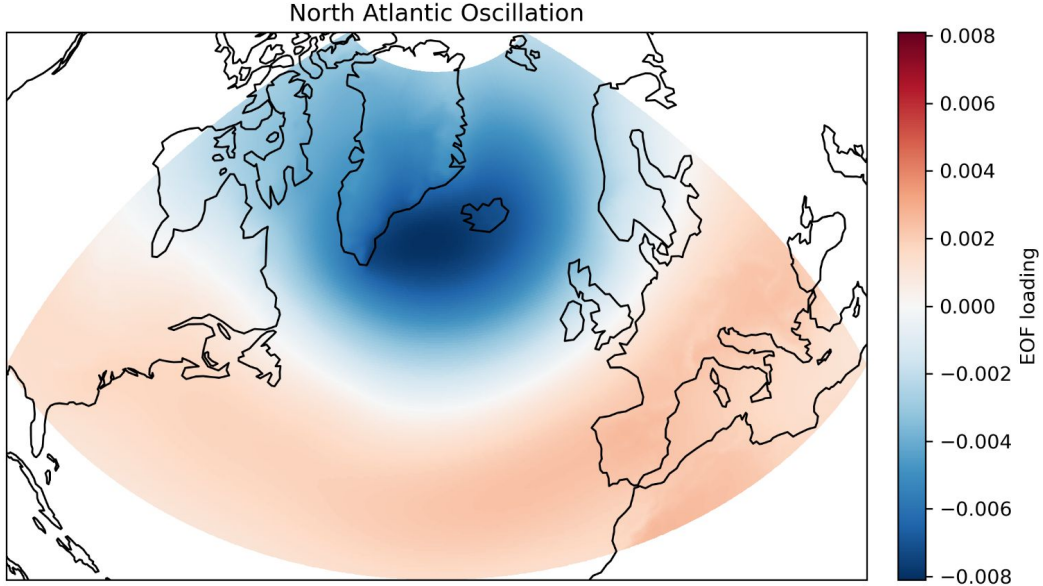
Interpretable target-aware deep learning: Linking weather patterns to precipitation

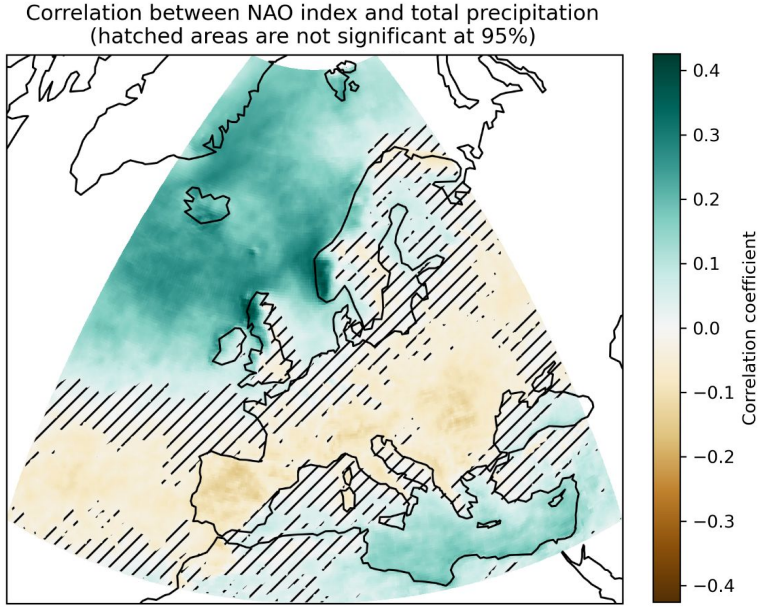
Jonathan Ortved Melcher, *Jens H. Christensen, Chongyang Zhang, Peter L. Langen, and Shuting Yang*

DANMARKS FRIE FORSKNINGSFOND
INDEPENDENT RESEARCH FUND DENMARK

Ed Hawkins

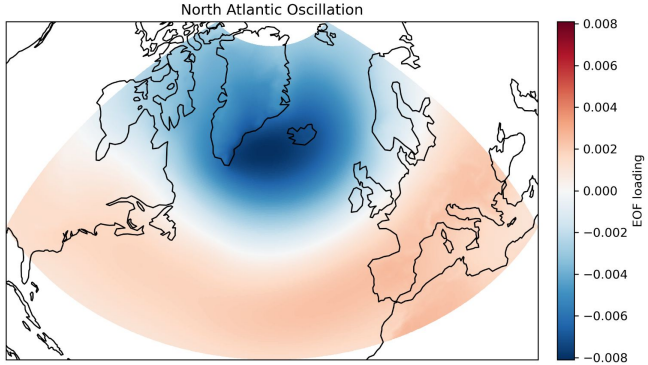
Crash course in climate physics

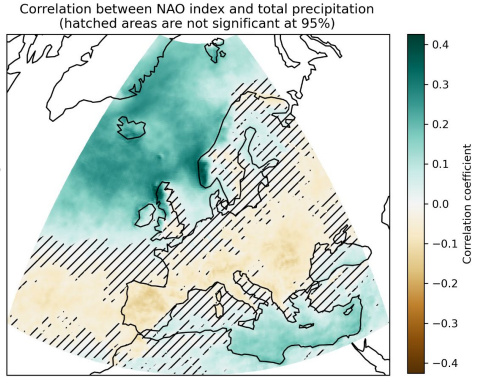




Classical model

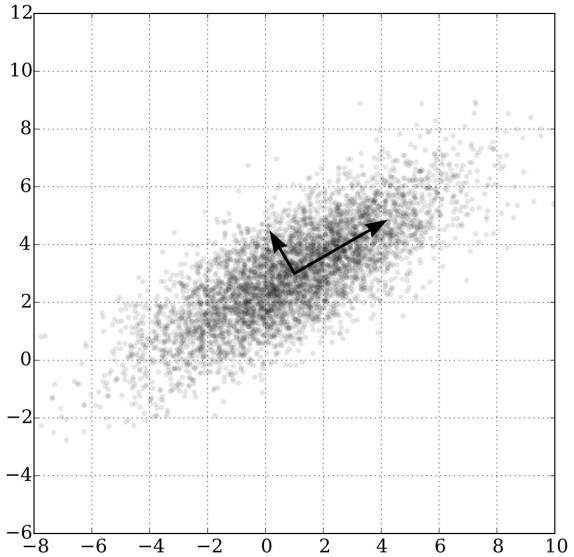
- NAO index is based on PCA
  - Linear
  - Orthogonal
  - Symmetric





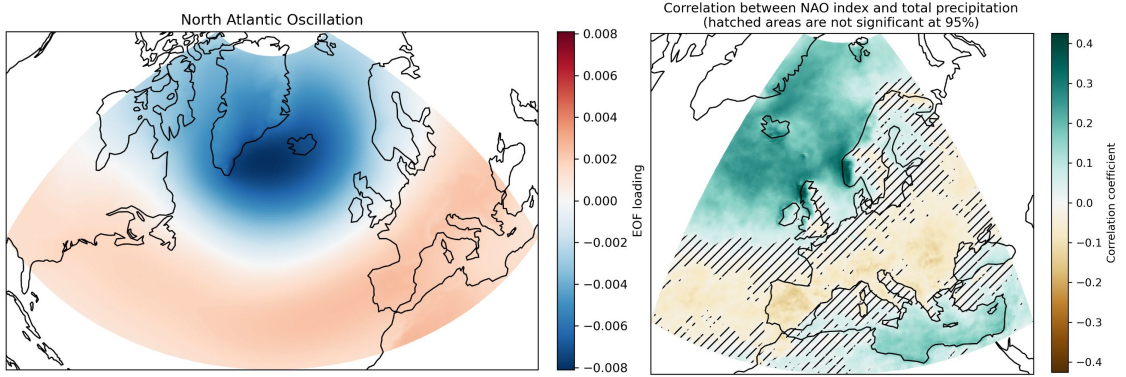
Classical model

- NAO index is based on PCA
  - Linear
  - Orthogonal
  - Symmetric



Classical model

- NAO index is based on PCA
  - Linear
  - Orthogonal
  - Symmetric
- Straight correlation to target.



