

Research progress and plans

Filip Vana
ECMWF



Three sites: one unique role

Reading

Bonn

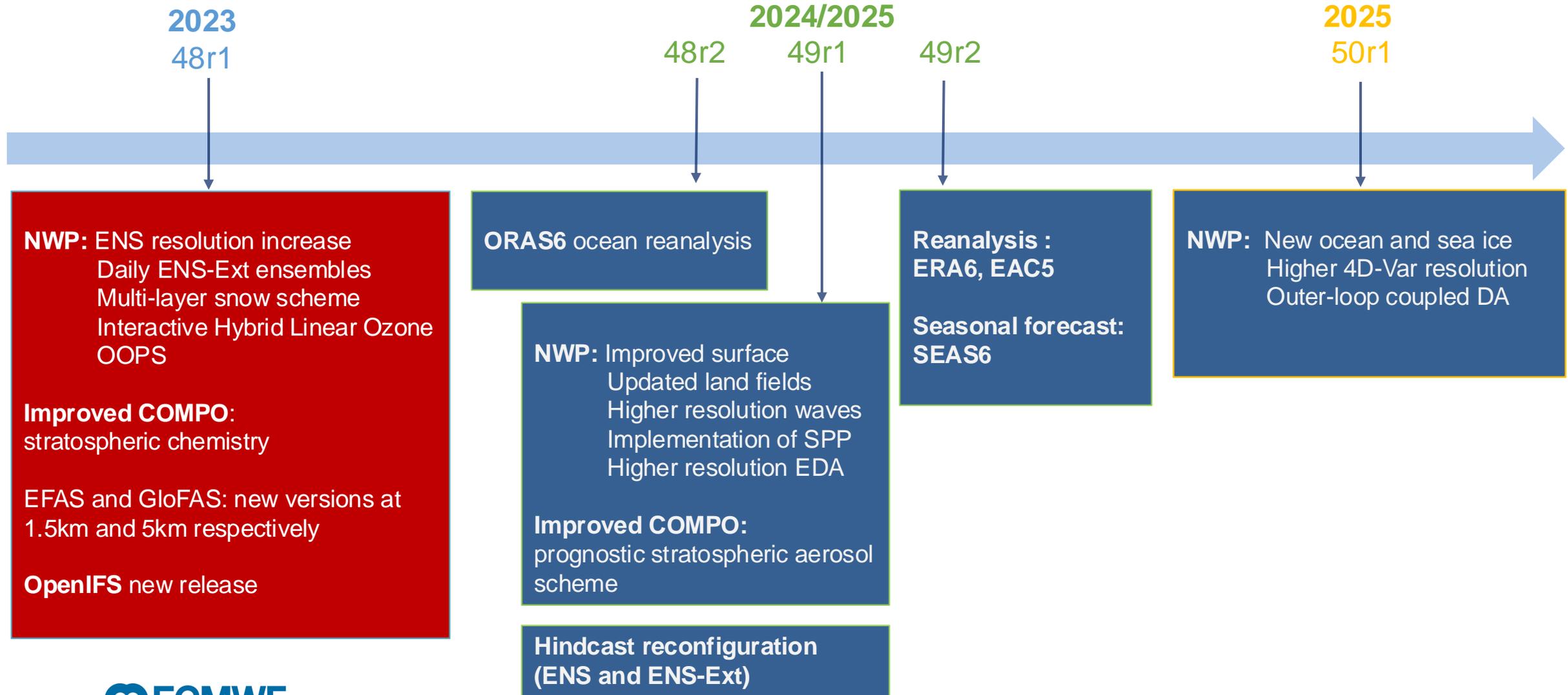
Bologna

ECMWF's role is to address the critical and most difficult research problems in medium-range NWP that no one country could tackle on its own.



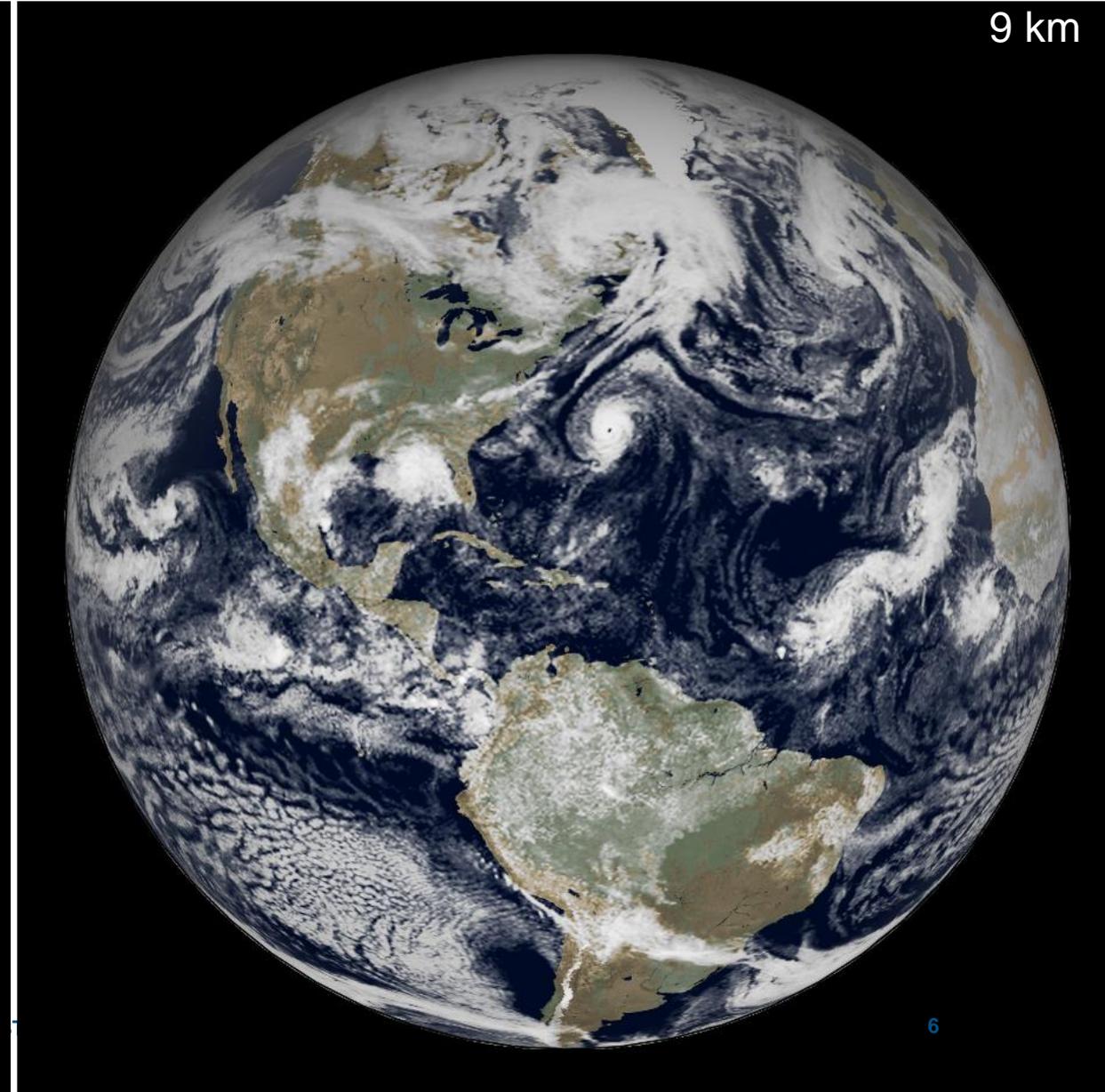
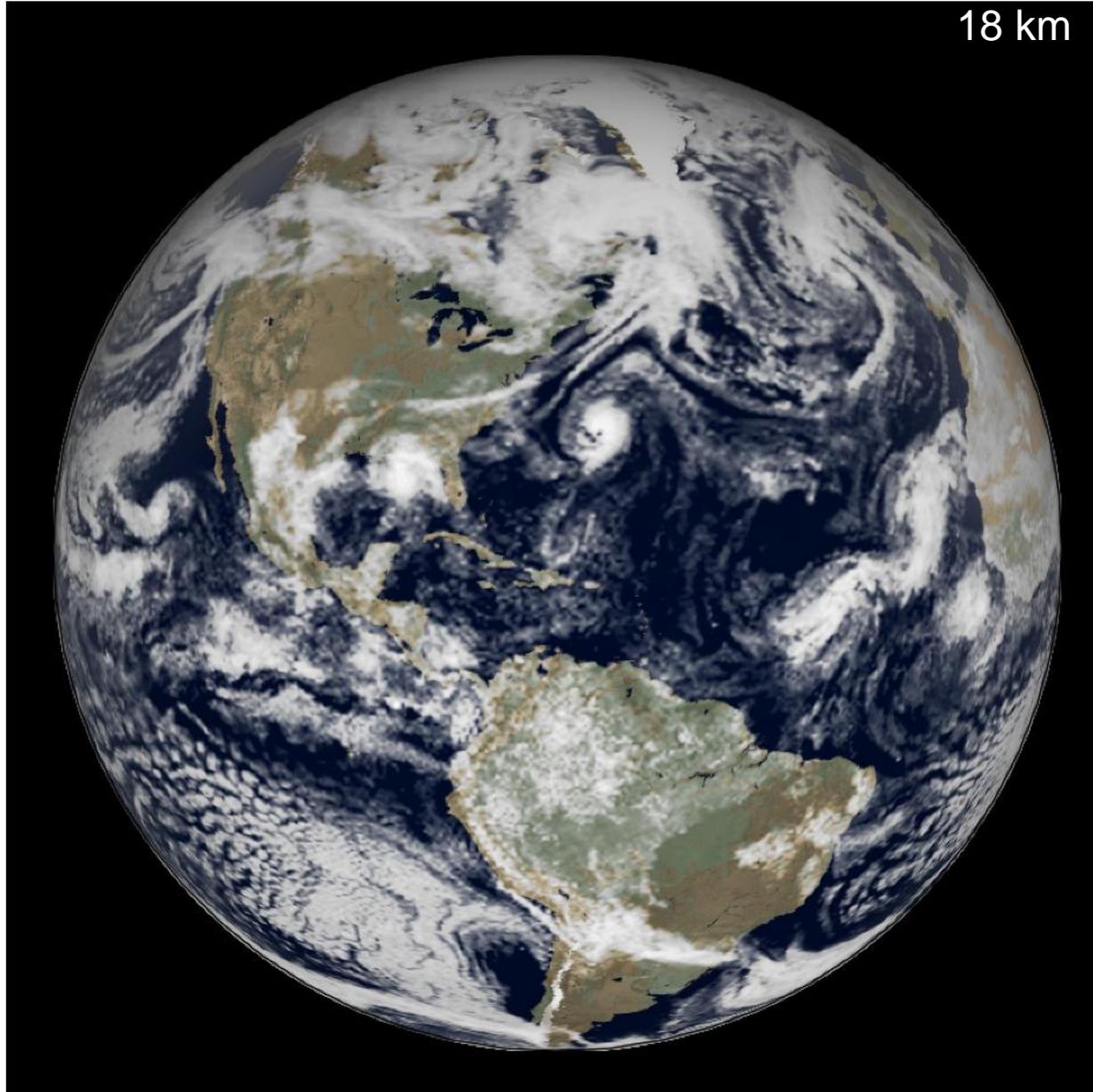


Integrated Forecast System (IFS) upgrades



Medium range ensemble: 18 km to 9 km (same as HRES)

Extended range ensemble: 50+1 members twice weekly to 100+1 members every day

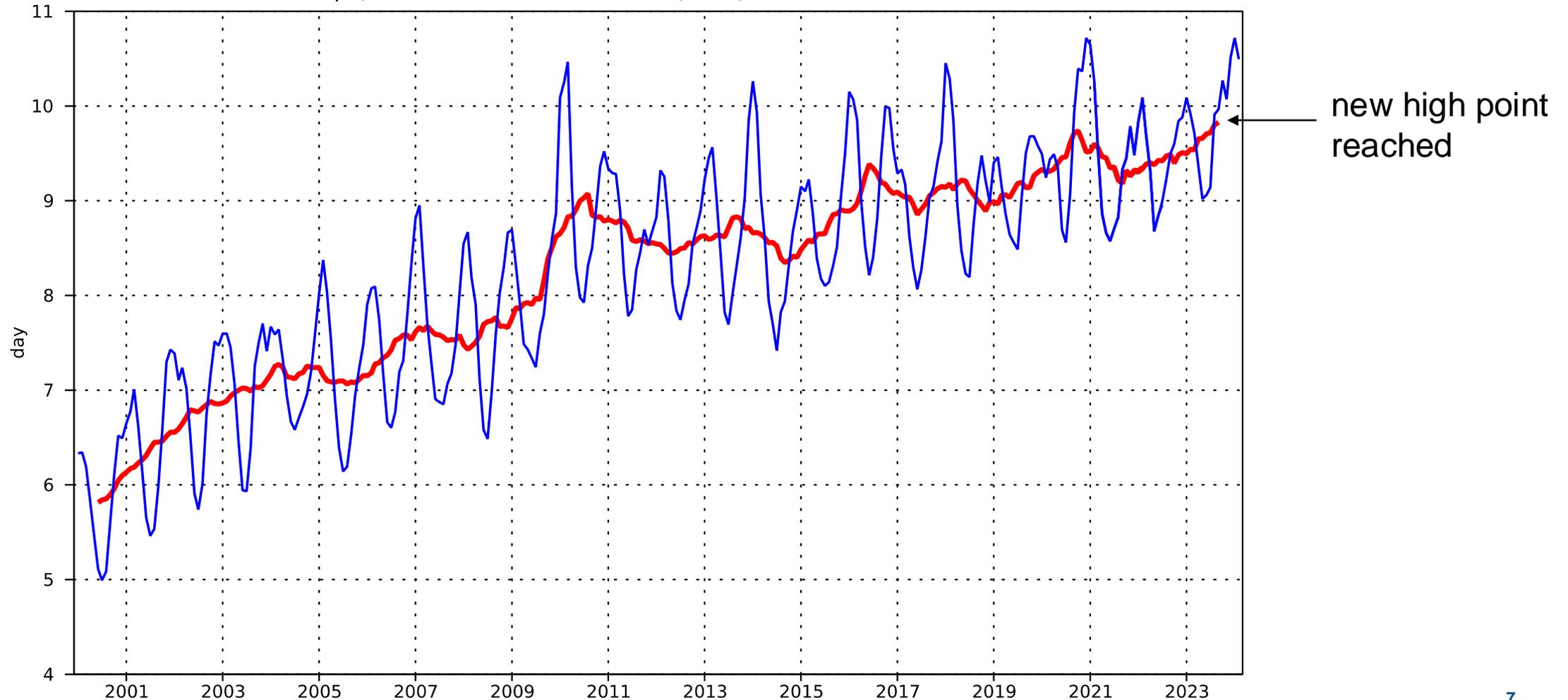


Evolution of ENS upper-air forecast skill

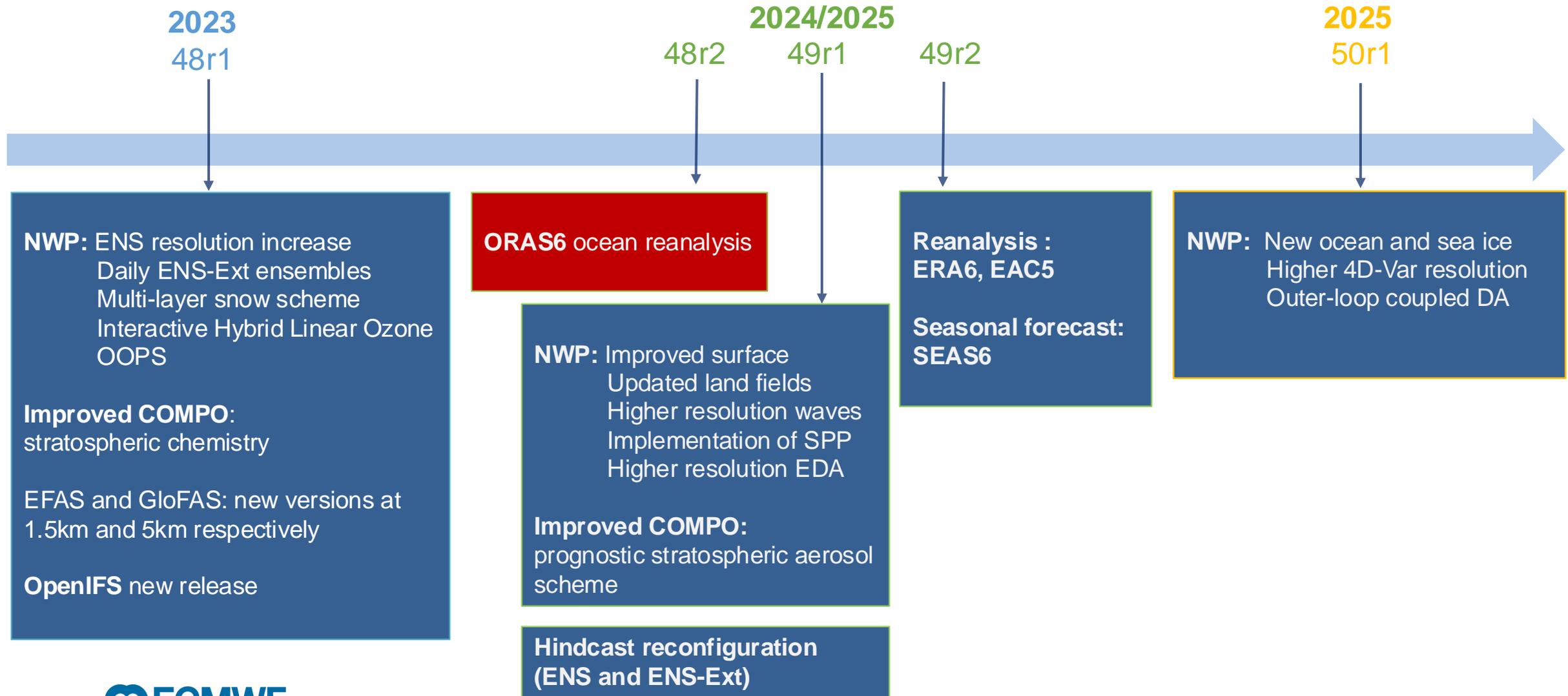
Continuous ranked probability skill score | 850hPa temperature

