ECMWF – DESTINATION EARTH

DIFFUSION DOWNSCALING WITH ANEMOI

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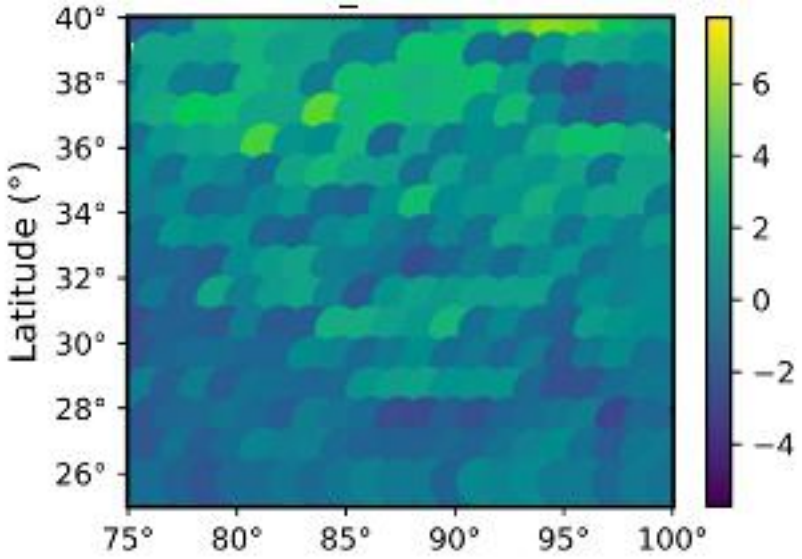
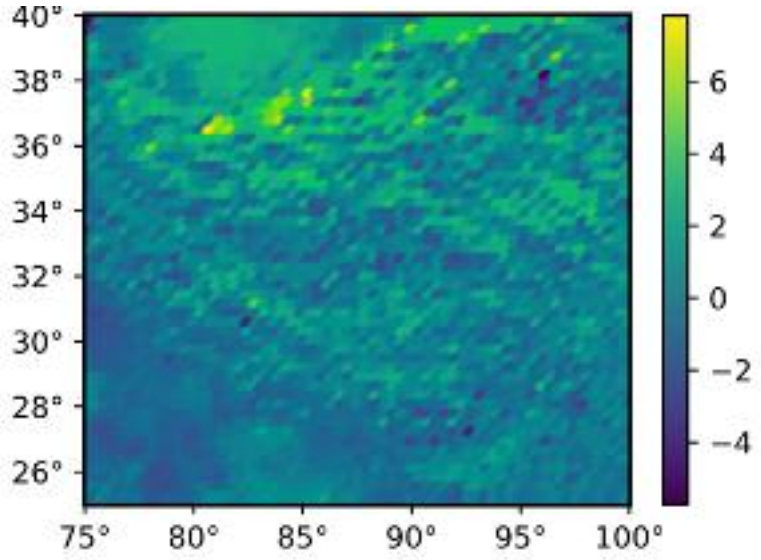
Funded by the European Union Destination Earth implemented by ECMWF esa EUMETSAT

WHAT IS DOWNSCALING?





Low resolution Himalayas input

High-resolution output

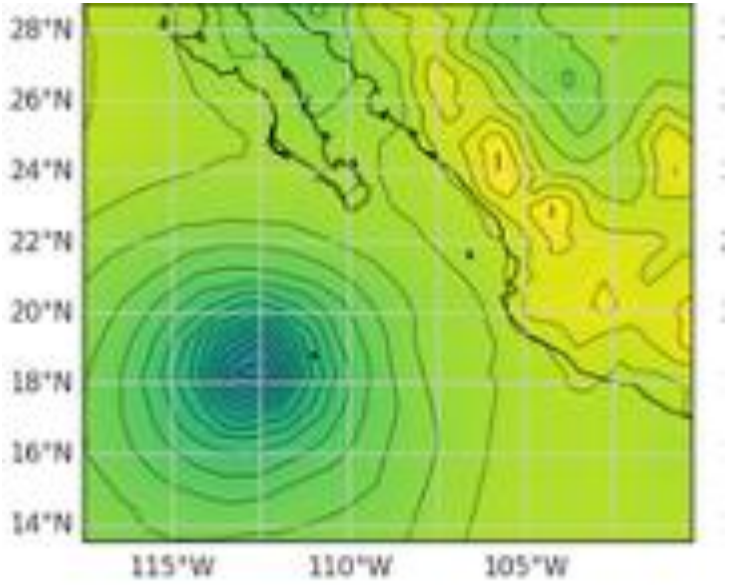
Low-resolution atmospheric fields contain only large-scale structures.
Downscaling aims to generate high-resolution fields consistent with these large-scale conditions.

WHY IS DOWNSCALING NEEDED ?

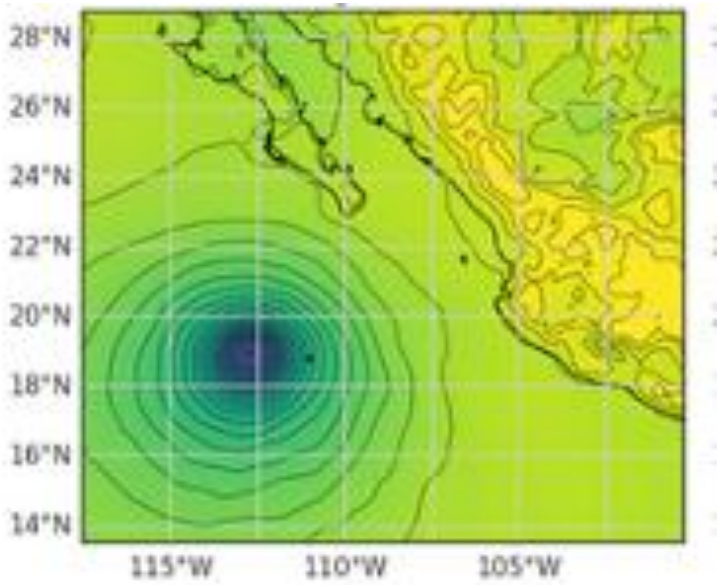
Low-resolution models cannot resolve:

- Extreme events
- Small-scale features (wind gusts, convection, orographic effects)

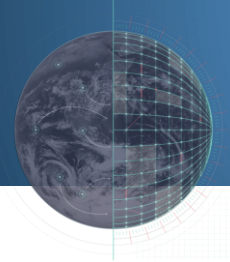
Example: Tropical cyclone intensity and structure strongly depend on resolution.



