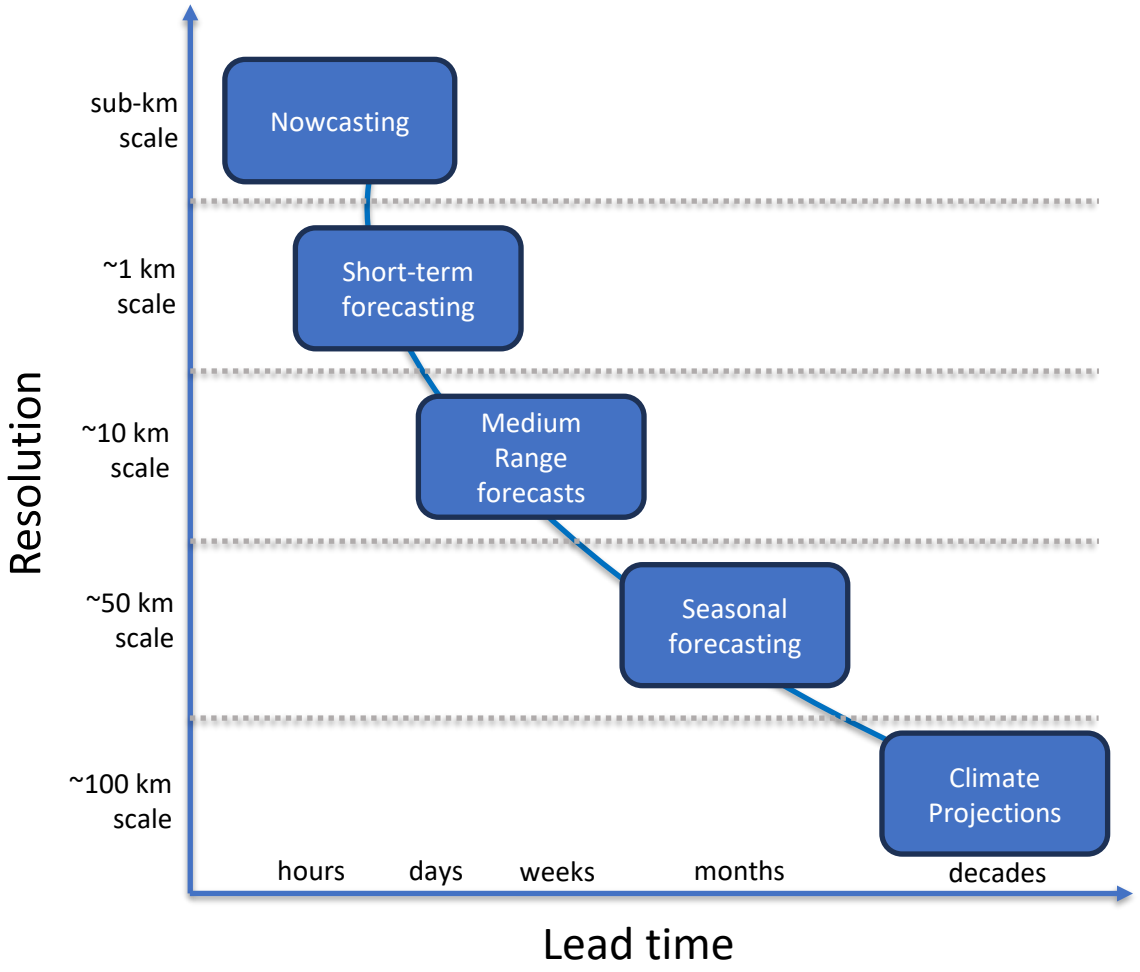
A Review of Recent Advances in AI Models for Weather Forecasting

Slides (strongly) adapted from G. Franch and E. Tomasi (FBK)

International Cooperation in Applied Meteorology for Reducing Hydroclimatic Risks

14-10-2025

AI for Weather and Climate



Enabling tools for the AI revolution:

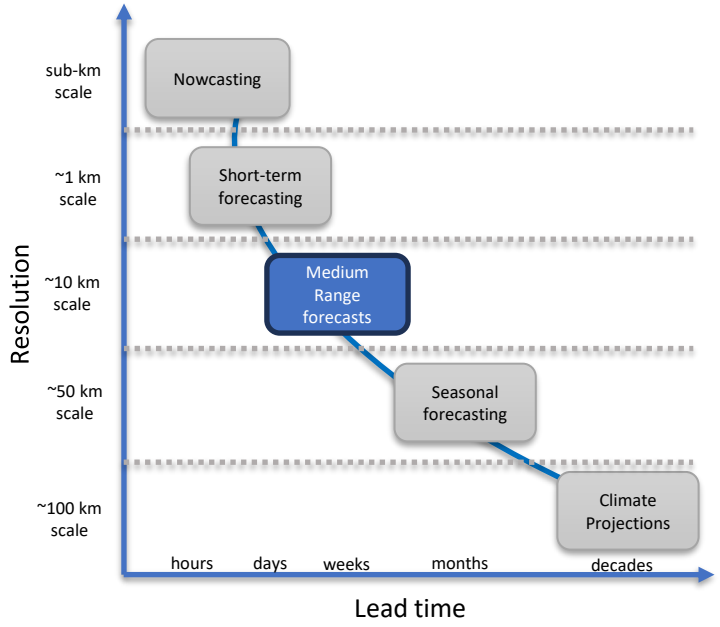
- Advances in Computing Power and Hardware
- Massive Datasets and Data Quality
- Machine Learning and Deep Learning Models

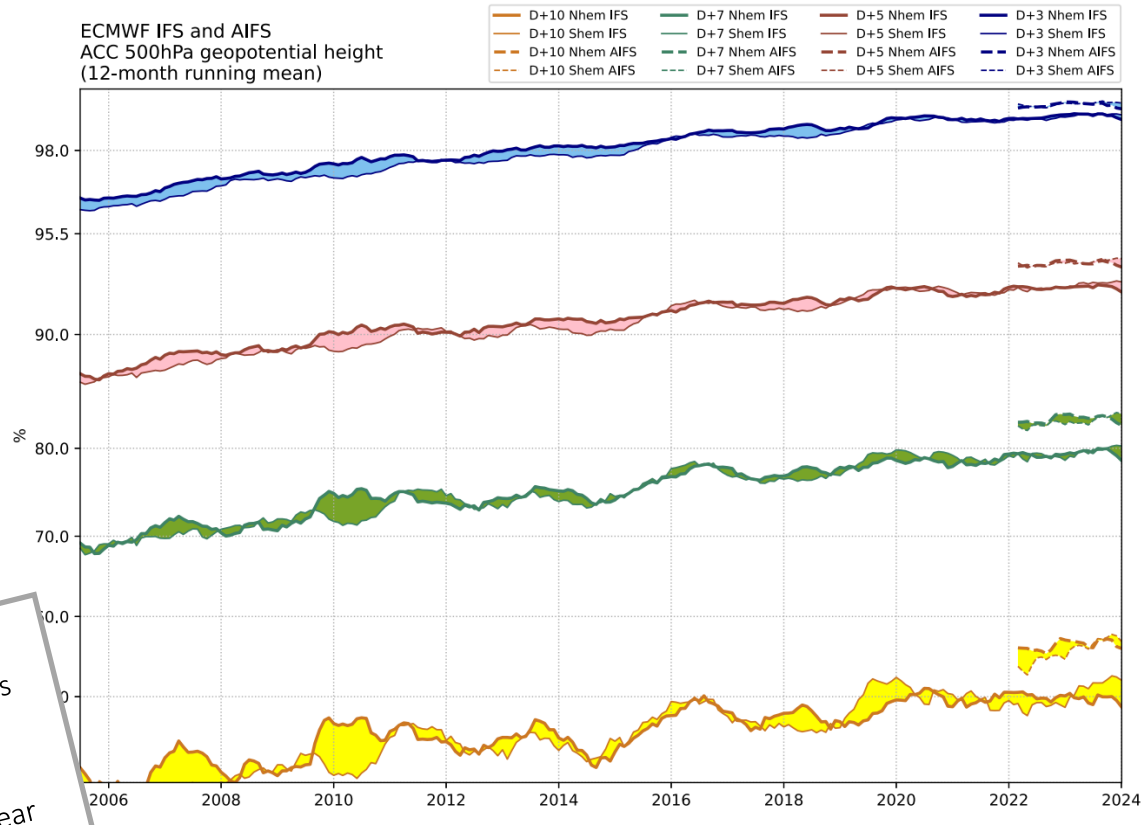
Why this success?

