QUANTIFYING ATMOSPHERIC AND LAND DRIVERS OF HOT TEMPERATURE EXTREMES USING EXPLAINABLE ARTIFICIAL INTELLIGENCE

EXPECT

AUTHORS

Arnau Garcia Mesa[1]*, Lluís Palma[1], Markus Donat[1,2], Stefano Materia[1,3], Raül Marcos Matamoros[4]

[1]Earth Sciences Department, Barcelona Supercomputing Center (BSC), Barcelona, Spain
[2]Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
[3]CMCC Foundation--Euro--Mediterranean Center on Climate Change, Bologna, Italy
[4]Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain

*arnau.garcia@bsc.es

INTRODUCTION

Hot extremes are intensifying, yet their physical drivers remain uncertain. Atmospheric circulation triggers most events, while soil-moisture deficits amplify local heat through land–atmosphere feedbacks. Rising CO_2 further shapes long-term warming.

We apply an explainable machine-learning model to quantify the roles of circulation, soil moisture, and CO_2 in summer hot extremes across six European and North-African sites.

METHODOLOGY

We combine gridded atmospheric and land-surface predictors with an explainable deep-learning classifier to apportion drivers of summer (JJA) hot extremes at six sites.

- Data: ERA5 / ERA5-Land fields for g500, g200, psl and swvl[1,2,3]; NOAA CO_2. Results are checked against E-OBS and drought indices (SPEI/SPI).
- 90th percentile threshold extreme definition
- Model: a hybrid architecture — a ConvNeXt CNN ingests the atmospheric maps, a MLP ingests local land/CO_2 features, and a final MLP fuses both streams to produce event probabilities. Ensemble training (20 members) increases robustness.
- Explainability: **SHAP** (GradientExplainer)

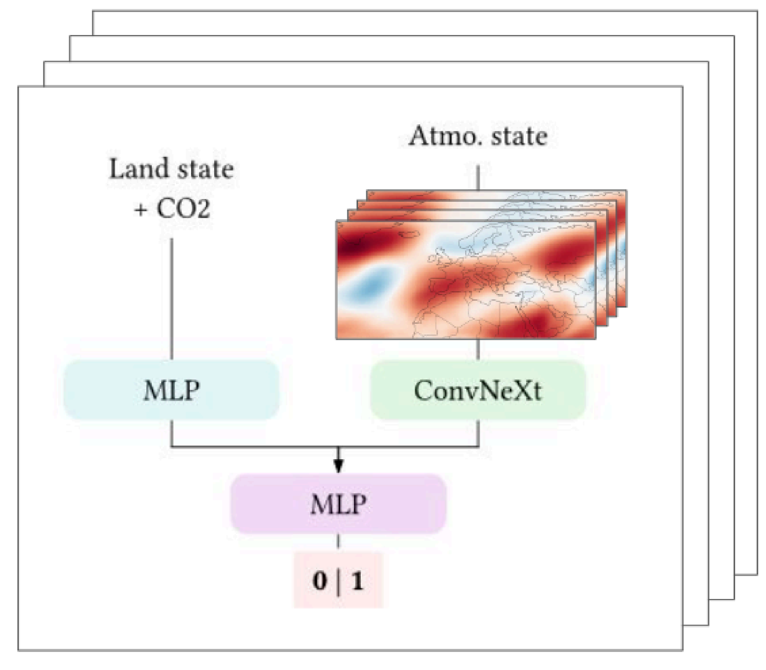

Figure 1: CombinedModel architecture: gridded atmospheric fields, ConvNeXt; local land (swvl1–3) & CO_2, MLP; outputs fused by final MLP classifier. SHAP is applied to the trained ensemble to produce spatial attributions and feature-wise contribution percentages.

RESULTS

- **Circulation** dominates and g500 is the leading predictor.
- **Soil-moisture** gradient: Influence strengthens northward — with dry soils amplifying heat (negative SM → positive SHAP).
- **CO_2** : Noticeable in regions or events showing long-term warming trends.
- Case studies: Córdoba (2021) and Hannover (2018) show localized circulation SHAP peaks. Hannover shows enhanced land effects.
- Robustness: Findings hold using the 80th-percentile definition and E-OBS + SPEI/SPI datasets.

