CAUSAL REPRESENTATIONS OF LARGE-SCALE DYNAMICS DRIVING REGIONAL EXTREME EVENTS

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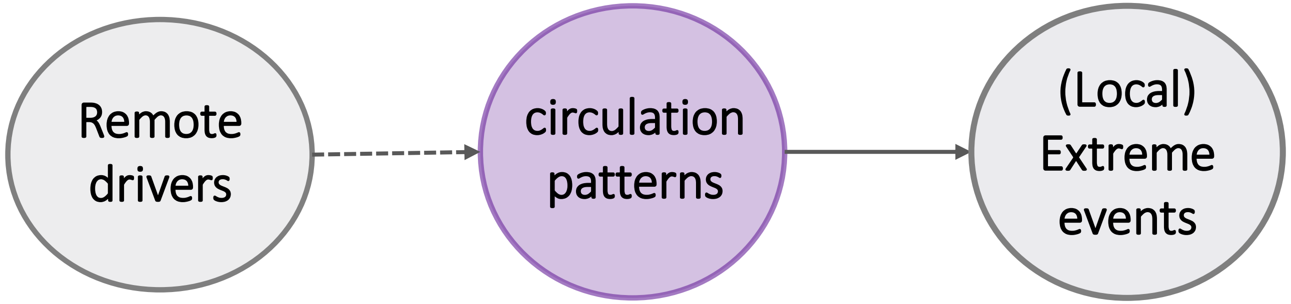
Motivation

Can we identify atmospheric circulation patterns that are

- informative of a target variable,
- predictable,
- physically robust?

Potential for machine learning!



We aim for *causal representations of large-scale dynamics* based on *interpretable machine learning* architectures

Task: Identifying Targeted Circulation Patterns

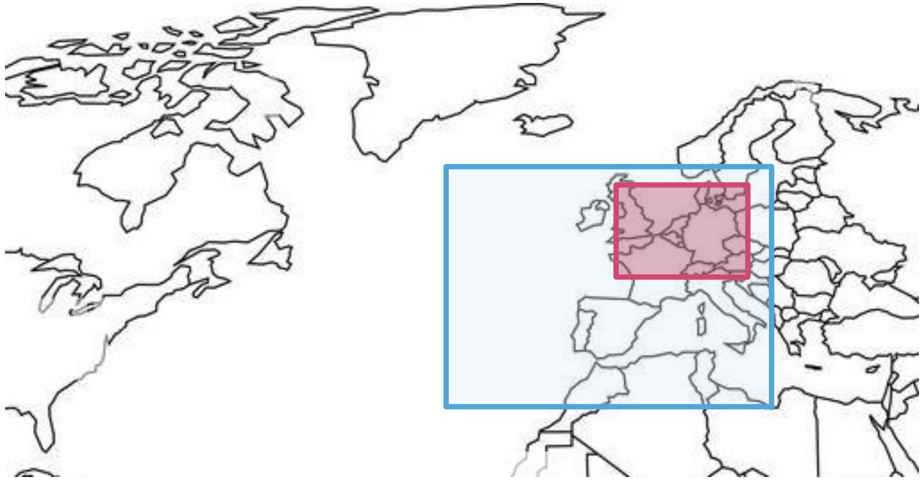
Example 1 (NDJFM)

Euro-Atlantic
(Z500)

Morocco
precip

Spuler et al. (2024); Spuler et al. (WCD, in revision)

Example 2 (JJA)



Euro-Atlantic
(sf500)

Western Europ.
temp

Carvalho Oliveira et al. (in preparation)

Combining Dimensionality reduction and clustering

Conventional approach (non-targeted):