- Outperforming Traditional Accuracy
- Revolutionary Speed and Efficiency
- Deal with Observations much better
- Accessibility and Operability

Medium Range – Global Models

- Boomed in 2023, kept improving since then
- Trained on ERA5, currently probabilistic, stable in time





The QUIET revolution
+1 day of predictability in 10 years

The AI revolution
+0.5 day of predictability in 1 year

HUAWEI

Google Research

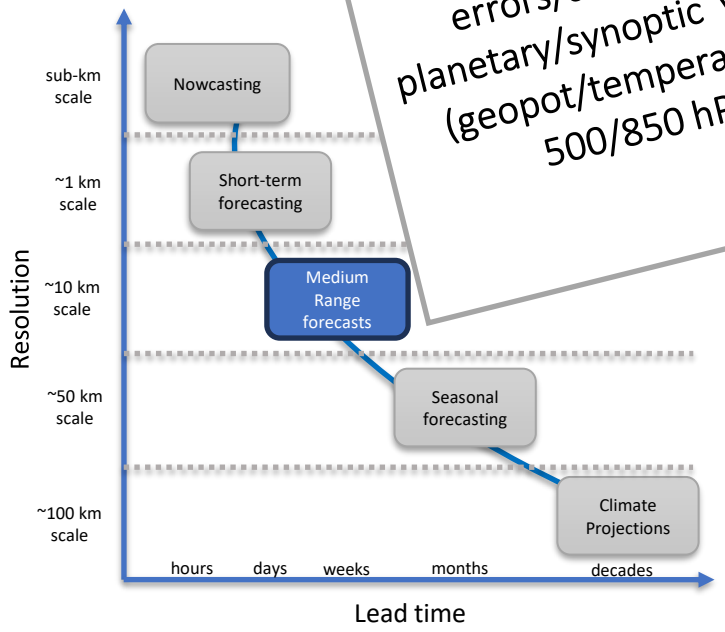
Google DeepMind

NVIDIA

ECMWF

Medium Range – Global Models

Medium-range and global models → accuracy relies on errors/correlation of planetary/synoptic variables (geopot/temperature @ 500/850 hPa)



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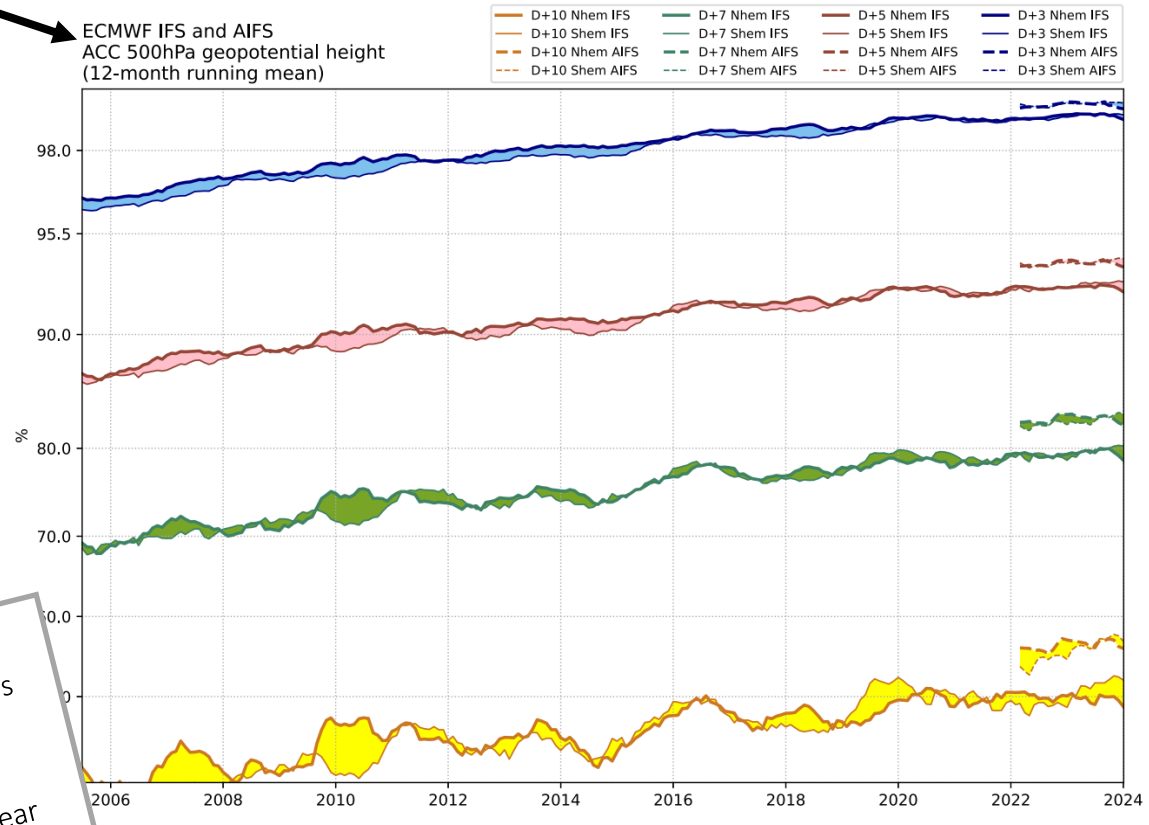

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Medium Range – Global Models

Recently synoptic-to-mesoscale-to-local scale features were evaluated (cyclone tracking, atmospheric river, 10m wind, 2m temp)

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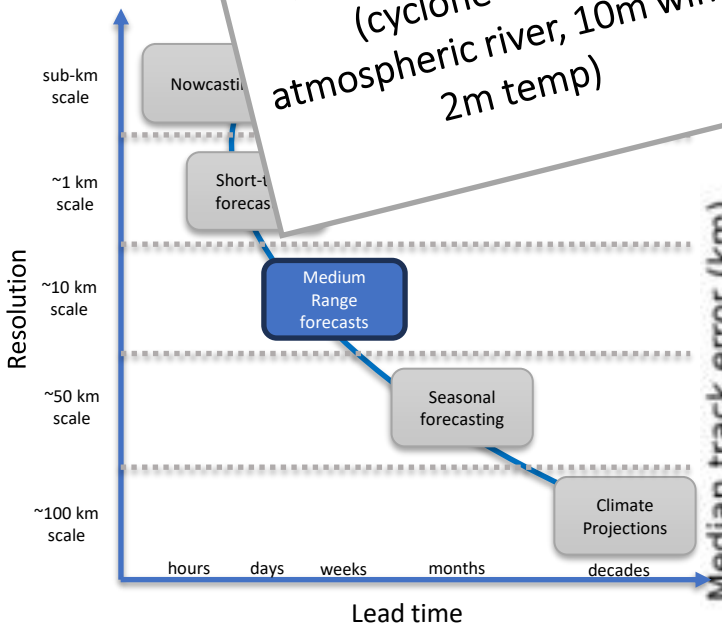

