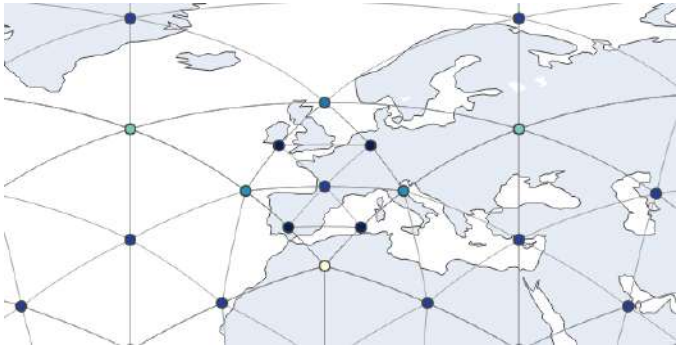
Aperçu des projets en IA pour la prévision du temps à Météo-France

Laure Raynaud, Météo-France
ODATIS, 27 January 2026

Current AI-NWP research topics at MF

1. Regional NWP emulation



Anemoi

2. Statistical downscaling

Climate Change Service

climate.copernicus.eu

3. Uncertainty quantification

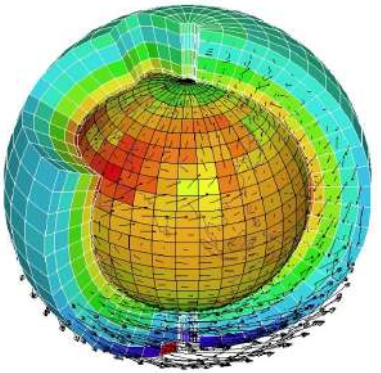
Destination Earth

anr

cnrs

METEO FRANCE

Weather prediction : a complex and high-dimensional problem



- State-of-the-art atmospheric models are resolved on spatial grid with resolution ~ 10km at the global scale and ~ 1km at the regional scale
- They simulate a wide range of scales, from large-scale flow to very localized phenomena (thunderstorms, turbulence), from minutes to several days ahead.
- They also integrate a large range of heterogeneous observations data for the computation of their initial conditions (through data assimilation techniques)

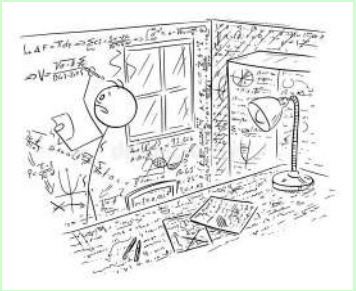
$$x^{t+dt} = \mathcal{M}(x^t) \; ; \; x^0 = \mathcal{F}(\tilde{x}^0, y)$$

Fundamental physical principles

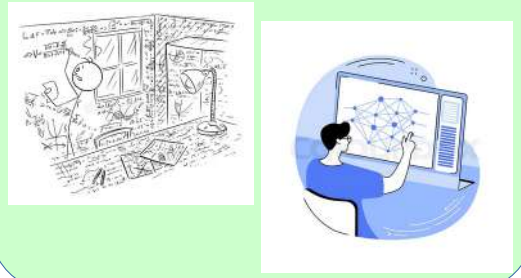
$\mathcal{M}$

- **Conservation of mass**
- **Conservation of energy**
- **Conservation of momentum**
- **Consider budgets of these quantities for a control volume**

From physics-based models to data-driven models : a range of possible solutions

Initial conditions → **Physics model**  → **Forecast**

Well established models, but performances limited by
- understanding of physics
- computing resources

Initial conditions → **Hybrid Physics/ML**  → **Forecast**

The 'in-between', ML could help
- uncover physical relationships
- reduce computational burden

while preserving the physical consistency of classical modeling

Initial conditions → **ML model**  → **Forecast**

A change of paradigm, very rapid predictions and some challenges
- availability of high quality data
- black box, physical consistency ?
- generalization to out of distrib ?

The rapid rise of NWP emulators

- **A (simplified) timeline**

2018

2021

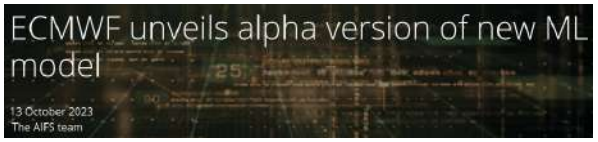
Challenges and design choices for global weather and climate models based on machine learning

Peter D. Dueben and Peter Bauer

European Centre for Medium-range Weather Forecasts, Shinfield Rd, Reading, RG2 9AX, UK

Can deep learning beat numerical weather prediction?

M. G. Schultz, C. Betancourt, B. Gong, F. Kleinert, M. Langguth, L. H. Leufen, A. Mozaffari and S. Stadtler



GenCast: Diffusion-based ensemble forecasting for medium-range weather

Ilan Price[*,1], Alvaro Sanchez-Gonzalez[*,1], Ferran Alet[1], Timo Ewalds[1], Andrew El-Kadi[2], Jacklynn Stott[1], Shakir Mohamed[1], Peter Battaglia[1], Remi Lam[1] and Matthew Willson[1]

[*]Equal contributions, [1]Google DeepMind, [2]Imperial College, London

Google, Huawei, NVIDIA, Microsoft, ECMWF

GraphCast: Learning skillful medium-range global weather forecasting

Remi Lam[*,1], Alvaro Sanchez-Gonzalez[*,1], Matthew Willson[*,1], Peter Wirnsberger[*,1], Meire Fortunato[*,1], [illegible]aton-Rosen[1], Weihua Hu[1], Alexander Merose[2], [illegible]dynn Stott[1], Alexander Pritzel[1], Shakir Mohamed[1] and

