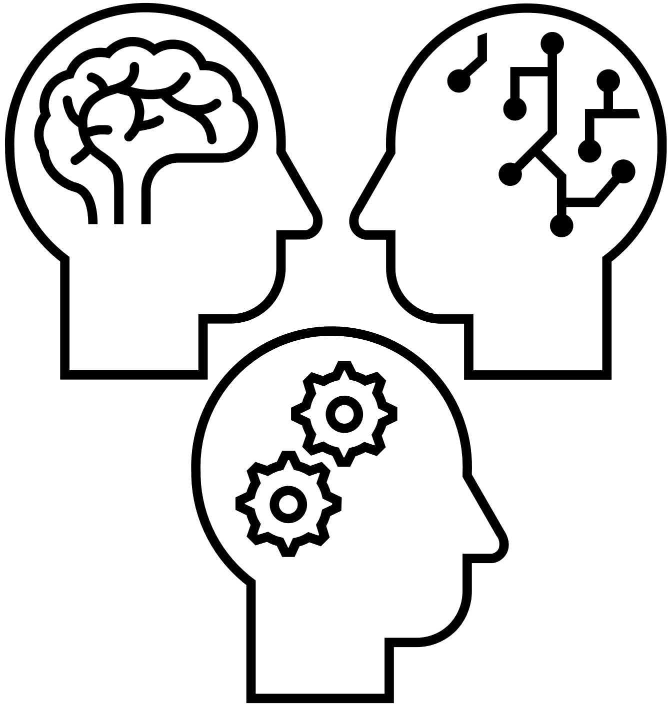
Machine Learning in NWP: Forecast evaluation

Linus Magnusson and colleagues at ECMWF



Think back a couple of decades:

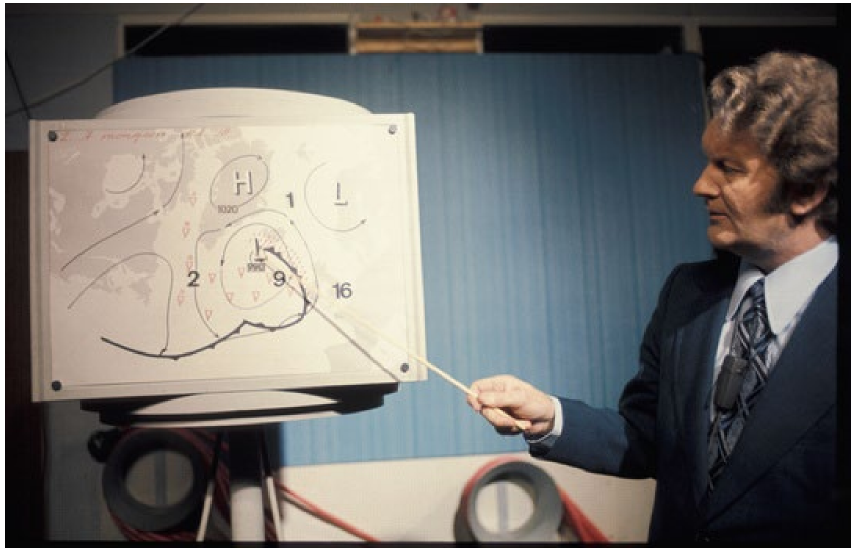
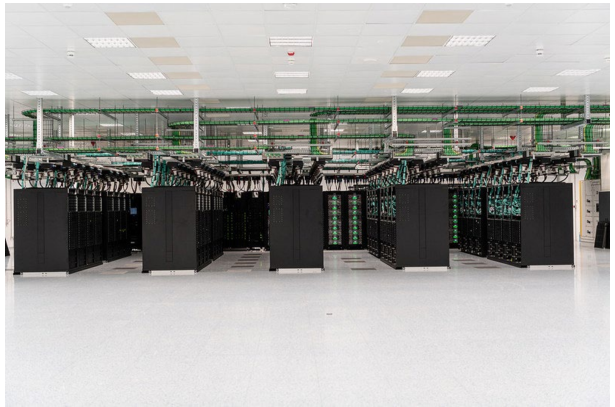
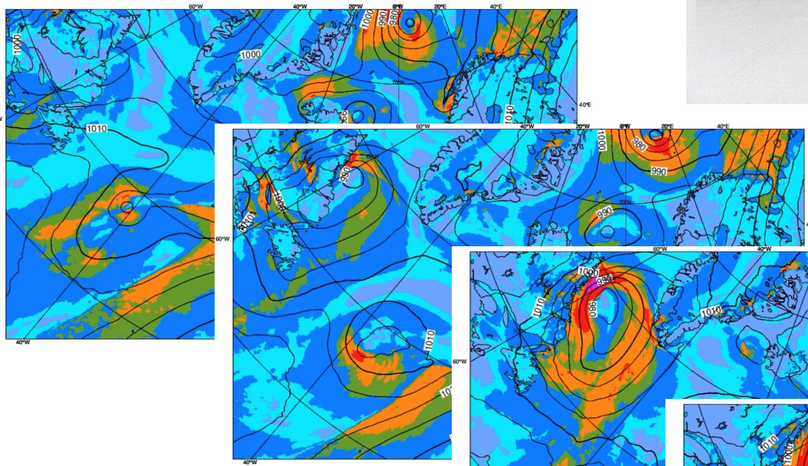
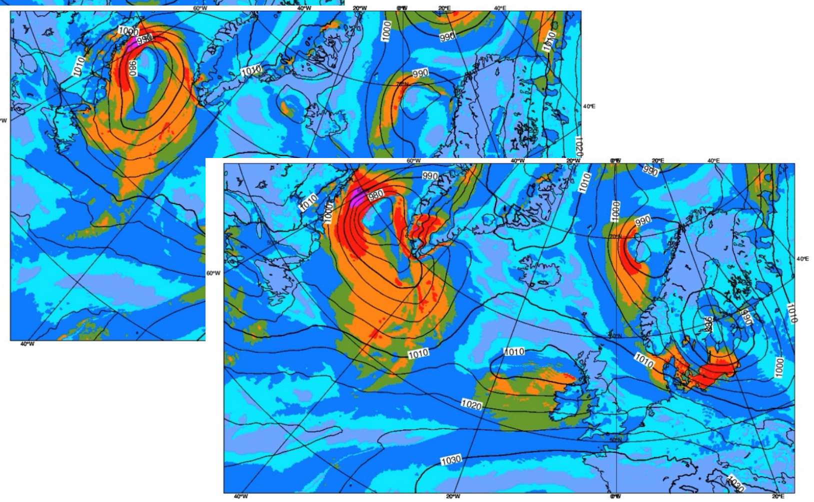


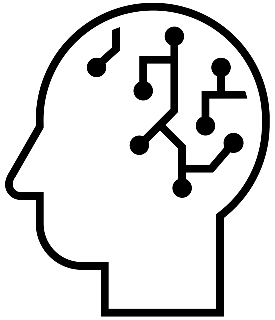
Photo credits: Icelandic Met service

With 40+ years of reanalysis, what if a computer could make forecasts based on the past experiences?









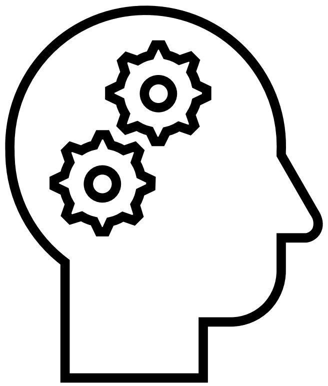
And what we are used to now:

$$\frac{D\mathbf{V}}{Dt} + f\mathbf{k}\times\mathbf{V} = -\nabla\Phi$$

$$\frac{\partial\Phi}{\partial p} = -\alpha = -\frac{RT}{p}$$

$$\nabla\cdot\mathbf{V} + \frac{\partial\omega}{\partial p} = 0$$

$$\left(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right)T - S_p\omega = \frac{J}{c_p}$$



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SUBROUTINE CALLPAR(YDGEOMETRY,YDVARS,YDSURF,YDMODEL,KDIM,&
 !---------------------------------------------------------------------------
 & PAUX, PRAD, FLUX, PDIAG, PSURF, PCGPP, PCREC, PAG, PRECO, PDDHS, AUXL, SURFL, LLKEYS, PERTL, &
 ! - Model variables (t)
 & PGFL,&
 & PPERT, PSLPHY9,&
 ! - UPDATED TENDENCY
 & PTENGFL,&
 & PHYS_MWAVE,&
 ! Stored quantities
 & PSAVTEND, PGFLSLP,&
 & STATE_T0, TENDENCY_DYN, TENDENCY_CML, STATE_TMP, TENDENCY_TMP,&
 & TENDENCY_VDF, TENDENCY_SATADJ, TENDENCY_LOC, TENDENCY_PHY&
 & )

!**** *CALLPAR * - CALL ECMWF PHYSICS

!     PURPOSE.
!     --------
!     - CALL THE SUBROUTINES OF THE E.C.M.W.F. PHYSICS PACKAGE.

