ACCORD Workshop 2026

ECMWF exploitation of observations with 4D-Var and Machine Learning

Tony McNally

THE STRENGTH OF A COMMON GOAL

Structure of presentation:

1) Higher spatial resolution 4D-Var

- Analysis better captures small-scale detail
- Improved exploitation of OBS
- Improved IFS and AIFS forecasts

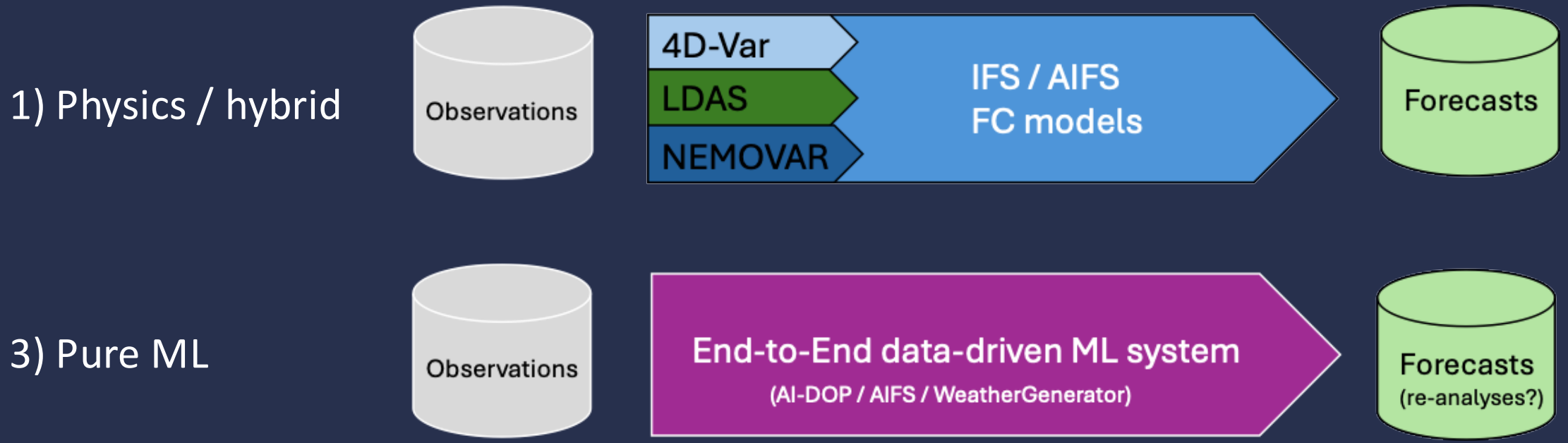
2) 4D-Var with Extending Windows

- Huge technical simplification of workflow suites
- Phase 1 aim – reproduce current operational products
- Future capability to provide MS with more frequent analyses

3) Direct Observation Prediction (DOP)

- Analysis trained ML forecast systems potentially unsustainable
- DOP learns a new physical model purely from observations
- Super fast – deployable to high-res DA / FC and re-analysis

Current ECMWF development landscape: 2 parallel but complementary forecast streams



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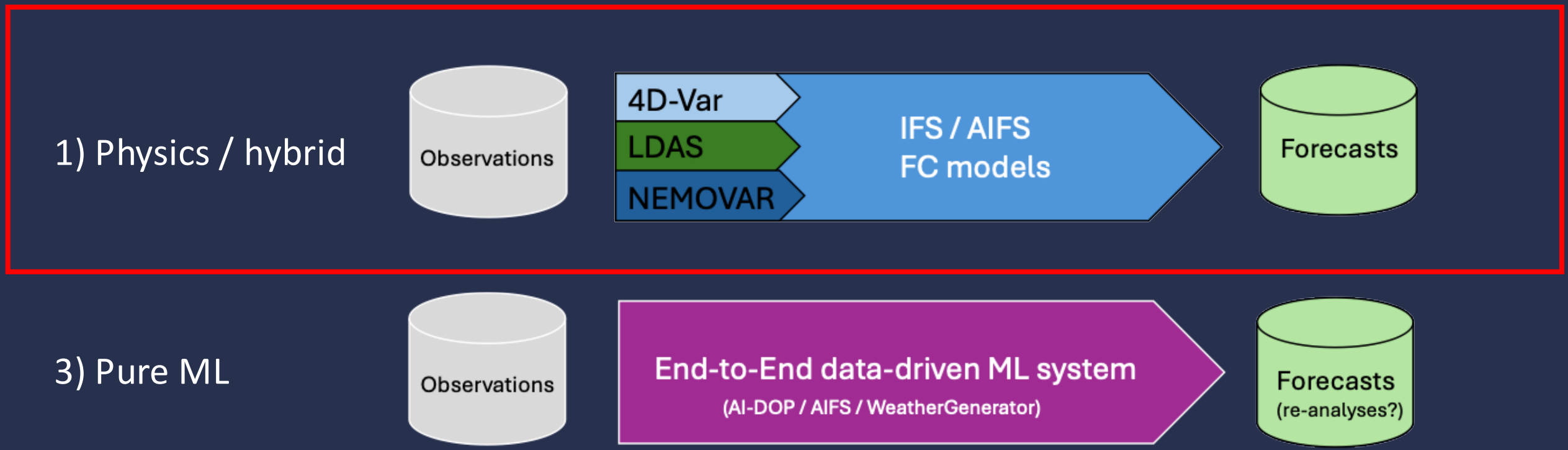
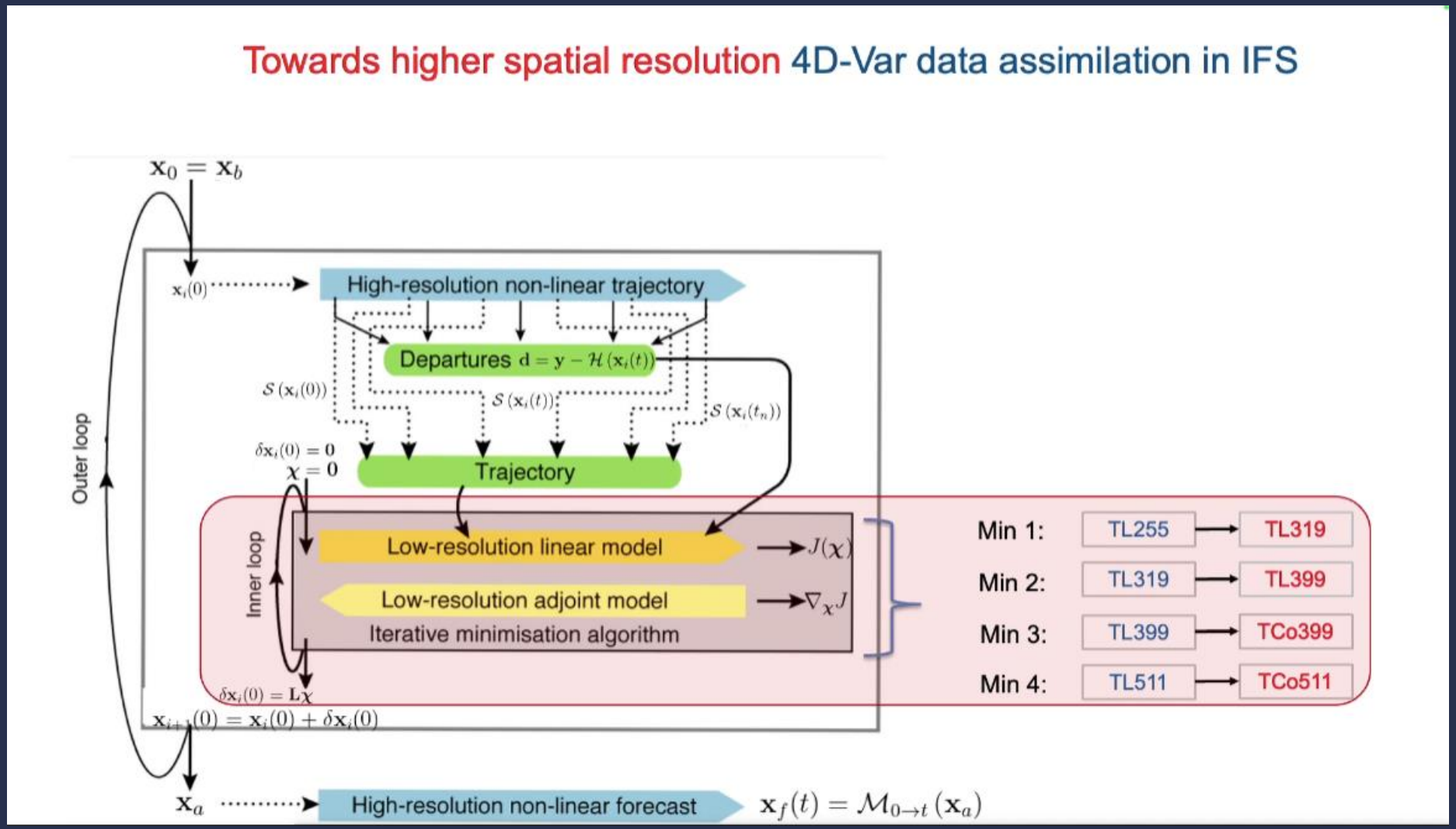


