



Atmospheric circulation and land-atmosphere interactions for weather and climate

Deliverable 5.1

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Document information

Grant agreement	101137656
Project title	EXPECT - Towards an Integrated Capability to Explain and Predict Regional Climate Changes
Project acronym	EXPECT
Project start date	1 April 2024
Related work package	WP5:
Related task(s)	Task 5.1
Lead organisation	ECMWF
Authors	Antje Weisheimer, Sofia Ermida, Isabel Trigo, Emanuel Dutra, Marlene Kretschmer, Fiona Spuler, Emily Black, Stefano Materia, Markus Donat, Arnau Garcia Mesa, Monalisa Sahoo, Jacob Maddison, Daniel Befort, Michael Mayer, Rikke Stoffels, Dim Coumou, Melissa Seabrook, Doug Smith, Paul Kushner, Eylon Vakrať, Hamed Ibrahim
Submission date	30 September 2026
Dissemination level	Public

History

Date	Submitted by	Reviewed by	Notes
31/08/2026	Antje Weisheimer	All co-authors	Initial version for internal review
21/09/2026	Antje Weisheimer	Christoper Kadow	Internal review
21/09/2026	Antje Weisheimer	Etor Lucio-Eceiza	Internal review
30/09/2026	Antje Weisheimer		Final version

Please cite this report as: Weisheimer, A., Ermida, S., Trigo, I., Dutra, E., Kretschmer, M., Spuler, F., Black, E., Materia, S., Donat, M., Garcia Mesa, A., Sahoo, M., Maddison, J.,

Befort, D., Mayer, M., Stoffels, R., Coumou, D., Seabrook, M., Smith, D., Kushner, P., Vakrat, E., Ibrahim H. (2026), Atmospheric circulation and land-atmosphere interactions for weather and climate, D5.1 of the EXPECT project

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About

This report summarises the research that has been carried out during the first 30 months of the EXPECT project to improve our understanding of how the atmosphere and land surface interact to influence weather and climate extremes. In particular, it examines the causes of extreme events such as heatwaves, droughts and heavy rainfall, with a strong focus on Europe. The report looks at how large-scale atmospheric circulation, rising temperatures, soil moisture and other land-surface conditions can work together to make extreme weather more intense or longer lasting. It brings together research from eight partner institutions and uses a wide range of observations, climate models and analytical methods to study these processes.

Overall, the report shows that climate extremes are caused by a combination of interacting factors rather than temperature increases alone. Changes in atmospheric circulation can influence where and how strongly warming and extreme rainfall occur, while dry soils and other land conditions can further increase the severity of heatwaves and droughts. The research also explores new approaches, including artificial intelligence, satellite observations and high-resolution climate modelling, to better understand and predict these events. The findings can help improve climate models and provide more reliable information for climate prediction, risk assessment and adaptation planning.

Executive Summary

Introduction

Global temperatures are increasing as a result of anthropogenic climate change, with Europe warming substantially faster than the global average. Northern Hemisphere midlatitudes have experienced pronounced summertime warming, particularly in Western Europe, where rising temperatures and increasingly severe heatwaves, droughts and heavy-rainfall events pose major risks to human health, agriculture, water resources, energy systems and ecosystems.

While greenhouse-gas forcing provides the underlying thermodynamic warming signal, regional climate extremes are strongly modulated by atmospheric circulation. Large-scale circulation can amplify or dampen regional warming, determine the spatial distribution of extremes and influence their persistence. Recent European warming has coincided with pronounced changes in upper-level circulation, including an increase in the waviness of a hemispheric Rossby wavenumber-5 pattern whose phase favours anomalously warm conditions over Europe. Determining the extent to which such circulation changes reflect externally forced climate change or internal climate variability remains an important scientific challenge.

Atmospheric circulation also plays a central role in precipitation extremes through its influence on moisture transport, convergence and the persistence of favourable dynamical conditions. However, the moisture pathways and circulation mechanisms associated with summertime extreme rainfall remain less well understood than the thermodynamic contribution to temperature extremes. Regional climate hazards therefore emerge from interactions among thermodynamic forcing, atmospheric circulation, remote teleconnections and local land-surface processes, with their relative importance varying substantially across regions and individual events.

Land-atmosphere interactions provide an additional mechanism through which summer extremes can be amplified. In particular, soil-moisture limitations affect the partitioning of available surface energy between latent and sensible heat fluxes and can intensify heatwaves and droughts. Accurately representing these processes in models remains challenging because direct observations of surface energy and water fluxes are sparse and subject to substantial uncertainty. Understanding how these local processes interact with large-scale circulation is therefore essential for explaining the intensity and persistence of European summer extremes and for improving their attribution and projection.

This Deliverable investigates these interacting mechanisms by combining Earth observations, reanalysis products, climate-model simulations, seasonal hindcasts, high-resolution regional modelling, and new statistical and machine-learning approaches. The studies examine how large-scale circulation patterns, remote teleconnections, soil

moisture, humidity, land–atmosphere coupling and model resolution shape past and present temperature, drought and precipitation extremes. Particular attention is given to distinguishing thermodynamic, dynamical and land-surface contributions and to assessing how well these processes are represented in climate models.

The eight partner contributions provide complementary perspectives spanning local land-surface controls, large-scale atmospheric circulation and teleconnections, artificial-intelligence approaches, climate-model evaluation, and event-scale high-resolution simulations. Together, they aim to improve understanding of the mechanisms governing European summer extremes and the extent to which these mechanisms can be represented and anticipated in current modelling systems.

The following partner institutions contributed to this Deliverable report: Portuguese Institute for Sea and Atmosphere (IPMA), Leipzig University (ULEIP), University of Reading (UoR), Barcelona Supercomputer Center (BSC), European Centre for Medium-Range Weather Forecasts (ECMWF), Free University Amsterdam (VUA), UK Met Office (MO) and University of Toronto (UTO). In the Executive Summary, the Method section is structured such that each partner group's approach is highlighted. For easier readability, the results following thereafter are, however, thematically grouped.

Methods

The IPMA team used Earth observation data to investigate the relationship between the daily amplitude of land surface temperature and soil moisture and to identify transitions between water-limited and energy-limited conditions. Land surface temperature amplitude was normalised by a potential amplitude to reduce seasonal and spatial variability. Piecewise regression was then used to estimate the critical soil-moisture threshold at which the strength of land–atmosphere coupling changes. The frequency with which European regions crossed this threshold was assessed, and the method was applied to the 2018 European summer heatwave. These diagnostics were designed to provide an independent, observation-based framework for evaluating land–atmosphere coupling in Earth system models and reanalyses.

The ULEIP team developed physically interpretable diagnostics combining causal inference, machine learning, information theory and climate-storyline approaches to investigate circulation patterns and teleconnections associated with climate extremes. Targeted weather regimes were used to identify circulation structures most relevant to predefined impacts, while causal representation learning and conditional mutual information were applied to disentangle interacting remote drivers and their pathways. Storyline methods were used to distinguish externally forced responses from internal variability. The analysis further linked large-scale circulation to land-surface responses through seasonal memory by examining impacts on vegetation, soil moisture and agricultural productivity. Together, these methods support attribution, prediction and model evaluation across different hazards and regions.