!     *********************************************************************
!     ****** IDIOSYNCRASIES *** IDIOSYNCRASIES *** IDIOSYNC
!     *********************************************************************
!     *** HEALTH WARNING:
!     *** ===============
!     *** NOTE THAT WITHIN THE E.C.M.W.F. PHYSICS HALF-LE
!     *** ARE INDEXED FROM 1 TO NFLEVG+1 WHILE THEY ARE B
!     *** 0 AND NFLEVG IN THE REST OF THE MODEL. THE CHAN
!     *** CARE OF IN THE CALL TO THE VARIOUS SUBROUTINES
!     *** PHYSICS PACKAGE
!     ***
!     ***   THIS IS SUPPOSED TO BE A "TEMPORARY" FEATURE
!     ***   STRAIGHTENED OUT IN THE "NEAR" FUTURE
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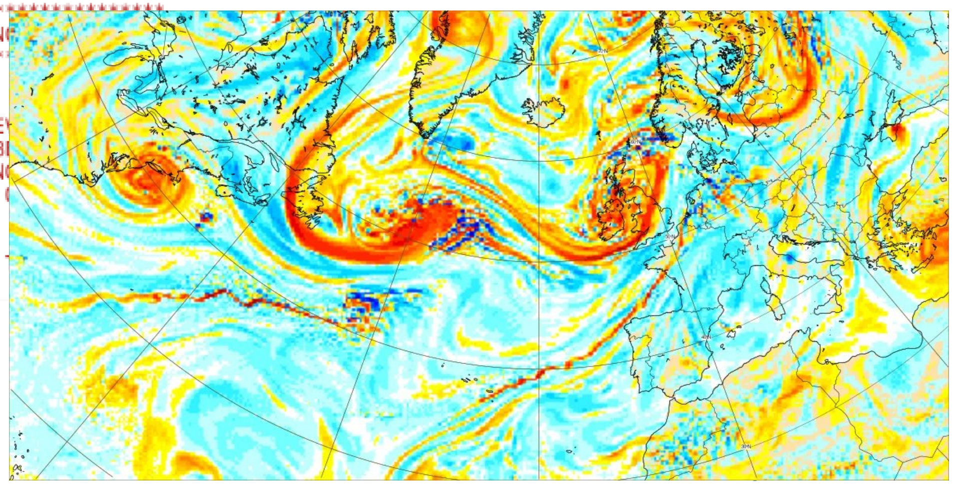


Physics-based forecast systems using IFS model

Medium-range

- Atmosphere: 9 km
- 15 days lead time
- 50 ensemble members + 1 unperturbed control forecasts
- Distributed around 8 hours after initialisation time*

Sub-seasonal

- Atmosphere: 36 km
- 6 weeks lead time
- 101 ensemble members
- Initialised every day at 00UTC
- Distributed in the evening (UTC time)

Seasonal (SEAS5)

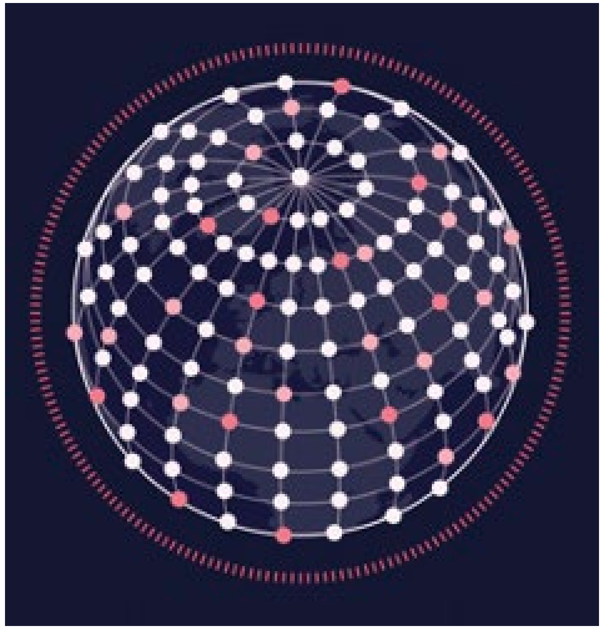
- Atmosphere: 36 km
- 7 months lead time
- 51 ensemble members
- Initialised 1st every month
- Distributed 5th every month

* In the assimilation system, it has used observations +3h after the labelled initialisation time

Machine-learning based forecast systems using AIFS model

Medium-range deterministic AIFS-single v1.1

- Atmosphere: AIFS Model v1.0 using **MAE loss**, N320 (0.25°, ~25 km)
- 15 days lead time
- Initialised from physics-based analysis



Medium-range ensemble AIFS-ENS v1.0

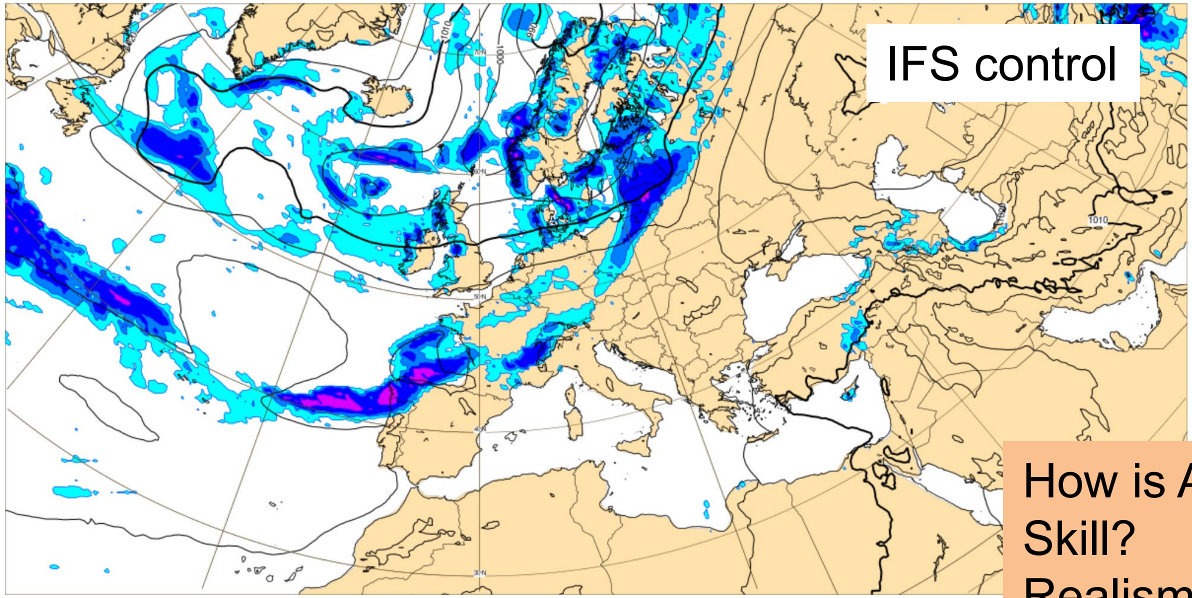
- Atmosphere: AIFS Model v1.0 using **CRPS loss**, N320 (0.25°, ~25 km), 13 vertical levels
- 15 days lead time
- 50 ensemble members + 1 unperturbed** control forecasts
- Same initial conditions including perturbations as physics-based ensemble

* In the assimilation system, it has used observations +3h after the labelled initialisation time
** With the use of CRPS-loss, also the control forecast include the “noise” to simulate model uncertainty

ECMWF

So here are forecast (MSLP and precipitation) from a week ago:

Base time: Wed 10 Sep 2025 00 UTC Valid time: Wed 17 Sep 2025 12 UTC (+180h) Area : Europe Interval (hr) : 6



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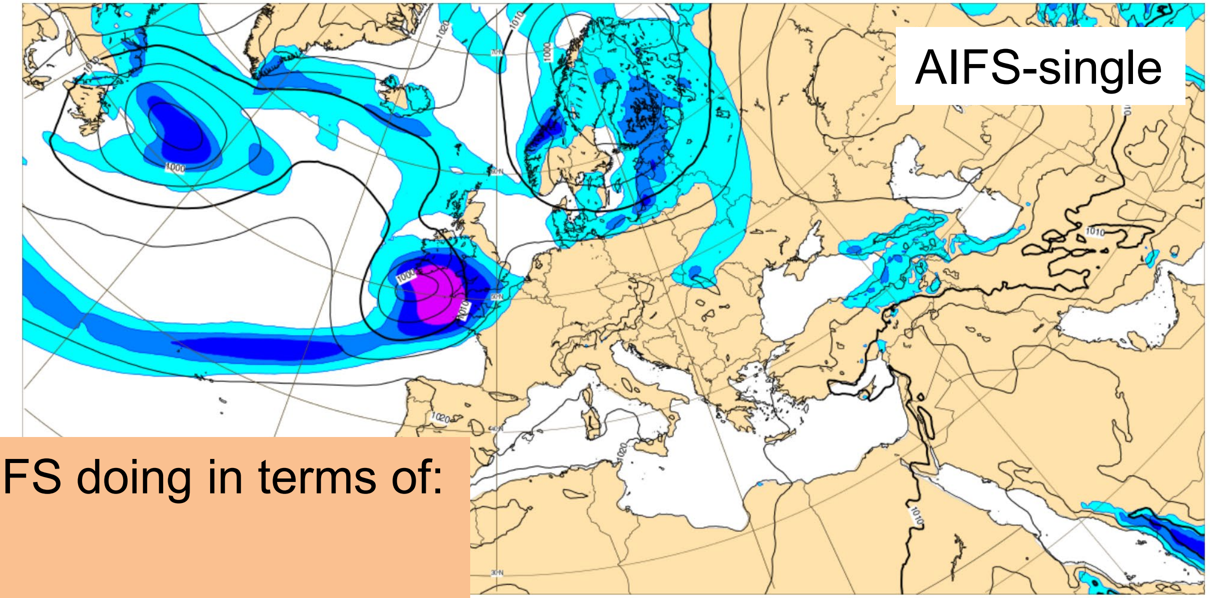
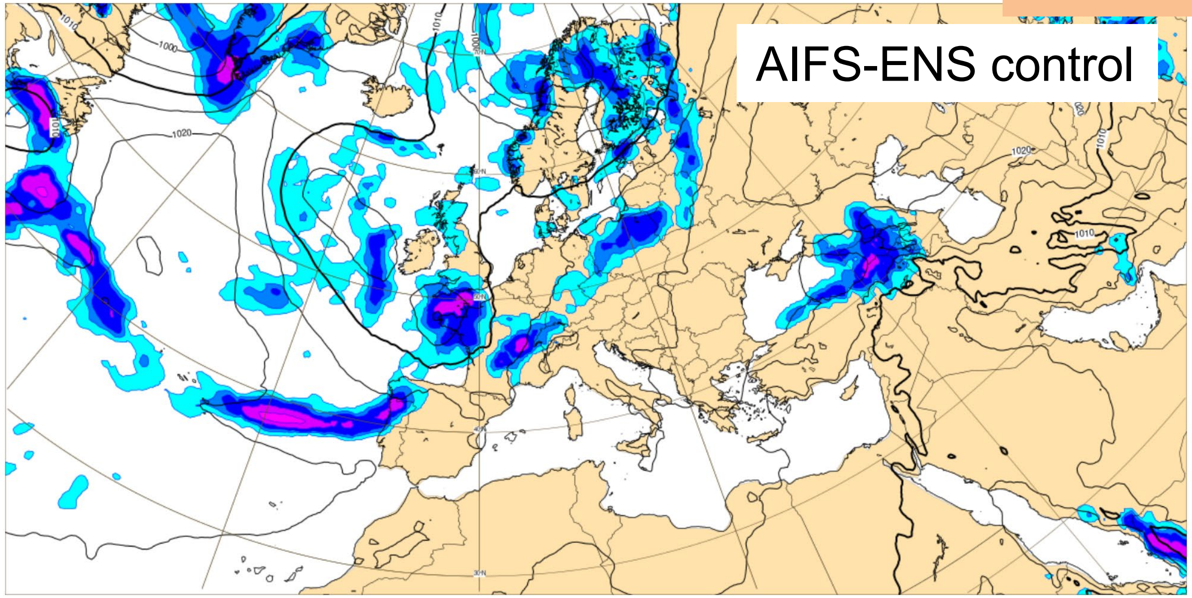
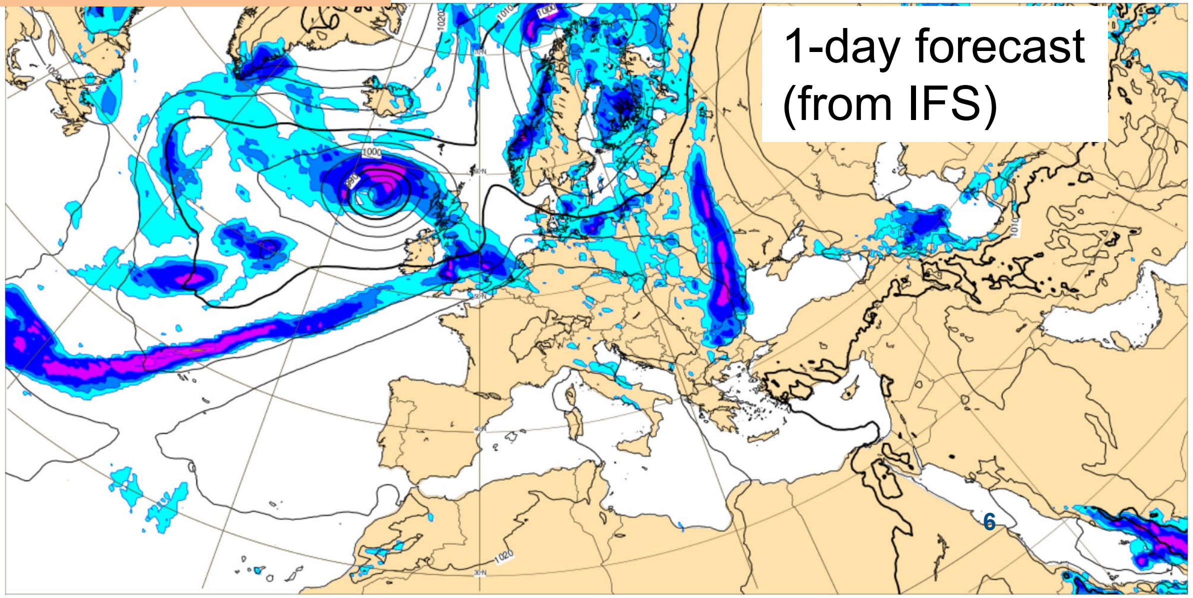