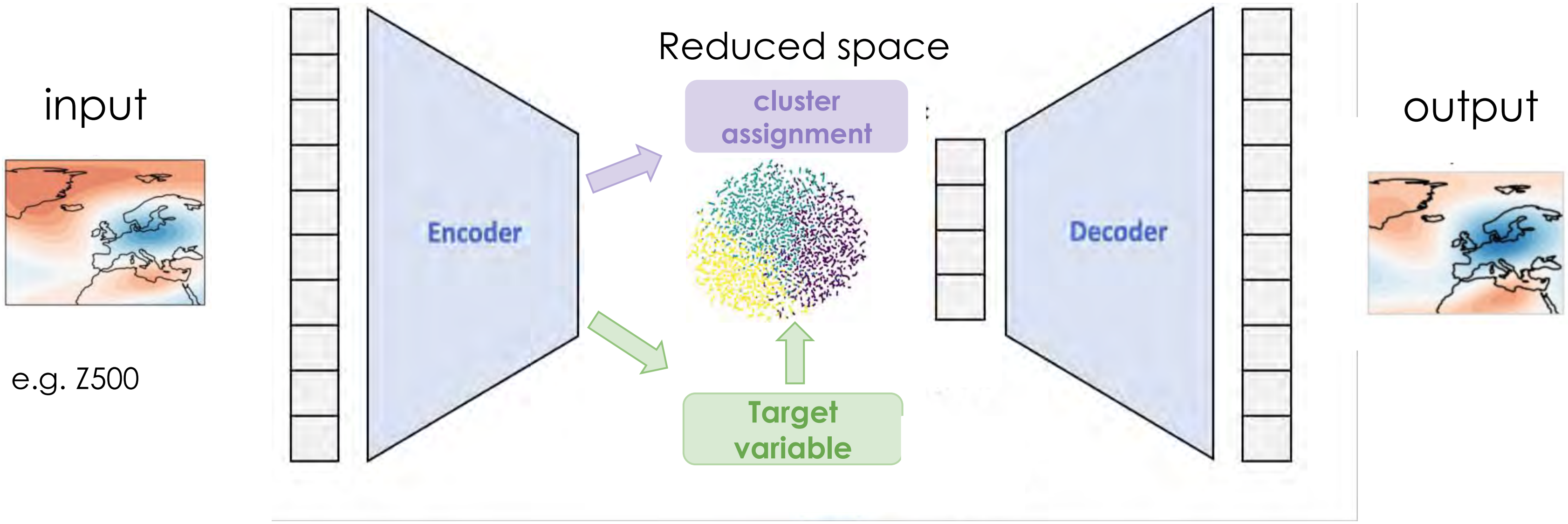
Principal component Analysis + k-means clustering (PCA/EOF + kmeans)

Our approach (targeted):

Variational autoencoder combined with a gaussian mixture model RMM-VAE / CMM-VAE

Scalar target variable

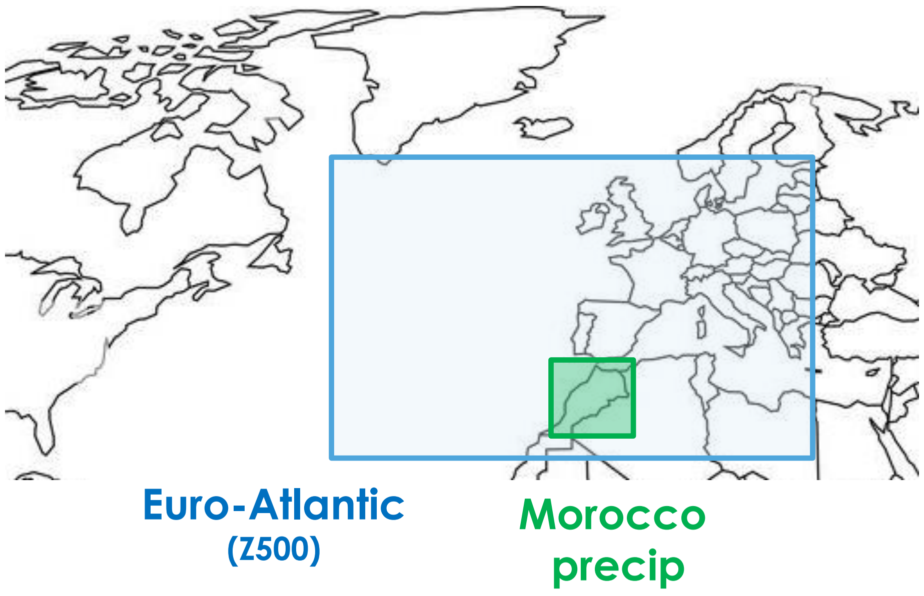
Categorical target variable



Spuler et al. (2024); Spuler et al. (WCD, in revision)