The UoR team combined a process-based assessment of agricultural drought with an observational diagnosis of heat stress during European heatwaves. For agricultural drought, reanalysis and CMIP6 data were used to distinguish the effects of antecedent soil-moisture conditions from those of the in-season water balance and to identify water-, energy- and vegetation-controlled evapotranspiration regimes. Drought occurrence, intensity and duration were assessed over locally relevant growing seasons and compared between historical and future periods. Heat stress was assessed using a simplified Wet Bulb Globe Temperature metric and an additive decomposition of temperature and humidity contributions, based on reanalysis, gridded observational datasets and station records. These complementary approaches were used to relate the physical mechanisms of drought and heat stress to changes in regional climate risk.

The BSC team developed three complementary explainable artificial intelligence approaches addressing seasonal prediction, event-scale attribution and strong land–atmosphere coupling. First, a data-driven model was developed to predict seasonal heatwave frequency and a composite heatwave-propensity index up to three months in advance, with predictions benchmarked against ECMWF's dynamical seasonal prediction system. Second, a hybrid deep-learning framework combined large-scale atmospheric circulation, local land-state variables and atmospheric CO₂ concentrations to quantify the drivers of daily hot extremes, with SHAP values used to interpret the relative contribution of individual predictors. Third, land–atmosphere coupling diagnostics and segmented regression were used to identify Mediterranean regions in which critical soil-moisture conditions were associated with particularly strong coupling (“supercoupling”) during hot and dry periods.

The ECMWF team investigated recent Northern Hemisphere midlatitude circulation trends using initialised seasonal hindcasts and novel counterfactual experiments in which the externally forced climate signal was modified. Seasonal prediction systems were used because they generally exhibit smaller circulation biases than CMIP-type climate simulations, while frequent re-initialisation from analysed atmospheric and oceanic states constrains key modes of model variability towards their observed evolution. Counterfactual experiments with reduced and amplified CO₂ forcing and ocean warming were performed to test the influence of external forcing on the proposed process chain linking the Indian Summer Monsoon, circumglobal teleconnections, upper-level circulation and European surface temperature. Monsoon and Rossby-wave-source diagnostics were combined with circulation and temperature trend analyses to assess these physical linkages.

The VUA team investigated temperature and precipitation extremes and their relationships with large-scale atmospheric dynamics. For temperature, a dynamical-adjustment framework was applied to reanalysis and CMIP6 data to separate circulation-driven and thermodynamic contributions to summertime warming and to identify circulation patterns associated with regional warming hotspots. For precipitation, intense summertime North Atlantic cyclones were analysed using

cyclone tracking, Lagrangian moisture trajectories and moisture-source diagnostics. The July 2021 Western European extreme-rainfall event was further investigated using reanalysis data, a boosted ensemble based on a dynamically similar event, and pseudo-global-warming simulations. Together, these approaches were used to quantify the respective roles of circulation, moisture transport and thermodynamic change across temperature and precipitation extremes.

The Met Office team assessed the Northern Hemisphere summer wave-5 circulation trend and its associated surface-temperature response using Large Ensemble Single-Forcing experiments and reanalysis data. A wave-5 index was used to quantify the observed circulation pattern. A wave-matching approach was then applied to select ensemble members whose circulation states most closely resembled observations at each time step. These dynamically matched members were used to evaluate the associated surface-temperature response and to test whether constraining the circulation towards observed states improved the representation of regional temperature trends. Historical and single-forcing experiments were additionally analysed to assess the contribution of external forcing and to investigate relationships among tropical Pacific variability, the wave-5 circulation pattern and extratropical temperature change.

The UTO team used complementary approaches to investigate persistent atmospheric circulation, extreme heat and precipitation across contrasting landform settings, bridging European and North American regional contexts. For heat extremes, persistence and archetype methods were used to identify circulation states characterised by both anomalous persistence and strong anticyclonic conditions. A new persistence metric was developed to quantify free-tropospheric circulation persistence as a predictor of impactful heatwaves and was applied to reanalysis and CMIP6 data. For precipitation extremes, kilometre-scale regional simulations were evaluated for three eastern Canadian events representing coastal, river-valley and lake-influenced urban environments. Simulations were evaluated against precipitation, rain-gauge and river-discharge observations. Additional sensitivity experiments modified urban land-surface and canopy representations to isolate their effects on the surface energy balance, moisture availability and near-surface wind convergence.

Results

Large-scale circulation and regional warming

Contributions: ULEIP, ECMWF, VUA, Met Office

The thermodynamic–dynamic decomposition shows that atmospheric circulation changes have substantially amplified recent summer warming across several Northern Hemisphere midlatitude hotspots. Approximately half of the observed summer warming in major hotspots, including eastern Europe, northwestern China, eastern

Siberia and western North America, is associated with dynamically induced warming. CMIP6 models generally underestimate this dynamical contribution over Eurasian hotspots, while partly compensating for the bias by overestimating the thermodynamic component.

Recent trends in Northern Hemisphere upper-level circulation also appear to be related to changes in the Indian Summer Monsoon through the circumglobal teleconnection. Reanalysis data show a significant weakening of the monsoon, while weak-monsoon summers are associated with hemispheric Rossby-wave propagation along the subtropical jet. Seasonal hindcasts reproduce the decline in monsoon strength but underestimate the downstream wave response. The increasing frequency of weak-monsoon summers may therefore contribute to more frequent amplified wave patterns with a phase and structure similar to the observed circulation trend.

Climate models also struggle to reproduce the observed Northern Hemisphere wave-5 trend and its associated surface-temperature response. The historical ensemble exhibits a pronounced signal-to-noise problem, with the simulated circulation signal being too weak relative to observations. Selecting ensemble members that closely match the observed wave-5 state improves the representation of both the circulation and associated extratropical temperature patterns. These dynamically matched members also exhibit a La Niña-like tropical Pacific trend, suggesting a possible connection between tropical Pacific biases and deficiencies in simulated extratropical circulation.

Targeted weather regimes provide complementary evidence of the importance of circulation for regional climate change. In Western Europe, a key southerly-flow regime combines persistent anticyclonic circulation, warm-air advection, dry soils and reduced precipitation. An increase in the frequency of this regime accounts for a substantial fraction of recent summer warming, highlighting how atmospheric circulation and land-surface conditions can jointly amplify regional heat extremes.

Circulation persistence and heat extremes

Contributions: ULEIP, UTO

Persistent anticyclonic circulation is closely associated with major heatwaves. Under high-emission CMIP6 scenarios, the persistence of circulation patterns associated with heat extremes is projected to increase by the end of the century in most analysed regions, although this response is not evident over Europe. Greater free-tropospheric circulation persistence is associated with longer-lasting surface heat extremes. Because persistent anticyclonic structures can form part of larger-scale wave patterns producing simultaneous circulation anomalies in geographically separated regions, changes in persistence in one region may also be related to prolonged heat conditions elsewhere.

The results further indicate that circulation anomalies can influence land-surface conditions beyond the duration of the initial atmospheric disturbance, providing a mechanism through which atmospheric variability can generate seasonal memory. Causal and information-theoretic diagnostics provide a transferable framework for separating interacting teleconnections and identifying periods during which large-scale drivers may enhance the predictability of regional extremes.