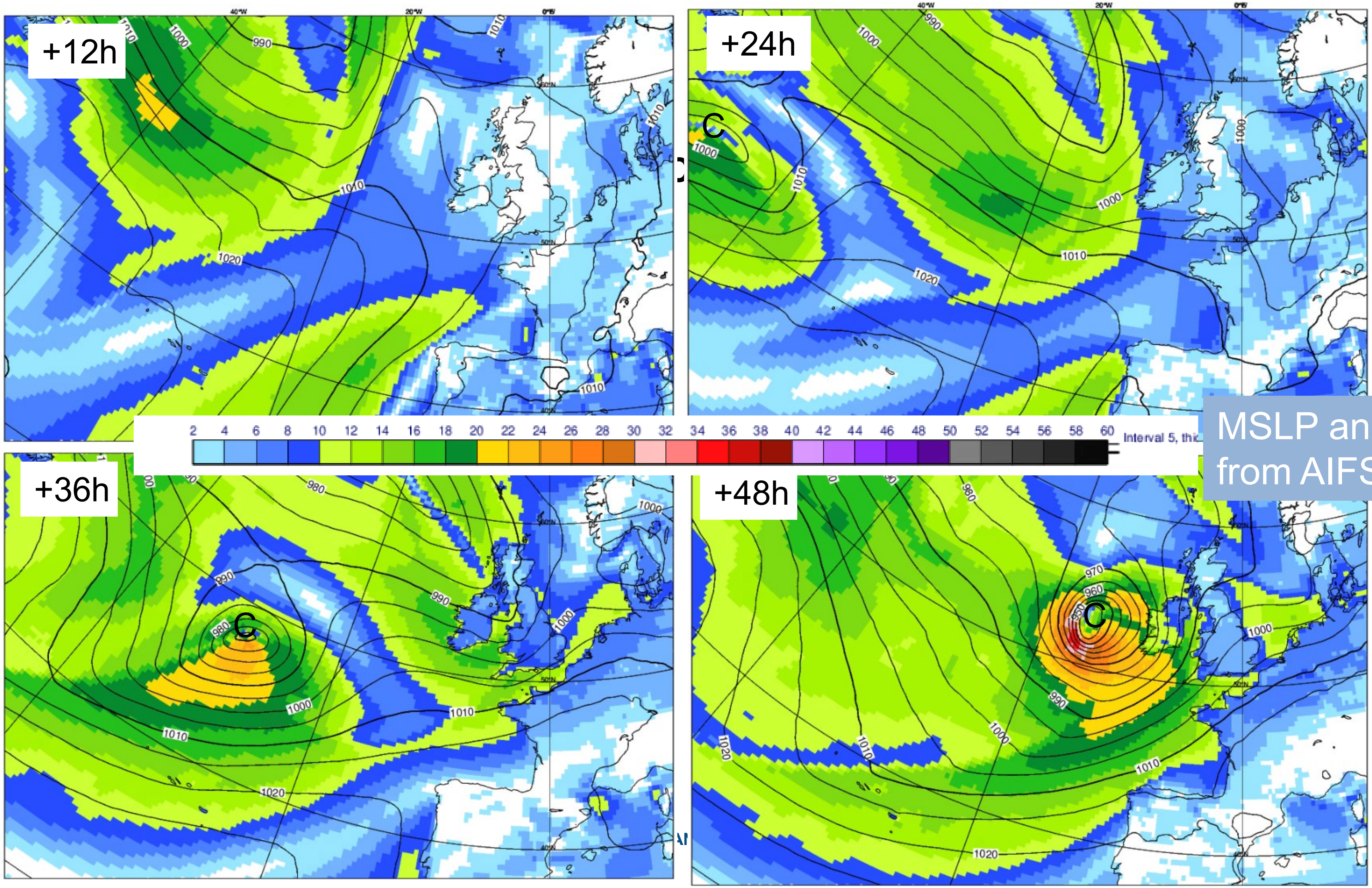
How is AIFS doing in terms of:
Skill?
Realism?
Extremes?

Base time: Wed 10 Sep 2025 00 UTC Valid time: Wed 17 Sep 2025 12 UTC (+180h) Area : Europe Interval (hr) : 6





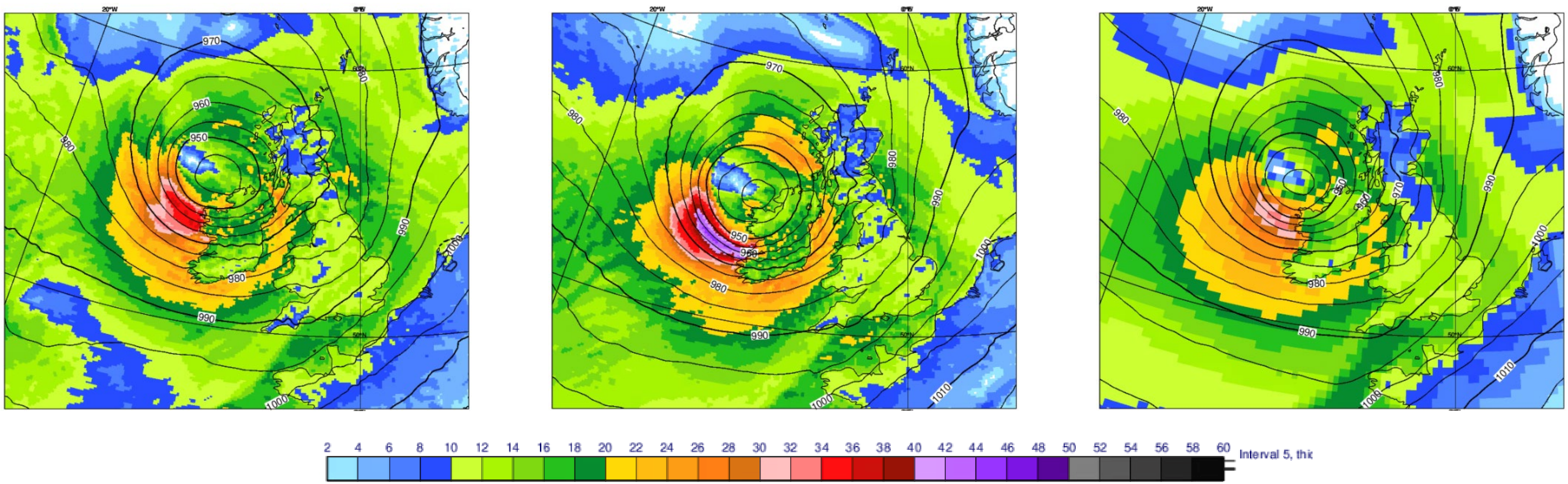
AIFS-single: Storm Eowyn (forecast from 22 Jan 2025 00UTC)



MSLP and wind speed from AIFS model

Storm Eowyn (2-day forecasts valid 24 Jan 2025 06UTC)