Identifying Targeted Circulation Patterns

Example 1 (NDJFM)



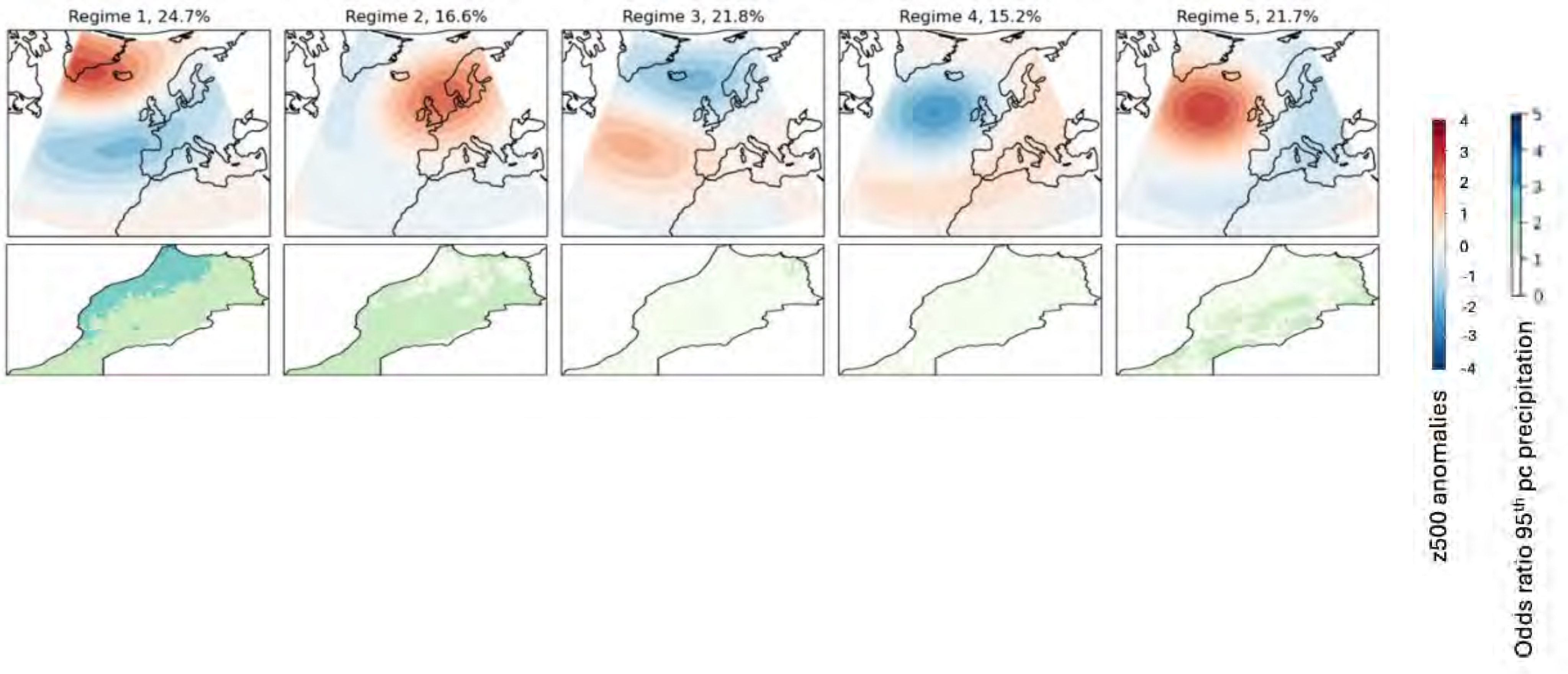
Data

- 5d-standardized z500 (Era5)
- (spatial clusters) of 3-day averaged precipitation over Morocco (CHIRPS v2.0)
- 1981-2022

