SWGEN 2025 - Conference on Stochastic Weather Generators

Generative Machine Learning for Downscaling Earth System Model Simulations

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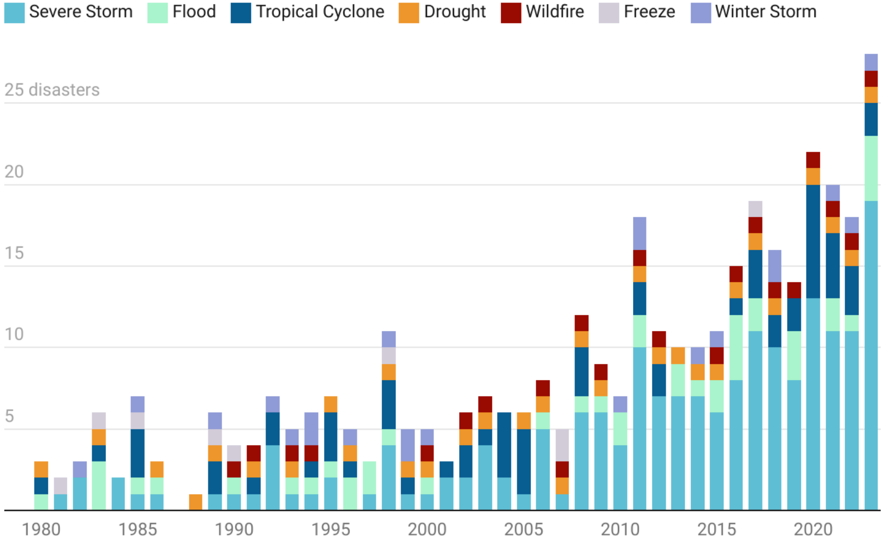
Funded by the European Union

Assessing the impacts of climate change

Credits: NASA Earth Observatory, Wikipedia

US billion-dollar disasters by year

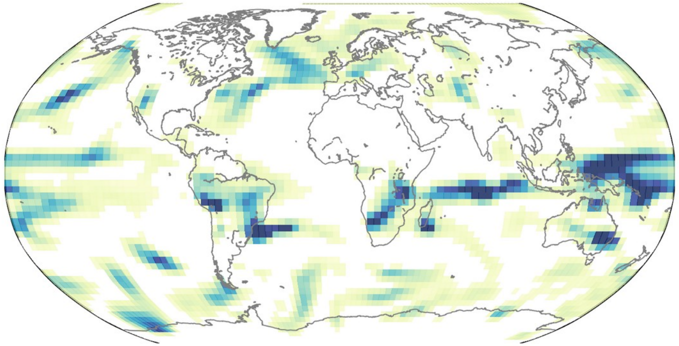
The number of weather and climate disasters exceeding $1 billion in damage each has grow in recent decades, with costs adjusted for inflation.



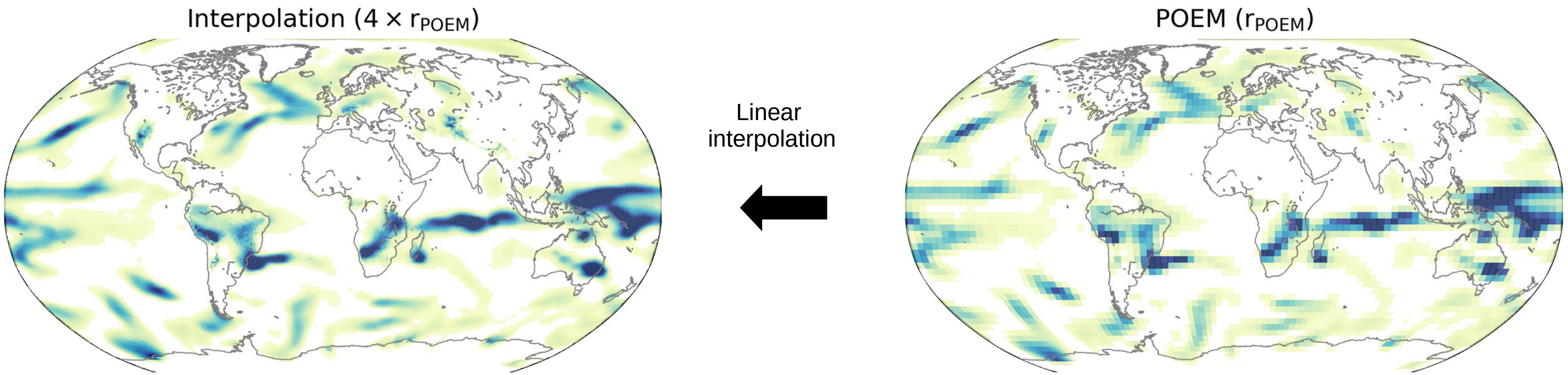
Data as of Jan 9, 2024. Wildfires are generally grouped together as a single event

Chart: The Conversation/CC-BY-ND • Source: NCEI/NOAA • Created with Datawrapper

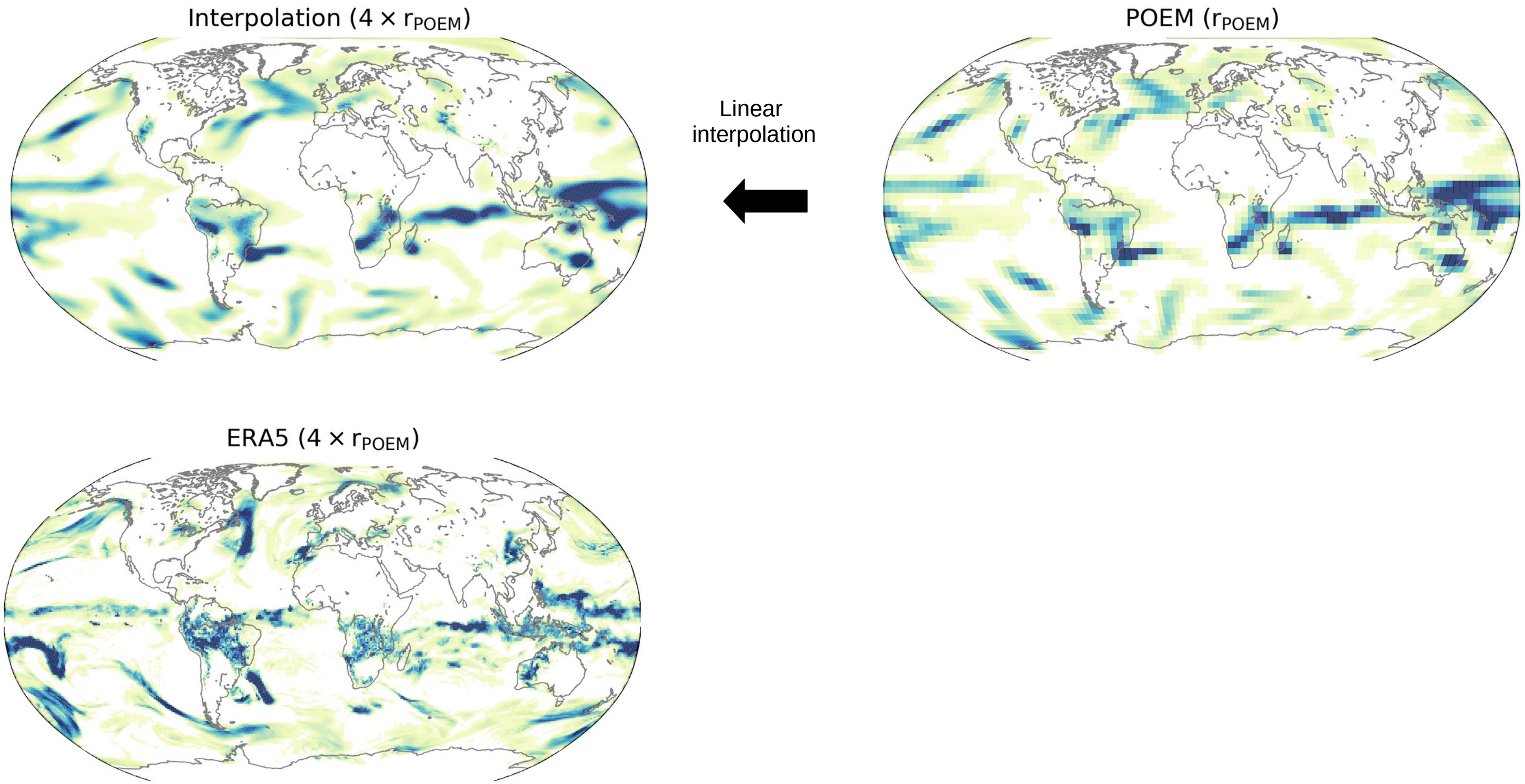
Downscaling Earth system model simulations