Analysis | IFS CF | AIFS-single v1.0

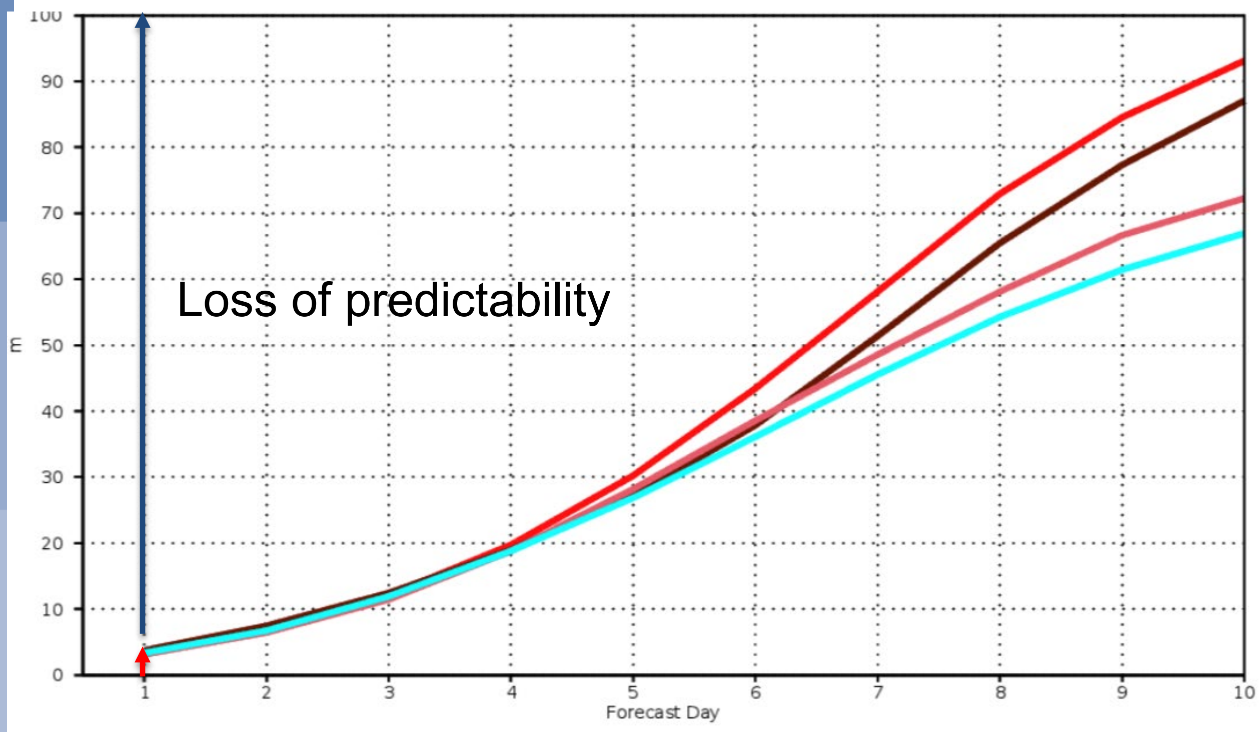


- Better position forecast in of the maximum wind in AIFS
- Similar minimum pressure 935-940hPa
- Less extreme wind speed in ML models 46 m/s vs. 33 m/s

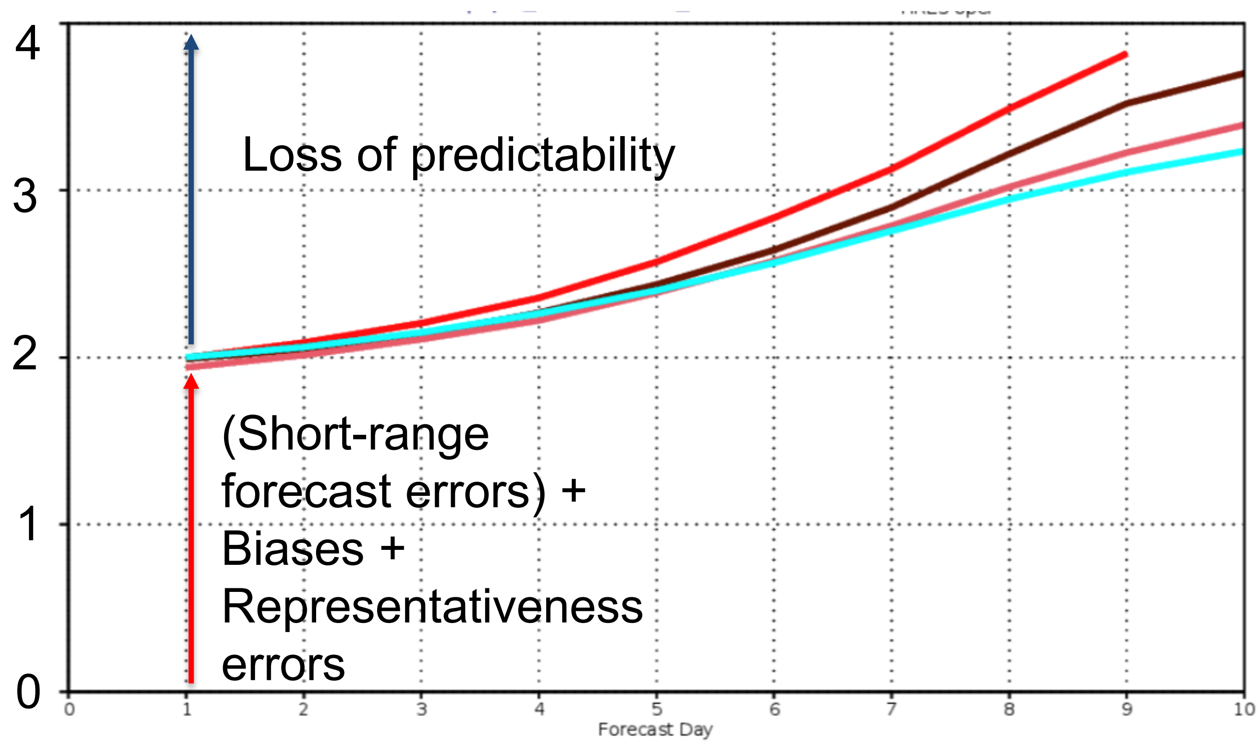
See ECMWF Newsletter 183

RMSE over Europe - 1 July to 1 September

500hPa geopotential height (against analysis)

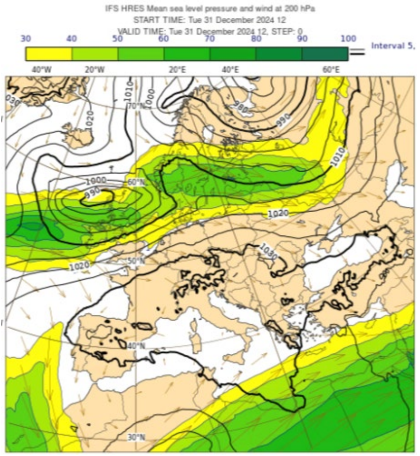


2-metre temperature (against obs)

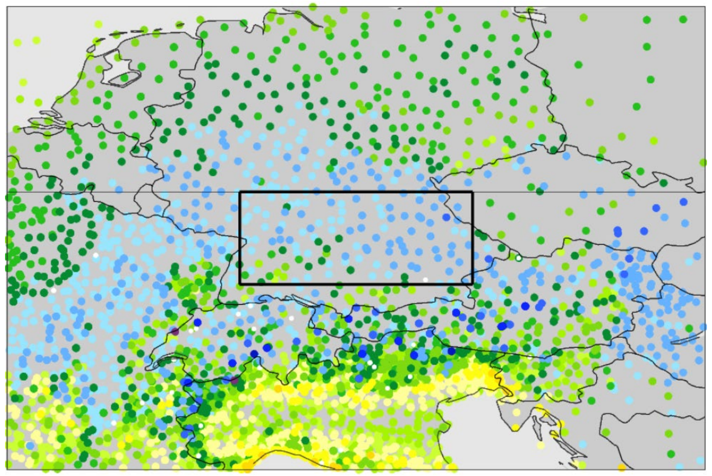


IFS control – red
AIFS-single - brown
IFS-ENS ensemble mean - pink
AIFS-ENS ensemble mean - cyan

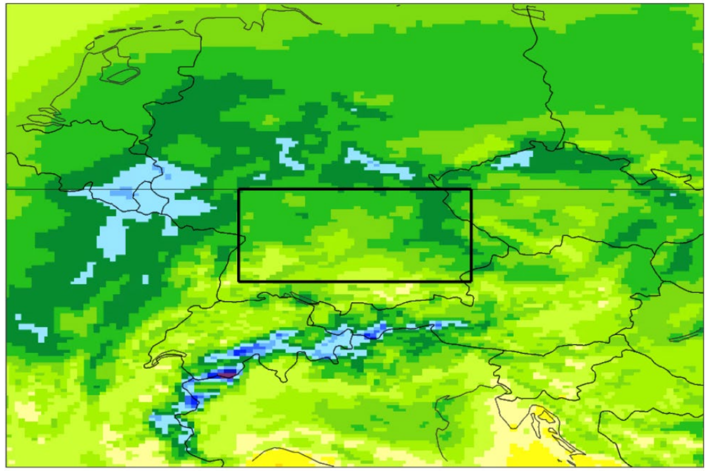
Conditional systematic errors:
Example valid 31 December 12UTC: 2-metre temperature