Pangu-Weather: A 3D High-Resolution System for Fast and Accurate Global Weather Forecast

Kaifeng Bi, Lingxi Xie, Hengheng Zhang, Xin Chen, Xiaotao Gu, and Qi Tian[✉], *Fellow, IEEE*

International context

- 2025 : First **operational models**

AIFS OPERATIONAL

Février 2025

La prévision du temps par IA devient opérationnelle au CEPMMT

Eulalie Boucher ; Gabriel Moldovan ; Zied Ben Bouallègue ; Nina Raoult ; Michael Maier-Gerber ; Mariana Clare ; Joffrey Dumont Le Brazidec

La Météorologie, 130, 4-7, 2025

Date de publication : Aug 01, 2025

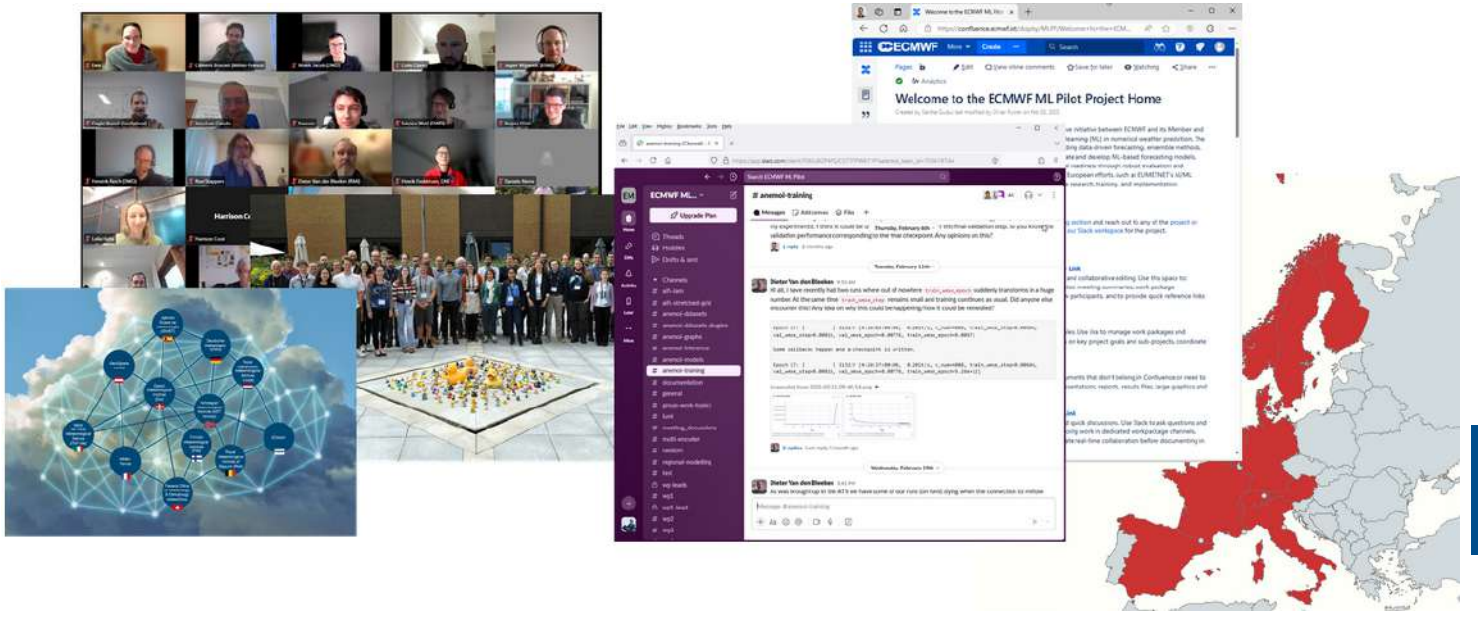
Introduction of AICON-Global

On **September 3, 2025**, starting at 06-UTC, deterministic global forecasts will be produced with DWD's AICON model. AICON-Global is DWD's first global, AI-based forecast model designed to complement and extend the existing ICON-based NWP system.

Juillet 2025

AIFS ENSEMBLE OPERATIONAL

- A new **european consortium around AI-NWP** : ECMWF ML Pilot Project



What is NWP emulation ?

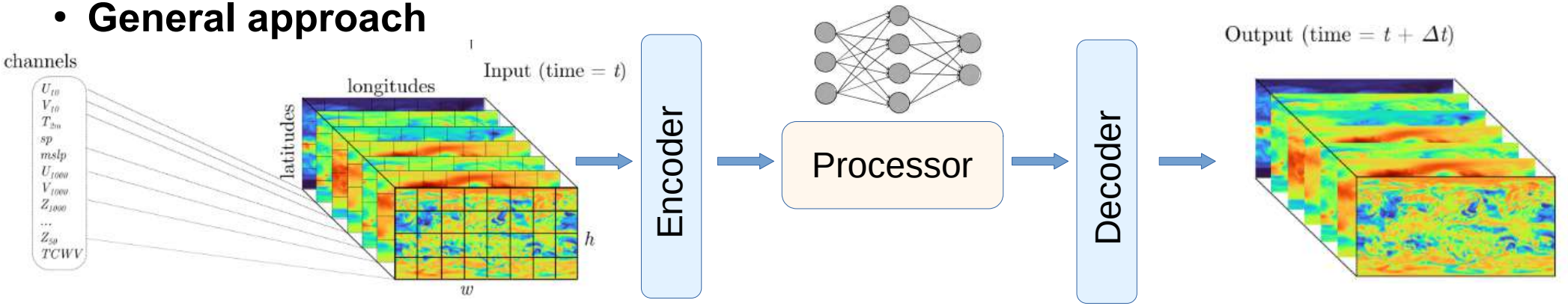
Deep learning approaches are used to emulate the forecasting model $\mathcal{M}$