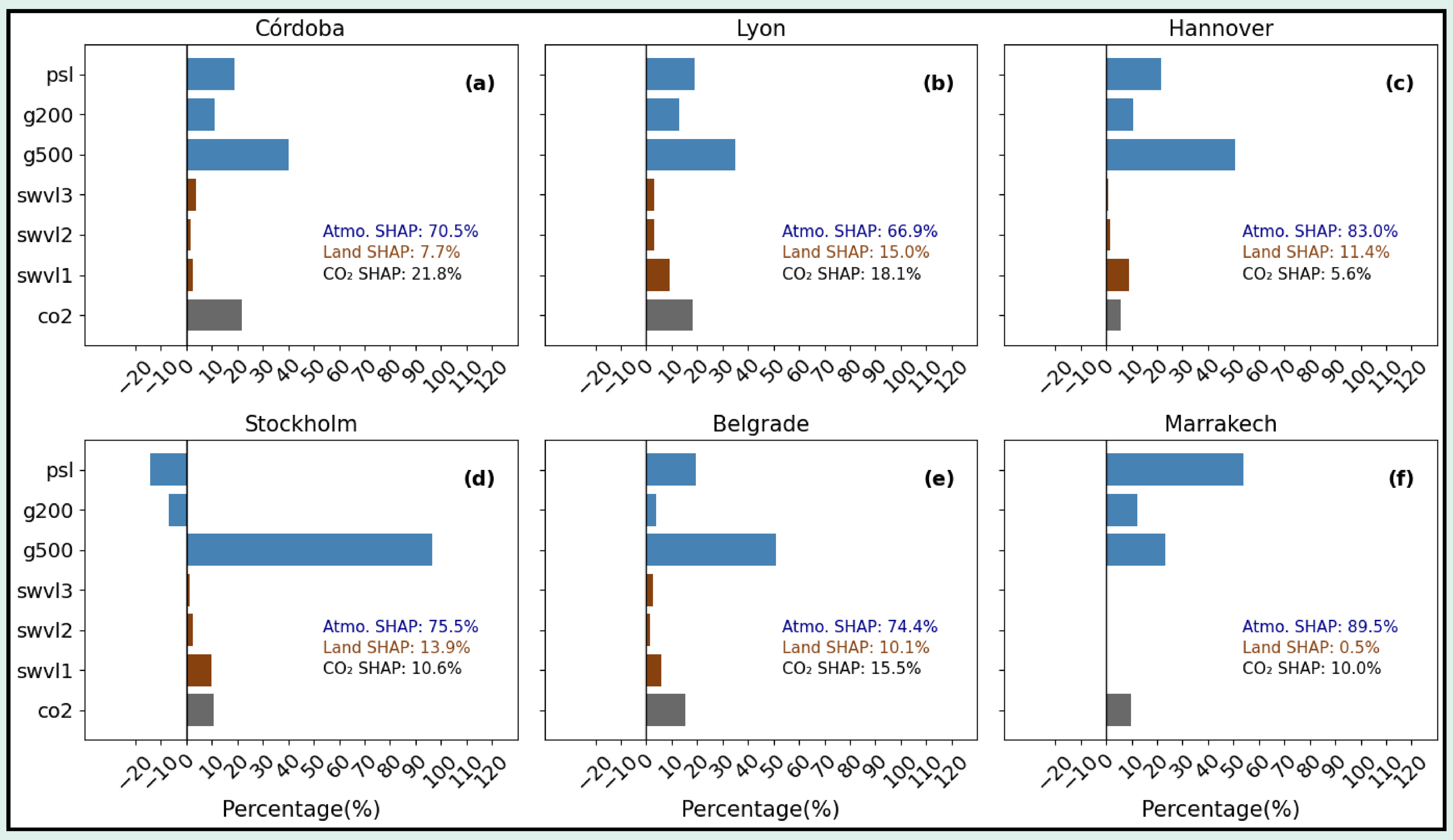

Figure 2. Mean SHAP value per site using ERA5 data and 90th percentile definition of extreme.