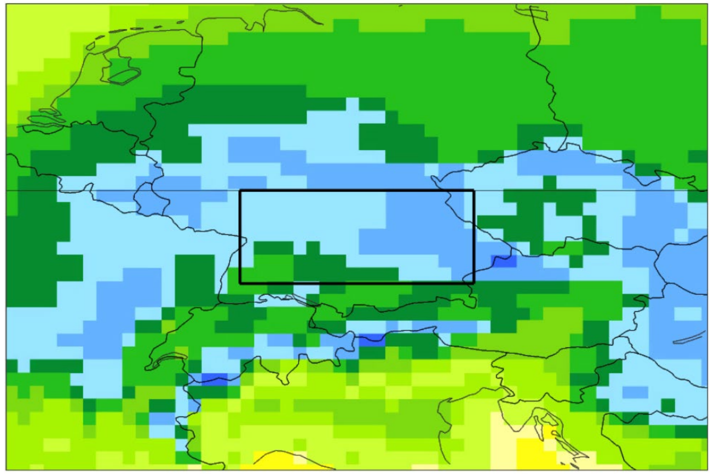
Observations



48-hour IFS Control



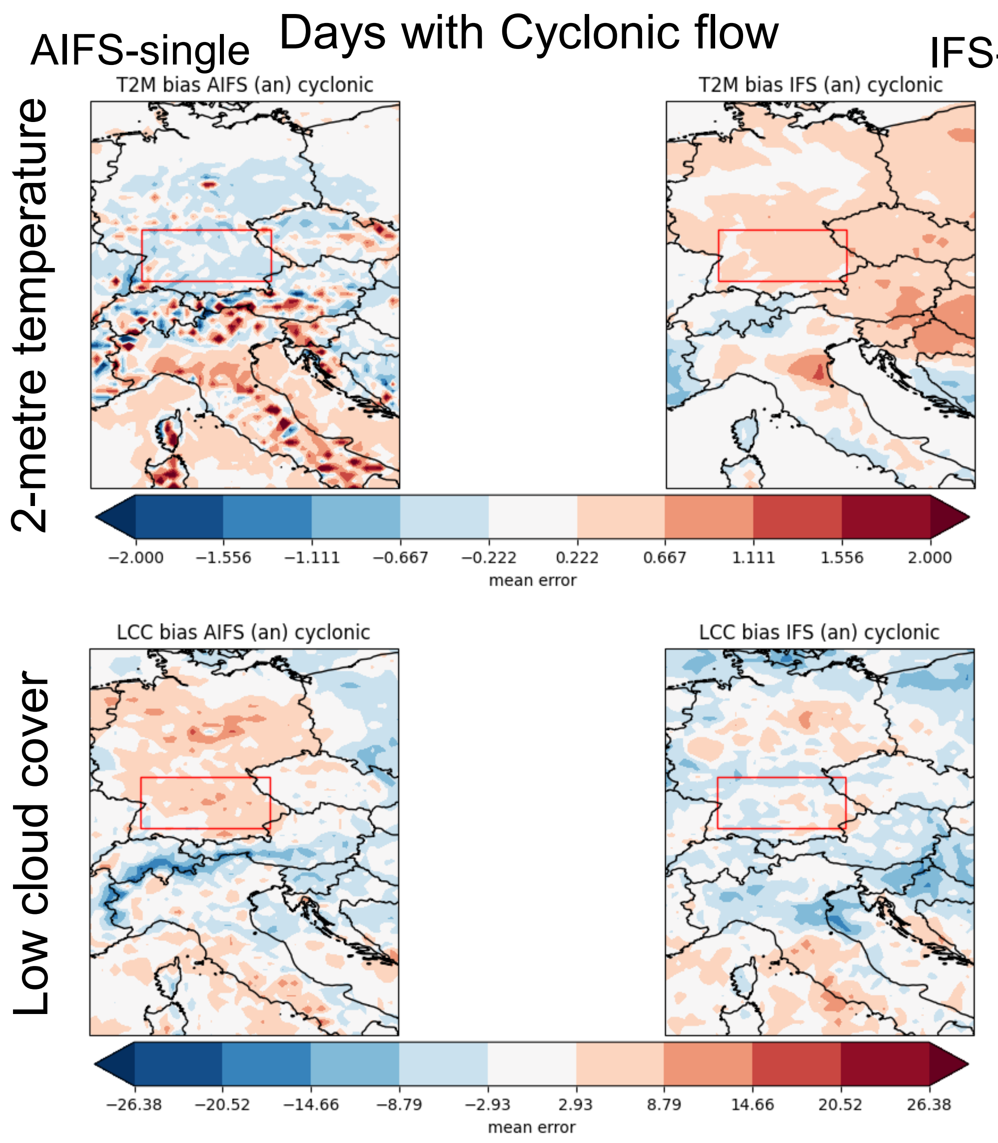
48-hour AIFS-single



Karmouche et al. (2025):
AIFS blog: https://www.ecmwf.int/en/about/media-centre/aifs-blog/2025/verifying-2-m-temperature-forecasts-wintertime-anticyclonic

Conditional verification based on flow pattern, Winter 2024/2025

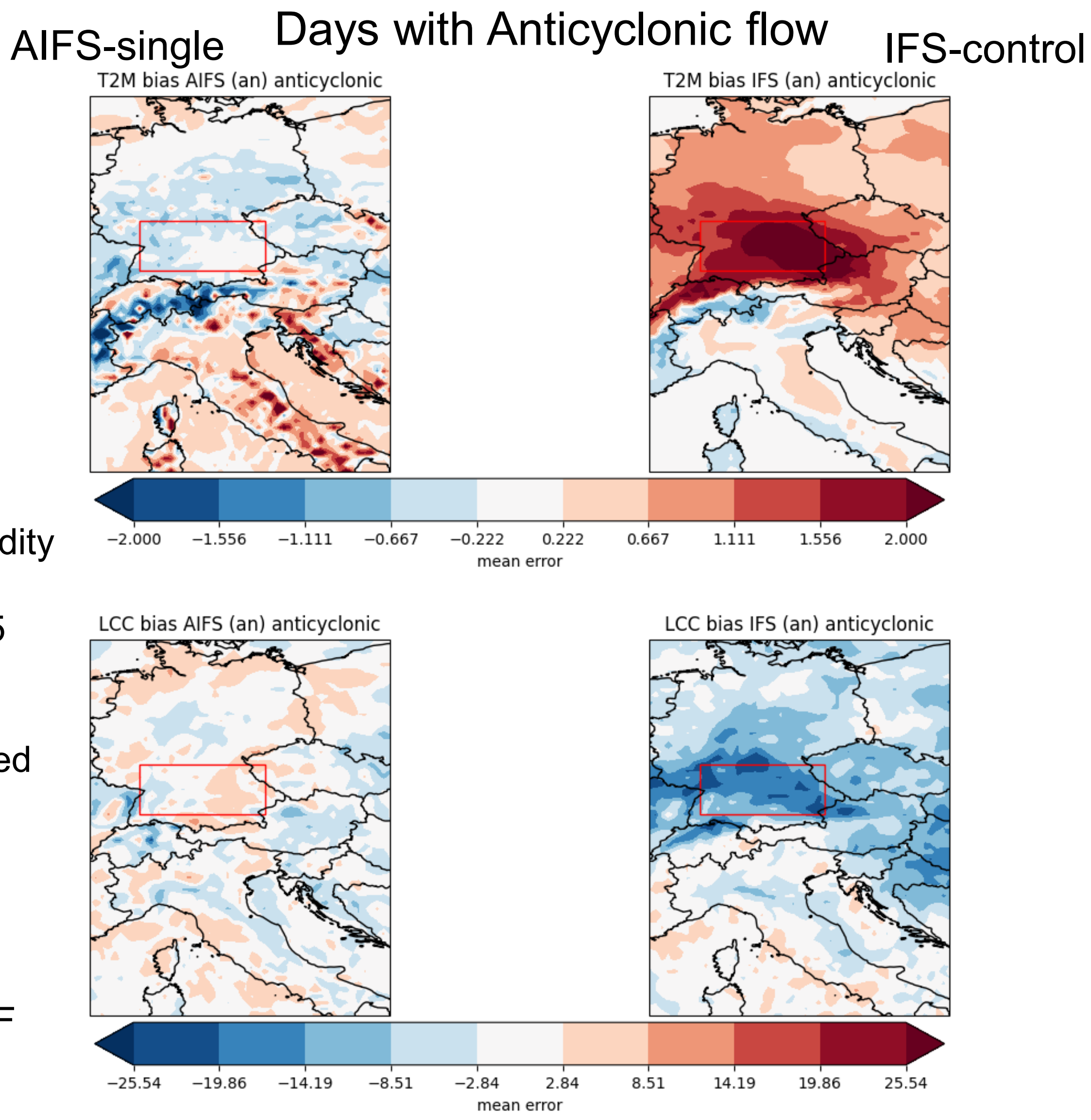
(verified against ECMWF analysis)



Bias, step +36h, validity dates (2024-10-02 12UTC - 2025-02-25 12UTC)

Flow conditions based on CURV index developed by Nigel Roberts, ECMWF

Thanks to Soufiane Karmouche, ECMWF

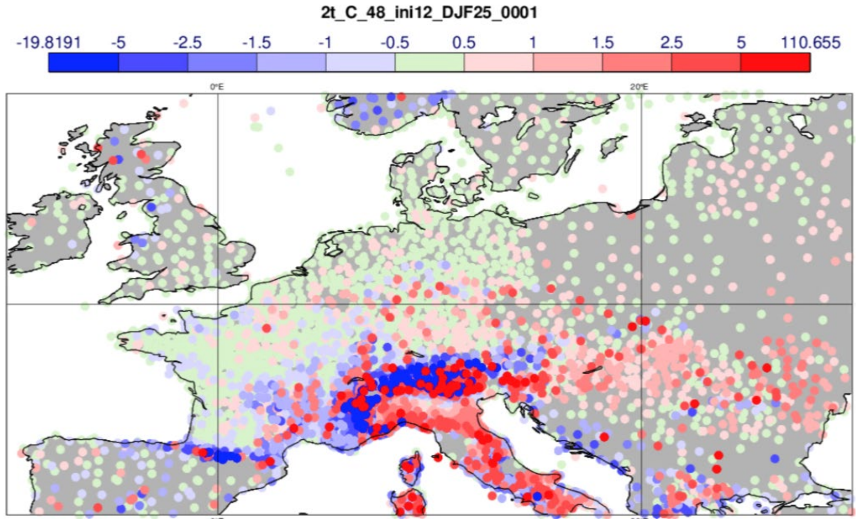


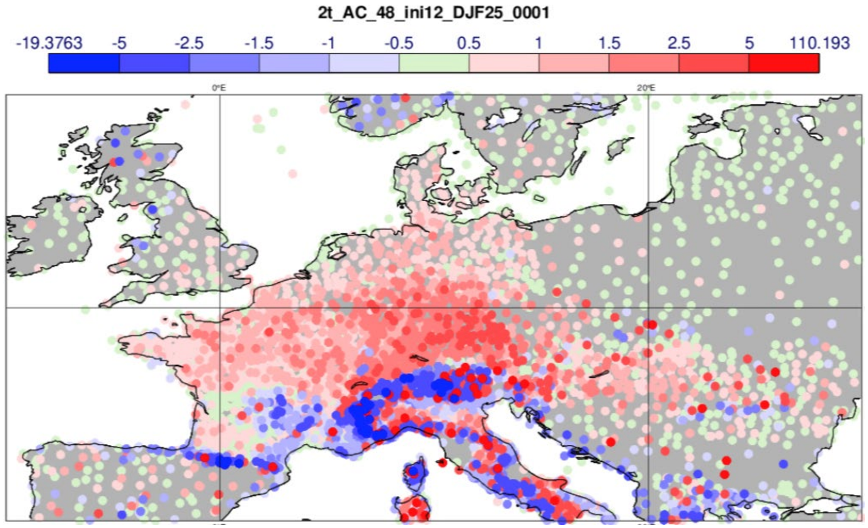
IFS Bias based on SYNOP observations winter 2024/25 (12UTC + 48h)

