Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss

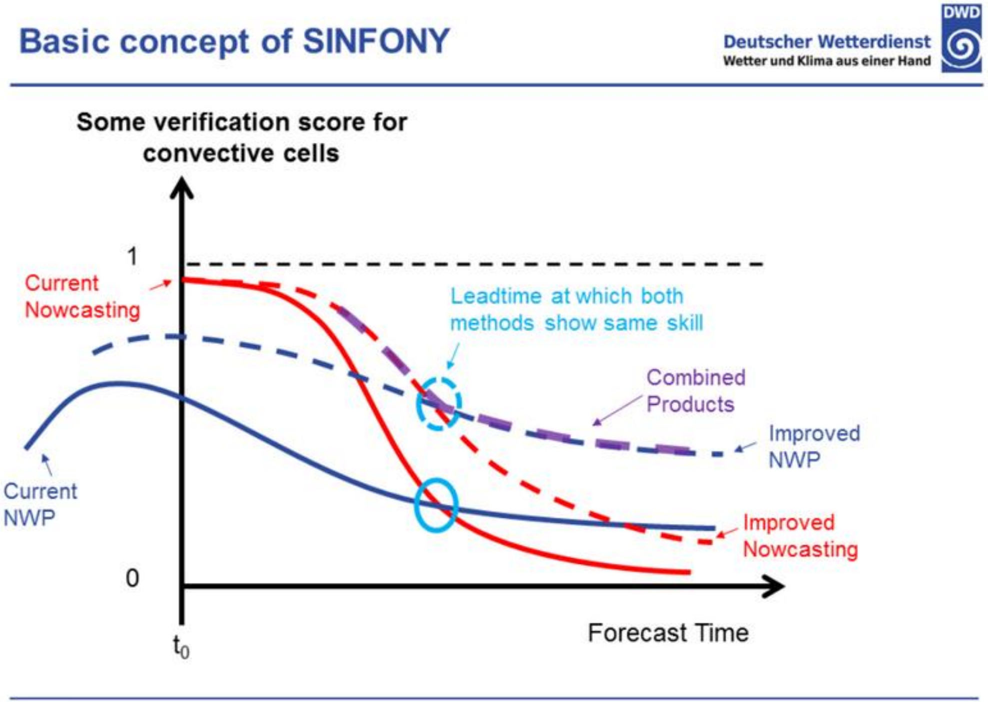
How ML is transforming our approach to seamless weather forecasting

PrePEP Conference, Seamless Prediction
Bonn, 19.03.2025

Daniele Nerini
with contributions from
Verena Bessenbacher, Jonas Bhend, Oliver Fuhrer, Ophélia Miralles, Carlos Osuna, Andreas Pauling, Albero Pennino, Radi Radev, Francesco Zanetta, Ioannis Sideris

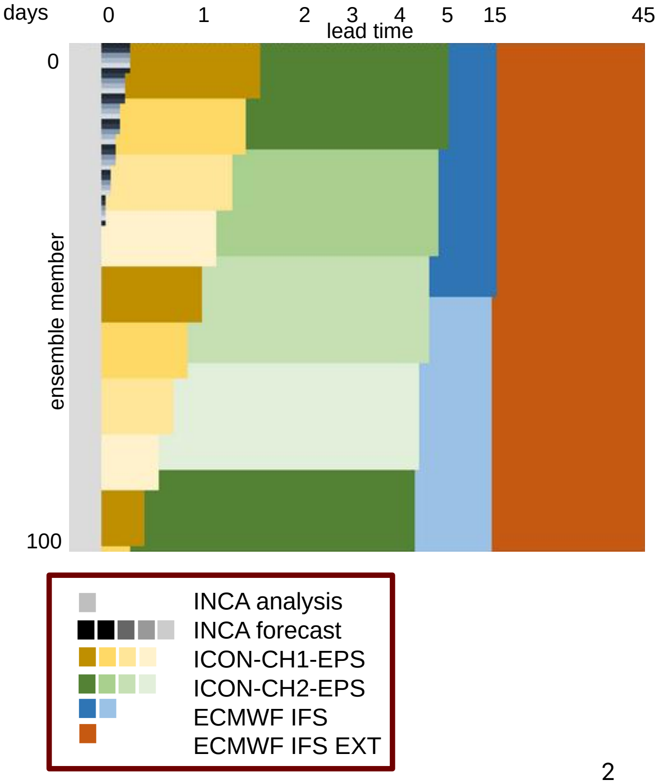
Contact: Daniele.Nerini@meteoswiss.ch

How to Seamless



Source: https://www.dwd.de/DE/forschung/forschungsprogramme/sinfony_iafe/sinfony_node.html

“Full-stack” seamless forecast

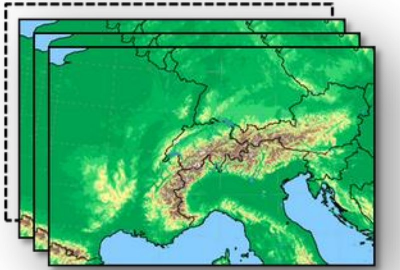


Improving NWP

ICON-CH1-EPS und **ICON-CH2-EPS**

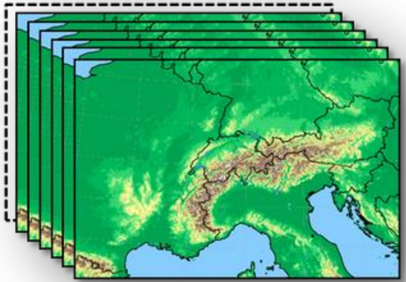
ICON-CH1-EPS

33 hour forecasts, 8x per day
1.1 km grid size
11 ensemble members

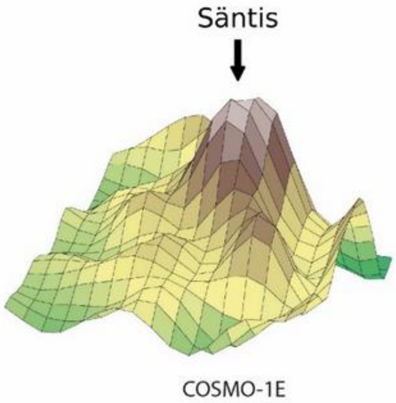


ICON-CH2-EPS

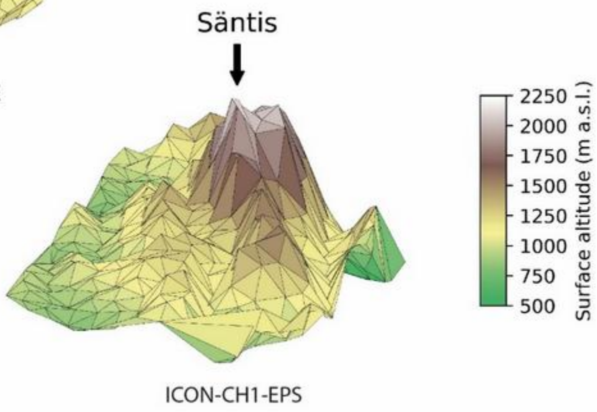
5 day forecasts, 4x per day
2.2 km grid size
21 ensemble members



3-8x in compute capacity would be needed for running ICON @ 500m !