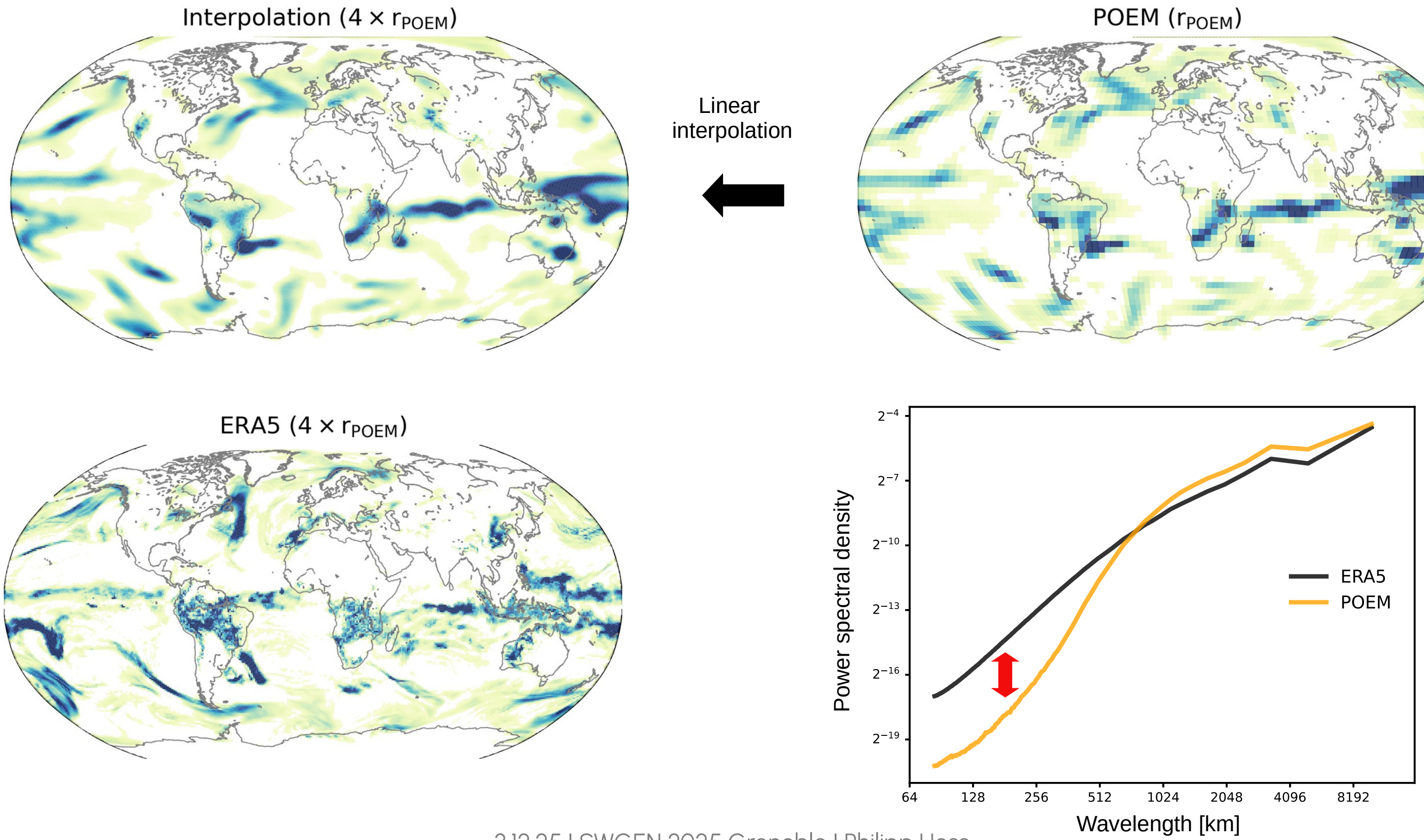
Downscaling Earth system model simulations



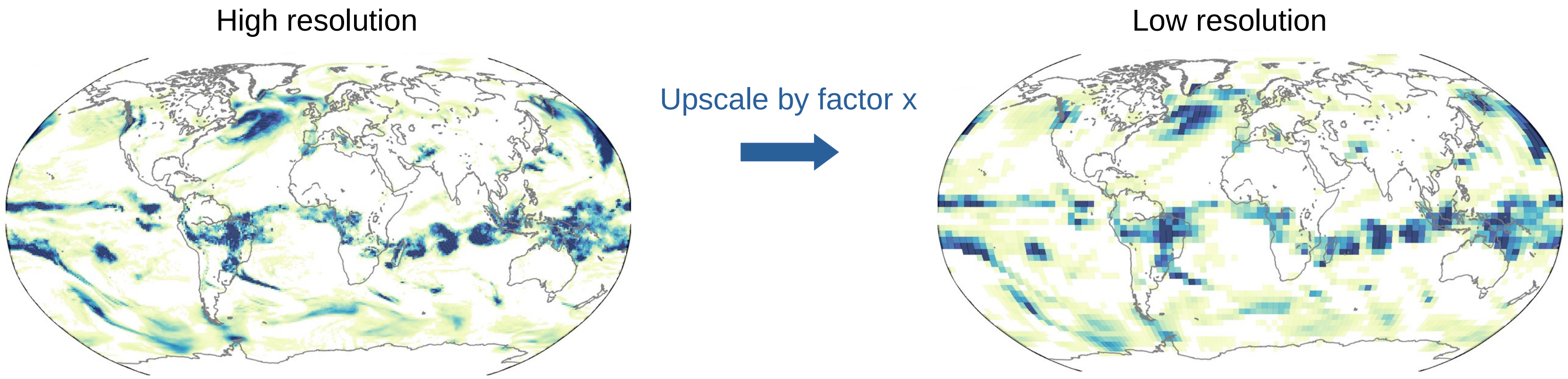
Downscaling Earth system model simulations



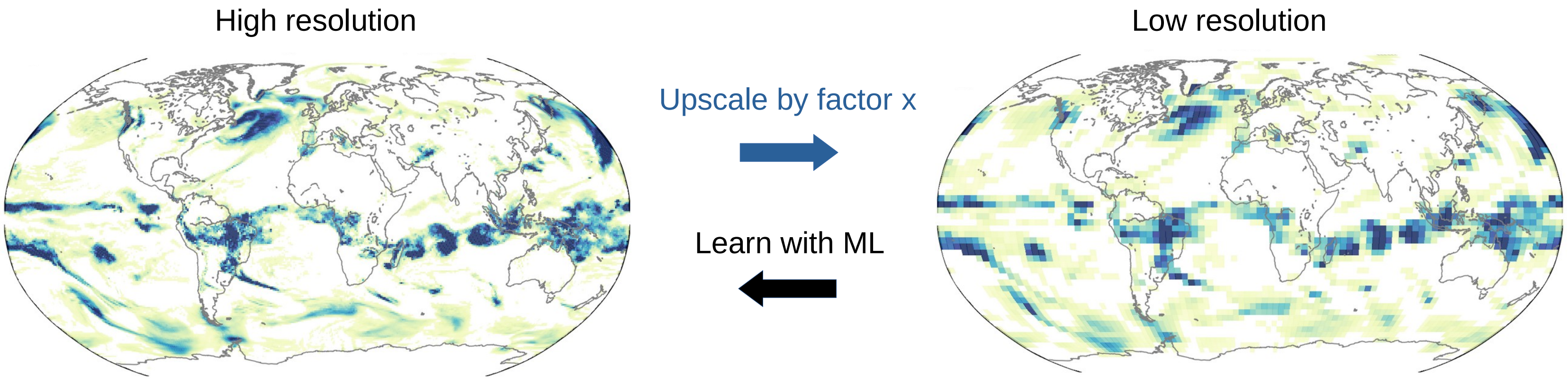
Downscaling Earth system model simulations



Downscaling as a super-resolution task

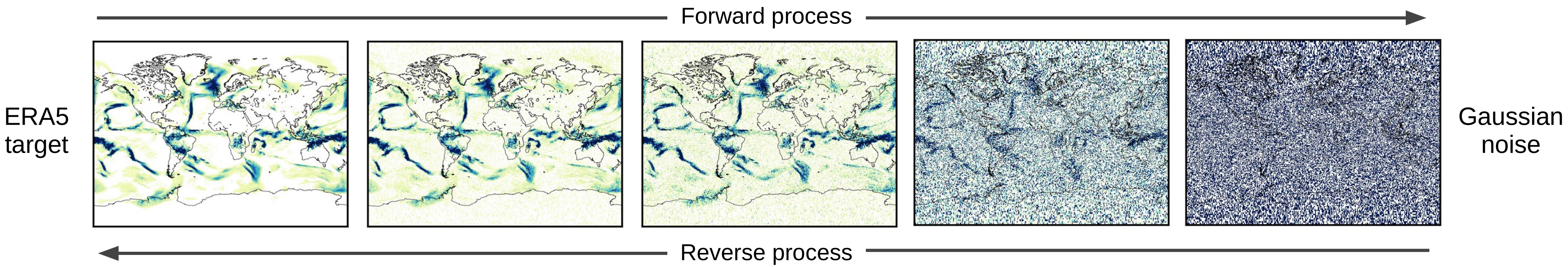


Downscaling as a super-resolution task



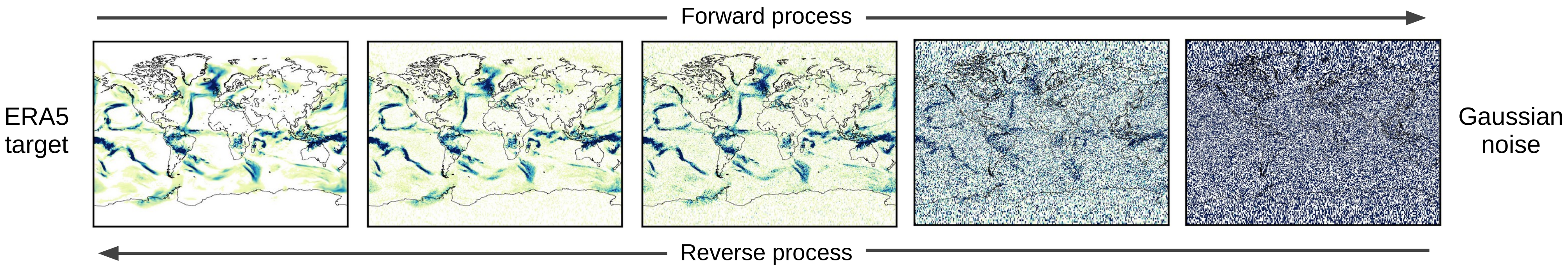
This approach requires retraining when changing the Earth system model.