Lack of long time series of observational data for soil mositure: SPEI and SPI as proxies

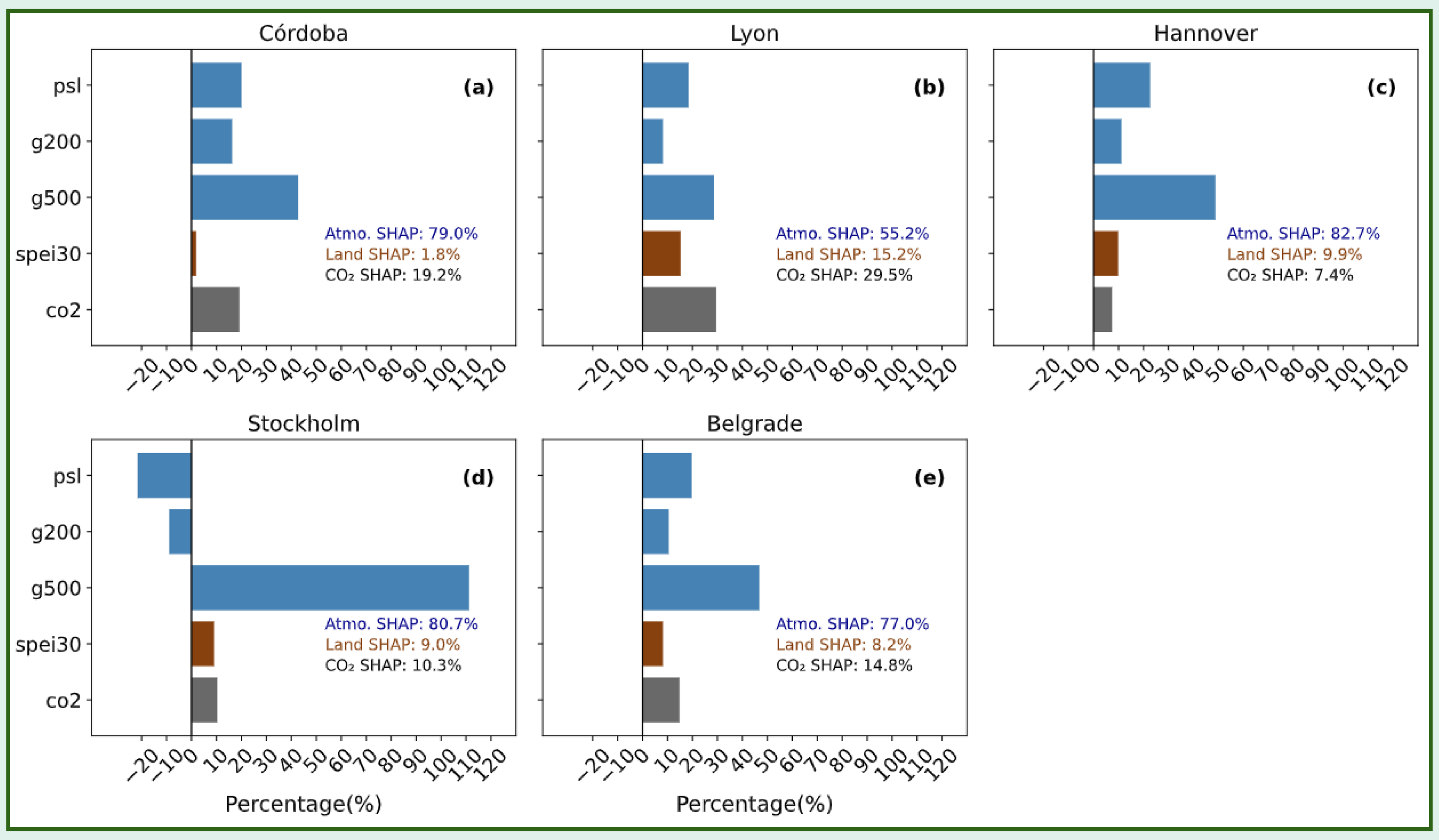

Figure 5. Mean SHAP value per site using ERA5 + E-OBS data and 90th percentile definition of extreme.