ML model wish list

- NAO index is based on PCA
  - Linear
  - Orthogonal
  - Symmetric
- Straight correlation to target.
- ML model

ML model wish list

- NAO index is based on PCA
  - ~~Linear~~
  - ~~Orthogonal~~
  - ~~Symmetric~~
- Straight correlation to target.

- ML model
  - Non-linear
  - Non-orthogonal
  - Non-symmetric

ML model wish list

- NAO index is based on PCA
  - ~~Linear~~ → Non-linear
  - ~~Orthogonal~~ → Non-orthogonal
  - ~~Symmetric~~ → Non-symmetric
- ~~Straight correlation to target.~~ → Non-linear connection to target

- ML model

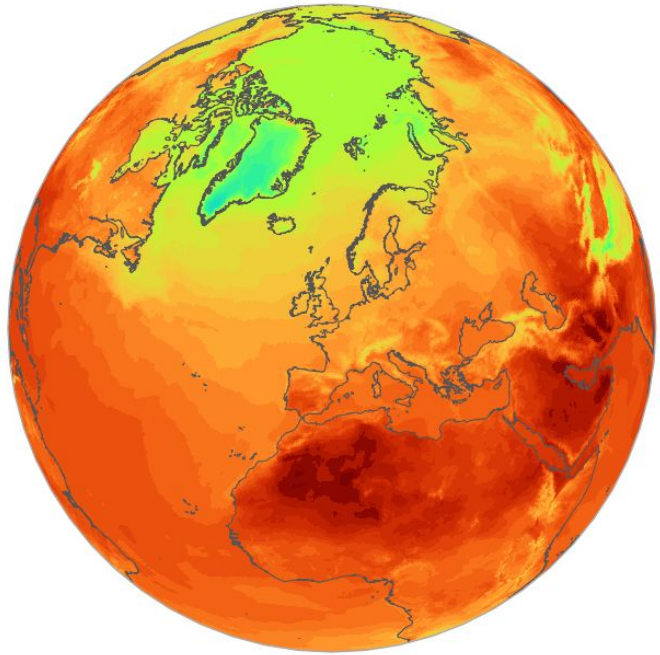
ML model wish list

- NAO index is based on PCA
  - ~~Linear~~
  - ~~Orthogonal~~
  - ~~Symmetric~~
- ~~Straight correlation to target.~~

- ML model
  - Non-linear
  - Non-orthogonal
  - Non-symmetric
- Non-linear connection to target
- Interpretable

Data for the data driven

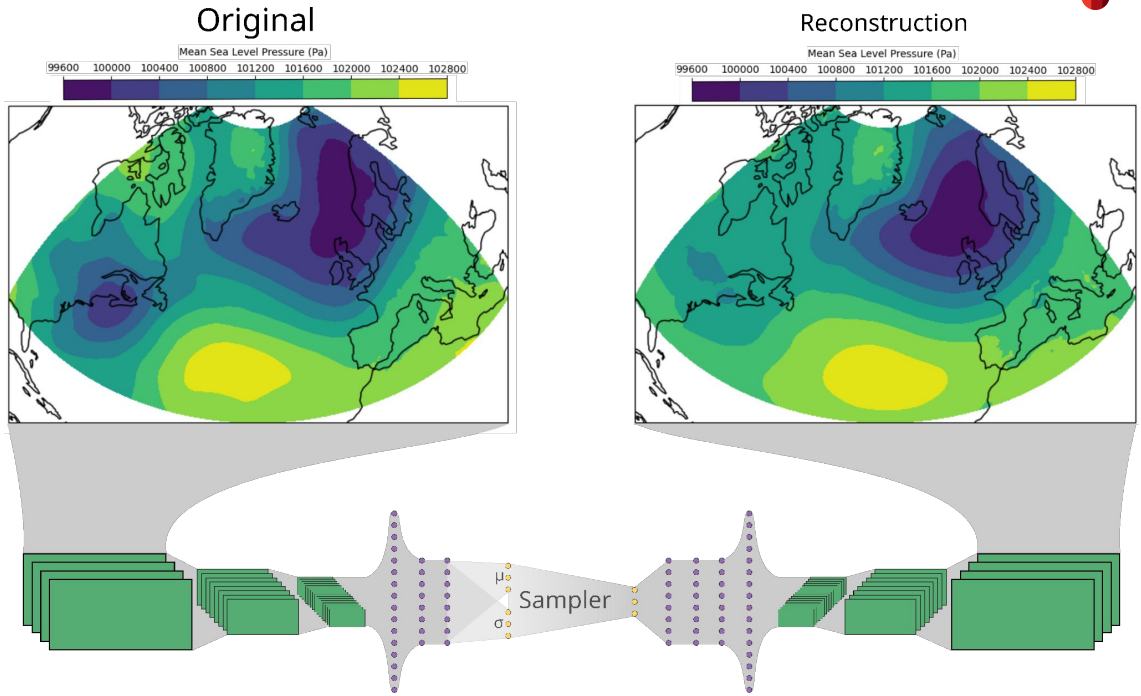
- ERA5 1940-2024
  - Interpolation to 0.25° x 0.25°
  - Daily data, all year
- Pressure field, 5-day lowpass
- Removed seasonality in mean and variance



Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., … Thépaut, J.-N. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049.