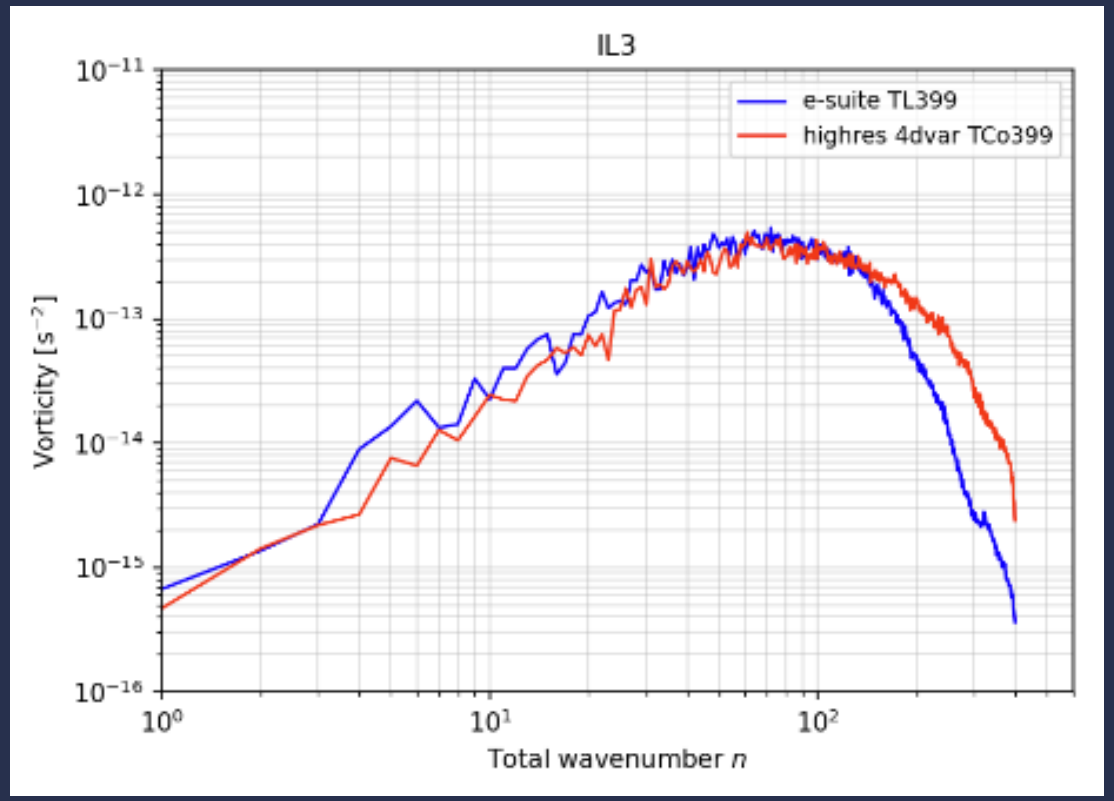
Higher spatial resolution 4D-Var

Higher spatial resolution 4D-Var…inner loop to ~ 20km

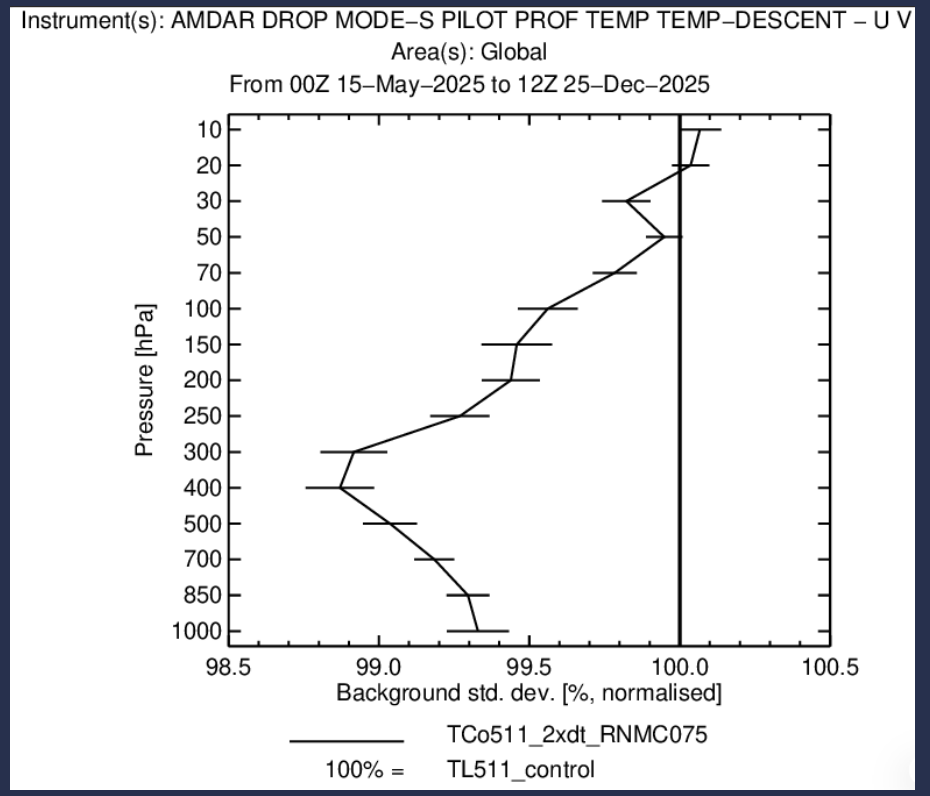


Higher-resolution 4D-Var…improved analysis detail

Better capturing of small-scale features in the analysis allowing the final inner-loop to add additional detail from the observations



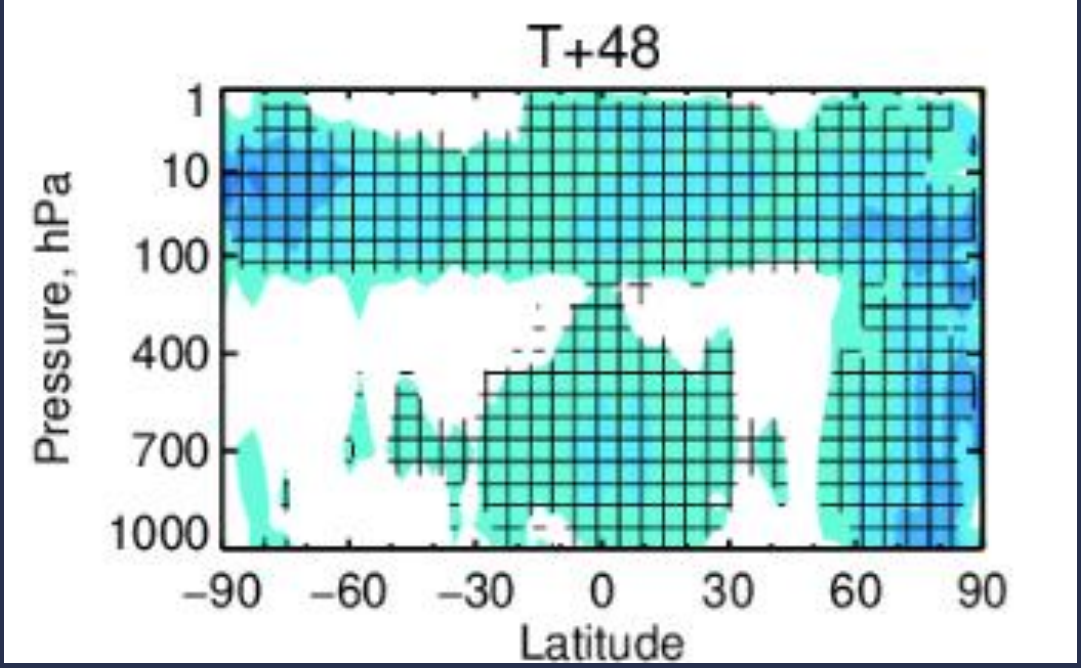
Better exploitation observations, which in future could allow a more optimal use of very dense data (without thinning)