Low resolution Tropical Cyclone (Hilary)



High resolution Tropical Cyclone – much more intense



WHY ML DOWNSCALING

Generating an ensemble for Destination Earth 4.4km climate or extreme digital twins:

- Physically accurate
- Extremely expensive computationally

ML provides much lower computation cost to generate large high-resolution ensemble forecasts

DOWNSCALING IS PROBABILISTIC

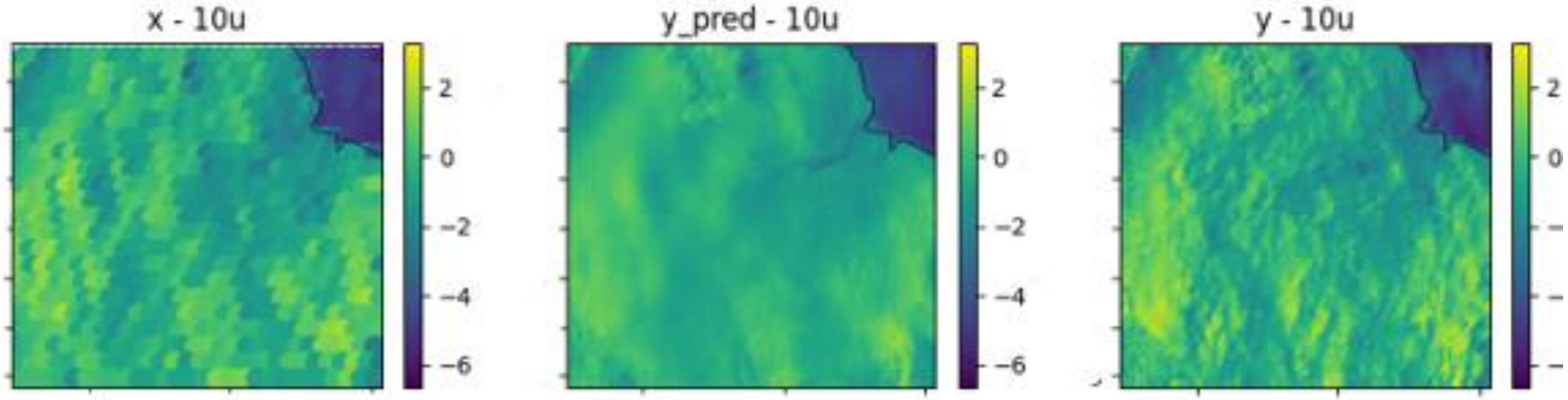
Downscaling is fundamentally probabilistic

Multiple high-resolution states are consistent with the same low-resolution state.

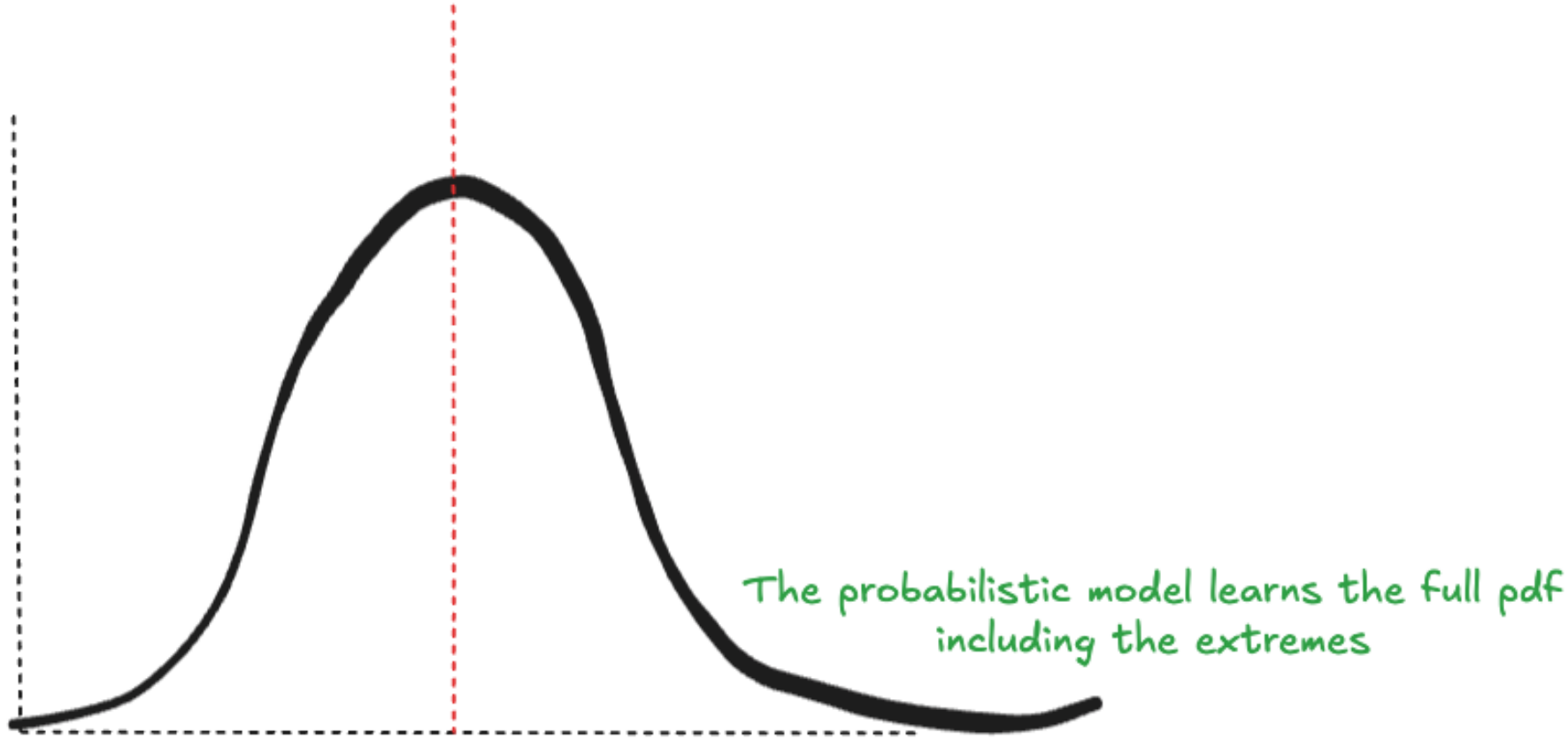
A deterministic model produces only the conditional mean.

This leads to:

- Loss of small-scale variability
- Smoothing of extremes



The MSE minimiser model learns the mean of the distribution



Conditional distribution of high-res weather field given the low resolution input

$$p(x_{HR} \mid x_{LR})$$

ENSEMBLE GENERATION = REALISTIC SPATIAL VARIABILITY, SPECTRA, AND EXTREMES

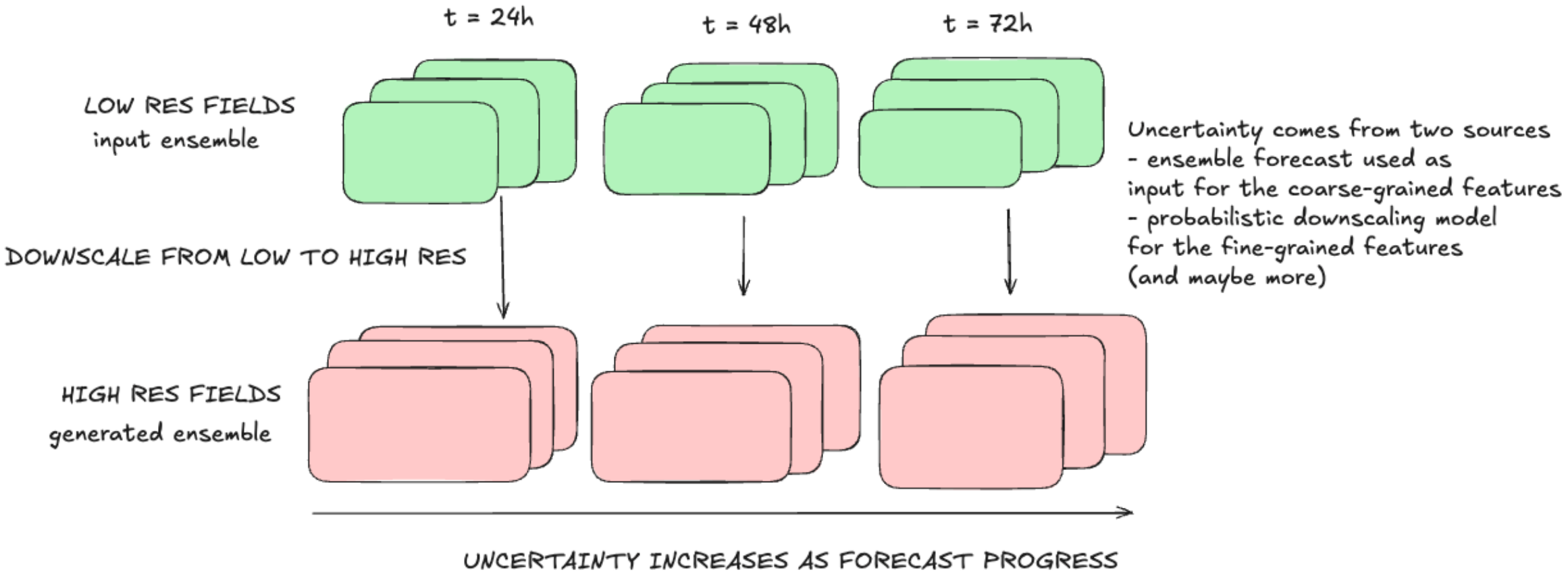
By generating an ensemble, we are not just generating spread.
It is about generating the correct spatial variability across all scales.

