

# Predicting High-Risk Atmospheric Patterns Linked to Northern Hemispheric Crop Failures with Spatiotemporal Transformers

## Motivation & Problem Definition

Concurrent heat extremes across multiple Northern Hemisphere breadbasket regions pose a growing risk to global food security. Such events are often linked to amplified Rossby-wave circulation patterns that persist for several days. Identifying and predicting these large-scale circulation regimes at subsessional lead times could enable earlier warnings of compound agricultural risk.

## Research Questions

RQ1: What rare Rossby waves could trigger co-occurring extreme weather events over several breadbasket regions with the potential to lead to multiple breadbasket failures?

RQ2: How can such circulation regimes be predicted?

## Data

We use the KNMI-LENTIS large-ensemble climate dataset to analyze 100 years of summer (JJA) simulations resembling 2000-2009 conditions. Daily fields are coarsened to  $2.1^\circ$  resolution, resulting in 9,200 samples. The large ensemble enables a diverse sampling of rare circulation regimes that are underrepresented in observations.

### Variables Used:

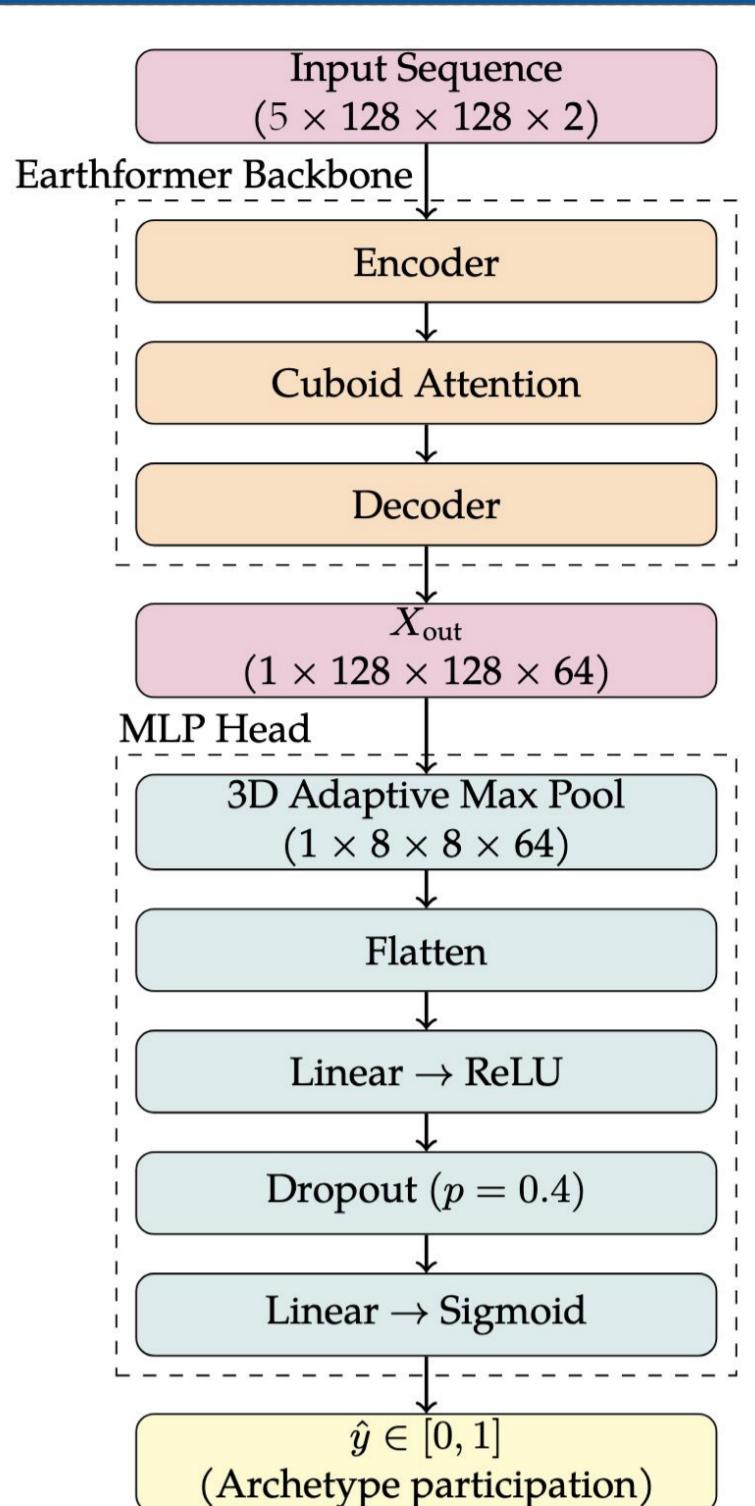
**Streamfunction (250 hPa):** Used to identify large-scale circulation archetypes and as the primary predictor input.