Spuler et al. (2024); Spuler et al. (WCD, in revision)

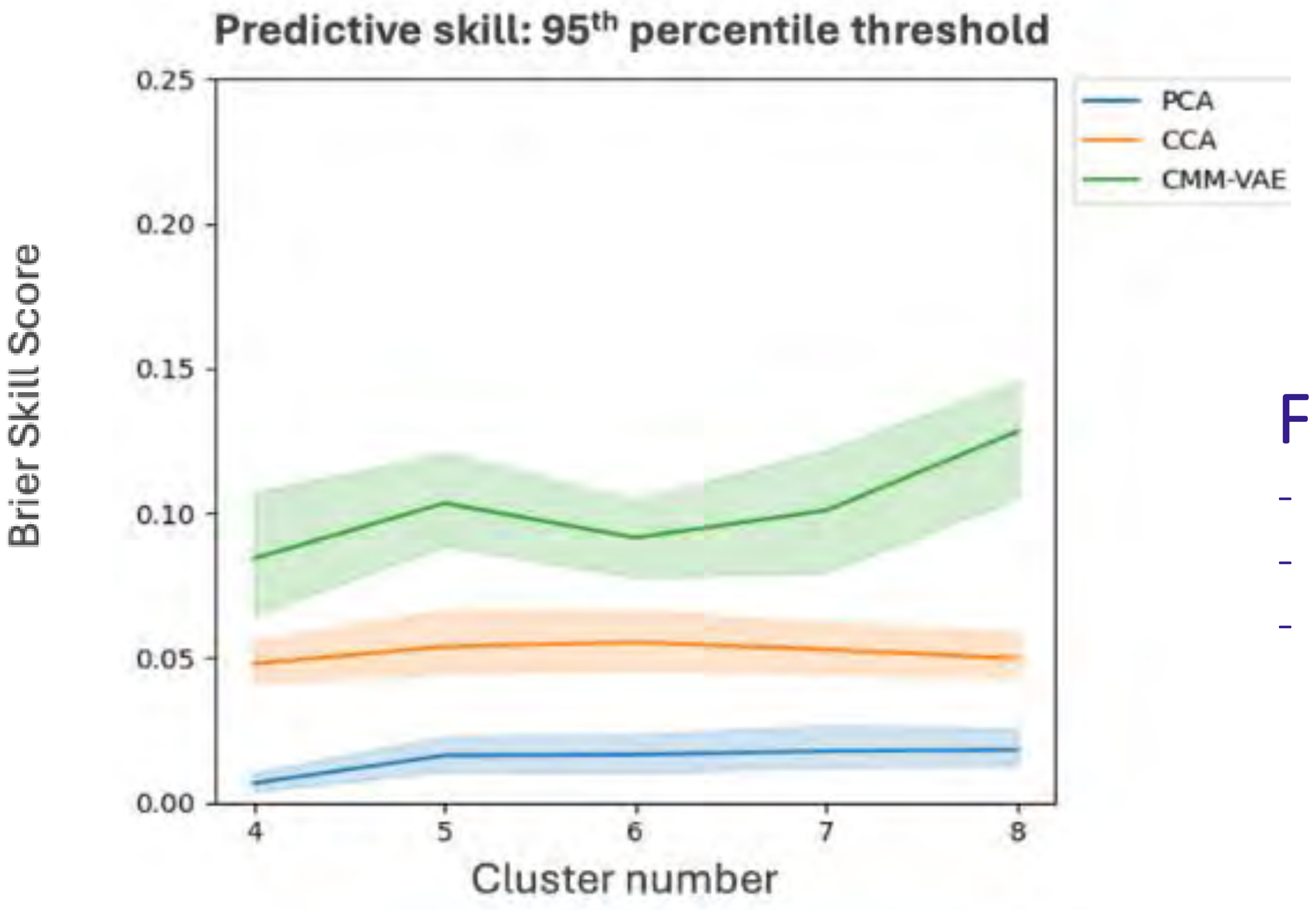
Circulation Patterns for Example 1: Morocco precip

