Downscaling with the Foundation Model AtmoRep

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1) Motivation

- High-resolved weather data is of great relevance for industry, society and for risk quantification of hazardous events
- Recent success of deep neural networks (DNN) for statistical downscaling
  - ✓ Computationally cheaper than dynamical downscaling → large ensembles
  - ✓ Accurate and plausible reconstruction of small-scale features
  - x Expensive training for a single application
  - x Pairing of coarse- and high-resolved data often limits data availability
- Foundation Models (FMs) for weather and climate such as ClimaX (*Nguyen et al., 2023*) and **AtmoRep** (*Lessig et al., 2023*) are potentially appealing
  - Self-supervised pre-training on large datasets
  - Scale well with data, compute and network size
  - Wide-range of downstream applications with SOTA performance after fine-tuning

Research question:
Can we push the frontiers of downscaling with Foundation Models?

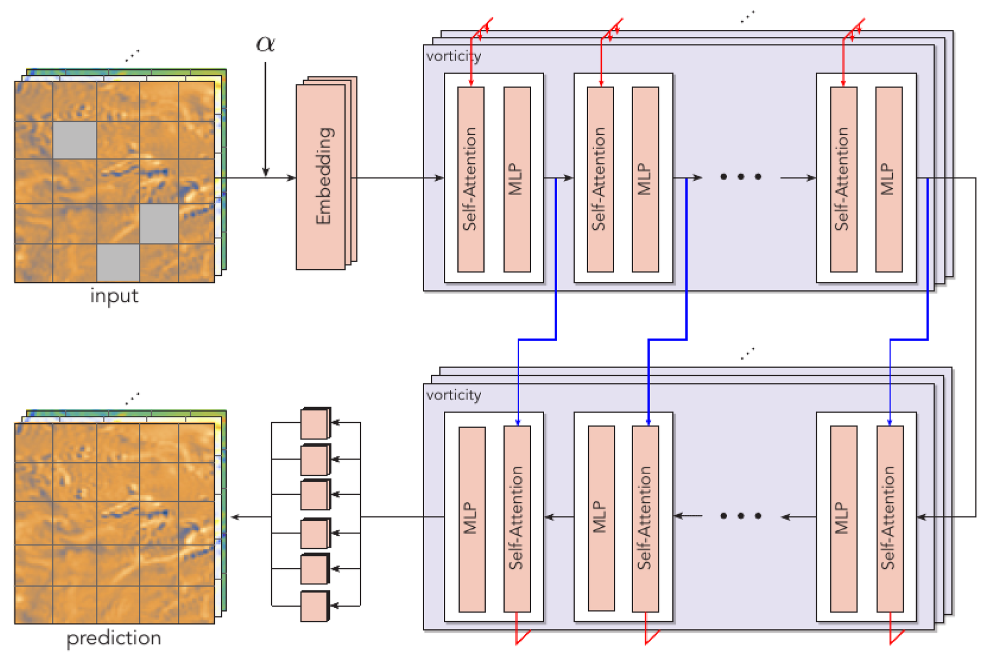
2) The AtmoRep model

- Modelling of the atmosphere as a stochastical system

$$p(\mathbf{y}|\mathbf{x}) \approx p_\theta(\hat{\mathbf{y}}|\hat{\mathbf{x}}, \boldsymbol{\alpha})$$

$\mathbf{y}, \hat{\mathbf{y}}$: dependant (model) state
$\mathbf{x}, \hat{\mathbf{x}}$: conditioning (model) state
$\boldsymbol{\alpha}$: auxiliary information