This ensures:

- Correct energy spectrum
- Realistic spatial structures
- Correct distribution tails (extremes)

Sampling from the correct conditional distribution ensures all these properties.

ENSEMBLE GENERATION



DOWNSCALING WITH DIFFUSION

Diffusion learns the conditional probability of the high-resolution field given the low-resolution one.

$$p(x_{HR} \mid x_{LR})$$

This allows generating an ensemble of plausible high-resolution states consistent with the large-scale conditions.

$$x_{LR} \rightarrow \text{multiple possible } x_{HR}$$

SAMPLING FROM A 1D DISTRIBUTION WITH DIFFUSION

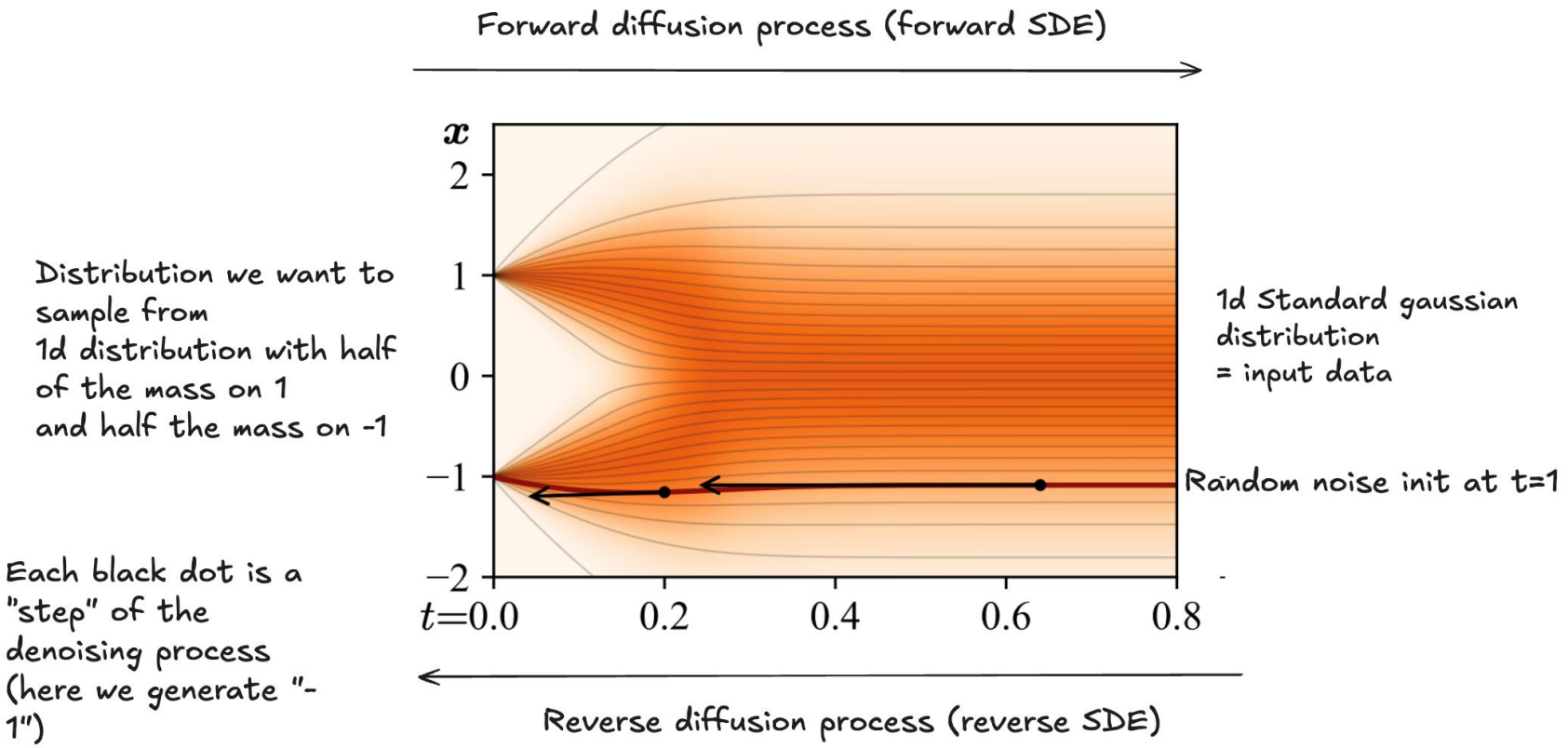
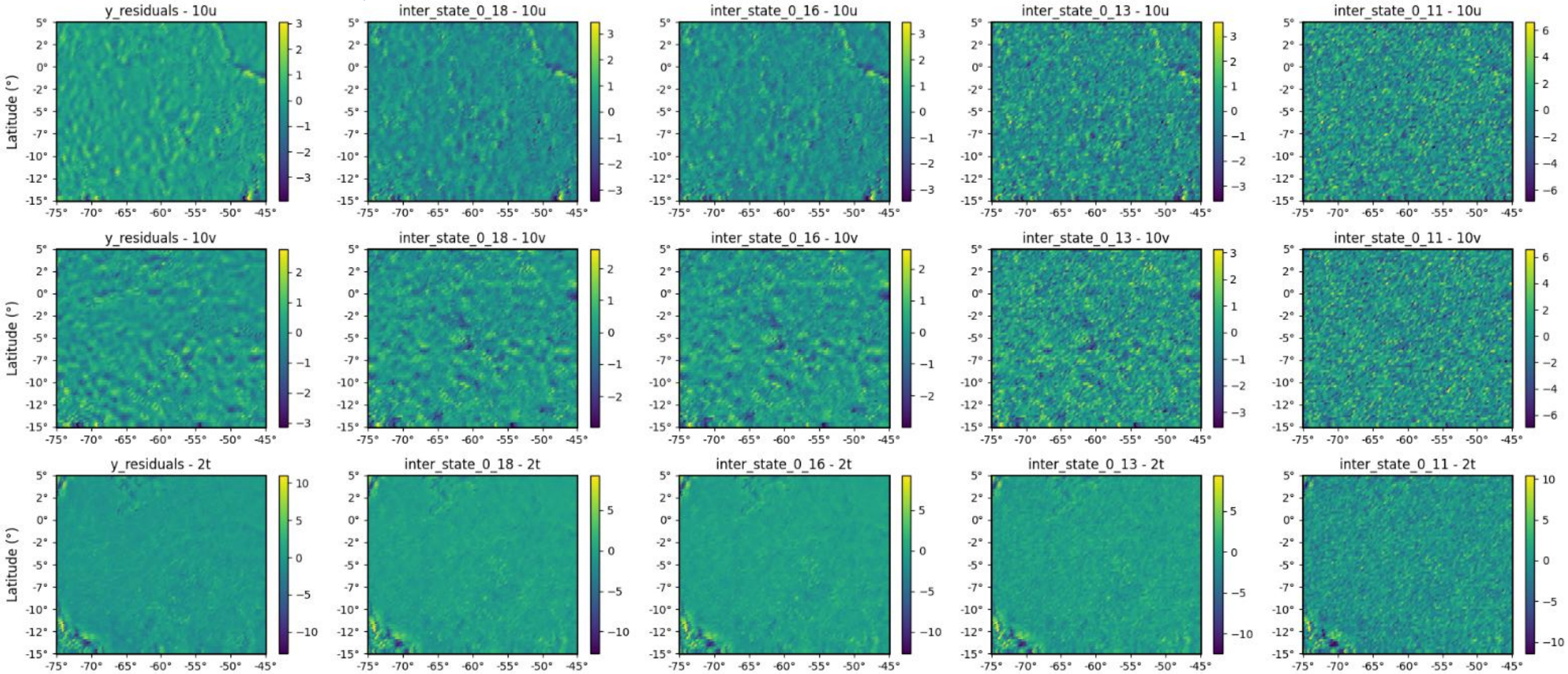