Same grid resolution, but more accurate topography

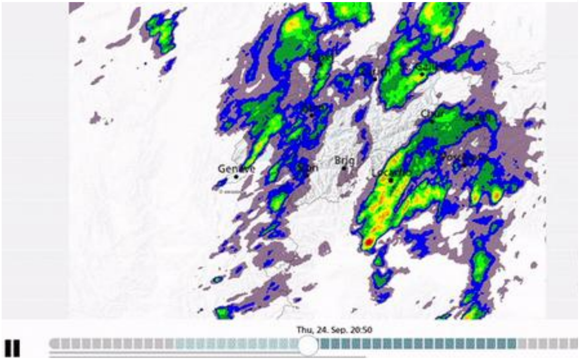


Improving nowcasting

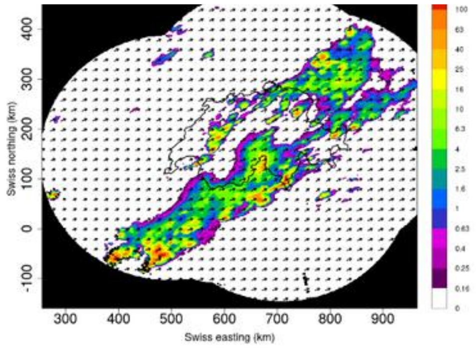
- Nowprecip is MeteoSwiss' operational precipitation nowcasting system.
- 10min / 1km res, +6 hrs
- Nowprecip =

  radar extrapolation
  + stochastic perturbations
  + tendency from NWP

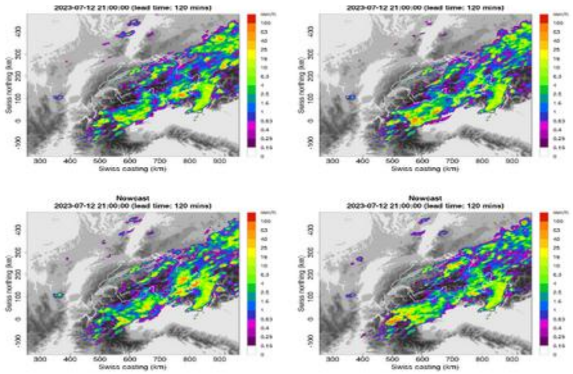
Realistic and seamless



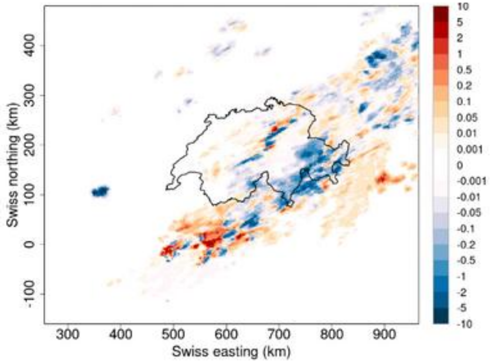
Optical flow



Ensemble



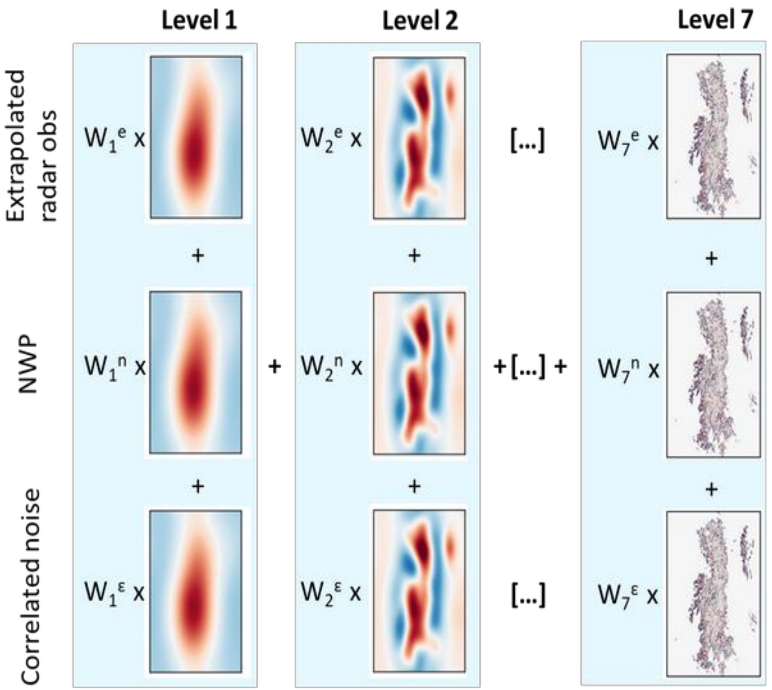
Growth-decay maps



Sideris et al. (*QJRMS*, 2020)

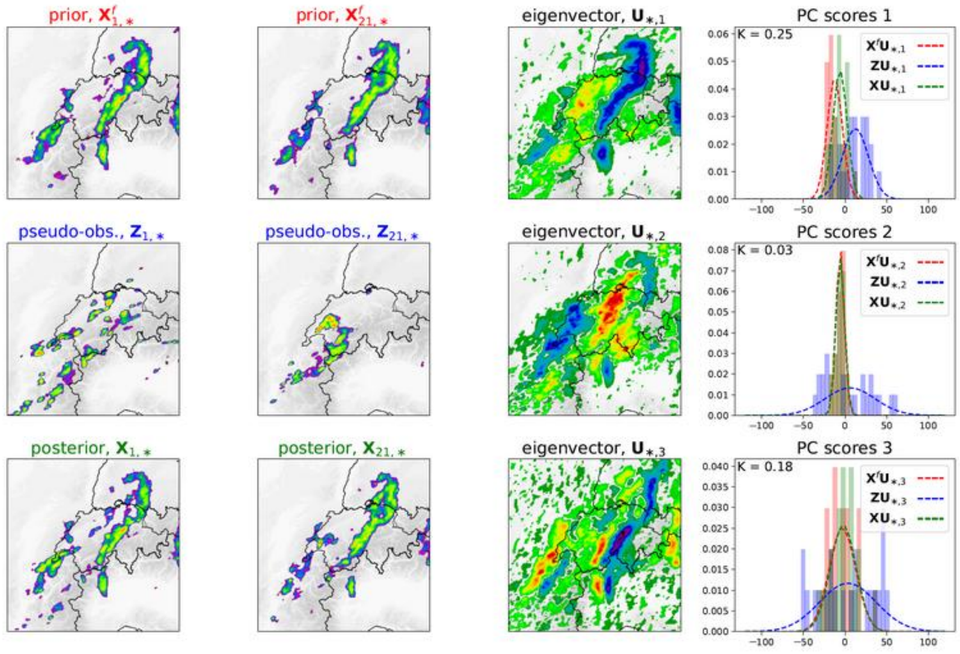
Improving blending

Scale dependent (STEPS)



Imhoff et al. (*QJRMS*, 2023)

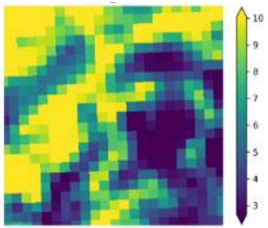
Bayesian update (EnKF)



Nerini et al. (*Weather Rev*, 2019)

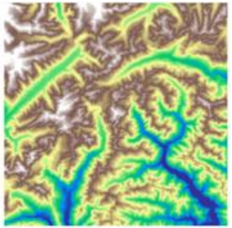
Statistical Postprocessing for seamless forecasting