Land-atmosphere coupling, drought and heat stress

Contributions: IPMA, ULEIP, UoR

Relationships between satellite-observed soil moisture and land surface temperature amplitude were used to identify dominant hydrological regimes and transitions between them. The resulting framework demonstrates the importance of considering the preconditioning of the land surface when assessing climate extremes.

This seasonal-memory perspective is also evident in agricultural drought. Across Europe and North America, drought occurrence and severity are strongly influenced by soil-moisture conditions preceding the main summer growing season, indicating that antecedent land-surface conditions can be as important as meteorological forcing during the event itself. Western North America, western Europe, and large parts of midlatitude central and eastern Europe emerge as agricultural-drought hotspots. In these regions, recent historical increases in drought are consistent with both future projections and the physical mechanisms underlying the projected changes.

Heat stress increased across Northern, Western and Central Europe and the Mediterranean between 1979 and 2023. Temperature was the dominant contributor across Europe, but changes in humidity modified the response regionally. Humidity amplified heat stress in Northern Europe, had a smaller and more uncertain influence in Western and Central Europe, and partly offset temperature-driven increases in the Mediterranean. These results demonstrate that changes in heat stress cannot be inferred from temperature trends alone and highlight the importance of local observations, particularly in warm urban environments.

Extreme precipitation and dynamical sensitivity

Contributions: VUA, UTO

Multiple lines of evidence from the July 2021 Western European extreme-rainfall event demonstrate a strong sensitivity to atmospheric dynamics. Relatively small changes in the position and intensity of the cut-off low substantially reduced accumulated rainfall over the affected region. Pseudo-global-warming experiments further indicate that, for this event, future dynamical changes may outweigh the thermodynamic effect of atmospheric warming, potentially reducing rainfall if a dynamically similar event were to occur in a warmer climate. This result highlights the importance of accounting for

changes in both atmospheric moisture and circulation when assessing future precipitation extremes.

Kilometre-scale simulations provide clear added value over coarse-resolution reanalysis for representing the atmospheric structure, intensity and physical drivers of extreme precipitation events over eastern Canada. However, no single model configuration performs best across all of the analysed landform settings, demonstrating the sensitivity of extreme-precipitation simulations to local surface characteristics and model configuration.

Preliminary results from the ongoing urban analysis further indicate that urban canopy representation can influence extreme-precipitation potential through two competing land-atmosphere pathways. A thermodynamic pathway strengthens the convective trigger, whereas a moisture-supply pathway acts to weaken it. Changes in near-surface wind convergence dynamically connect these competing responses, illustrating the complex influence of urban land-surface representation on local precipitation extremes.

Seasonal prediction and explainable AI

Contributions: BSC

For seasonal heat extremes, CO₂ was identified as the most influential predictor across most regions and seasons, while soil moisture played a particularly important role in the Mediterranean and Scandinavia. Machine-learning approaches also showed promise for seasonal prediction of heat extremes, providing a transparent and explainable-AI framework that can potentially be adapted to other types of climate extremes. The analysis additionally identified areas in which further methodological improvements could enhance predictive performance.

Conclusions and Implications

This Deliverable provides a set of complementary observational, diagnostic and modelling approaches for understanding how external forcing, internal variability, atmospheric circulation and land-surface processes interact to shape temperature, drought and precipitation extremes. Across the contributions, a consistent picture emerges: thermodynamic warming provides the background increase in heat-related hazards, but regional extremes cannot be understood from thermodynamic change alone. Atmospheric circulation can amplify, dampen or redistribute regional warming, determine the persistence of extreme conditions and control moisture transport, while land-surface conditions, particularly soil moisture and its seasonal memory, can further modulate the local response. The intensity, duration and predictability of regional extremes therefore depend on interactions among processes operating across a wide range of spatial and temporal scales.

The findings provide evidence that recent circulation changes affecting Europe contain an externally forced component and may be linked to forced changes in the tropics through tropical–extratropical teleconnections. At the same time, substantial uncertainty remains regarding the magnitude of the forced circulation response and its representation in climate models. In particular, deficiencies in simulated tropical teleconnections, Rossby-wave responses and midlatitude circulation can affect the representation of regional temperature trends and extremes. Further work is therefore needed to determine how reliably climate models reproduce the circulation response to external forcing and how these uncertainties propagate into projections of regional surface climate.

These results have direct implications for climate attribution, prediction and model evaluation. Circulation-aware approaches, including targeted weather regimes, wave matching and counterfactual hindcasts, provide additional information beyond conventional comparisons of regional climate statistics. They can help distinguish thermodynamic and dynamical contributions to observed change, identify sources of model error and assess whether models reproduce the physical mechanisms underlying observed hazards. Process-based evaluation is particularly important where apparently realistic regional trends may result from compensation between biases in thermodynamic and dynamical responses.

The land-surface analyses developed within EXPECT provide a complementary framework for understanding how local processes modulate and amplify climate hazards. Relationships among soil moisture, evapotranspiration, surface radiation, land-surface temperature and vegetation state can be evaluated across satellite observations, reanalyses and climate-model simulations. This provides a bridge between observational and modelling activities and enables land–atmosphere coupling to be assessed in terms of physically interpretable regimes and thresholds rather than individual variables alone. The results further demonstrate the importance of antecedent land-surface conditions, showing that seasonal soil-moisture memory can influence the development and severity of subsequent heat and drought extremes.

Agricultural drought illustrates the practical importance of this perspective. Recent drying across western North America and large parts of western, central and eastern Europe is consistent with physical mechanisms underlying projected increases in future drought risk, indicating that climate-related changes in the seasonal land-surface water balance are already emerging in some regions. Combining locally relevant growing seasons, antecedent soil-moisture conditions and physically distinct controls on evapotranspiration provides a transferable framework for assessing these changes across observations, reanalyses and different generations of climate models. Such process-based assessments can identify robust drought signals even where models disagree on precipitation changes and can therefore provide more physically grounded information for climate-risk assessment and adaptation planning than metrics based on precipitation or annual-mean soil moisture alone.

The precipitation analyses similarly demonstrate the importance of atmospheric dynamics, model resolution and local context. Extreme rainfall emerges from interactions among large-scale circulation, moisture transport, landform and land-surface processes, and small changes in atmospheric dynamics can substantially alter event-scale rainfall. Kilometre-scale simulations provide important additional information on these processes, particularly in regions where complex terrain, coastlines, lakes or urban surfaces influence local atmospheric development. The results therefore support process-aware and regionally tailored modelling approaches for understanding future precipitation hazards and informing flood forecasting, early warning and climate adaptation.

Taken together, the work demonstrates the value of combining Earth observations, reanalyses, climate-model ensembles, seasonal prediction systems, high-resolution regional simulations and data-driven methods to investigate climate extremes across scales. No single method can fully separate the interacting effects of external forcing, internal variability, atmospheric dynamics and land-surface feedbacks. Their combined use, however, provides a more robust basis for identifying the mechanisms responsible for observed change, diagnosing model deficiencies and assessing future regional risk. A key priority for future work is therefore to improve the representation and evaluation of circulation, teleconnections and land-atmosphere coupling in climate models, while translating this process-level understanding into more reliable information for prediction, attribution and adaptation.