Figure from Karras et al 2022

DIFFUSION TO GENERATE SMALL-SCALE FEATURES

Sampling progresses from noise to data



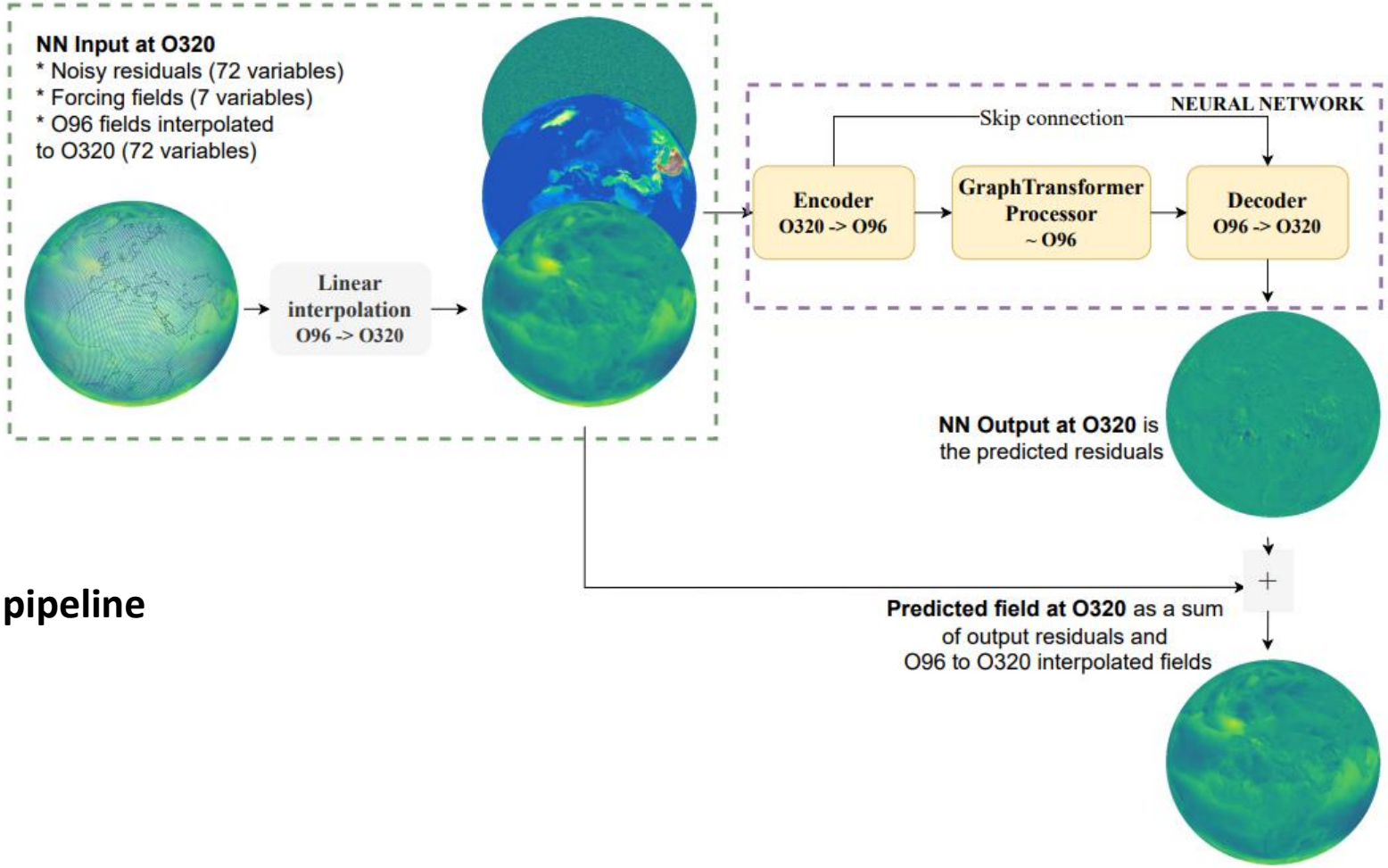
DIFFUSION TRAINING STRATEGY

Architecture adapted from AIFS-Diffusion.
Based on Karras et al. (2022) EDM framework also used by most of the diffusion models in the literature

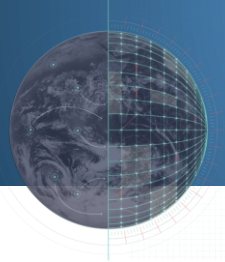
- CorrDiff
- GenCast
- Google Climate diffusion models

But our strategy is adapted to the consideration of weather/climate data and the downscaling problem