Raw forecast @ 2km



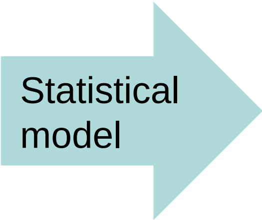
+

DEM @ 50m

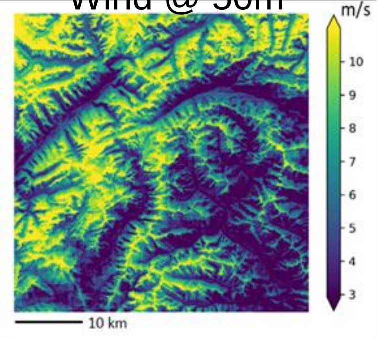


+

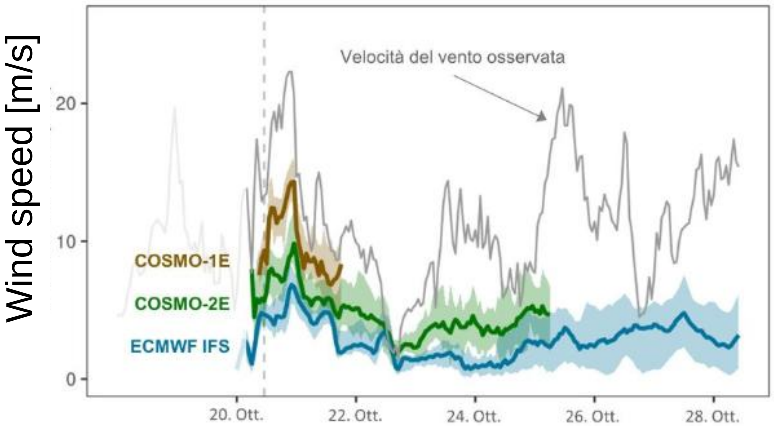
Station obs

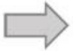


Wind @ 50m

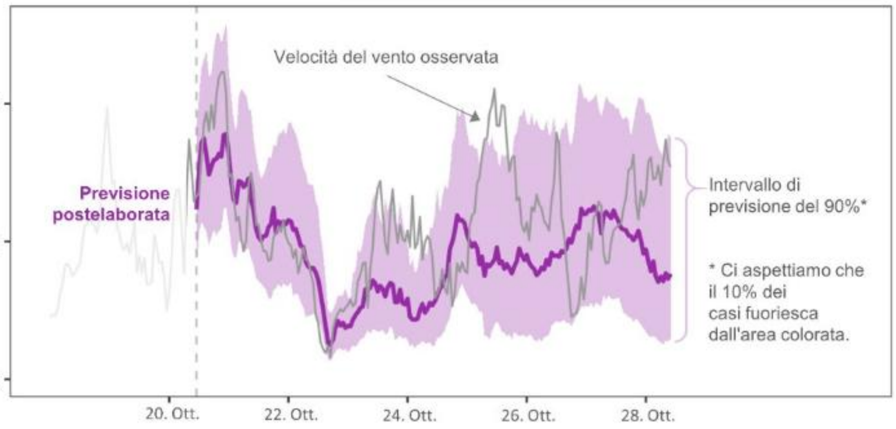


Raw forecasts





Postprocessing

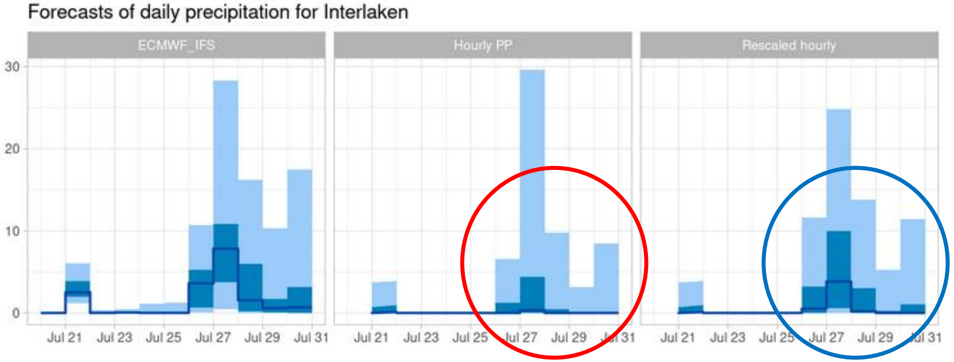


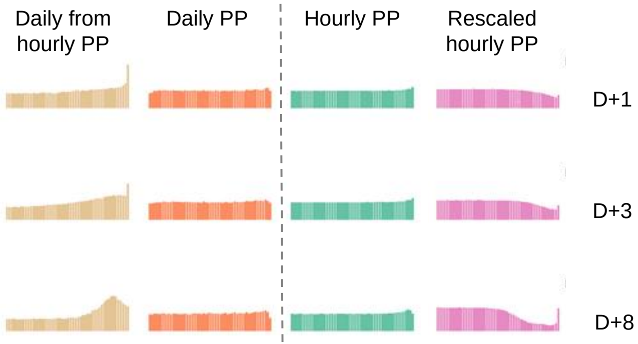
Postprocessing at multiple temporal scales

Problem:
Univariate PP on hourly precip. +
limited predictability of hourly precip.
→ climatological pred. (very little rain)
→ we lose rain in daily accumulations

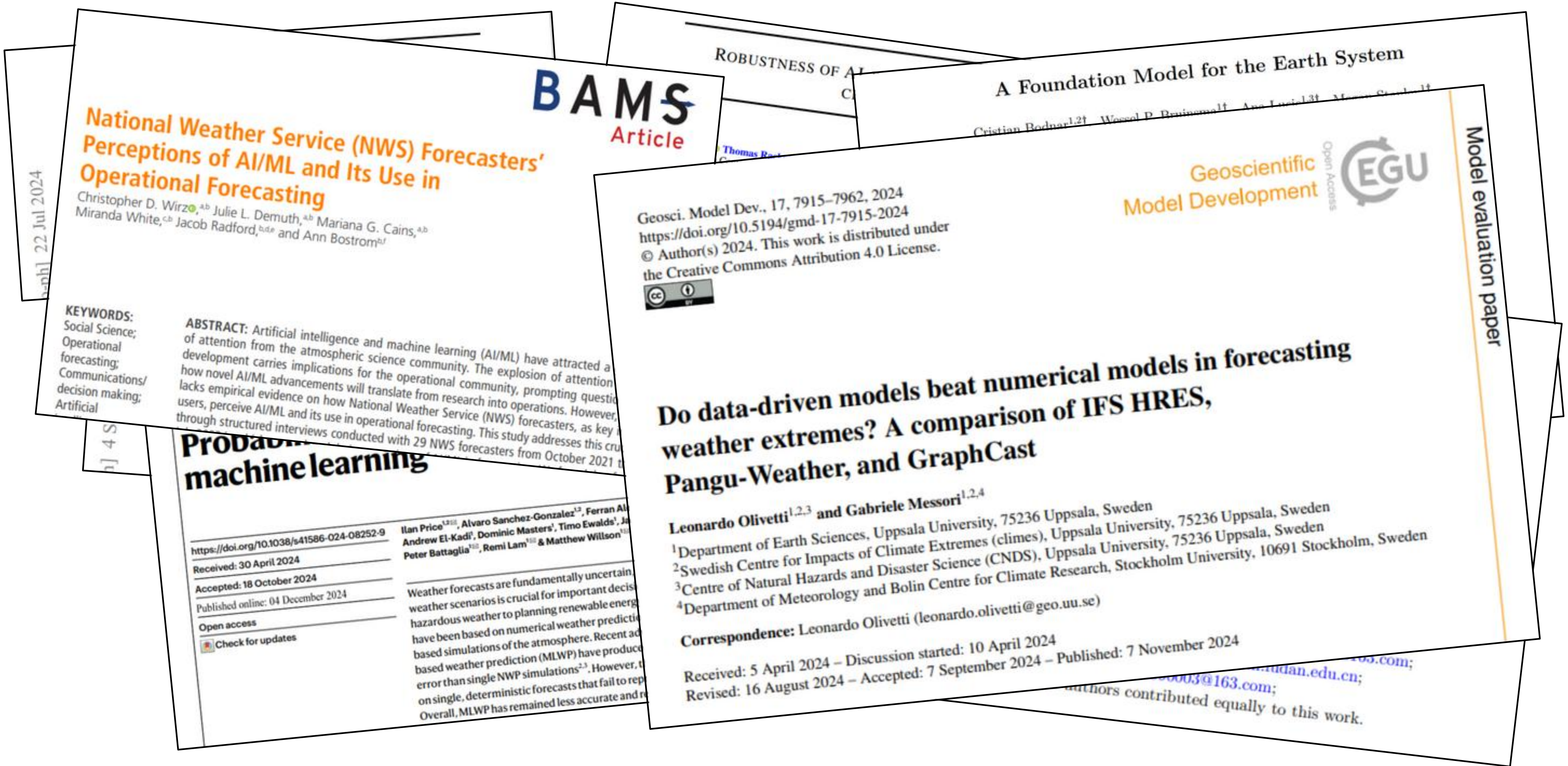
Solution:
Rescale hourly postprocessed precip.
with daily postprocessed precip.

