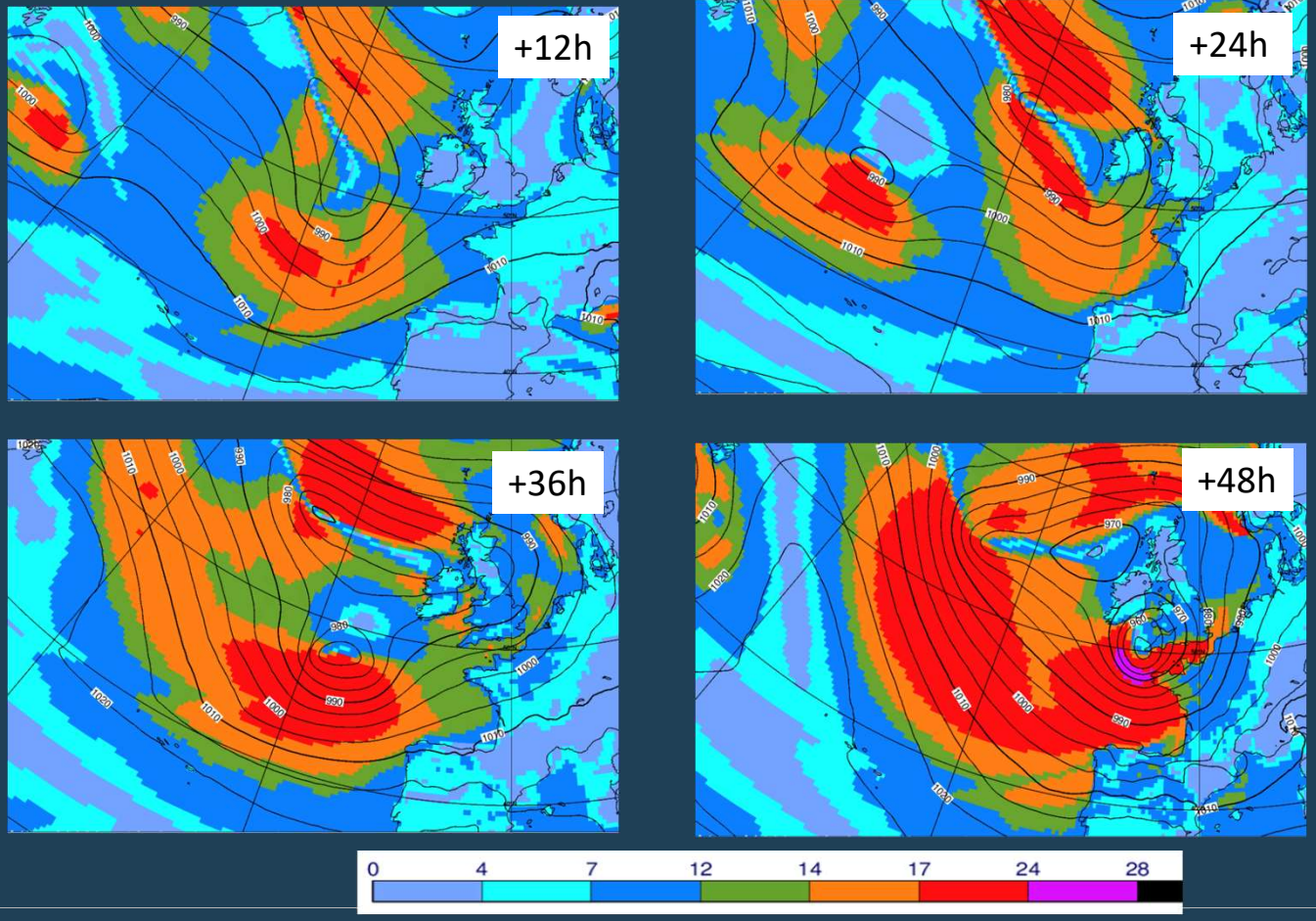
* Difference between forecasts initialised 12 hours apart, but valid at the same time

Extreme weather cases



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

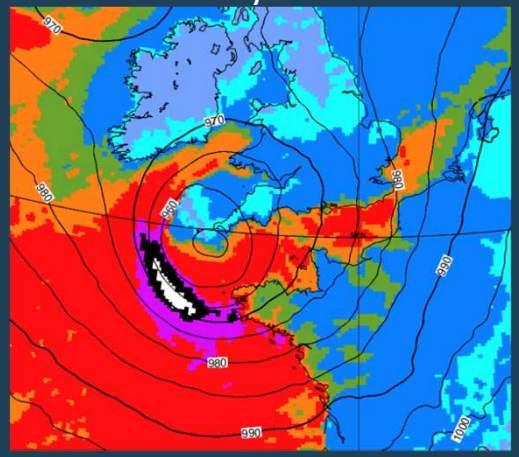
AIFS: **Storm Ciaran (forecast from 31 Oct 2023 00UTC)**



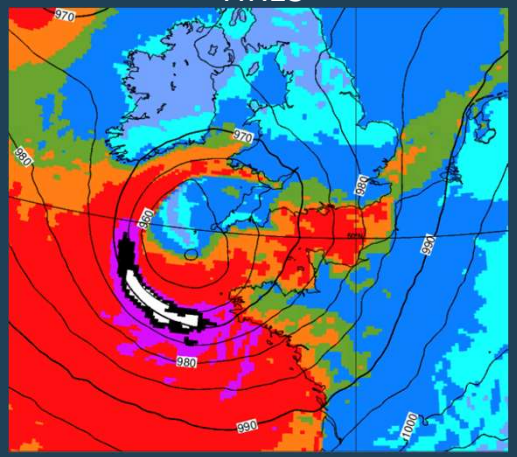
MSLP and wind speed from AIFS model

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

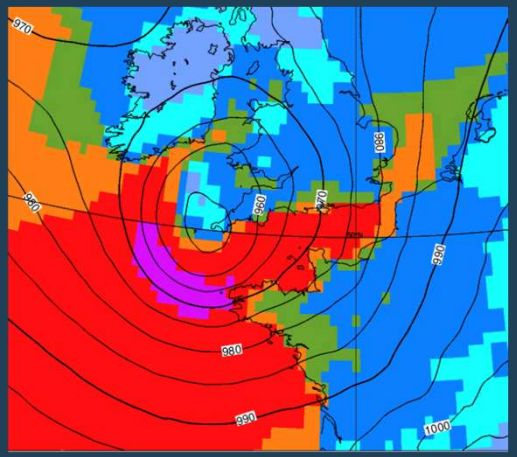
Analysis

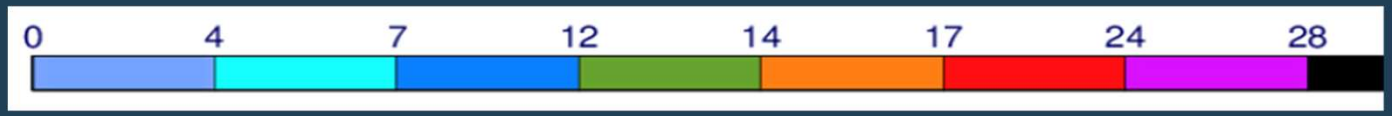


HRES



AIFS



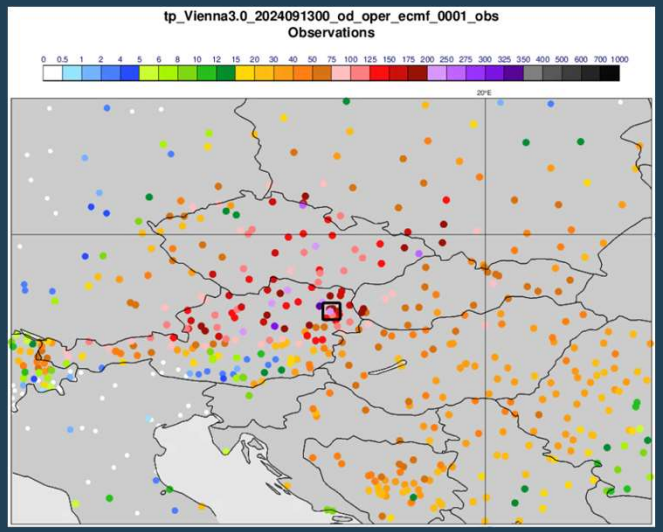


- Better position forecast in the ML models
- Similar minimum pressure 960-965hPa
- Less extreme wind speed in ML models
- See Charlton-Perez et al. (2024, Nature)