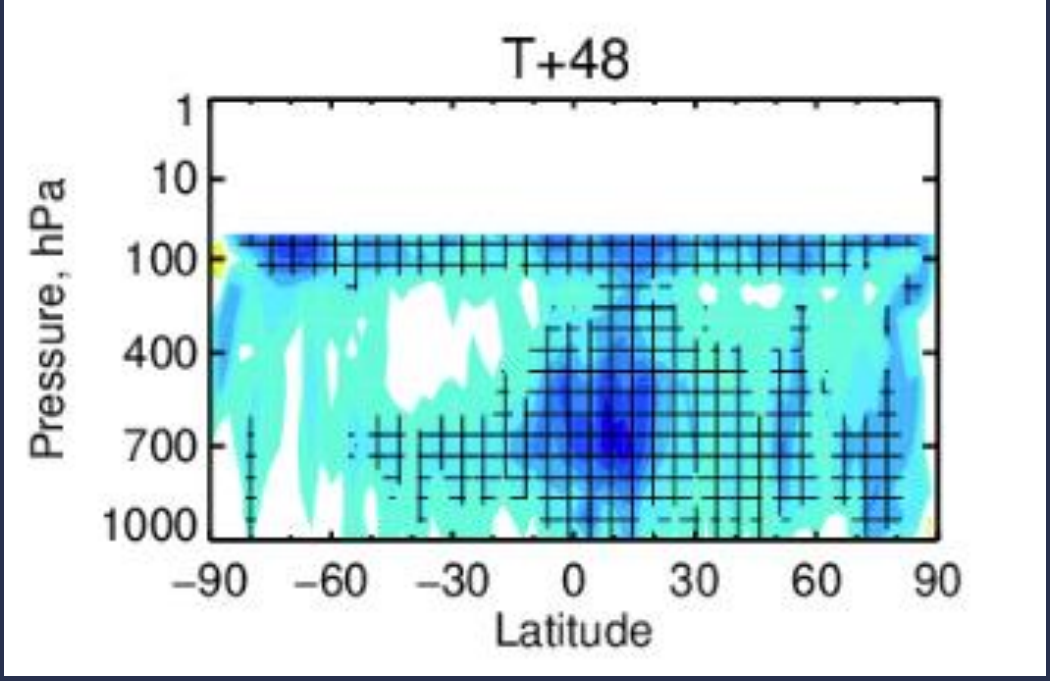


Higher spatial resolution 4D-Var…improved forecasts

The more accurate and more detailed initial conditions result in modest but consistent improvements in IFS medium-range forecast accuracy.

But the better initial conditions also improve AIFS forecasts! This improvement is expected to be even larger when AIFS is fine-tuned against the new 20km analysis





4D-Var with Extending Windows (ExWin)

4D-Var with Extending Windows (ExWin)

Rationale

- Simplify numerous operational suites to a single workflow
- Phase 1 aim – reproduce current operational analysis schedule (with a single suite)
- Future capability to provide Member States with more frequent analyses on demand

Goals

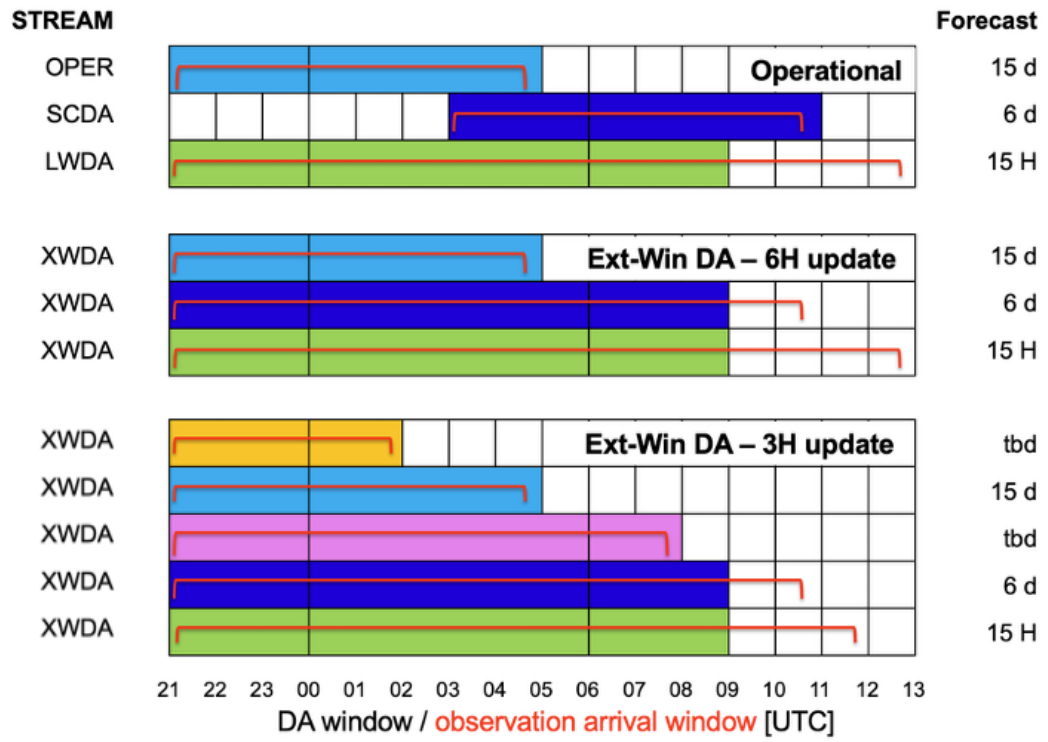
- Simplify DA system and ***its upgrades***
- Improve forecast scores
- ***Increase analysis update frequency***
- ***Uniformly distribute HPC resources***

Status

- Scripts/code porting to CY50R1 near completion
- MARS+EcCode compatible backends promised by end of September 2025
- Proposed for CY51R1
  - 6H update version
  - Neutral to positive impact against operational setup