**Surface air temperature (TAS):** Used only for composite analysis to measure surface impacts of each archetype.

**Outgoing longwave radiation (OLR):** Lagged by 14 days and used as an additional predictor to capture tropical heating signals that precede mid-latitude circulation changes.

## Method

1	Archetypal Analysis	2	Composite Analysis
	<p>Extract extreme circulation patterns in the form of 'archetypes' from deseasonalized and reduced-dimension 250 hPa streamfunction using archetypal analysis.</p> <p>Every archetype represents a physically interpretable configuration.</p> <p>Each day is expressed as a convex combination of the computed archetypes, with non-negative membership weights that sum to one.</p>		<p>Compute temperature anomaly composites conditioned on the prevalence of each archetype to reveal associated surface temperature impacts.</p> <p>Rank archetypes by the magnitude of temperature anomalies over major EU + US breadbasket regions.</p> <p>Select archetypes most strongly linked to concurrent heat extremes for prediction.</p>
3	EarthformerPredictor	4	Prediction Task
	<p>Use Earthformer, a spatiotemporal transformer, to capture long-range dependencies and large-scale flows with cuboid attention.</p> <p>Using a simple MLP head (architecture shown on the right), convert the output of Earthformer into a scalar value representing the prevalence of a chosen archetype.</p>		<p>Predict the prevalence of a chosen archetype at a lead time of 3–10 days.</p> <p>Targets are smoothed using a <b>7-day rolling mean</b> to reduce noise and emphasize persistent regimes:</p> $\hat{y}_t = \frac{1}{7} \sum_{k=0}^6 y_{t-k}$



## Evaluation & Baselines

Model skill is evaluated on the test set using correlation, RMSE, and accuracy\* metrics, and compared against two baselines:

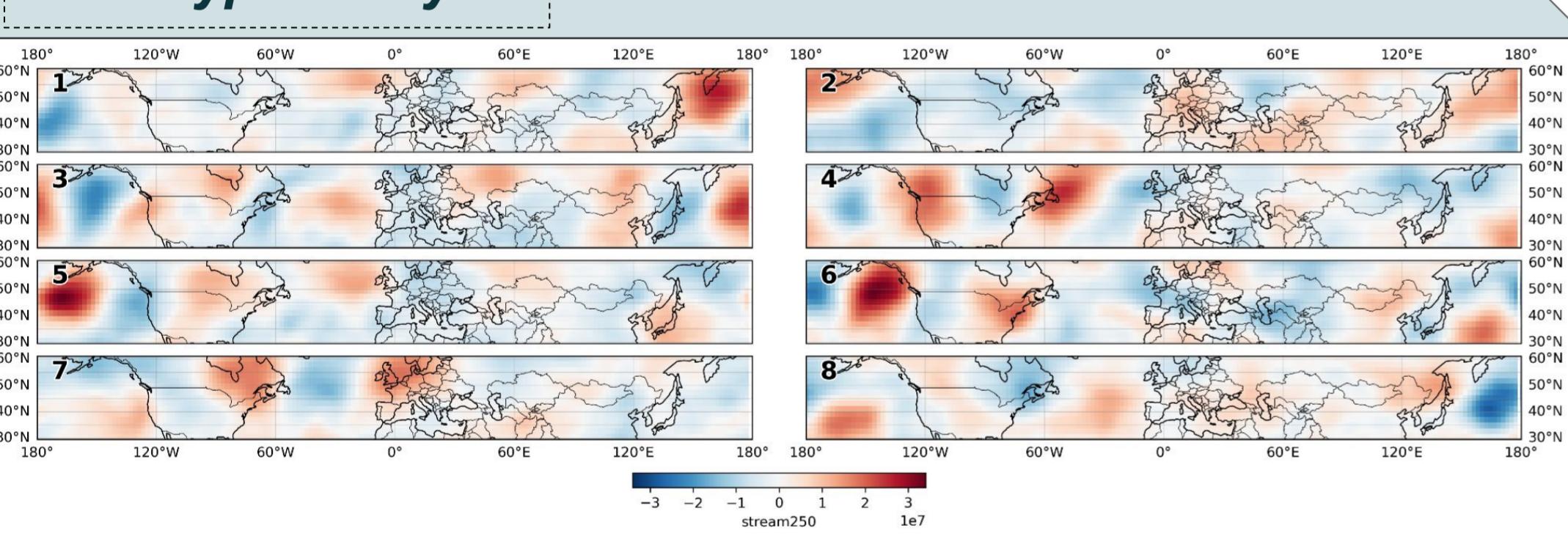
**Climatology** (predict-the-mean) and **persistence** (repeat the target of last input day).