PCA + k-means



Spuler et al. (WCD, in revision)

CMM-VAE PATTERNS ARE MORE INFORMATIVE OF EXTREMES



Furthermore:

- they are similarly robust
- are equally well predictable
- capture known teleconnection signals

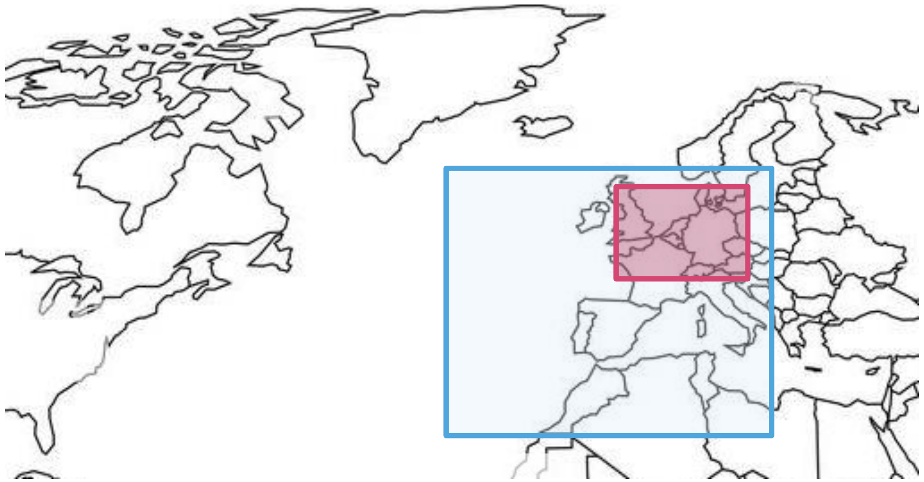
Spuler et al. (2024), Spuler et al. (WCD, in revision)

Identifying Targeted Circulation Patterns

Example 2 (JJA)

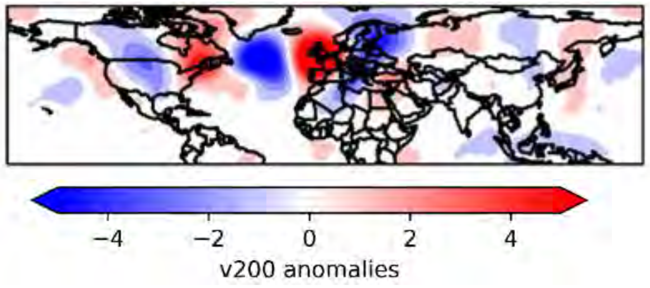
Data

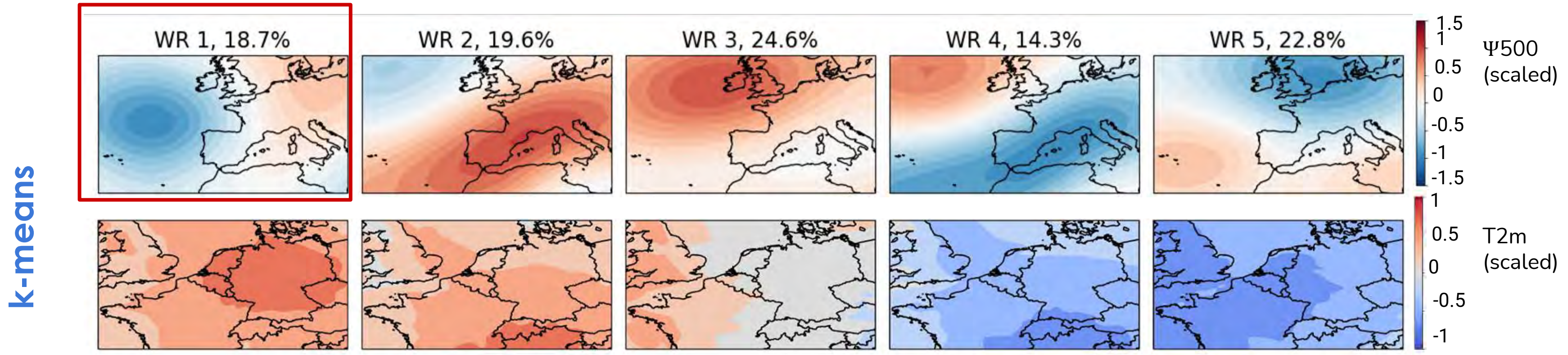
- 5d-standardized sf500 (Era5)
- 5-day standardized t2m average (Era5)
- 1950-2022