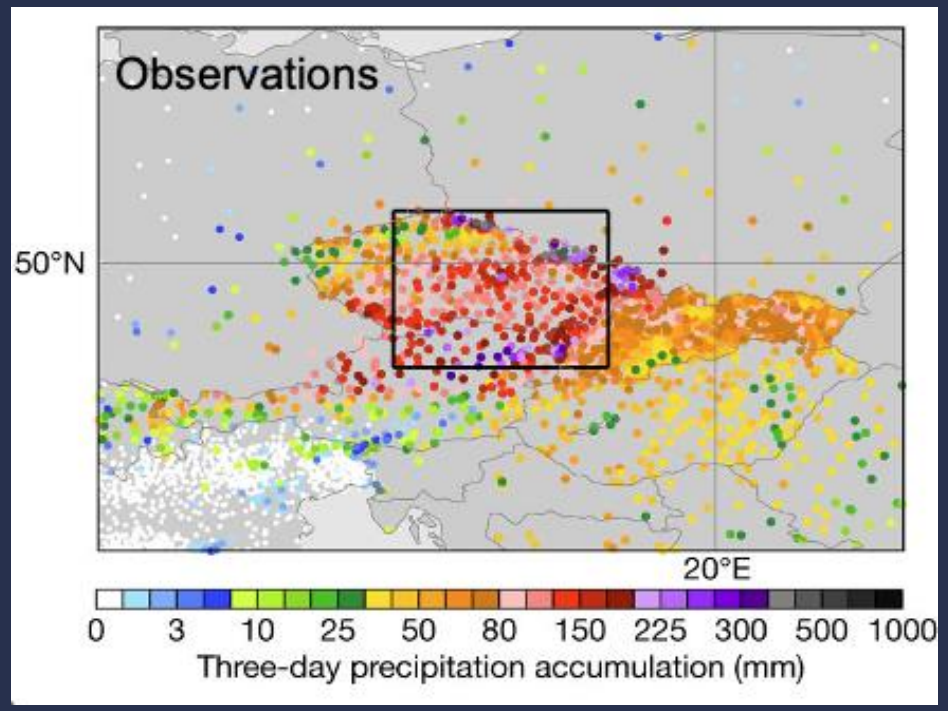
Upgradable to 3H update freq

- Case study @ TCo1279



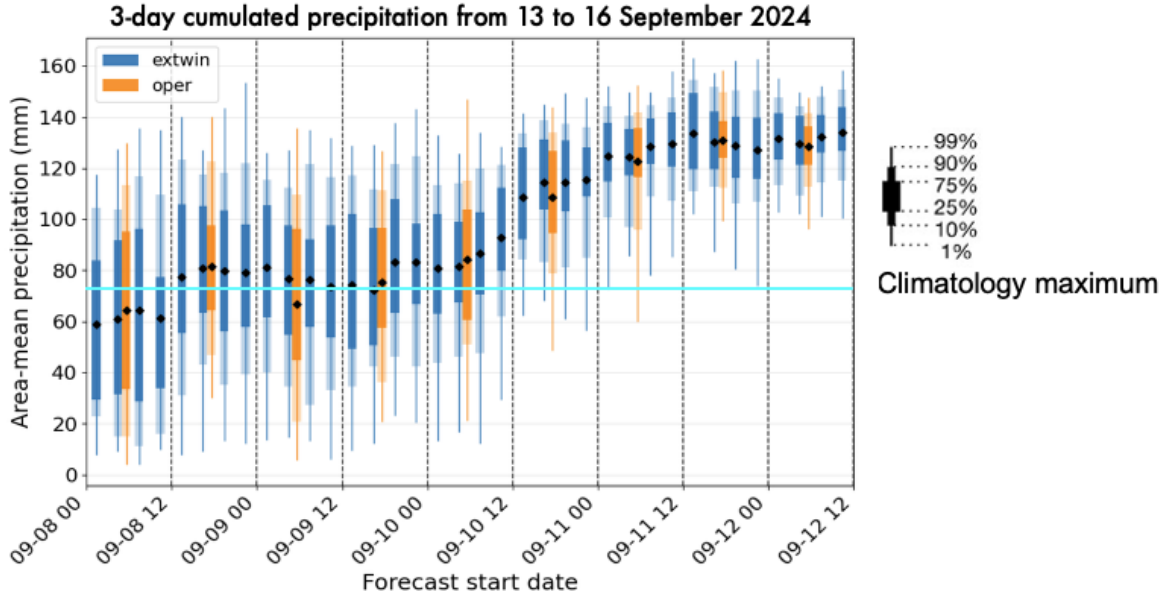
4D-Var with Extending Windows (ExWin)

More frequent analyses can be vital in severe weather

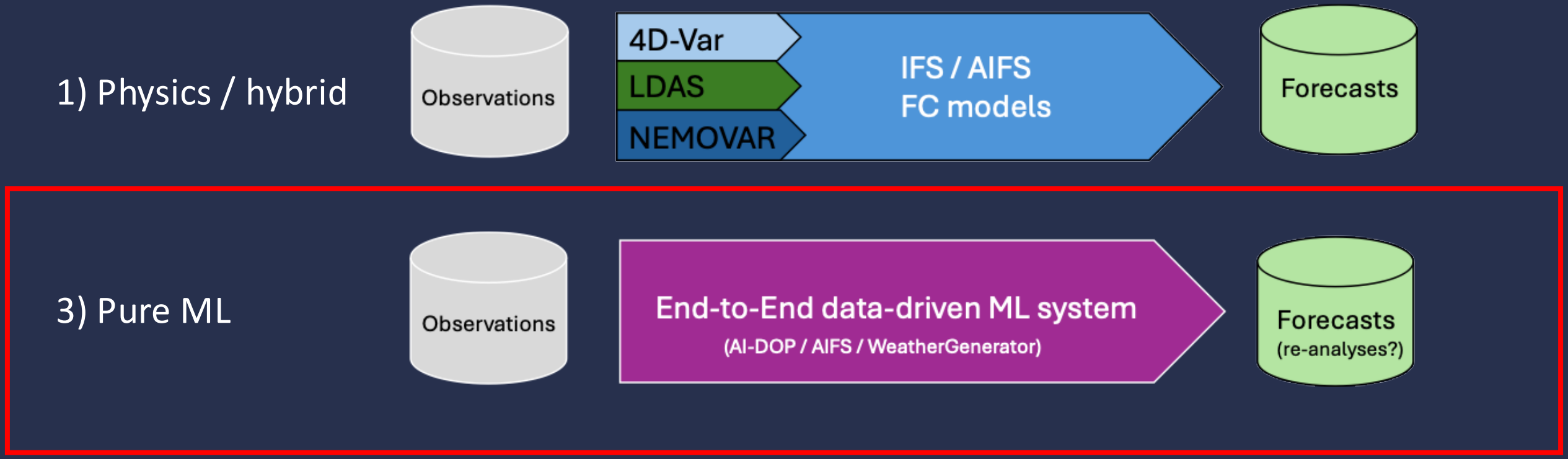


Storm Boris September 2024 @ TCo1279

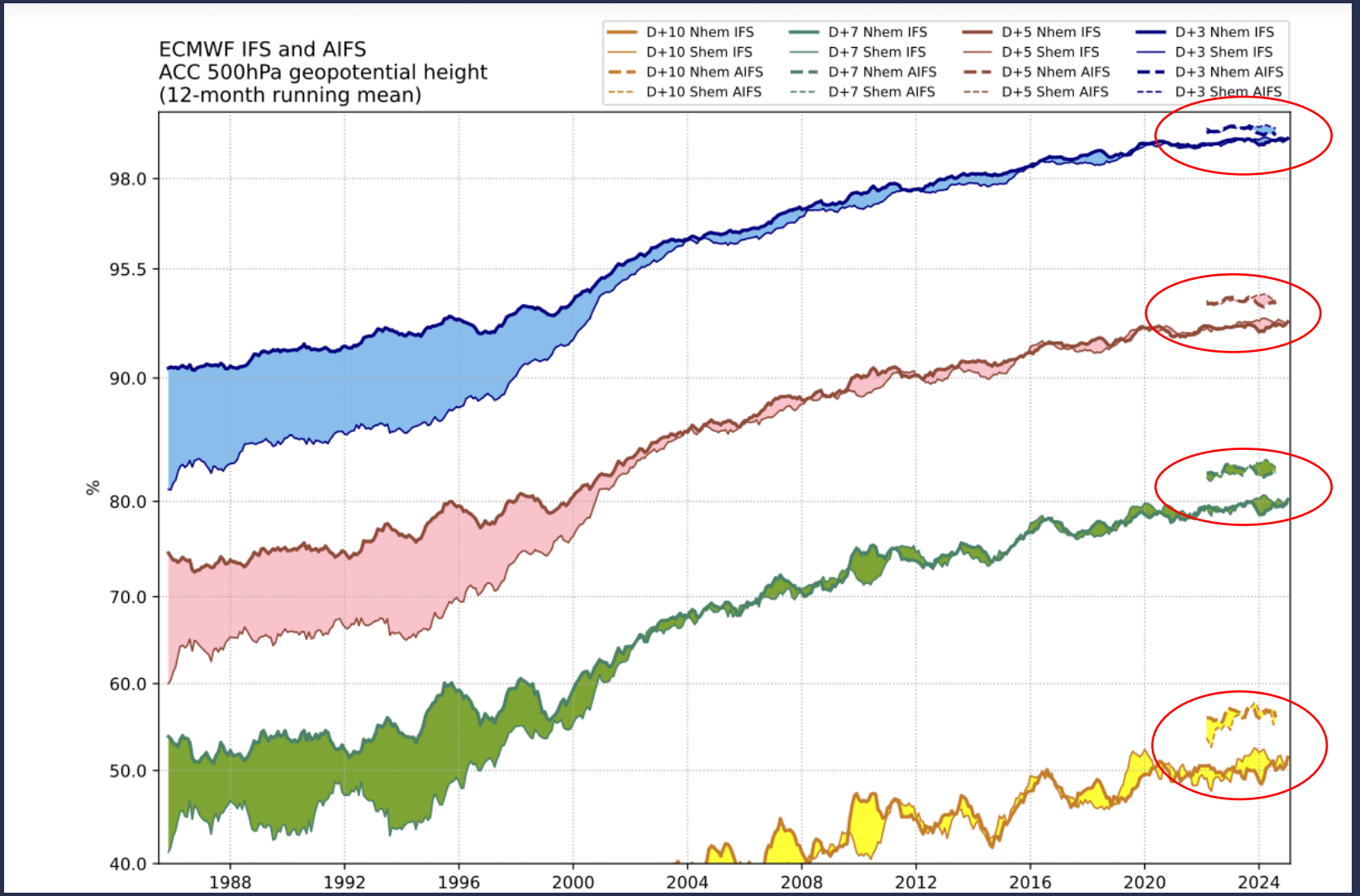
- Extending window: 3 hourly analysis and forecast update frequency
- Continuously follow the evolution of the forecast
- Increase confidence in issuing alerts



Current ECMWF development landscape: 2 parallel but complementary forecast streams



AIFS delivers skill gains over physics-based models similar to10 years of R+D…but…