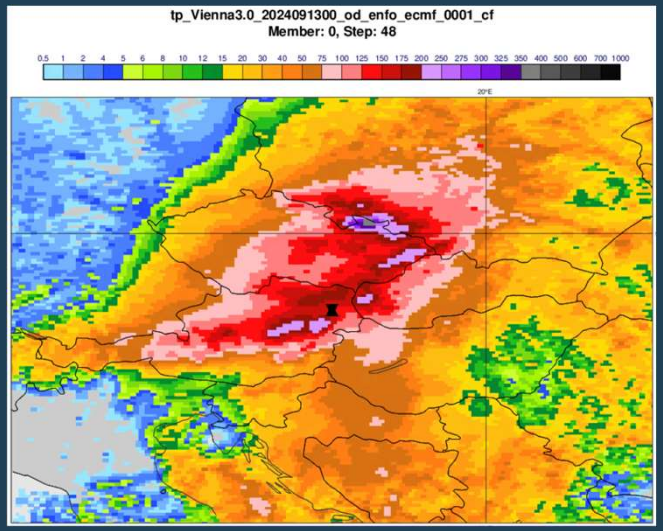
Extreme precipitation in central Europe, September 2024

72-hour precipitation 13 September 00UTC – 16 September 00UTC

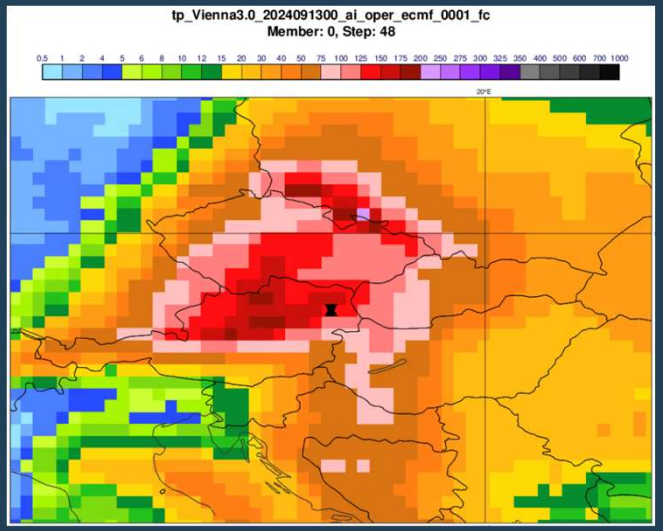
Observations



IFS control (48-120h)



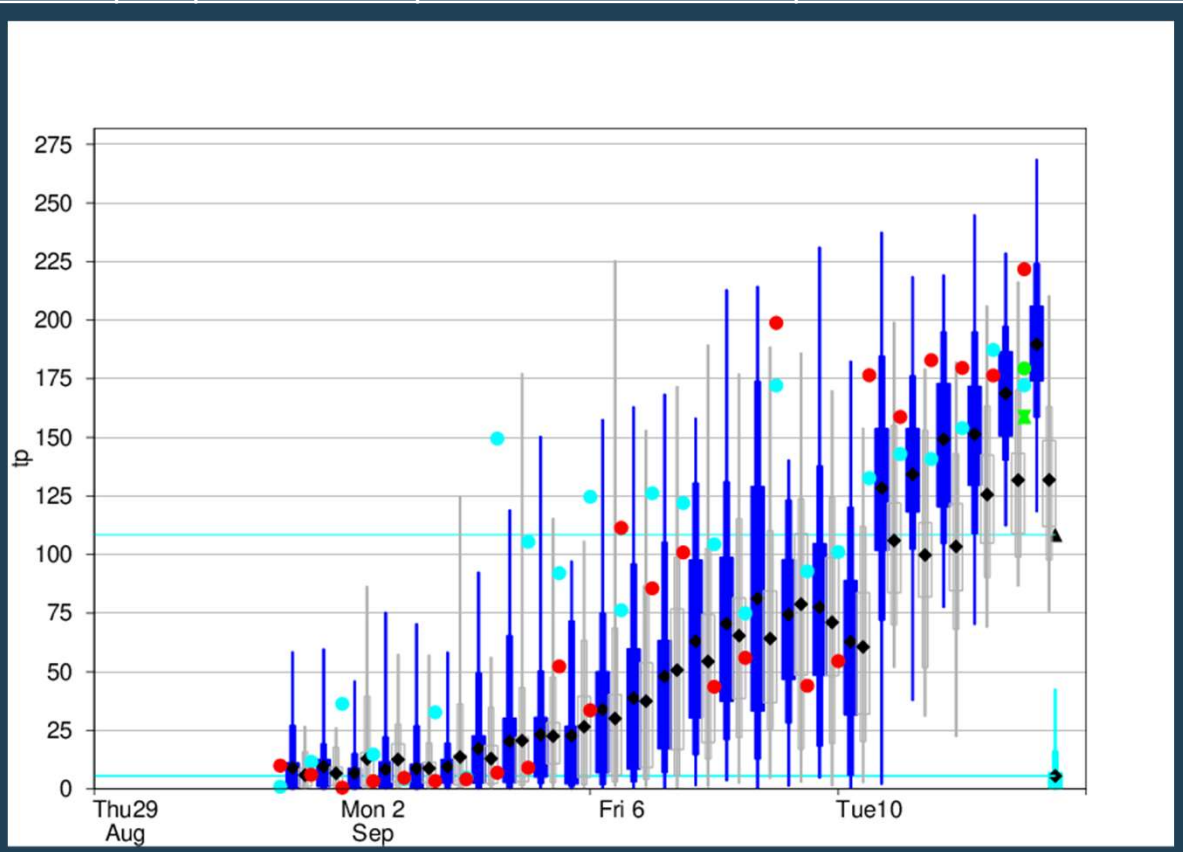
AIFS (48-120h)



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

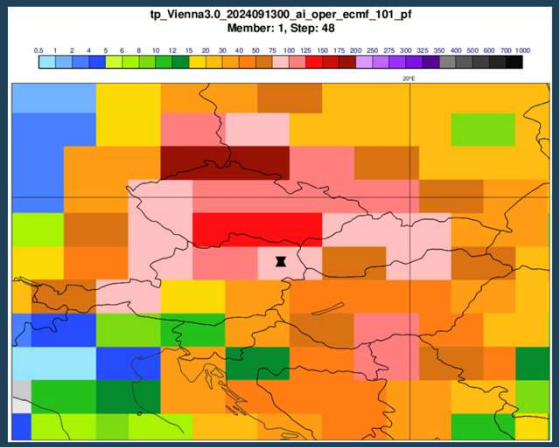
Extreme precipitation in central Europe, September 2024

72-hour precipitation 13 September 00UTC – 16 September 00UTC for Vienna



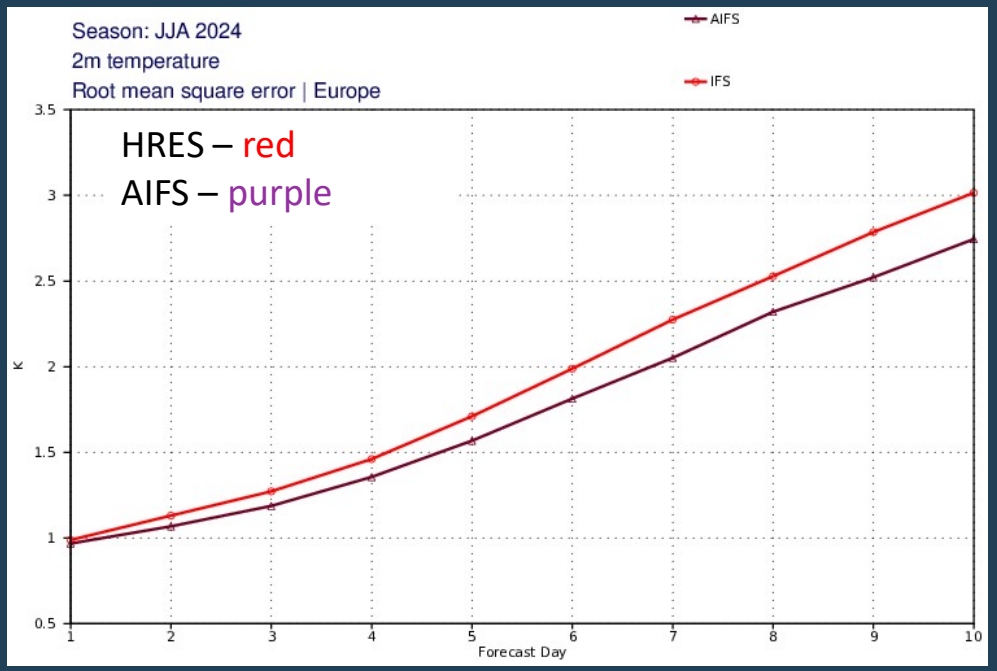
Observation mean: Green hourglass
IFS control: red
AIFS: Cyan
IFS-ENS : blue box-and-whisker
AIFS-ENS: grey box-and-whisker
M-climate: cyan box-and-whisker
M-climate max: black triangle