IPMA: European summer extremes based on Earth Observations

The Portuguese Institute for Sea and Atmosphere (IPMA) team explored the relationship between land surface temperature daily amplitude (ΔT) and soil moisture (SM), to assess land surface processes and to identify hydrological regimes based on Earth Observations. The coupling between SM and land surface temperature (LST) is conceptually divided into three major regimes: dry, transitional and wet. These are usually divided into two parts: energy limited and a soil moisture limited part (Akbar *et al.*, 2018; Budyko & Miller, 1974; Sehgal *et al.*, 2021; Sehgal & Mohanty, 2024;

Seneviratne *et al.*, 2010). These dependencies are illustrated in Figure 1. Under water limited conditions, i.e. when SM is below a critical point (θ_c ; Figure 1), SM is a predominant constraint on evapotranspiration and, therefore, on LST. This indicates a strong surface-atmosphere coupling where decreasing SM leads to a decrease of evaporation and increased sensible heat flux, culminating in a reduction of the evaporative cooling effect and an increase in LST amplitude. If SM is further reduced and reaches the wilting point (WP; Figure 1), there is not enough water for evapotranspiration and SM - LST cease to be correlated. In the energy limited part, SM content is usually high, and LST is independent of the soil water content. It is also possible to observe a dependence of LST amplitude on SM when SM surpasses the field capacity (FC; Figure 1). In this case, the LST amplitude may be further controlled by the large amount of water on the surface, where evaporation may surpass plant transpiration.

This study focuses on the critical point of transition between water limited and energy limited regimes, θ_c , as it is paramount to determine regime dependent evapotranspiration to improve its representation in earth system models (Paul *et al.*, 2025). Several other factors/variables influence this relationship however it has been shown that the linear dependencies described provide a first order approximation of the land-atmosphere coupling (Feldman *et al.*, 2019; Koster *et al.*, 2004; Paul *et al.*, 2025; Teuling *et al.*, 2006). Surface vegetation also influences this relationship as it behaves differently under vegetated and bare soil conditions, influencing the LST amplitude through thermal inertia, shading effects and evapotranspiration rates (Lozano-Parra *et al.*, 2018).

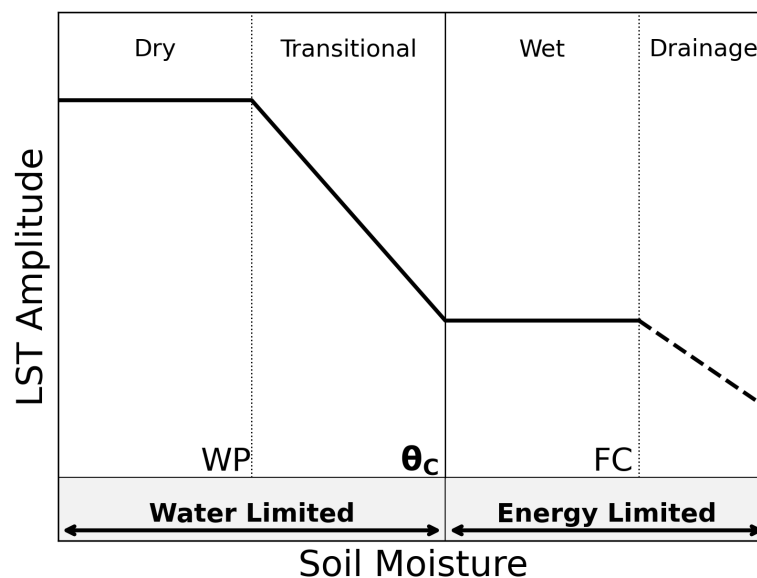


Figure 1: Conceptual relationship between soil moisture and land surface temperature. WP=wilting point; FC=Field Capacity.

Model based methodologies are widely used to understand the energy partition and dependencies between other variables such as vegetation indices, wind speed and insolation (Black *et al.*, 2026; Dirmeyer *et al.*, 2000; Koster *et al.*, 2009; Schwingshackl *et al.*, 2017). Although useful, these methodologies are based on several a priori assumptions that can significantly impact the results. Earth observation-based methodologies, namely satellite remote sensing products, can provide more robust metrics even though data availability is lower due to limitations in sensor characteristics and atmospheric conditions. Nonetheless, the relationship between LST and SM should be apparent from earth observation data (Feldman *et al.*, 2019, 2022).

The present analysis aims to understand if the previously developed methodology (WP1) based on earth observation data is able to identify the LST/SM relationship and consequently, regions that spend time in both water limited and energy limited conditions and the associated SM breakpoint between these two regimes. The 2018 summer heatwave over Europe was used as an example of application of the developed method. Ultimately, this methodology provides an independent, data-driven framework to evaluate earth system models representation of land-atmosphere coupling, as well as to characterize warm extreme events in terms of land-atmosphere coupling.

Data and Methodology

The work was developed based on five Earth Observation data datasets: soil moisture, land surface temperature, downward short wave flux (SW), albedo (α) and the fraction of vegetation cover (FVC). All datasets covered the period from 2004 to 2025, over the European continent and northern Africa.

The SM data is provided by the Copernicus Climate Change Service (Dorigo *et al.*, 2018) and corresponds to the volumetric surface soil moisture, i.e. the content of liquid water in a surface soil layer of 2 to 5 cm depth based on the combined active and passive sensors. Data is available on a daily basis on a 0.25° by 0.25° spatial grid.

The LST, SW, α and FVC were provided by the Satellite Application Facility on Land Surface Analysis (LSA SAF), part of the Application Ground Segment of EUMETSAT. These datasets are derived from observations performed by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) onboard the MSG series of geostationary satellites and are available for the full MSG disk at a 0.05° by 0.05° spatial grid. LST and SW have a 15-minute temporal resolution while the α and FVC are available as daily products (Trigo *et al.*, 2011). View zenith angles above 55 degrees were not considered. The characteristics of the datasets are summarized in Table 1.

Variable	Temporal coverage	Spatial resolution	Temporal resolution	Reference
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Soil Moisture	2004-2025	0.25°x0.25°	Daily	(Dorigo et al., 2018)
Land Surface Temperature	2004-2025	0.05°x0.05°	15-minute	(EUMETSAT LSA SAF, 2026)
Short Wave Flux	2004-2025	0.05°x0.05°	15-minute	(EUMETSAT LSA SAF, 2020)
Albedo	2004-2025	0.05°x0.05°	Daily	(EUMETSAT LSA SAF, 2025)
Fraction of Vegetation Cover	2004-2025	0.05°x0.05°	Daily	(EUMETSAT LSA SAF, 2017)

Table 1: Summary of datasets characteristics including Soil Moisture (SM), Land Surface Temperature (LST), Shortwave Radiation (SW), Albedo (a) and Fraction of Vegetation Cover (FVC).

The methodology for defining the best diurnal LST amplitude proxy was developed in WP1 on “Bridging Earth Observations and Earth System Models for new climate knowledge and improved predictions” and explained in the Deliverable Report D1.1 on “Novel approaches bridging EO and ESM data”. Here, the surface energy balance equations were used to derive a theoretical maximum diurnal amplitude that corresponds to the maximum potential warming if all absorbed SW is used to heat the surface:

$$\Delta T_p = \frac{(1-\alpha)SW_{\downarrow\max}}{4\varepsilon\sigma LST_{\text{mean}}^3},$$

where ε is the surface emissivity, σ is the Stefan–Boltzmann constant and α is the surface albedo.