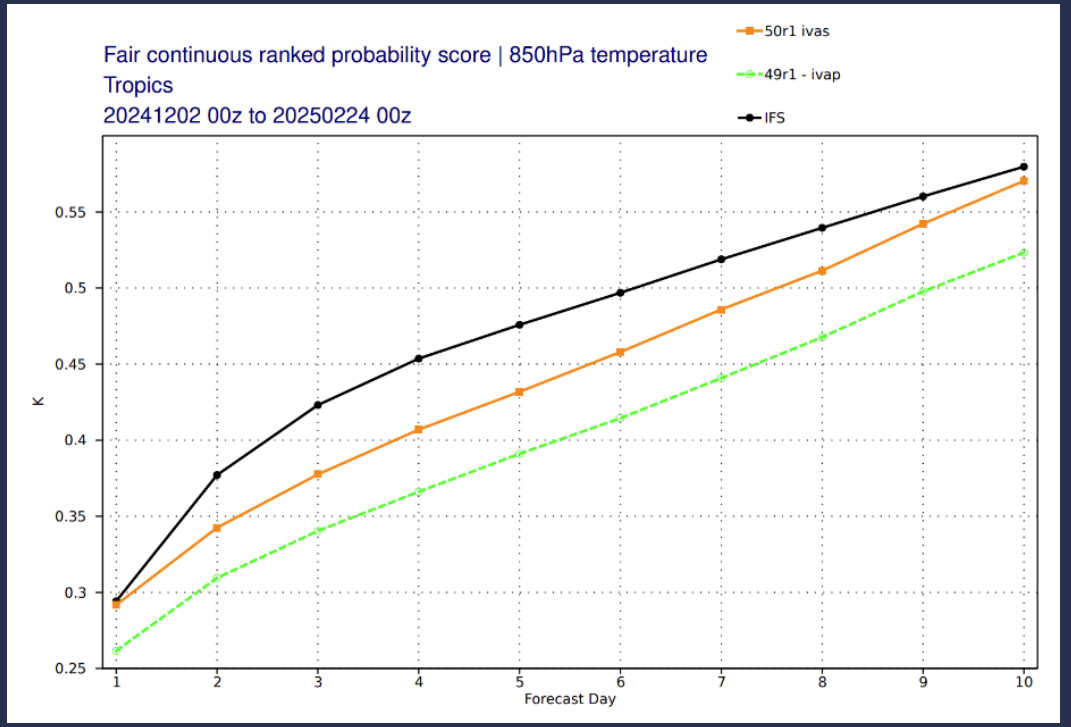
…questions over AIFS future operational sustainability and skill ceilings

AIFS (and all other ML models) are critically dependent on 4D-Var (ERA5) for training and / or initialisation (they are hybrids!!)

- AIFS requires the full resources of the operational physics model and DA to be maintained and improved in parallel…as well as maintaining AIFS itself!
- AIFS needs to be re-tuned when the 4D-Var, or the model or the OBS change (R2O)

New AIFS operational cycle v2: unexpected adverse reaction to 50r1 initial conditions!

- We know the 50r1 DA changes produced a more accurate 4D-Var analysis
- However, initializing AIFS forecasts with this analysis significantly degraded AIFS!
- AIFS skill was recovered only when retrained / fine-tuned against 50r1 analyses



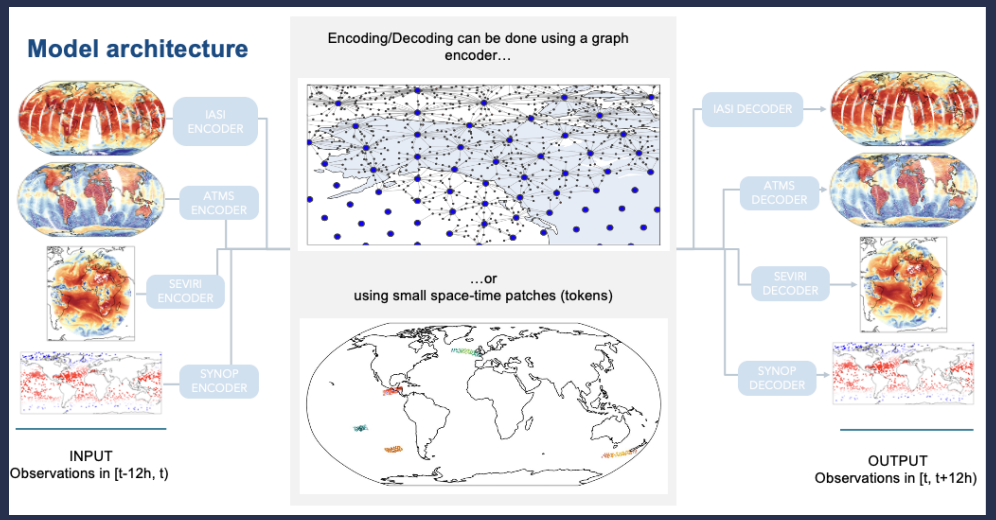
Direct Observation Prediction

Direct Observation Prediction – learning a new model

DOP learns a physical model of the entire Earth system directly from decades of historical observations…then initializes this model with the latest daily observations to make forecasts

Several decades of historical observations (1978 to 2026)

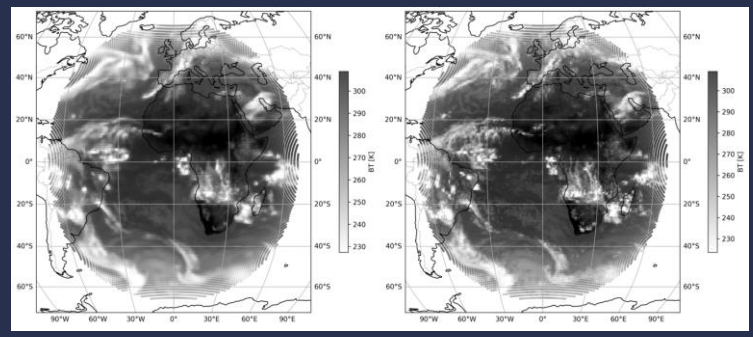
Training



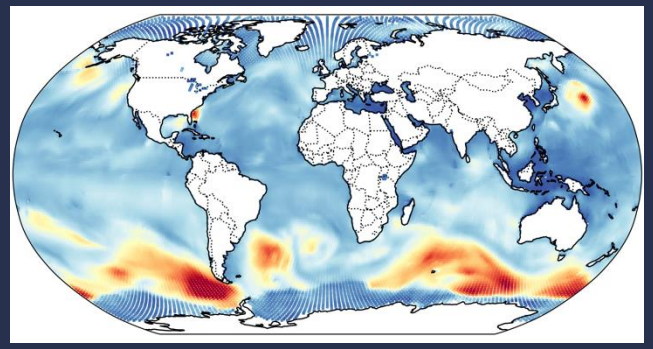
New prediction model generalizes outside of training

DOP

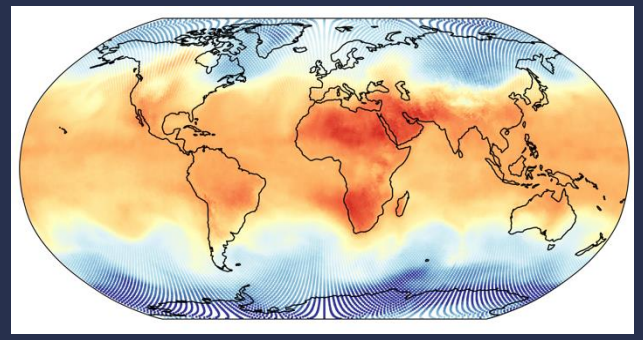
real observations



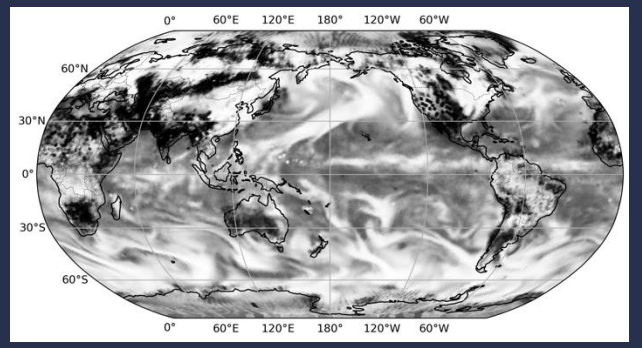
DOP can make predictions for any observed variable…at any location