$$x^{t+dt} = \tilde{\mathcal{M}}(x^t)$$

- Prediction over several time steps obtained with an auto-regressive approach

$$x^t \rightarrow x^{t+dt} = \tilde{\mathcal{M}}(x^t) \rightarrow x^{t+2dt} = \tilde{\mathcal{M}}(x^{t+dt}) \ldots \rightarrow x^{t+ndt} = \tilde{\mathcal{M}}(x^{t+(n-1)dt})$$

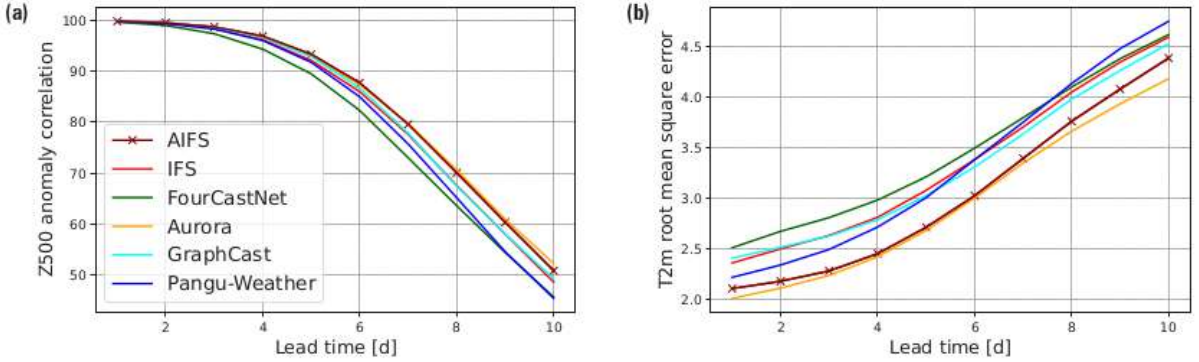
- **General approach**



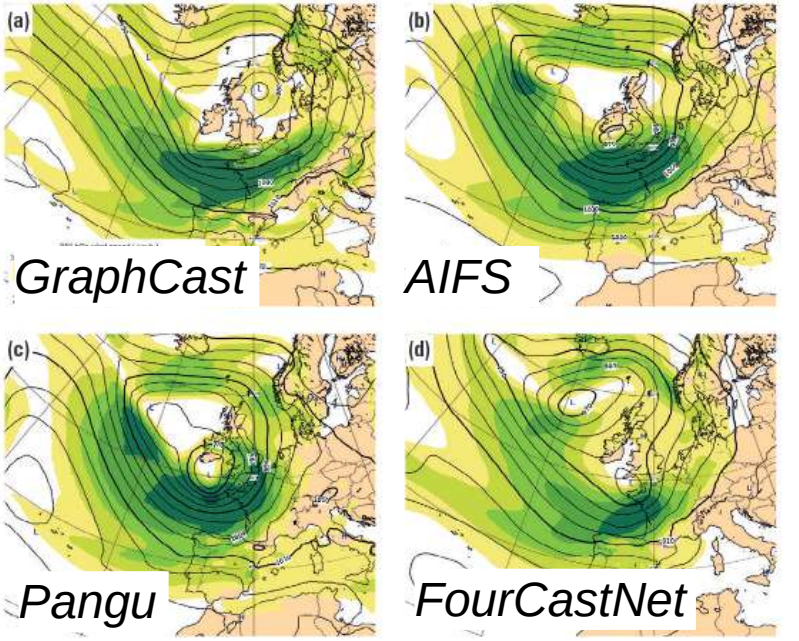
- **Inputs** : gridded data of atmospheric variables at different altitudes

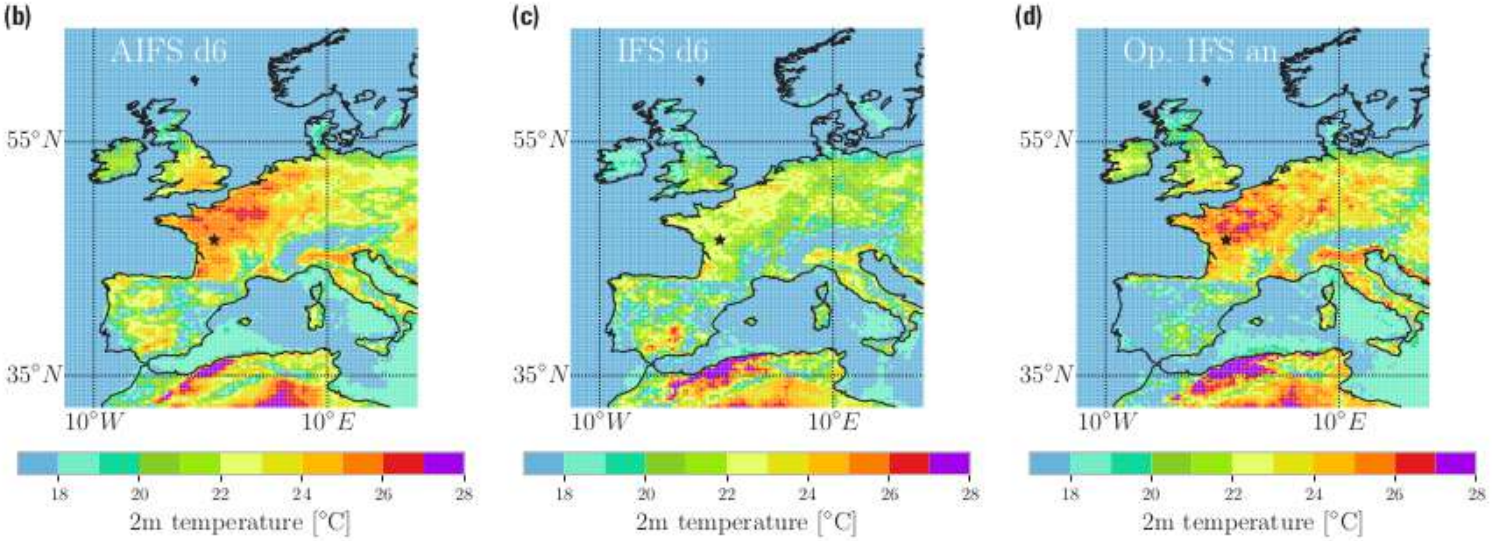
How does it perform ?