The potential (ΔT_p) and actual observed (ΔT_a) LST diurnal amplitudes were then combined:

$$f_{\Delta T} = \frac{\Delta T_a}{\Delta T_p}$$

The ratio of actual to potential LST amplitude ($f_{\Delta T}$) quantifies how active land processes are in dissipating available solar radiation, particularly via latent heat flux

(evaporative cooling), but also through sub-diurnal changes in sensible (atmospheric mixing) and ground (dependent on surface and soil temperature gradient) heat fluxes. Furthermore, since $f_{\Delta T}$ carries the strong seasonal and spatial variability associated with solar radiation forcing, comparisons of $f_{\Delta T}$ estimated over different periods of the year or regions will highlight differences in land surface processes.

Taking into account the theoretical relationship between SM and $f_{\Delta T}$ as shown in Figure 1, the main purpose of this analysis is to find the critical soil moisture point for which regime transition occurs. For that purpose, a linear piecewise regression is fitted to each pixel:

$$f_{\Delta T} = \begin{cases} \beta + \alpha_1 \times SM, & SM \leq BP \\ \beta + (\alpha_1 - \alpha_2) \times BP + \alpha_2 \times SM, & SM > BP \end{cases}$$

where β corresponds to the intercept point, α_x corresponds to the slope and BP corresponds to the breakpoint. The fitting is only performed if each year in the time series had at least 60 valid observations. The BP search is limited to values within the time series' percentiles 5% and 95%. BPs with confidence interval (at 95%) that spans more than half of the 5-95% percentile range are also discarded. We further compute the $f_{\Delta T}$ at which the BP occurs as given by the model:

$$f_{\Delta Tc} = \beta + \alpha_a \times BP$$

As an example, the 2018 European heatwave was selected to illustrate the developed methodology. The summer of 2018 was especially hot and dry in northern central Europe with parts of the continent experiencing record breaking temperatures (Bastos *et al.*, 2020; Liu *et al.*, 2020; Rousi *et al.*, 2023; Salomón *et al.*, 2022). The heatwave days considered in this study were identified following (Salomón *et al.*, 2022).

Results

The spatial distribution of the identified SM critical points, θ_c , is shown in Figure 2, together with the respective 95% confidence interval, slopes and $f_{\Delta Tc}$. It was not possible to obtain the critical point for both areas in the northernmost and southernmost part of the interest region. This is likely because of a strong prevalence of energy- and water-limited conditions, respectively. The figure also shows the distribution of identified θ_c values. The values are mostly within 0.15 and 0.3 m³/m³, and 50% of the pixels have values between 0.20 and 0.25 m³/m³.

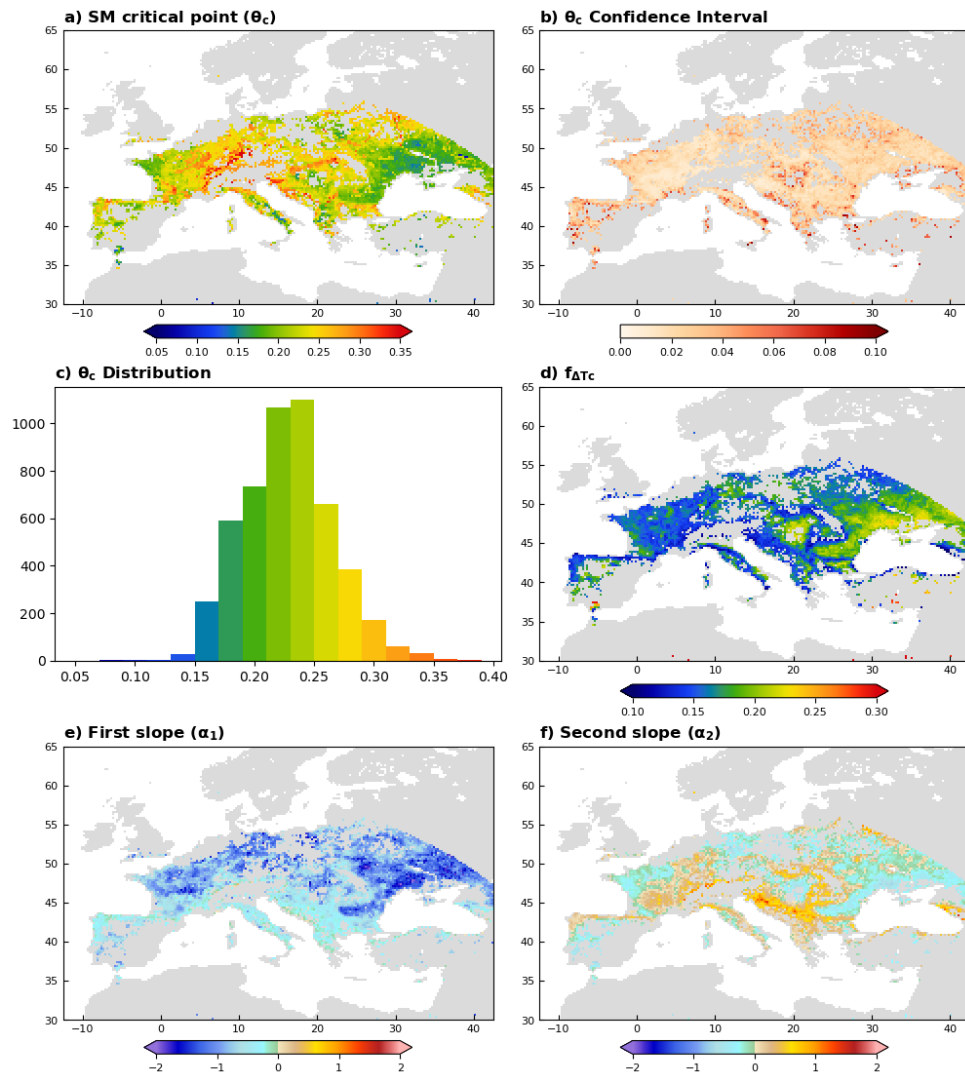


Figure 2: Spatial distribution of the pixels identified with regime transition: a) critical point values; b) critical point 95% confidence interval; c) distribution of critical point values; d) ratio of actual to potential LST amplitude at the SM critical point ($f_{\Delta T_c}$); e) fit first slope; f) fit second slope. Grey areas do not have sufficient data or it was not possible to identify the critical point.

The climatological month at which the transition from energy to water limited regime occurs as well as the fraction of days below the critical soil moisture are displayed in Figure 3. The results show a broad south-north gradient with later transition in the northern areas, where time spent in energy-limited conditions prevails. The month of transition diagnostic also indicates that in large northern areas the climatological soil moisture is always above the critical point, demonstrating that in those regions only in some years soil moisture falls below the critical point, constraining the surface energy balance. Figure 4 shows the yearly anomaly of the fraction of days with SM values lower than the θ_c . It is possible to identify several years with a significant increase in the number of dry days, e.g. 2018 shows a marked increase particularly high over central

Europe, while 2024 and 2025 the increase is more significant over the eastern part of Europe.