Unsupervised training with denoising generative models



Song et al., 2020; Hess et al., 2024

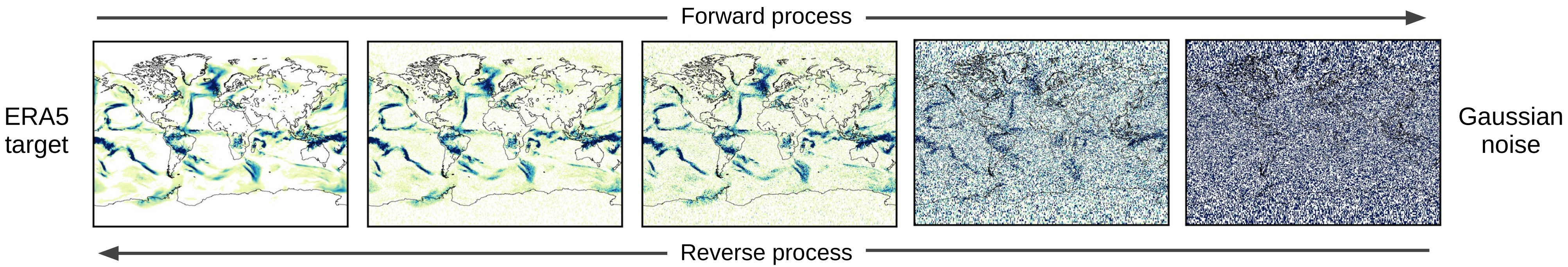
Unsupervised training with denoising generative models



Reverse diffusion SDE: $$\mathrm{d}\mathbf{x} = [\mu(\mathbf{x}, t) - g(t)^2 \nabla_{\mathbf{x}} \log p_t(\mathbf{x})]\mathrm{d}\bar{t} + g(t)\mathrm{d}\bar{\mathbf{w}}$$

Song et al., 2020; Hess et al., 2024

Unsupervised training with denoising generative models



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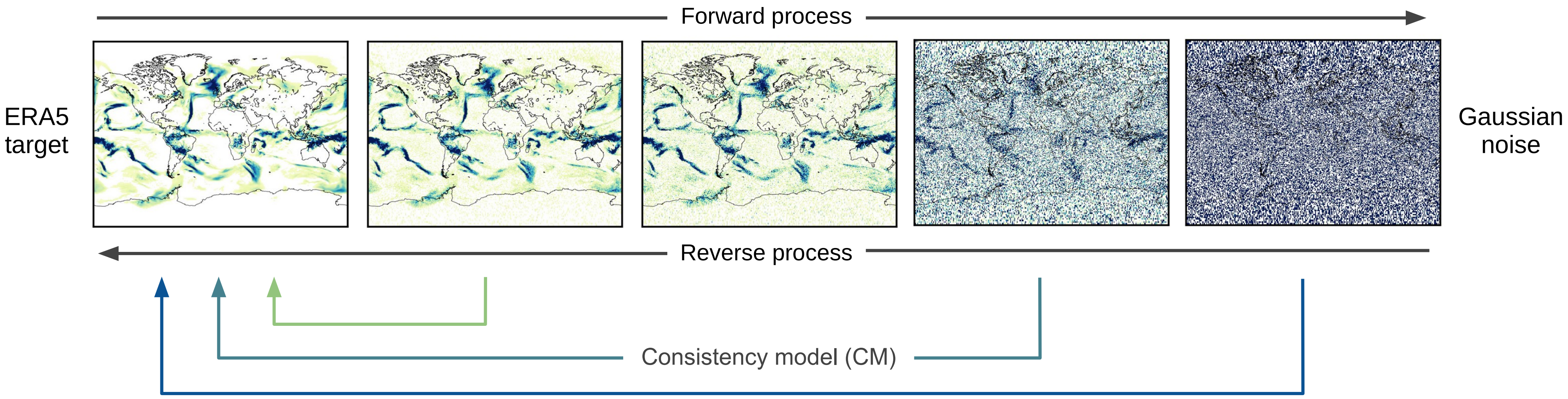
Learn with denoising score matching: $$s_\phi(\mathbf{x}, t) \approx \nabla_{\mathbf{x}} \log p_t(\mathbf{x})$$

Song et al., 2020; Hess et al., 2024

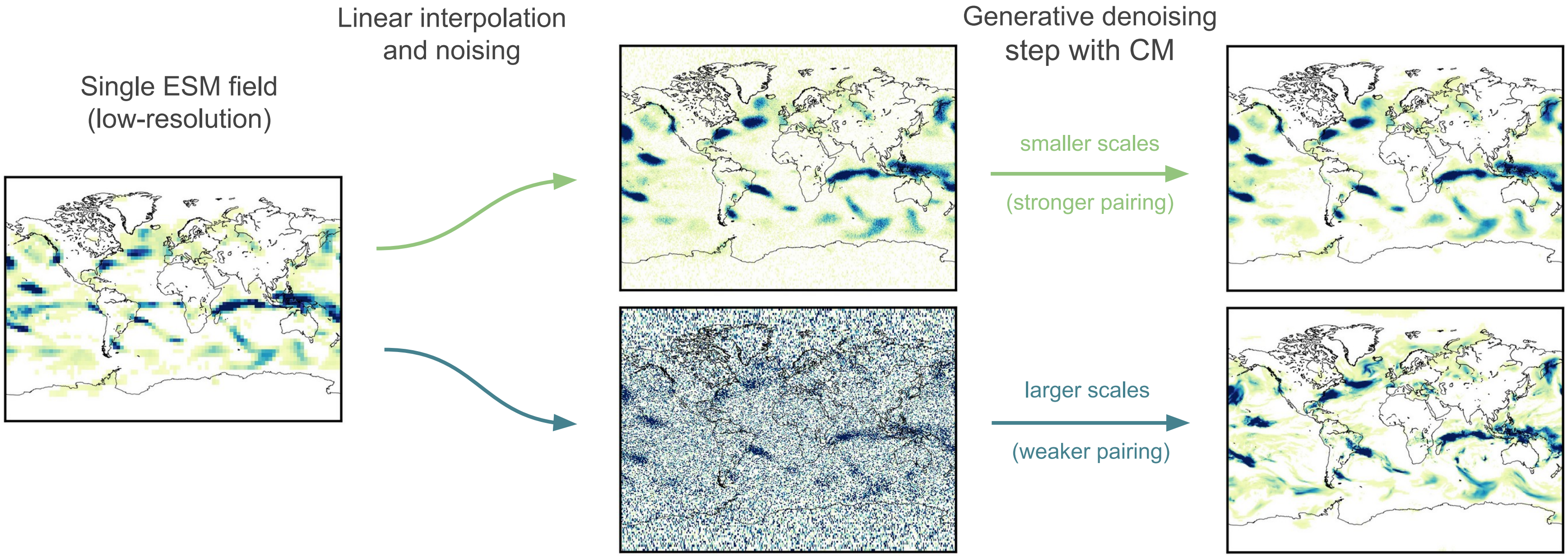
Efficient denoising with consistency models



Consistency models: $\mathbf{x}_0 = f_\theta(\mathbf{x}_t, t), \quad f_\theta(\mathbf{x}_t, t) = f_\theta(\mathbf{x}_{t'}, t') \; \forall \; t, t' \in [t_\epsilon, T]$

Song et al., 2023; Hess et al., 2024

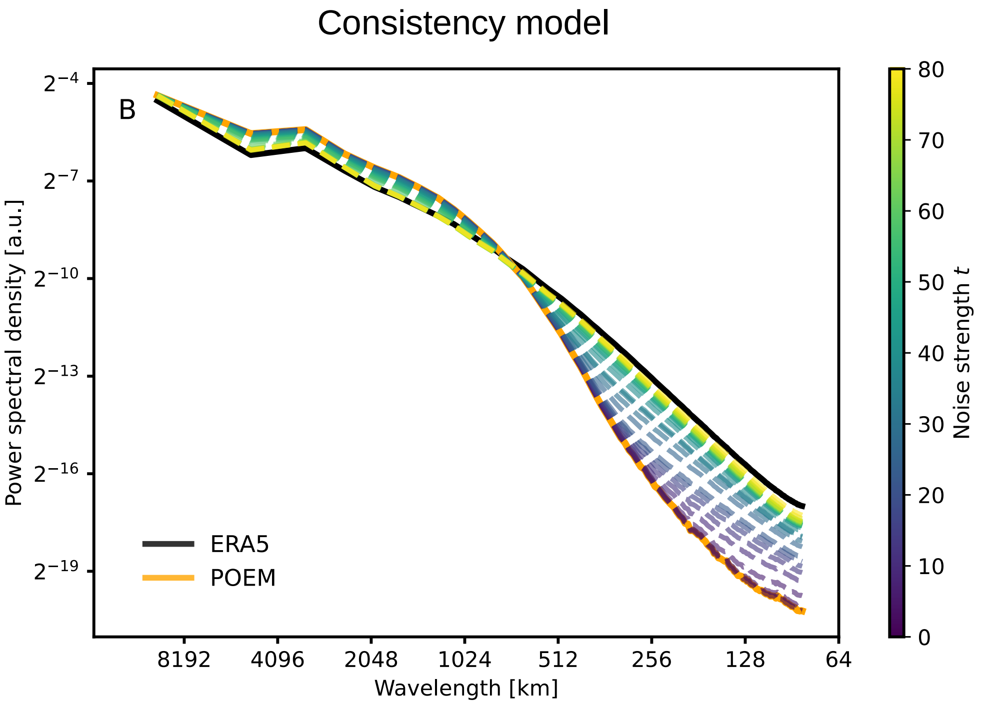
Scale-adaptive downscaling after training



➡ The noise variance determines the spatial scale that is preserved in the Earth system model.