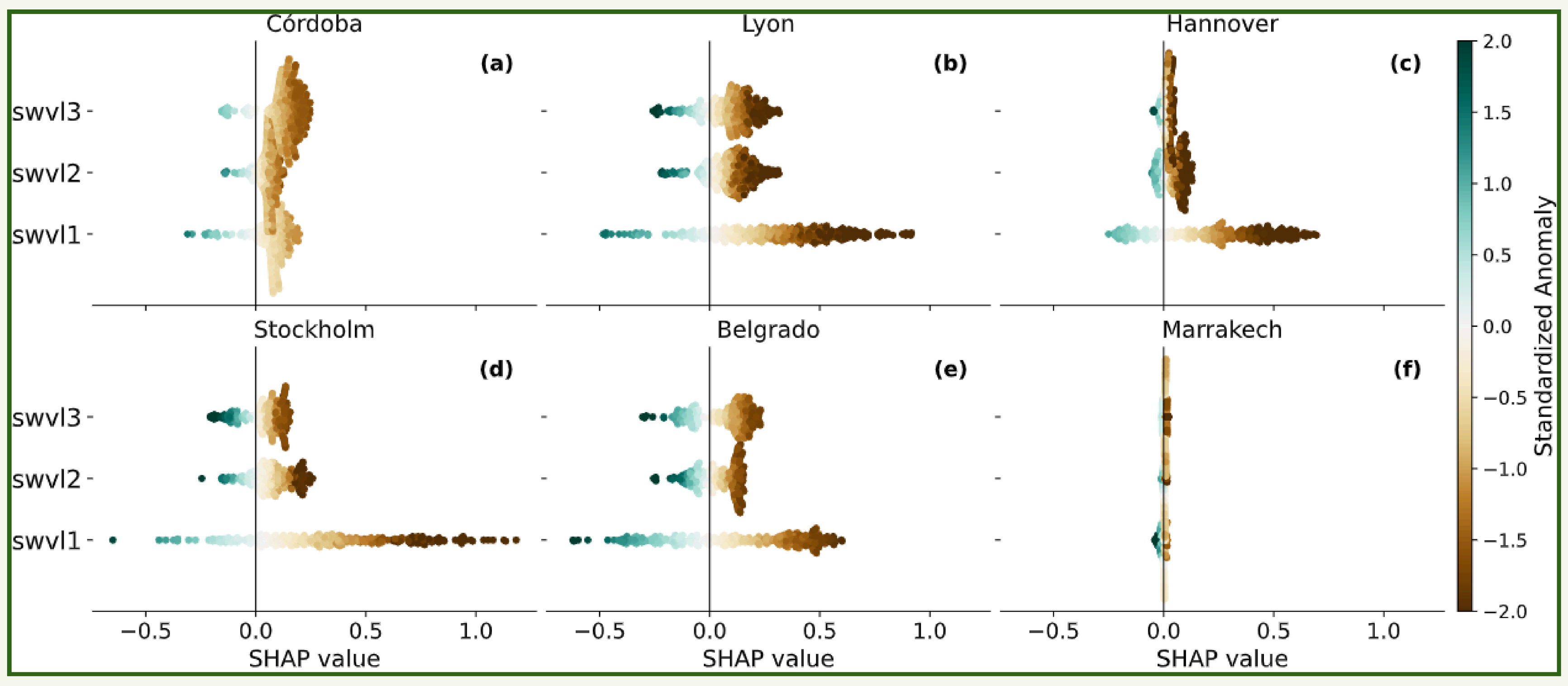

Figure 3. SHAP per sample vs standardized soil-moisture anomaly — shows negative relationship