AIFS ensemble member (48-120h)

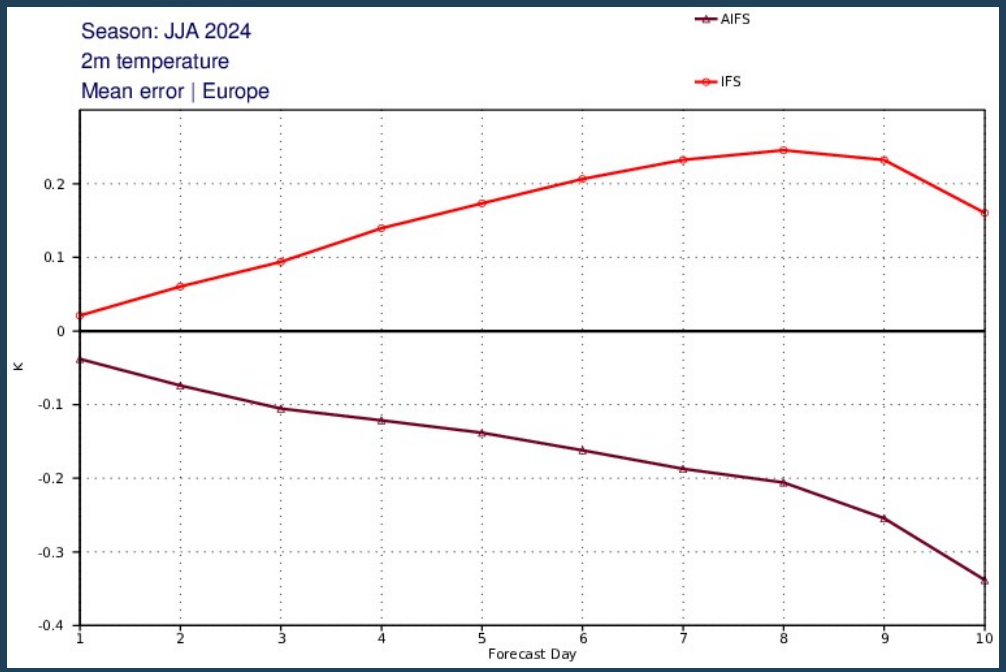


2-metre temperature error for Europe, JJA 2024

RMSE

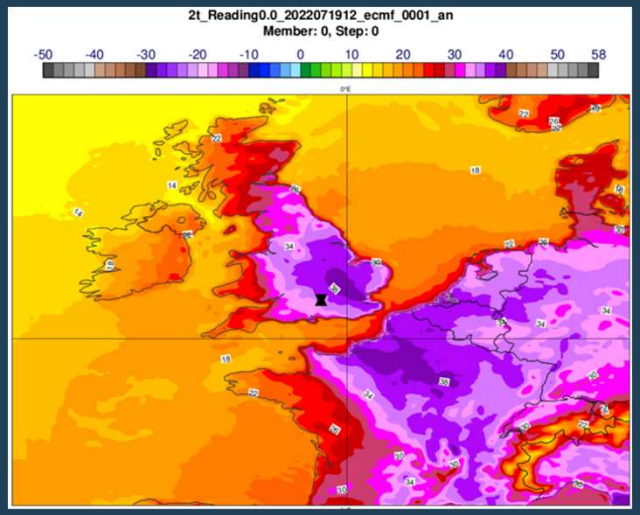


Bias

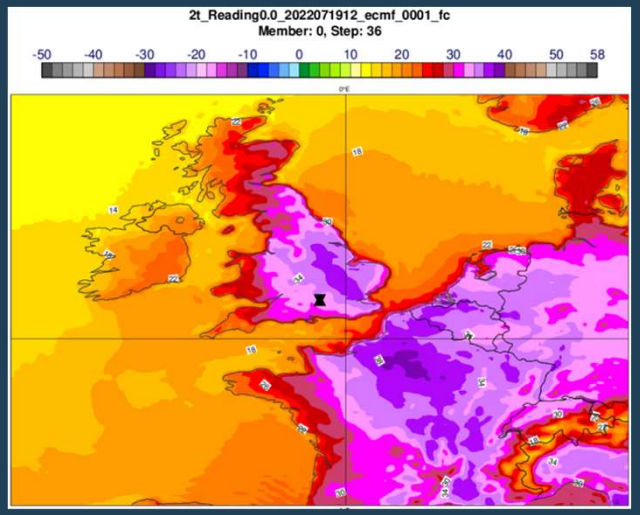


UK heatwave July 2022 (1.5 temperature day forecast)