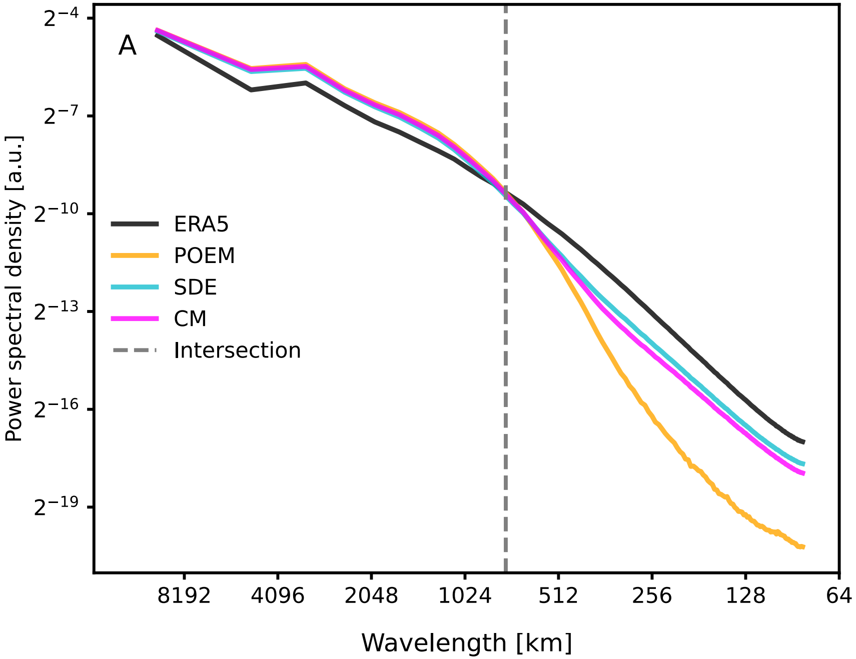
Bischoff and Deck, 2023; Hess et al., 2024