DIFFUSION DOWNSCALING IN ANEMOI



Downscaling pipeline

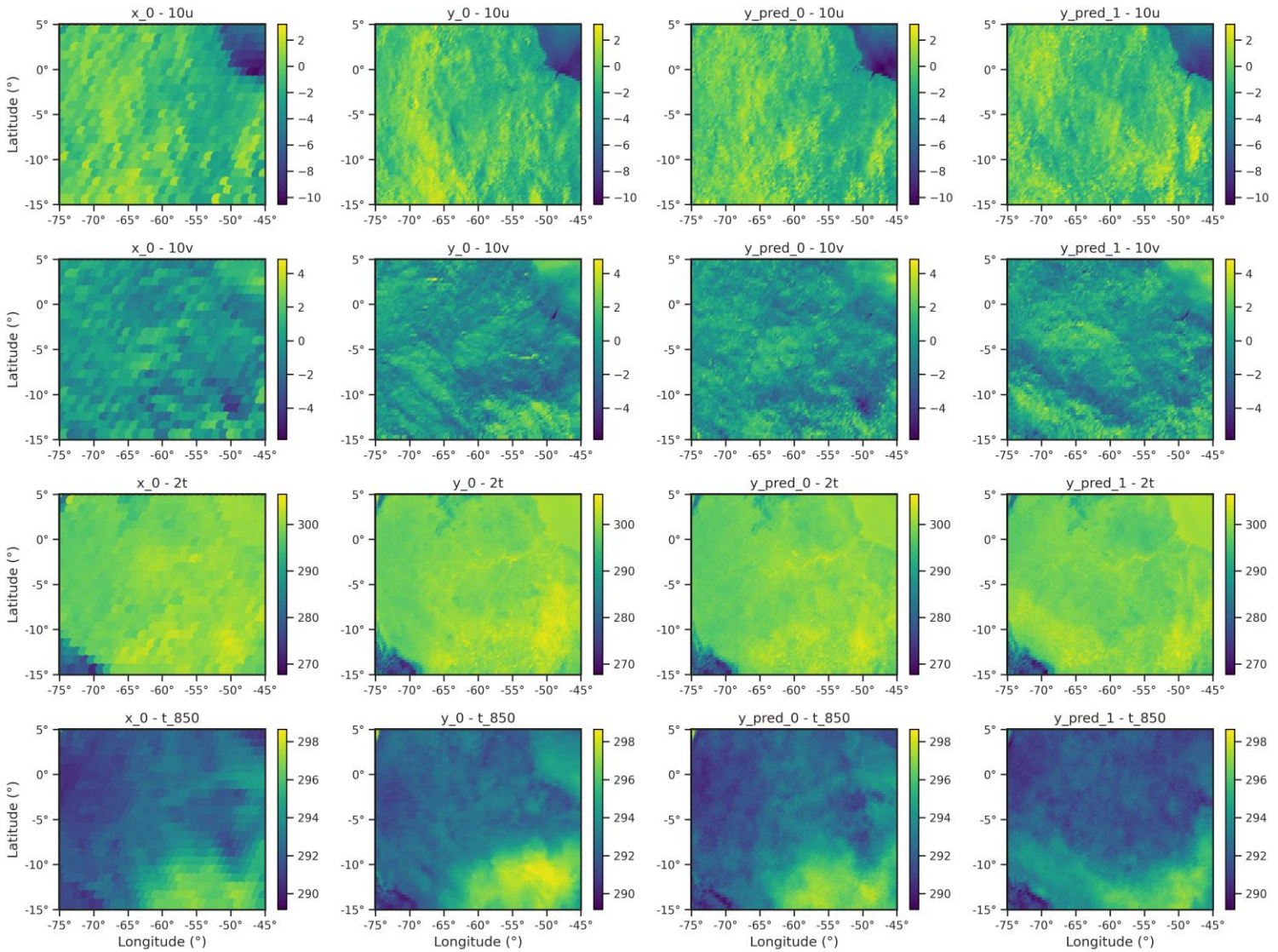


HOW TO EVALUATE DOWNSCALING

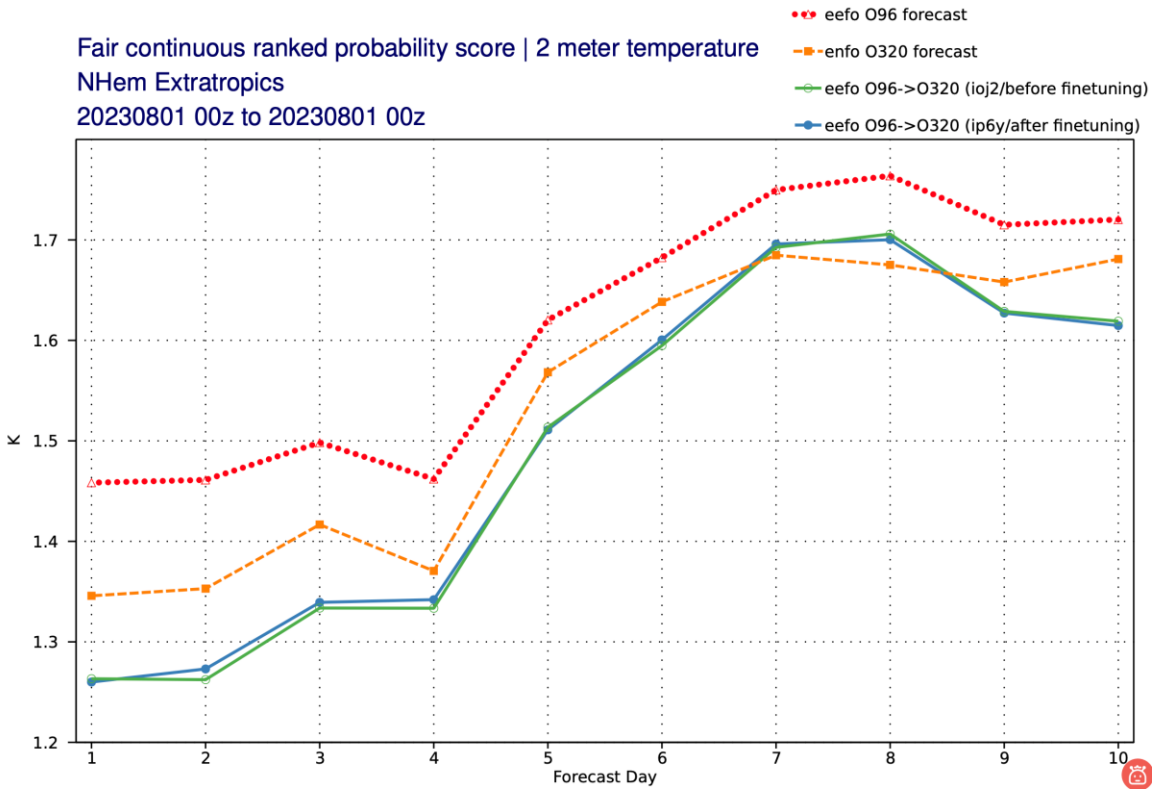
- Physical realism (visual inspection ?)
- Right amount of features across all scales / all wavenumbers (spectrum inspection)
- Ensemble score (since this is probabilistic, we are generating an ensemble)
- Good results on extreme events / long-tail variables
- Should you also expect debiasing of the pressure level variables ?