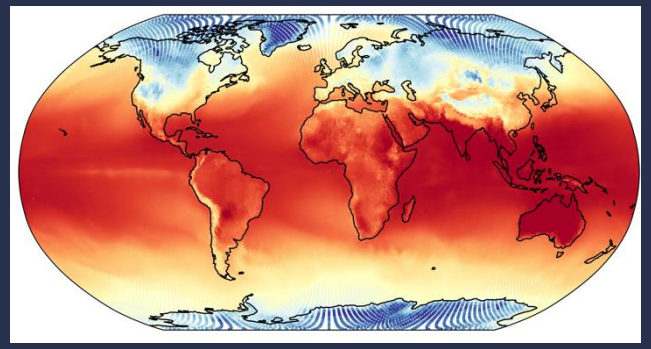
Significant wave height



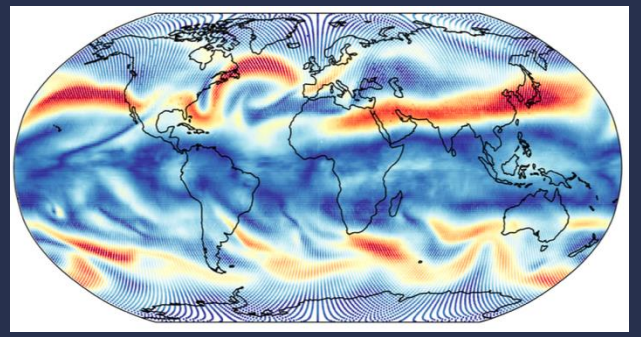
850hPa temperature



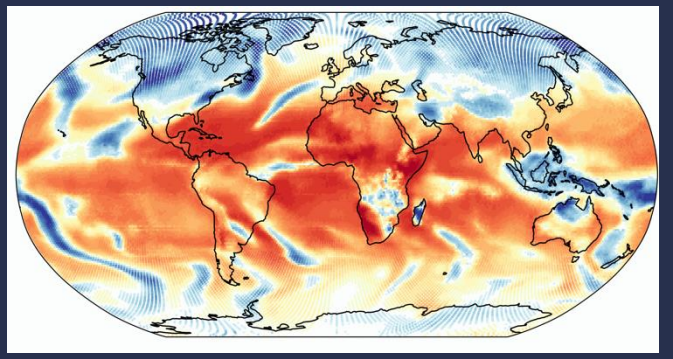
Cloud fraction



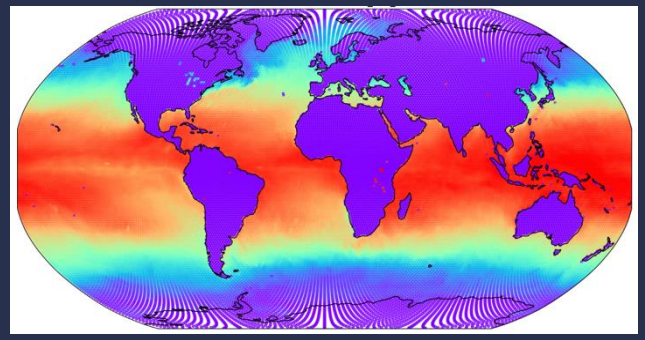
2-meter temperature



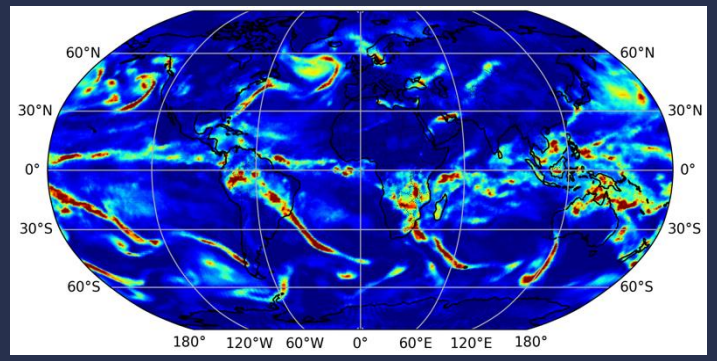
200hPa winds



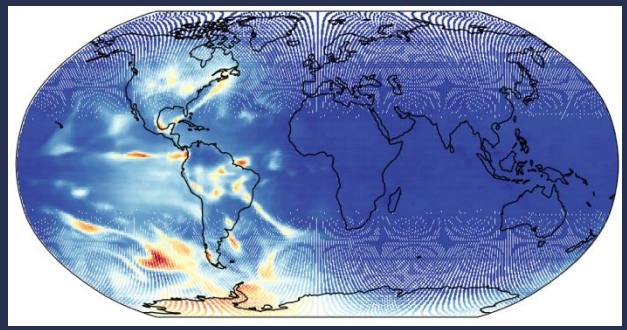
SEVIRI infrared window channel



Sea surface temperature



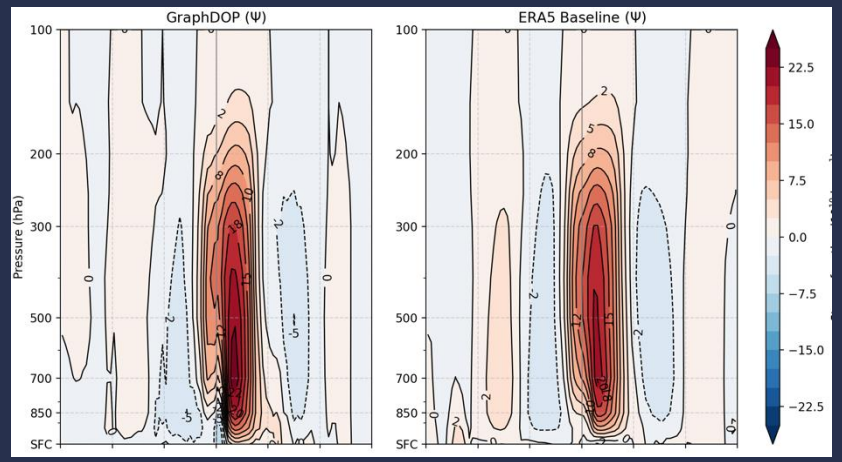
1 hour precipitation accumulation



AVHRR visible channel

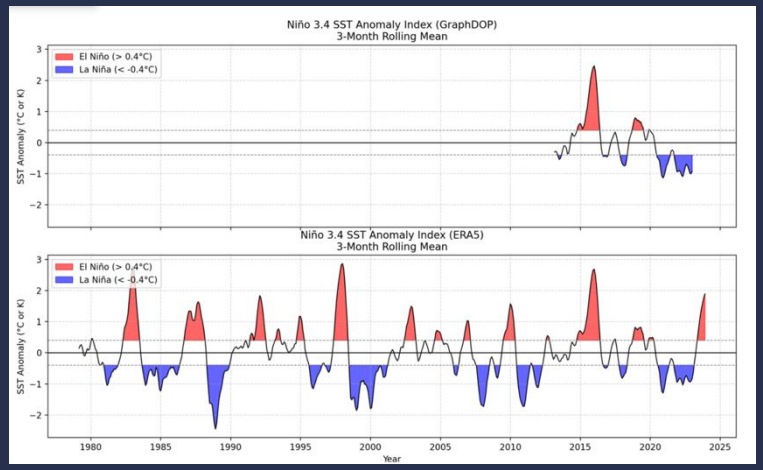
DOP predictions show very realistic climate features

Hadley Circulation (stream function)

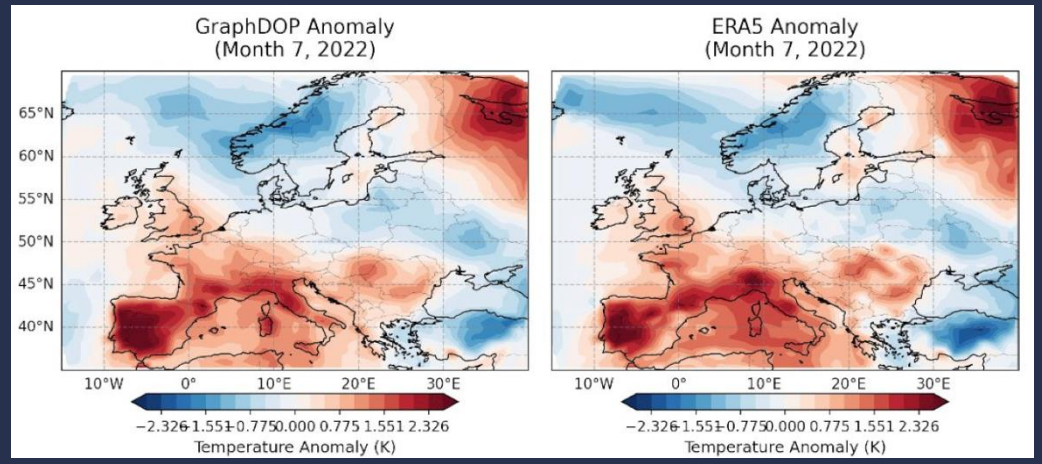


Reanalysis of the decade took just a few hours on 4 GPUs. But DOP is non-serial, and could be parallelized over many GPUs to run in minutes