Ciaran storm
Pardé et al., 2024



From Boucher et al., 2025

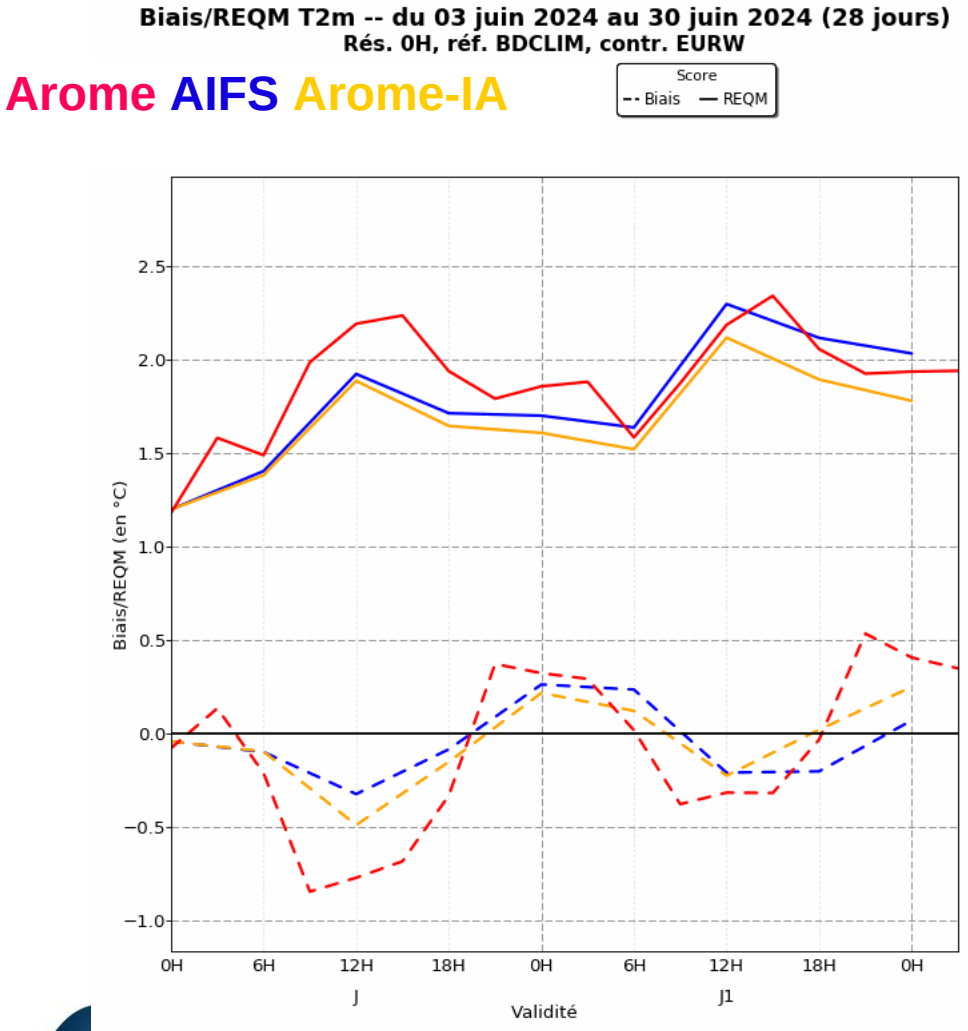




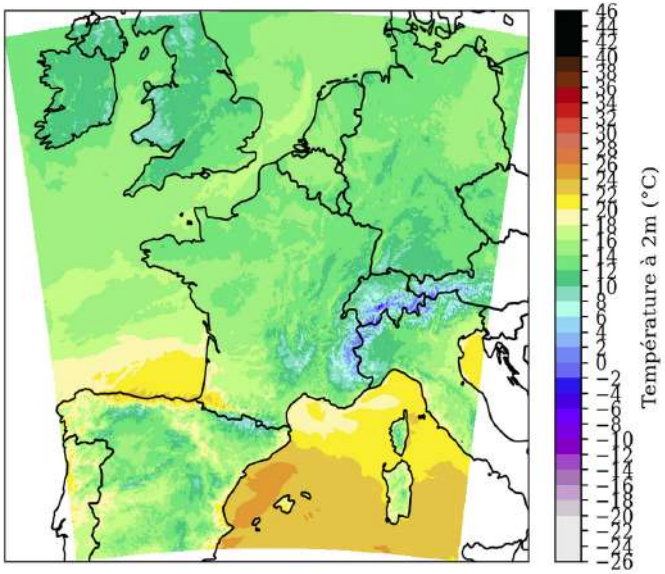
Boucher et al., 2025

Regional emulator at Météo-France : preliminary results

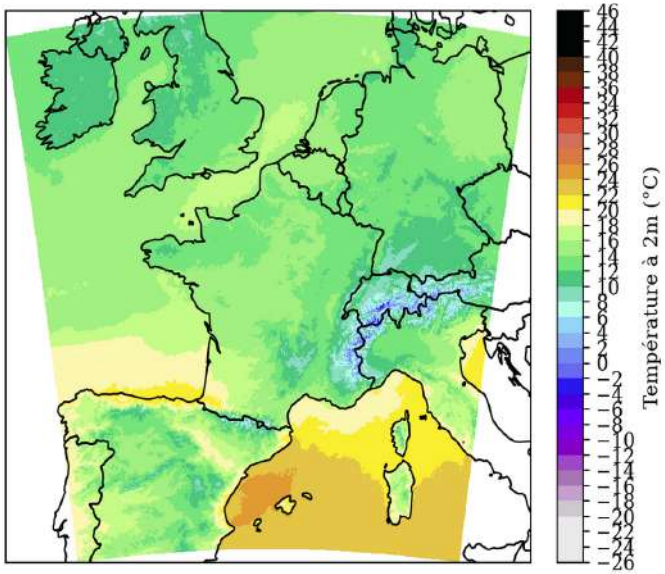