NHem Extratropics

T+12 T+24 ... T+360 | oper_ano d enfo 0001 00z,12z beginning



Integrated Forecast System (IFS) upgrades



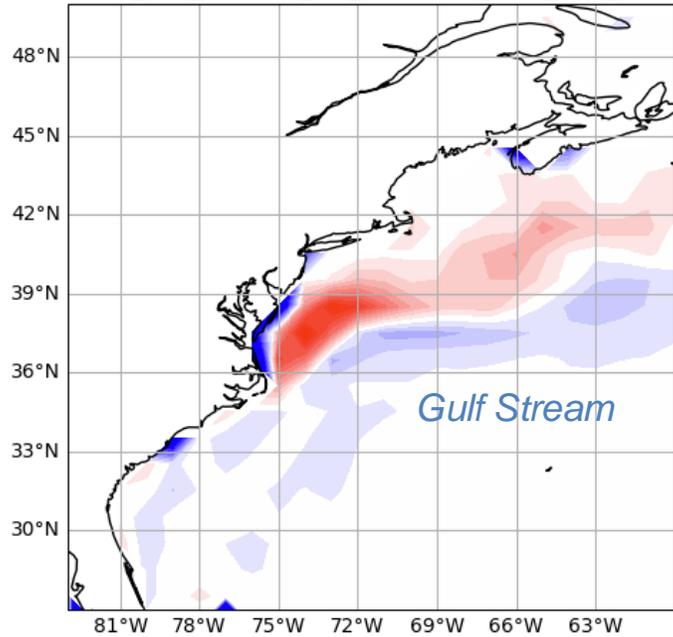
New ocean reanalysis performance

Mean SST biases (2015-2021)

Verf. CCIv2 SST

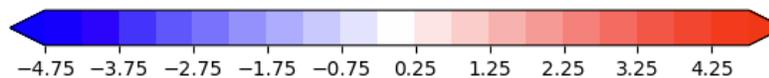
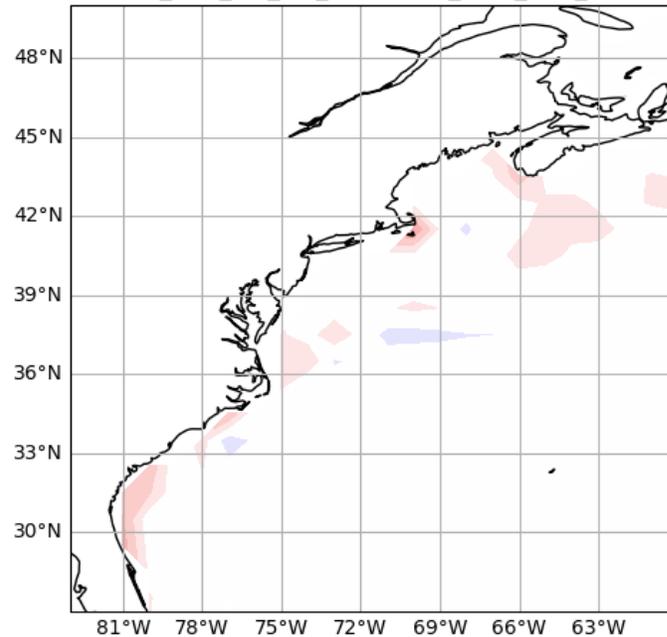
ORAS5

0001_cci2_sosstsst_tos_20152021_r1x1_bias_1.nc

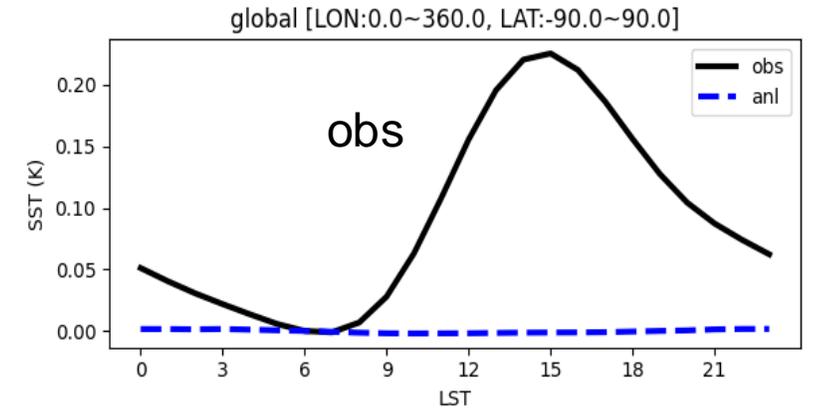


ORAS6

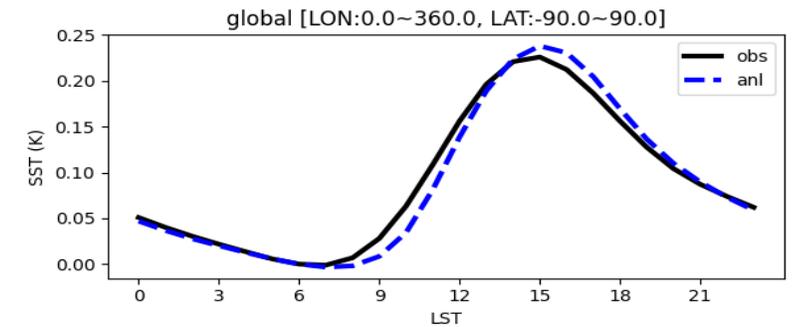
i5ou_cci2_tos_tos_20152021_r1x1_bias_1.nc



Global-mean SST Diurnal Cycle

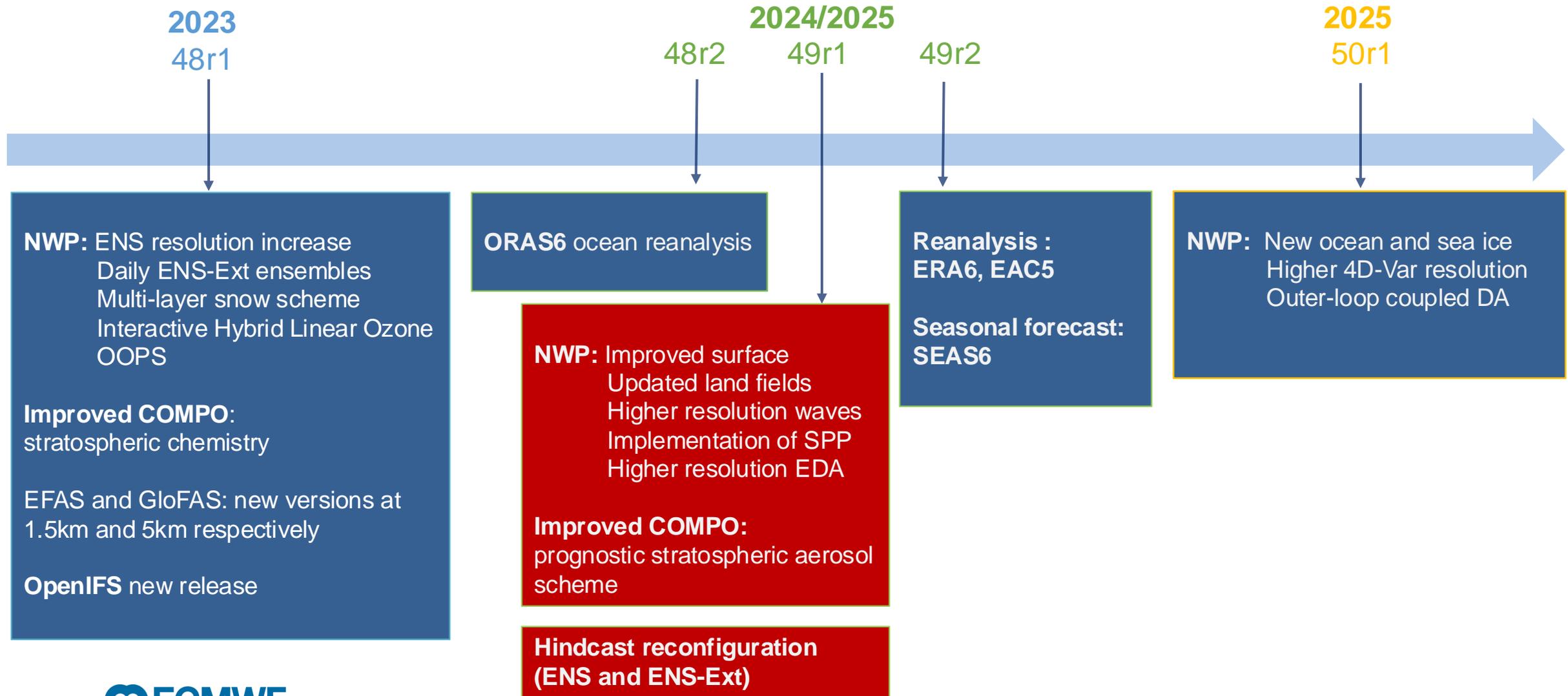


ORAS5 doesn't have a diurnal cycle



ORAS6 has a diurnal cycle close to observation

Integrated Forecast System (IFS) upgrades



Summary of contributions to cycle 49R1

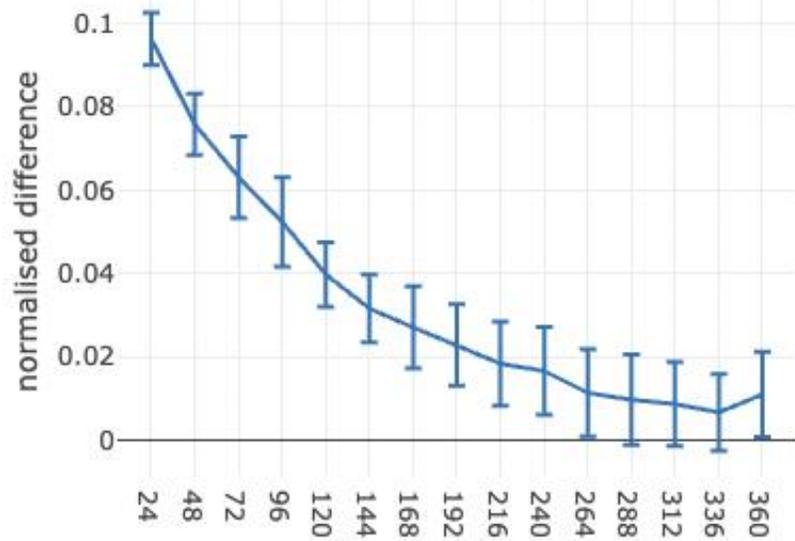
Model changes

Data assimilation changes

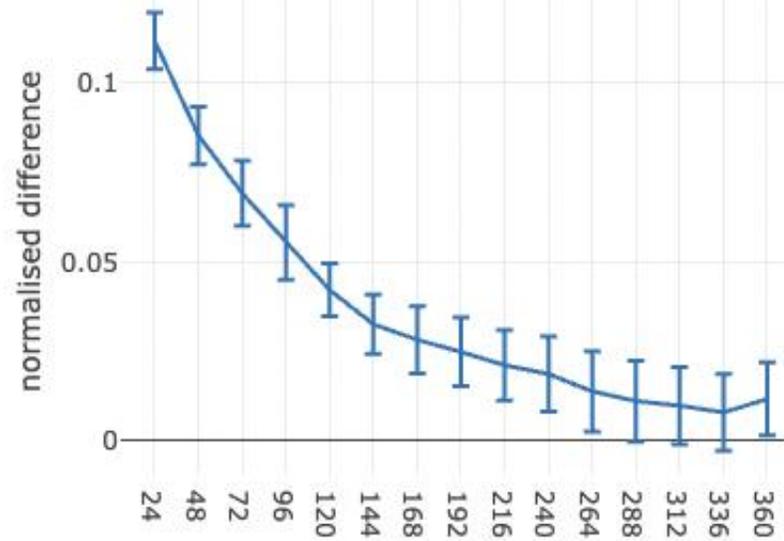
- **V1 – Microwave and RTTOV assimilation package**, including updates to RTTOV and all-sky all-surface assimilation of sea-ice areas for GMI/ASMR2 amongst other changes.
- **V2 – Wave model and convection package**, including waves on Tco grid, new wind input parameterizations, sea-state dependent heat and moisture fluxes, hourly wave DA, improved CAT diagnostics, and updated non-orographic GWD.
- **V3 – Non-microwave observations package**, including observation updates from IR and active sensing groups.
- **V4 – Land-surface model updates**, including updated climate fields, modified vegetation properties, activation of urban tile, updated T2m interpolation, and shadowing of snow under high vegetation.
- **V5 – T2m assimilation package**, activates assimilation of T2m observations.
- **V6 – VarQC and stratospheric balance assimilation package**, including activation of VarQC in first trajectory, increased weight to GRAS/COSMIC-2 measurements, and activation of stratospheric balance in 4DVar.
- **V7 – Land-surface assimilation package**, including changes to soil moisture background errors, updates to snow assimilation, and lapse rate correction for T2m assimilation.
- **V8 – Activation of the Stochastically Perturbed Parametrizations (SPP) scheme**, which replaces the Stochastically Perturbed Parametrization Tendencies (SPPT) scheme in all IFS ensemble configurations.
- **V9 – Physics and numerics contributions**, which includes ecRad optimizations, improved 10m wind diagnostics, improvements in TOA radiation budget, flexible aerosol treatment in radiation, time-dependent methane oxidation, and preparation for reordered sequence of physics chain in IFS.
- **V10 – Atmospheric composition package**, including revisions to aerosol optical properties, chemistry updates, and many other changes.
- **V11 – Other technical/neutral changes**, including bit-identical Ensemble control forecast and HRES.
- **Updates to EDA**, including Tco1279 FC+Traj, soft recentering, and new climatology for SES calculation.