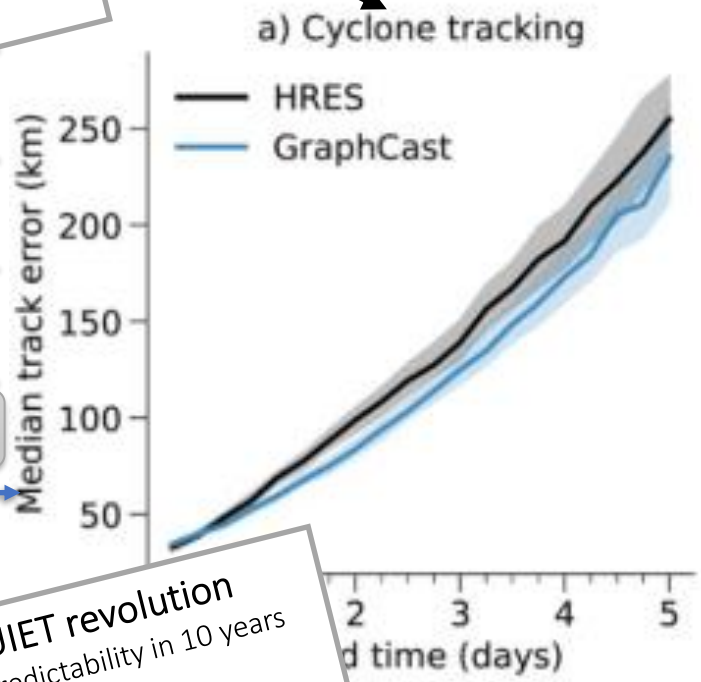

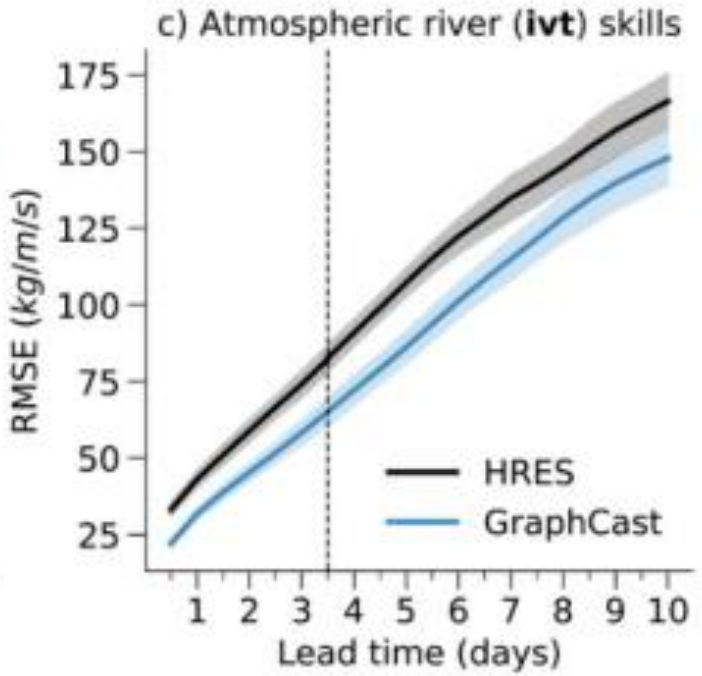

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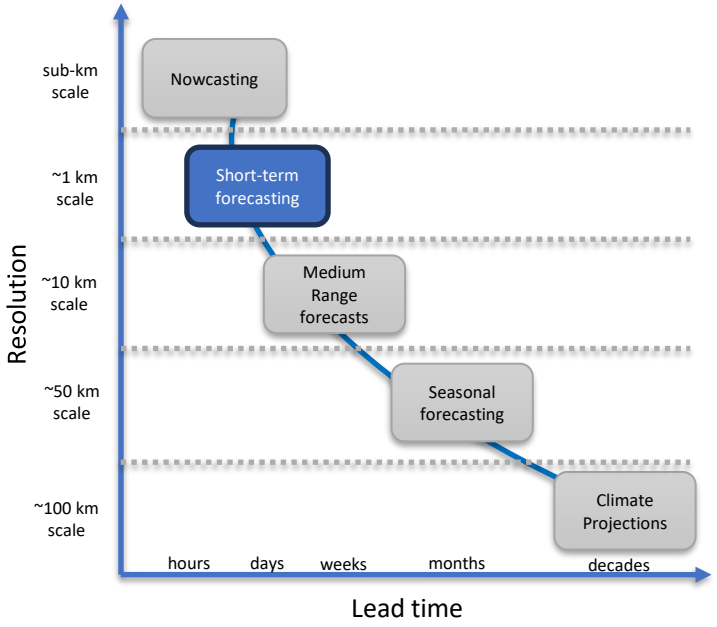
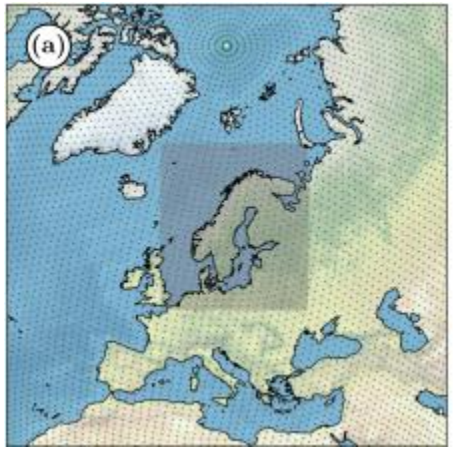
Short-term – Limited Area Models

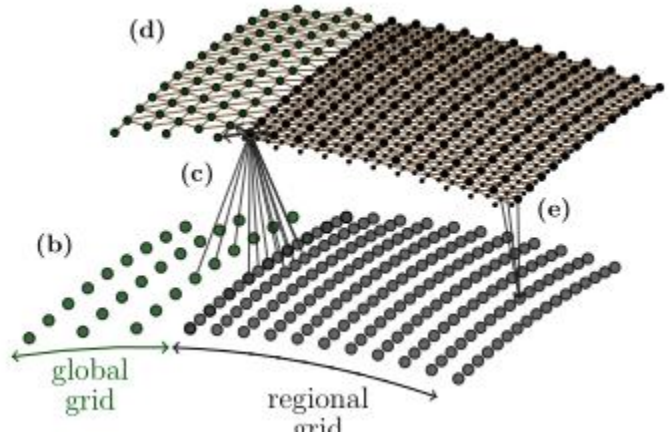


Very new implementations (2024)

- Training on numerical LAMs with Anemoi (framework by ECMWF)

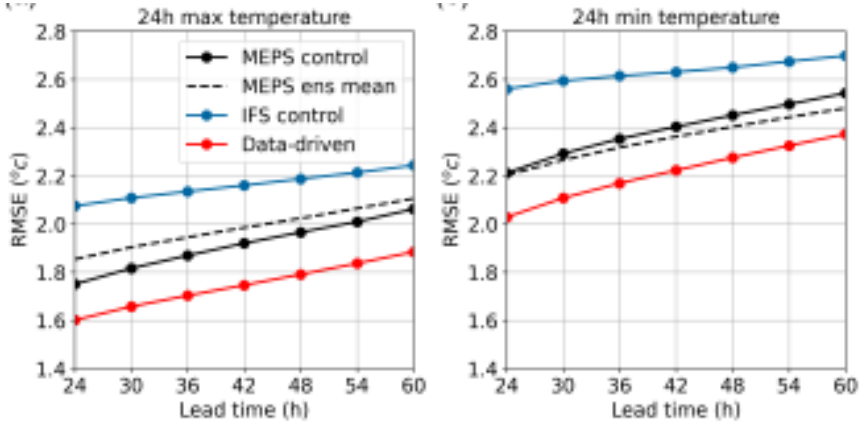
e.g., Nipen et al. 2024



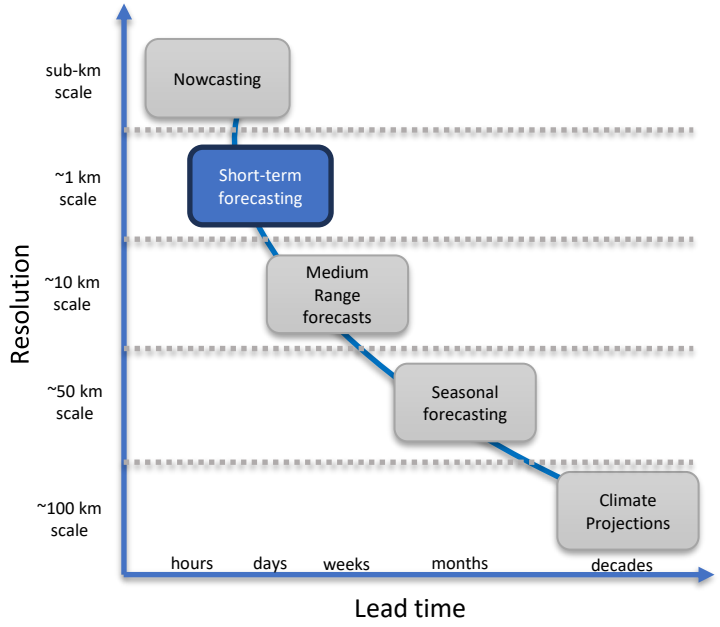


Meteorologisk institutt

ECMWF



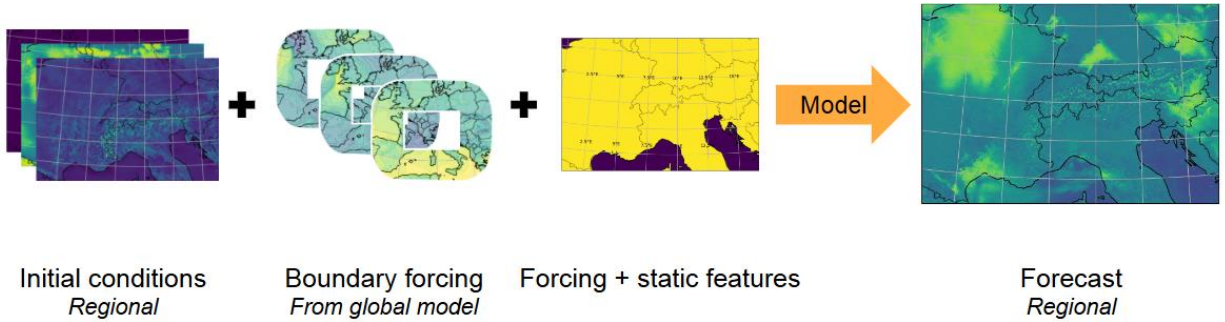
Short-term – Limited Area Models

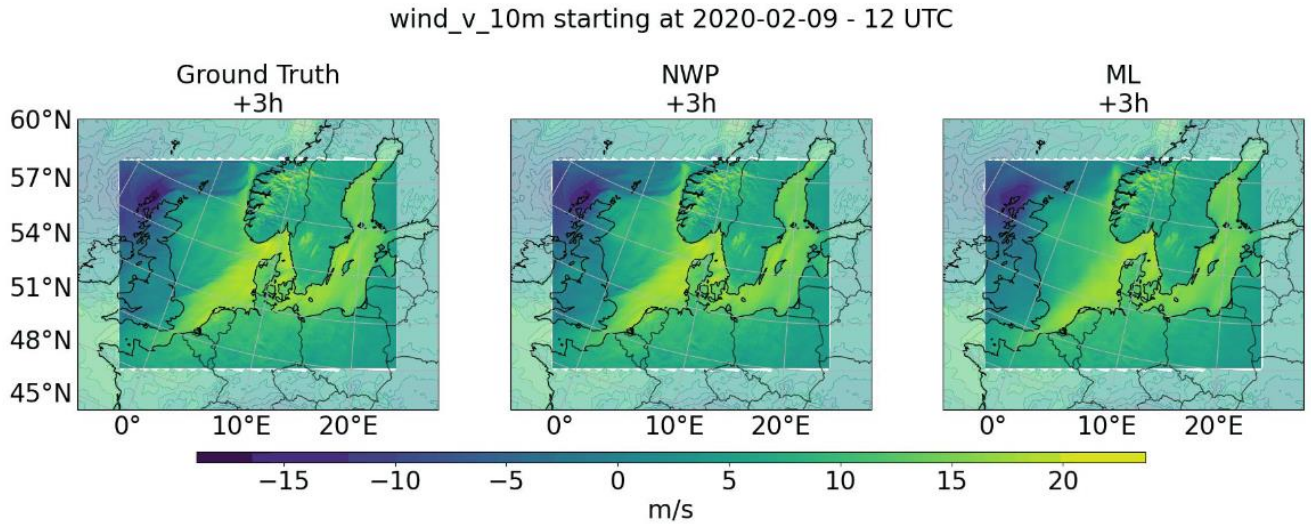


Very new implementations (2025)