Cyclonic

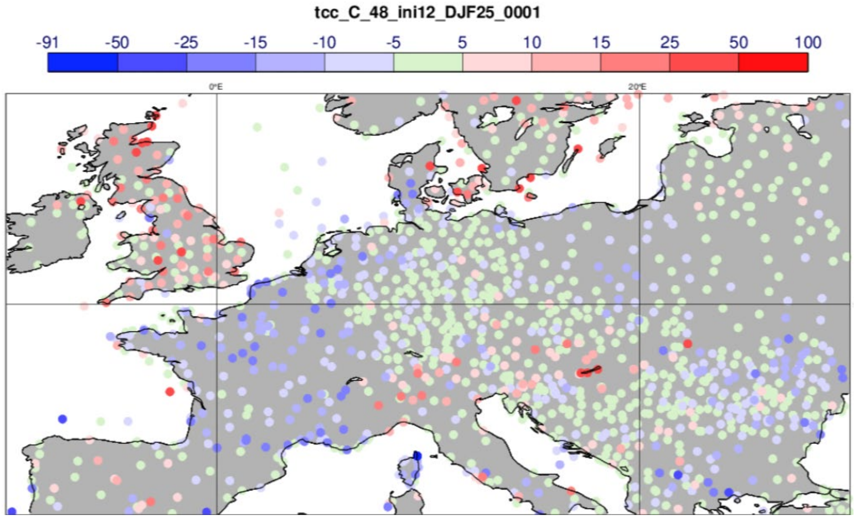
Anticyclonic

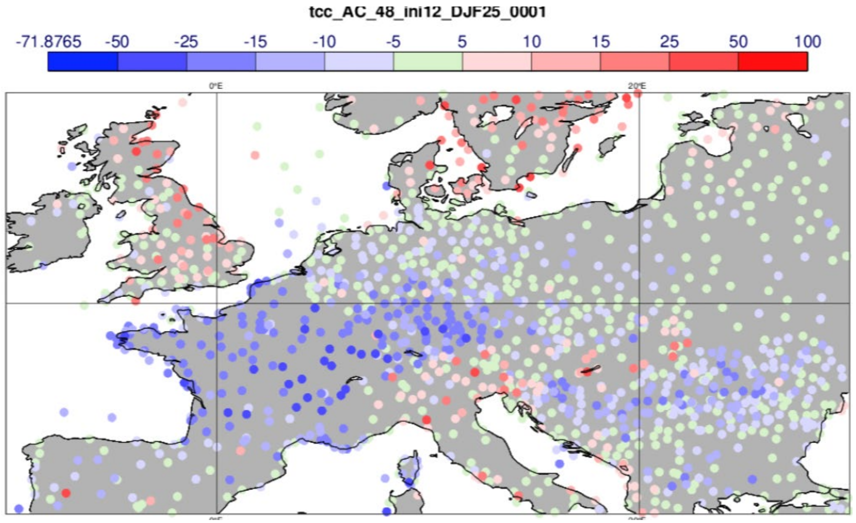
2-metre temperature

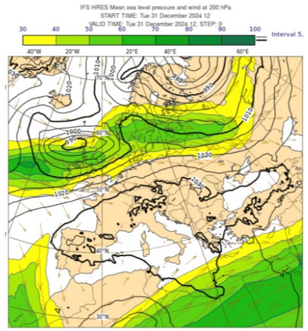
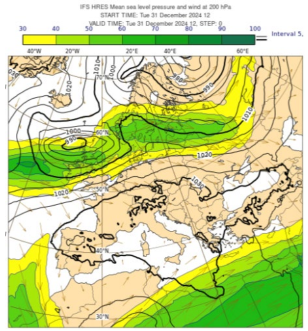
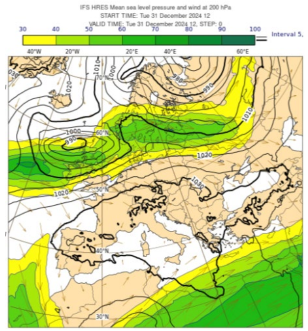


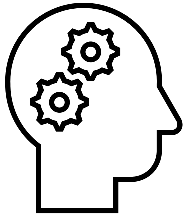
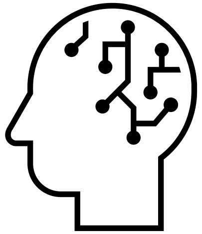


Total cloud cover

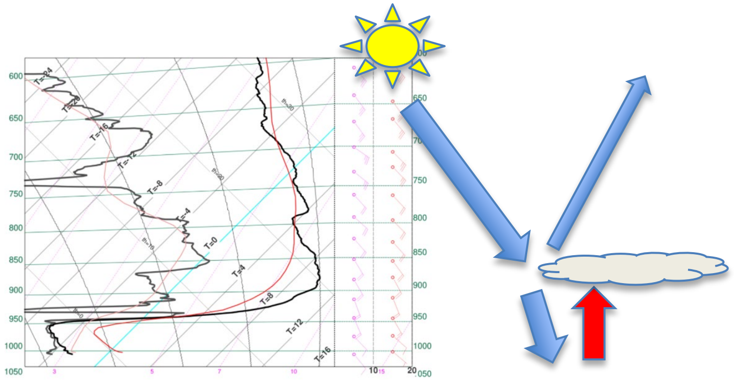
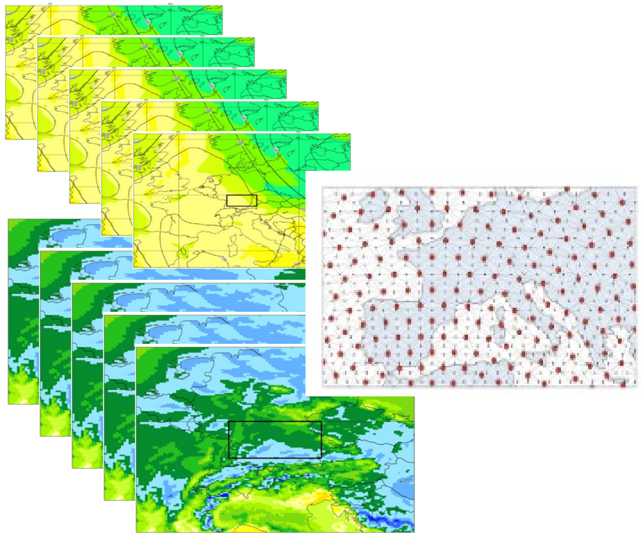
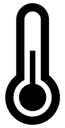
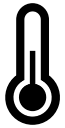


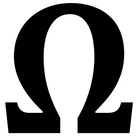


Ω + winter

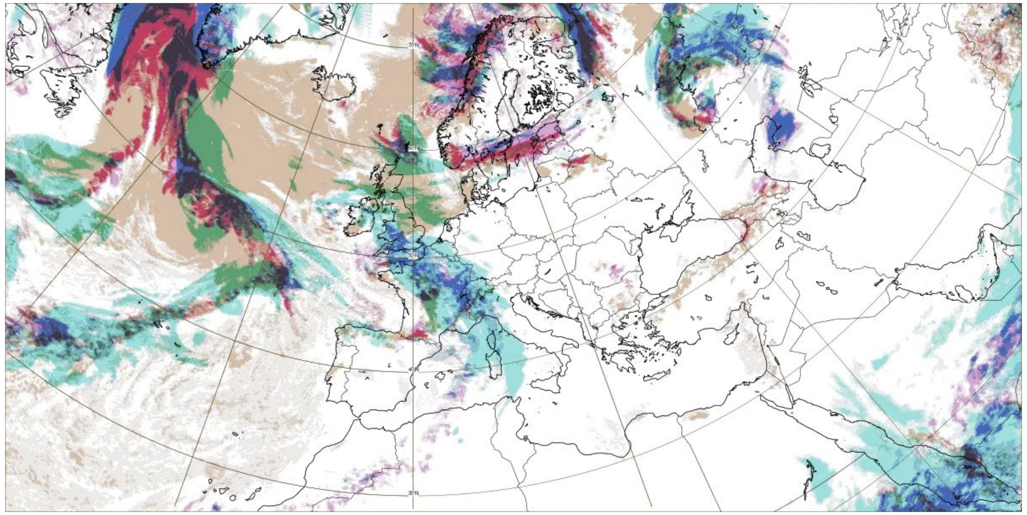


But not everything is perfect (yet) in the AI model world…

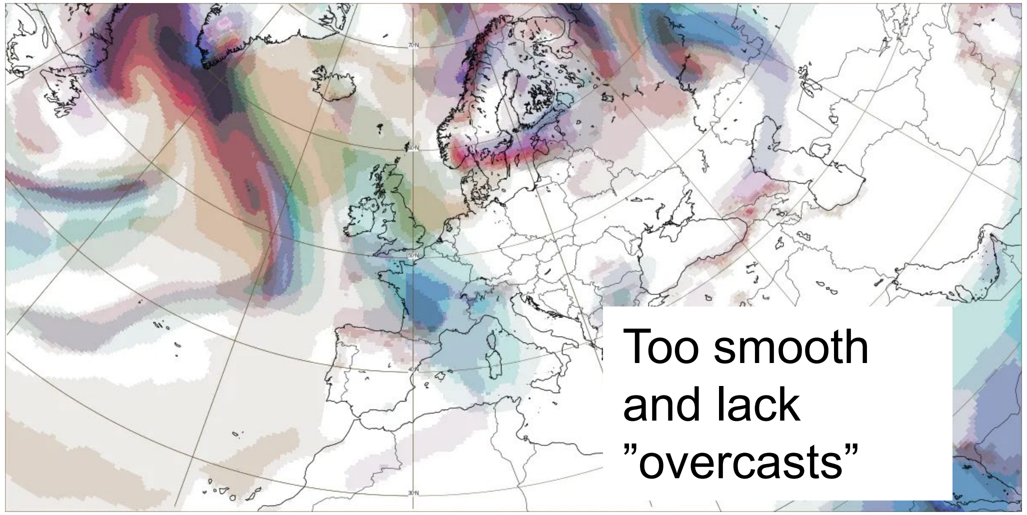
Remember that AIFS is still a very new model…