➢ **Trained on km-scale analyses from our AROME model**



Arome oper +24h



Arome-IA +24h

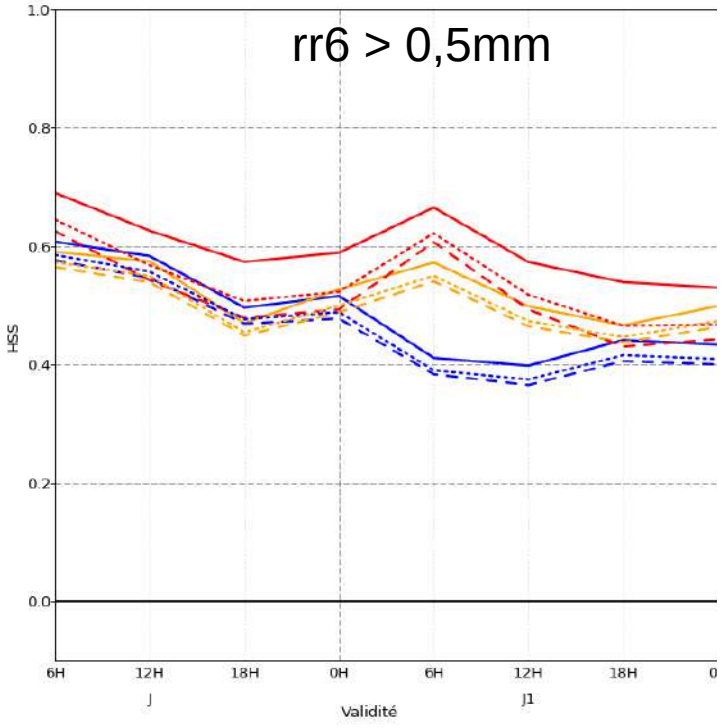


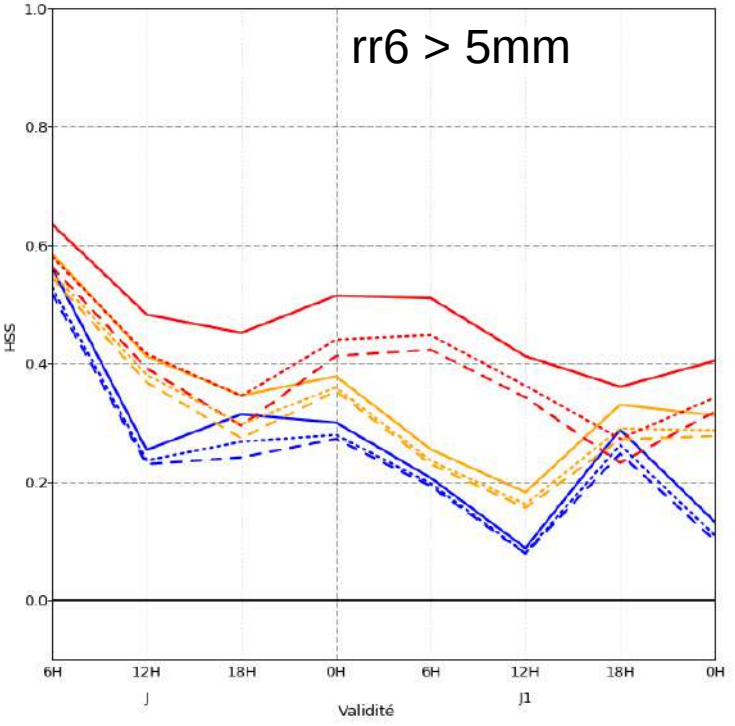
Regional emulator at Météo-France : preliminary results

But still some work to do ...