- **The network**



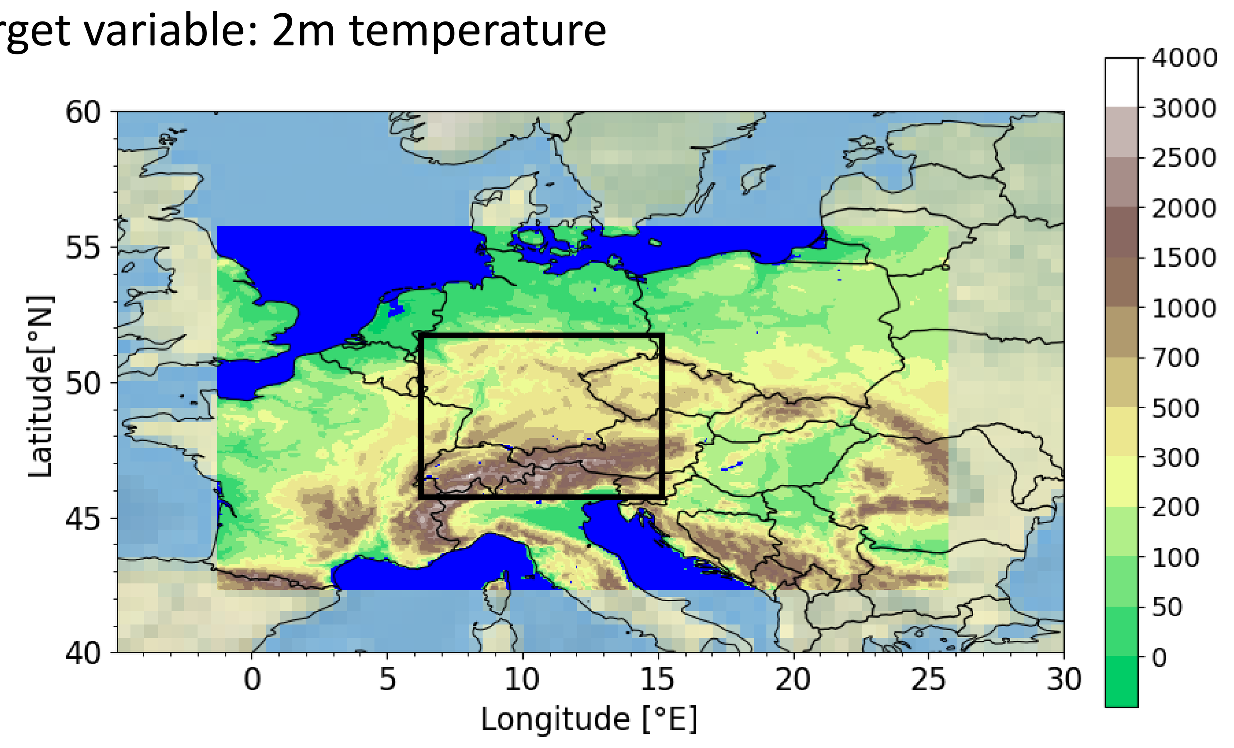
- Trained with ERA5 reanalysis data (1979 – 2017)
- Variables: $T, q_v, \mathbf{v}_h, w$ on model levels [96, 105, 114, 123, 137] + $precip$
- Modular AtmoRep configuration with two-step training (singleformer → multiformer)

Want to learn more about AtmoRep?
Attend the AtmoRep talk: ***ESSI 1.1, 16:30 – 16:50 CEST***

3) Downscaling with AtmoRep

The downscaling task

- Downscale ERA5-data ($\Delta x_{ERA5} = 0.25°$) to (re-projected) COSMO-REA6 data ($\Delta x_{CREA6} = 0.0625°$) → downscaling factor: 4
- Target downscaling domain (216 x 432 grid points) over Central Europe (Fig. 2) Paired training data between 1995 and 2017
- Test data from 2018
- Target variable: 2m temperature