Building the RMM-CVAE

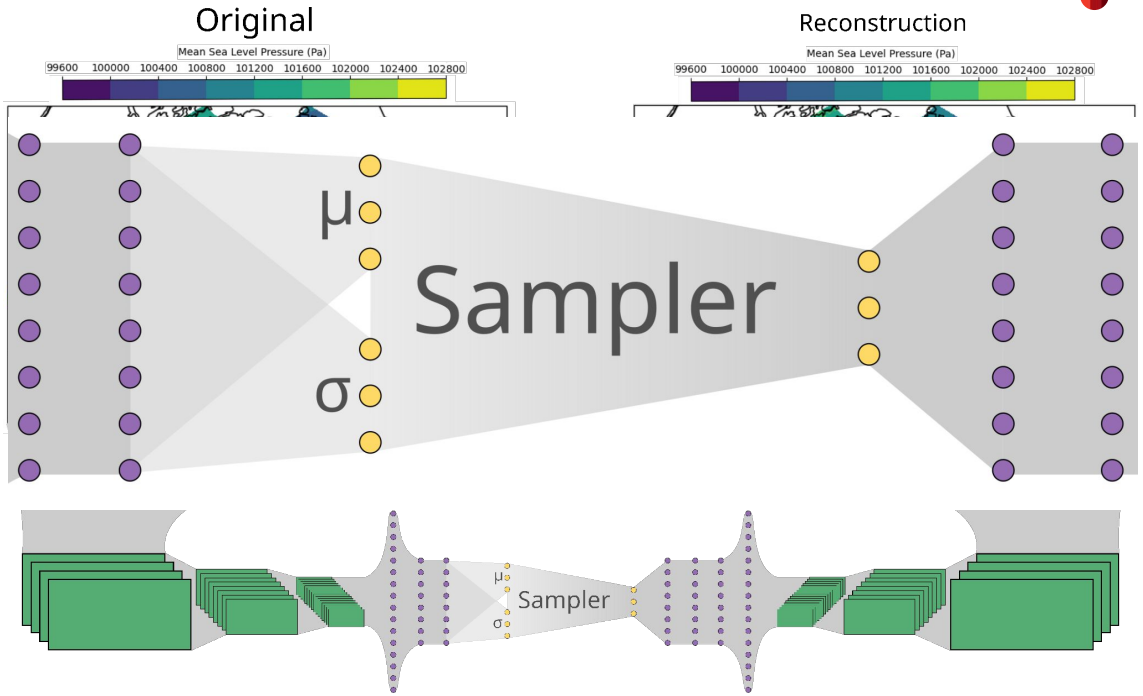
- Convolutional Variational AutoEncoder



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Building the RMM-CVAE

- Convolutional Variational AutoEncoder



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

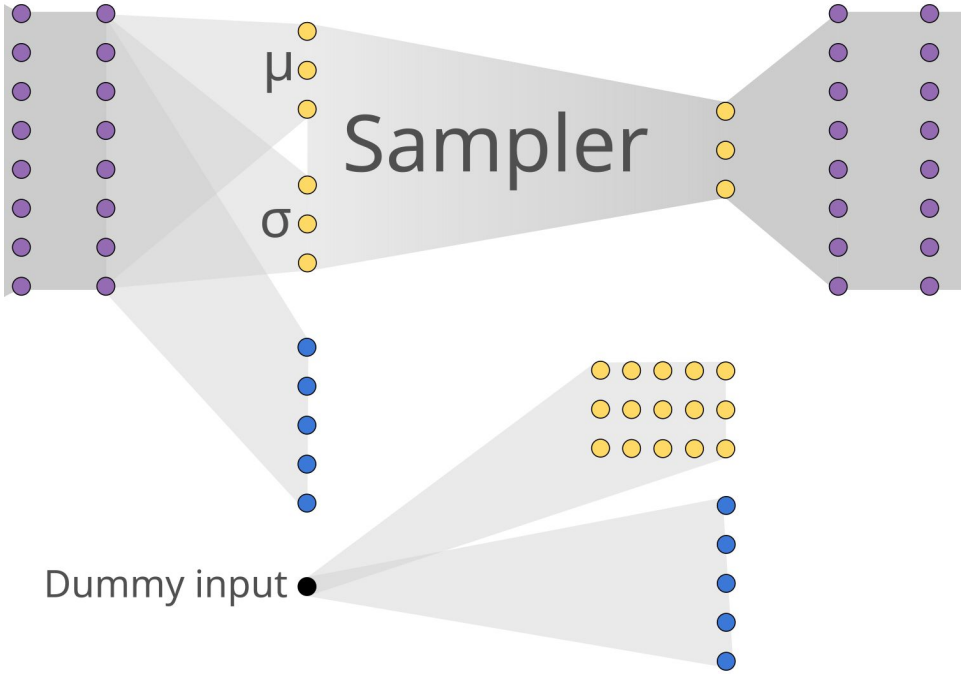
Building the RMM-CVAE

- Convolutional Variational AutoEncoder
  - Regularization

Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Building the RMM-CVAE

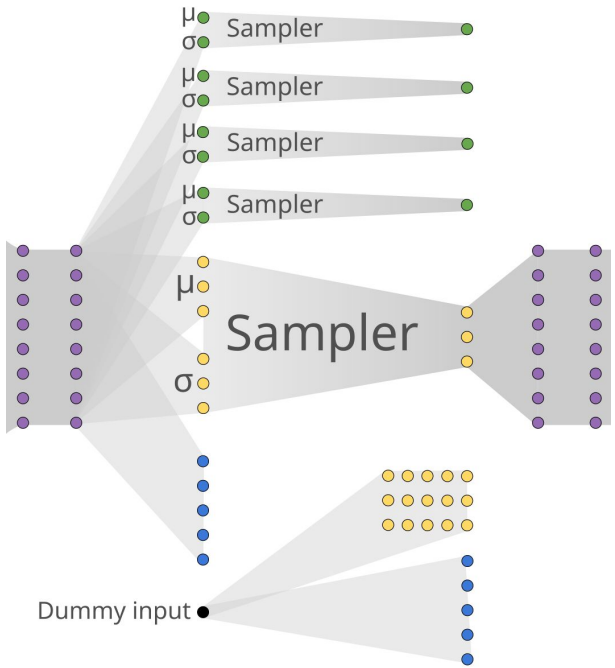
- Convolutional Variational AutoEncoder
  - Regularization
  - Add in a GMM



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Building the RMM-CVAE

- Convolutional Variational AutoEncoder
  - Regularization
  - Add in a GMM
- Target regularization



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

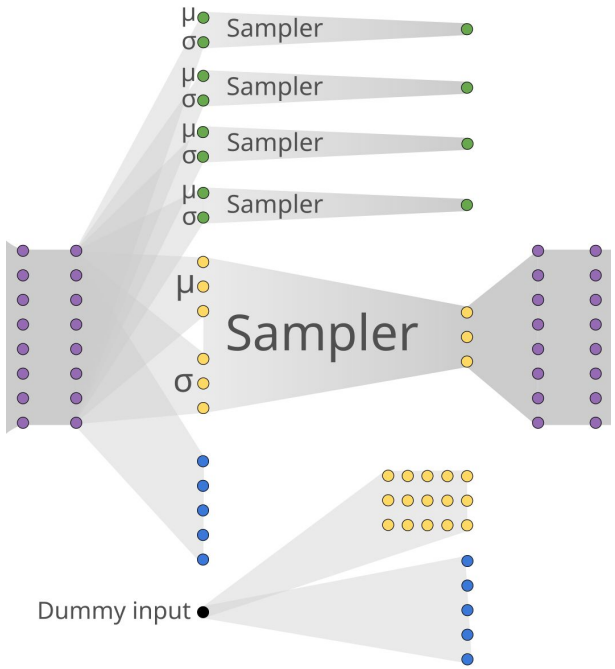
Building the RMM-CVAE

- Convolutional Variational AutoEncoder
  - Regularization
  - Add in a GMM
- Target regularization

$$L(x,r) = (x - x')^2 - D_{KL}(E(r'|x) \,||\, p(r)) -$$

$$D_{KL}(E(c^k|x)||p(c^k)) -$$

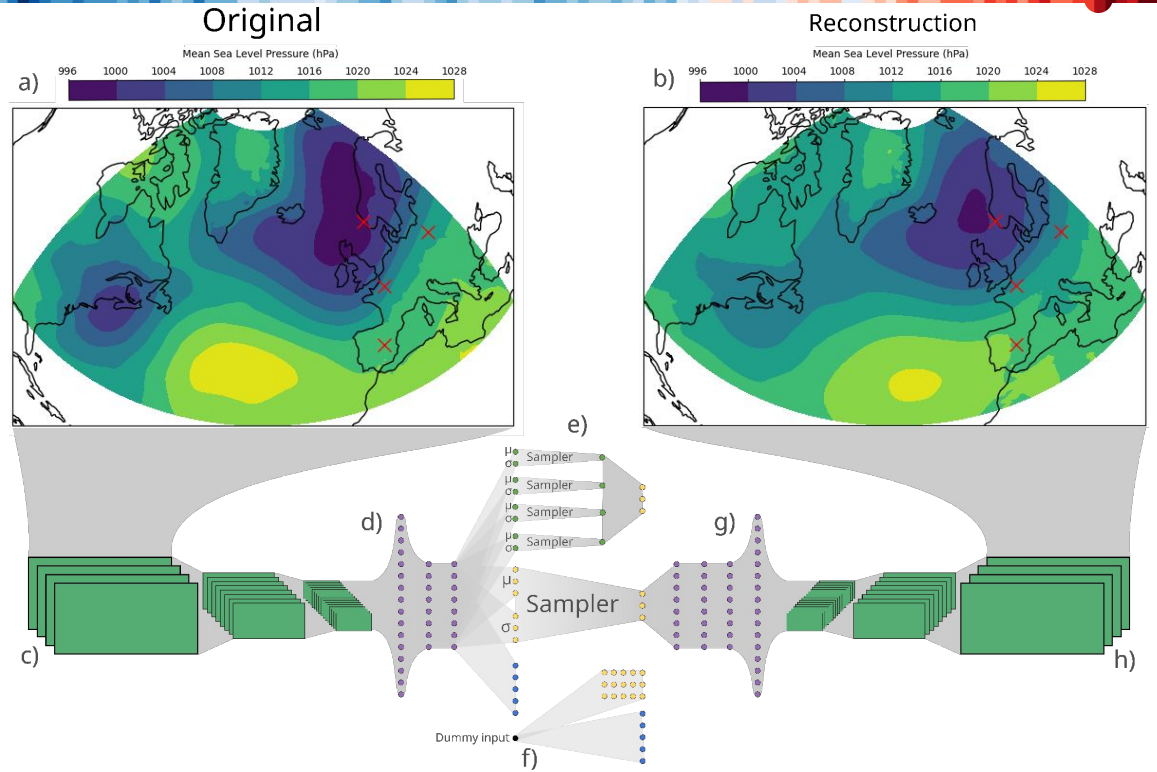
$$\sum_k E(c^k|x) D_{KL}(E(z|x)||p(z|c^k))$$