but remaining issues with calibration →

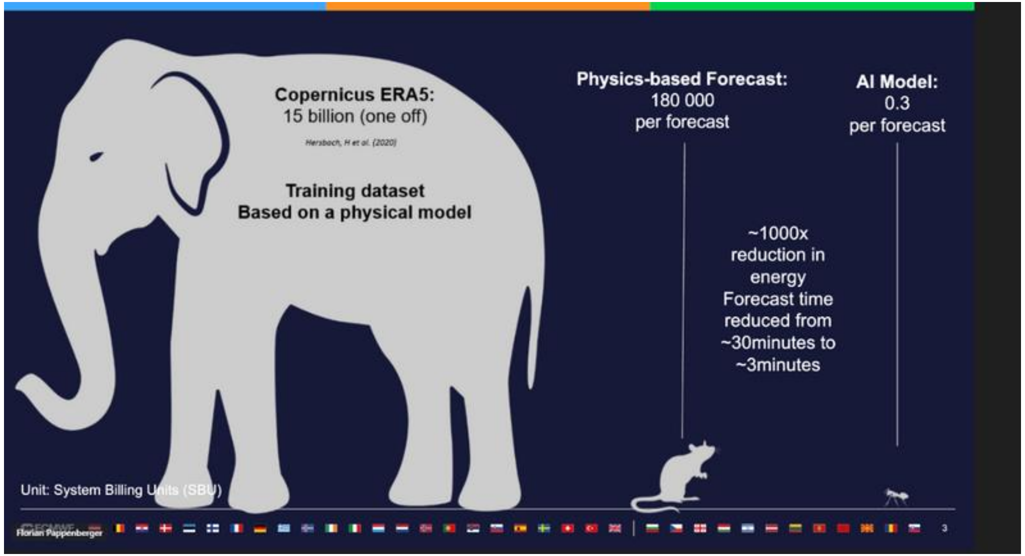




Machine Learning



AIFS goes Operational (Feb 25, 2025)!



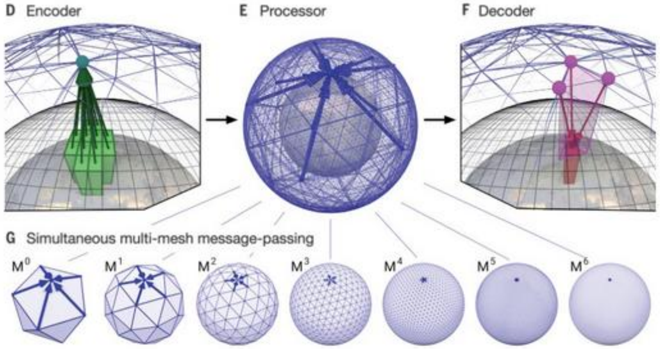
https://www.ecmwf.int/en/about/media-centre/news/2025/ecmwfs-ai-forecasts-become-operational

Model architecture

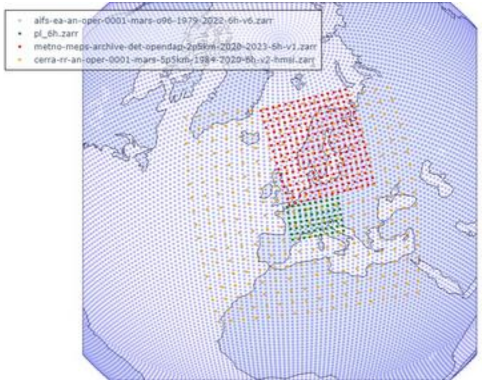
- **Graph-based**: use graph neural networks to encode and process input data in a flexible way.

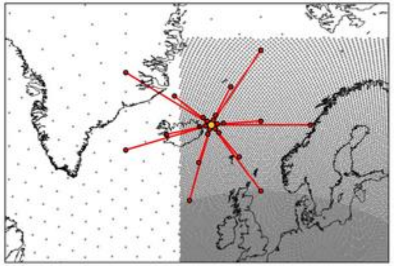
- **Autoregressive**: rollout forecast iteratively, typically with 6h steps.

- **Stretched-grid**: high-resolution over a localised domain of interest and lower resolution elsewhere with seamless information passing across boundaries.

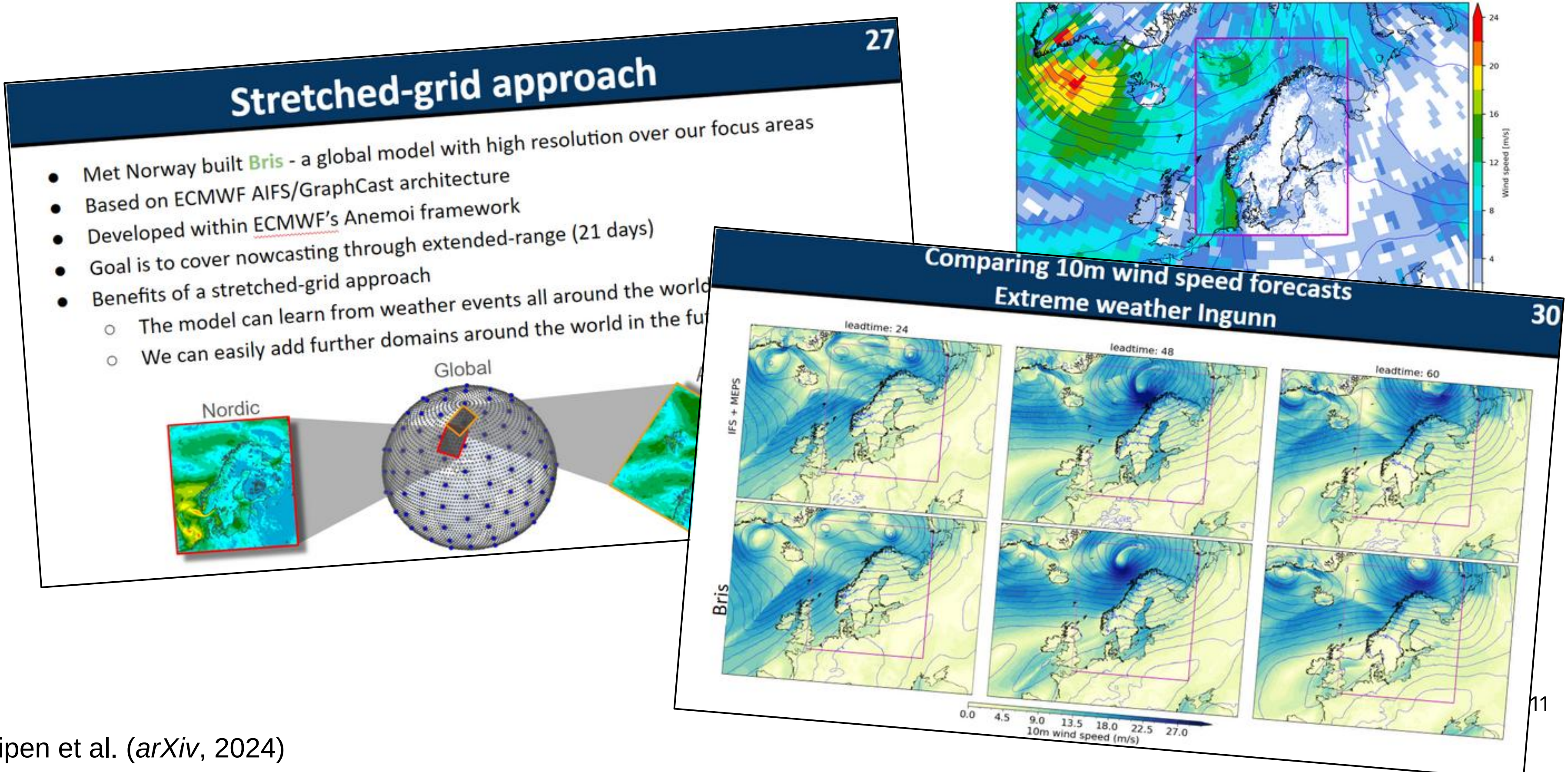


Remi et al. (*Nature,* 2023), "GraphCast"