Scale-adaptive downscaling after training



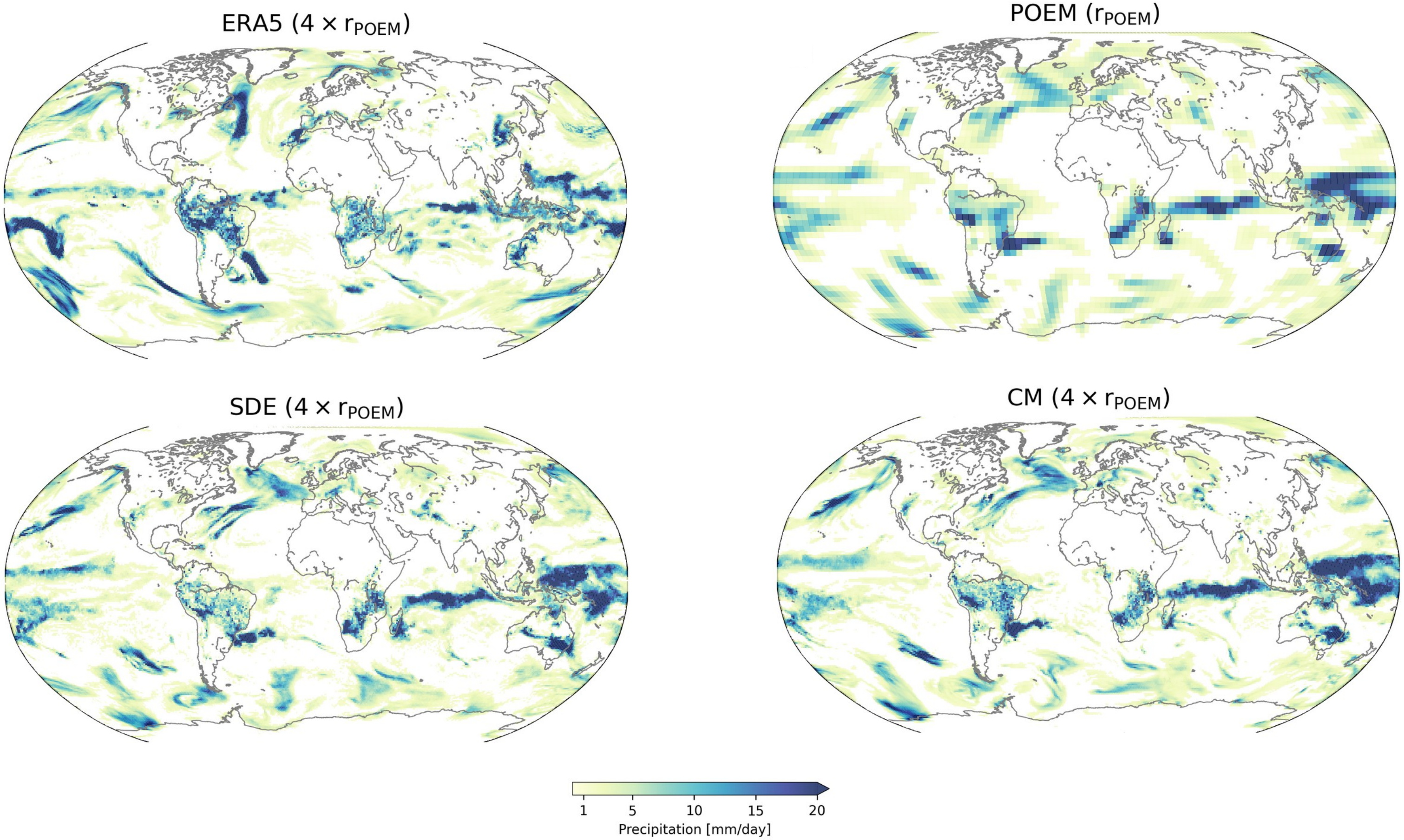
Hess et al., 2024

Choosing a suitable noise scale



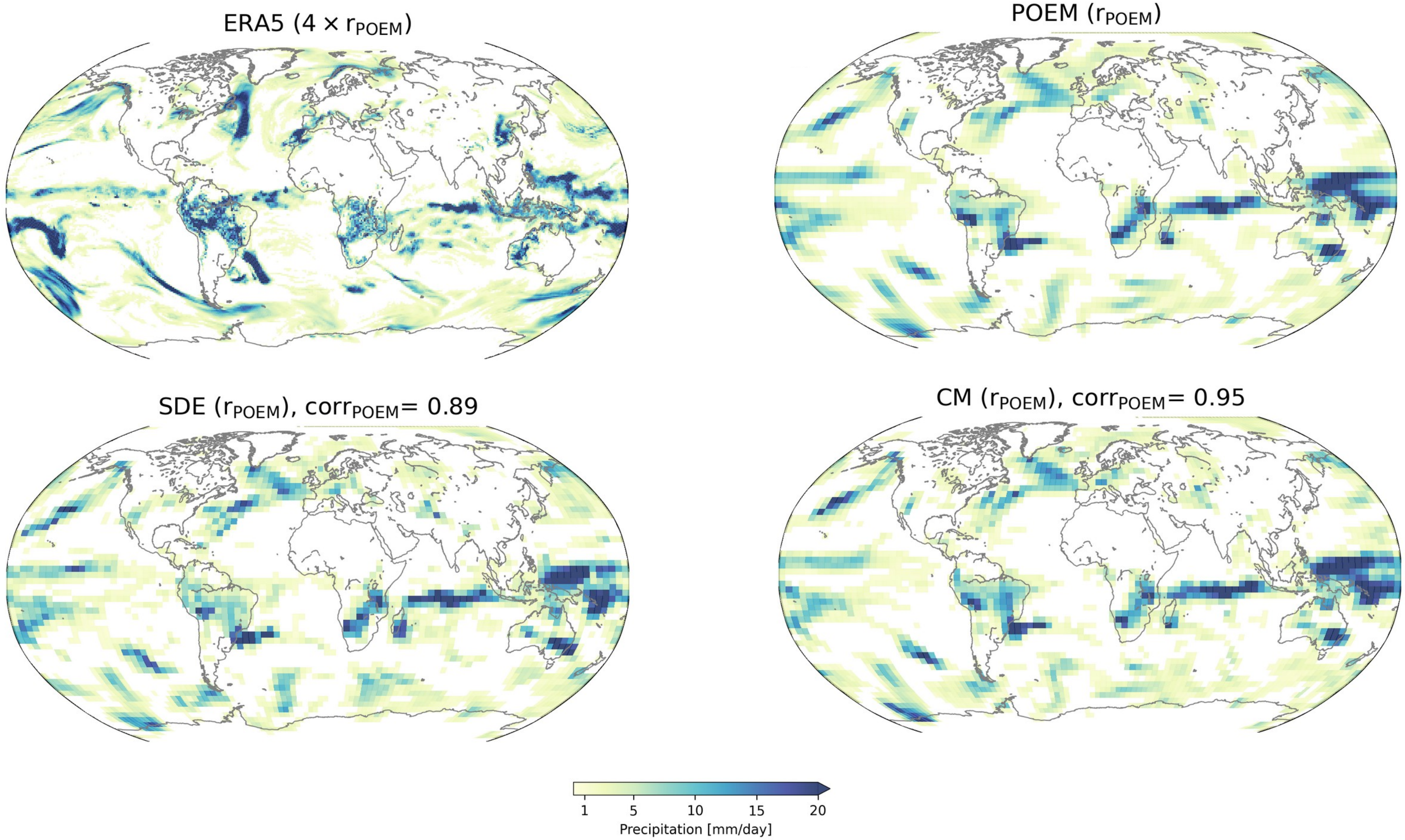
Hess et al., 2024

Qualitative comparison of high-resolution fields



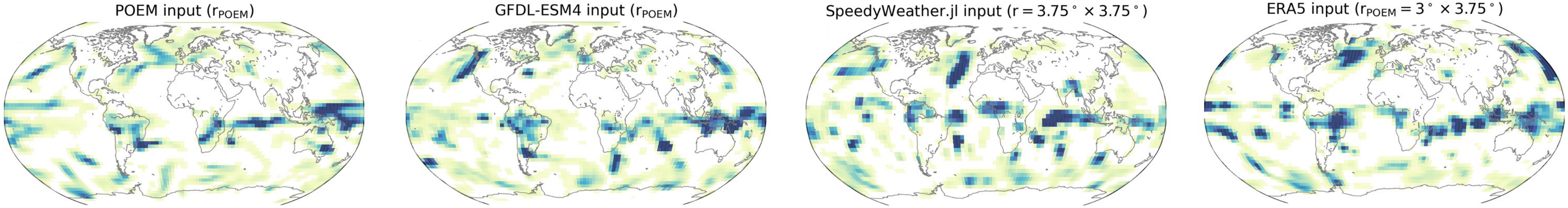
Hess et al., 2024

Preserving large-scale patterns on the coarse grid



Hess et al., 2024

Downscaling any atmosphere model without retraining



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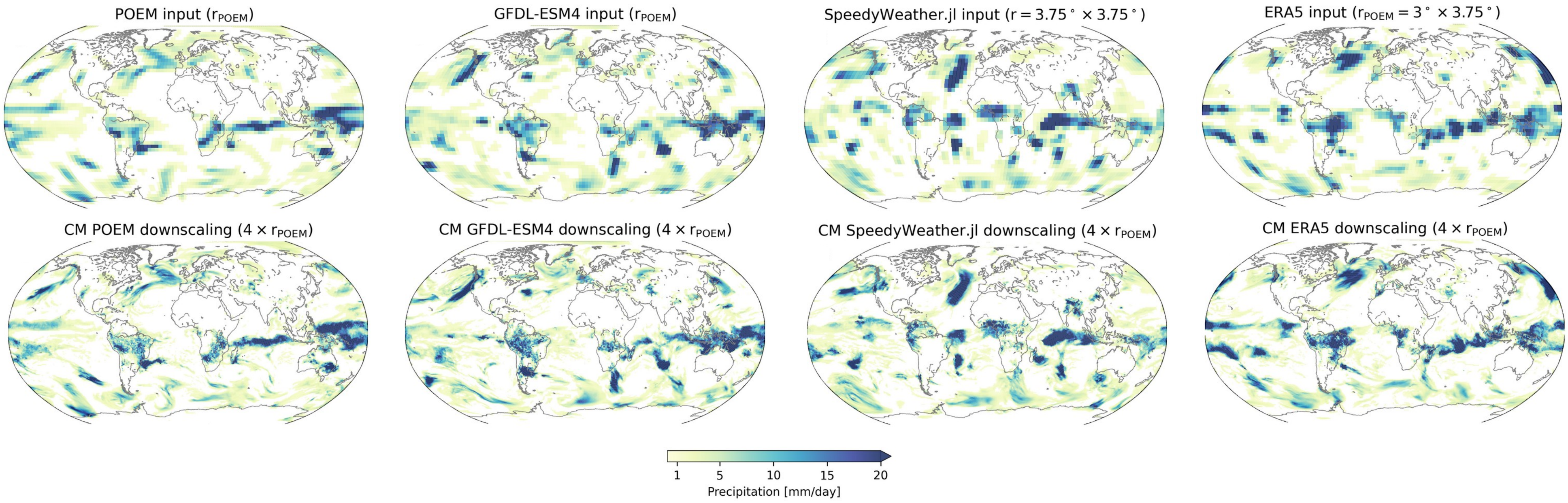
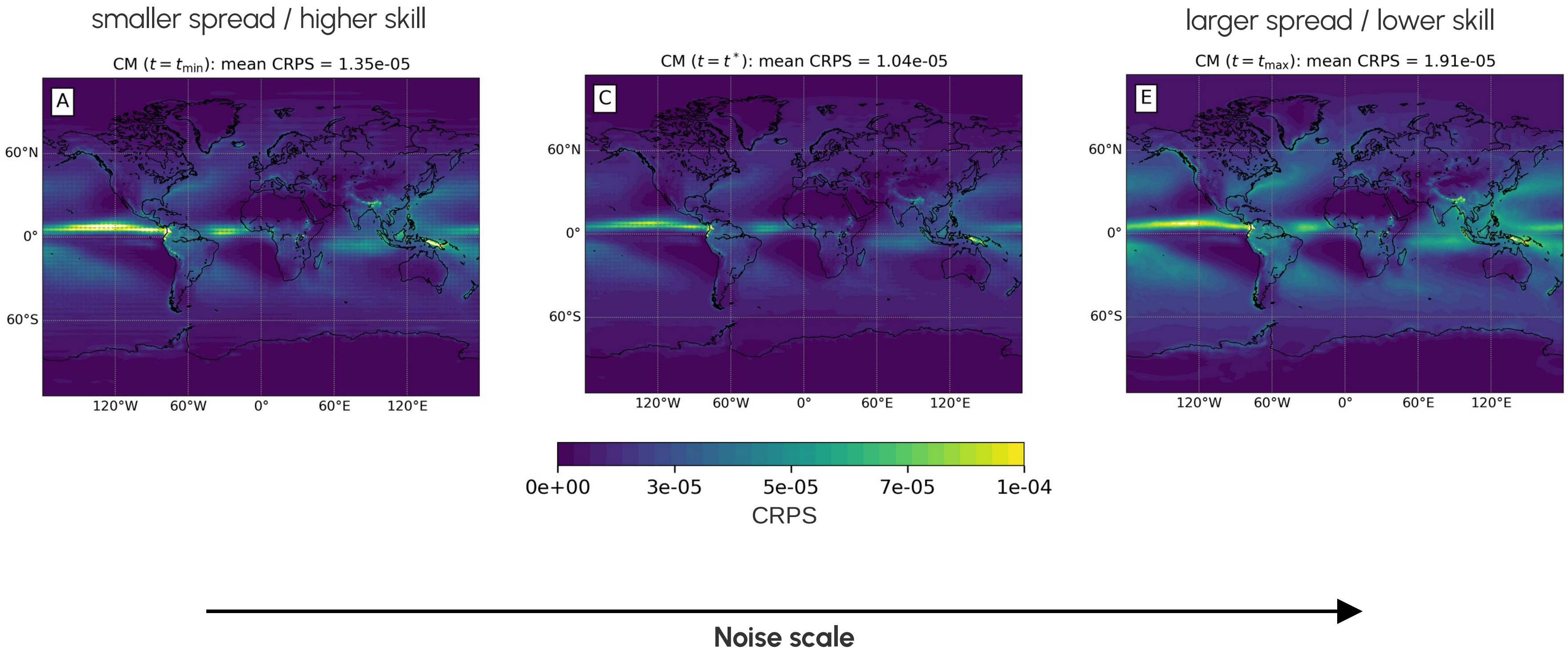
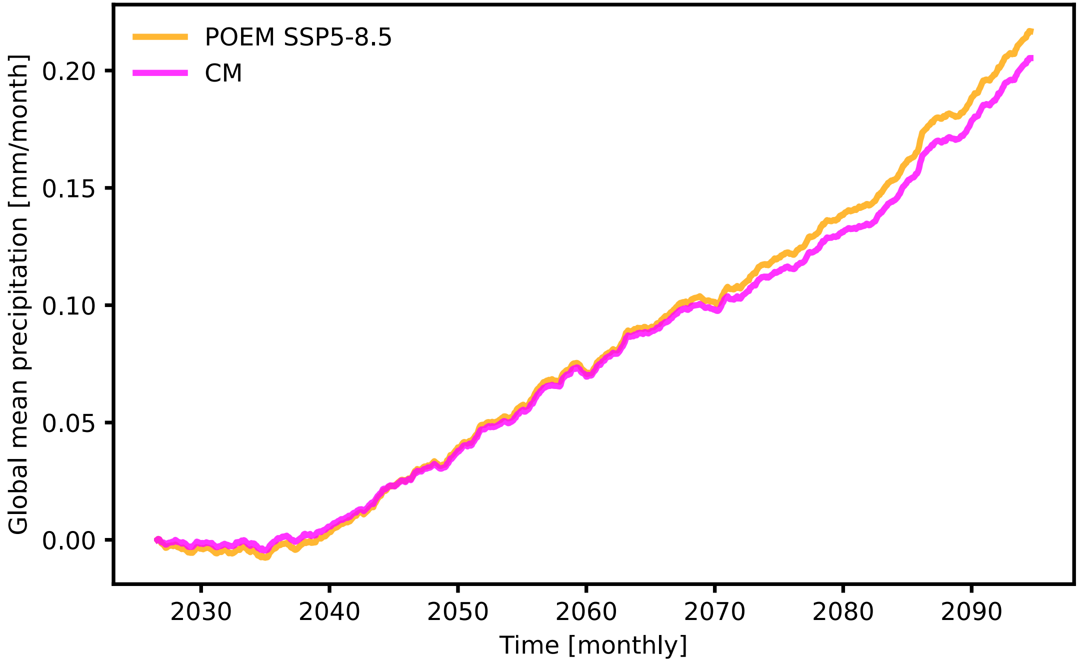


Uncertainty-aware downscaling



Hess et al., 2024

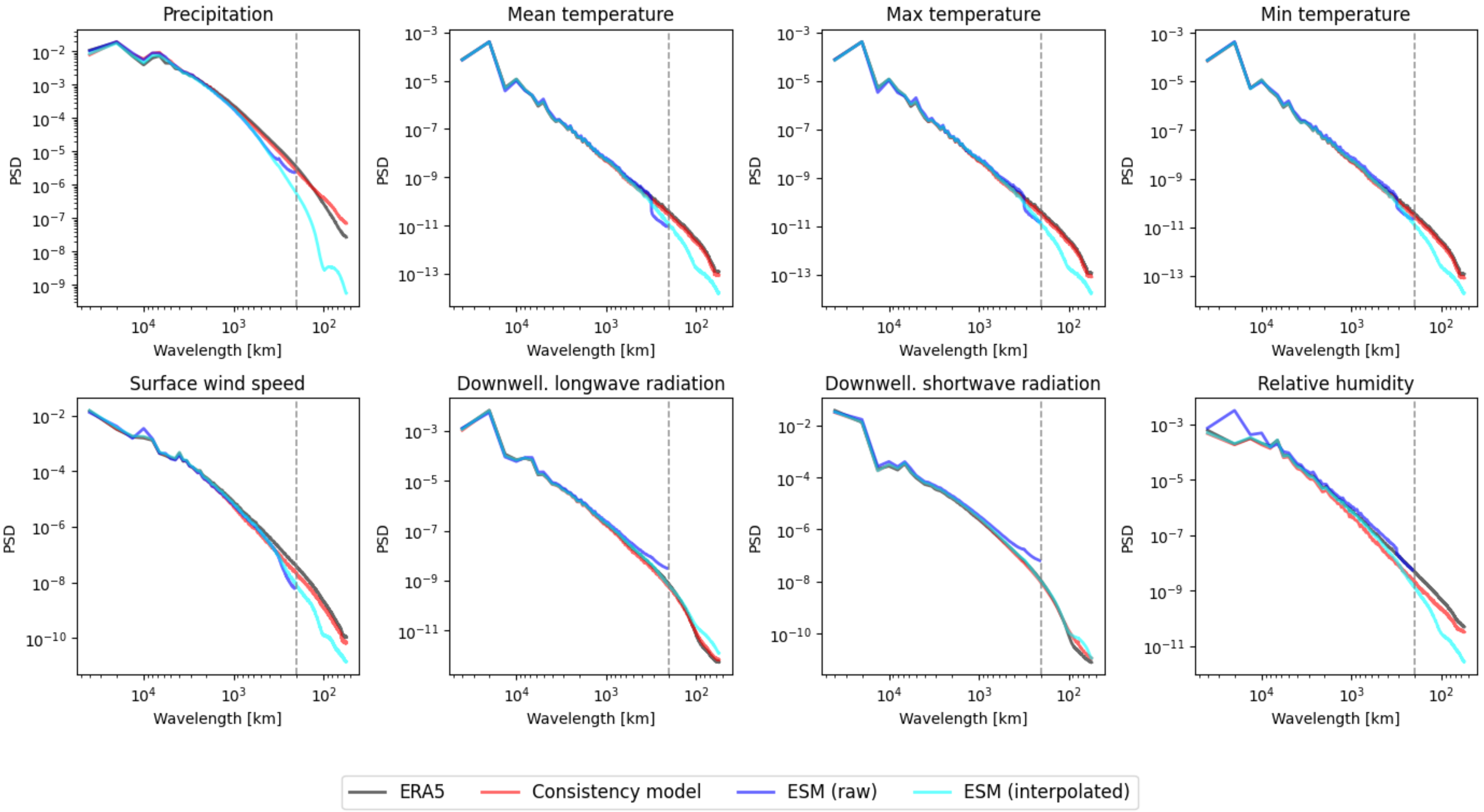
Preserving trends in non-stationary climates