Arome **AIFS** **Arome-IA**

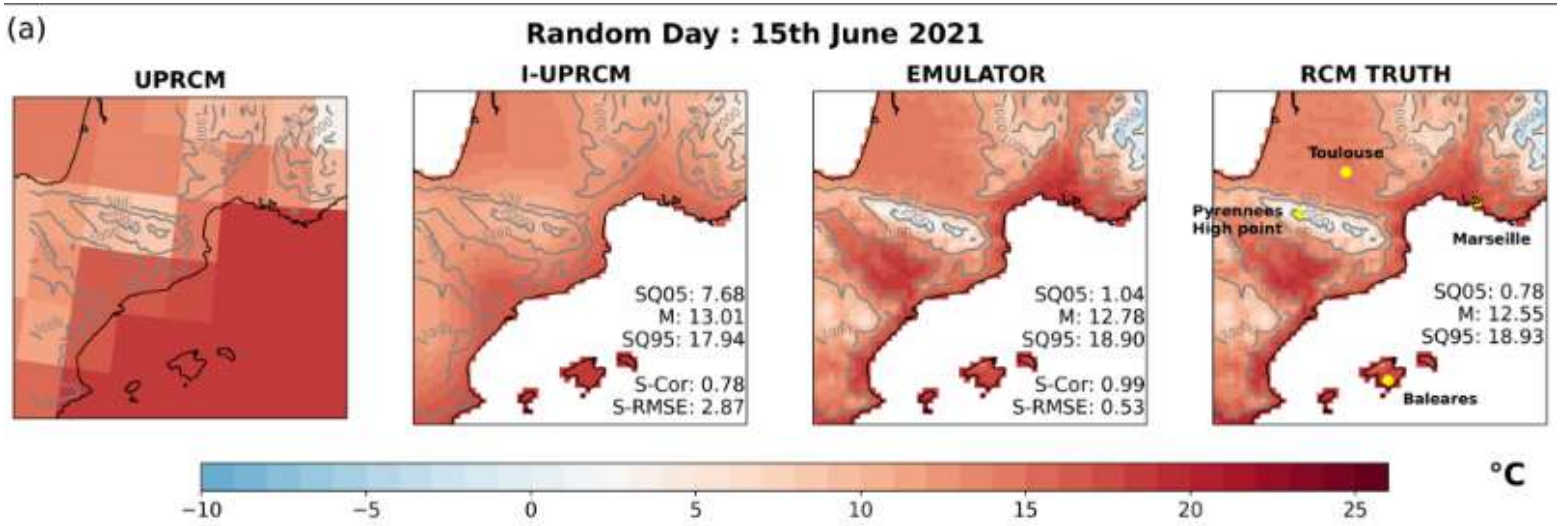
Heidke Skill Score



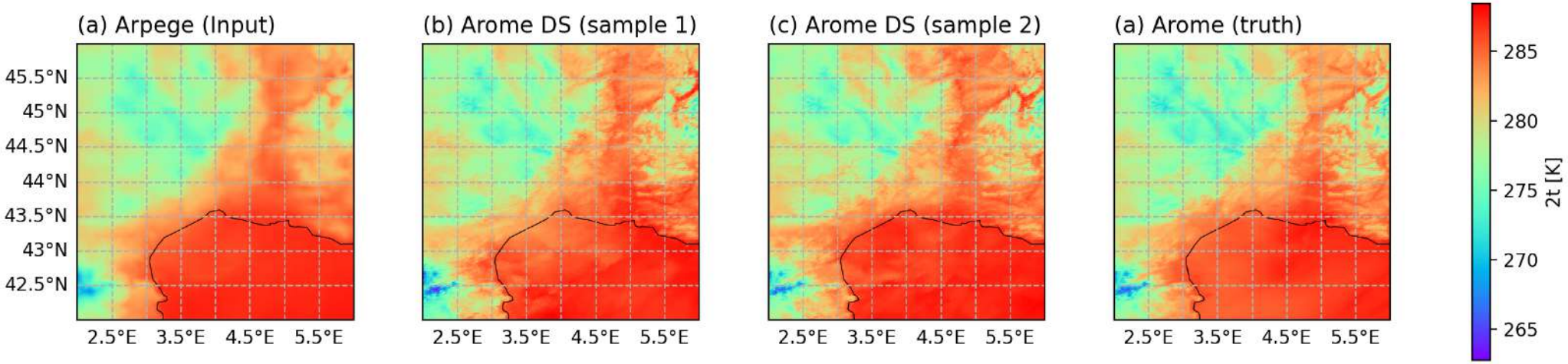


Downscaling applications

- From GCM to RCM emulators (Doury et al., 2022)