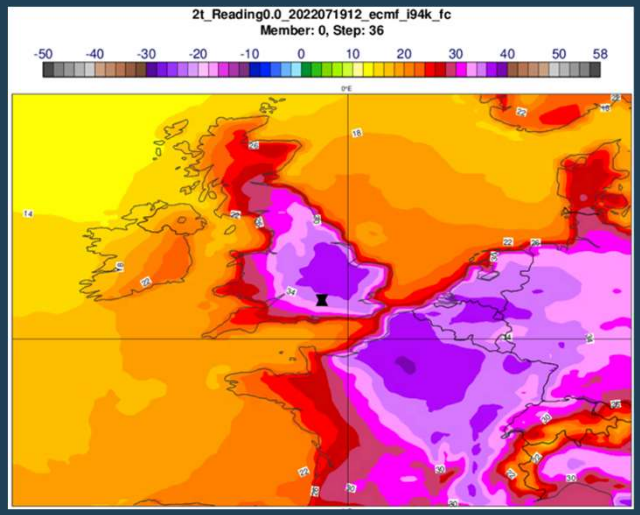
Analysis



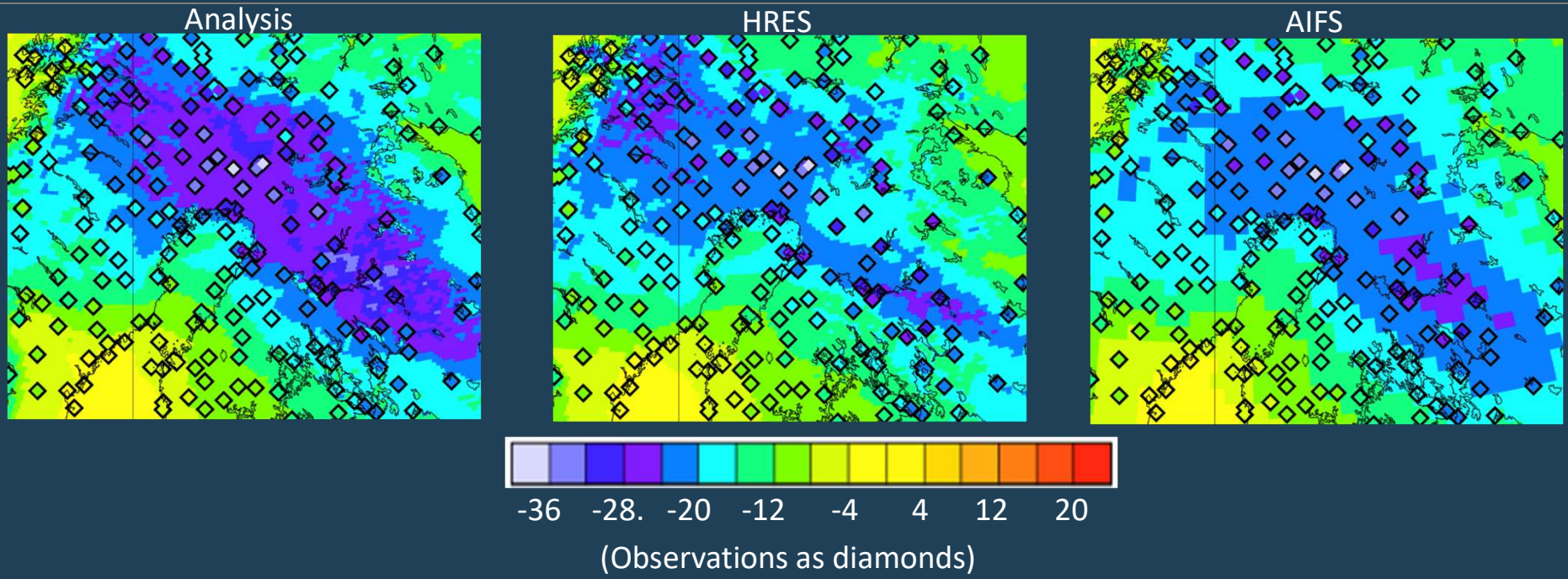
HRES



AIFS



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



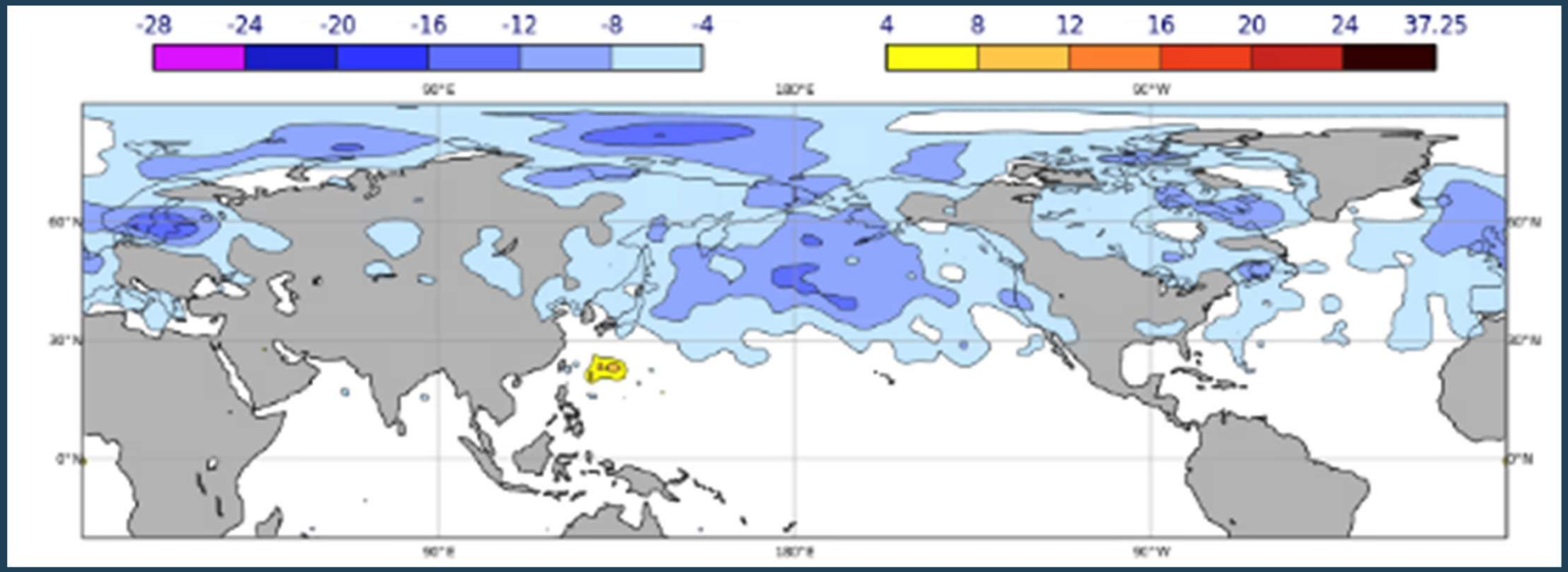
Summary

- Superior RMSE for z500 for AIFS compared to HRES
  - AIFS more consistent from forecast for forecast (less jumpy)
- AIFS predicts well large-scale features of extremes
  - Lacking mesoscale structures
- Convincing predictions of various extreme events

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

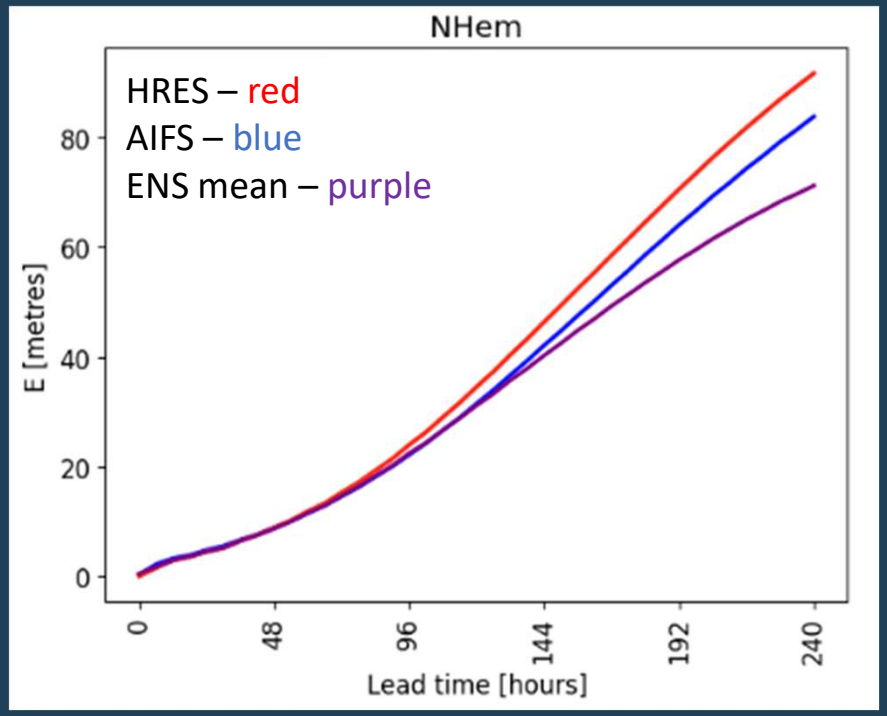
- Currently not directly impact parameters like predicting clouds (and some models missing precipitation). More parameters in the next version of AIFS.
- Another ensemble systems under development
- Aim to increase resolution to 0.1 degree
- Experimentation has started for sub-seasonal forecasts. Promising results, but some complications..
- Limited-area initiatives at SMHI/LiU, met.no, …