- Training on numerical LAMs

e.g., Oskarsson et al. 2025



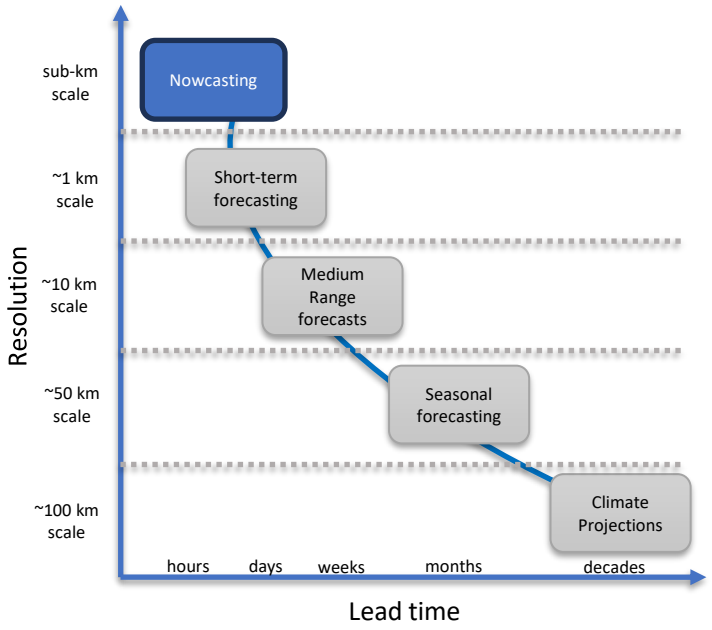


LINKÖPING UNIVERSITY

ETH zürich

MeteoSwiss

Nowcasting

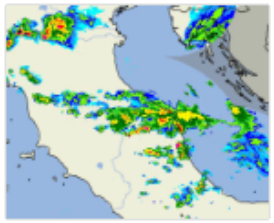


10 years of achievements (from 2015)

ConvLSTM (2015)

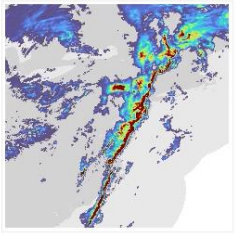
Better RMSE

TrajGRU (2017)



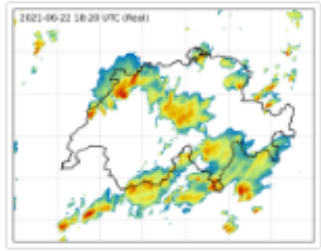
Growth and decay (better CSI)

DGMR (2021)



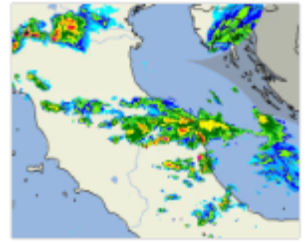
Ensembles (better CRPS)

LDCAST (2023)



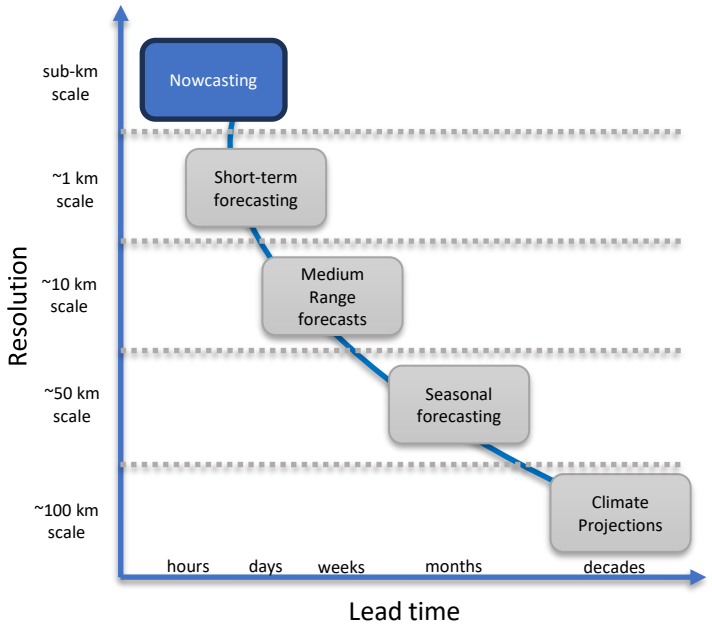
Reliable ensembles (better Rank Hist)

GPTCast (2024)



Conditionability and interpretability

Nowcasting



GPTCast (2024)

INPUT – Past Observations
- Radar (acc. 30´)
- MSG (SEVIRI)

BANDS: 0.6 (vis) / 6.2 / 7.3 / 10.8 (ir) µm

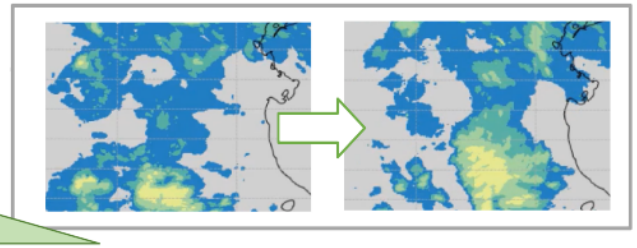
INPUT – Future
Forecast AI-based @25km (AIFS)
Initial conditions from OpenIFS

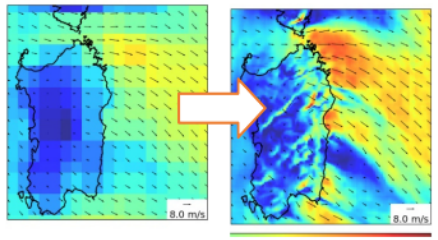
INPUT – Static
DTM, landcover, lat, lon, …

Extrapolation
Observations weighted higher near t=0

0h 6h 24h

Conditioning & Downscaling
Forecast weight increases with lead time



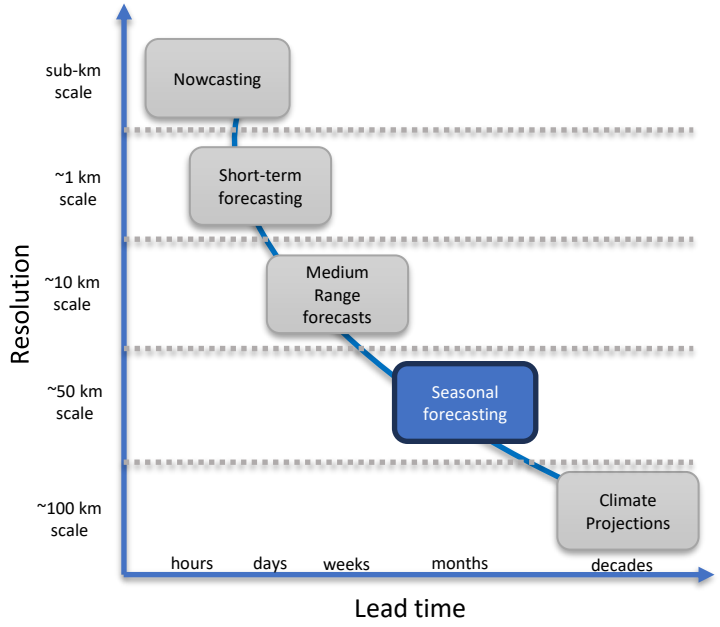


OUTPUT – National domain forecast
- 24h lead time
- 1km resolution
- 30 min timestep - precipitation accumulation (radar)

Core engine:
Latent Diffusion Model (sequence-to-sequence, multi-scale)

Builds on two previous works:
LDCast: LDM for precipitation nowcasting (Leinonen et al. 2023)
LDM_res: AI-driven NWP downscaling (Tomasi et al. 2025)

Seasonal Forecasting



Open research topic (2025)

e.g., ECMWF AI-Weather Quest for sub-seasonal prediction (i.e., 3rd and 4th week)

ECMWF

AI Weather Quest
AIFS team

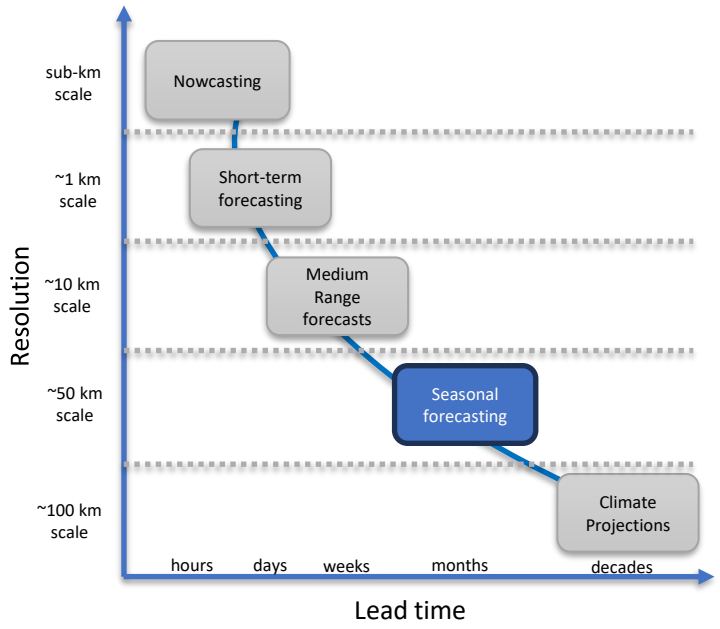
AIFS-hera
medium-range model
- Troposphere + Surface variables
- 6h time-step
- 12-step rollout-finetuning