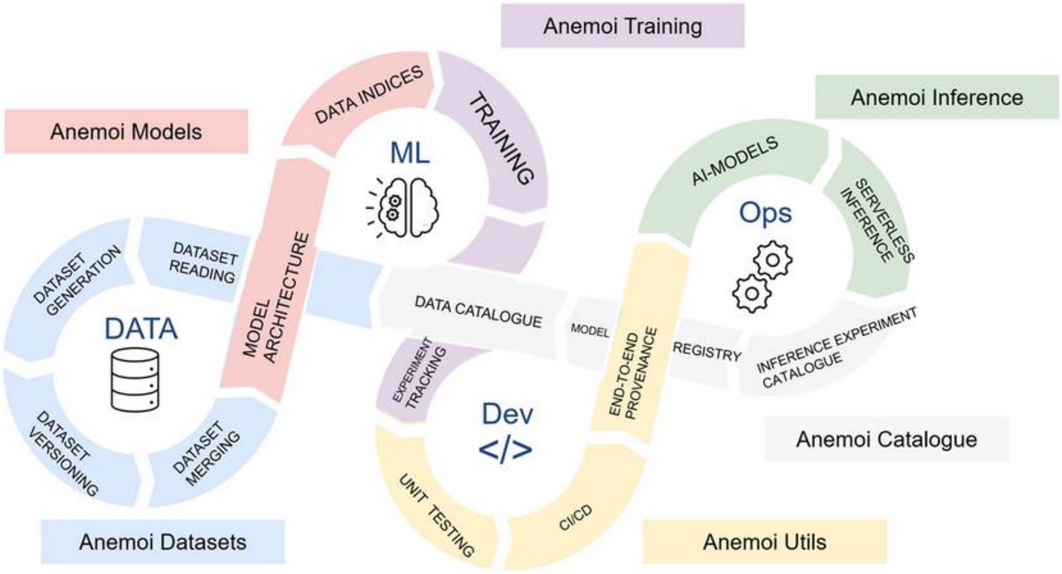
Regional Emulators



Nipen et al. (*arXiv*, 2024)

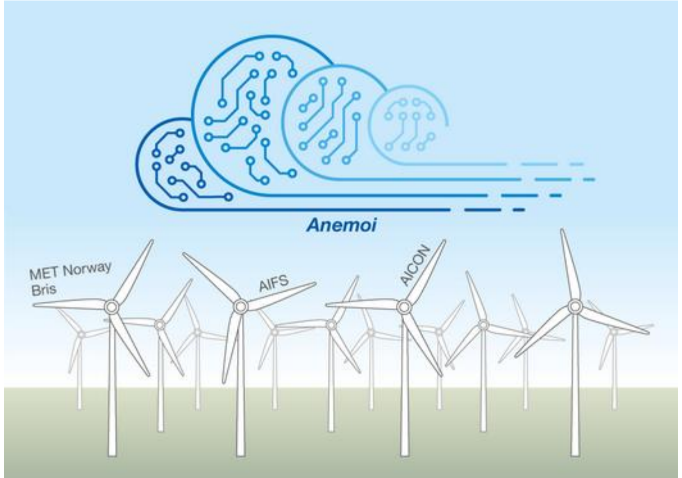
Anemoi Framework

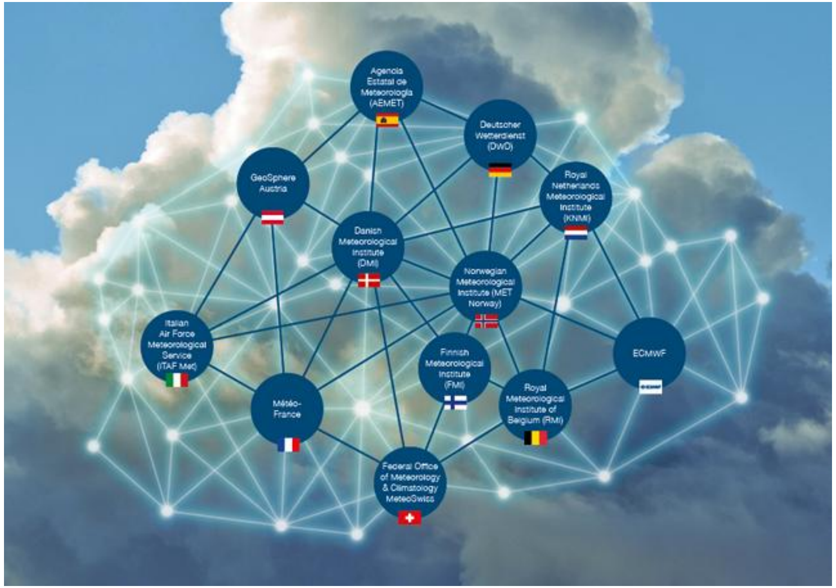
- Provide cutting-edge ML tools for meteorological applications covering the whole ML lifecycle.
- Foster a collaborative and open-source ecosystem.
- Facilitate R2O, reduce maintenance.



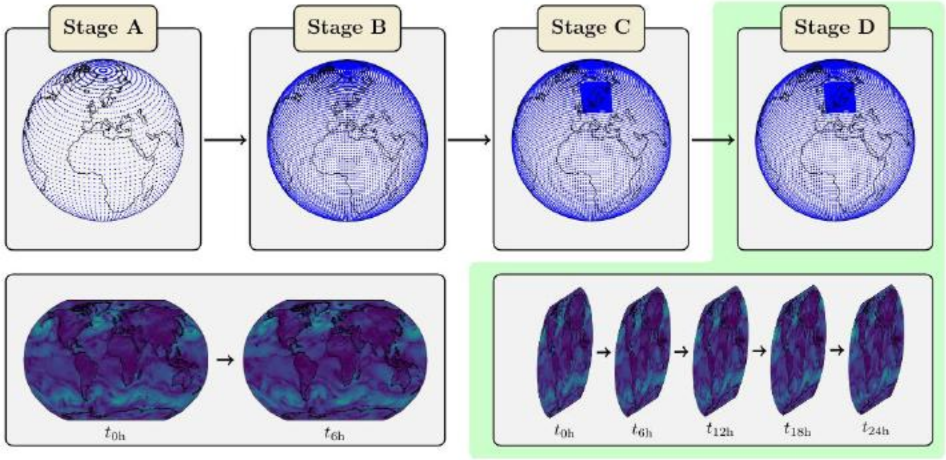
Anemoi Community

- Collective expertise of 12 European meteorological institutions, led by ECMWF.
- Over 40 contributors, 700 pull requests and counting.





Data-driven regional forecasting



Stage	A: 1° global	B: 0.25° global	C: 0.25° + 2.5km	D: rollout
Iterations	200,000	15,000	5,000	300
GPU hours	1,750	2,500	1,900	180

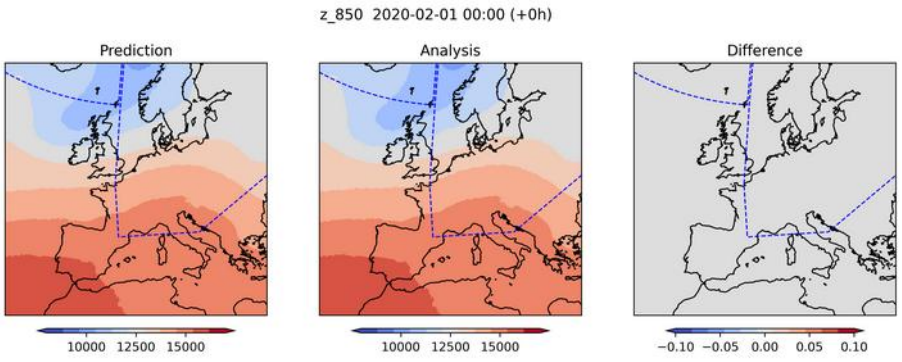
ECMWF to provide pre-trained Stage B models!