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Machine Learning Method

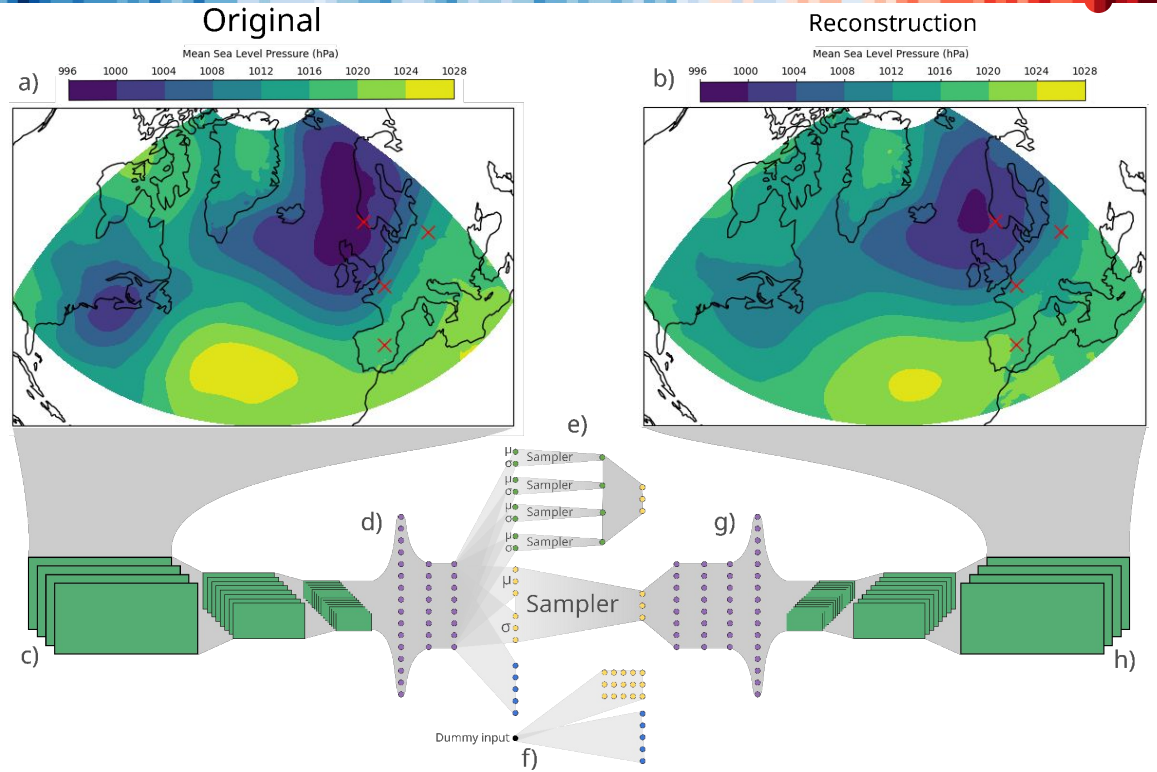
- Constructs **latent space**



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Machine Learning Method

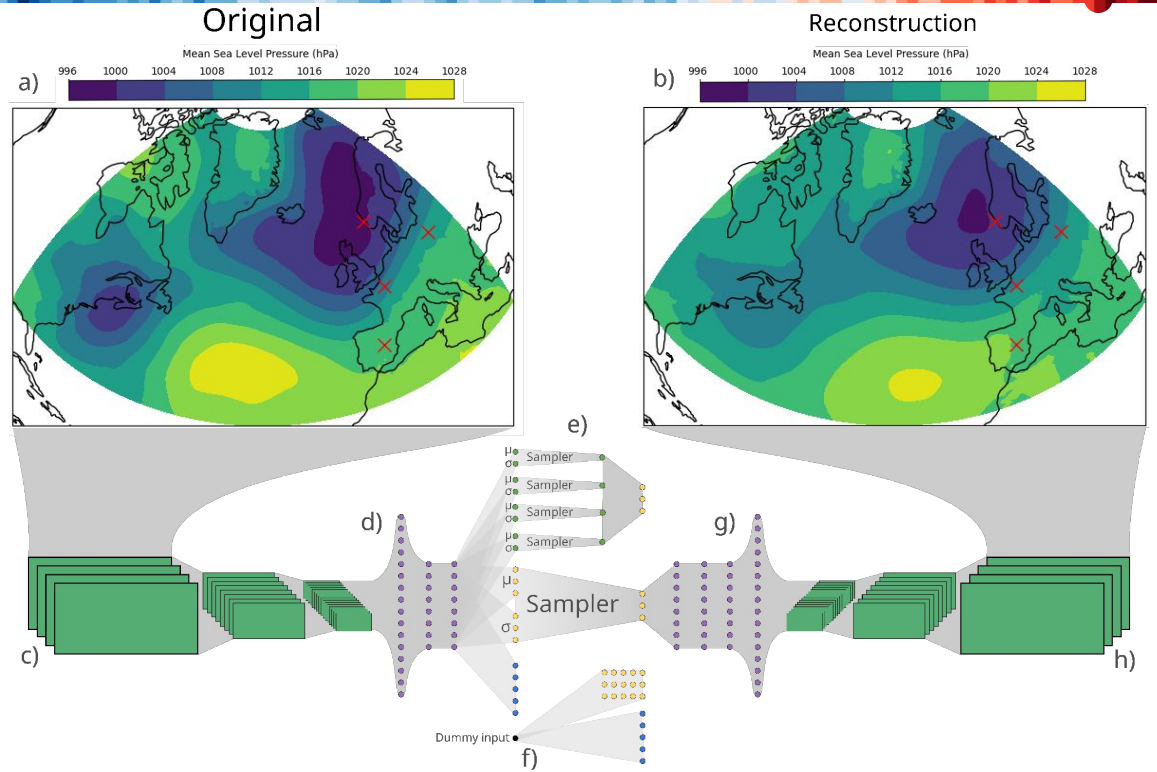
- Constructs **latent space**
- Makes weather patterns



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

Machine Learning Method

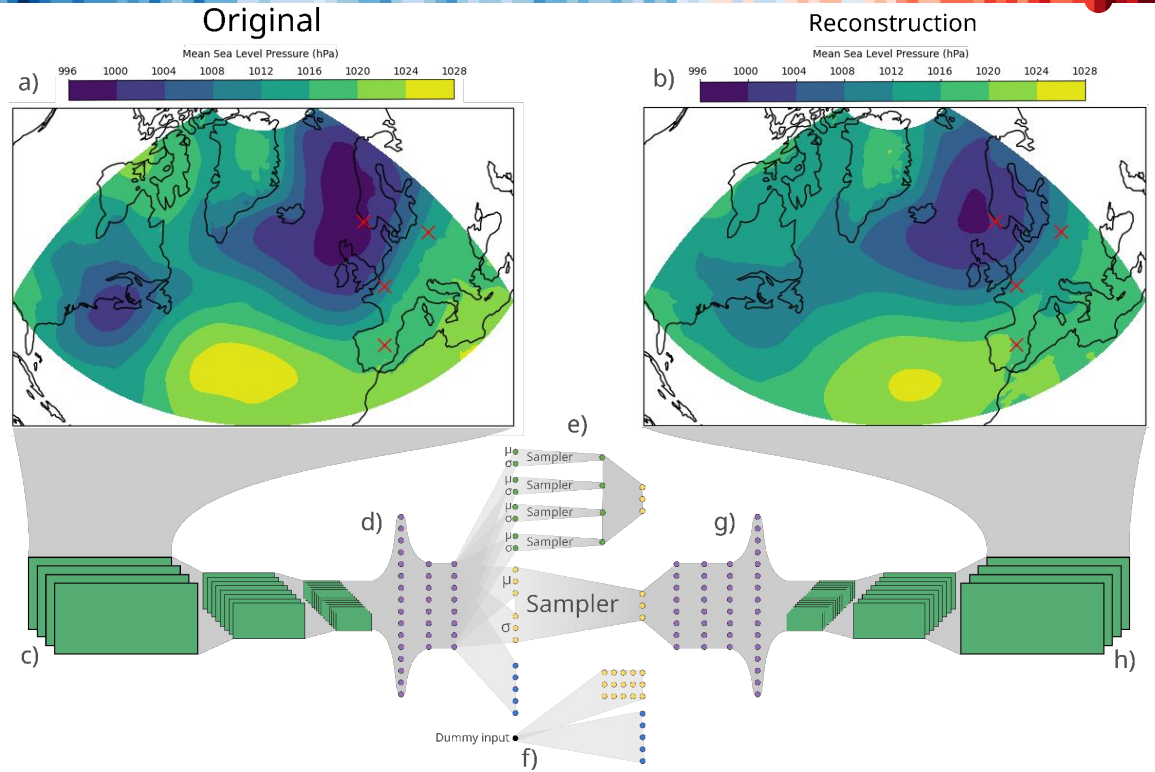
- Constructs **latent space**
- Makes weather patterns
- Gives probability to each weather pattern