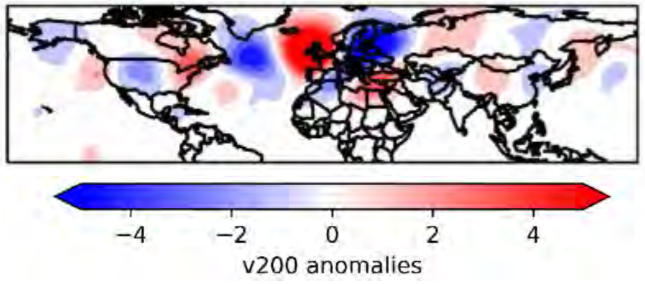


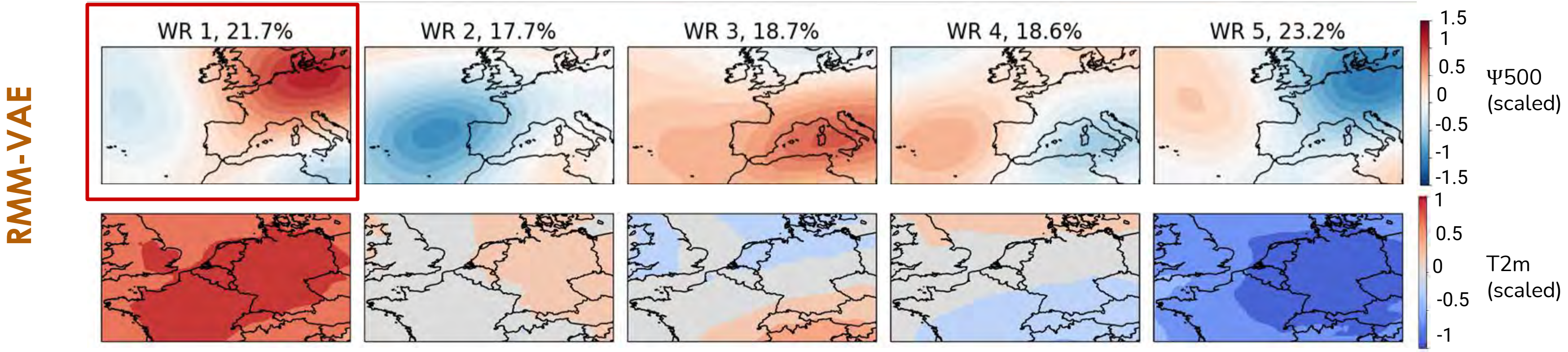
Carvalho Oliveira et al. (in preparation)