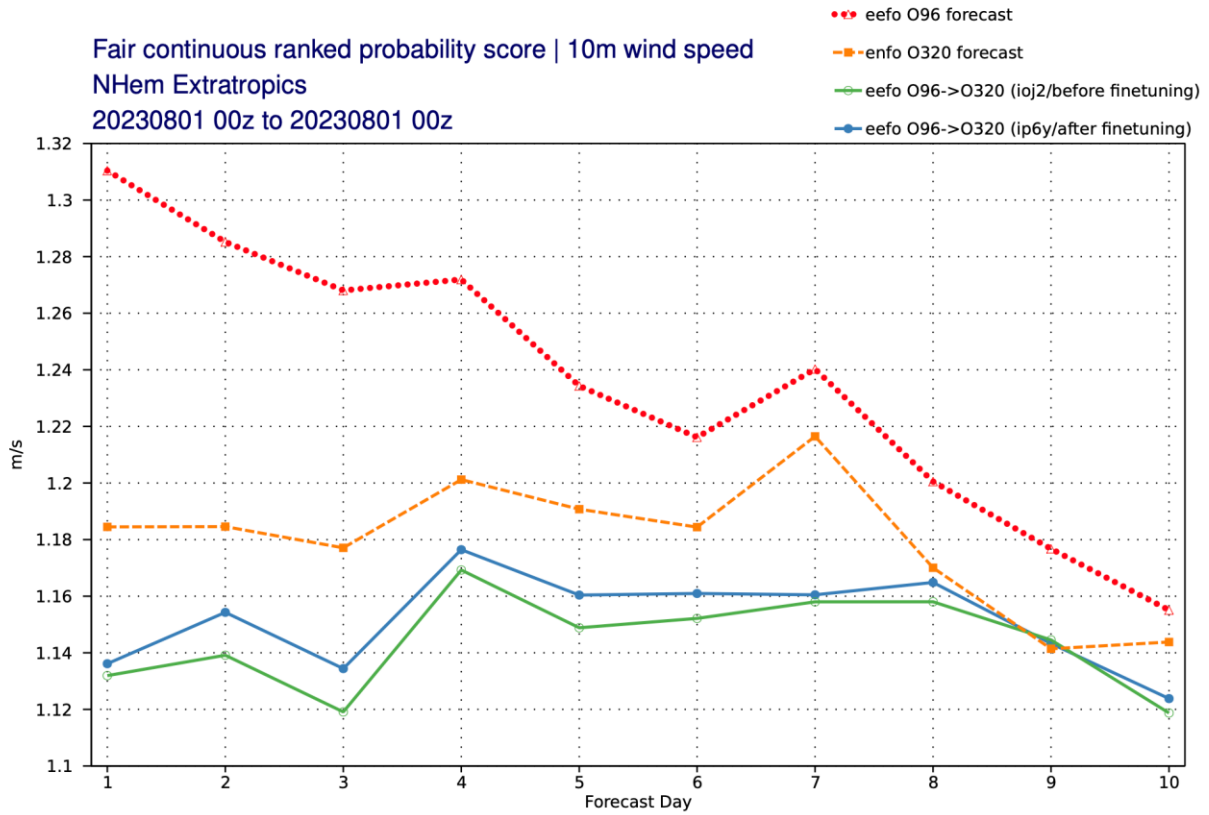
PHYSICAL REALISM

Amazonian rainforest – 2023.08.01

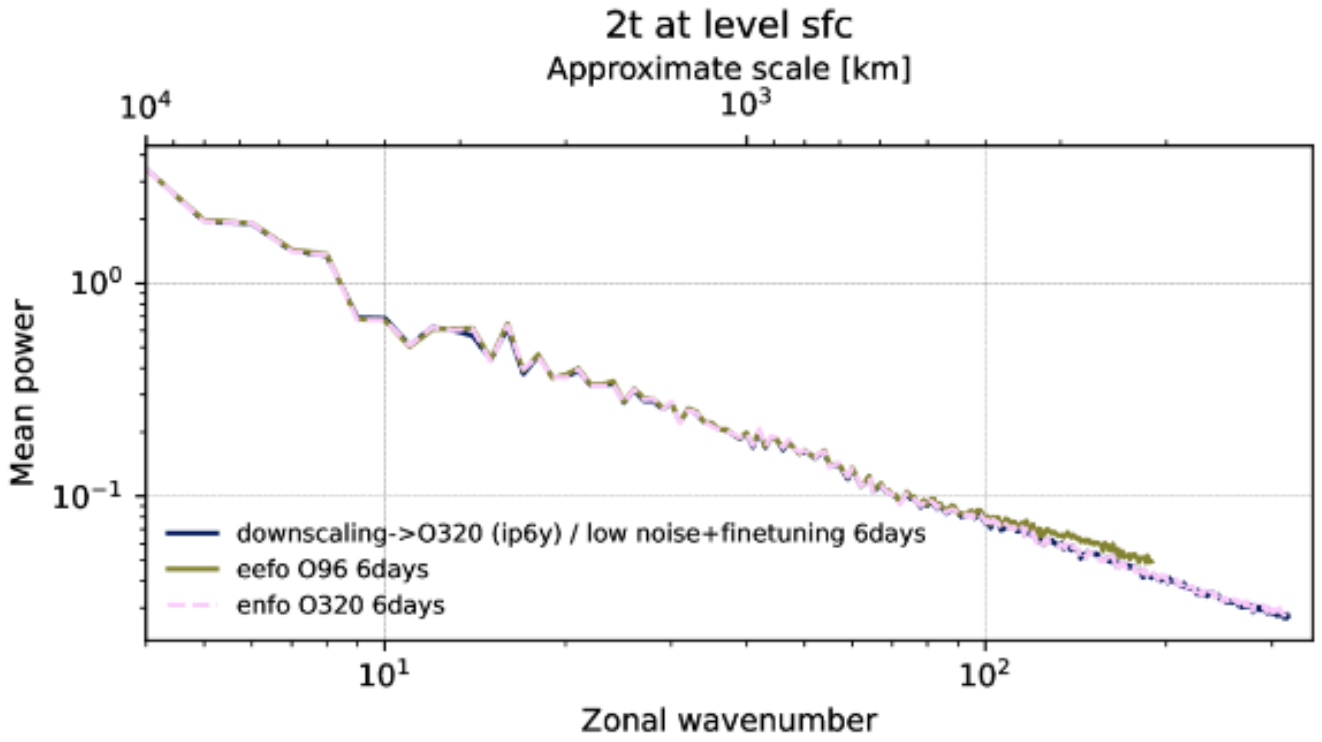


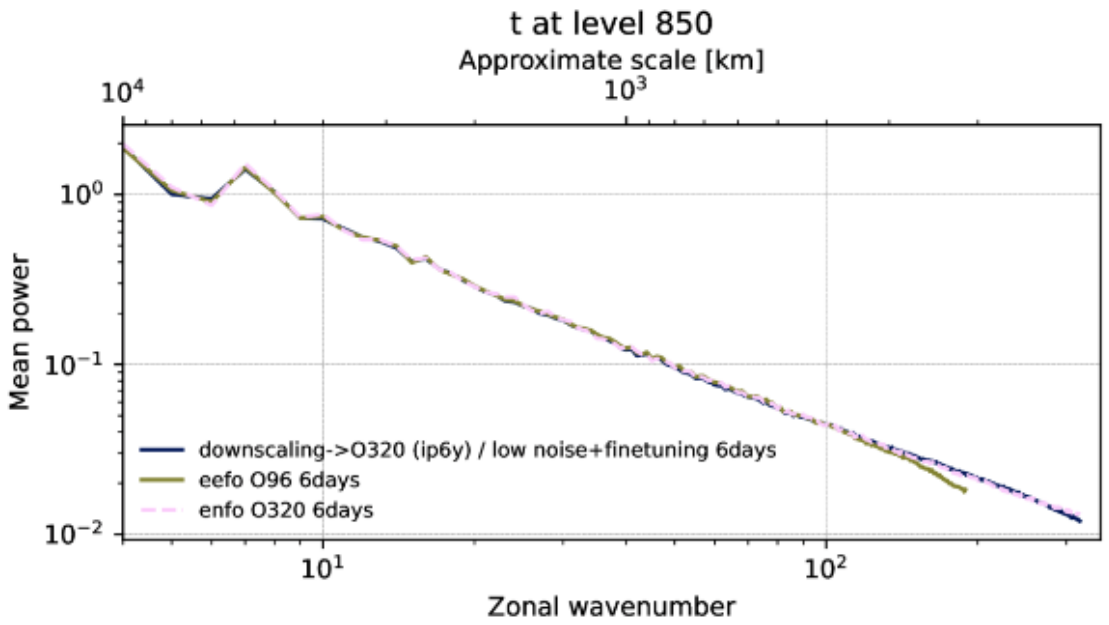
ENSEMBLE SCORING



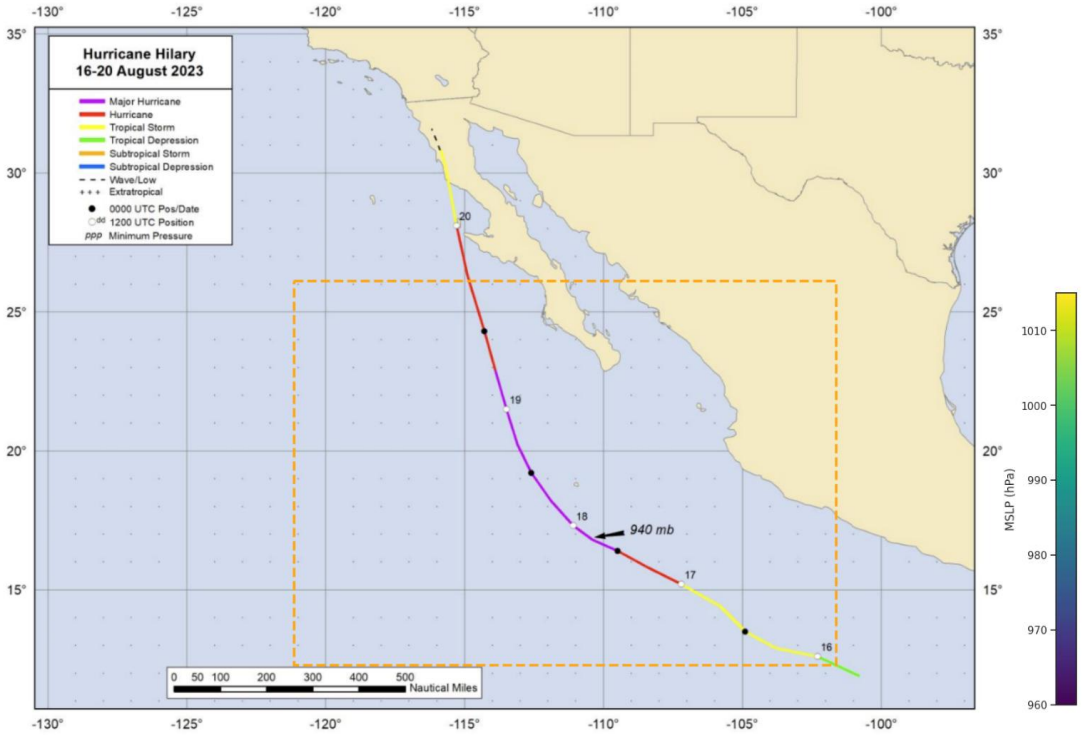


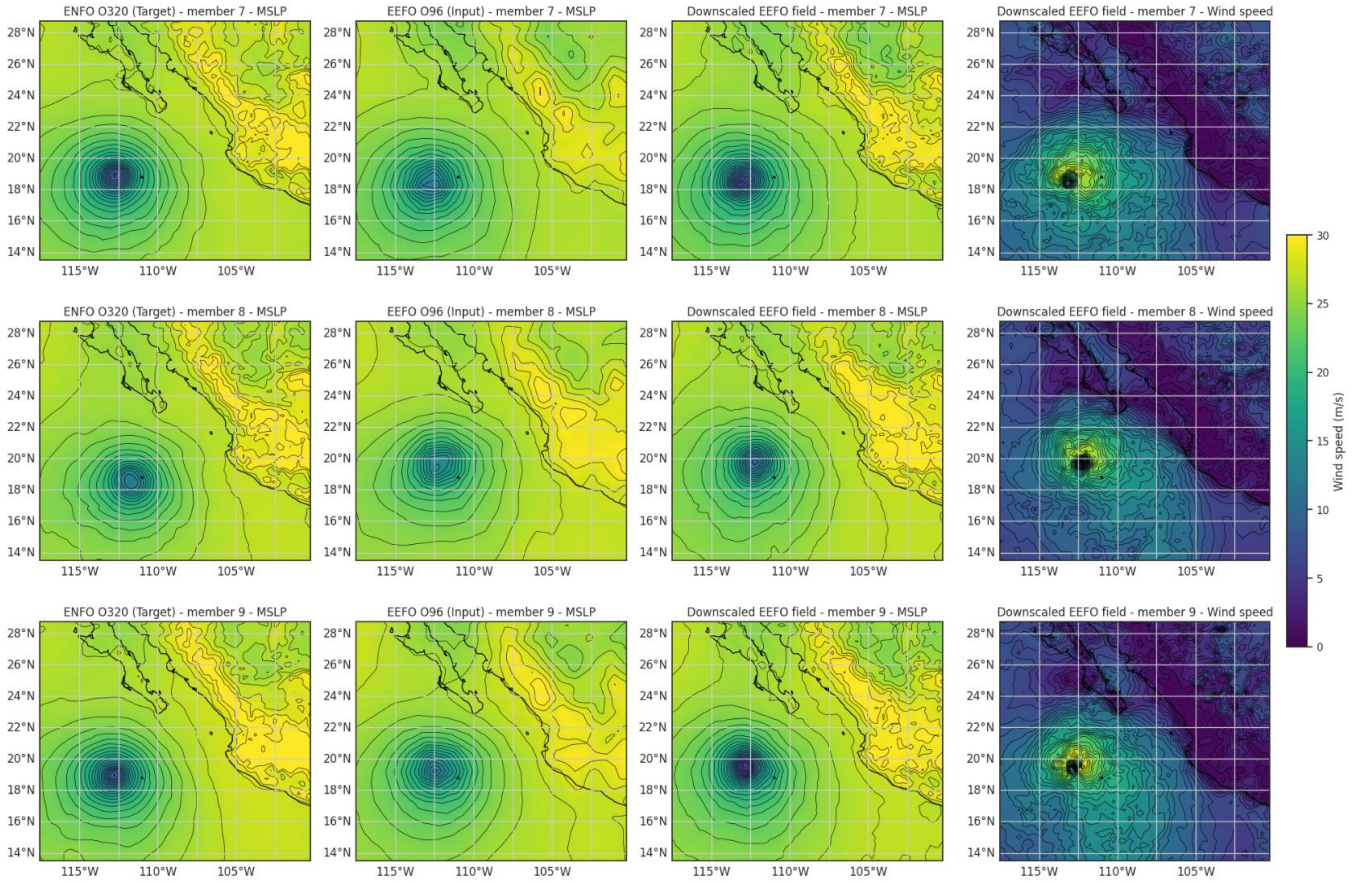
SPECTRA – RIGHT AMOUNT OF ENERGY AT ALL SCALES





EXTREMES AND LONG-TAIL VARIABLES





IN ANEMOI

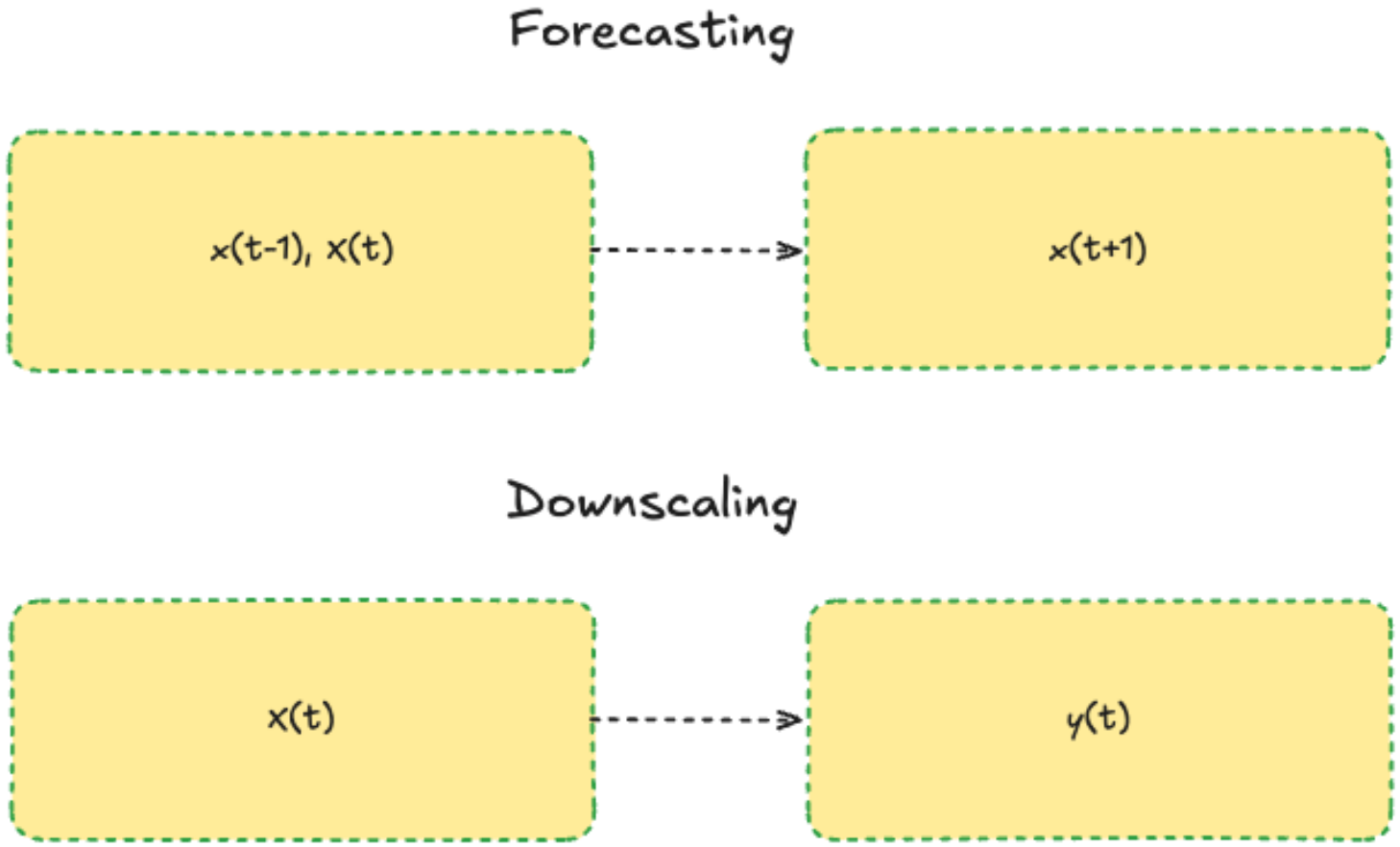
Very close to forecasting but key differences

Forecasting

- One dataset is needed, same resolution
- Conception of time, rollout
- Strong dependence on large-scale dynamics (e.g. geopotential at 500 hPa)
- Global problem

Downscaling

- Two datasets are needed (low res, high res)
- Requires precise dataset alignment