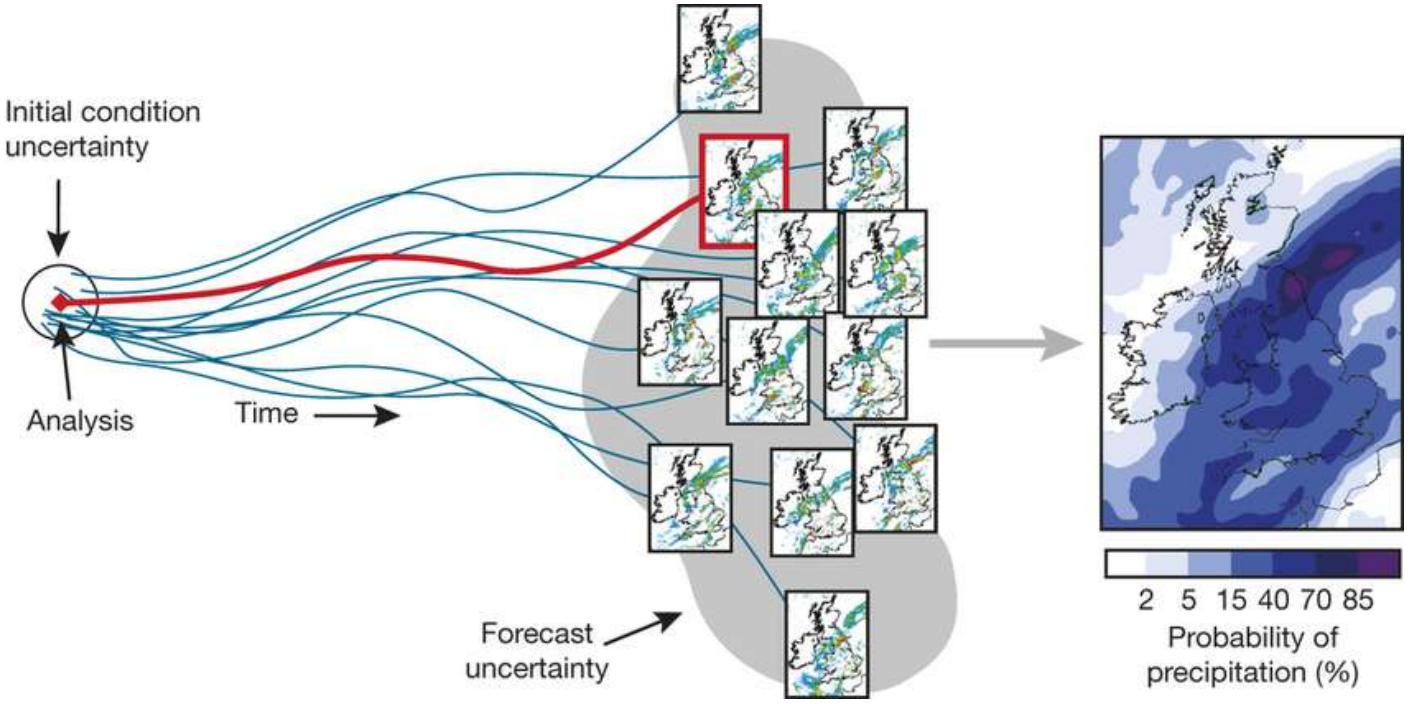


- From 5km to 1km weather forecasts with stochastic DS (E. Lumet)



How do we handle UQ in weather ?

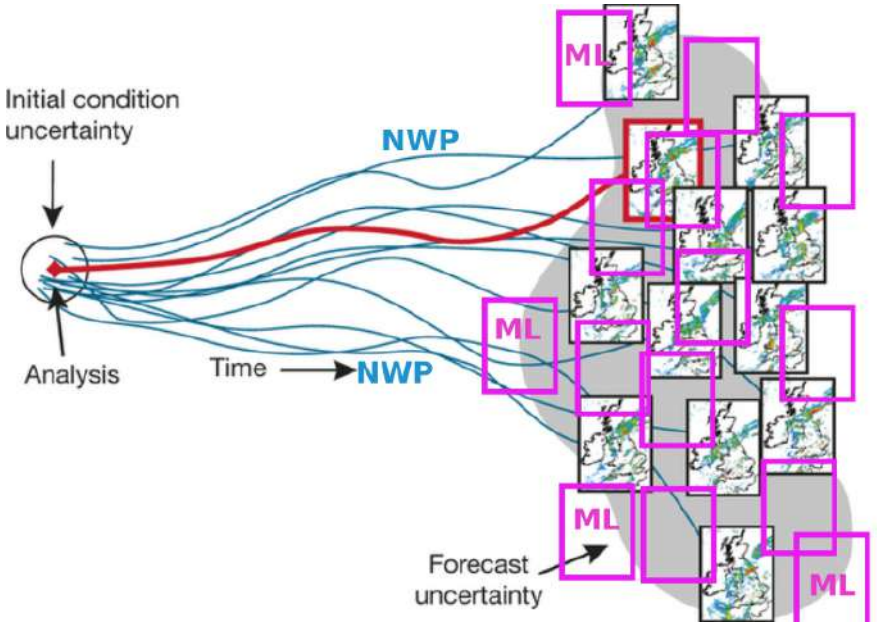
➢Generally with a Monte Carlo estimation of the forecast probability distribution, also known as **Ensemble Forecasting**



Operational at MF
Arome-EPS : 25 members, 1.3km

ML to boost EPS : the concept

- **One limitation of EPS is their small size** (constrained by compute resources), can we leverage ML to generate additional members ?



- **Research questions**
  - Are the ML members physically-consistent ?
  - What is the added value of ML members ?
  - Can the ML ensemble emulate a very large NWP ensemble ?
  - Which ML algorithm is best suited to this task ?
  - Which type of uncertainty ML represents ?