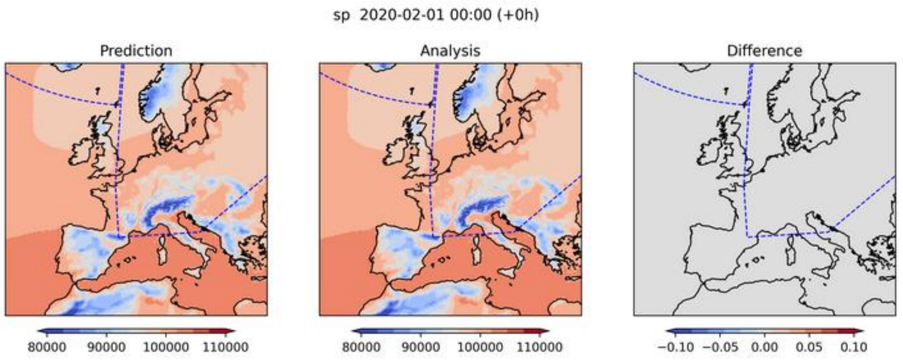
Transfer Learning:

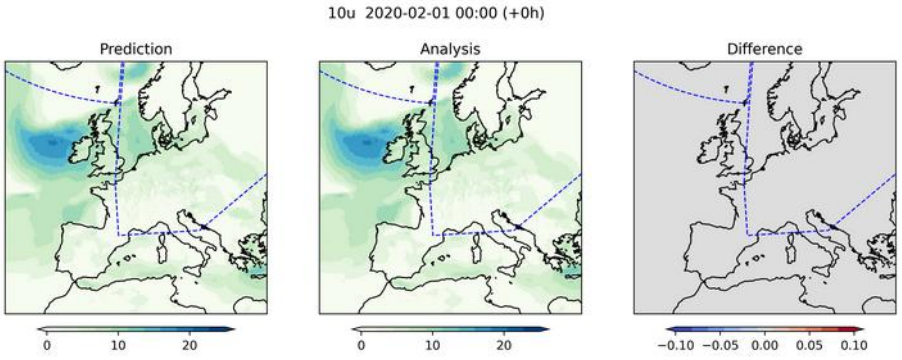
- Sequentially adapt the model to more complex tasks.
- Harness the greater data availability of ERA5.
- Gradually refines the model, allowing it to reach a local minima.
- Drastic increase in performance vs starting directly at stage C.

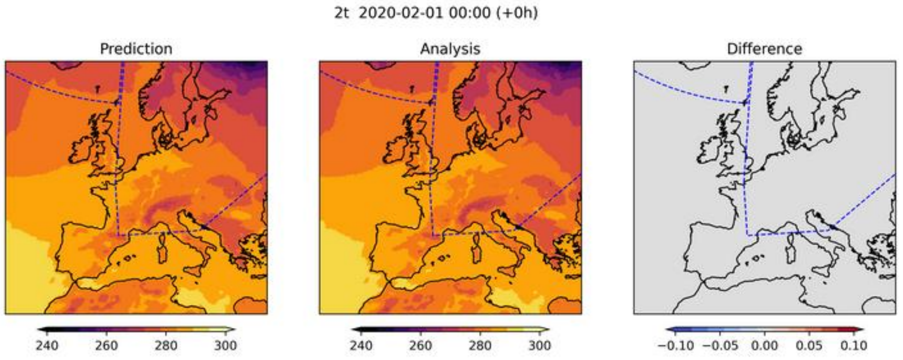
Nipen et al. (*arXiv*, 2024)

AICON Results

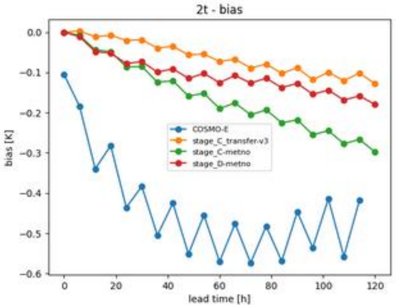


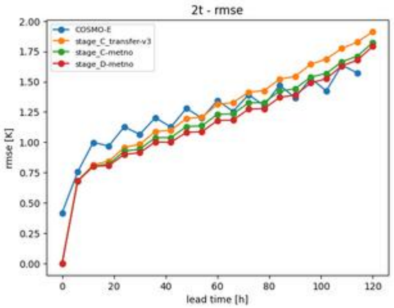


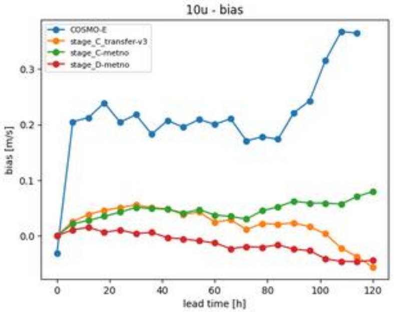


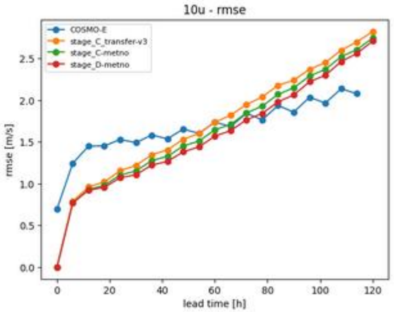


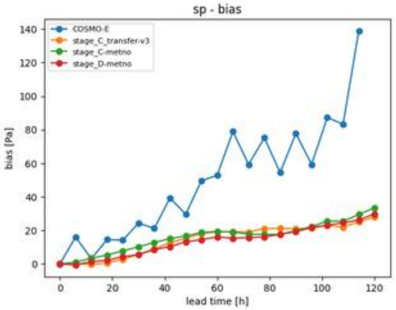
AICON „Verification“

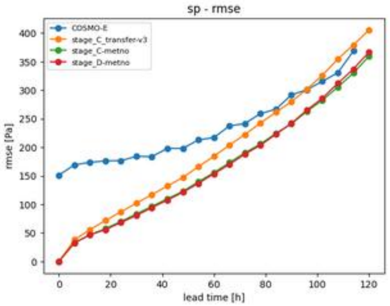












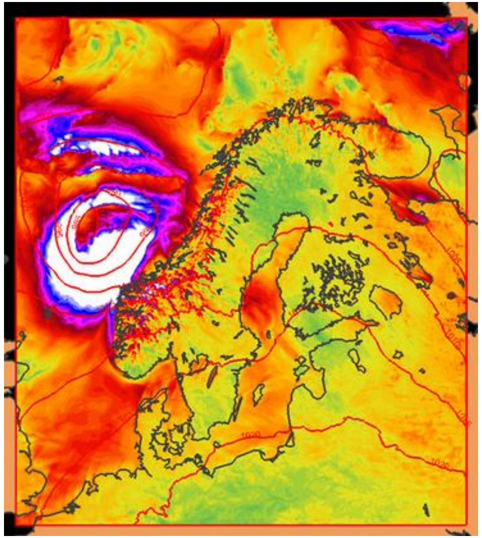
Running Bris in Switzerland

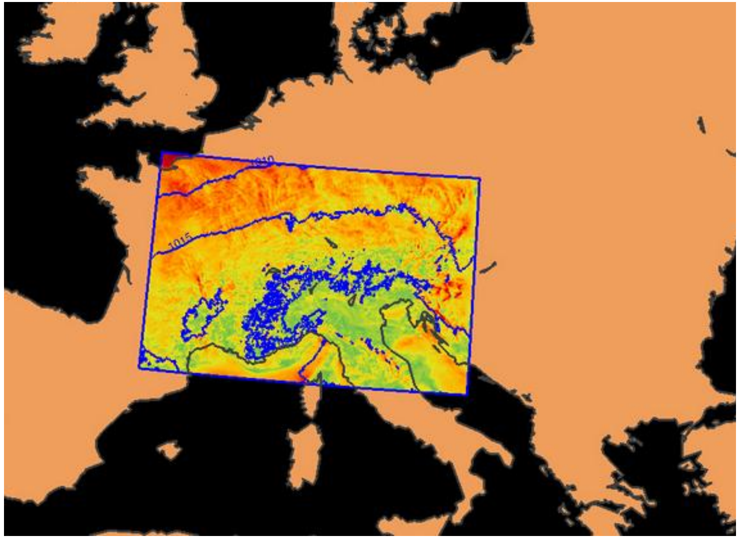
Trained on:

- MEPS 2.5km analyses 2020-2023
- 1000 * 950 grid points
- Biggest mountain: 2019 m