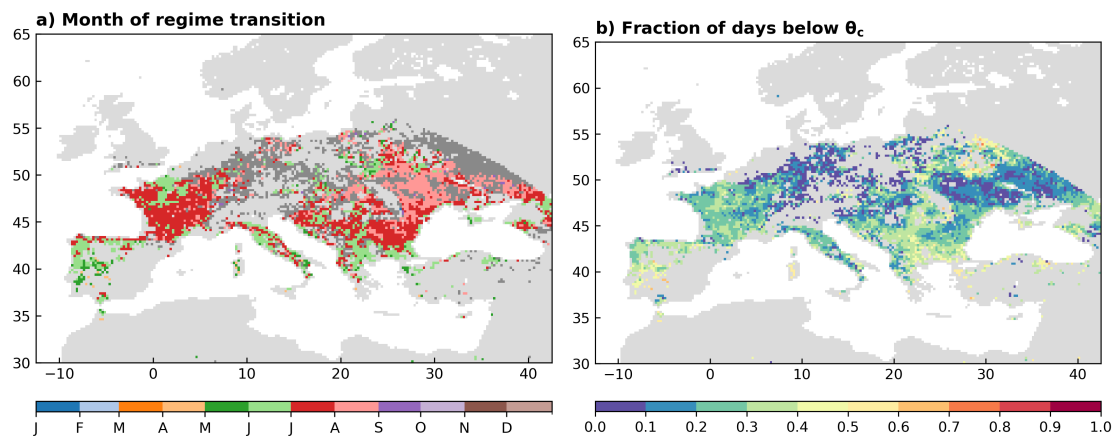


Figure 3: a) Month at which occurs the transition from energy- to water-limited regimes; b) Fraction of days with $SM < \theta_c$. Both values are derived from SM daily mean values for the full 2004-2025 period. Dark grey points in a) indicate that the critical point was not reached in the SM climatology.

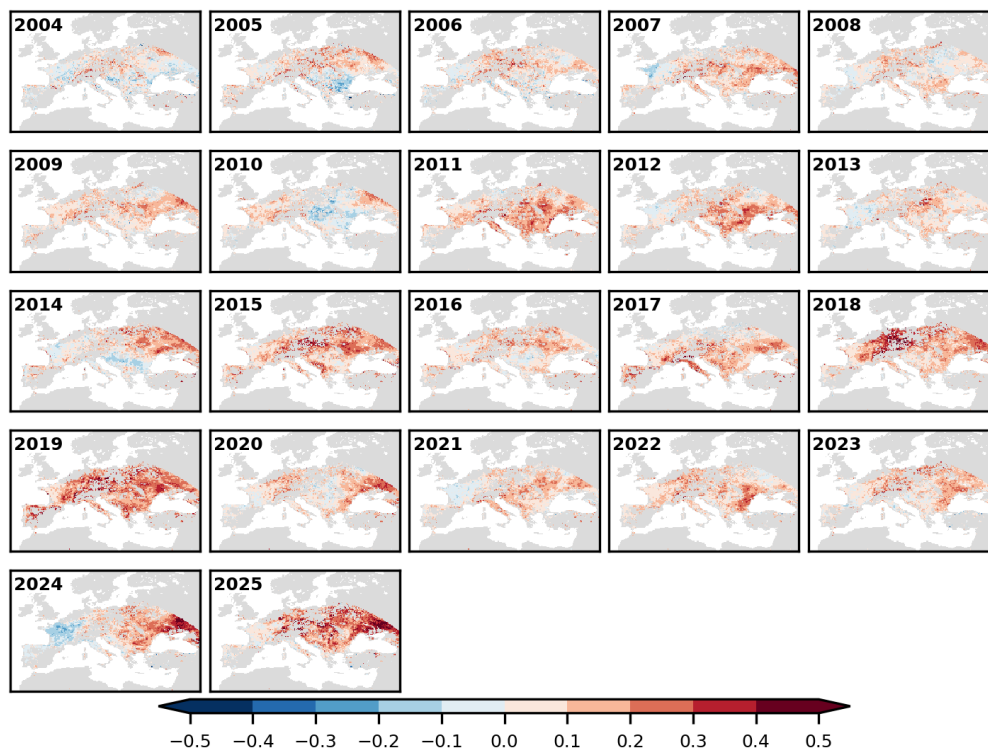


Figure 4: Yearly anomalies of the fraction of days with $SM < \theta_c$, with respect to the 2004-2025 climatological value (Figure 3b).

The 2018 summer European heatwave

The 2004-2025 climatology of SM, FVC, ΔT_p and ΔT_a over a selected area in central Europe, and the respective values for 2018 are shown in Figure 5. The data presented are computed from daily values using a moving window of ± 15 days. When compared to the corresponding 2004-2025 climatological means, the year 2018 starts with above normal SM and positive FVC anomalies of about 10%. ΔT_p and ΔT_a remain below normal for most of the first half of the year: warmer and wetter conditions in January 2018 (not shown, but available e.g. in <https://climate.copernicus.eu/hydrological-variables>) set the scenery for the observed anomalies in 2018 early days, then steadily approaching climatological means by April 2018. In mid-June the SM starts to decrease drastically with respect to the normal, reaching a minimum in early August. ΔT_p and ΔT_a increase rapidly with a few days of delay from the SM decrease, but because they start with values below the normal, positive anomalies only occur around mid-July and last until late November. The ratio of actual to potential LST amplitude, ΔT_p , shows a particularly sharp increase in October/November, revealing the cumulative effect of persistent negative anomalies of SM, which, together with below average vegetation, lead to a strong decrease in evapotranspiration. Typically, the SM conditions allow some vegetation to continue transpiration during summer, with climatological FVC values remaining stable at 70% before decreasing in winter. The exceptionally dry conditions in 2018 affected the vegetation over the full summer and autumn, leading to a marked temperature anomaly, suggesting an evapotranspiration deficit in October/November that is more marked than in summer when the heat wave occurs.

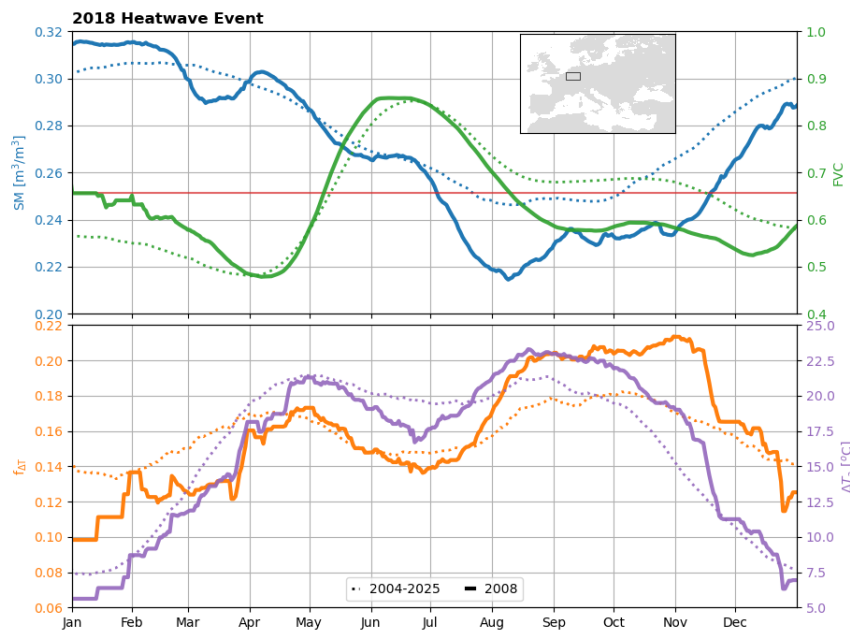


Figure 5: 30-day averages over the area indicated on the inset map: SM (upper panel in blue; left y-axis), FVC (upper panel in green; right y-axis), $f_{\Delta T}$ (lower panel in orange; left y-axis), ΔT_a (lower panel in purple; right y-axis). Dashed lines represent the averages over the full 2004-2025 period, while the solid lines correspond to the 2018 year.