Hess et al., 2024

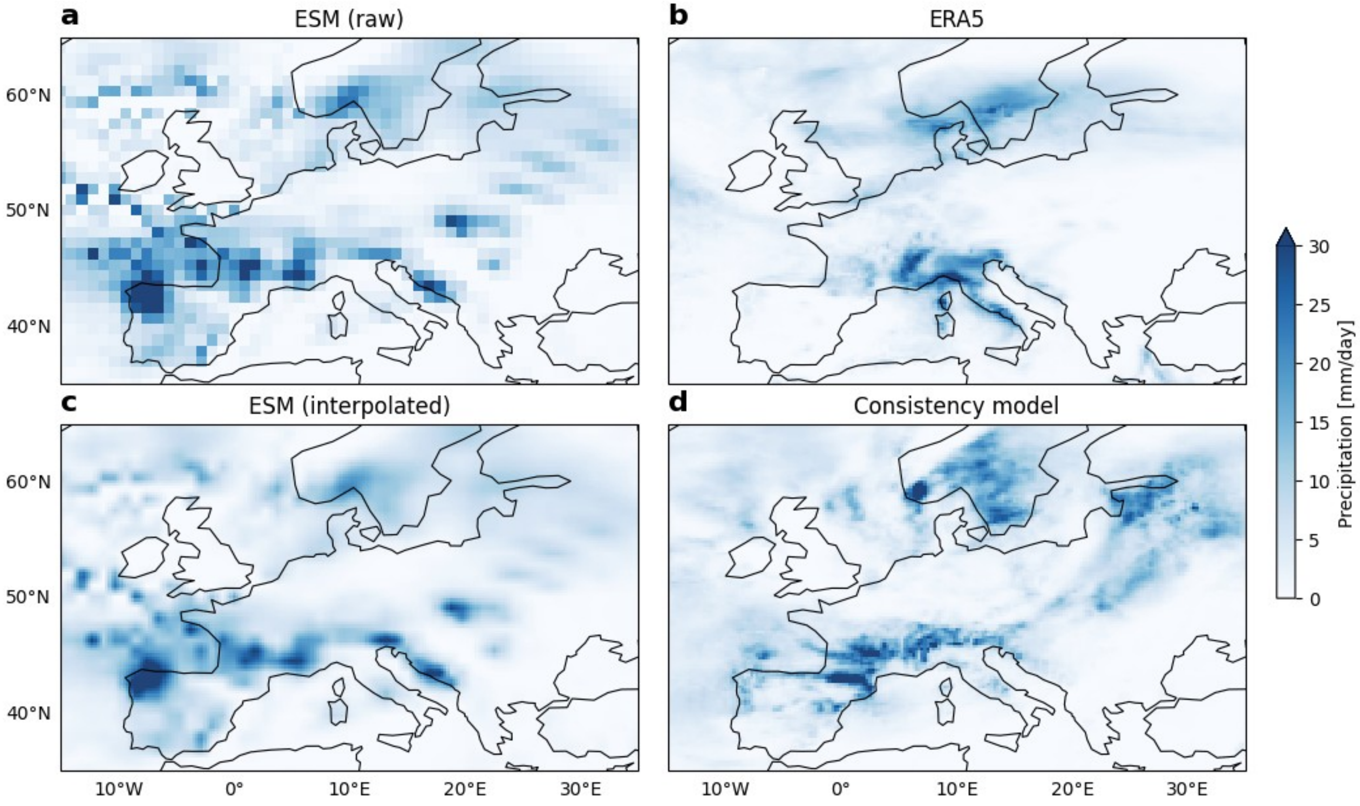
Multivariate downscaling of global Earth system model simulations

Multivariate downscaling results



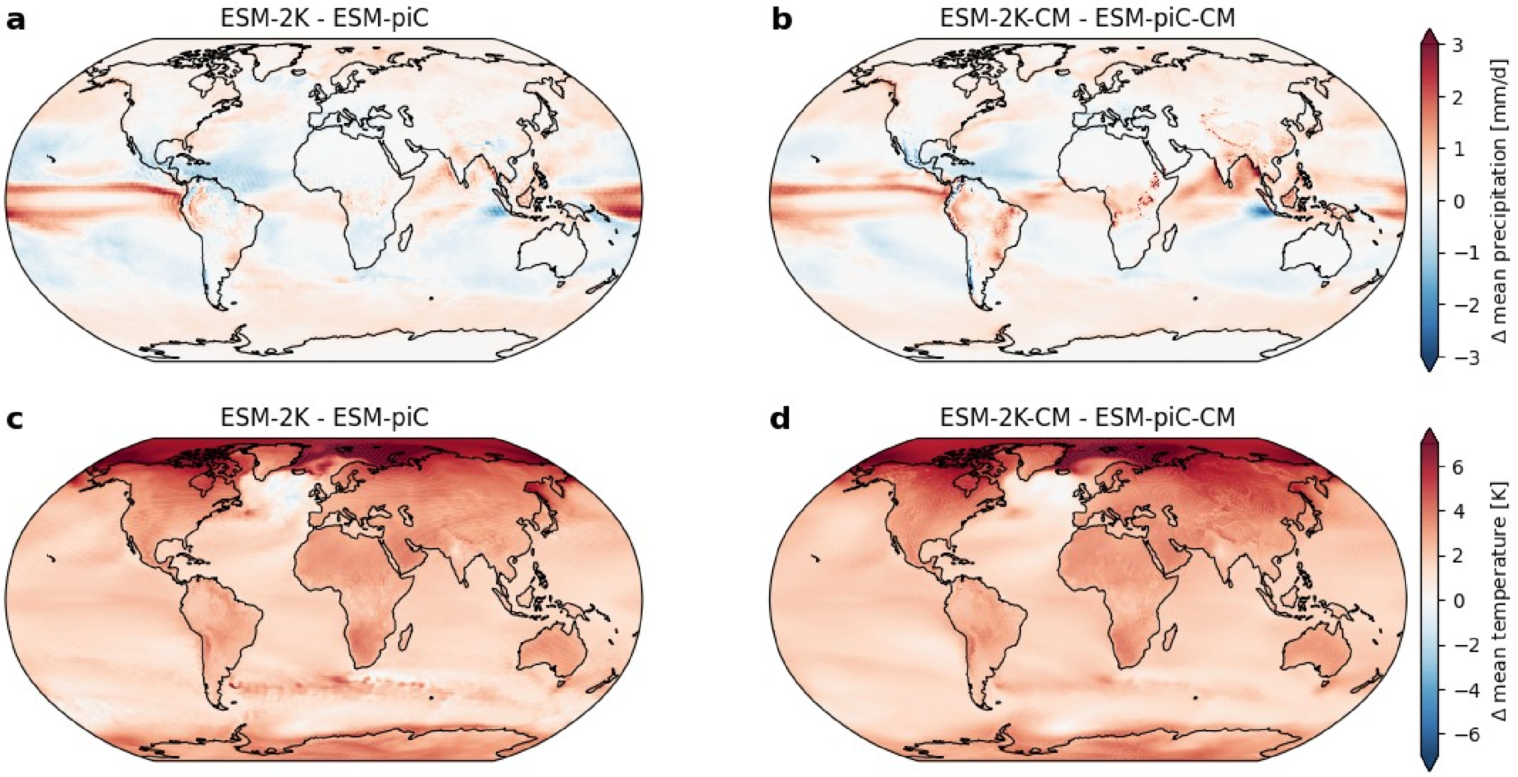
Hess et al., in prep.

Qualitative comparison on regional scales



Hess et al., in prep.

Preserving global warming trends



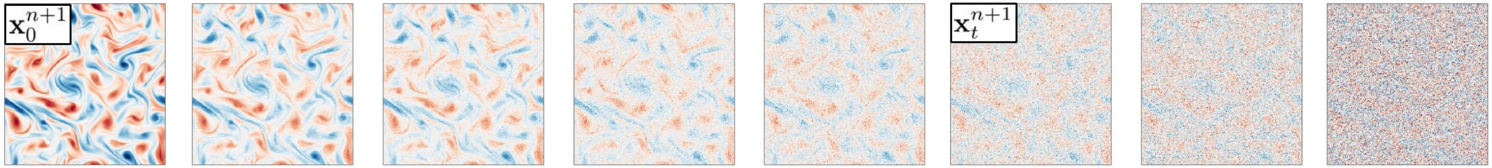
Hess et al., in prep.