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

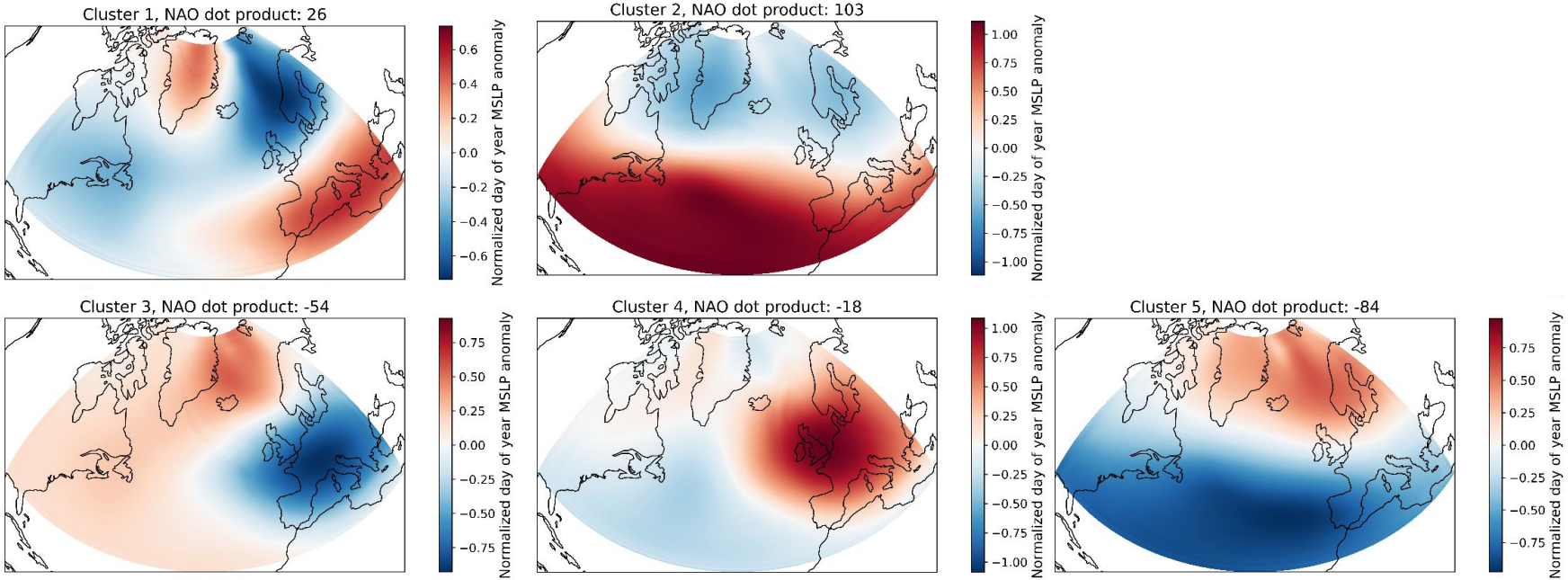
Machine Learning Method

- Constructs **latent space**
- Makes weather patterns
- Gives probability to each weather pattern
- Relates to precipitation in four key regions



Spuler, F. R., Kretschmer, M., et al. (2024). Identifying probabilistic weather regimes targeted to a local-scale impact variable. Environmental Data Science, 3, e25.
Spuler, F. R., Kretschmer, M. et al. (2025). Learning predictable and informative dynamical drivers of extreme precipitation using variational autoencoders. Weather and Climate Dynamics, 6(3), 995–1014.