T2m verification against observations (NHEM, winter 2022/23)

2t|0|n.hem|rmsef|ob



2t|0|n.hem|crps|ob



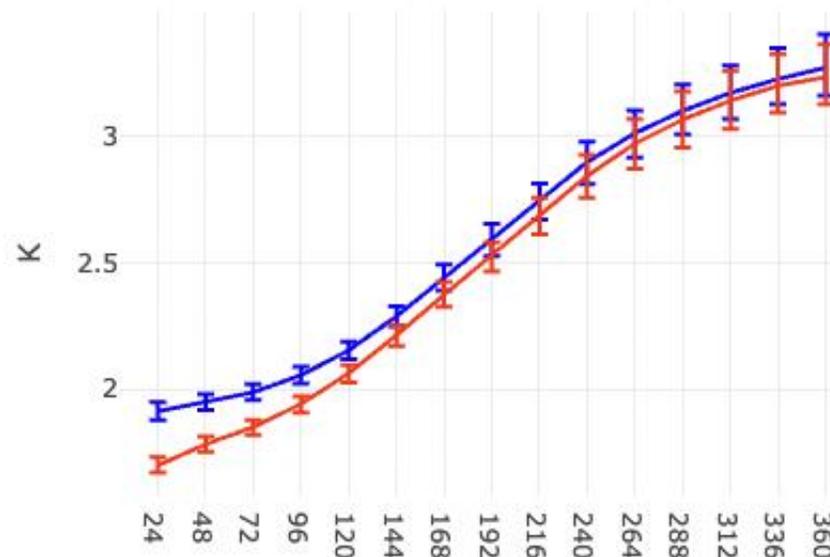
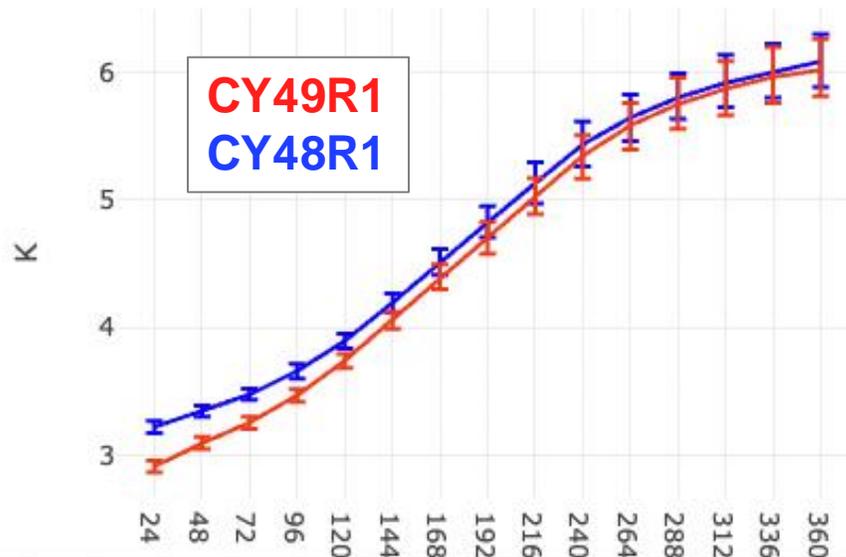
CY49R1 improves NHEM T2m forecasts.

- Impact from several contributions.
- Largest impacts during NHEM winter.

RD esuite ensemble scores

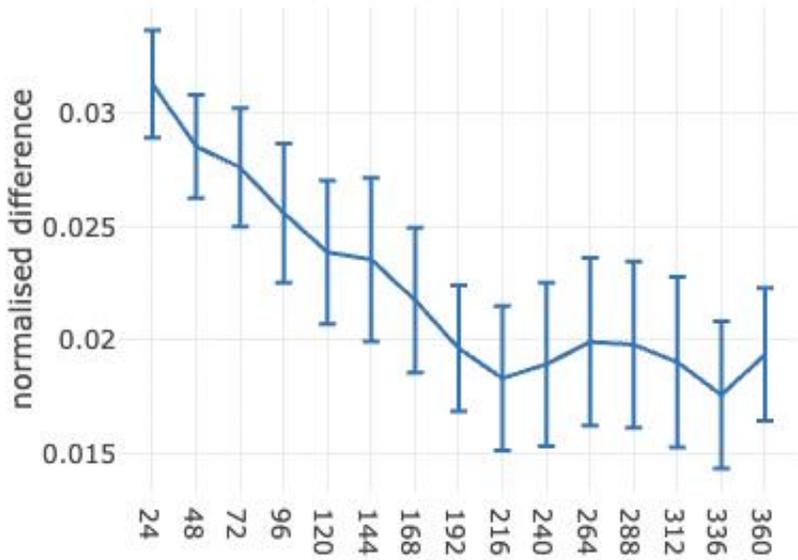
Region (season)	CRPS (day 5)	RMSE (day 5)
N. Hem (DJF)	4.2 %	4.0 %
Tropics (DJF)	2.5 %	1.8 %
S. Hem (DJF)	0.3 %	0.6 %
N. Hem (JJA)	0.7 %	1.4 %
Tropics (JJA)	-0.7 %	-1.5 %
S. Hem (JJA)	-0.2 %	0.0 %

Bold values significant at 95% confidence level

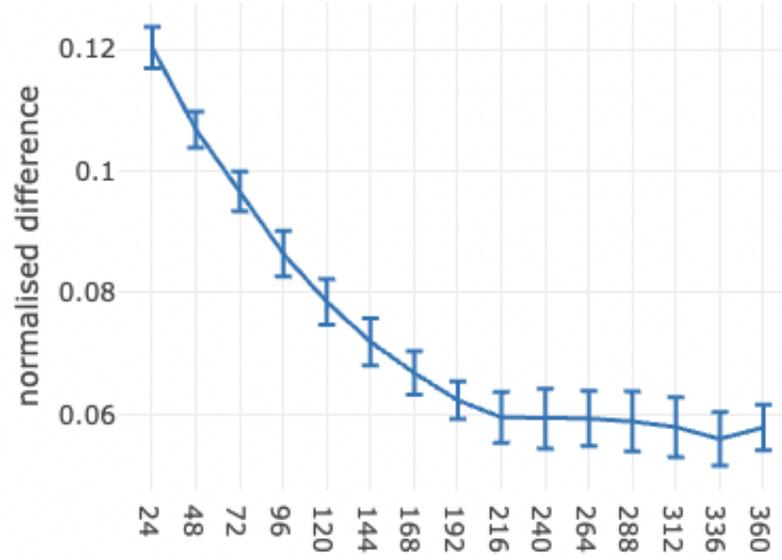


10m wind verification against observations (NHEM, winter 2022/23)

10ff|0|n.hem|rmsef|ob



10ff|0|n.hem|crps|ob



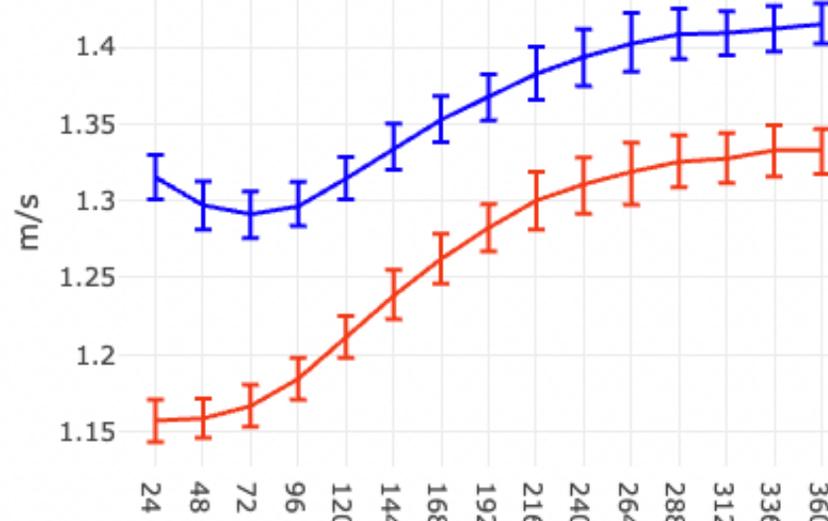
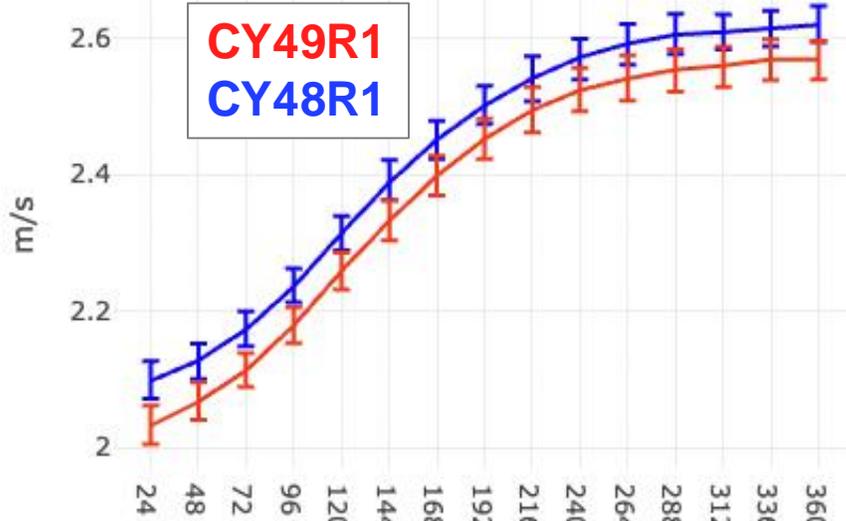
CY49R1 improves 10m wind forecasts.

- Impact from several contributions.
- Increased spread from SPP is important.

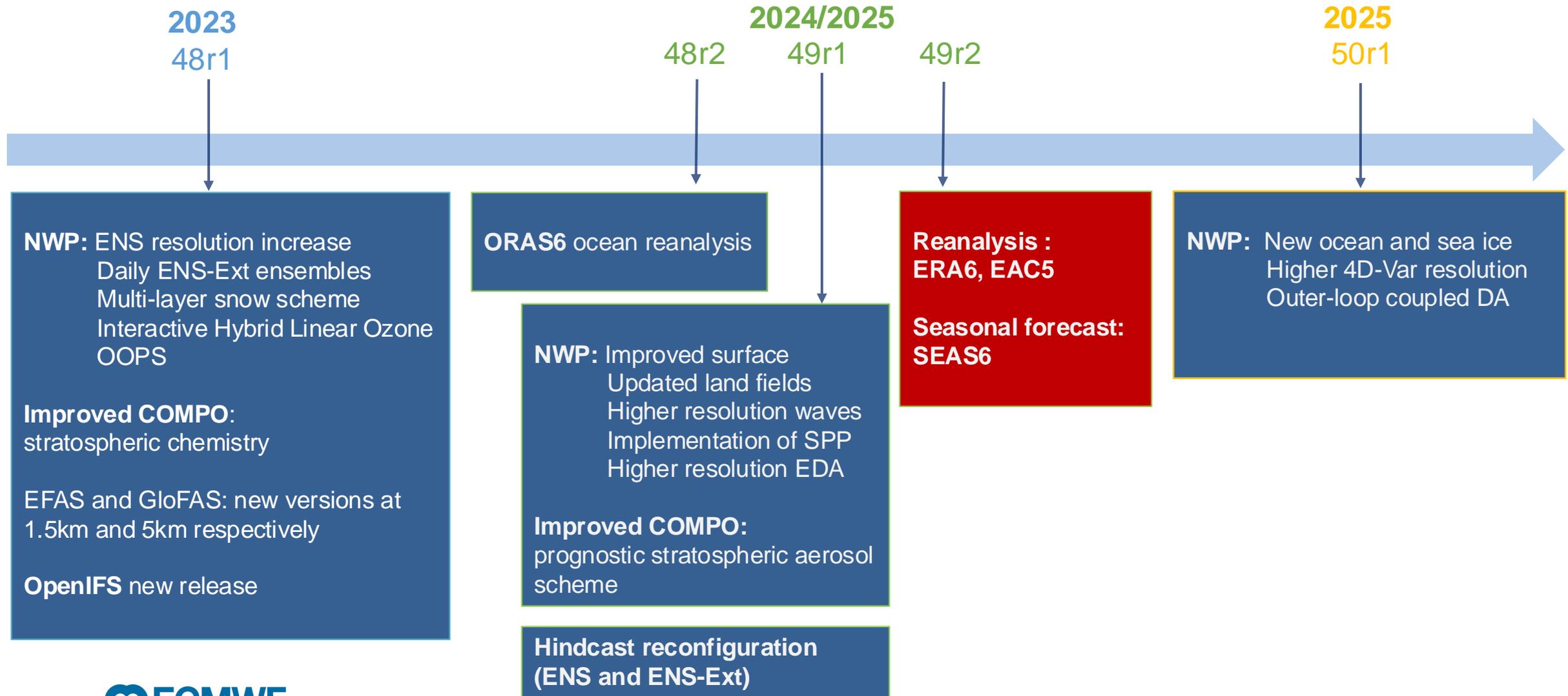
RD esuite ensemble scores

Region (season)	CRPS (day 5)	RMSE (day 5)
N. Hem (DJF)	7.8 %	2.4 %
Tropics (DJF)	6.8 %	1.9 %
S. Hem (DJF)	3.8 %	1.4 %
N. Hem (JJA)	3.6 %	1.1 %
Tropics (JJA)	5.3 %	0.8 %
S. Hem (JJA)	5.1 %	1.1 %

Bold values significant at 95% confidence level



Integrated Forecast System (IFS) upgrades

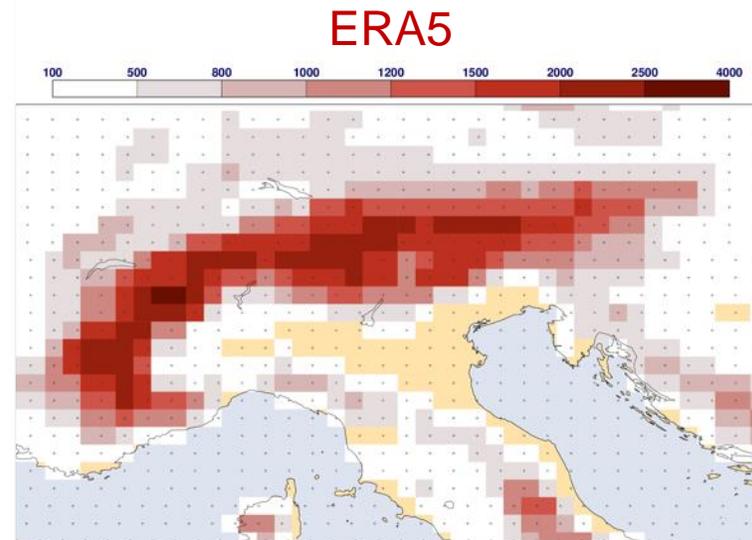
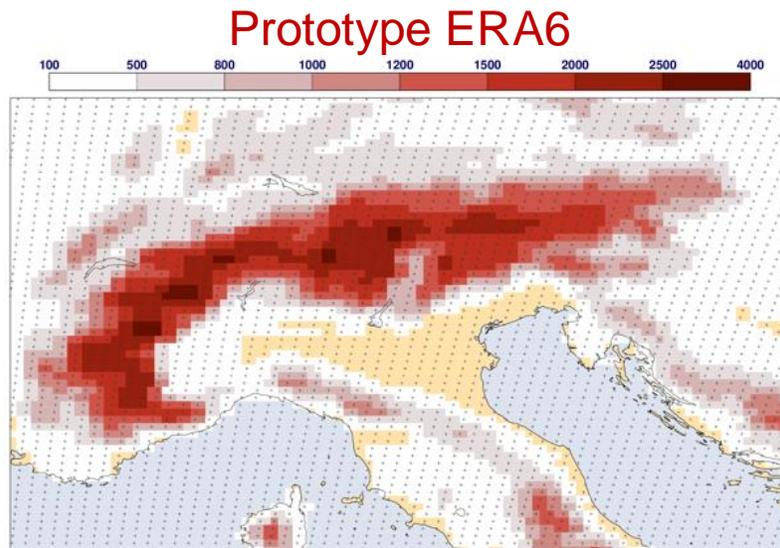


From ERA5 to ERA6; new climate dataset is being developed

ERA5 is *the* world-leading climate dataset for many applications.

Preparations of its follow-up, ERA6 are well underway:

- Taking onboard recorded user requirements from our huge ERA5 user base (over 160,000)
- Will capitalize on an additional **8 years of R&D** at ECMWF plus increased compute power
- Double the atmospheric resolution: **14km globally** vs 31km; **ocean waves 14km** vs 40km.
- Has coupling with the ocean, providing additional information on the climate system.