CIRCULATION PATTERNS FOR EXAMPLE 2: WEST EUROP TEMP





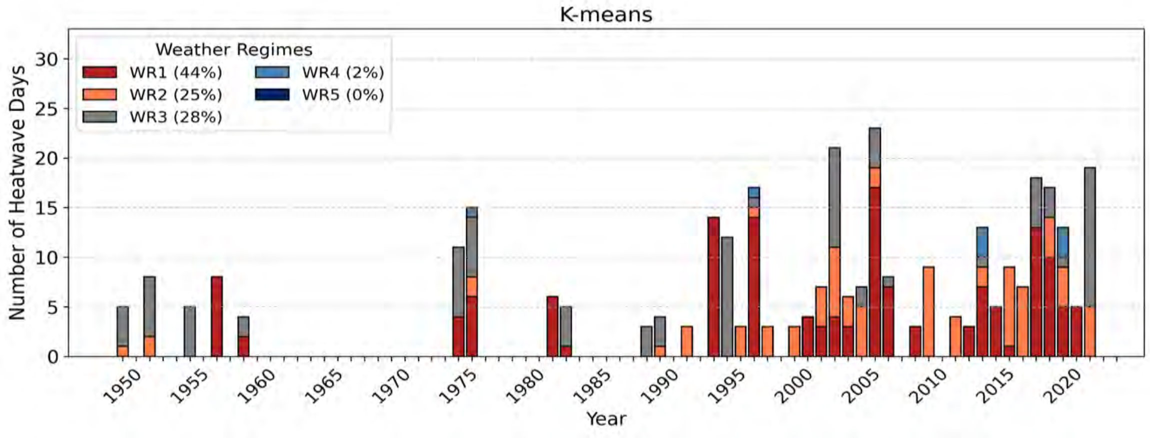




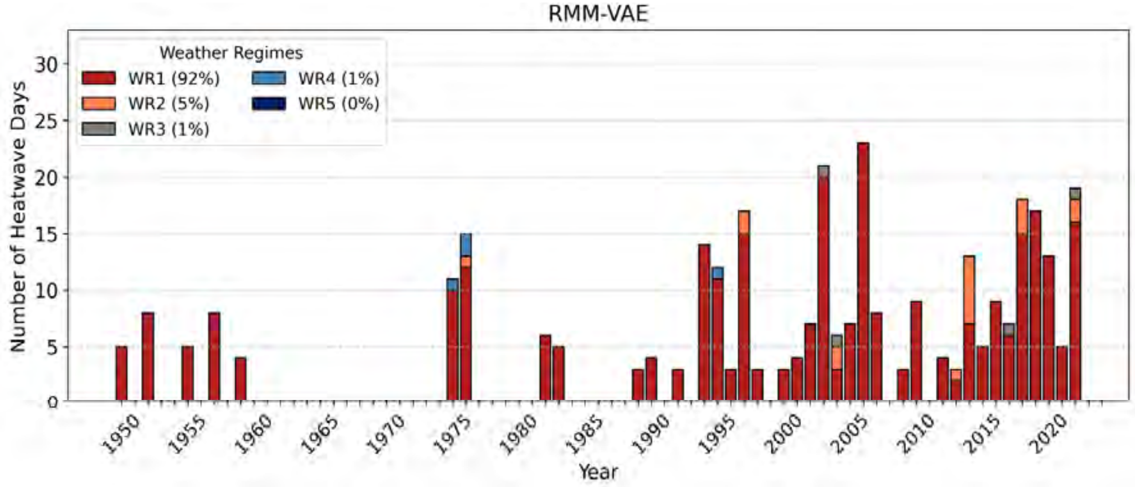
Carvalho Oliveira et al. (in preparation)