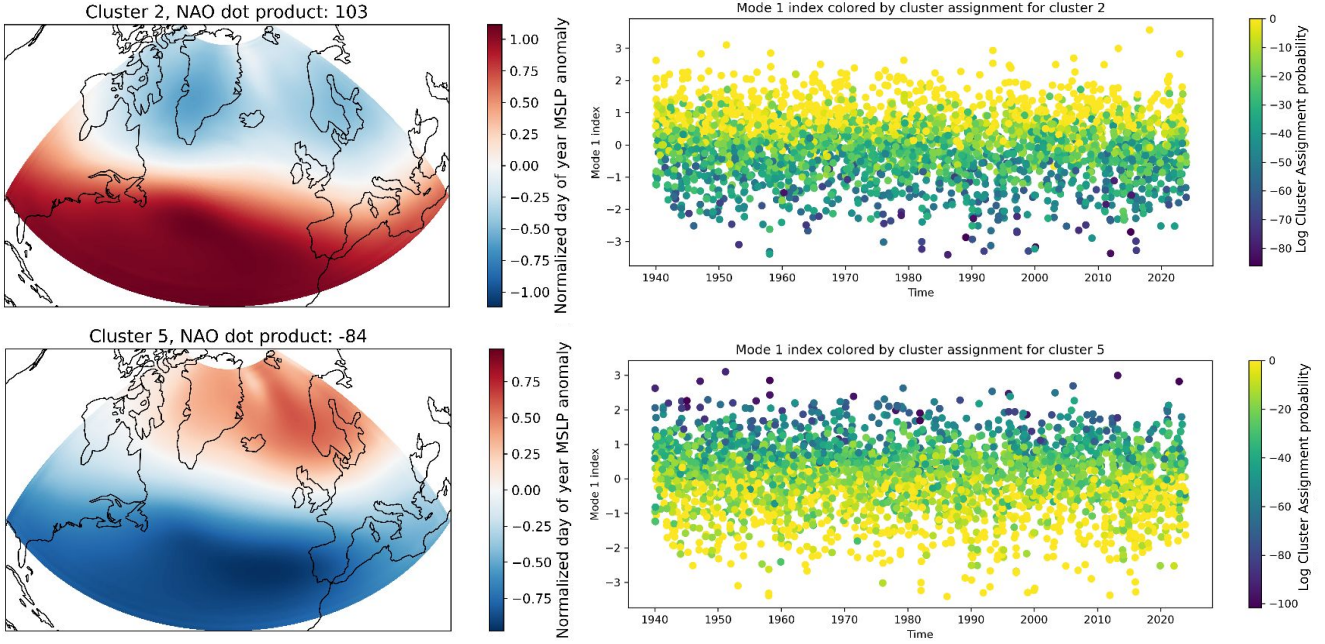
Weather Patterns



Relation to NAO

Sanity check

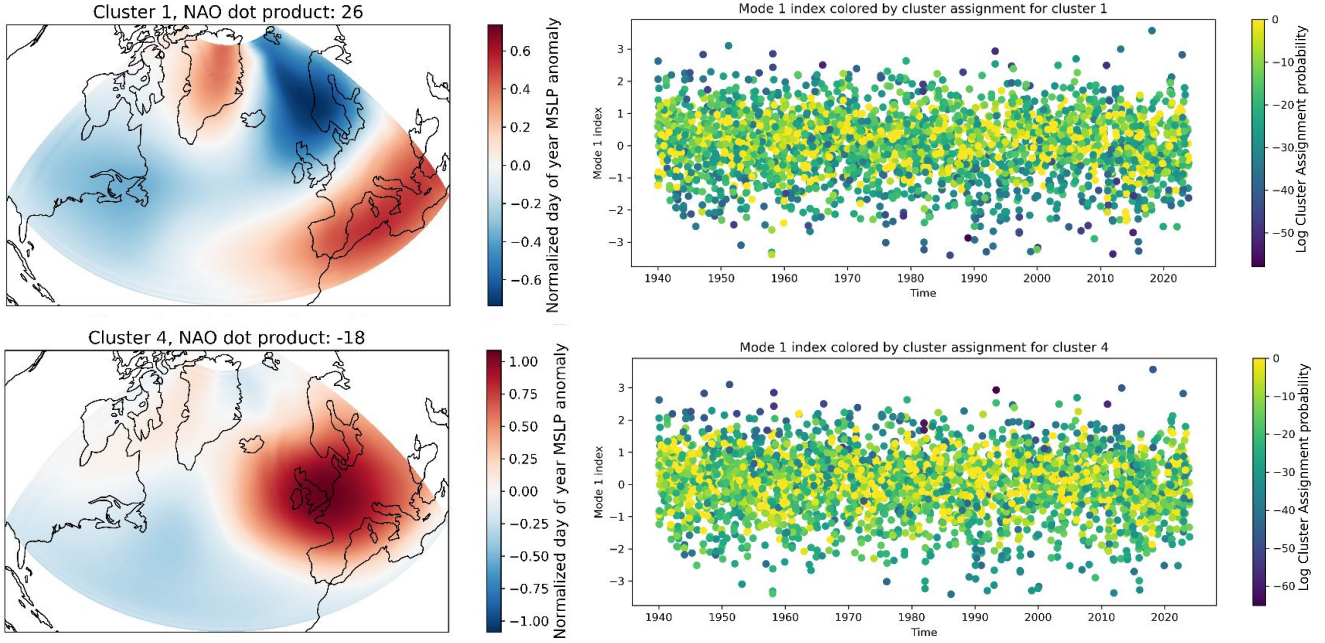
- NAO matches EOF
- non-NAO noise



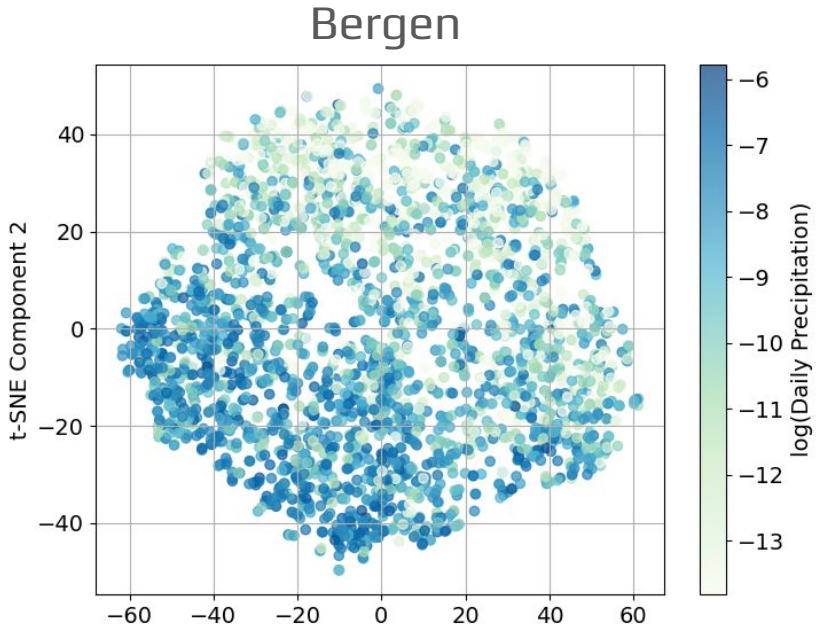
Relation to NAO

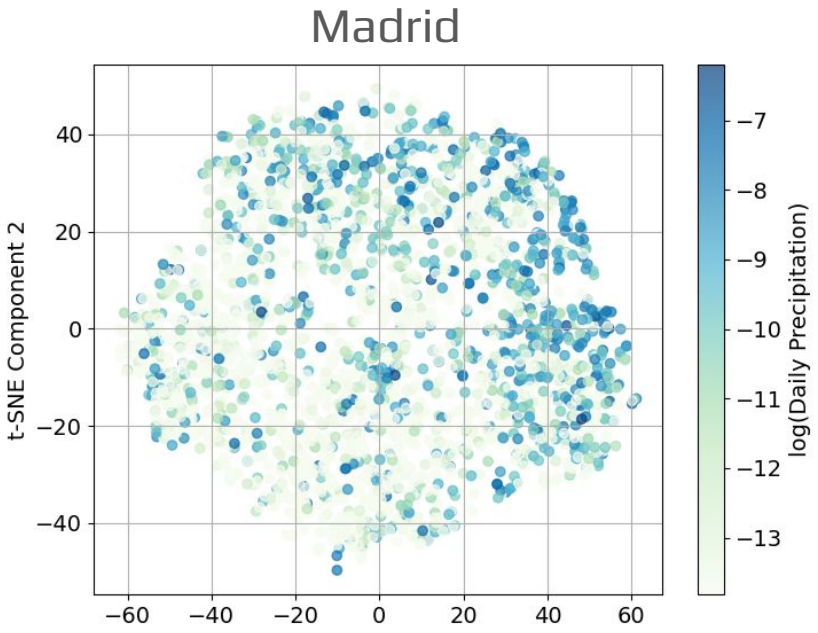
Sanity check

- NAO matches EOF

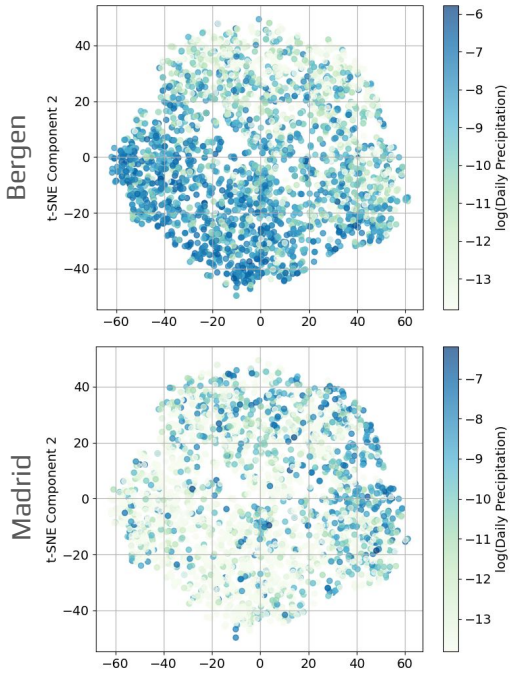


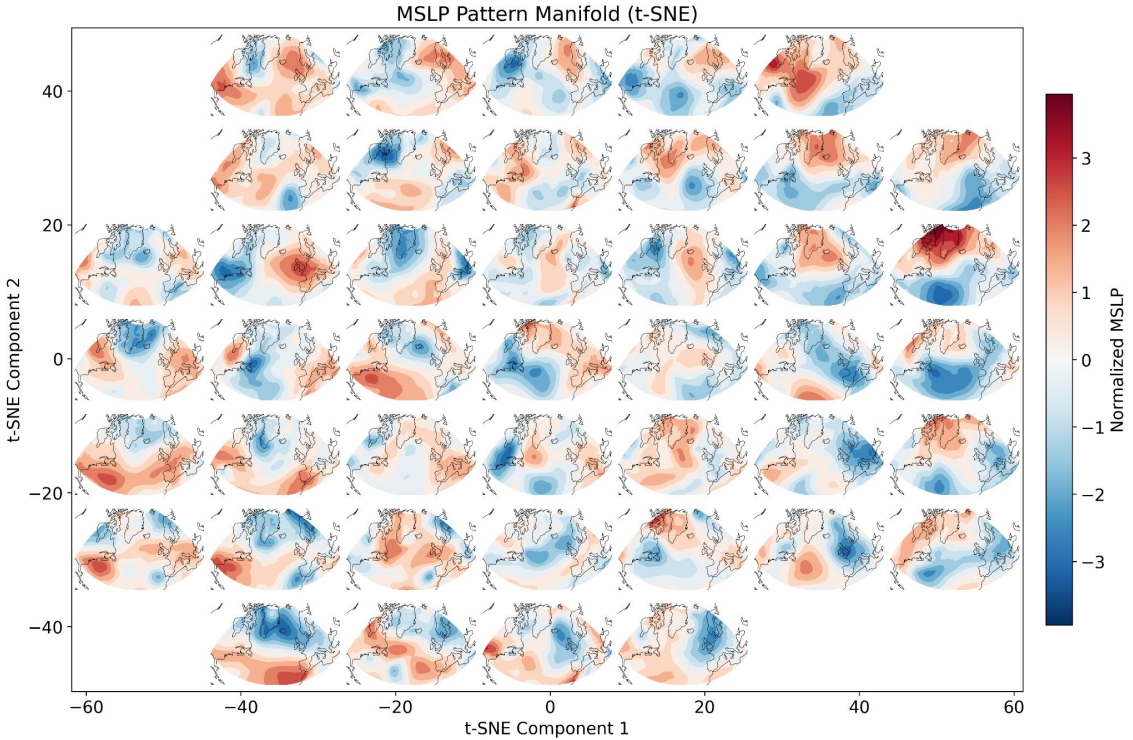
Latent space, t-sne





Latent space, t-sne

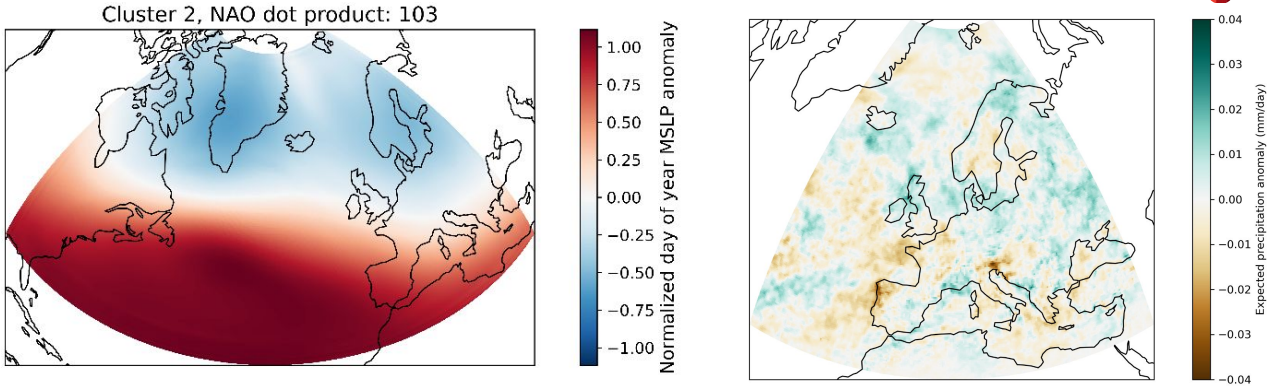