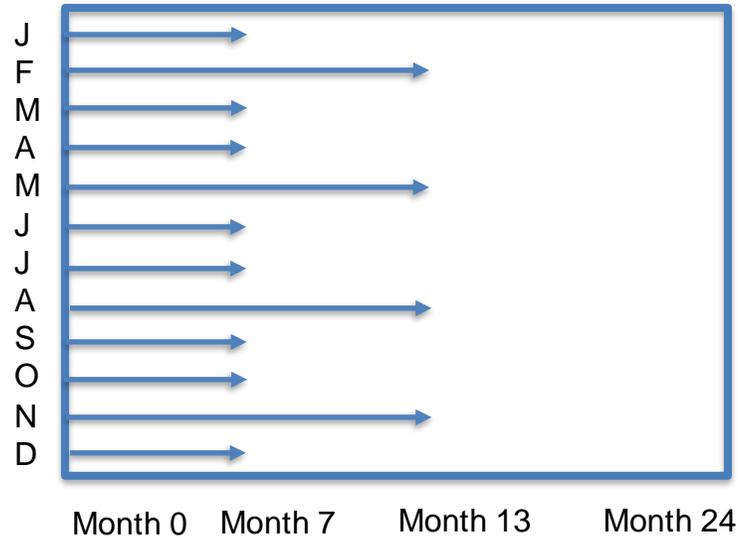


ERA6 to start production in early 2025
Aim to make the first 20 years (2006-2026) available around Autumn 2026

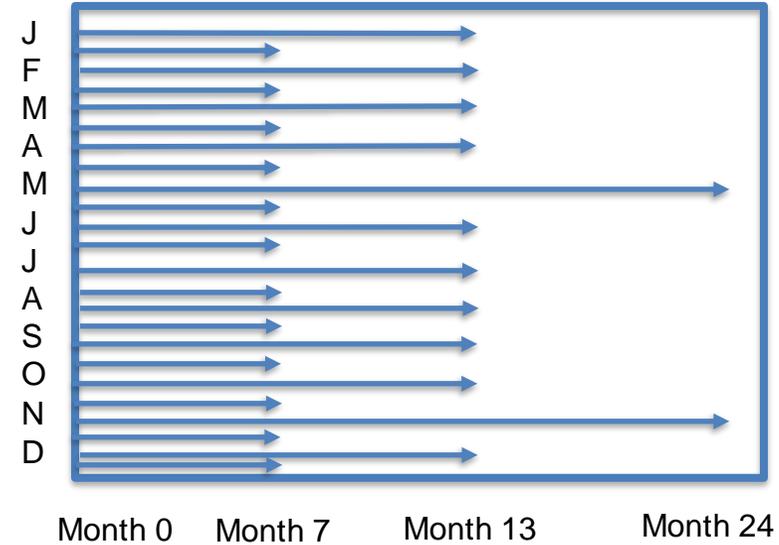
SEAS6 Real-time forecast enhancements at a glance:

- 7m twice a month (101 members)
- 13m every month (33 members)
- 24m twice a year (33 members)

SEAS5



SEAS6



SEAS6 Reforecasts

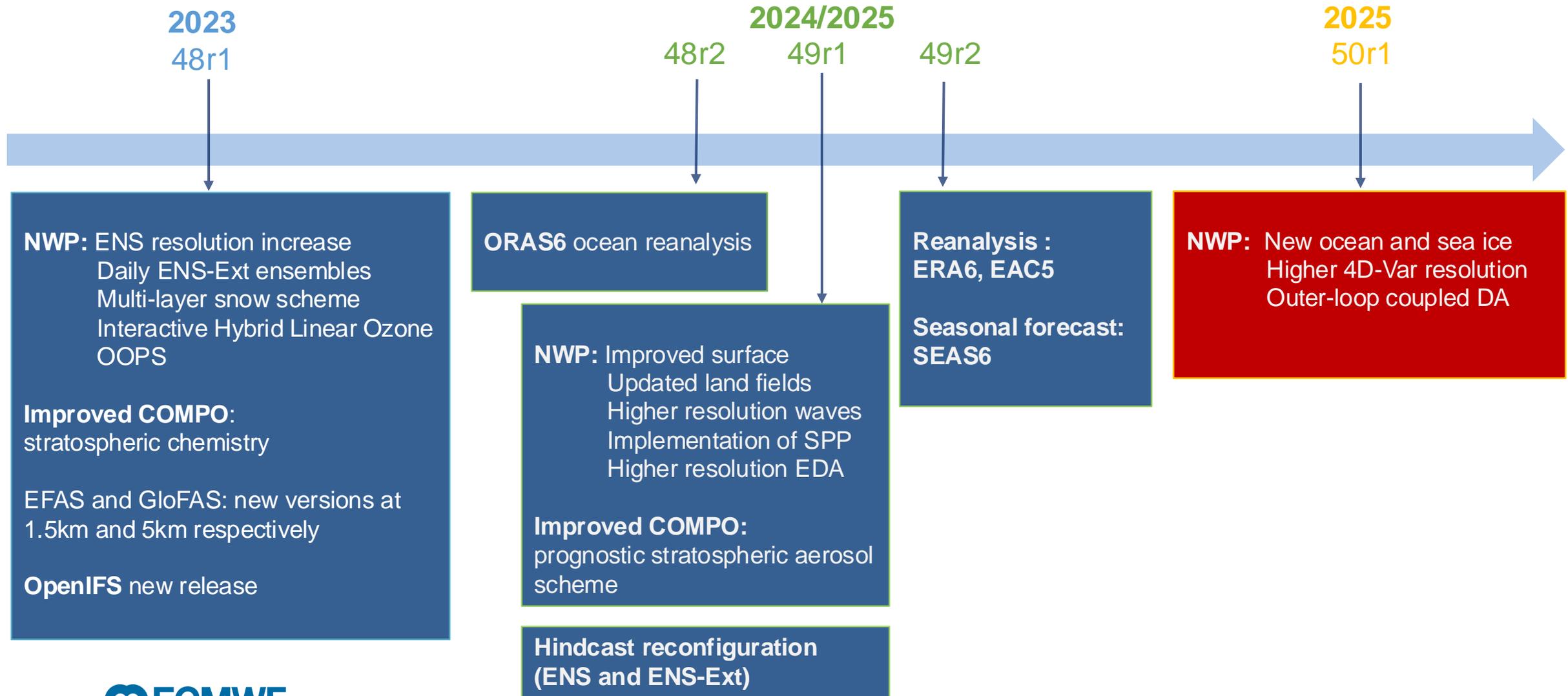
Main set 1993-2022

7m fc: 33 members twice a month
13m fc: 22 members monthly
24m fc: 22 members twice a year

Supplementary set :

Back extension to 1961 for all
Enhanced ensemble (up to 55
members) for 7m fcs quarterly

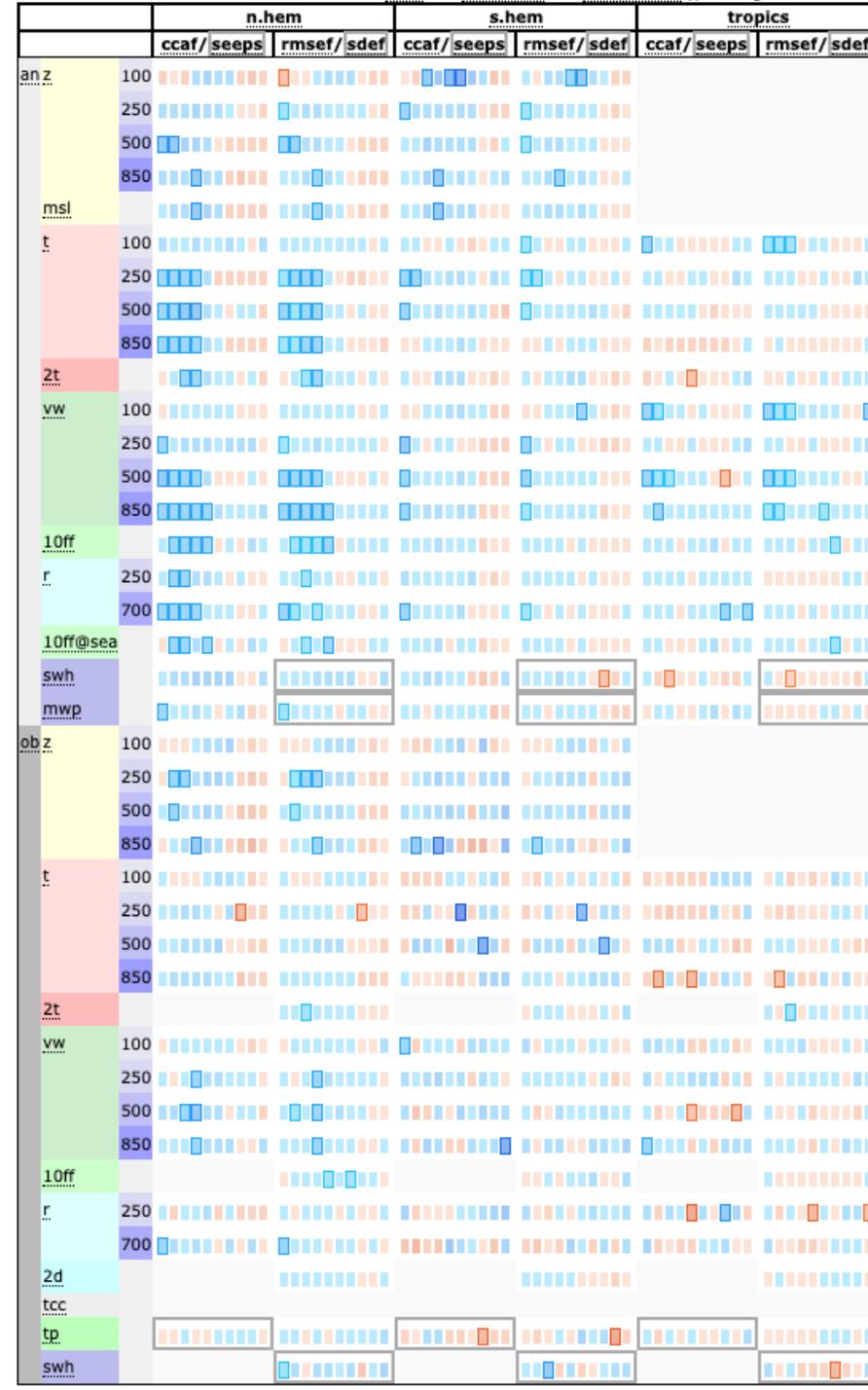
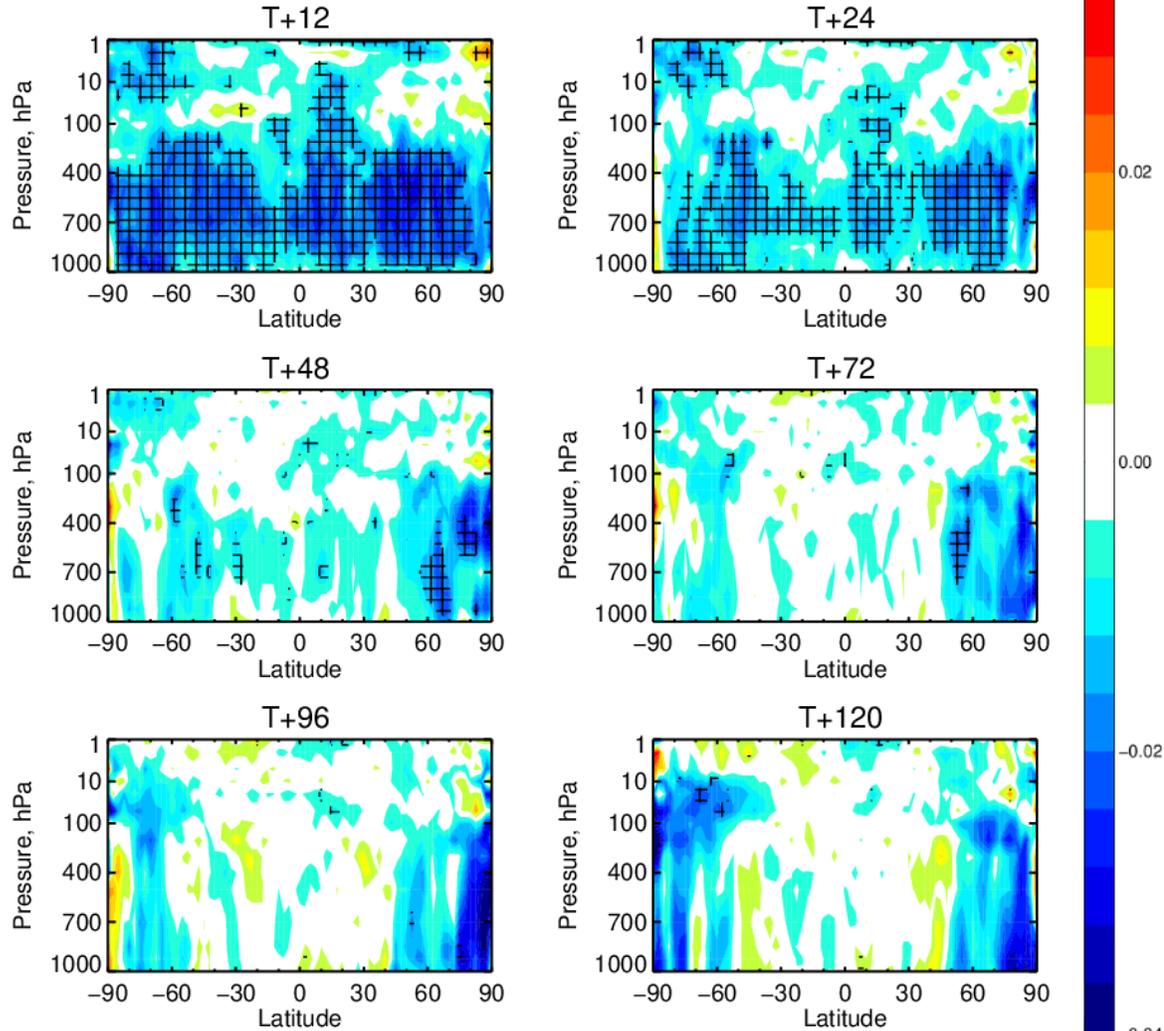
Integrated Forecast System (IFS) upgrades



Higher-resolution 4D-Var data assimilation

Change in RMS error in VW (TCo511_399-TL511_control)

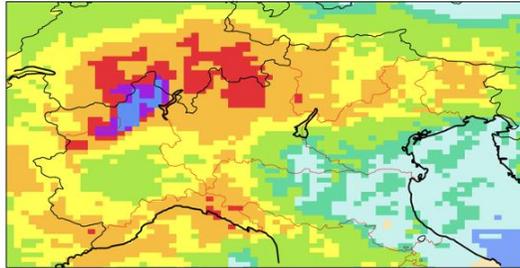
1-Jun-2022 to 31-Aug-2022 from 164 to 183 samples. Verified against own-analysis. Cross-hatching indicates 95% confidence with Sidak correction for 20 independent tests.



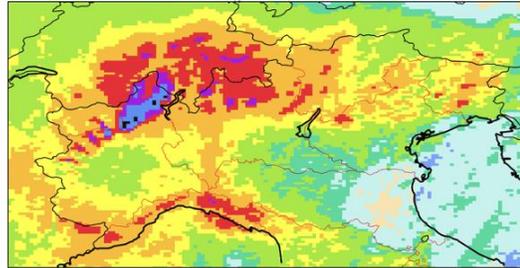
Local benefits of km-scale

Storm Alex 2020/10/01 24h TP

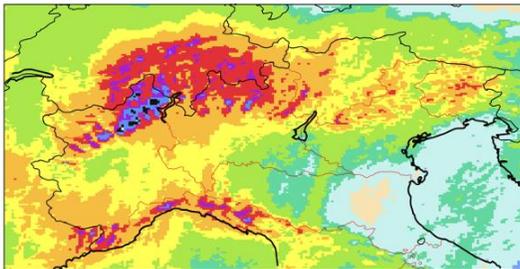
HRES (9km)



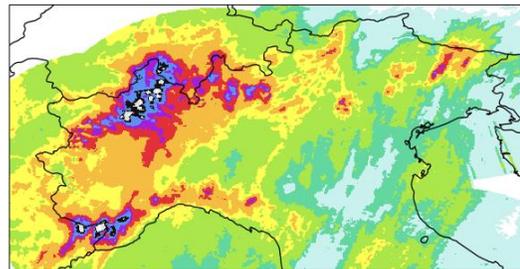
DestinE (4.4km)



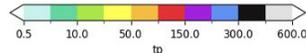
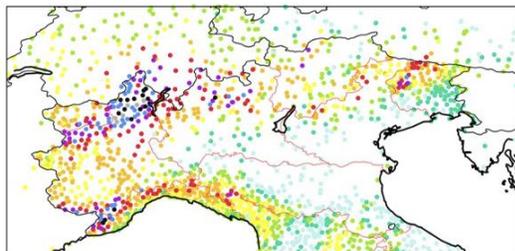
DestinE (2.8km)