Conclusions

Soil Moisture levels determine the prevailing hydrological regime. Under water-limited conditions, evaporative fraction (EF) is low and/or varies as a function of SM, thereby strengthening land-atmosphere coupling. Conversely, when water availability is not a limiting factor, evaporation is primarily controlled by the available energy, resulting in an energy-limited regime in which EF is high and remains approximately constant. Thus, SM is a key variable governing the hydrological regime and, consequently, the strength of land-atmosphere coupling (e.g., Seneviratne, 2010).

Although the identification of the SM thresholds (critical SM) using observations only is not straightforward, previous works have assessed the link between LST and SM for this purpose (Feldman et al., 2019, 2022). One of the main caveats of using satellite LST for this purpose are the complex confounding effects influencing LST and its link to SM. The strong seasonal cycles of available solar radiation, surface albedo and LST itself partially mask the signature of energy partitioning on daily LST amplitudes. To overcome these issues, we have developed a framework, where at each location daily LST amplitude is normalized by a potential value that would occur in the absence of energy dissipation via latent heat flux.

Within EXPECT we have demonstrated that by using the normalized LST ($f_{\Delta T}$) we are able to perform the SM – LST analysis using all available data, without restricting the analysis to dry-downs as in previous studies and therefore retain more robust critical SM values. A first characterization of critical SM, together with statistics of time spent in different hydrological regimes has been presented for Europe. When applicable, we estimated the sensitivity of $f_{\Delta T}$ with respect to SM, as a measurement of land-atmosphere coupling. Finally, we have checked the inter-annual variability of time spent under water-limited conditions for all points in Europe, during the 2004-2025 period; results clearly show their increase in this time in years and in regions affected by heat waves.

Land-atmosphere interactions are known to modulate, or even amplify summer extremes in Europe (heatwaves, droughts). However, the mechanisms that control exchanges of water and energy in response to available radiation at the surface and soil moisture are hard to model, as direct observations of those fluxes are sparse and prone to large uncertainties. Within EXPECT, we explored the relationship between variables directly linked to satellite observations, namely soil moisture and land surface temperature amplitude, to infer dominant hydrological regimes and regime transitions.

The framework developed within EXPECT targets the better understanding and therefore modelling land surface processes, namely by providing

- Metrics of land-atmosphere coupling based on satellite SM and LST products, that can be compared to similar metrics based on SM and turbulent fluxes (e.g., evaporative fraction)
- Detailed assessment of dominant hydrological regimes and the identification of shifts in the dominant regime per season/month.
- The evolution of the SM – LST amplitude link, and implications for the actual SM – evaporative fraction link, during the full life cycle of extreme heat waves in different parts of Europe, from their onset to the end.

We show that this methodology has the potential to act as an independent, data-driven framework to investigate land-atmosphere coupling, particularly before and during warm extremes, as well as to evaluate their representation in earth system models. Keeping in mind that this approach relies on satellite products that are close to top-of-atmosphere observations (so-called level 2), it can be used beyond EXPECT for assessing land surface processes in earth system models and reanalysis.

ULEIP: Novel diagnostics of the large-scale circulation and climate extremes

The contribution of Leipzig University (ULEIP) has primarily focused on developing novel diagnostics to identify, quantify and interpret the role of large-scale atmospheric circulation in past and present climate extremes. The work combines physically based diagnostics with modern machine learning and causal inference methods. This includes the development and application of causal representation learning methods (Carvalho Oliveira *et al.* 2026, Spuler *et al.* 2026), interpretable deep learning approaches for teleconnections (Bommer *et al.* 2025), information-theoretic diagnostics (Kretschmer *et al.*, 2026), and extensions of the climate storyline framework (Mindlin *et al.*, 2025; Mex *et al.*, in preparation). A secondary contribution addresses the large-scale circulation linked to land-surface responses and land-atmosphere interactions (Carvalho Oliveira *et al.* 2026; Friedel *et al.*, in preparation). Together, we provide novel diagnostic tools for understanding how large-scale circulation variability, internal climate variability and long-term climate change contribute to the occurrence and evolution of temperature and precipitation extremes.

Targeted weather regimes for diagnosing summer temperature extremes

A major contribution to Task 5.1 is the development and application of targeted weather regimes, a novel causal representation learning framework for identifying circulation patterns associated with specific classes of extreme events. This work is presented in Carvalho-Oliveira *et al.* (2026) and builds upon the methodology originally introduced by Spuler *et al.* (2024, 2025), extending it from winter circulation

and precipitation extremes to European summer dynamics and temperature extremes.

Unlike conventional weather regime classifications based on PCA analysis combined with k-means clustering, which partition the atmospheric state space into a fixed number of circulation regimes, the targeted weather regime approach explicitly identifies circulation patterns that maximize their relevance for a predefined target variable. The method, called RMM-VAE, integrates a regression task (R) and a Gaussian Mixture Model (MM) into a variational autoencoder and provides circulation diagnostics specifically optimized for understanding the target variable.

Applied to ERA5 reanalysis (Hersbach *et al.*, 2020) streamfunction data at 500 hPa in the summer (June, July, August) and using temperature averaged over Western Europe as a target variable, the framework identifies the dominant circulation structures associated with Western European summer heatwaves. Figure 6a shows the five identified weather regimes and the associated temperature anomalies (Figure 6a+b), soil moisture conditions (Figure 6c) and total precipitation anomalies (Figure 6d) in the target region. The identified circulation weather regime 1 (WR1) corresponds to persistent large-scale anticyclonic flow with enhanced warm-air advection into Western Europe, dry soils and reduced precipitation. This suggests that persistent circulation anomalies not only drive temperatures directly but also precondition land-surface moisture deficits that can further amplify extreme temperatures. This finding links to Task 5.2, where the role of land-atmosphere feedback is investigated in more detail. The study demonstrates that past Western European summer heat extremes are primarily associated with this southerly-flow weather regime (WR1) as identified by the RMM-VAE approach. In contrast, a conventional k-means clustering approach distributes heatwave days across several circulation clusters, resulting in a less distinct attribution of the underlying dynamical drivers.