Lang et al. AIFS-CRPS (2024b)

AIFS-gaia
longer time-step model
- Troposphere + surface variables (+ stratosphere)
- 24h time-step
- no rollout fine-tuning
- Revised variable weighting

AIFS-thalassa
model with surface ocean
- Troposphere + surface variables + surface ocean + sea ice
- 24h time-step
- 3-step rollout fine-tuning

Seasonal Forecasting



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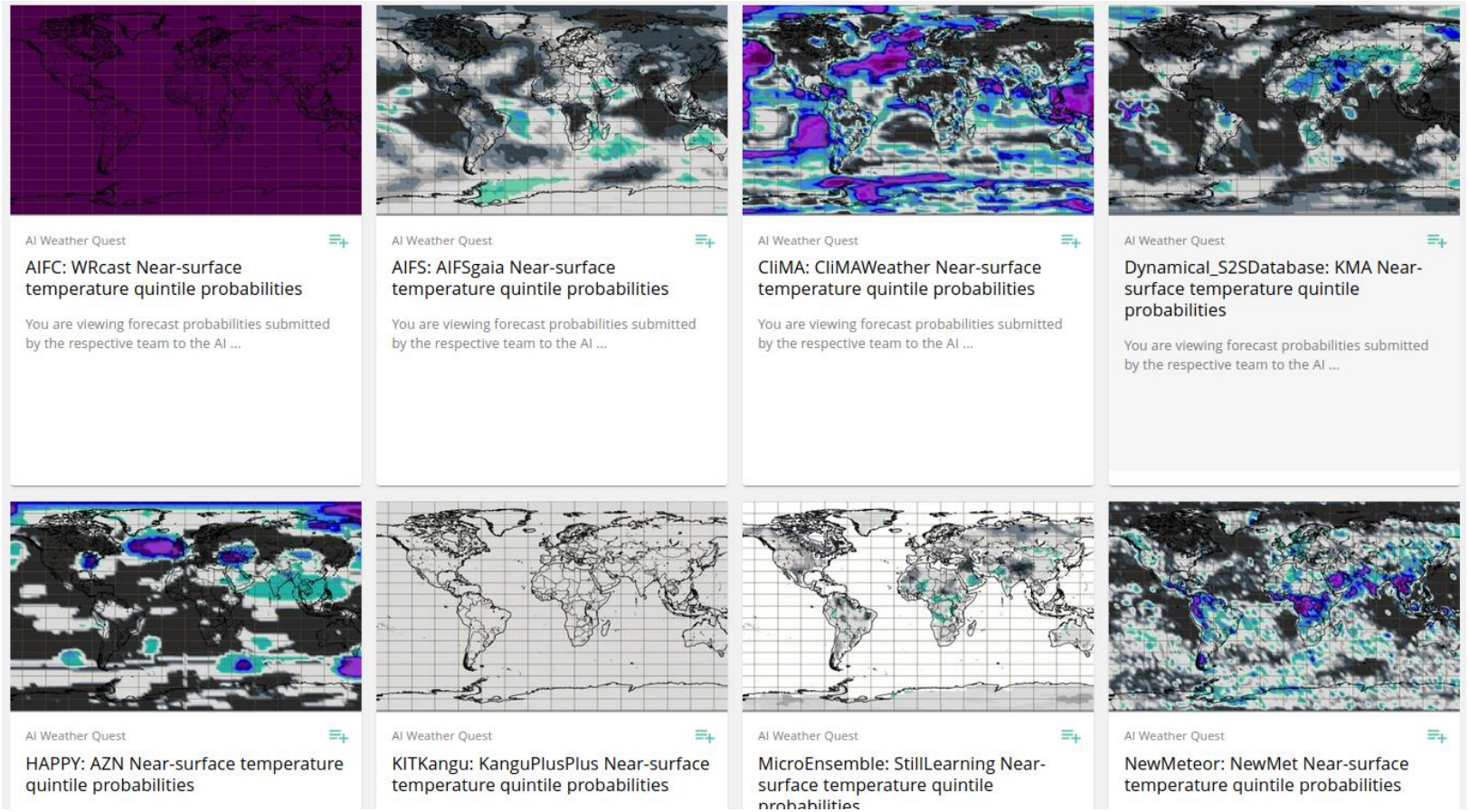
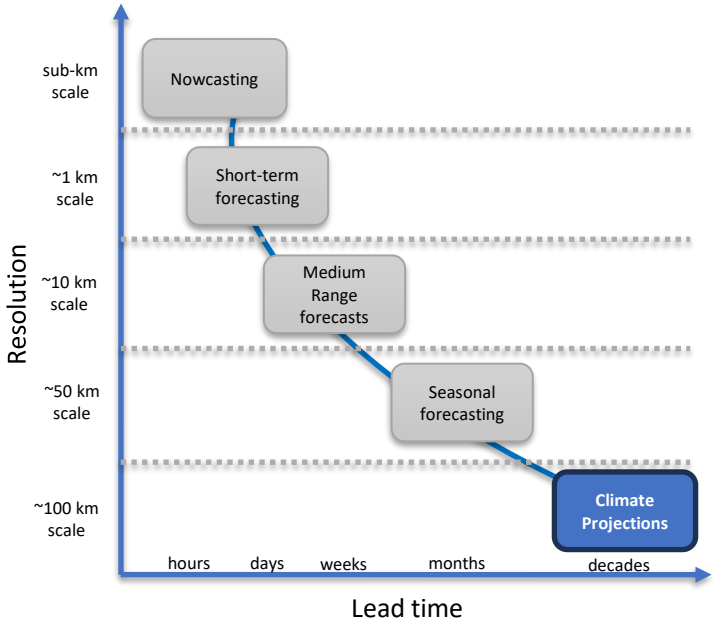
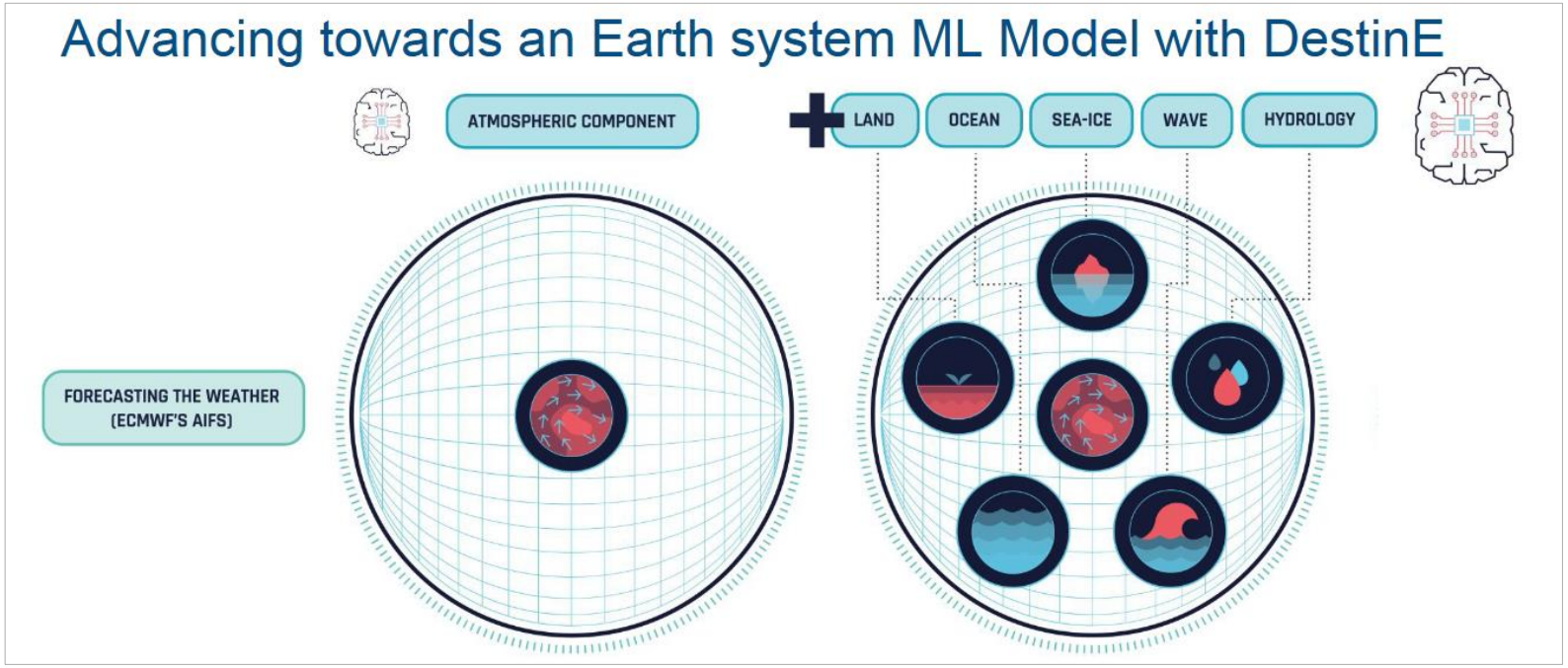