Difference in z500 RMSE (AIFS – HRES) Day 6

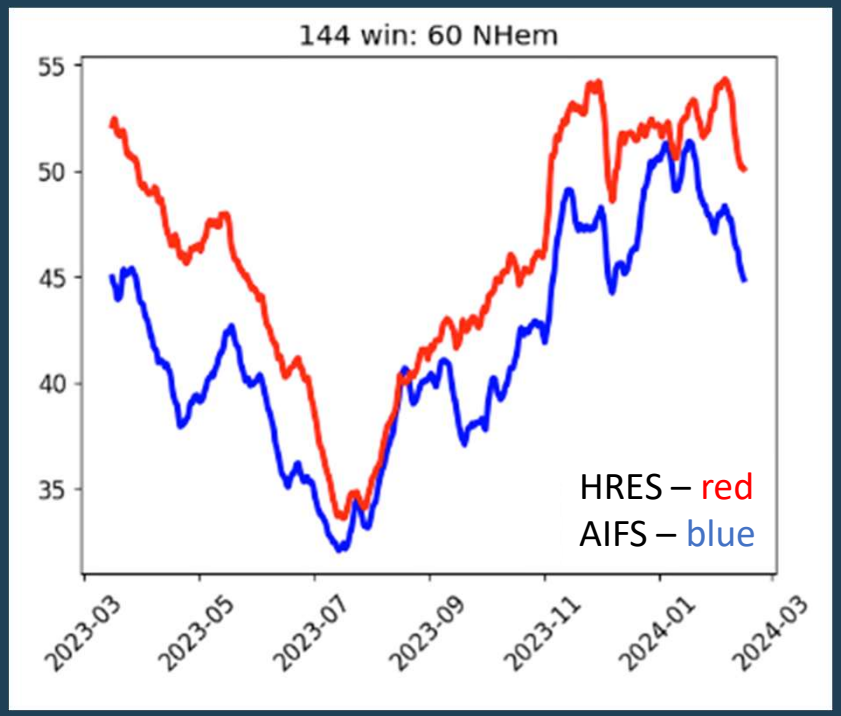


z500 RMSE for N.Hem - HRES vs AIFS, 1 March 2023 – 1 March 2024

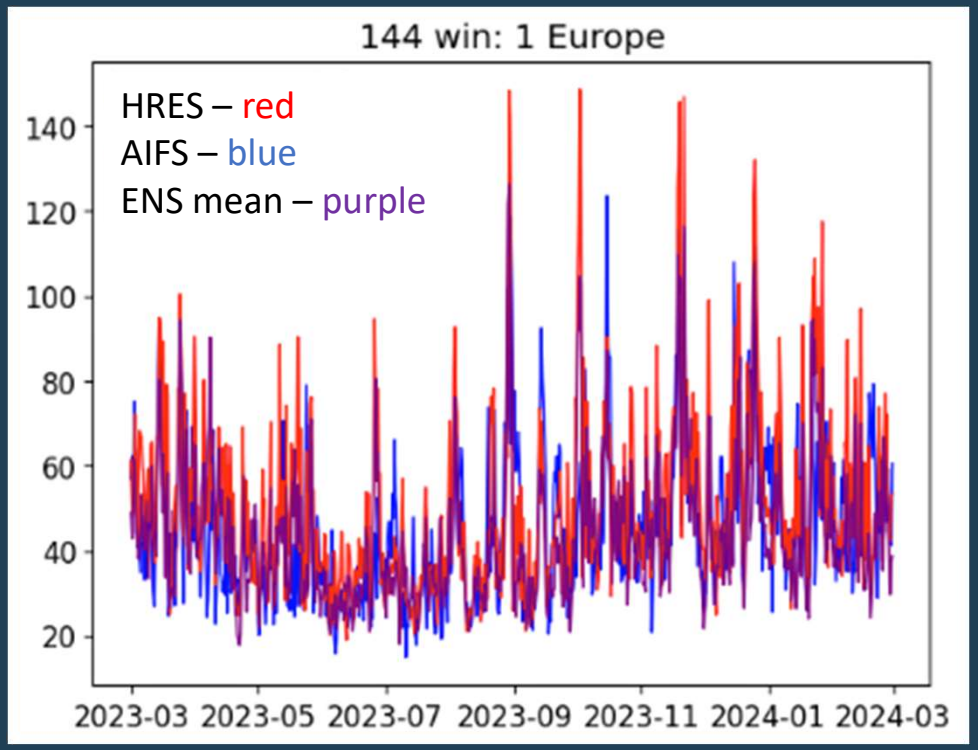
RMSE for 1 March 2023 – 1 March 2024

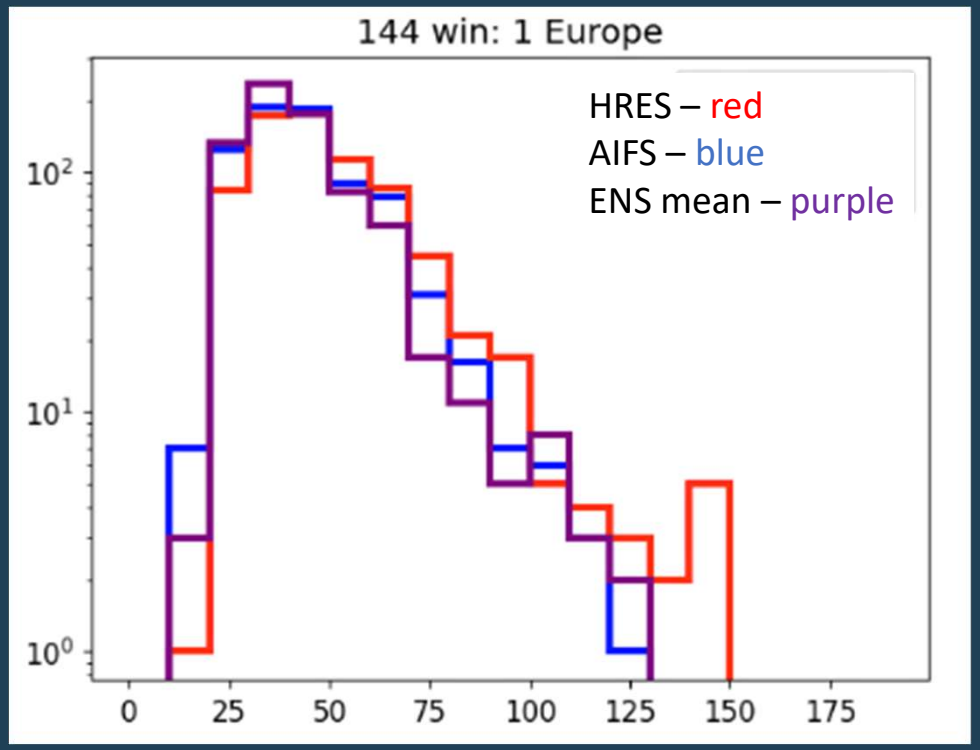


Day 6 RMSE with 30 day running mean



Day-to-day z500 RMSE for Europe

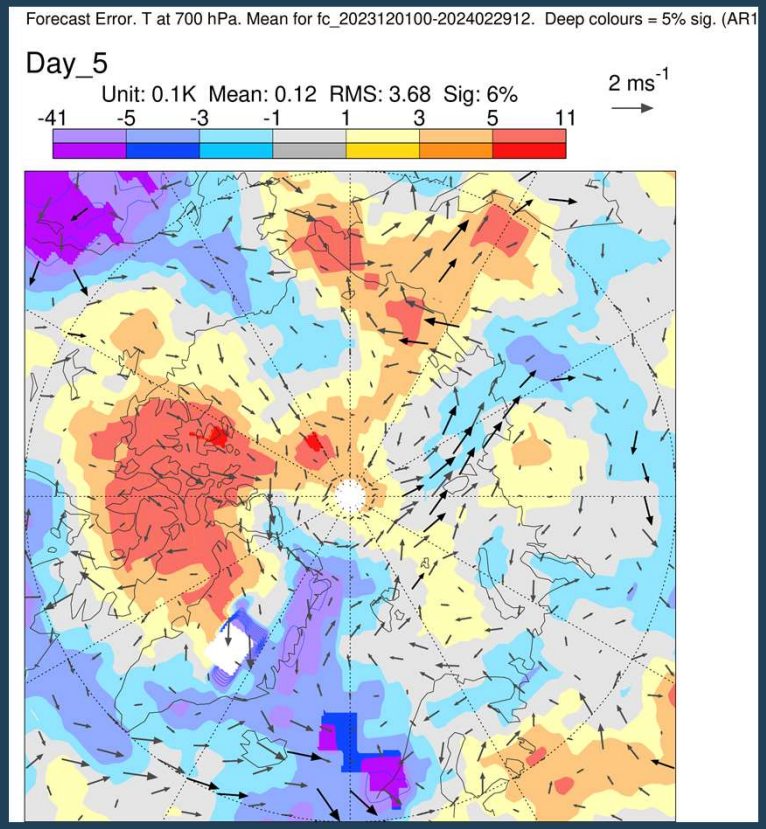




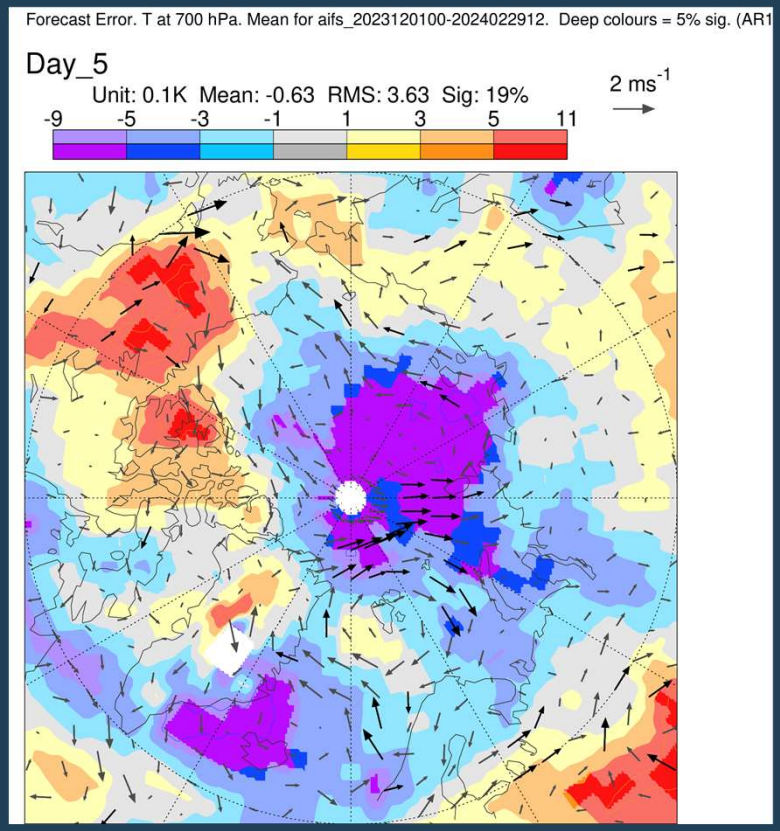
Less forecast busts in AIFS compared to HRES (and also ensemble mean)