Expected Precipitation

Precipitation

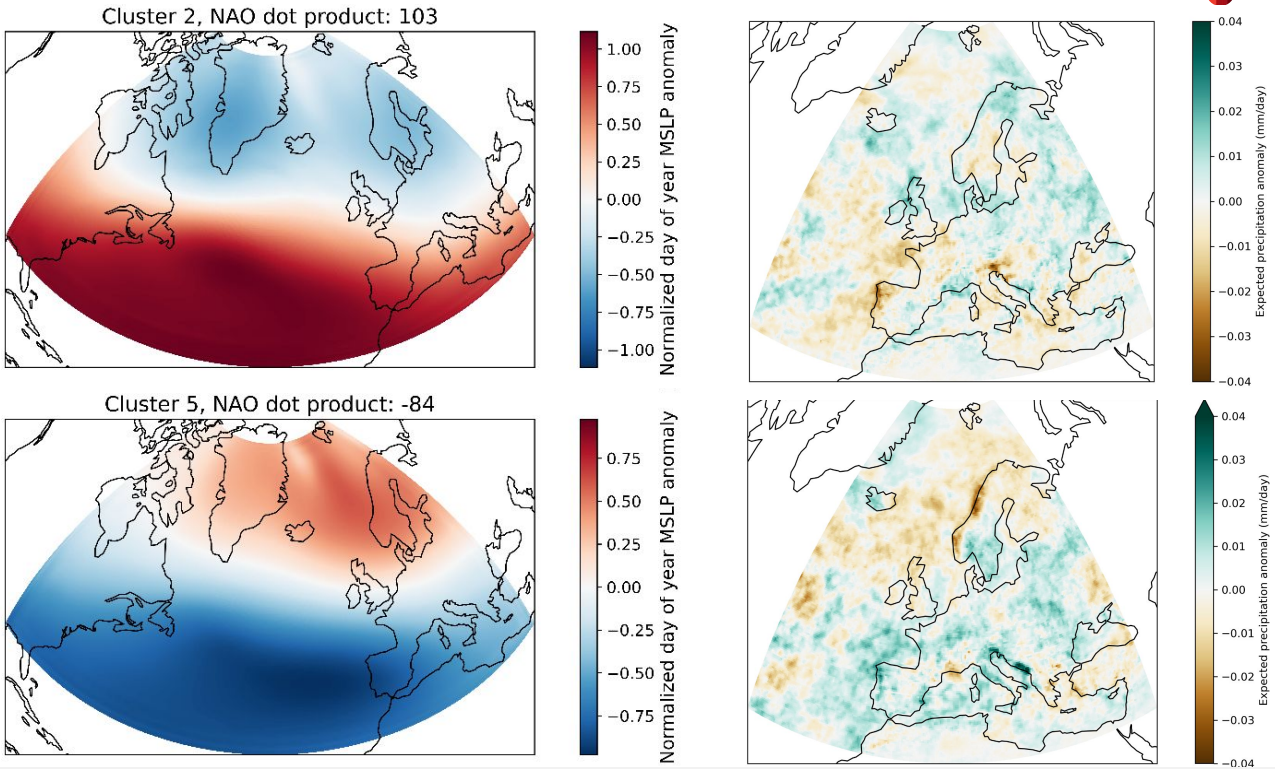
- Noisy



Expected Precipitation

Precipitation

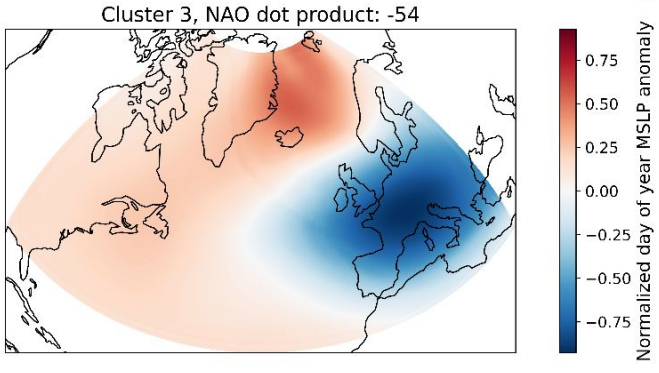
- Noisy
- NAO north, south

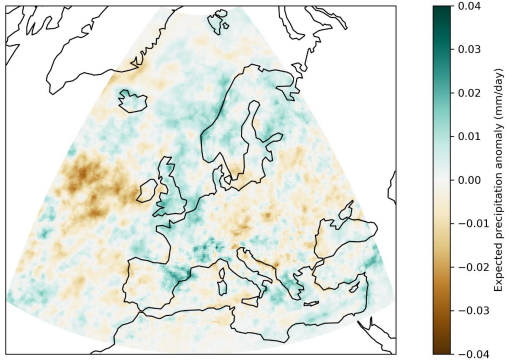


Expected Precipitation

Precipitation

- Noisy
- NAO north, south
- Western EU wet/dry

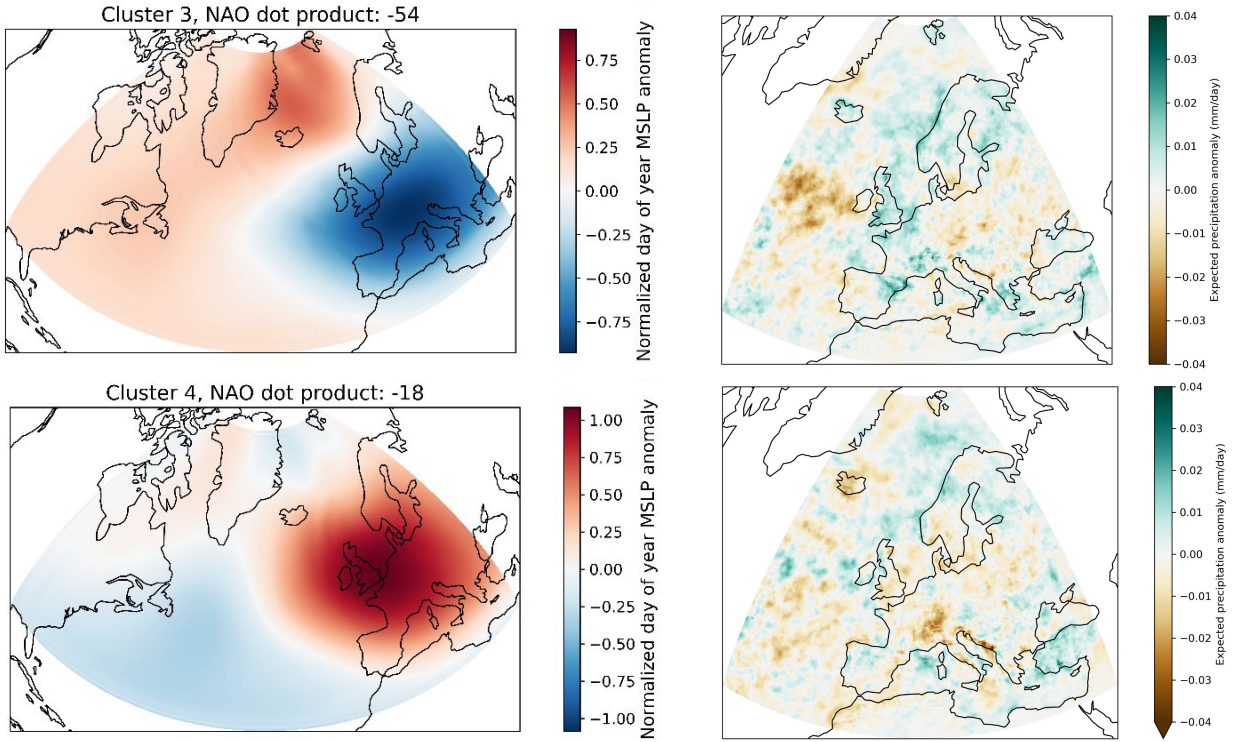




Expected Precipitation

Precipitation

- Noisy
- NAO north, south
- Western EU wet/dry



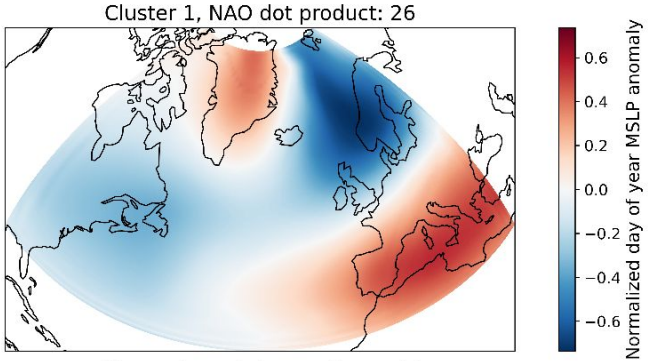