Climate Modeling

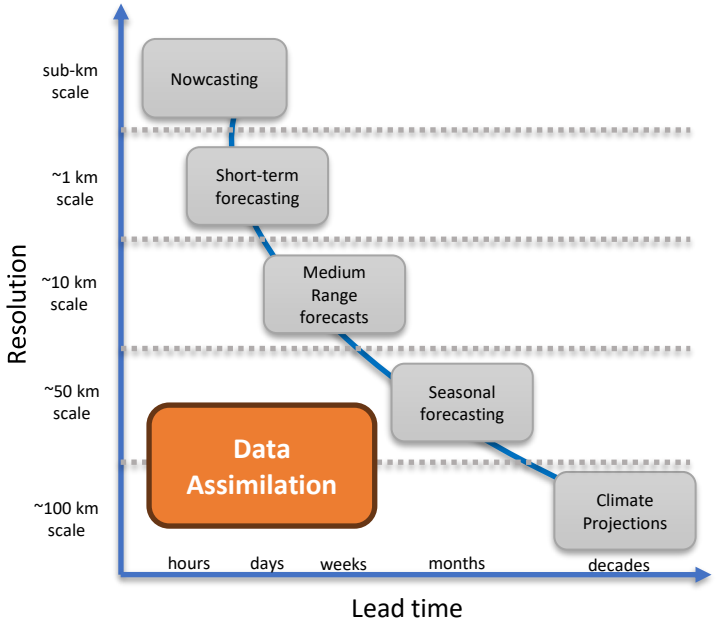
Open research topic (2024)

e.g., ECMWF Earth System Model





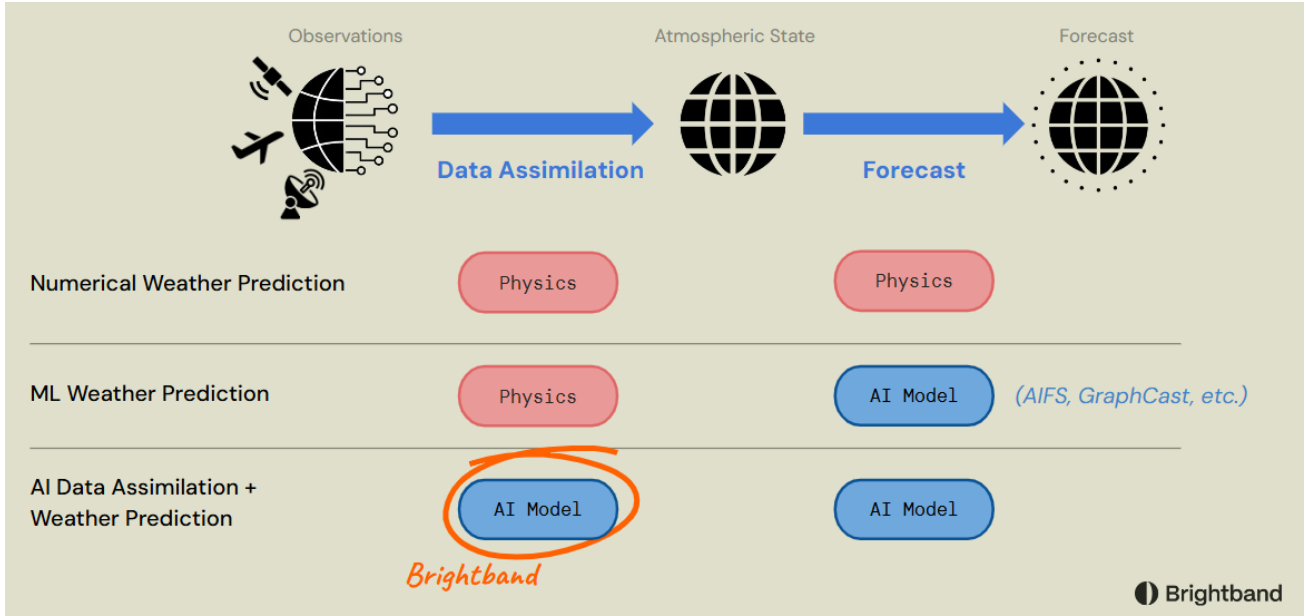
Data Assimilation



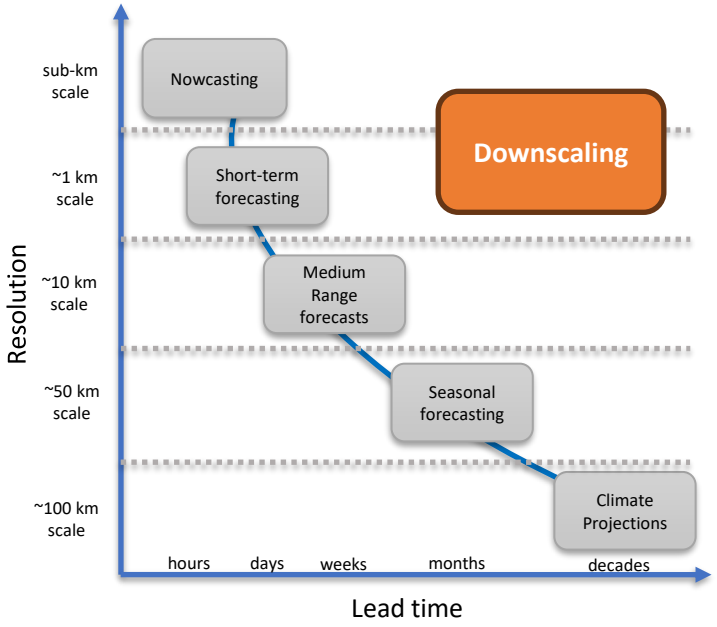
Open research topic:

- The core idea is to completely untangle AI-based forecasts from analyses (i.e., from numerical modeling)
- Goal: End-to-end Data-Driven models

e.g., AIDA from Brightband



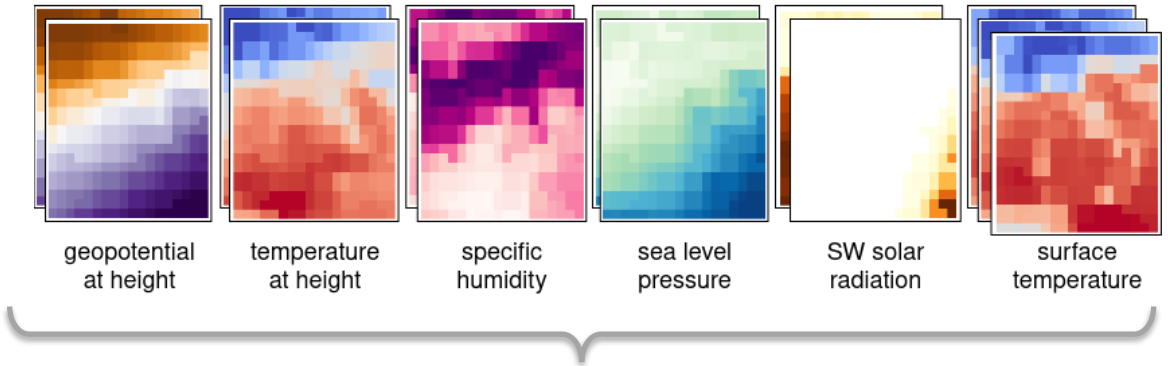
Downscaling

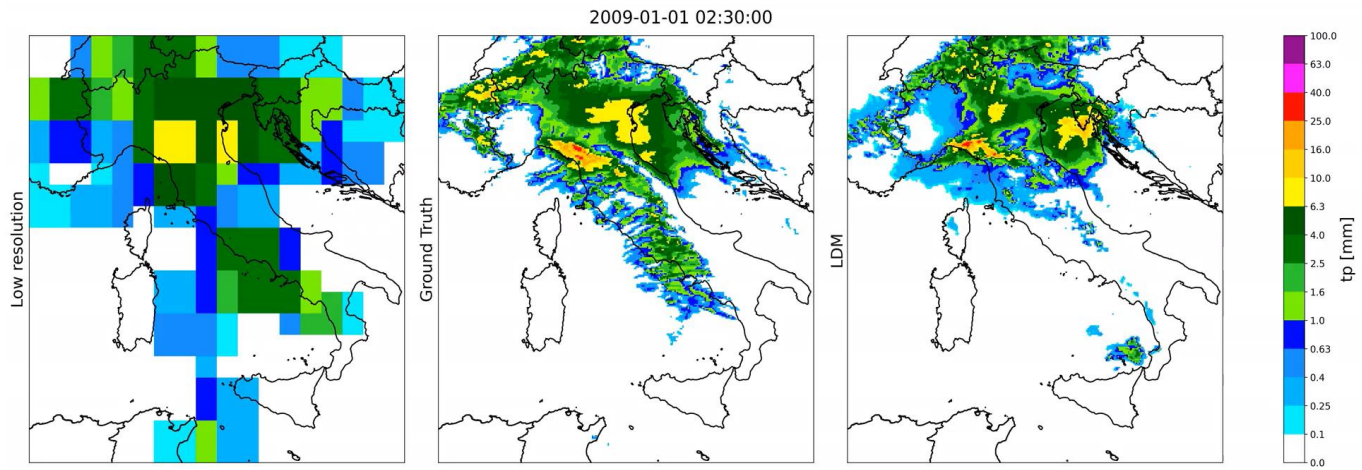


Many available techniques (from 2017)