700hPa temperature bias DJF 2023/24 over Arctic

IFS



AIFS

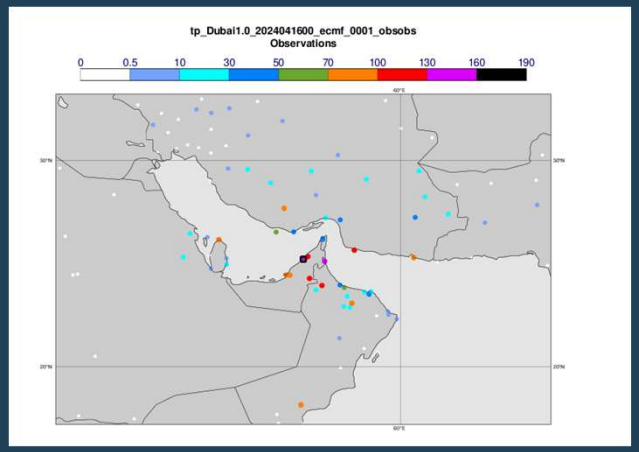


Thanks to Mark Rodwell and Tim Hewson

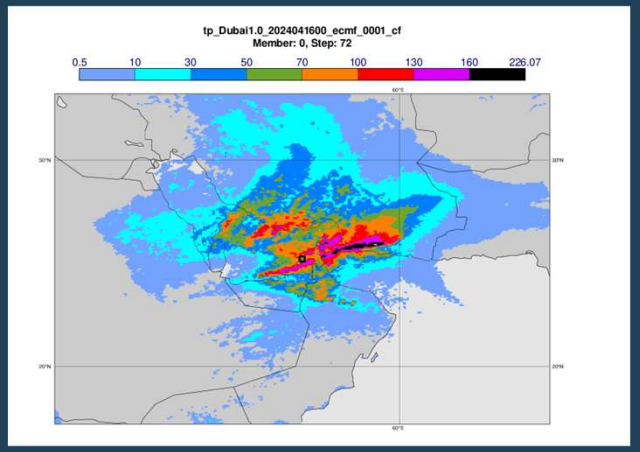
Extreme precipitation in the United Arab Emirates and Oman April 2024

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

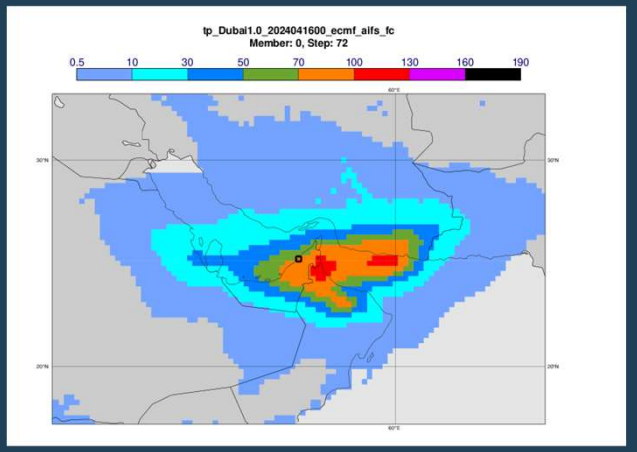
Observations

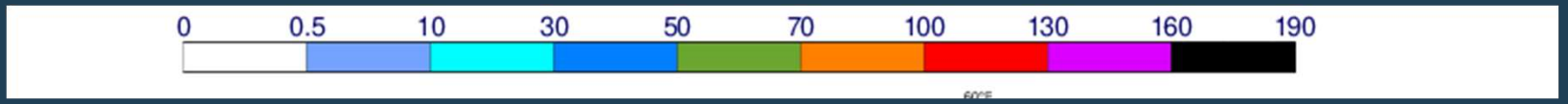


HRES (72-96h)



AIFS (72-96h)

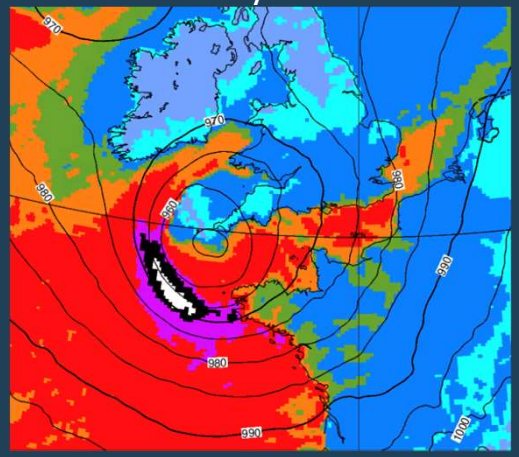




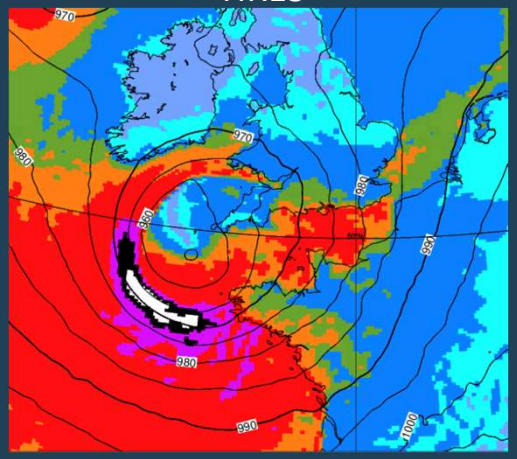
- Smooth precipitation field from AIFS (do not capture local structures)
- AIFS predicted very extreme values for this region

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

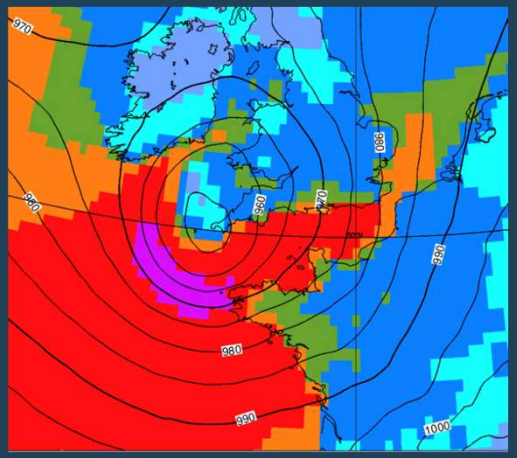
Analysis



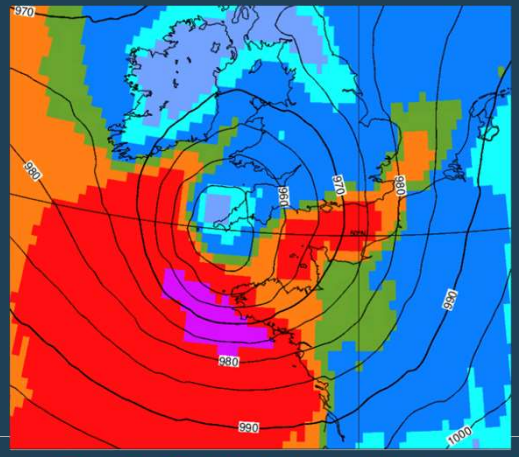
HRES



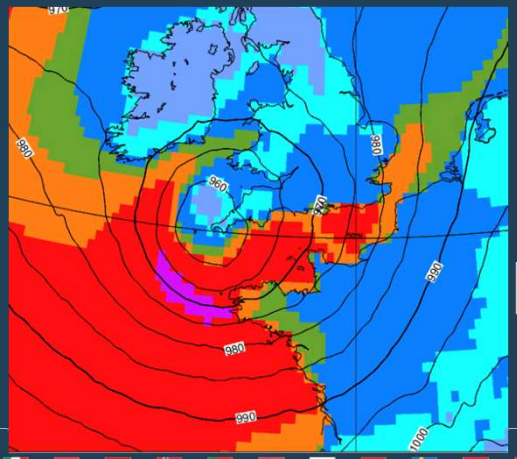
AIFS



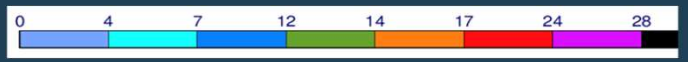
PanguWeather



Graphcast

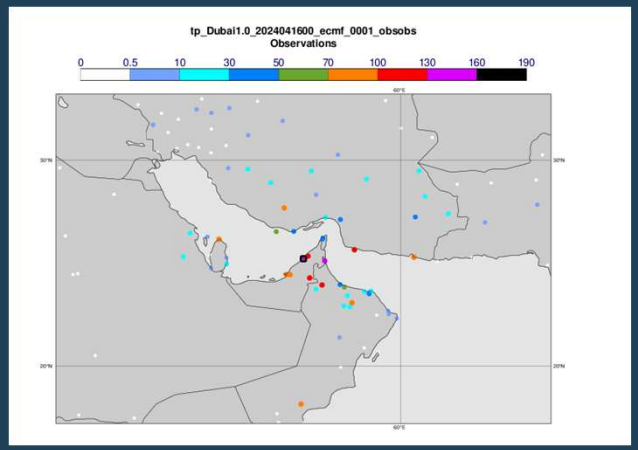


- Better position forecast in the ML models
- Similar minimum pressure 960-965hPa
- Less extreme wind speed in ML models