Generating time-consistent dynamics with discriminator-guided image diffusion models

Discriminator-guidance for plug-in time consistency

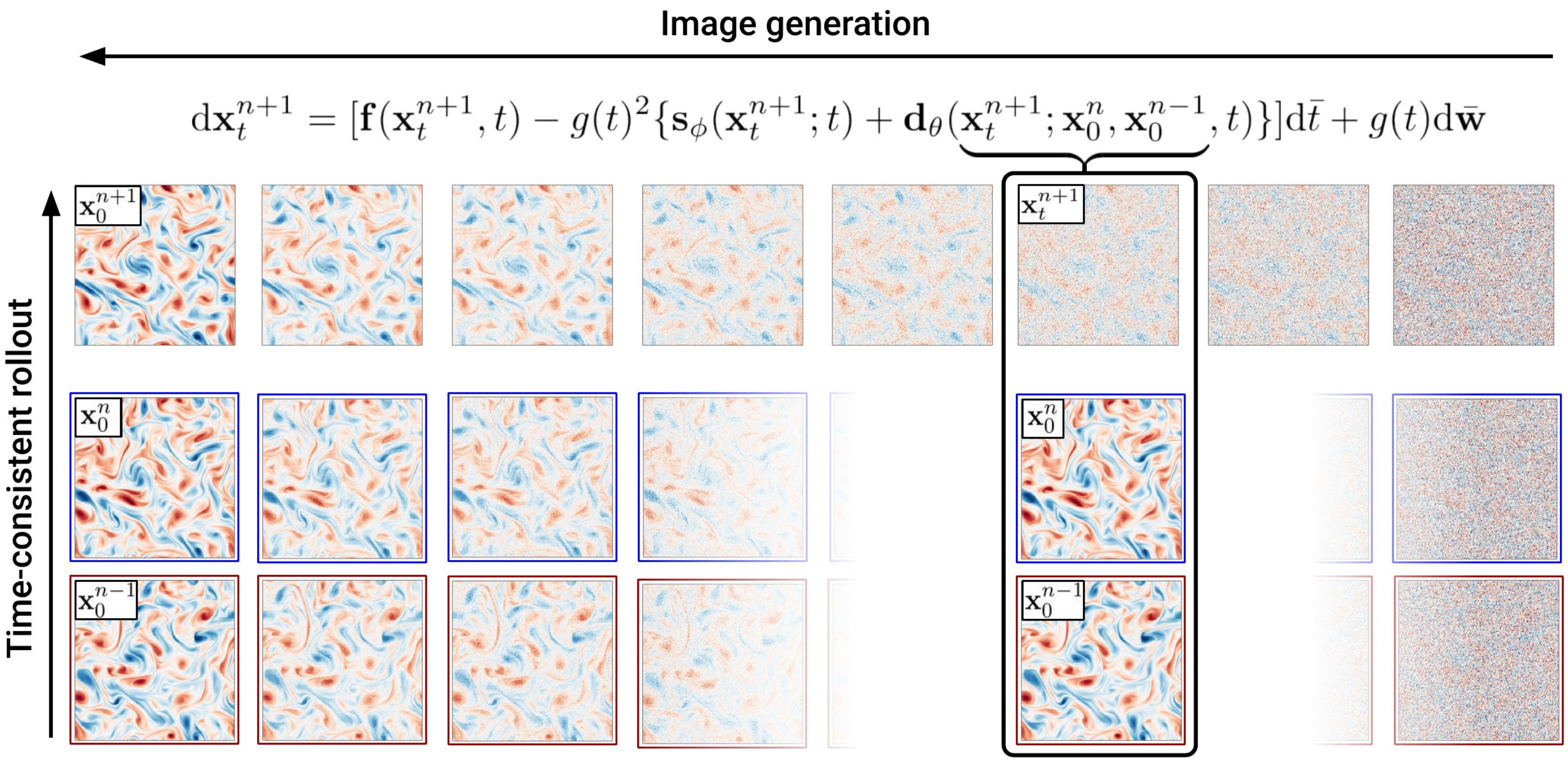
Image generation

$$\mathrm{d}\mathbf{x}_t^{n+1} = [\mathbf{f}(\mathbf{x}_t^{n+1}, t) - g(t)^2\{\mathbf{s}_\phi(\mathbf{x}_t^{n+1}; t) \qquad \}]\mathrm{d}\bar{t} + g(t)\mathrm{d}\bar{\mathbf{w}}$$



Hess et al., submitted, 2025

Discriminator-guidance for plug-in time consistency



Hess et al., submitted, 2025

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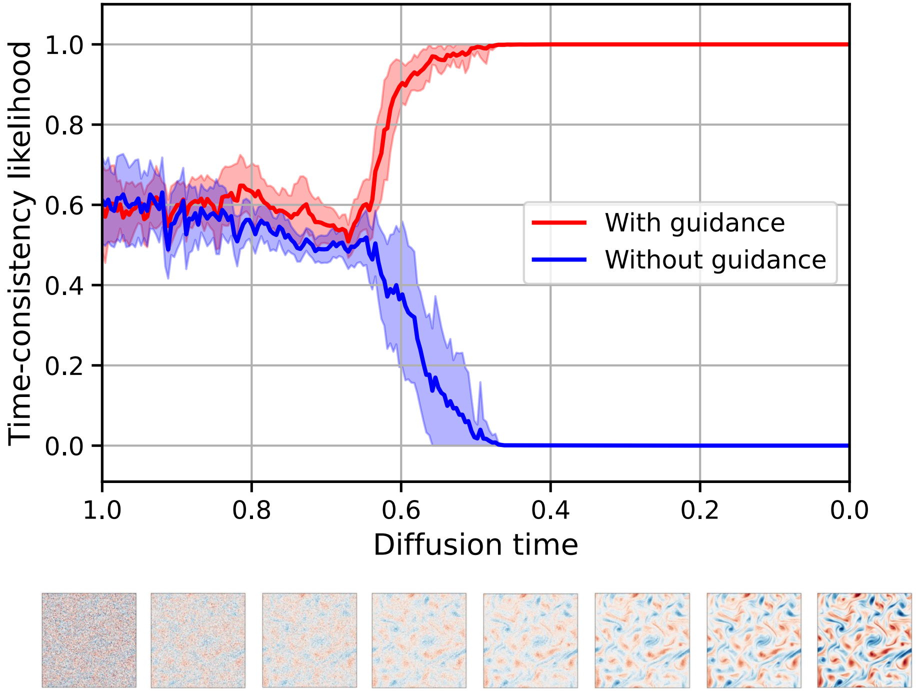
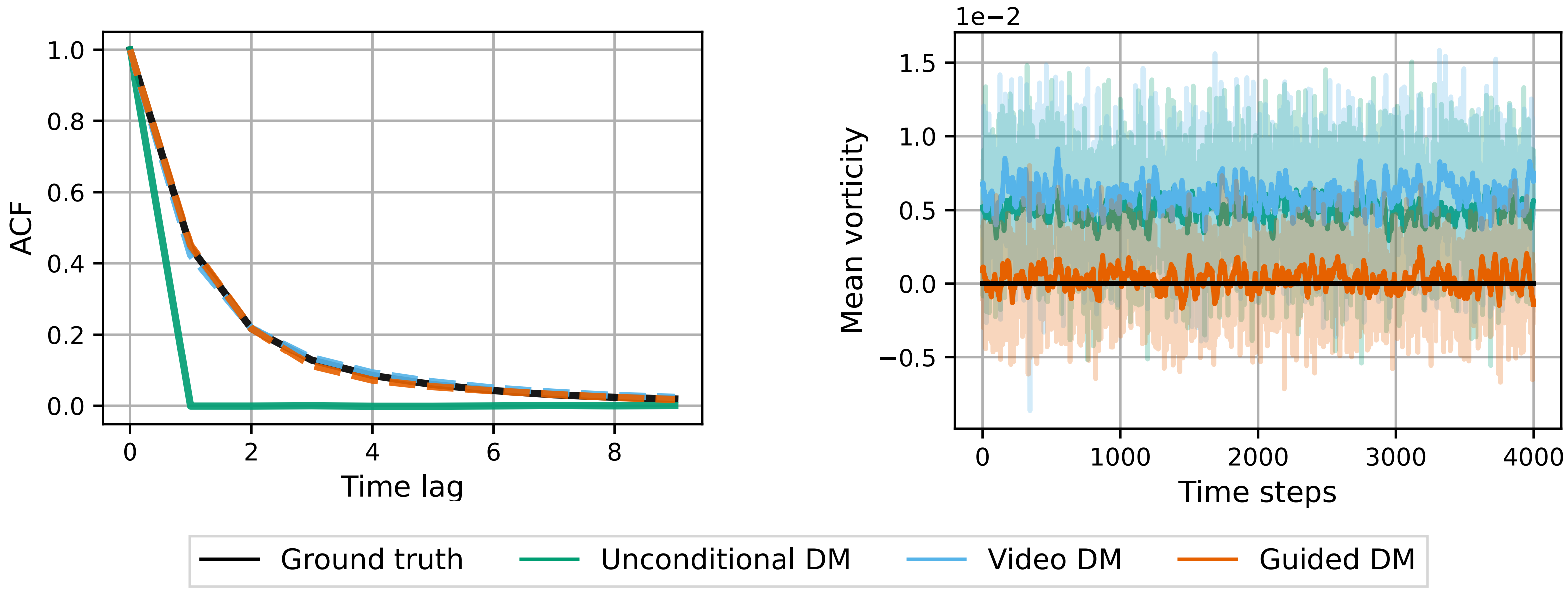