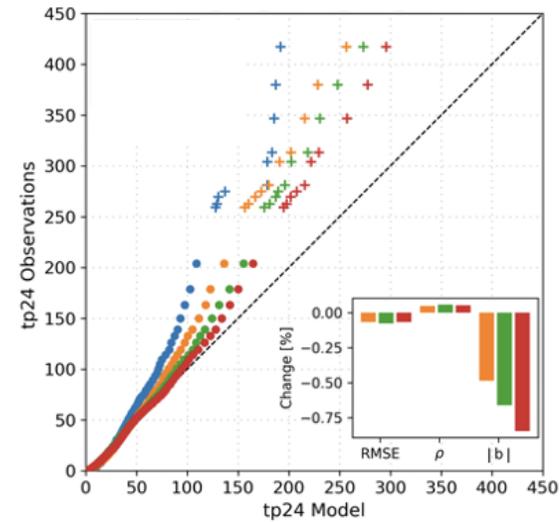
Radar + gauges



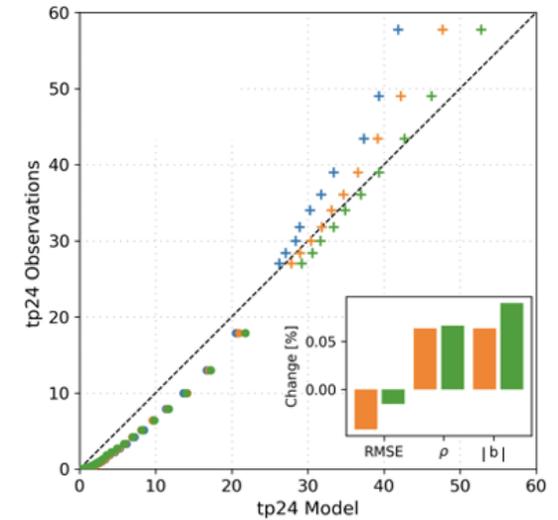
SYNOP



4 case studies



winter 2022 daily forecasts



- 28 km
- 9 km
- 4.4 km
- 2.8 km

Hybrid 2024 – Forecast component adaptation progress

Model component		Porting method	CPU run time	GPU (Nvidia)			GPU (AMD)	
				Status	Performance	Expected Completion	Status	Perf.
Dynamical core	Spectral Transform	Manual, OpenACC	16%	Done	Good	MS1 (Q1-24)	Optimising	GPU-MPI
	Grid point dynamics	FIELD API + Loki	10%	Porting		MS2 (Q4-24)	Porting	Compiler says no!
	Semi-Lagrangian	FIELD API + Loki	12%	Optimising	Data transfer MPI comms	MS2 (Q4-24)	Porting	
Physics	EC-physics	FIELD API + Loki	30%	Porting	Data transfer	MS1 / MS 2 *	Porting	
	Surface model	FIELD API + Loki		Porting		MS2 (Q4-24)	Porting	
	Radiation	Loki	5%	Porting	Memory use	MS2 (Q4-24)	Porting	
	Perturbation	FIELD API + Loki	N/A	Porting		MS2 (Q4-24)	Porting	
Wave model	Dy-core	Manual, OpenACC	8%	Done	Good	Q3 2024	Porting	
	Source term	FIELD API + Loki		Porting				
Atmospheric composition		FIELD API + Loki	N/A					
Diagnostics	DDH	CPU-only	N/A					
	FULLPOS	Manual	6%					
Ocean model (NEMO)		CPU-only, PSyclone	6%	Exploring				

Complete
Demonstrated
Working on it
External issues
Not started yet
Out of scope

OpenIFS



+ Rapidly increasing amounts of IFS code open source (e.g. land, waves, convection,

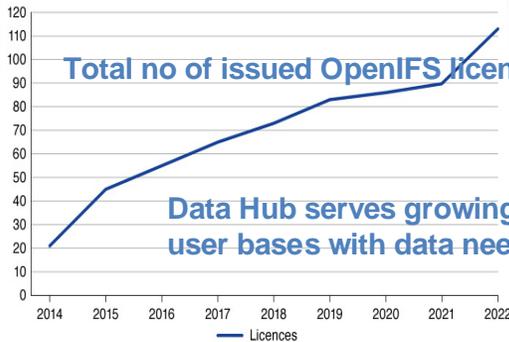
Since Sept 2023:

OpenIFS 48r1 beta release available, full release by Q4

- in line with current operational IFS model cycle
- build procedure changed to ecBuild/cmake
- closely aligned with IFS working practice, which facilitates easier upgrades
- OpenIFS can now be run as 3D model or as SCM



6th OpenIFS User Meeting, Barcelona
42 participants, showcase of OpenIFS/AC



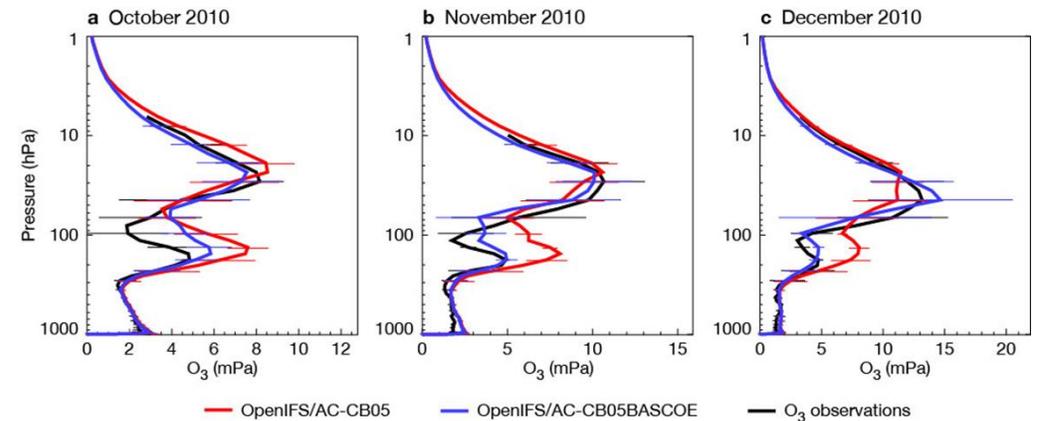
ECMWF | OpenIFS Data Hub

Dashboard

Data requests

Id	Status	Created at	Last updated at	
309	COMPLETED	Tue, 26 Sep 2023 10:46:05 UTC	Tue, 26 Sep 2023 11:05:16 UTC	📄 🗑️ ⋮
265	COMPLETED	Mon, 21 Aug 2023 13:01:45 UTC	Mon, 21 Aug 2023 13:22:29 UTC	📄 🗑️ ⋮
151	COMPLETED	Wed, 12 Jul 2023 16:30:11 UTC	Wed, 12 Jul 2023 16:58:03 UTC	📄 🗑️ ⋮
152	COMPLETED	Wed, 12 Jul 2023 16:30:35 UTC	Wed, 12 Jul 2023 16:54:28 UTC	📄 🗑️ ⋮
123	COMPLETED	Fri, 30 Jun 2023 16:46:26 UTC	Fri, 30 Jun 2023 17:07:34 UTC	📄 🗑️ ⋮

OpenIFS Data Hub publicly released in Bologna, May 2023
500+ GB of initial data provided since July 2023
supports data production for cycles 43r3, 48r1 and beyond

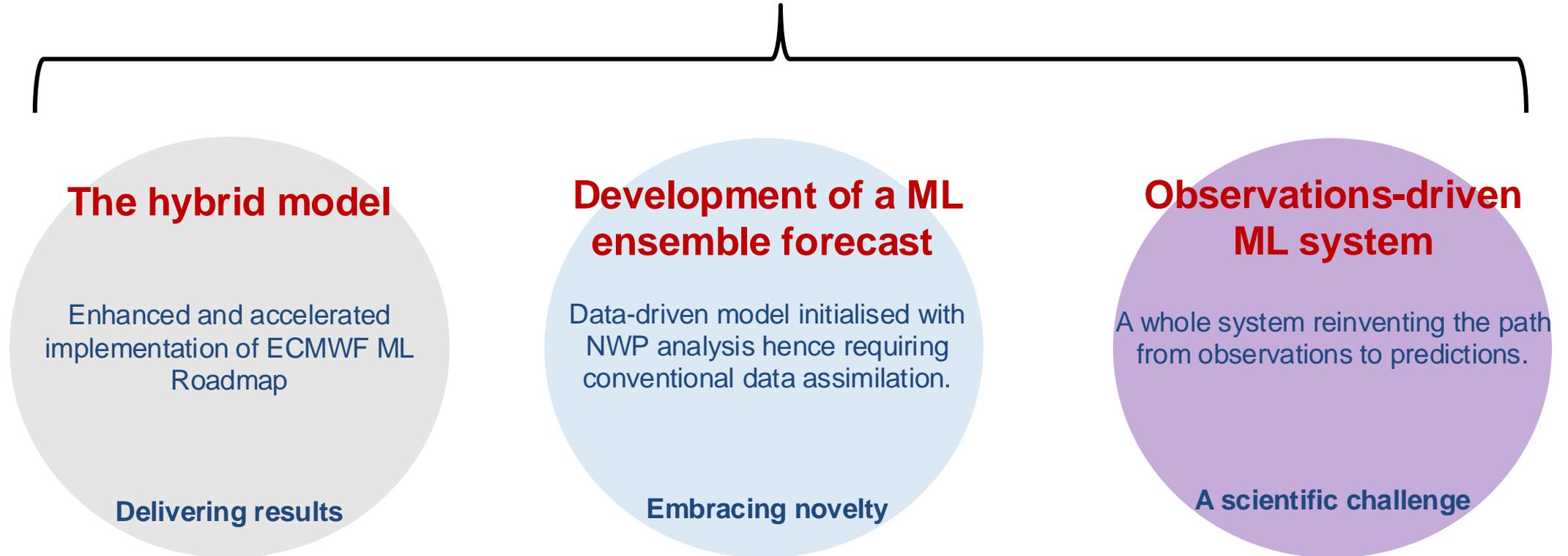


OpenIFS/AC composition modelling now includes
Strat (BASCOE) + Trop (CB05) + AER in OpenIFS 48r1 (single code base)



EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Enhanced ML efforts at ECMWF – project overview

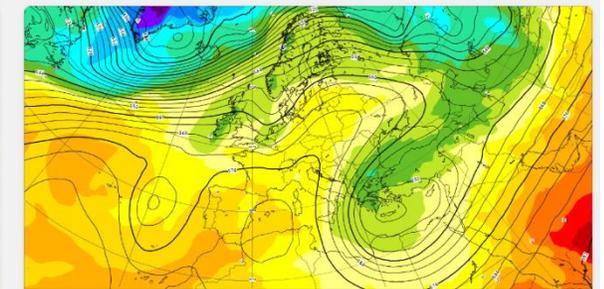
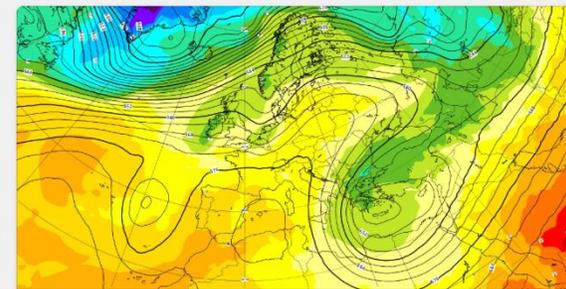
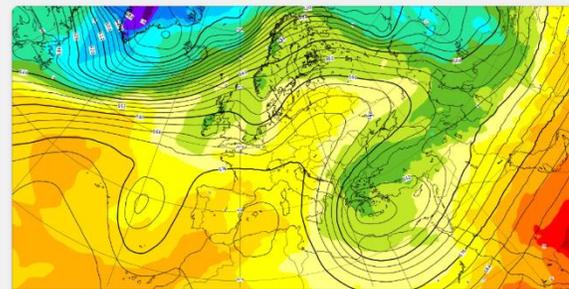
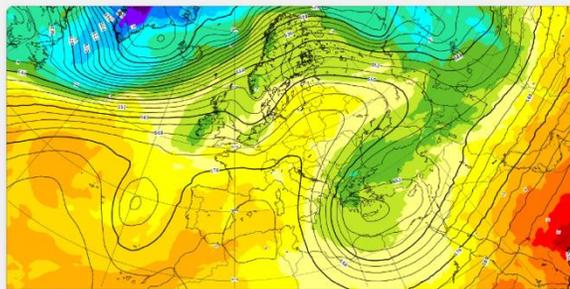
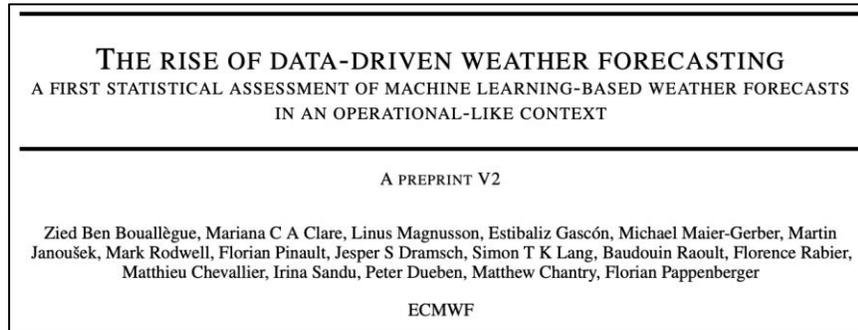


ECMWF collaborative project with Member States as one project of a EUMETNET programme

Step 1: Evaluation in an operational setting

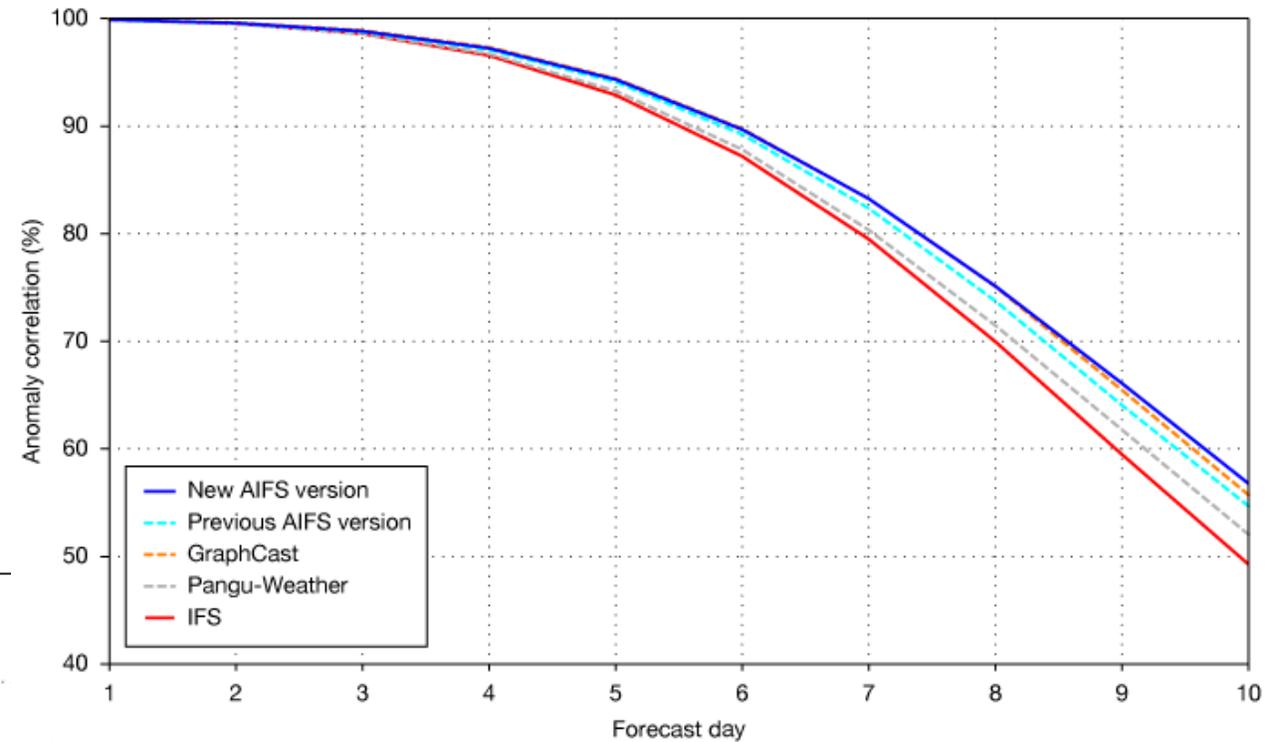
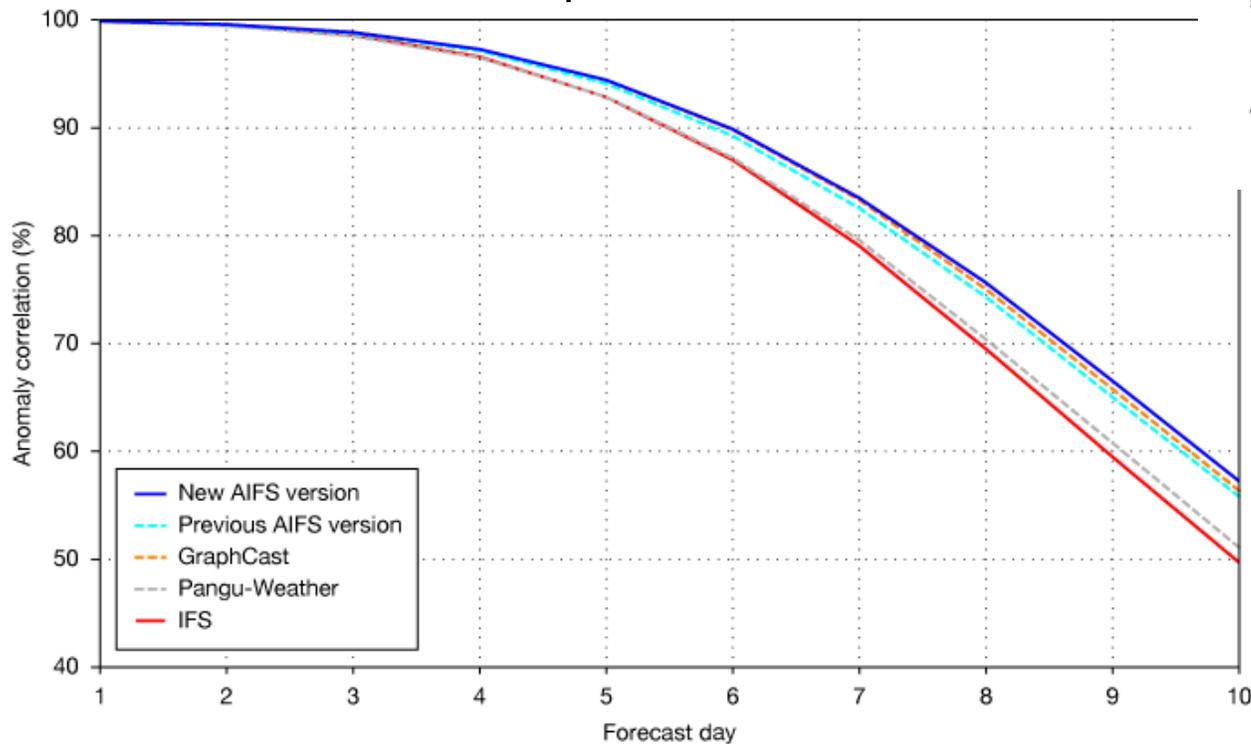
How to establish trust in a new type of forecasting system?