Expected Precipitation

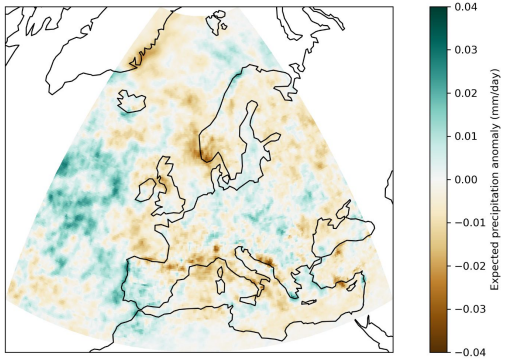
Sanity check

- NAO matches EOF
- non-NAO noise

Precipitation

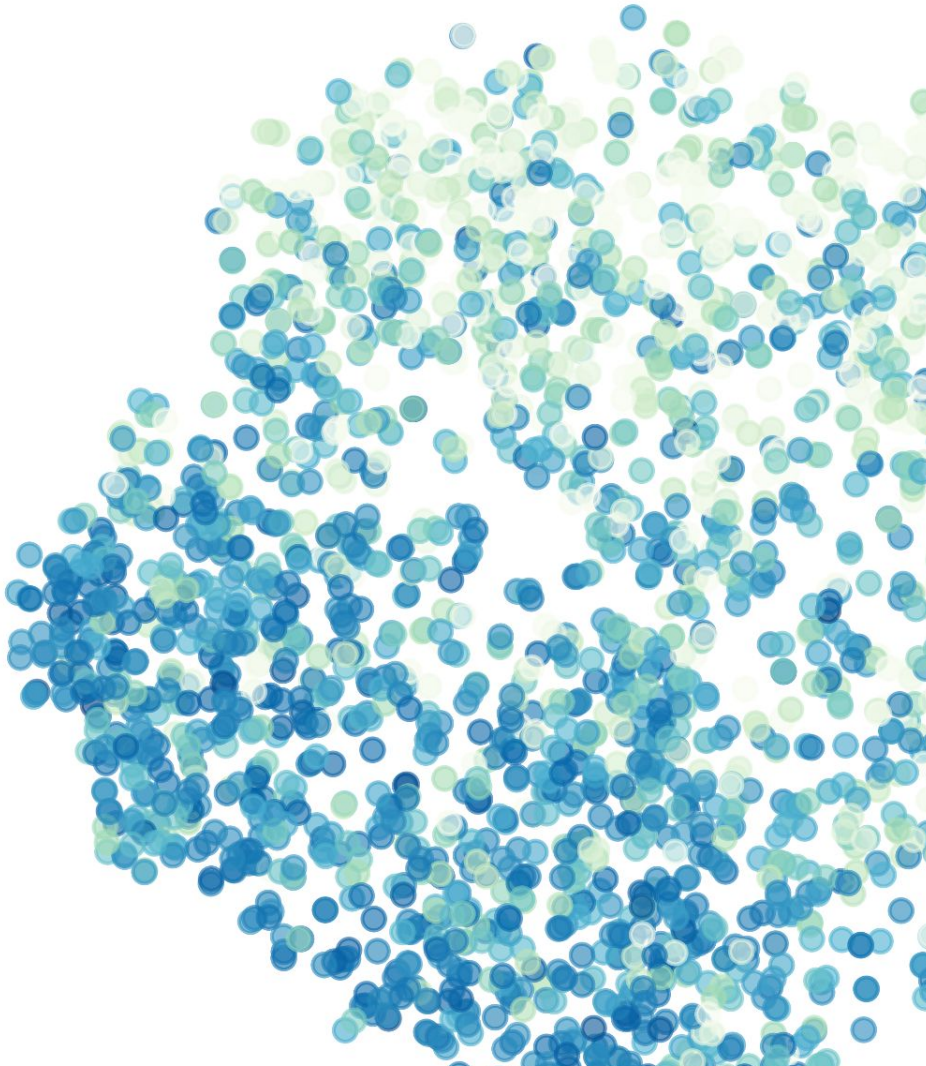
- Noisy
- NAO north, south
- Western EU wet/dry





Take home message

- Regularization gives many options
  - GMM in a VAE allows for clustering in the latent space
  - Including a target can steer informative clusters
- Still physically interpretable



Contact: jonathan.melcher@nbi.ku.dk