- Few variables, extremely fast

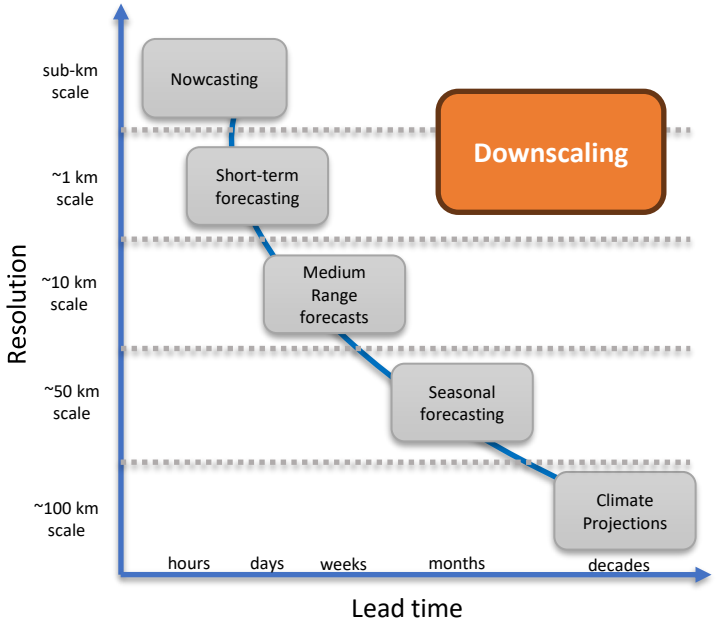
e.g., NVIDIA CorrDiff, FBK Diffscaler





FONDAZIONE BRUNO KESSLER

Downscaling



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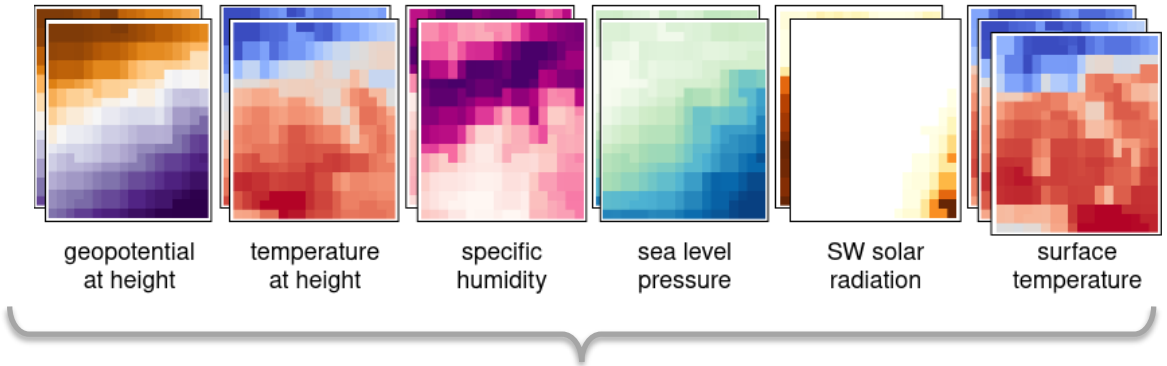
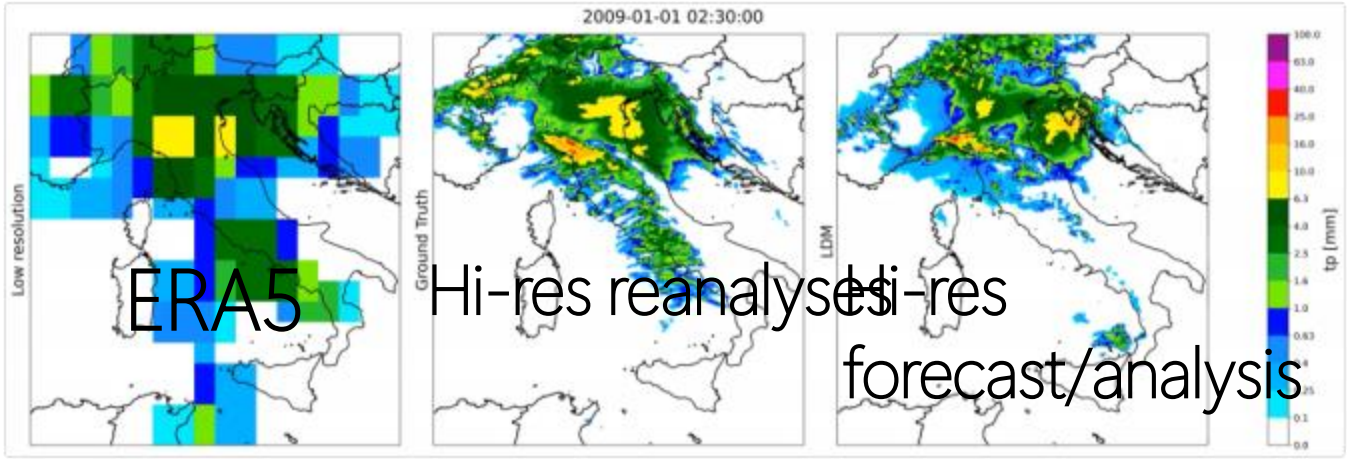
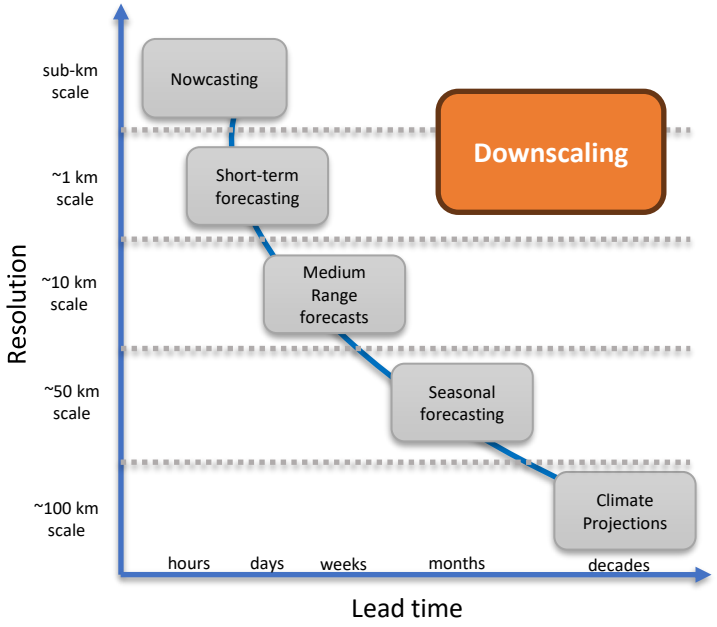
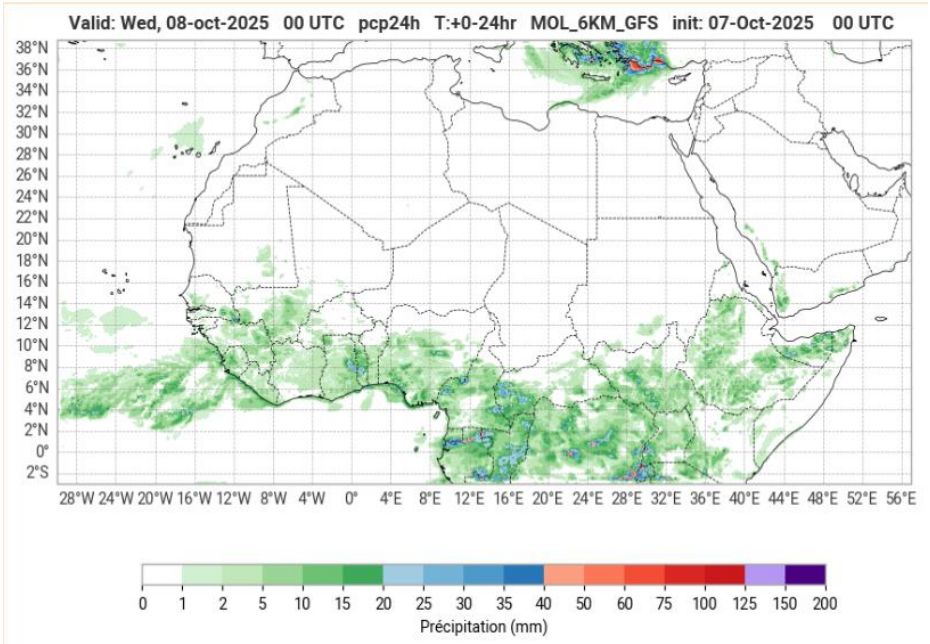