drier → larger positive land SHAP

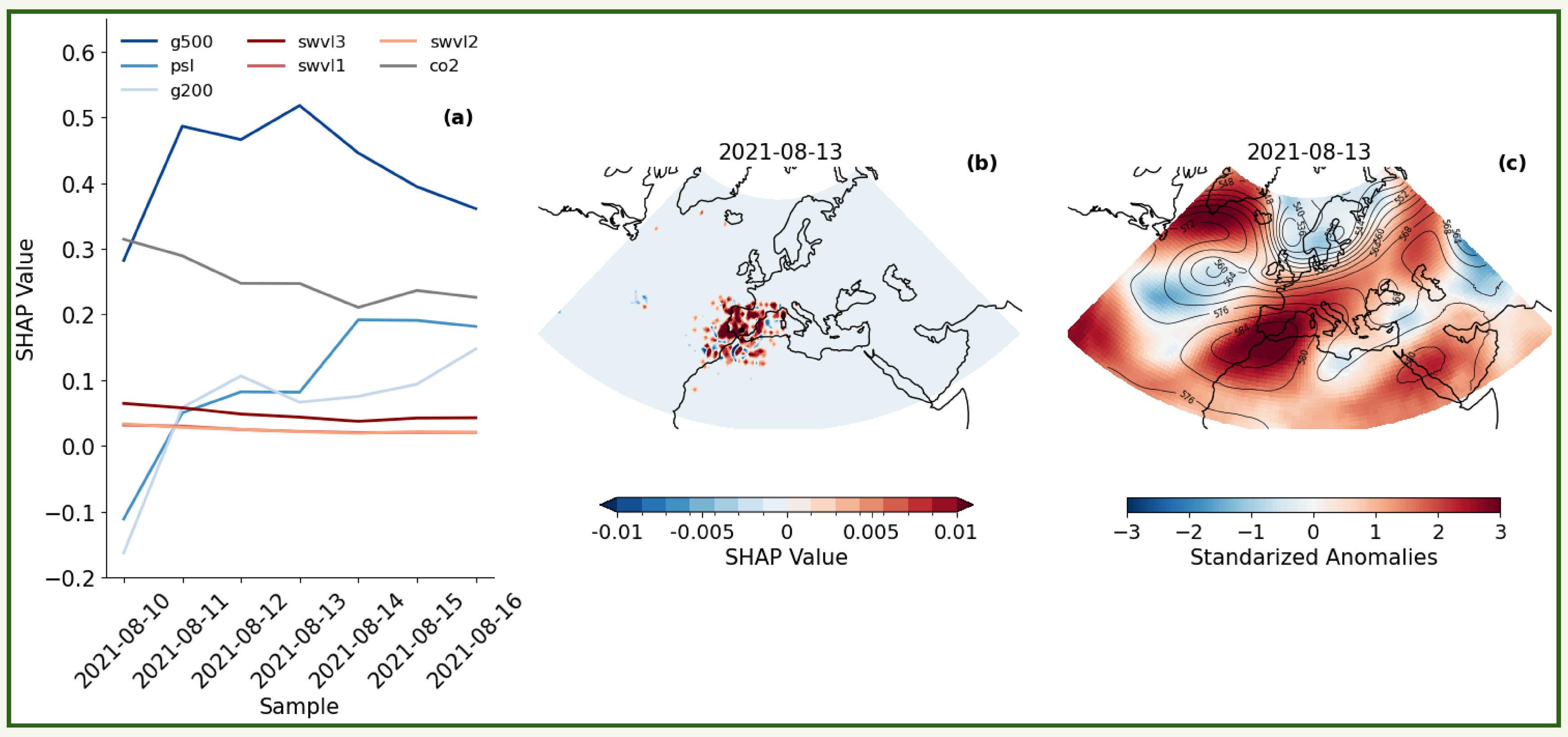

Figure 4. Córdoba SHAP time series + g500 spatial SHAP during peak day of importance for this field.