- Live daily forecasts provided openly
 - Only possible because of open-source contributions from NVIDIA, Huawei, Deepmind.
- Enables real time evaluation of extreme events by operational analysts.
 - As a community we can better identify strengths and weaknesses.



AIFS v0.2 – atmospheric skill

Northern hemisphere z500 ACC

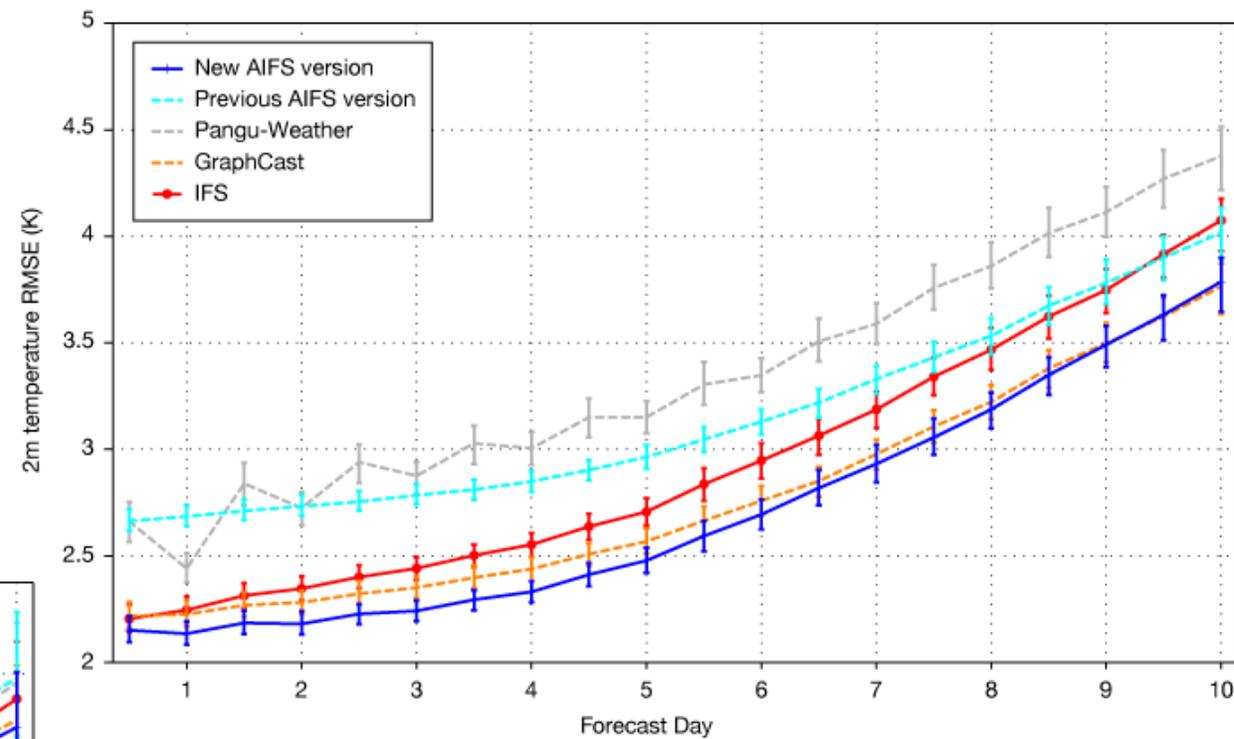
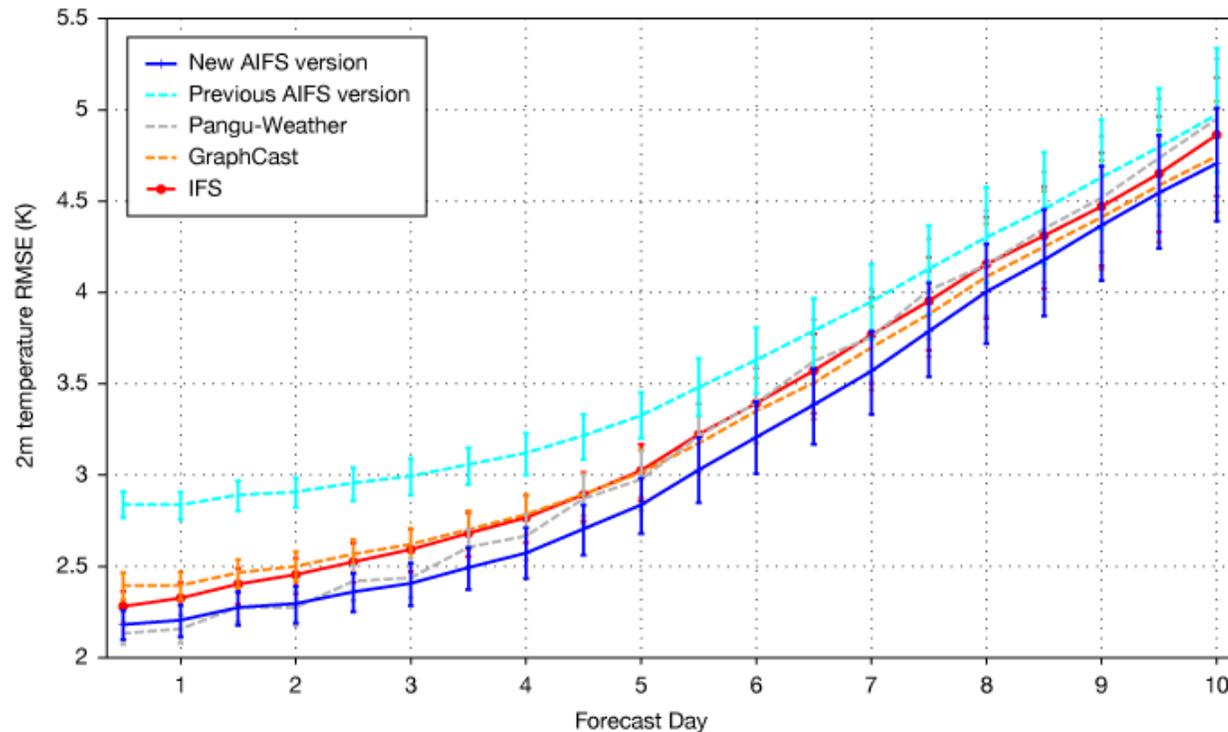


Southern hemisphere z500 ACC

Higher = better

AIFS v0.2 – surface against observations

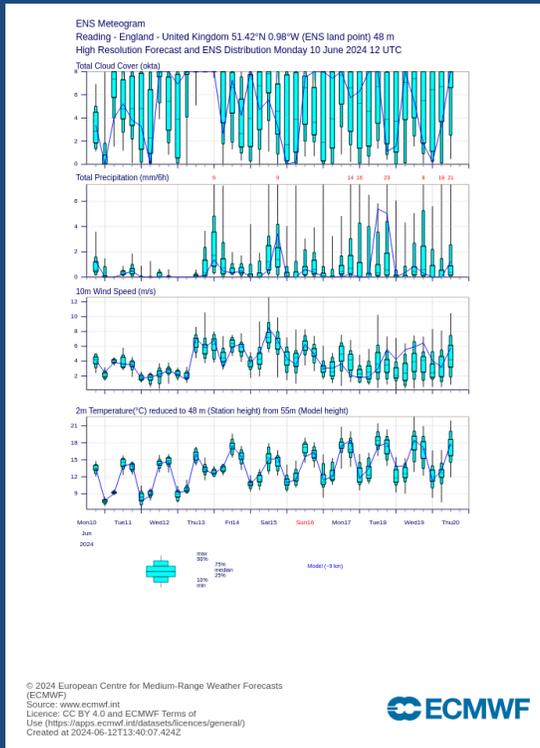
Northern hemisphere 2m-temperature



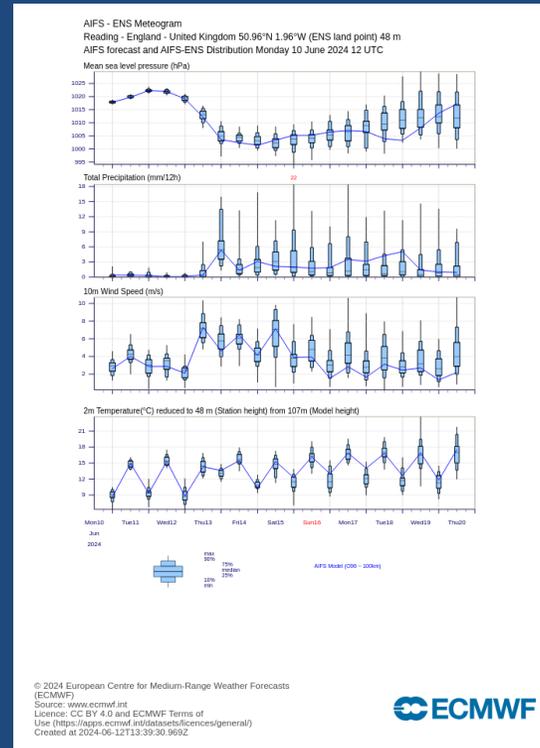
Southern hemisphere 2m-temperature

Lower = better

AIFS Ensemble...



ENS meteogram



AIFS ENS meteogram

Regional modeling with Member States

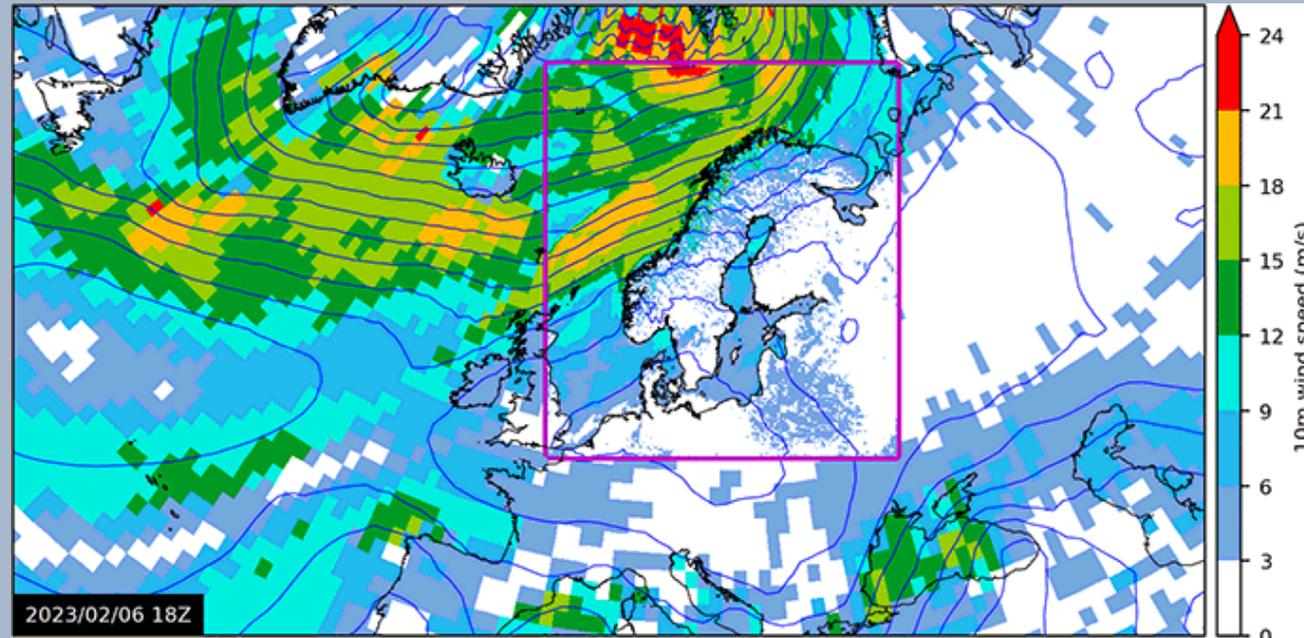
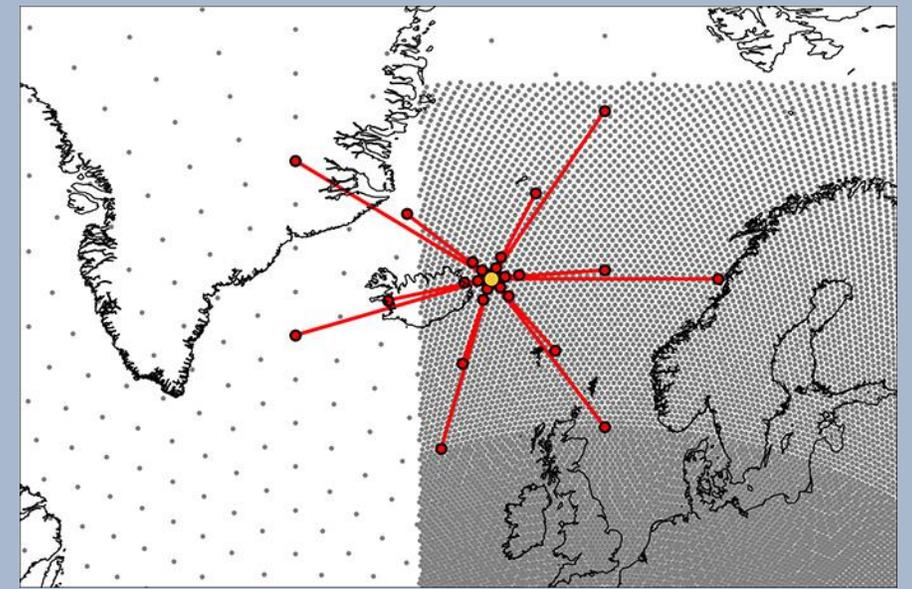
Data-driven regional modelling

23 April 2024

Thomas Nipen (MET Norway)

Matthew Chantry (ECMWF)

The AIFS teams from ECMWF and MET Norway



7-day forecast
of 10m
10km over the
Nordics
100km global

 Norwegian
Meteorological
Institute

Member State Pilot Project
kicked off recently.
Meteo France co-lead work
package 1 on data-driven
forecasting.