- Strong dependence on small-scale features (e.g. surface winds, convection, orography)
- Local, spatial problem
- Fundamentally probabilistic problem



DATASET ALIGNMENT

Downscaling requires paired datasets that describe the same atmospheric state at different resolutions.
The large-scale structures must be aligned, must agree on location of large-scale features
Downscaling reconstructs small-scale detail, not large-scale structure.

Examples of properly matched datasets

- Reanalysis ERA5 and CERRA as CERRA dynamically forced by ERA5
- GCM → RCM. Regional Climate Model (RCM) is forced by Global Climate Model (GCM)

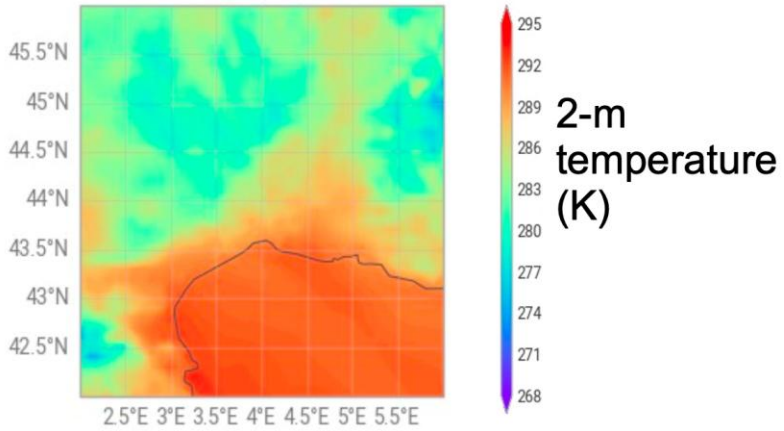
EXAMPLE APPLICATIONS

ARPEGE -> AROME

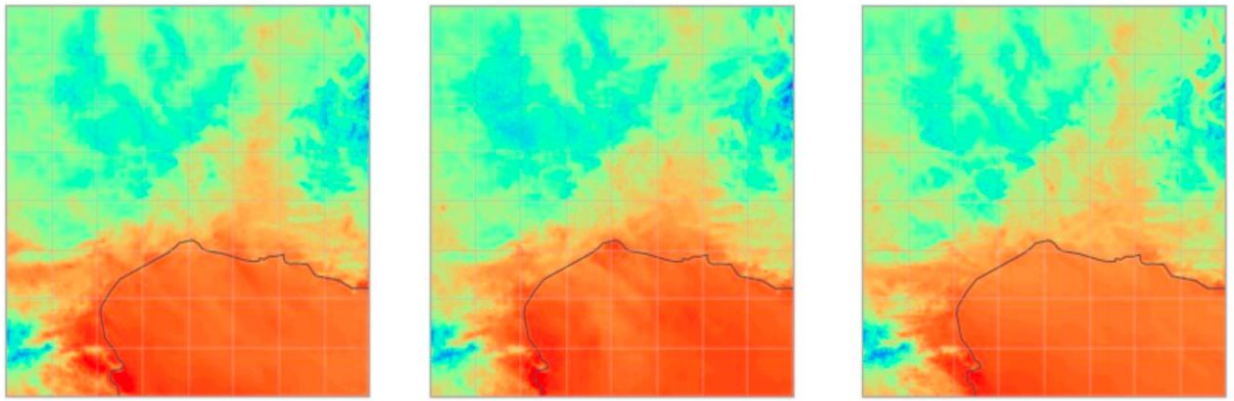
Input:

Arpege – Test

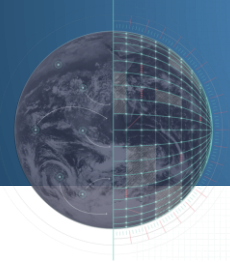
(01/06/2024 00h00)



Outputs: Arome & 2 Arome-DS samples → Who's who?



Eliott Lumet, team of Laure Raynaud (Météo-France)



DOWNSCALING WITH ANEMOI IN PRACTICE

1. Prepare aligned low-resolution and high-resolution datasets
2. Train deterministic downscaling model to debug – this should produce smoothed fields that look like the conditioning (the low-resolution input)
3. Train diffusion model following recommended configuration
4. Generate an ensemble at high resolution
   - from a single input (uncertainty is only recovered for small-scale features)
   - from an ensemble at low resolution (uncertainty is represented at all scales)
5. Evaluate
6. Spectra
   - Ensemble scores
   - Physical realism / Spectra
   - Extremes