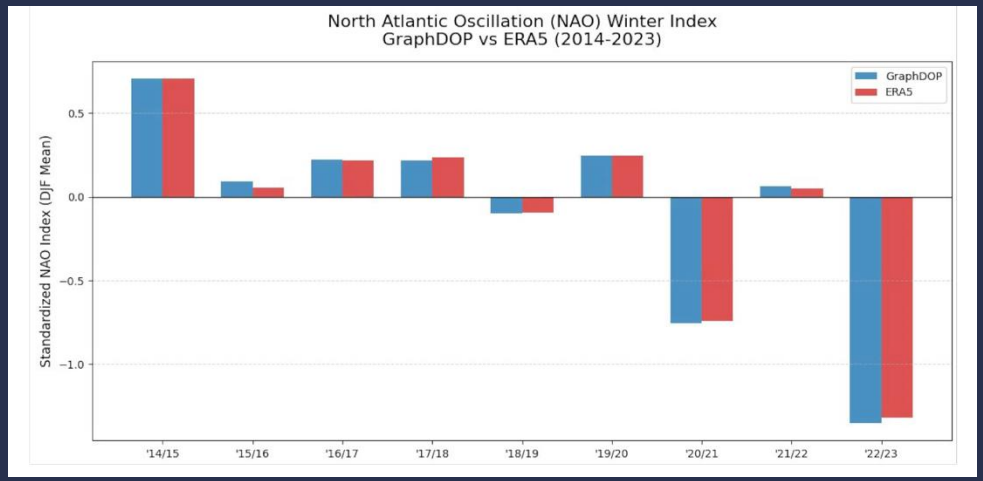
ENSO SST (Nino 3.4)



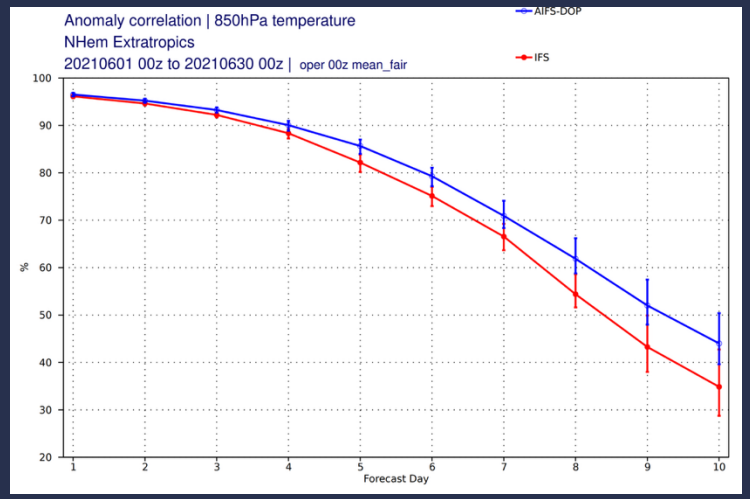
2022 European severe heatwave

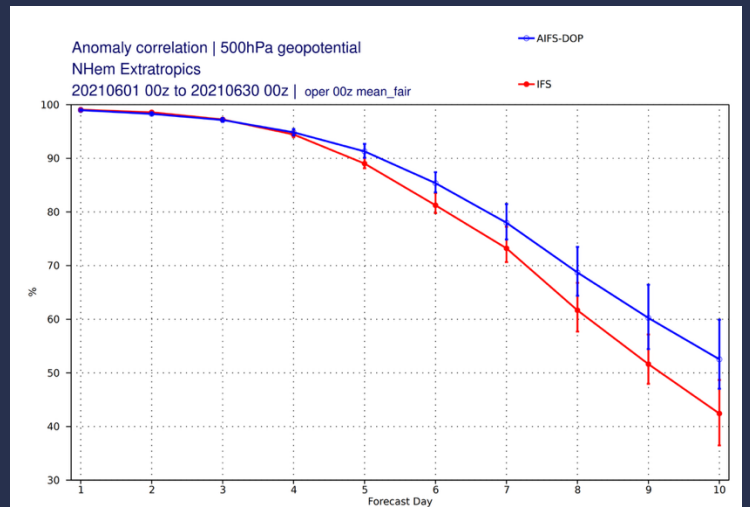


Large-scale teleconnections

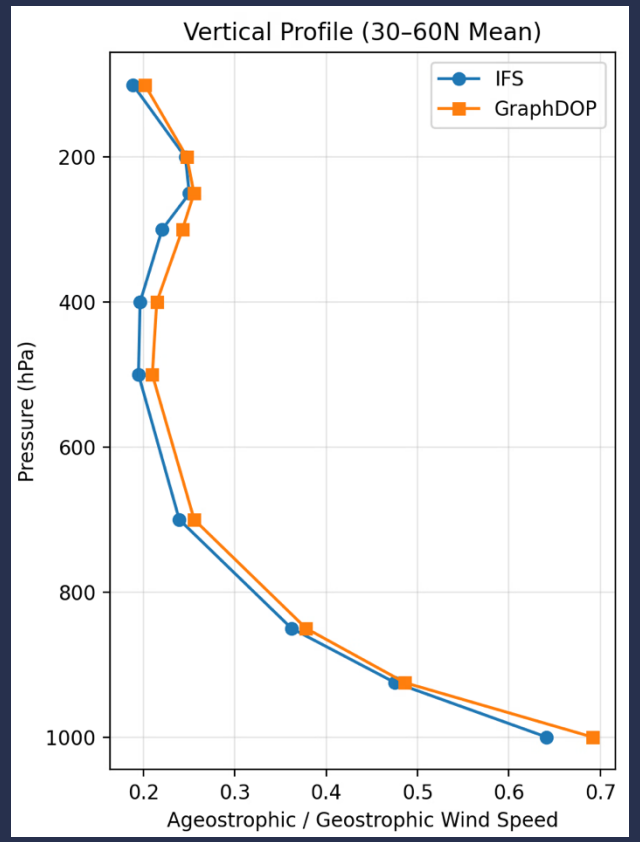


DOP forecasts out-perform the IFS for many surface and upper-air parameters…while still demonstrating characteristics of a “physical model”





Ratio of G to AG flow in the DOP forecasts compared to the IFS

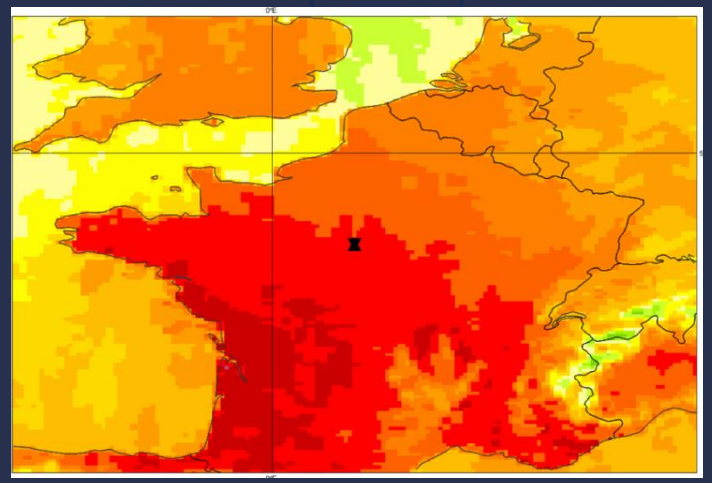


DOP is now running every day in real-time (immediately after OBS ingest) to build up synoptic confidence

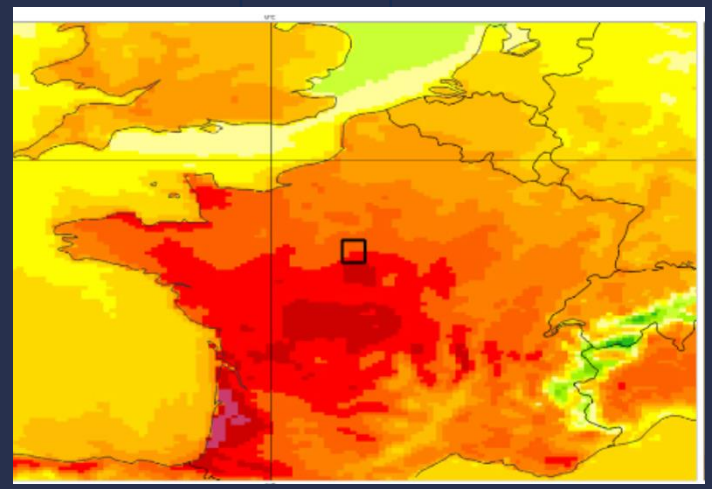
Forecast available approximately 10 mins after cut off (4D-Var / IFS approximately 3hrs)