Downscaling – Slapis project

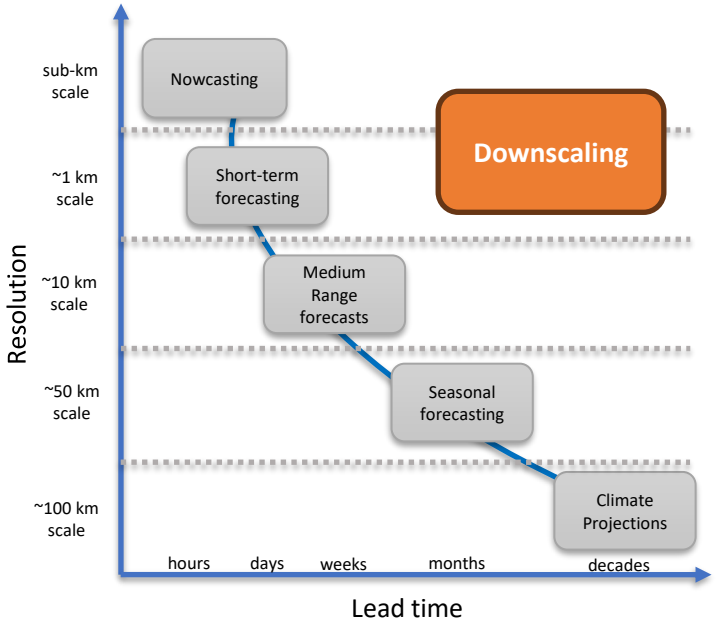
Produce a high-resolution hindcast over the Sahel region





- ERA5 as IC/BC
- Grid spacing ~ 4-6 km
- Time: 1979-2025
- Output: every 15 min

Downscaling – Slapis project



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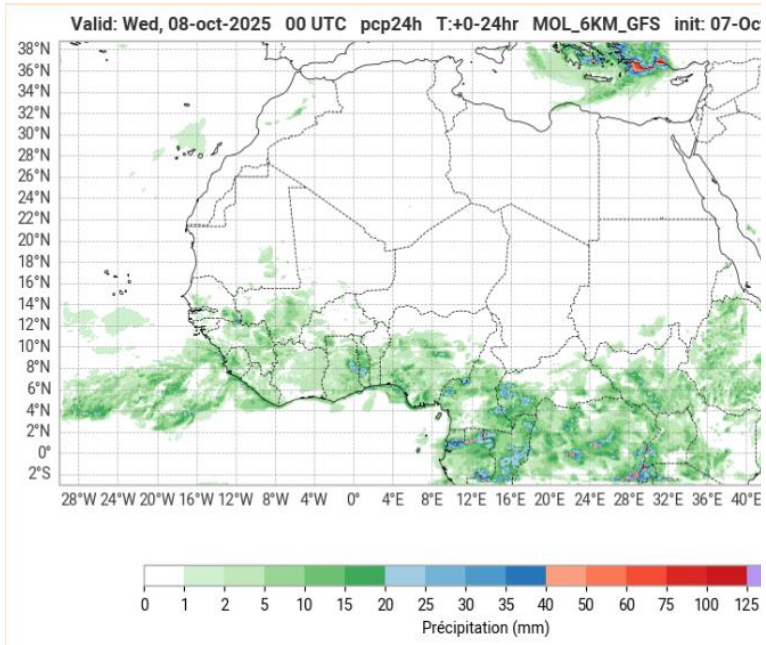


HPC resources from ECMWF

REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: ITALY

Principal Investigator[1]: Valerio Capecchi

Affiliation: Consorzio LaMMA, Laboratorio di Meteorologia e Modellistica Ambientale per lo sviluppo sostenibile & Agenzia Nazionale per la Meteorologia e Climatologia "ItaliaMeteo"

Address: Via Madonna del piano, 10, Sesto Fiorentino, Florence, Italy

Other researchers: *Vieri Tarchiani* – Institute for Bioeconomy of the National Research Council of Italy
Francesco Pasi – Consorzio LaMMA & Institute for Bioeconomy of the National Research Council of Italy
Younoussa Adamou Sayri - National Meteorology Directorate of Niger & Institute for Bioeconomy of the National Research Council of Italy
Thomas Bere - National Meteorology Agency of Burkina Faso & Institute for Bioeconomy of the National Research Council of Italy

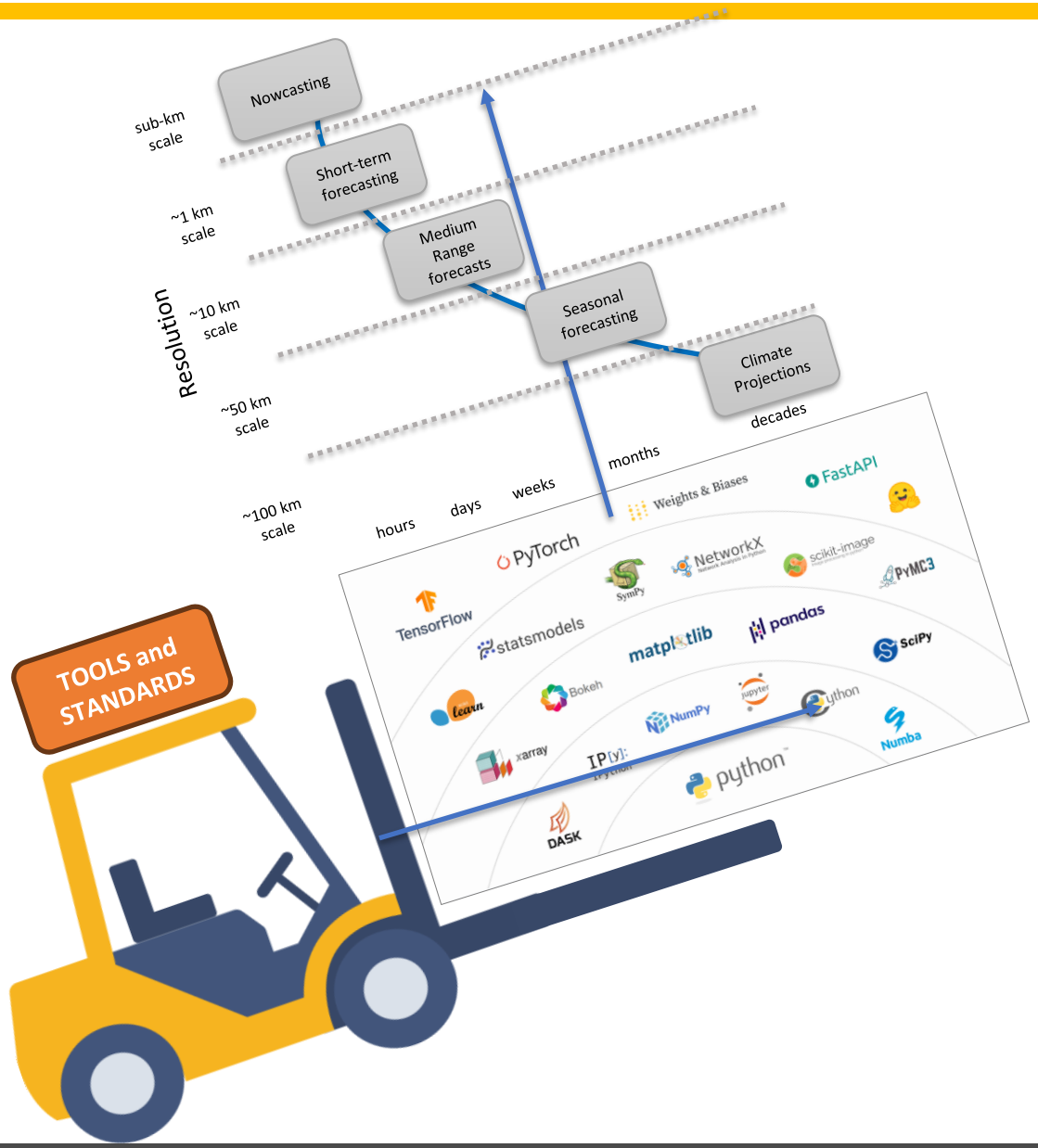
Project Title: **A High-Resolution Hindcast for the Sahel Region Based on ERA5 data and the MOLOCH model**

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP**ITCAPE	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2026	
Would you accept support for 1 year only, if necessary?	YES	NO X

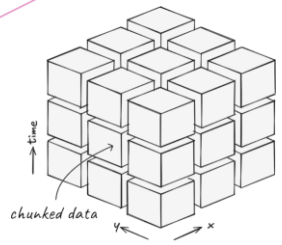
Computer resources required for project year:		**2026**	**2027**	**2028**
High Performance Computing Facility	[SBU]	4.5 M	3 M	3 M
Accumulated data storage (total archive volume)[2]	[GB]	4.5 K	7.5 K	10.5 K

Data and software ecosystem



DATA MANAGEMENT

Zarr



The poster child of HDF5/NetCDF: inherits the data model and metadata capabilities

Analysis Ready & Cloud Optimized (ARCO) format: Chunk-based and object-storage friendly (API / S3)

Streamable and parrallel-friendly (Dask)

Perfect for creating AI training datasets

FRAMEWORKS AND LIBRARIES

PyTorch Lightning

Anemoi

Python-based framework for weather forecasting based on machine learning providing the key building blocks to train state-of-the-art data-driven models and run them in an operational context (Datasets, Training, Models, Inference, Graphs).

Thank you