ML used for state estimation, not for propagation

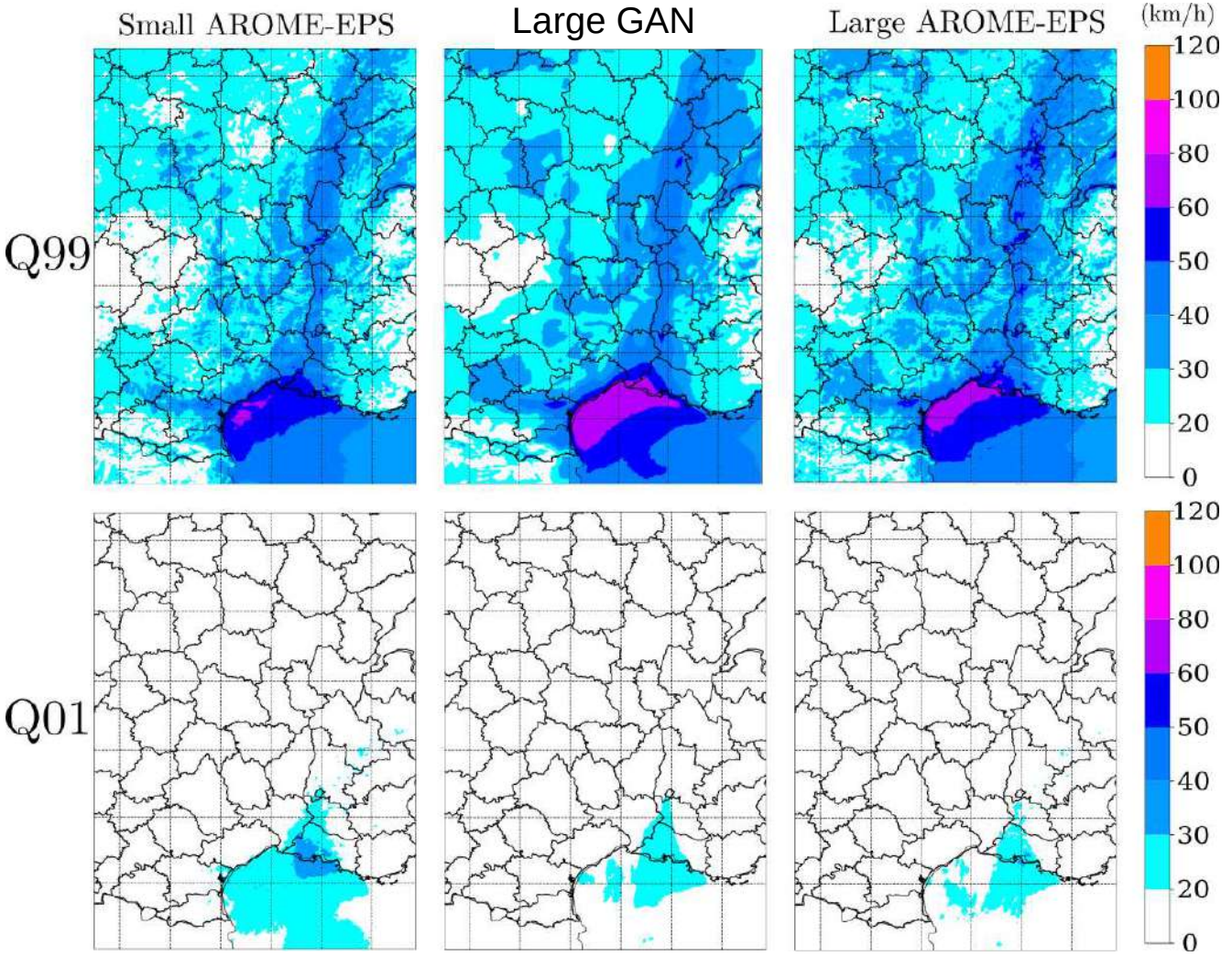
(Li et al., 2024 ; Brochet et al., 2025)

ML-boosted ensemble vs very large NWP ensemble

We use 2 families of generative models

- **Generative Adversarial Network (GAN)**
- **Diffusion models**

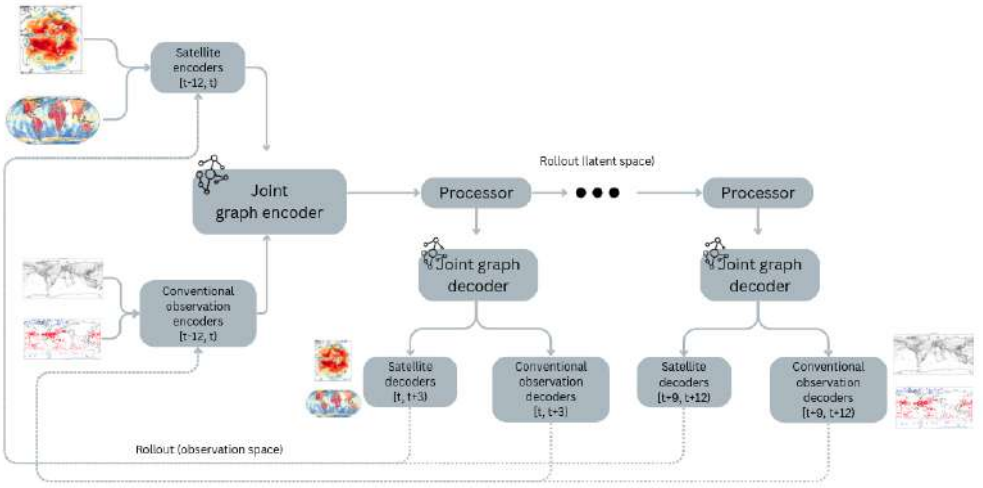
Brochet et al., 2025



Conclusions and future works

- AI for weather is a very active field of research worldwide
- It's potentially a game changer, with already convincing demonstrations at the global scale
- The current focus is on high-resolution forecasting and ensembles
- At Météo-France different flavours of AI models are under development for weather and climate applications, with operational expectations

- The next challenges will be
  - Learning from multi-source data (observations)
  - Uncertainty quantification
  - Data assimilation
  - Physics-informed ML
  - Explainability



Learning from observations : GraphDOP (Lean et al., 2025)