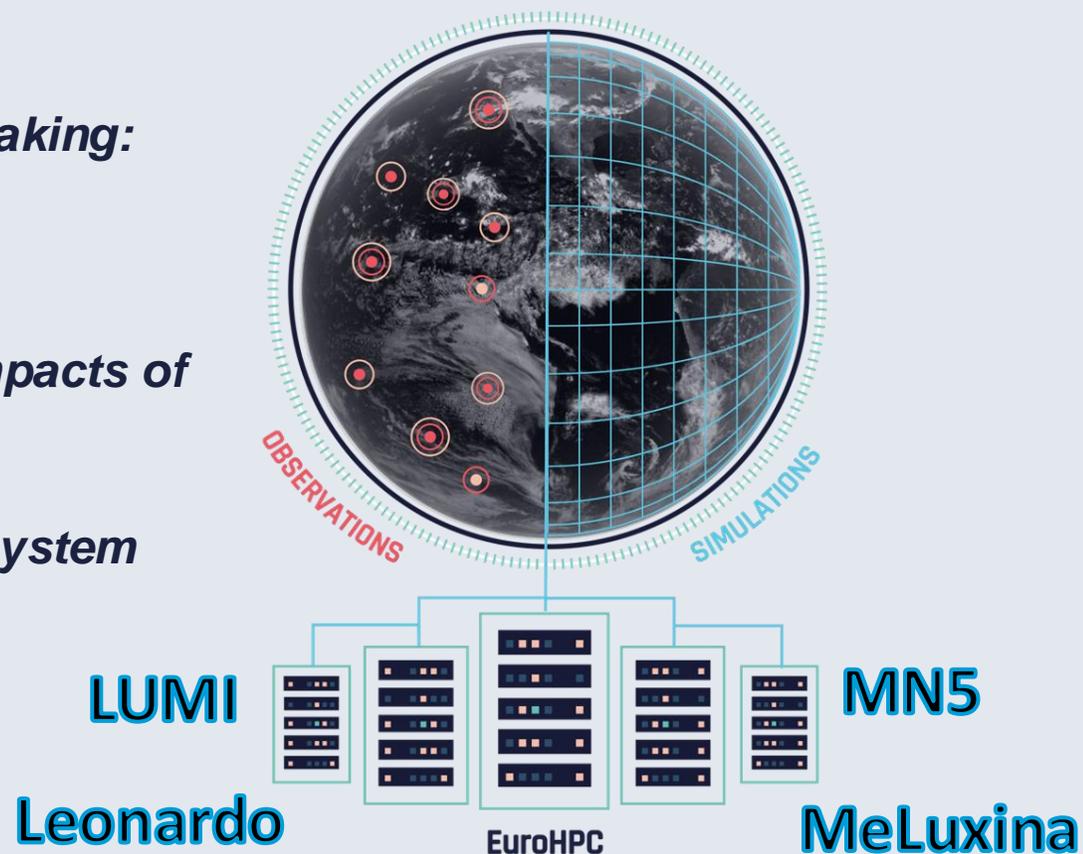




DEstine: a digital replica of our planet to respond and adapt to climate change and extreme events

DestinE, in strategic partnership with EuroHPC Joint Undertaking:

- *Establishes bespoke cutting-edge simulation capabilities*
- *Provides Earth-system information at scales where the impacts of extreme events and climate change are felt*
- *Fosters an innovative and thriving AI-enabled digital ecosystem*



Huawei – PanguWeather
0.25° hourly product

“More accurate tracks” than the IFS.

Nov 2022
Tropical cyclones

Microsoft – ClimaX

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

Jan 2023
Global & Limited Area

NVIDIA – SFNO
0.25° 6-hour product

Extension of FourCastNet to Spherical harmonics, improved stability

Spherical harmonics

Jun 2023

2018 first attempt

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

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

Dec 2022
Extensive predictions

Deepmind – GraphCast
0.25° 6-hour

Many variables and pressure levels with comparable skill to IFS.

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)

Diffusion modelling

Alibaba – SwinRDM
0.25° 6-hour product

Sharp spatial features

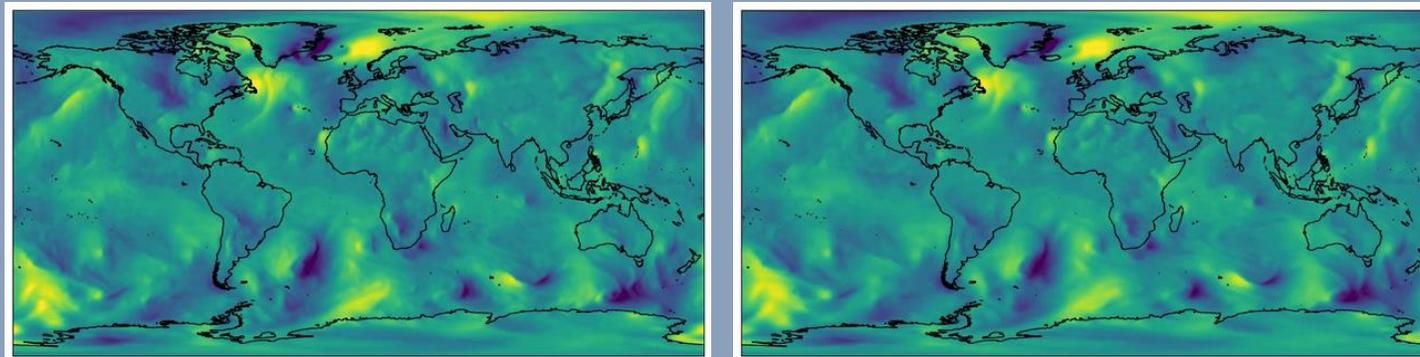
AIFS - Artificial Intelligence Forecasting System

First implementation (~ 1deg resolution) in 2023, following Keisler 2022 and Lam et. al 2022:

- GNN architecture: Interaction Networks (Battaglia et. al 2016)
- Graph representation, hidden multi-scale mesh, edge features
- Scales to > 1000s of GPUs ; tensor parallel implementation, split model across multiple GPUs

Update beginning of 2024, update to ~ 0.25 deg:

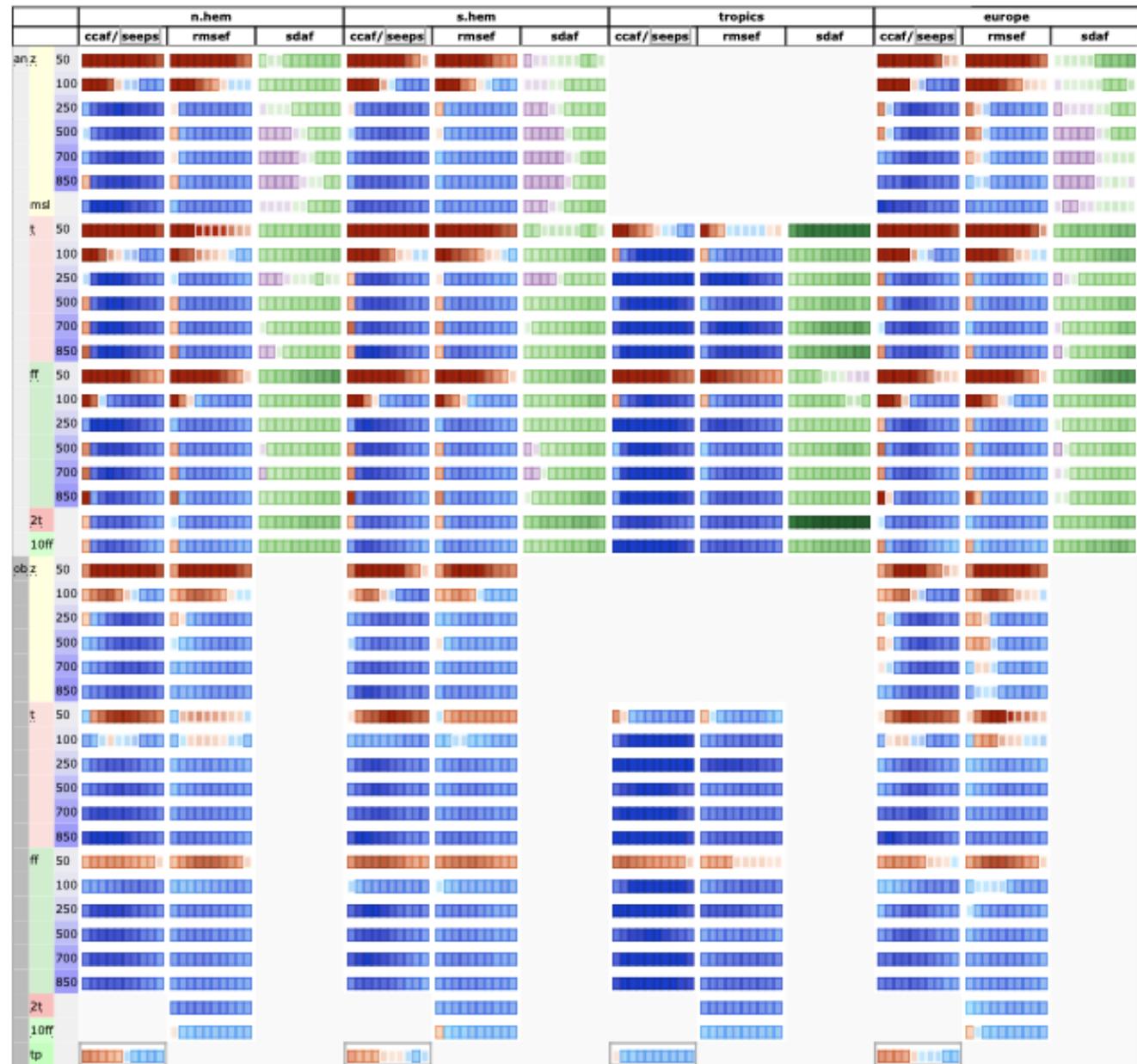
- Attention based GNN for encoder, decoder
- Transformer backbone in processor
- Trained on 64 GPUs ~ 1 Week



Why GNN Encoder / Decoder: can handle arbitrary input / output grids, local and ad hoc grid refinement, changing grids etc. ; attractive for use in earth system science

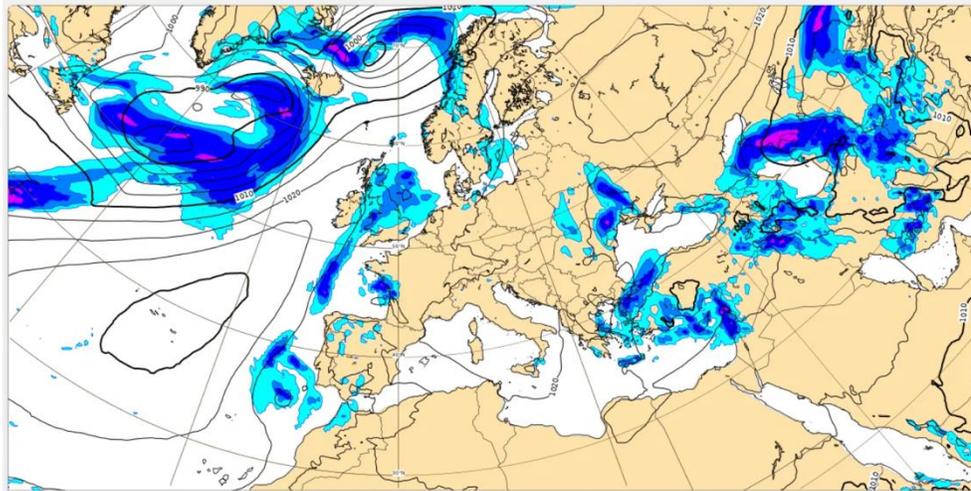
Lang, S., Alexe, M., Chantry, M., Dramsch, J., Pinault, F., Raoult, B., Clare, M.C., Lessig, C., Maier-Gerber, M., Magnusson, L. and Bouallègue, Z.B., 2024. AIFS-ECMWF's data-driven forecasting system. *arXiv preprint arXiv:2406.01465*.

Scorecard -> compared to IFS (2022)

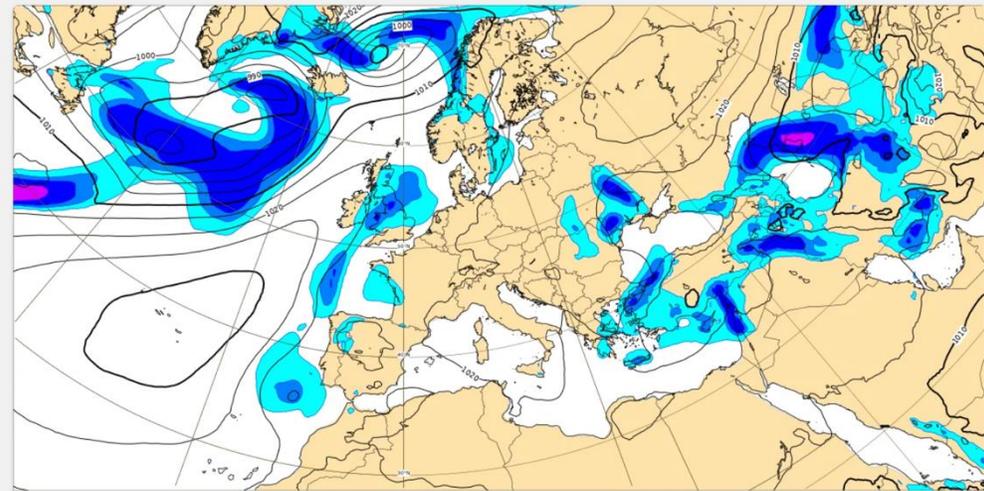


Scorecard comparing forecast scores of AIFS versus IFS (2022). Forecasts are initialised on 00 and 12 UTC. Shown are relative score changes as function of lead time (day 1 to 10) for northern extra-tropics (n.hem), southern extra-tropics (s.hem), tropics and Europe. Blue colours mark score improvements and red colours score degradations. Purple colours indicate an increased in standard deviation of forecast anomaly, while green colours indicate a reduction. Framed rectangles indicate 95% significance level. Variables are geopotential (z), temperature (t), wind speed (ff), mean sea level pressure (msl), 2 m temperature (2t), 10 m wind speed (10ff) and 24 hr total precipitation (tp). Numbers behind variable abbreviations indicate variables on pressure levels (e.g., 500 hPa), and suffix indicates verification against IFS NWP analyses (an) or radiosonde and SYNOP observations (ob). Scores shown are anomaly correlation (ccaf), SEEPS (seeps, for precipitation), RMSE (rmsef) and standard deviation of forecast anomaly (sdaf, see text for more explanation).

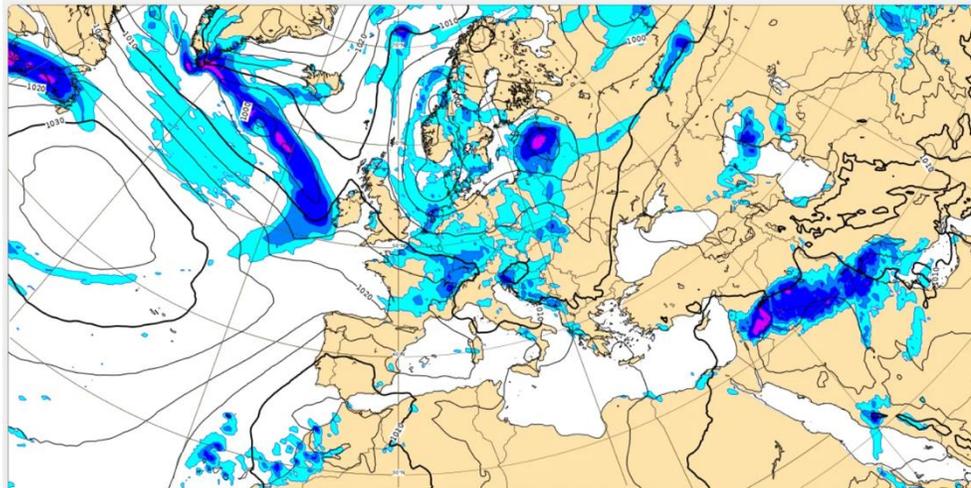
Precipitation currently lacking intensity and small-scale structure