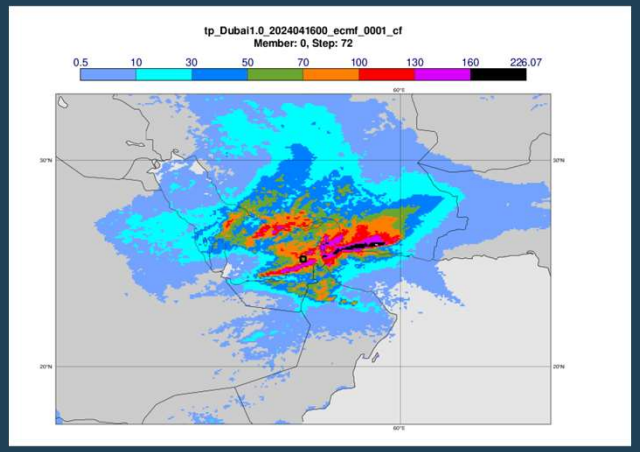


Extreme precipitation in the United Arab Emirates and Oman April 2024

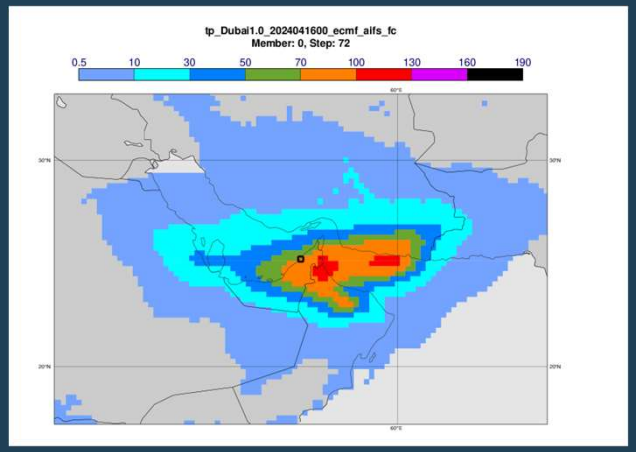
Observations

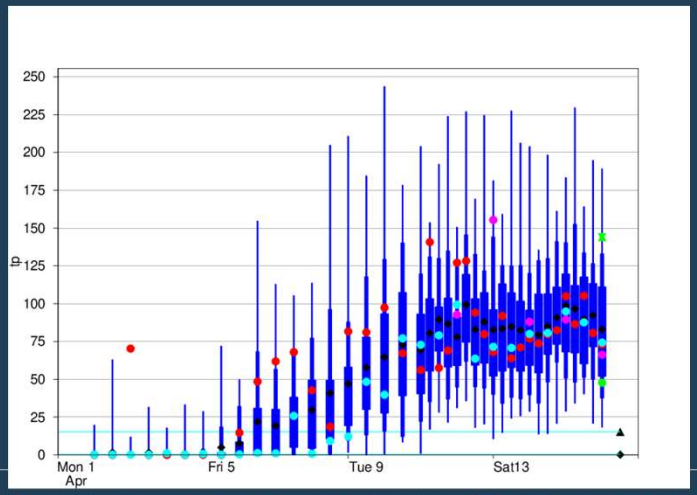


HRES



AIFS





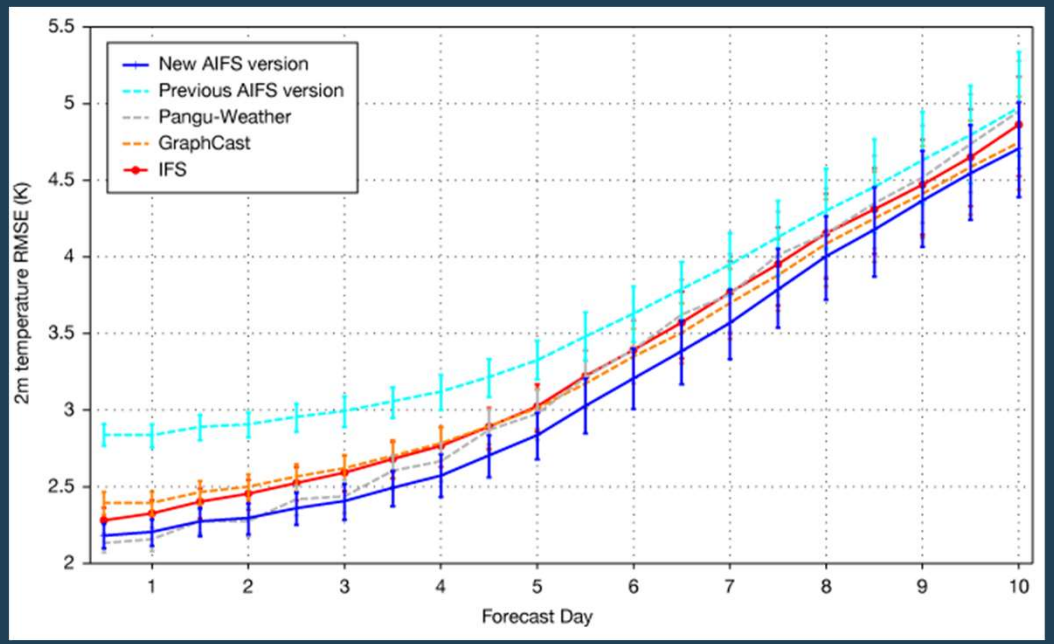
Observation - green hourglass
Analysis - green dot
ENS control–red
DestinE4.4km - purple dot
ENS - blue box-and-whisker
AIFS - pcyan dot

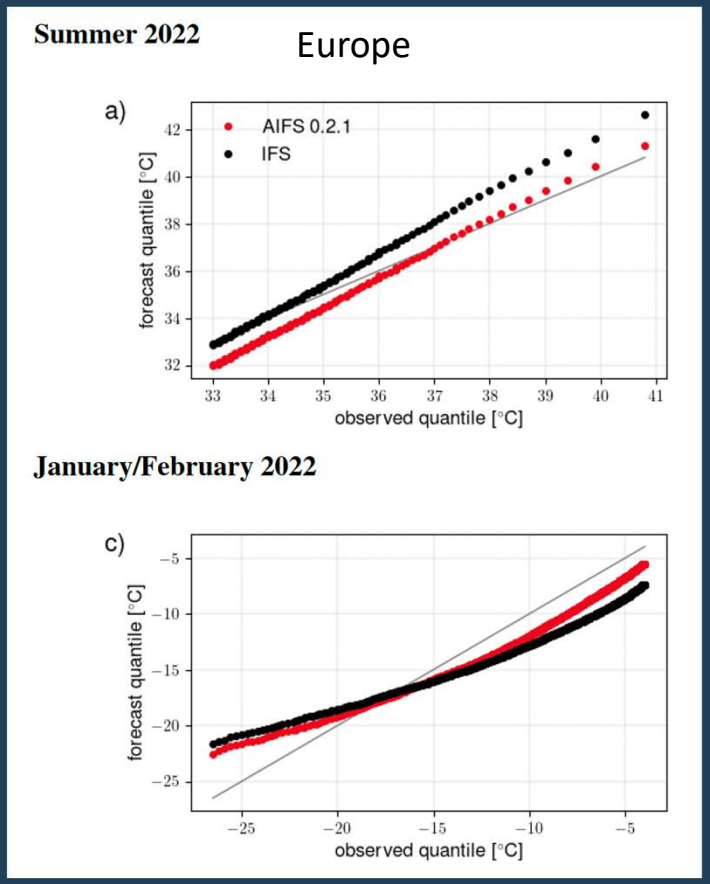
Model climate – cyan box-and-whisker

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

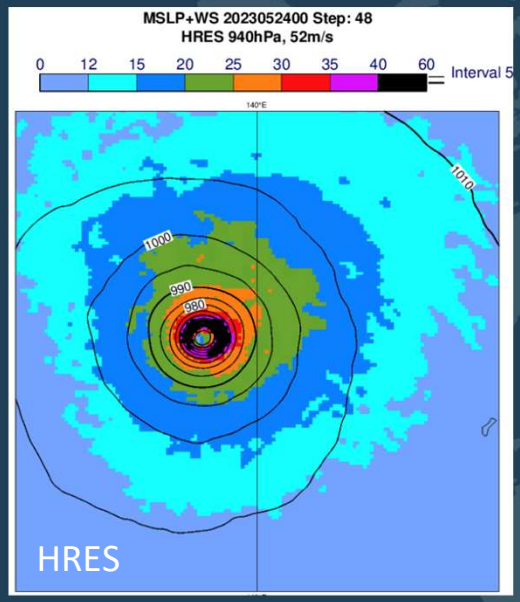
Root-mean-square errors for 2-metre temperature over N.Hem (against observations)