Explaining Observed extreme events

k-means

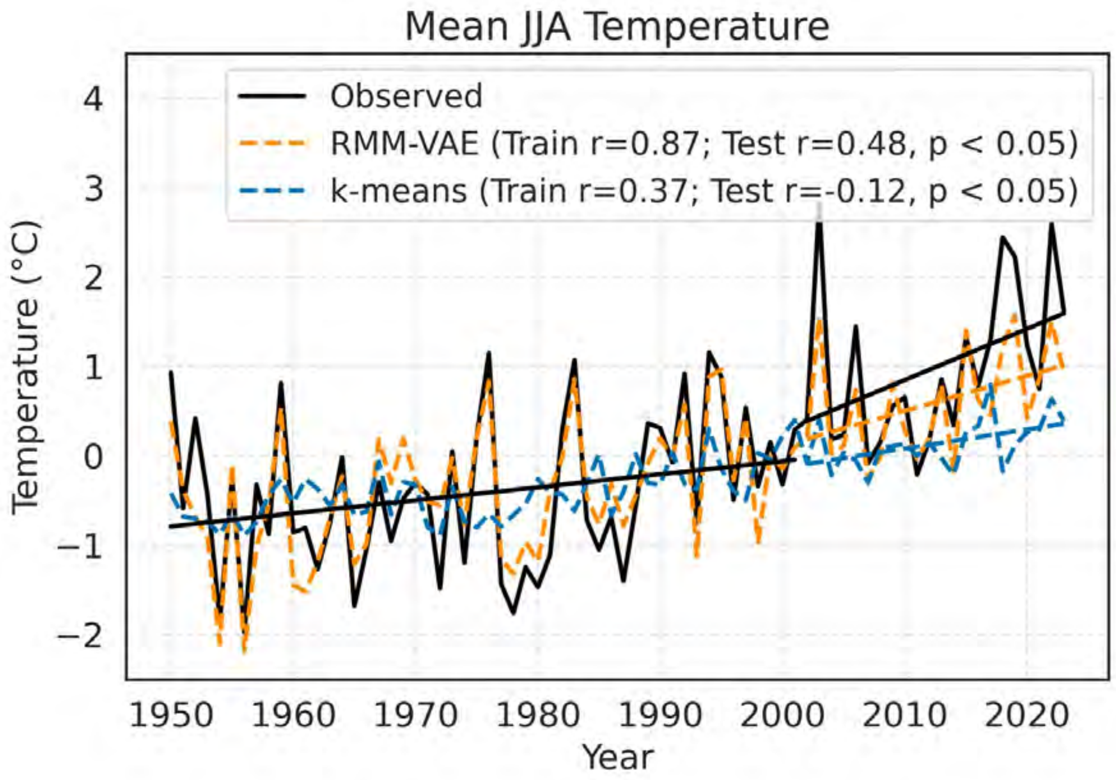


RMM-VAE



EXPLAINING OBSERVED TRENDS

$T_{JJA} = a\ WR1_{JJA} + b\ GMT_{JJA} + \varepsilon$

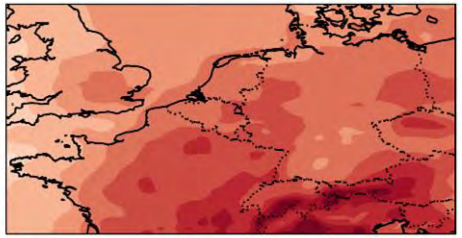


0.57°/dec

0.39°/dec

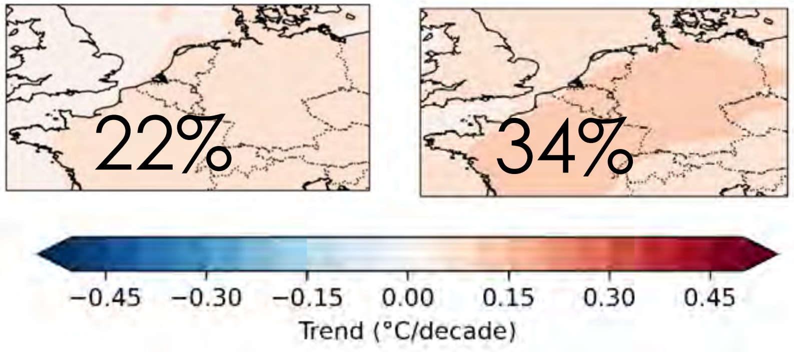
0.21°/dec

Total trend (°C/dec)



WR1-induced trend (°C/dec)

k-means RMM-VAE



Conclusions & Outlook

Thank you!

- Our aim is finding causal representations of large-scale dynamics
- We introduce a new method (RMM/CMM-VAE) for identifying atmospheric circulation patterns targeted to a local-scale impact variable which has key advantages over conventional approaches
- Similar line of thinking:

Bommer et al. *(2025, Machine Learning: Earth)*

arXiv:2504.07625v1 [cs.LG] 10 Apr 2025

Deep Learning Meets Teleconnections: Improving S2S Predictions for European Winter Weather

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Mindlin et al. *(2025, PNAS)*

RESEARCH ARTICLE | APPLIED PHYSICAL SCIENCES

Explaining and predicting the Southern Hemisphere eddy-driven jet

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