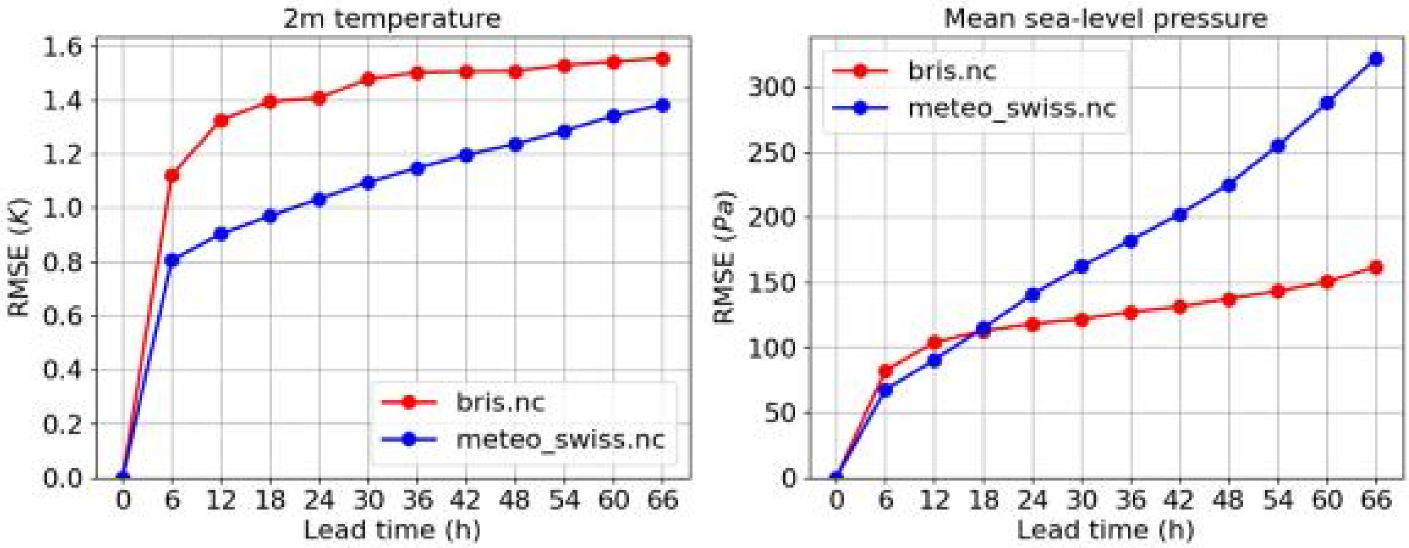
Inference on:

- COSMO 2.2km analyses
- 290 * 582 gridpoints
- Biggest mountain: 3867 m



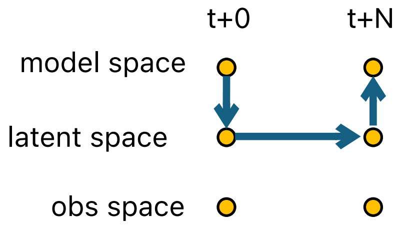


How robust are stretched-grid models?
Running Bris on the Swiss domain



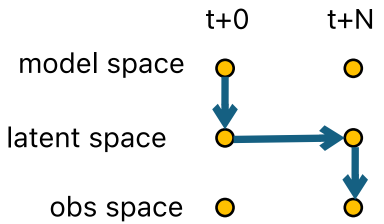
1) Predict analysis from analysis

e.g. current AIFS



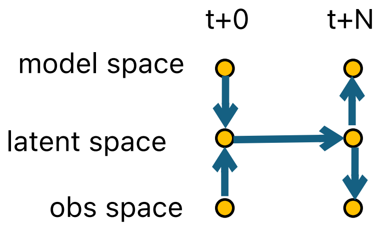
2) Predict obs targets from analysis ICs

e.g. fine tune AIFS to predict SYNOPs



3) Augment analysis driven ML with ob

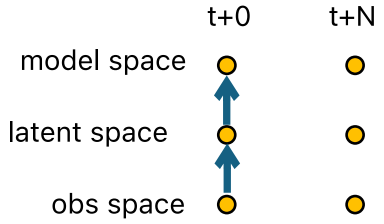
e.g. obs not used by 4D-Var



Augmenting existing analysis driven approaches with observational data

4) Learn the analysis

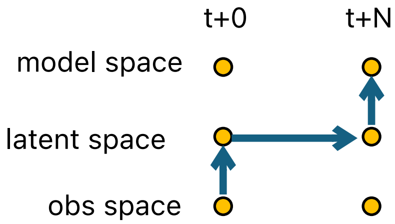
e.g. emulate 4D-Var



Initializing + learning from observations

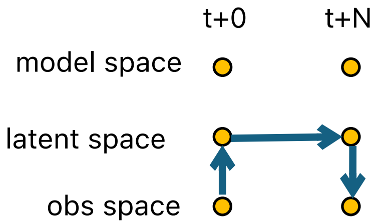
5) Predict future analysis from obs

e.g. make predictions in model space use reanalysis as truth



6) Predict future obs from obs

e.g. make predictions in obs space, using obs as truth



Direct Observation Prediction – making a forecast directly from observations

Courtesy of Matthew Chantry (ECMWF)

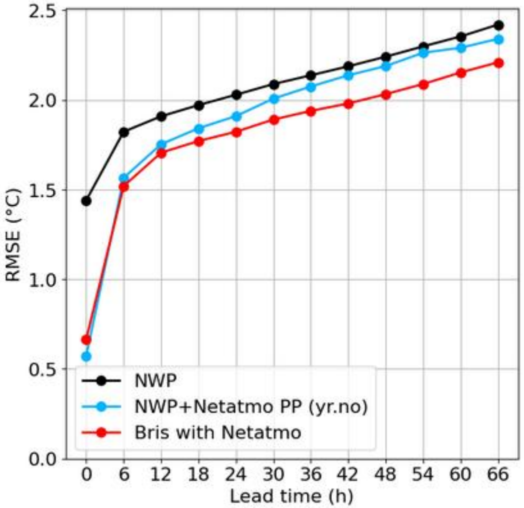
Data Assimilation – Multiple Encoders/Decoders

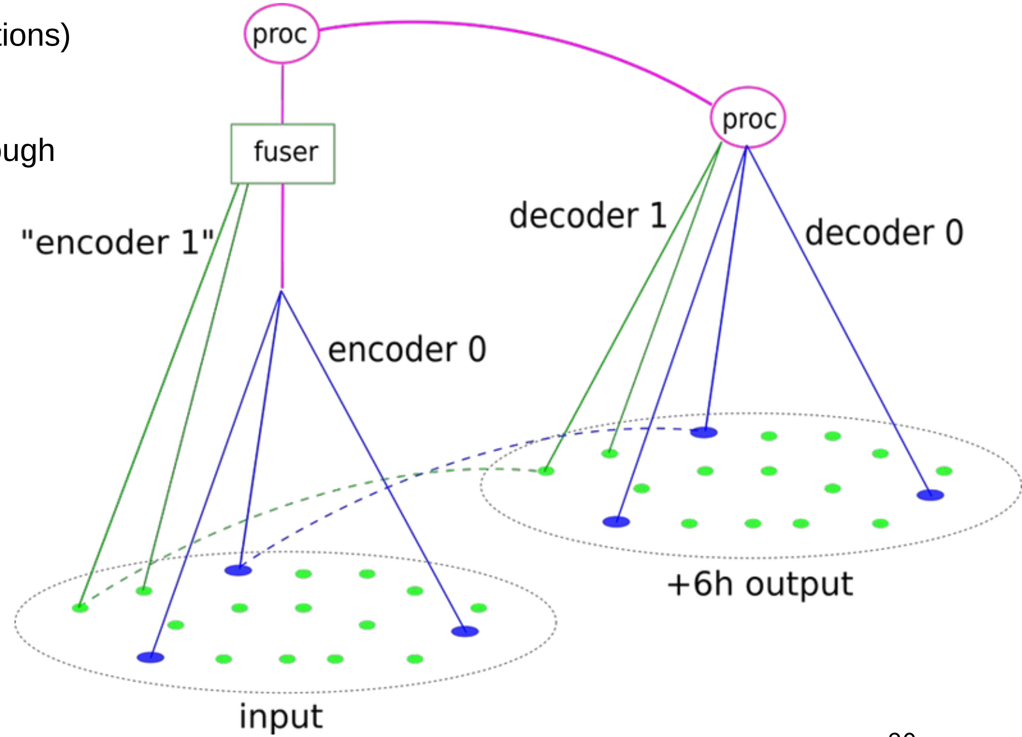
Blue points is the standard analysis input