\*Accuracy: % of predictions within 0.05 absolute range of true values

## Results

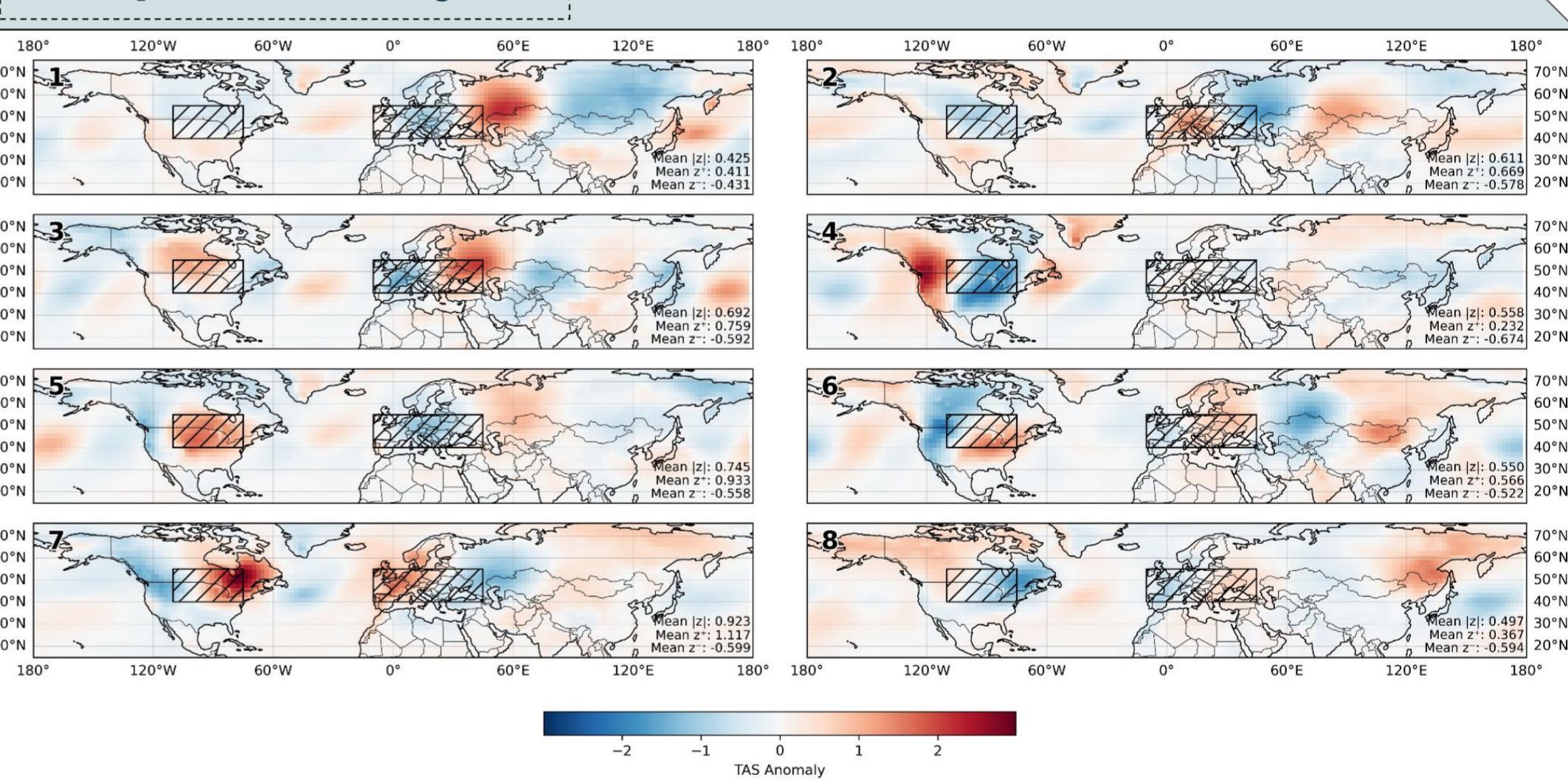
**KEY TAKEAWAY:** Archetypal analysis, together with composite analysis, identifies amplified Rossby-wave circulation regimes linked to concurrent breadbasket heat extremes, and the Earthformer-based model predicts regime prevalence beyond persistence baselines at lead times up to 10 days. Predictive performance remains consistent across archetypes.