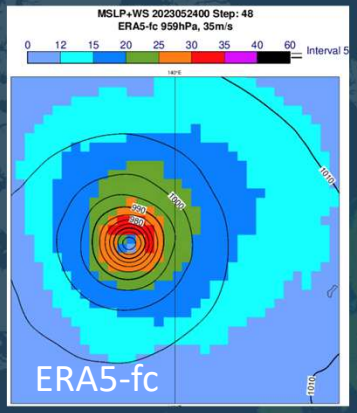
Thanks to Zied

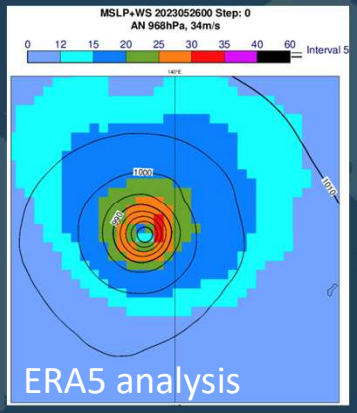


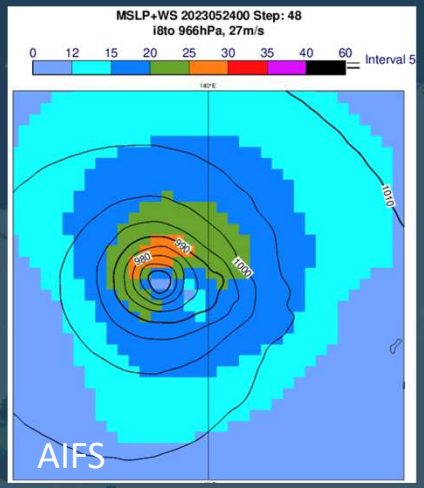


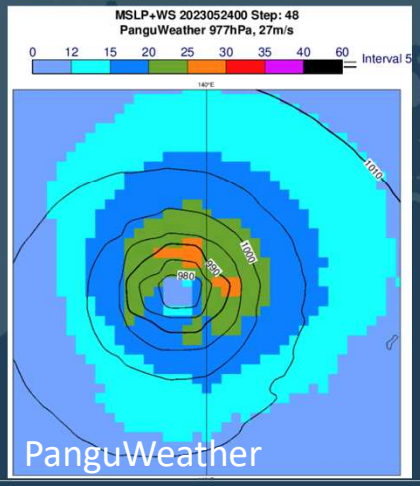
What the forecasts are showing: **Tropical cyclone MAWAR (26 May 2023 00UTC)**

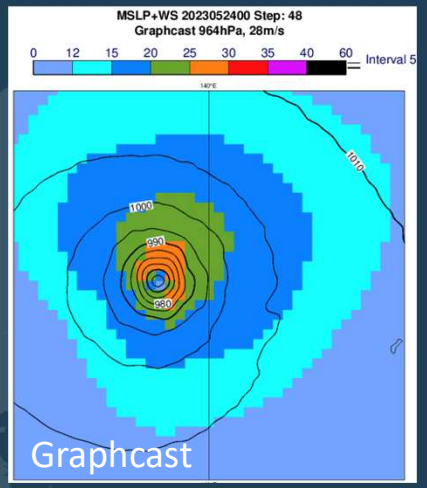


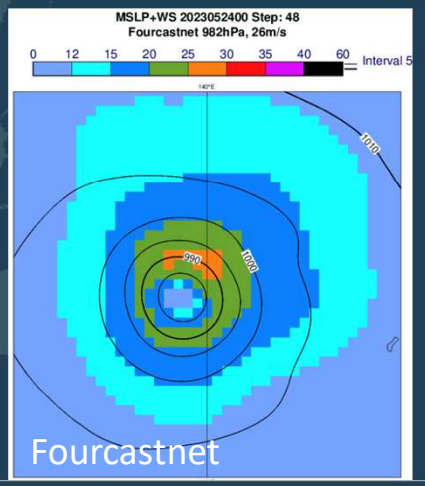




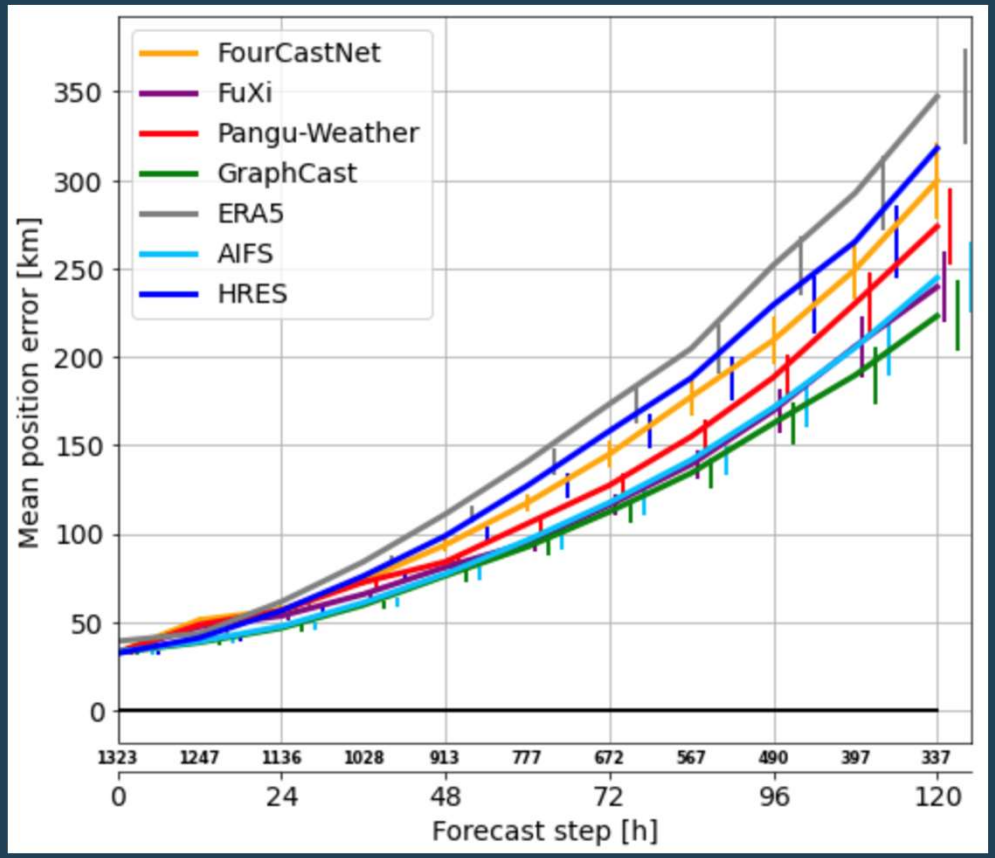








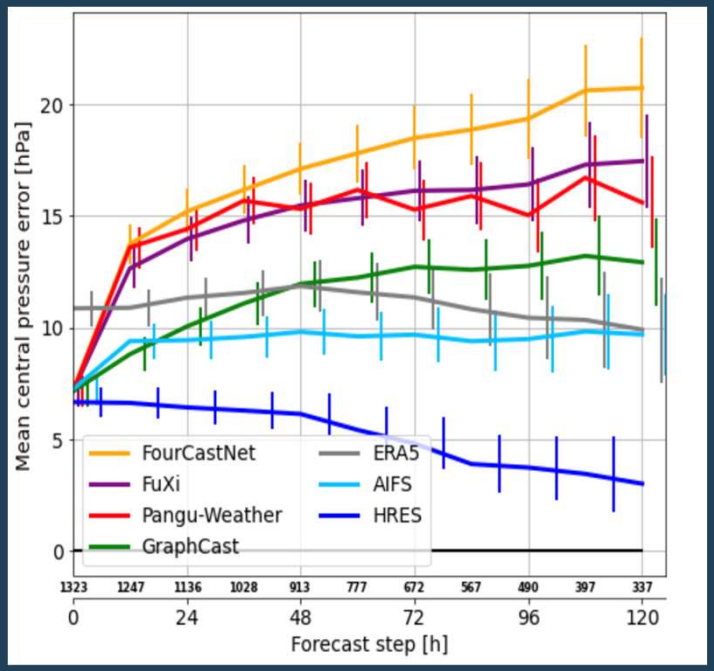
Tropical Cyclone track error (2022-2023)



Thanks to Michael Meier-Gerber

Tropical cyclone intensity (central pressure)

Bias



Mean abs. error