Example of cloud forecasts, 14 August 2025 00UTC+144h

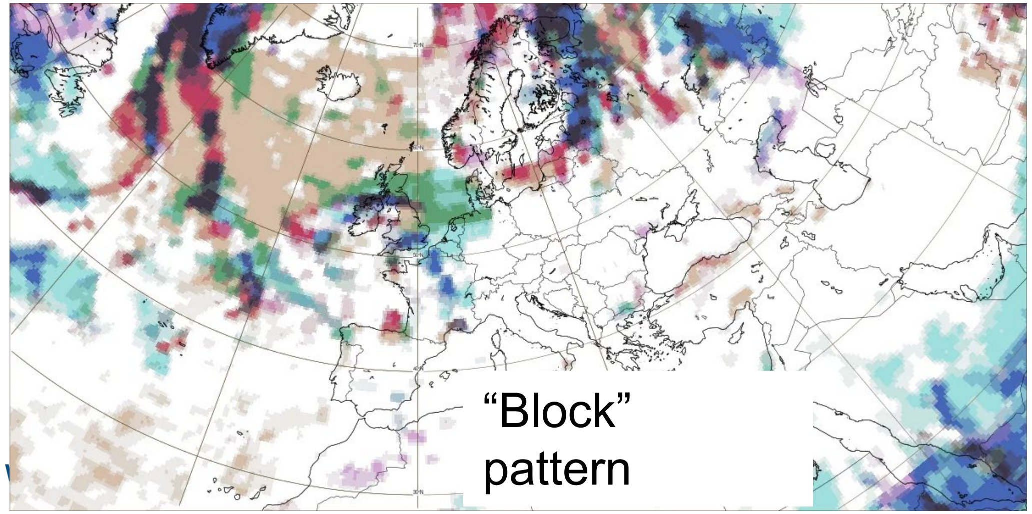
IFS CF

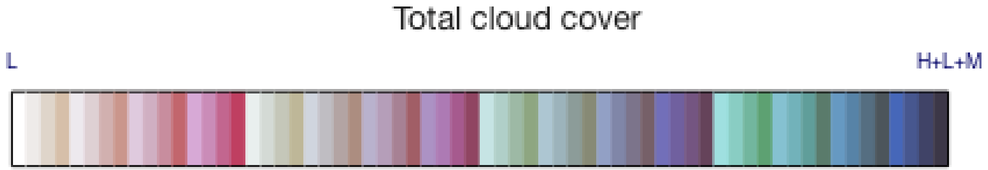


AIFS-single



AIFS-ENS control

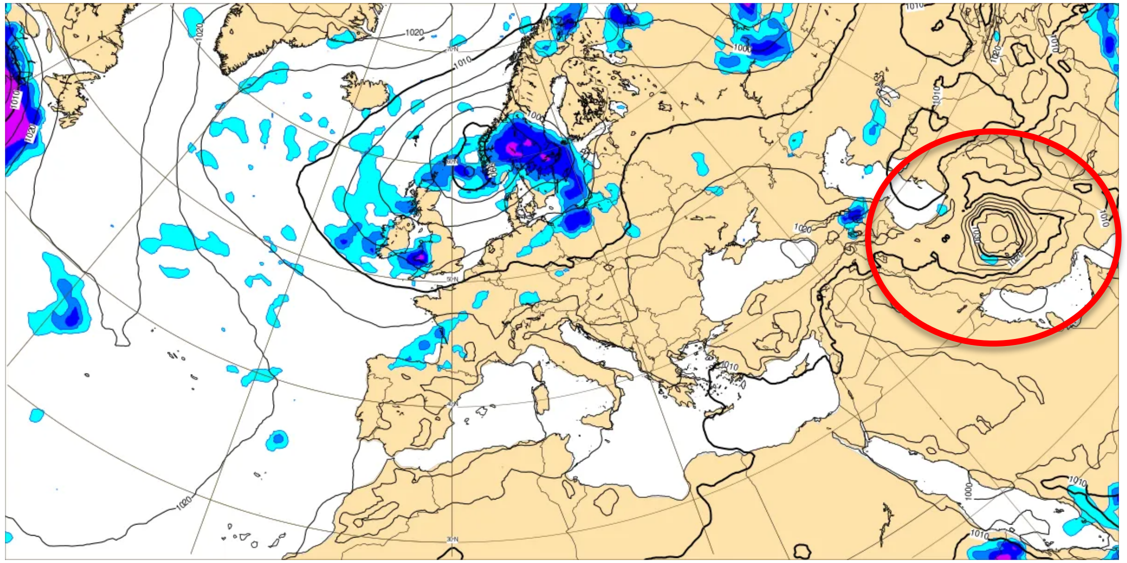




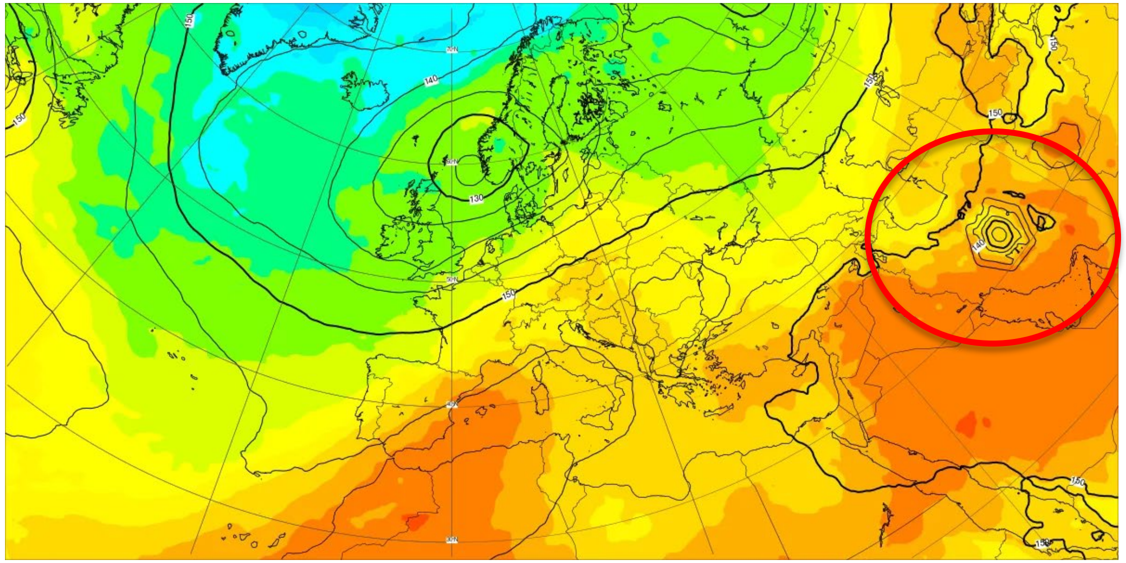
Problem over ”warm” orography in AIFS-ENS