Model setup for downscaling with AtmoRep

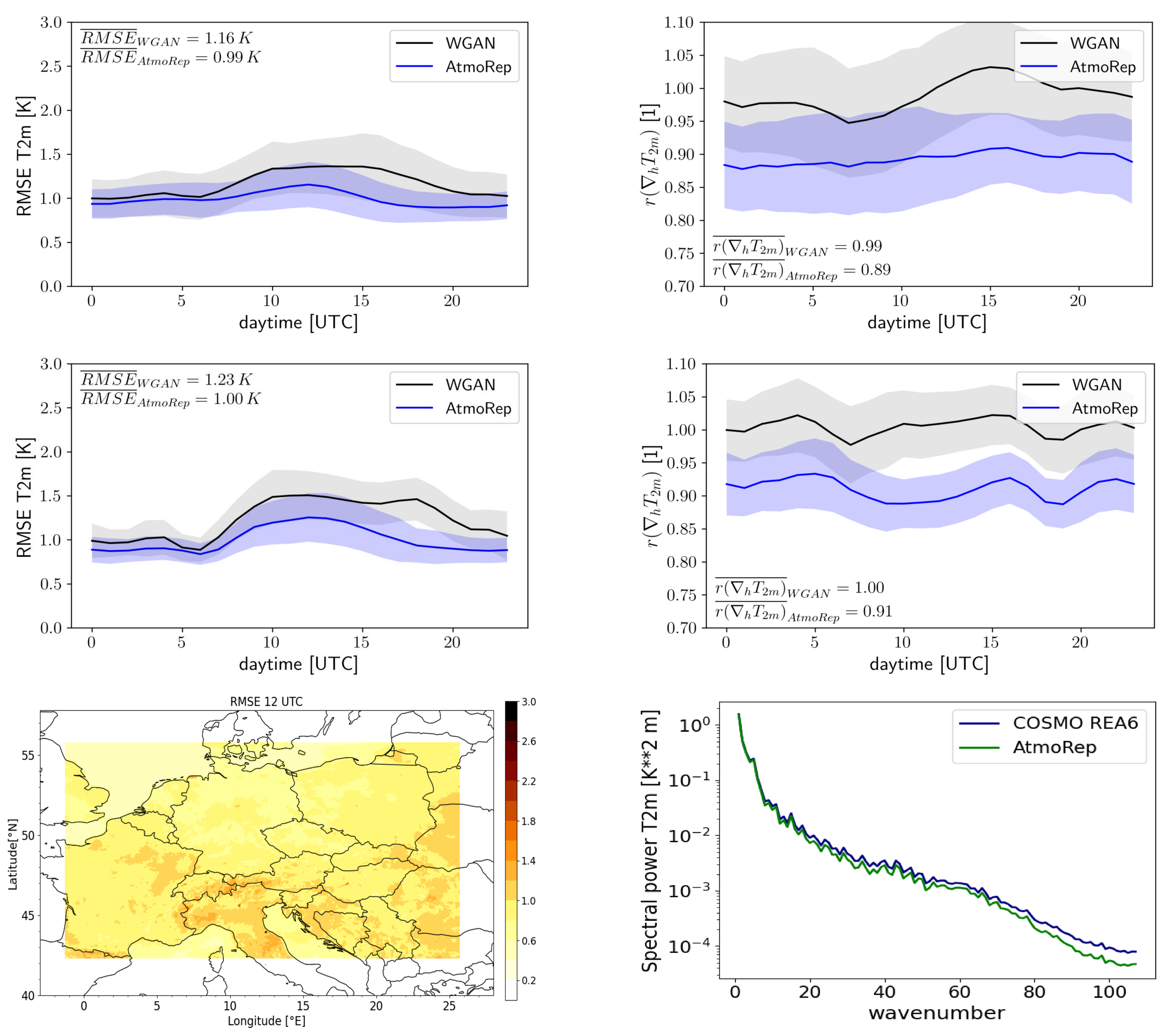
- Use three-field AtmoRep-configuration ($[\mathrm{u}, \mathrm{v}, T]$) with data from model level 137 only
- Tail network appended to AtmoRep core model:
  - Increased token size at the beginning of tail network
  - Further embedding layer with doubled embedding dimension and updated positional encoding
  - Six transformer layers for downscaling
  - Ensemble tail for probabilistic output
- Trainable core model and tail network (→ very deep network)

Competing model

- Train a competing Wasserstein GAN to contextualize AtmoRep results
- Generator model of WGAN: U-Net by *Sha et. al, 2020*, standard ConvNet for critic model
- Smaller target domain (96x120 grid points) due to shift invariance of CNNs
- Training data:
  - T from model levels [96, 105, 114, 123, 137]
  - $\mathbf{v}_h$ from model level [137]

4) Results

Point-wise evaluation | **Evaluation of spatial variability**



5) Conclusion and outlook

- Downscaling with AtmoRep has the potential to outperform existing solutions
- RMSE of initial AtmoRep downscaling model matches that of WGAN trained with comprehensive set of predictors (not shown)
- Very deep neural network (1.85B parameters) → barely utilizes FM benefits

Next steps:

- Improve set-up of architecture (e.g. diffusion model) with prob. downscaling
- Analyse added value of FM approach
- Multivariate downscaling and application to arbitrary region

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References:
[1] Lessig et al., 2023, *arXiv preprint arXiv:2308.13280*
[2] Nguyen et al., 2023, *arXiv preprint arXiv:2301.10343*
[3] Sha et al., 2020, J. Appl. Meteorol. Clim, 59.12

AtmoRep-paper

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