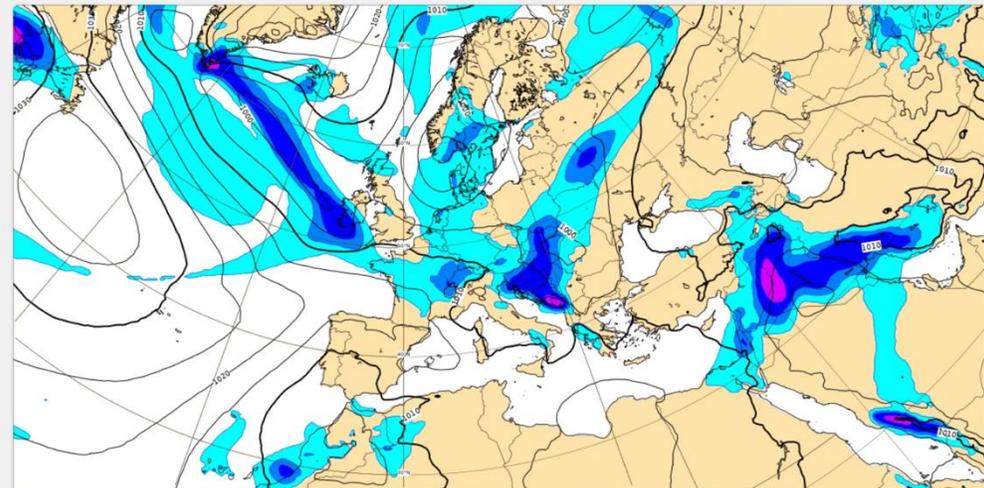
Rain and mean sea level pressure



Experimental: AIFS (ECMWF) ML model: Rain and mean sea level pressure



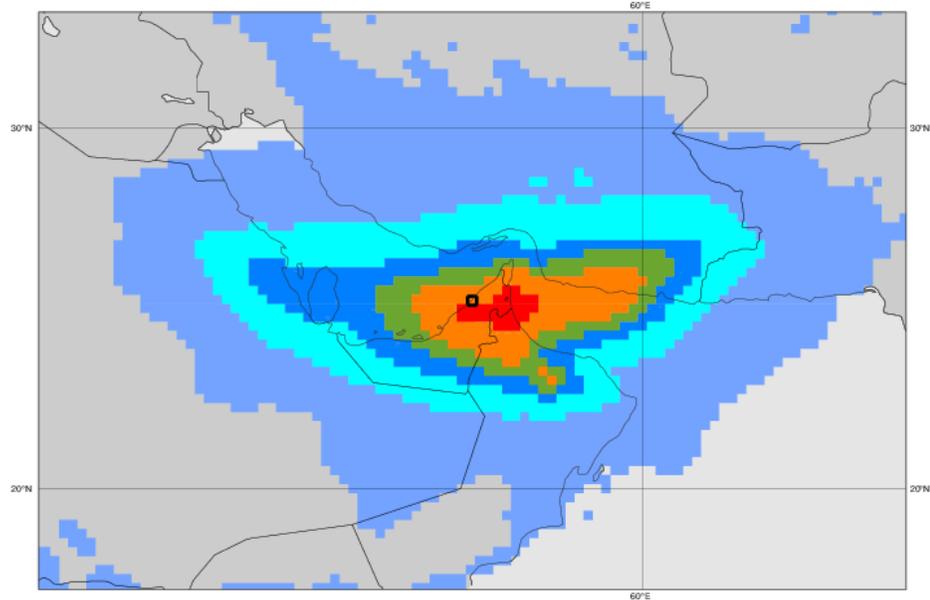
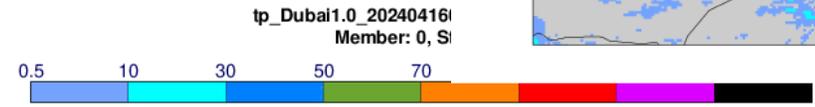
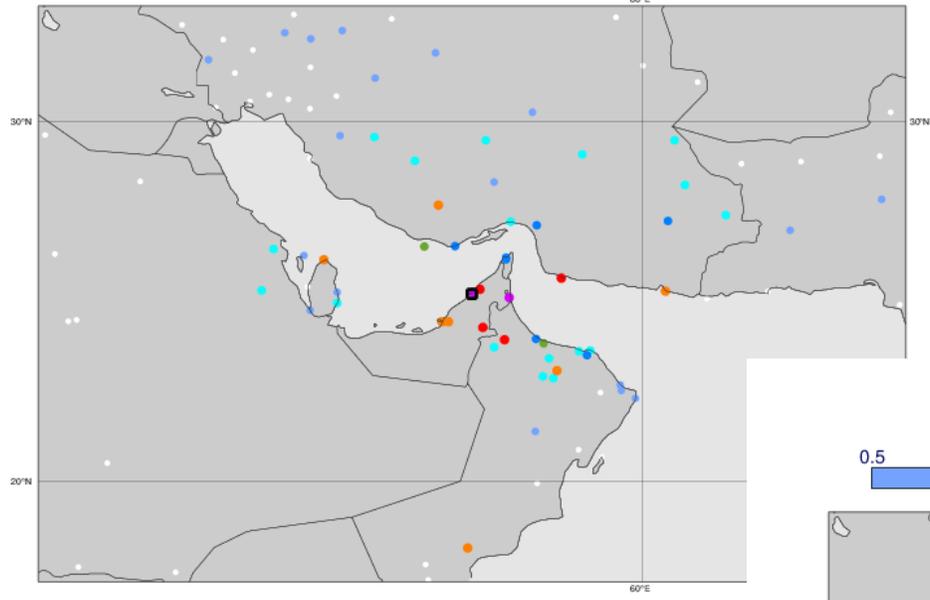
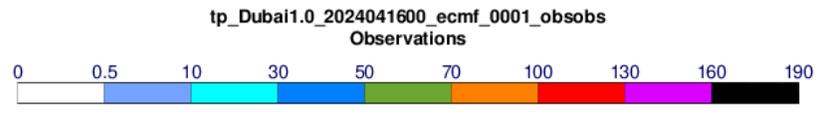
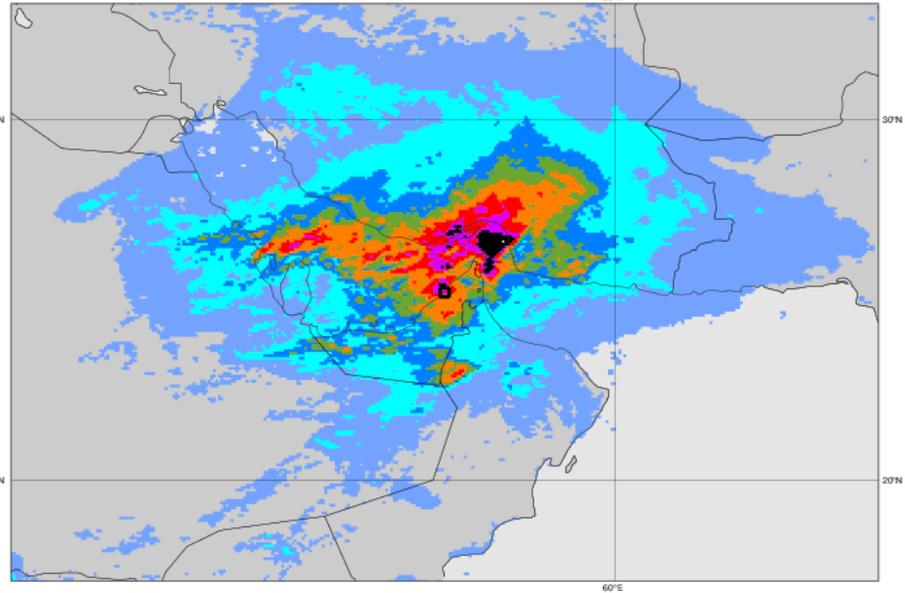
Rain and mean sea level pressure



Experimental: AIFS (ECMWF) ML model: Rain and mean sea level pressure

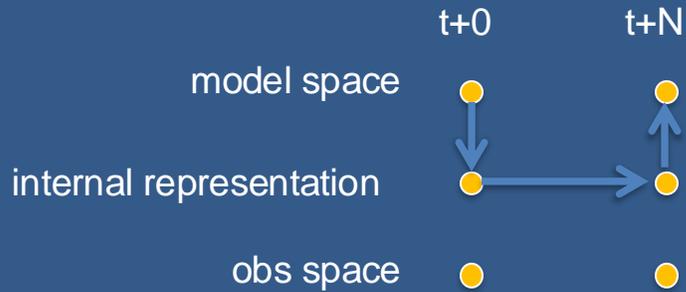


Recent extreme precipitation in UAE & region



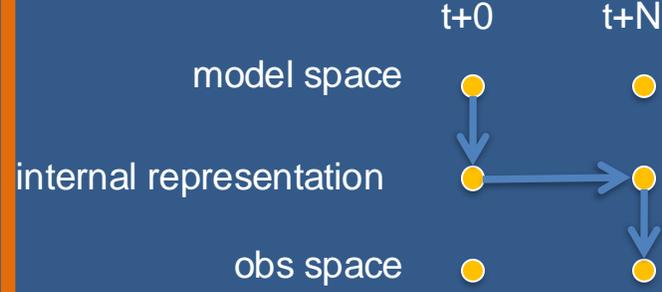
1) Predict analysis from analysis

e.g. current AIFS



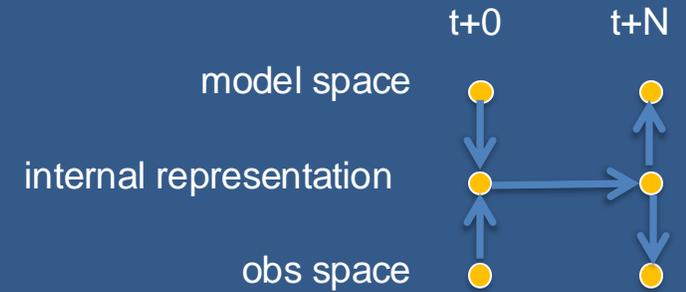
2) Predict obs targets from analysis

e.g. fine tune AIFS to predict SYNOPSIS



3) Augment analysis driven ML with obs

e.g. obs not used by 4D-Var

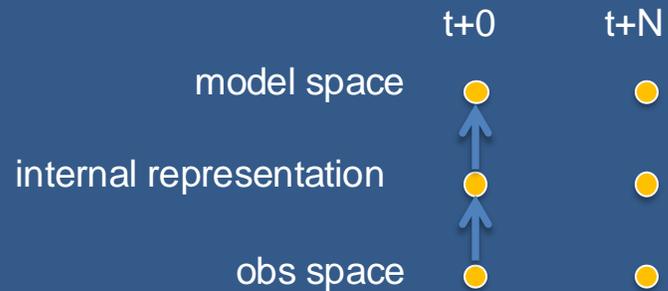


Augmenting existing analysis driven approaches with observational data

Initializing + learning from observations

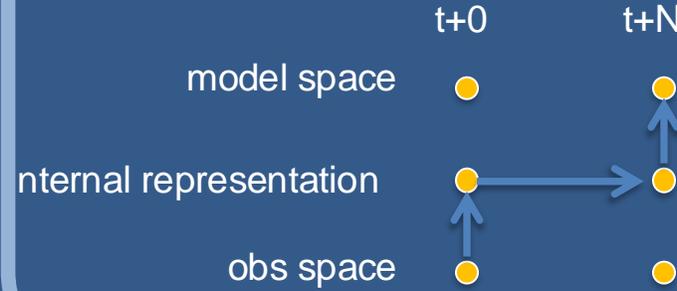
4) Learn the analysis

- emulate 4D-Var



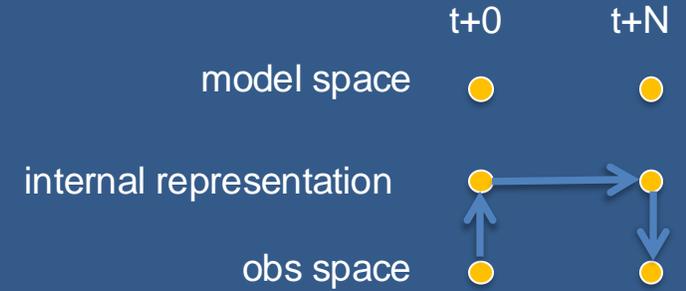
5) Predict future analysis from obs

- make predictions in model space
use reanalysis as truth



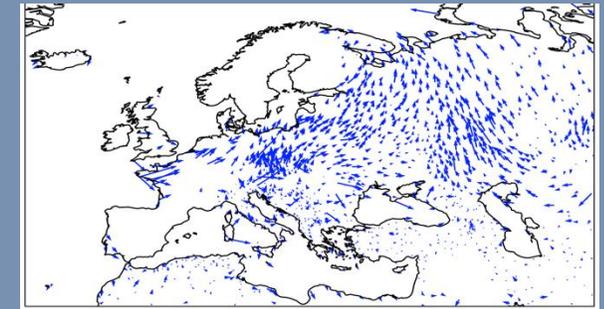
6) Predict future obs from obs

- make predictions in obs space
use obs as truth

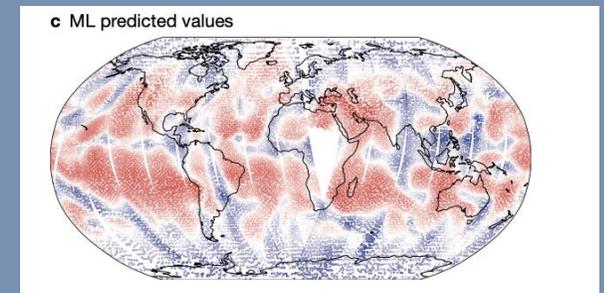


Data Driven Machine Learning Forecast trained / initialised from observations

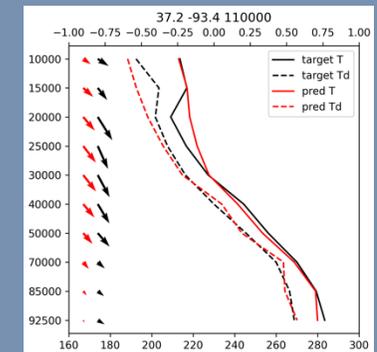
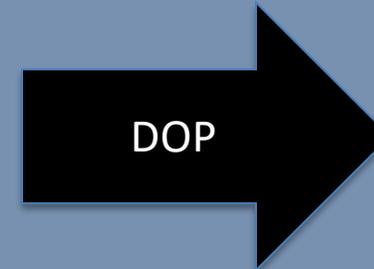
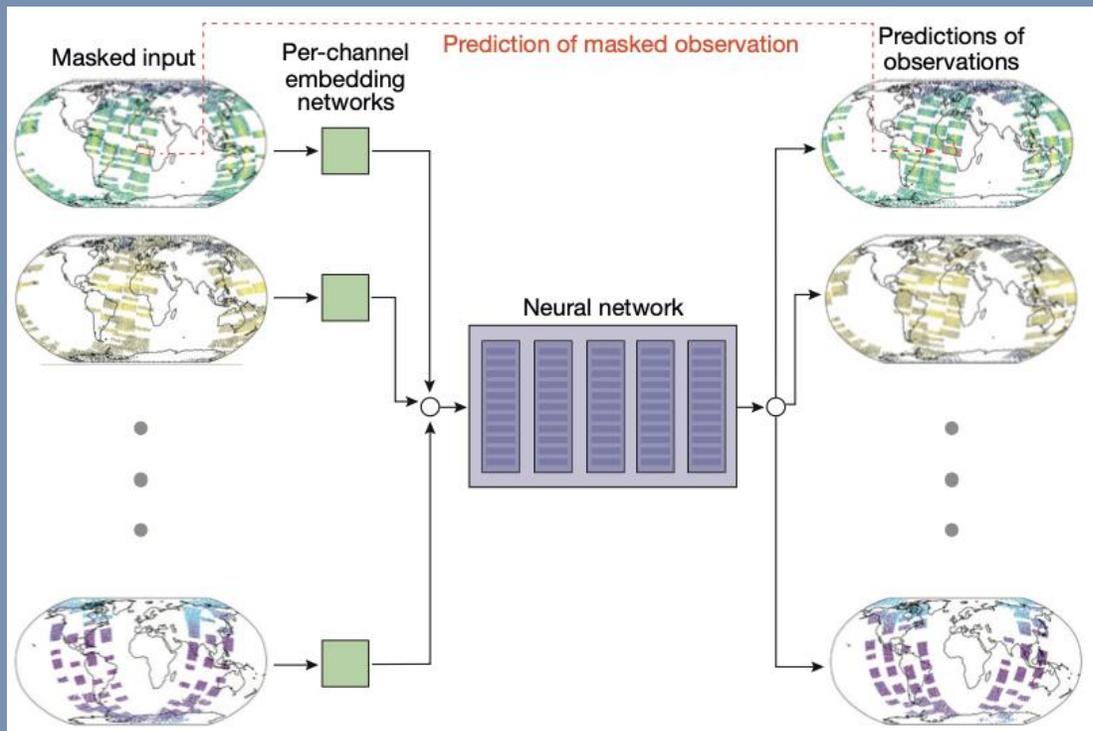
- Using historical measurements (10yrs ++) the network learns correlations between observations from different sources, at different locations and (crucially) at different times.
- Then from an input set of real-time observations the network can predict an observation of any type at any required future location and time.



Future SYNOP (T2m / wind)



Future radiances (MW/IR/VIS)



October 29, 2014
Future SONDEN (T / Q / wind)