Applying ML methodology to CMIP6 models

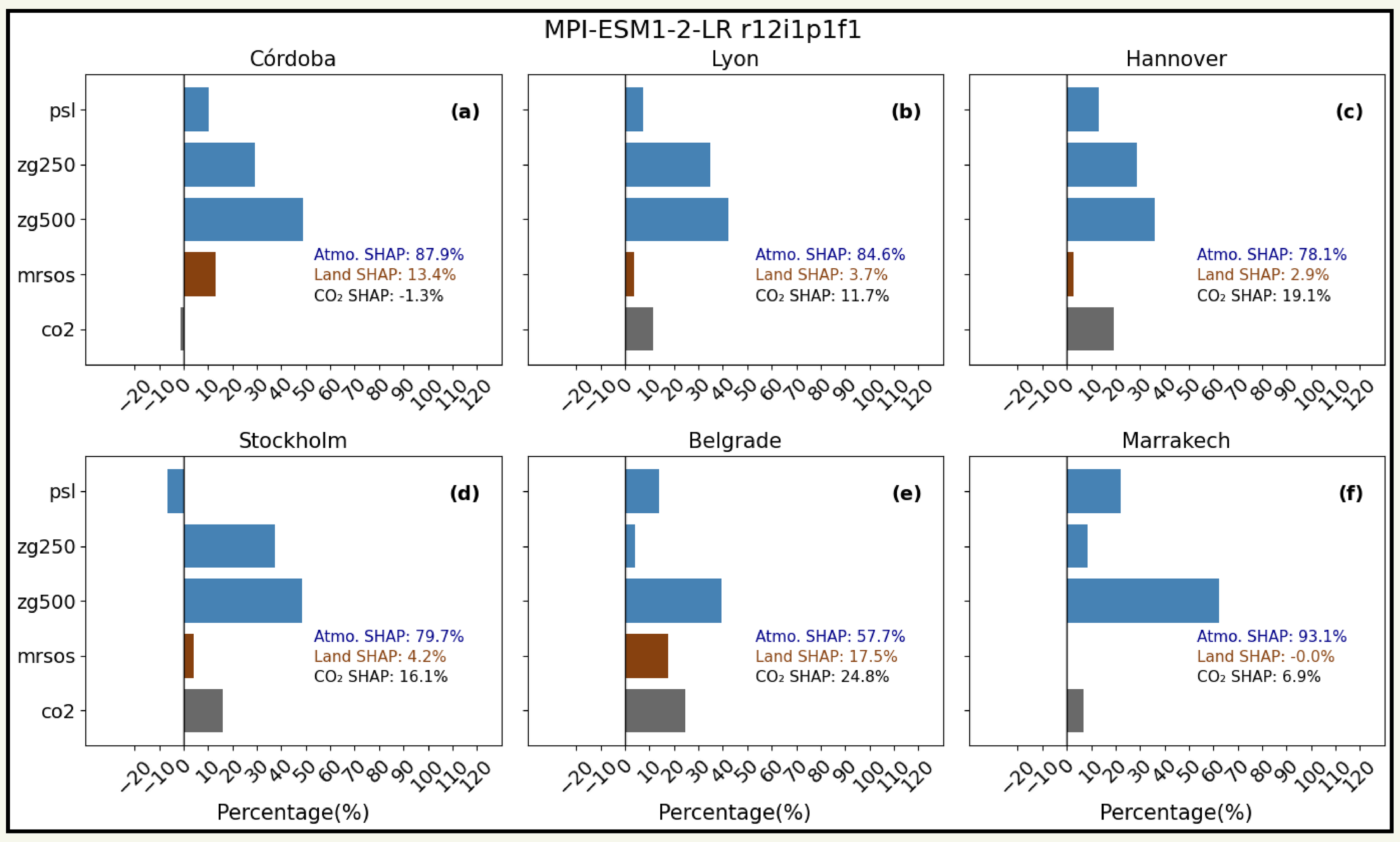

Figure 6. Mean SHAP value per site using MPI-ESM1-2-LR data and 90th percentile definition of extreme.

CONCLUSIONS

- Atmospheric circulation is the primary driver of summer hot extremes across all sites.
- Soil moisture acts as a regional amplifier, with influence strengthening northward.
- CO_2 variability contributes, aligning with observed warming trends.
- Results are robust across thresholds (90th/80th percentile) and datasets (ERA5, E-OBS).
- The explainable ML framework provides a way to separate and quantify physical drivers of heat extremes, and be used as a process-based model evaluation tool

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