Recent extreme heatwave over France (10 April)

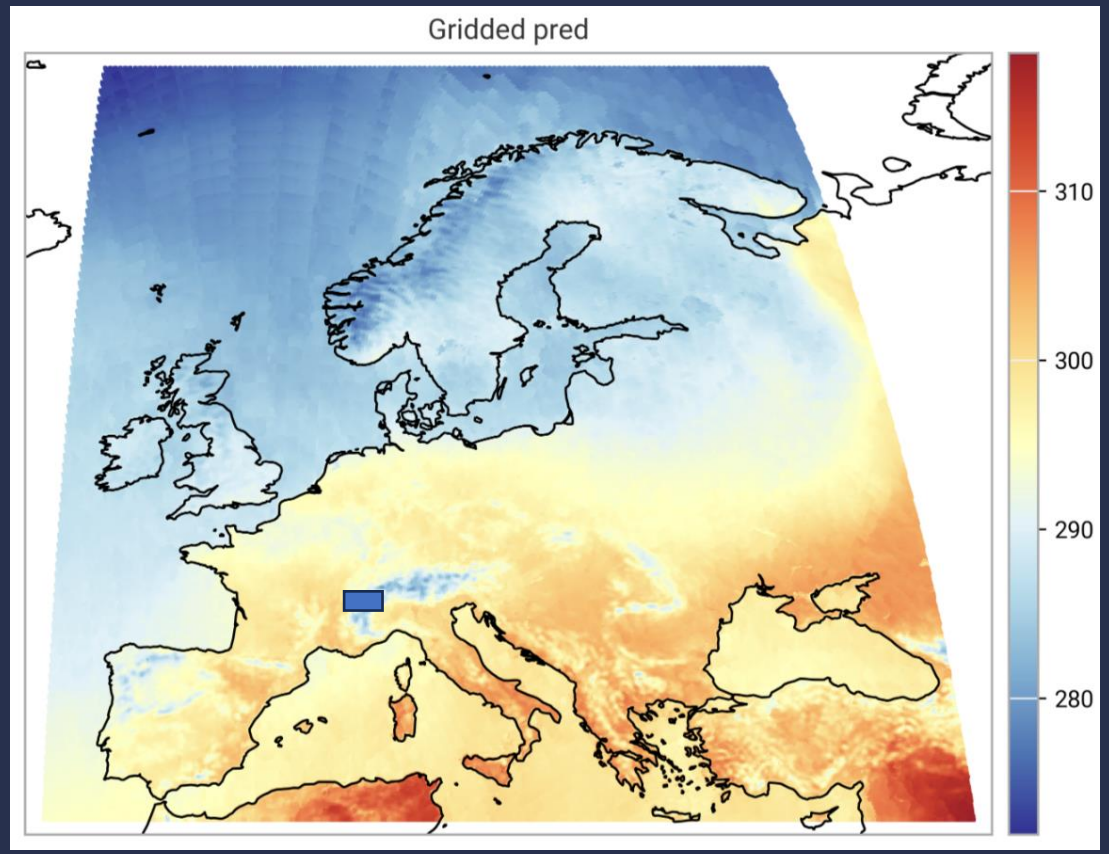
DOP 84hr T 2m forecast



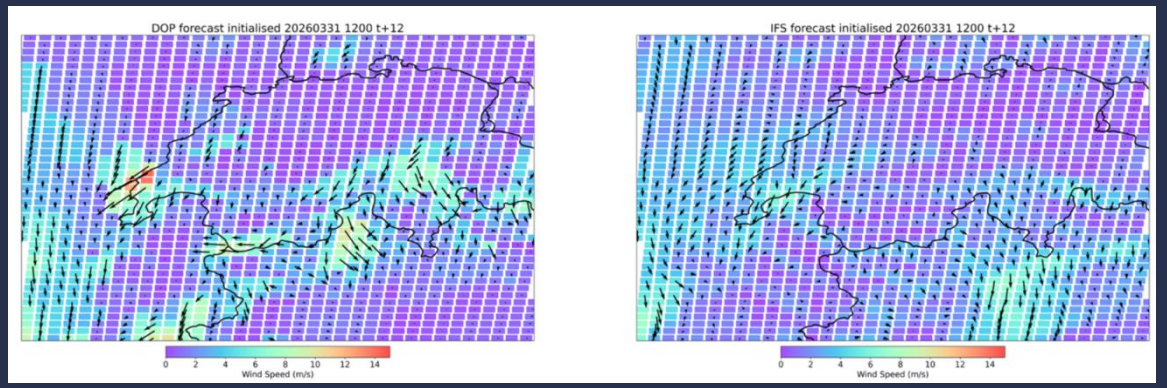
Verifying (IFS) analysis



DOP has exciting potential to operate at very high spatial and temporal resolution…even over complex terrain



DOP has the ability to predict down to the spatial resolution of individual observation locations…



…current collaboration with Meteo Swiss to look at performance over complex Alpine orography…also with DMI to look at the Arctic!

Summary:

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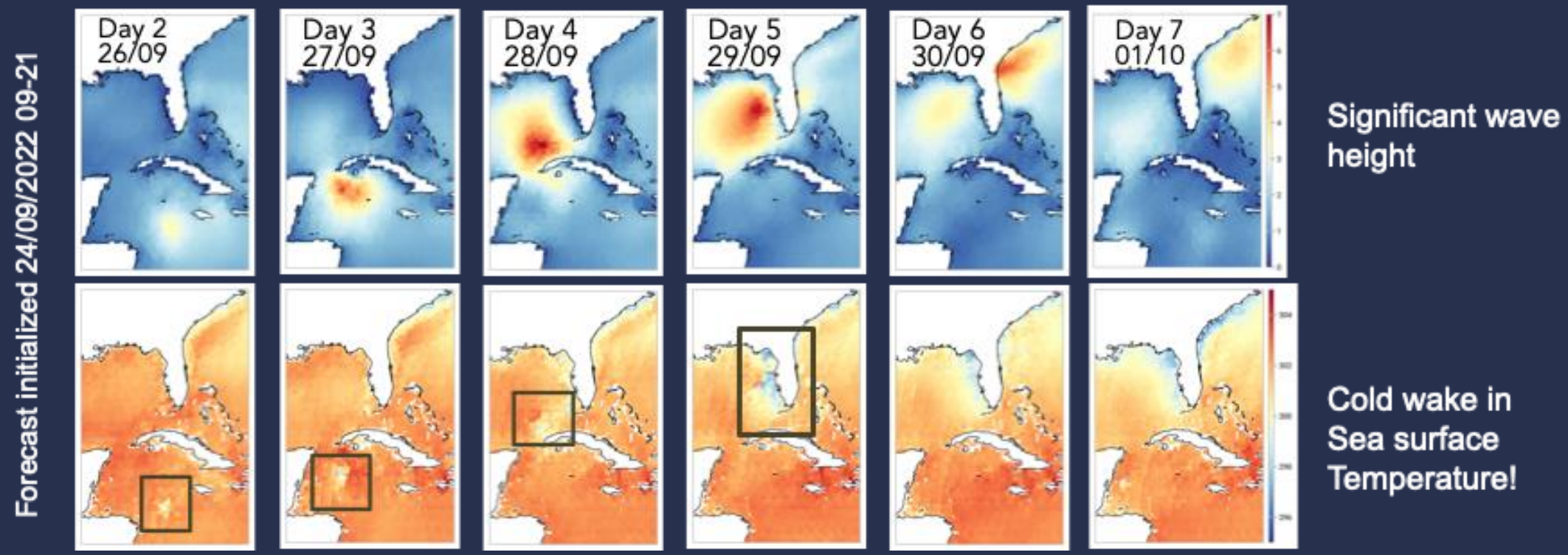
Spare slides

Indications that AI-DOP is learning real physics from observations…

By simultaneously learning from atmosphere, ocean and land observations, AI-DOP can produce forecasts of the complete (observable) Earth system without the need for any explicit coupling between components



Indications that AI-DOP is learning better physics from observations…

- All analysis trained ML models cluster around the **incorrect** wind / central pressure relationship for Tropical cyclones
- The DOP predictions improve upon these but are also better than the physics-based IFS model!
- DOP has **not** seen the IBTRACS data in training or at inference!