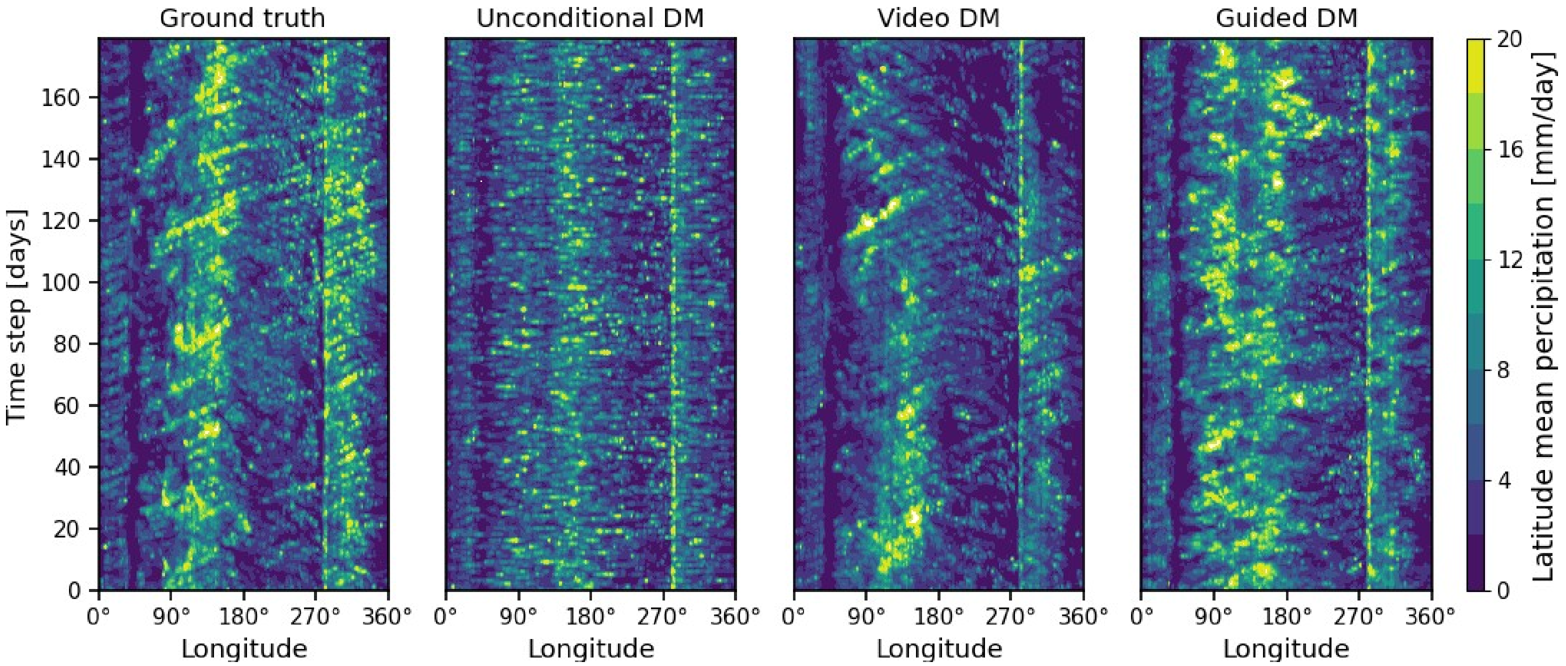
Hess et al., submitted, 2025

2D Navier-Stokes vorticity results



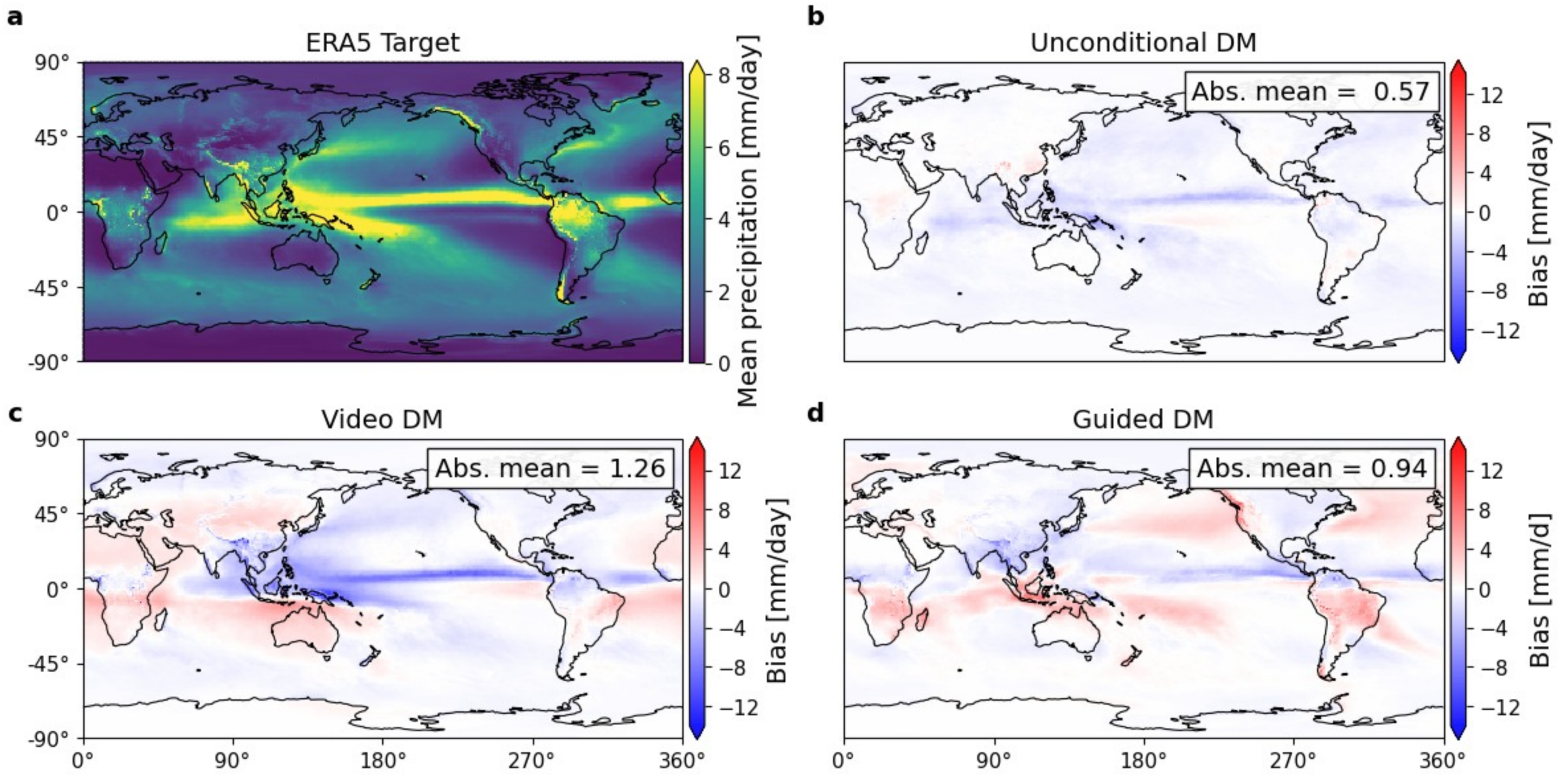
Hess et al., submitted, 2025

Global precipitation dynamics



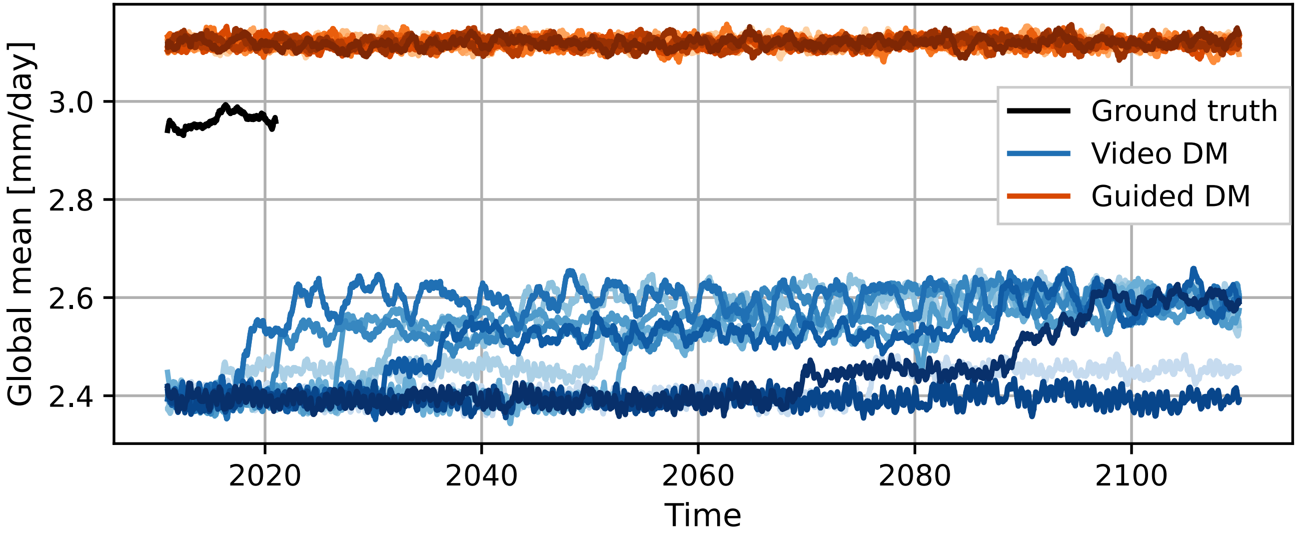
Hess et al., submitted, 2025

Reduced precipitation biases



Hess et al., submitted, 2025

Improved stability in long-term simulations



Hess et al., submitted, 2025

Summary

- **Generative downscaling:**
  - Can be adapted to any model resolution.
  - Consistency models are skillful and particularly efficient.
  - Stochastic approach is uncertainty-aware.

- **Time consistency guidance.**
  - Can be "plugged" into any image diffusion model.
  - Only requires cheap training of a binary classifier.
  - Reduces biases and improves long-term stability.

Downscaling paper:

Guidance paper:

Feel free to contact me: hess@pik-potsdam.de

Thanks!