### Archetype Analysis



Streamfunction archetypes capture dominant Rossby-wave structures that characterize the mid-latitude upper-tropospheric flow.

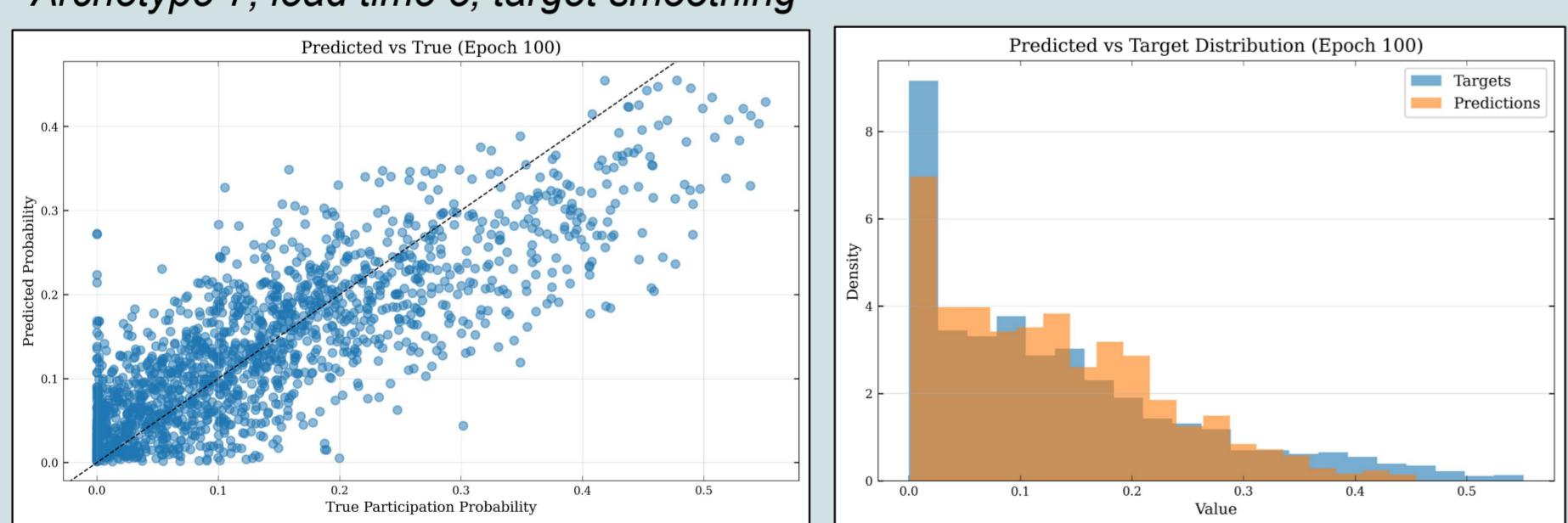
### Composite Analysis



When archetypes are ranked based on their z+ scores over regions of interest, archetypes 7 and 5 lead to strongest concurrent warm anomalies over American and European breadbaskets.