Day 15 forecast from AIFS-ENS control

MSLP and precipitation

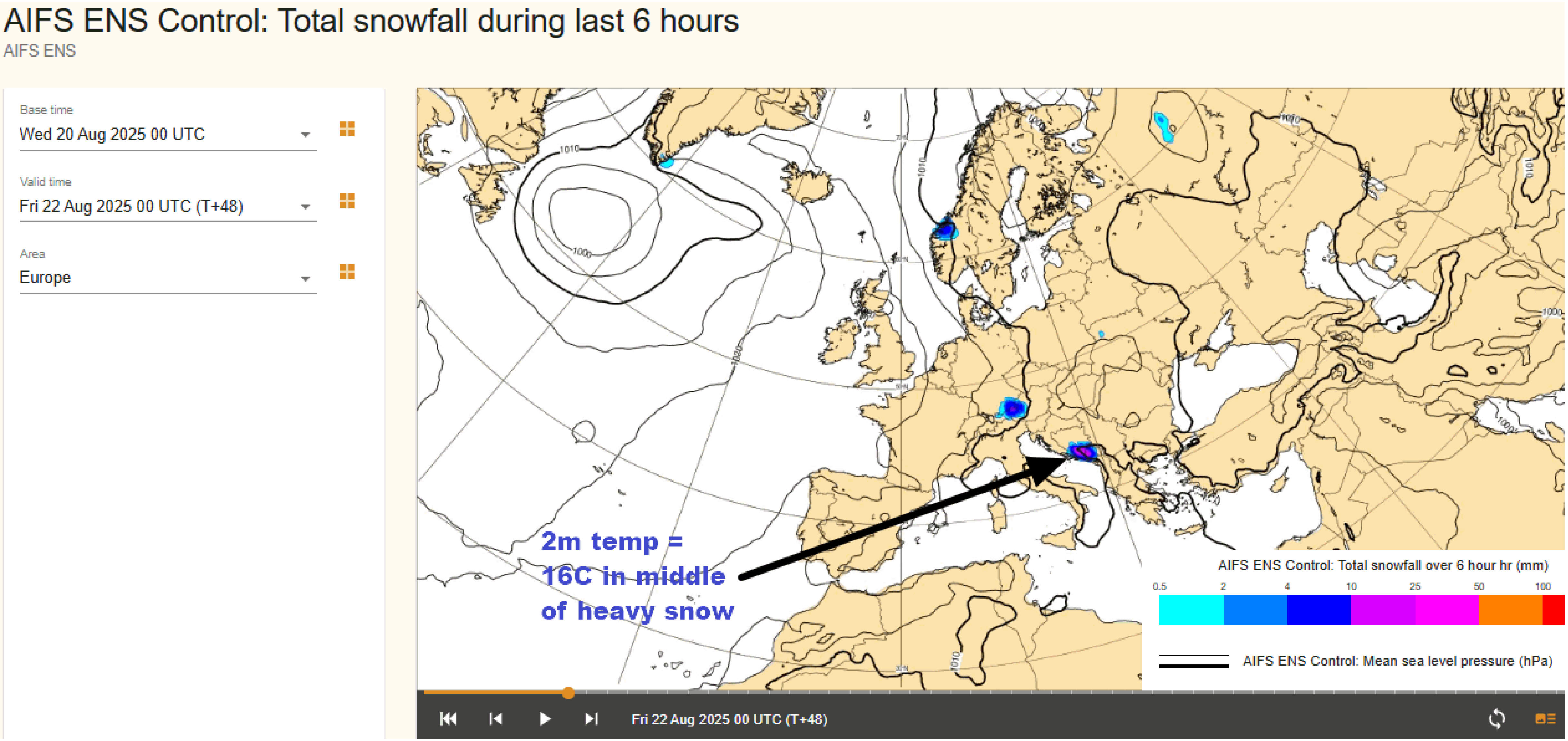


850hPa temperature and geopotential



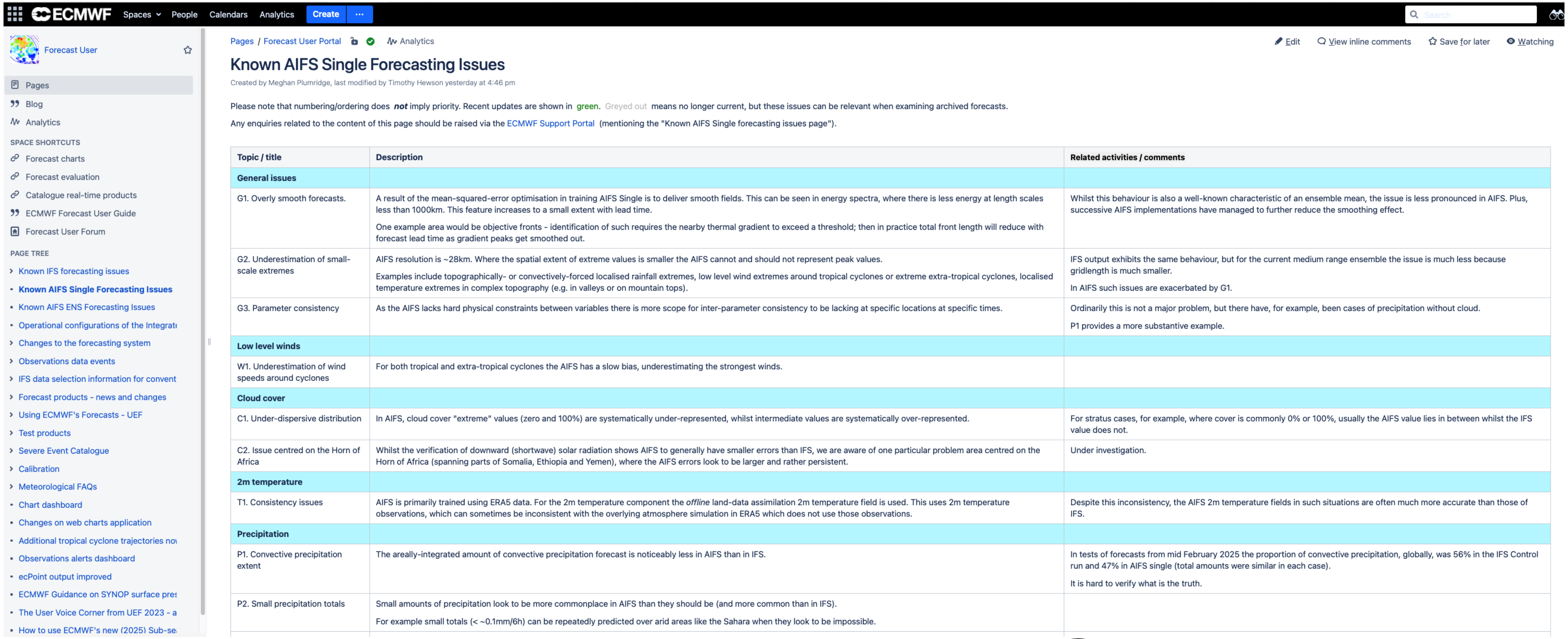
Seems to develop after day 10

Spurious snowfall in AIFS-ENS



Known forecast issues page for AIFS-single / AIFS-ENS

(in a similar way as we document issues in IFS)



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Forecast evaluation
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ECMWF Forecast User Guide
Forecast User Forum

PAGE TREE

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Known AIFS Single Forecasting Issues
Known AIFS ENS Forecasting Issues
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Changes to the forecasting system
Observations data events
IFS data selection information for convent
Forecast products - news and changes
Using ECMWF's Forecasts - UEF
Test products
Severe Event Catalogue
Calibration
Meteorological FAQs
Chart dashboard
Changes on web charts application
Additional tropical cyclone trajectories no
Observations alerts dashboard
ecPoint output improved
ECMWF Guidance on SYNOP surface pres
The User Voice Corner from UEF 2023 - a
How to use ECMWF's new (2025) Sub-se

Pages / Forecast User Portal · Analytics · Edit · View inline comments · Save for later · Watching

Known AIFS Single Forecasting Issues

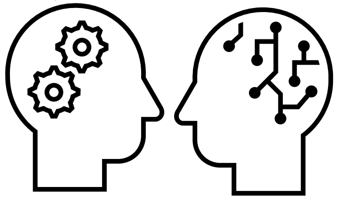
Created by Meghan Plumridge, last modified by Timothy Hewson yesterday at 4:46 pm

Please note that numbering/ordering does ***not*** imply priority. Recent updates are shown in green. Greyed out means no longer current, but these issues can be relevant when examining archived forecasts.

Any enquiries related to the content of this page should be raised via the ECMWF Support Portal (mentioning the "Known AIFS Single forecasting issues page").

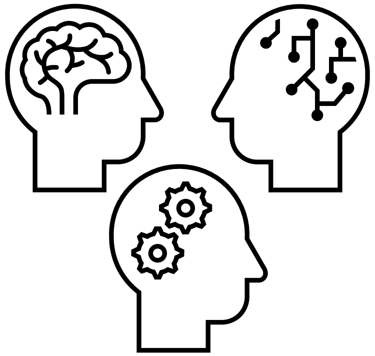
Topic / title	Description	Related activities / comments
General issues		
G1. Overly smooth forecasts.	A result of the mean-squared-error optimisation in training AIFS Single is to deliver smooth fields. This can be seen in energy spectra, where there is less energy at length scales less than 1000km. This feature increases to a small extent with lead time. One example area would be objective fronts - identification of such requires the nearby thermal gradient to exceed a threshold; then in practice total front length will reduce with forecast lead time as gradient peaks get smoothed out.	Whilst this behaviour is also a well-known characteristic of an ensemble mean, the issue is less pronounced in AIFS. Plus, successive AIFS implementations have managed to further reduce the smoothing effect.
G2. Underestimation of small-scale extremes	AIFS resolution is ~28km. Where the spatial extent of extreme values is smaller the AIFS cannot and should not represent peak values. Examples include topographically- or convectively-forced localised rainfall extremes, low level wind extremes around tropical cyclones or extreme extra-tropical cyclones, localised temperature extremes in complex topography (e.g. in valleys or on mountain tops).	IFS output exhibits the same behaviour, but for the current medium range ensemble the issue is much less because gridlength is much smaller. In AIFS such issues are exacerbated by G1.
G3. Parameter consistency	As the AIFS lacks hard physical constraints between variables there is more scope for inter-parameter consistency to be lacking at specific locations at specific times.	Ordinarily this is not a major problem, but there have, for example, been cases of precipitation without cloud. P1 provides a more substantive example.
Low level winds		
W1. Underestimation of wind speeds around cyclones	For both tropical and extra-tropical cyclones the AIFS has a slow bias, underestimating the strongest winds.	
Cloud cover		
C1. Under-dispersive distribution	In AIFS, cloud cover "extreme" values (zero and 100%) are systematically under-represented, whilst intermediate values are systematically over-represented.	For stratus cases, for example, where cover is commonly 0% or 100%, usually the AIFS value lies in between whilst the IFS value does not.
C2. Issue centred on the Horn of Africa	Whilst the verification of downward (shortwave) solar radiation shows AIFS to generally have smaller errors than IFS, we are aware of one particular problem area centred on the Horn of Africa (spanning parts of Somalia, Ethiopia and Yemen), where the AIFS errors look to be larger and rather persistent.	Under investigation.
2m temperature		
T1. Consistency issues	AIFS is primarily trained using ERA5 data. For the 2m temperature component the *offline* land-data assimilation 2m temperature field is used. This uses 2m temperature observations, which can sometimes be inconsistent with the overlying atmosphere simulation in ERA5 which does not use those observations.	Despite this inconsistency, the AIFS 2m temperature fields in such situations are often much more accurate than those of IFS.
Precipitation		
P1. Convective precipitation extent	The areally-integrated amount of convective precipitation forecast is noticeably less in AIFS than in IFS.	In tests of forecasts from mid February 2025 the proportion of convective precipitation, globally, was 56% in the IFS Control run and 47% in AIFS single (total amounts were similar in each case). It is hard to verify what is the truth.
P2. Small precipitation totals	Small amounts of precipitation look to be more commonplace in AIFS than they should be (and more common than in IFS). For example small totals (< ~0.1mm/6h) can be repeatedly predicted over arid areas like the Sahara when they look to be impossible.	

However, solving the issues require different strategies for an AI model compared to NWP



Summary

- Different characteristics in AIFS-single and AIFS-ENS, but both:
  - Able to make very skilful prediction of the large-scale flow
  - Capture extremes, but missing the magnitude for some types of extreme weather
  - Improves on (conditional) systematic error in IFS
- Continued efforts in the evaluation team to find strange behaviours in AIFS
- AIFS limited by the skill of the training data (ERA5 + operational analysis)
  - Efforts to add observation data into training
- Under development:
  - Including more earth-system components (e.g waves)
  - Higher resolution
  - Reforecast dataset
  - Sub-seasonal system
- How are we going to use the information from the different models in practice?
  - Come and discuss this afternoon!



Further reading:

ECMWF newsletter articles over the past year about extreme events like Storm Eowyn, Storm Boris, …

AIFS: Lang et al., AIFS -- ECMWF's data-driven forecasting system https://arxiv.org/abs/2406.01465

AIFS-ENS: Lang et al., AIFS-CRPS: Ensemble forecasting using a model trained with a loss function based on the Continuous Ranked Probability Score
https://arxiv.org/html/2412.15832v1

AI-Model assessments: Ben Bouallègue et al., The Rise of Data-Driven Weather Forecasting: A First Statistical Assessment of Machine Learning–Based Weather Forecasts in an Operational-Like Context: https://doi.org/10.1175/BAMS-D-23-0162.1