Green points secondary data source (e.g. observations)
Multiple encoders in sequence

- Encoder 0 encodes the analysis input
- Encoder 1 encodes the secondary input through a fuser (perceiver)

Multiple decoders (similar to single decoder case)

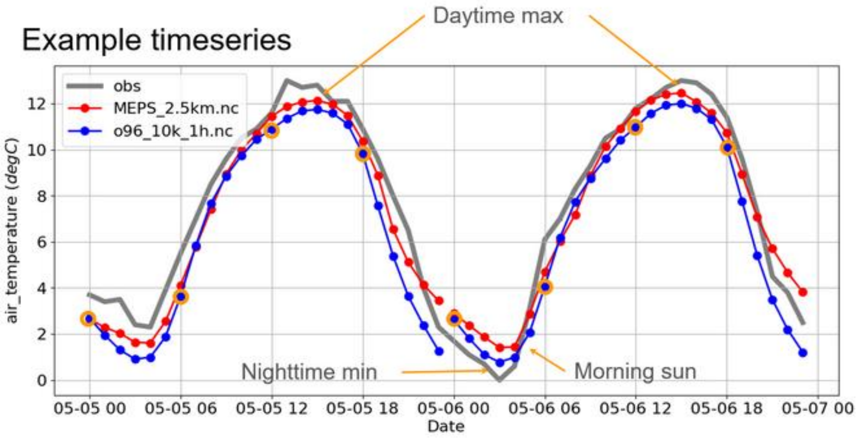


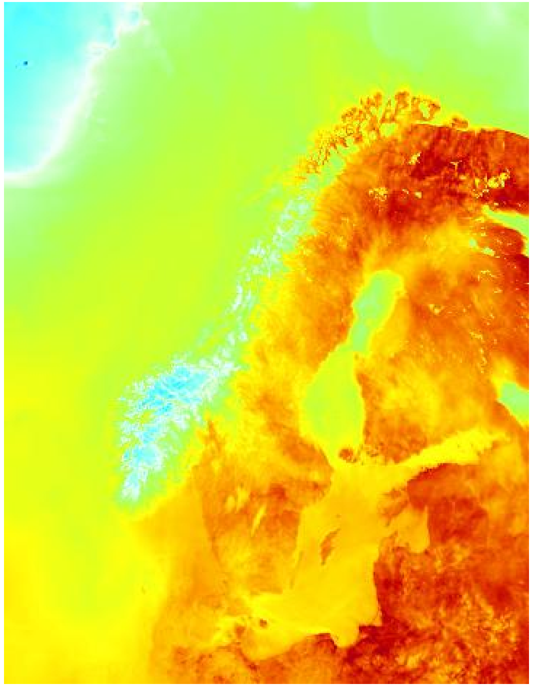


Courtesy of MetNorway

Time Interpolator

- Training a model directly at 1h steps would decrease model skill during long rollouts.
- Time interpolation allows to progressively produce finer temporal resolution forecasts while maintaining model skill at long lead times.





Hourly 2m Temperature

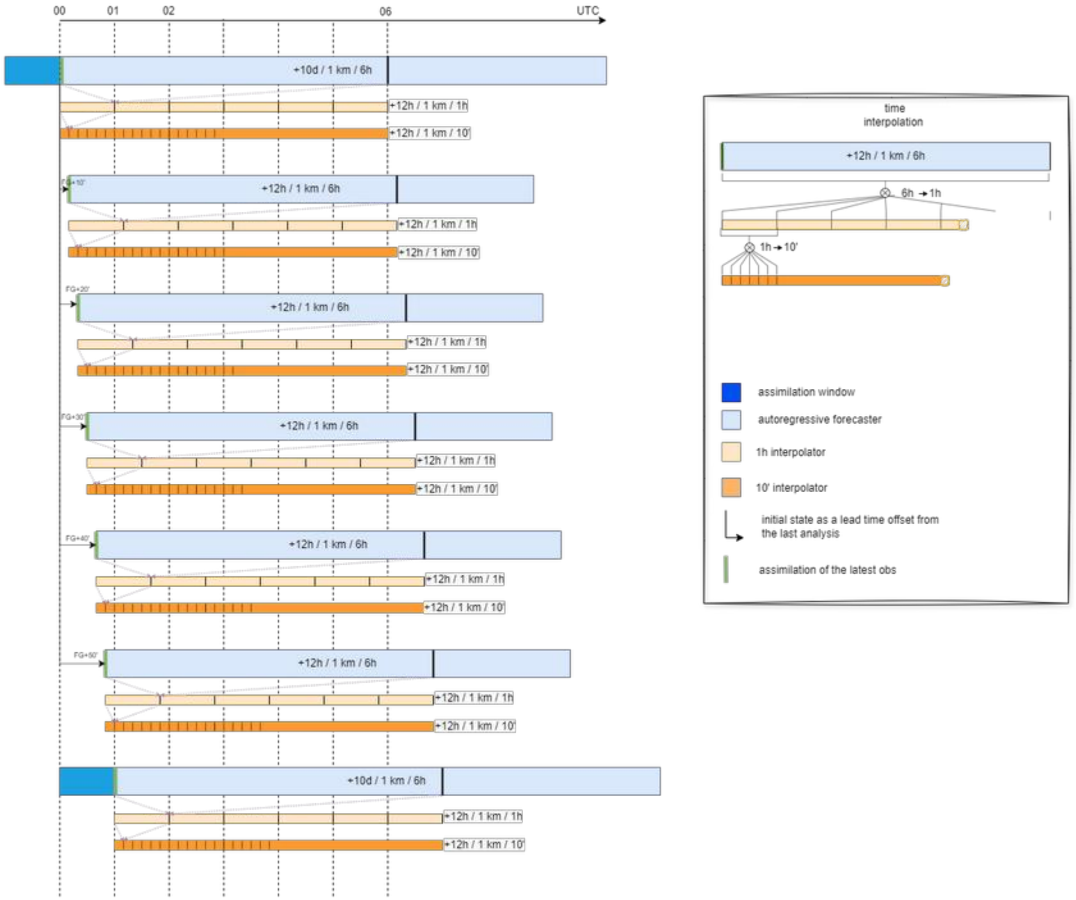
Courtesy of MetNorway

Putting it together: Seamless RUC

Components

- ☐ Conventional DA (KENDA)
- ☐ Forecaster (6 hourly outputs)
- ☐ Time interpolator (hourly outputs)
- ☐ Data assimilator

Seamless by design.



Wrap up

- Conventional approach is “post-hoc” seamless
  - Blend of forecasts that historically have been developed in separated communities.

- ML is changing the traditional boundaries of how things are being done
  - DA, nowcasting, postprocessing, downscaling – all in a single model!

- New community are forming around ML, offering synergies and enabling quicker adoption.
  - Anemoi: sharing data and sharing models!

- MeteoSwiss is building an ML-based model that can be competitive in quality for nowcasting-, short, and medium-range forecasts (“Seamless RUC”).

MeteoSwiss
Operation Center 1
CH-8058 Zurich-Airport
T +41 58 460 91 11
www.meteoswiss.ch

More questions? Get in touch! Daniele.Nerini@meteoswiss.ch

MeteoSvizzera
Via ai Monti 146
CH-6605 Locarno-Monti
T +41 58 460 92 22
www.meteosvizzera.ch

MétéoSuisse
7bis, av. de la Paix
CH-1211 Genève 2
T +41 58 460 98 88
www.meteosuisse.ch

MétéoSuisse
Chemin de l'Aérologie
CH-1530 Payerne
T +41 58 460 94 44
www.meteosuisse.ch