### Archetype Prediction Task

Archetype 7, lead time 5, target smoothing

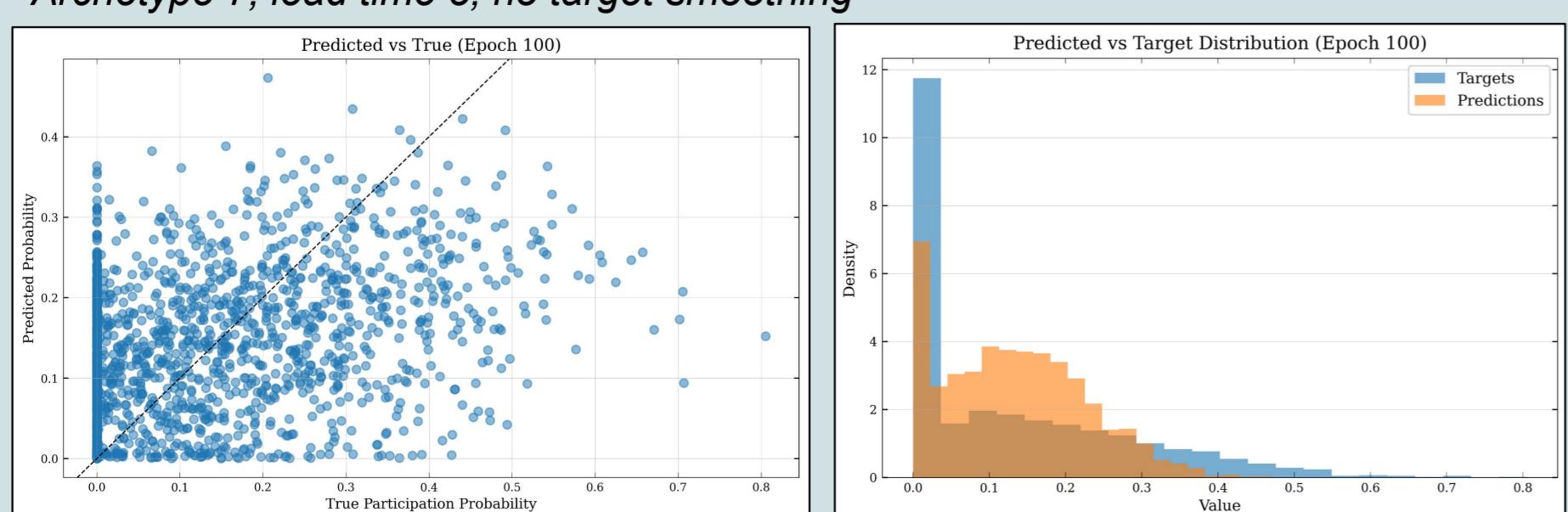


EarthformerPredictor successfully learns the target distribution.

Predicted archetype participation closely follows validation targets (left), with distributions that closely match the observed skewed target distribution (right), demonstrating strong predictive skill.

The model slightly overestimates lower values and underestimates higher values.

Archetype 7, lead time 5, no target smoothing



When target smoothing is not enabled, the model's predictive skill reduces drastically due to higher noise. Target smoothing enhances predictability by emphasizing persistent regimes.

### Lead Time Experiments

Lead Time Method	Pearson r	Spearman ρ	Kendall τ	RMSE	Accuracy
3 days	Climatology	—	—	—	0.13 0.27
	Persistence	0.79	0.78	0.59	0.09 0.54
	Model	0.90	0.89	0.71	0.05 0.70
5 days	Climatology	—	—	—	0.13 0.27
	Persistence	0.56	0.55	0.39	0.12 0.40
	Model	0.83	0.82	0.62	0.06 0.60
7 days	Climatology	—	—	—	0.13 0.27
	Persistence	0.35	0.34	0.23	0.15 0.33
	Model	0.63	0.63	0.45	0.09 0.45
10 days	Climatology	—	—	—	0.13 0.27
	Persistence	0.20	0.19	0.12	0.16 0.29
	Model	0.27	0.29	0.20	0.11 0.33

Predictive skill decreases linearly with lead time but remains consistently above persistence and climatology baselines up to 10 days, indicating meaningful subsessional predictability of circulation regime prevalence.

## Limitations + Future Work

### Methodology-related limitations

- Earthformer's cuboid decomposition may cause Hemispheric-scale structures to lose coherence

### Data-related limitations

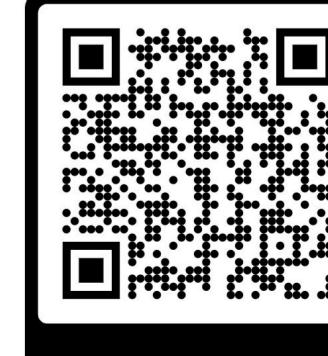
- Archetype prevalence targets are dominated by low values
- Target smoothing affects the interpretation of predictability

### Possible extensions

- Seasonal: Winter extremes
- Regional: Southern Hemisphere
- Run analysis on full 1600 years of LENTIS
- Apply to real-world data (e.g. ERA5)

## Conclusion

Results indicate that combining pattern-extraction methods with spatiotemporal deep learning provides a viable pathway for anticipating heat extremes driven by amplified Rossby-wave circulation patterns. Our framework offers both interpretive value and predictive potential for applications related to agricultural risk assessment, particularly in a climate system where circulation-related extremes are expected to intensify. The code and data used in this research are **openly available** on GitHub.



CODE | PAPER