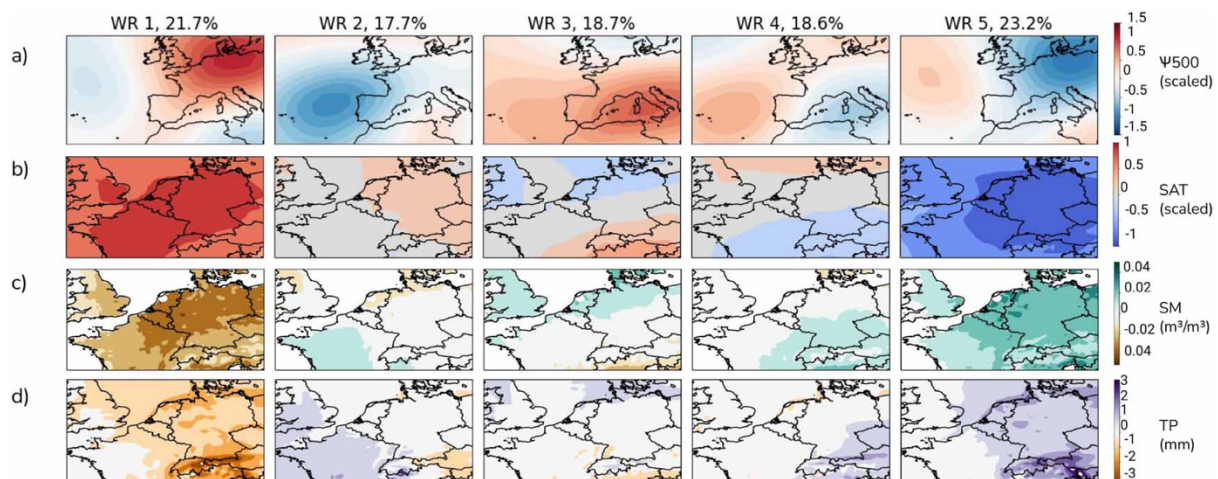


Figure 6. Weather regime composites from RMM-VAE clustering for $k=5$. (a) Streamfunction at 500 hPa showing the RMM-VAE regime patterns (cluster centres), with corresponding frequency of occurrence above each panel; (b)–(d) surface air temperature (SAT), soil moisture (SM), and total precipitation (TP) anomalies, respectively, composited with respect to each regime. The regimes are ordered in terms of

the associated average temperature anomaly in the target region, with the first regime being associated with the highest temperatures. Figure taken from Carvalho Oliveira et al. (2026).

Moreover, the seasonal frequency of this impact-relevant WR 1, combined with global mean temperature, explains a large fraction of interannual variability in both mean ($R^2=0.84$) and extreme summer temperatures ($R^2=0.65$), with predictive skill persisting in out-of-sample tests. This simple multiple linear regression model can not only be used to explain seasonal temperature variability but also observed trends and provides a physically interpretable framework for separating circulation-induced variability from thermodynamic climate change. This allows us to attribute 34% of total summer warming in Western Europe and about 70% of the observed 'excess' warming (relative to the global mean) to an observed increase in the identified southerly flow circulation pattern, which we quantify to be largely forced.

Overall, our results demonstrate that the targeted weather regime framework provides physically interpretable circulation patterns that strengthen the link between large-scale atmospheric circulation and regional climate hazards. The approach enables a more robust attribution of past and present summer temperature extremes and regional warming, while offering a scalable diagnostic framework that can be consistently applied to reanalysis products, observations and CMIP6 climate simulations to quantify changes in the frequency, persistence and impacts of circulation patterns associated with summer extremes.

Causal representation learning for joint teleconnections

ULEIP further advanced diagnostics for identifying and quantifying the influence of large-scale climate drivers through the development of interpretable machine learning and causal representation learning frameworks. These methods are designed to disentangle the joint effects of multiple teleconnections on regional climate extremes while providing physically interpretable representations of the underlying dynamical processes. Two complementary methodological developments were pursued: (i) a causal representation learning framework (DAG-VAE; Spuler et al., 2026) that explicitly models causal interactions among teleconnections, and (ii) interpretable deep learning models for diagnosing and predicting the influence of teleconnections on European weather regimes (Bommer et al., 2025).

First, building on the targeted weather regime framework as also used in Carvalho Oliveira et al. (2026), Spuler et al. (2026) developed DAG-VAE, which combines variational autoencoders (VAEs) with directed acyclic graphs (DAGs). The motivation is that many regional climate extremes arise from the simultaneous influence of multiple large-scale climate modes, making it difficult to disentangle their individual contributions using conventional regression-based techniques. By combining deep learning with causal inference, the framework learns physically meaningful latent representations of large-scale climate variability while explicitly encoding the causal dependencies between remote climate drivers and regional climate impacts.

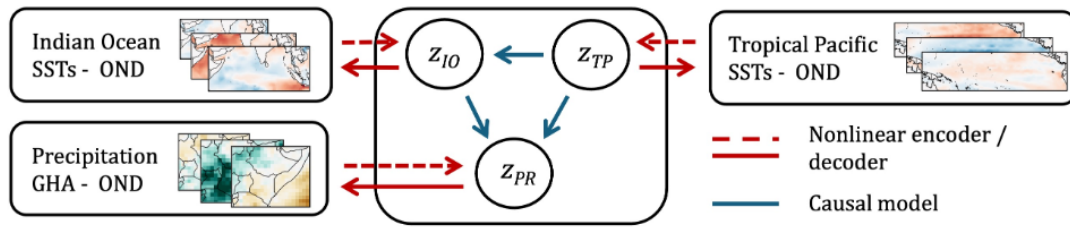


Figure 7. Illustration of the DAG-VAE method and architecture. z_{TP} , z_{IO} and z_{PR} refer to the low-dimensional representations identified by the model for the three high-dimensional input spaces: tropical Pacific SSTs, Indian Ocean SSTs and GHA precipitation. The red arrows refer to encoder and decoder neural networks that dimensionality-reduce the high-dimensional input space. The blue arrows refer to the directed acyclic graph (DAG) hypothesized in the latent space. Figure taken from Spuler et al. (2026).

The first application focuses on seasonal precipitation variability over the Greater Horn of Africa (GHA) during the short rain season (October–December). The DAG-VAE framework disentangles the individual and joint influences of tropical Pacific and Indian Ocean variability on regional rainfall, demonstrating how interacting teleconnections contribute to seasonal climate anomalies. Figure 7 shows a schematic overview of the network architecture, including sea surface temperature anomalies over the tropical Pacific and Indian Ocean together with precipitation over the GHA region as input fields. The analysis is based on seasonal hindcast experiments from SEAS5, which provide a large ensemble for sampling internal variability and training the deep learning model. The model is subsequently fine-tuned using reanalysis and observational datasets (ERA5 and CHIRPS).

The method identifies dynamically meaningful latent representations and recovers spatial response patterns that are consistent with SST replacement experiments (McLeod et al., 2021). DAG-VAE therefore provides a complementary, data-driven approach for estimating spatial causal response patterns directly from observations. Furthermore, we demonstrate that the framework can generate data-driven counterfactuals of extreme short rain seasons, opening potential new opportunities for forecast-based early action and scenario planning.

This work represents one of the first applications of causal representation learning to climate dynamics and provides an important methodological contribution to the diagnostics developed within this task. Although the first application focuses on African precipitation, the methodological advances are generic and directly transferable to European summer extremes, where multiple drivers, including large-scale atmospheric circulation and regional land-surface conditions such as soil moisture, interact to shape temperature extremes.

Second, in a complementary line of work, we developed interpretable deep learning models for identifying teleconnection drivers of European weather regimes (Bommer et al., 2025). The problem is formulated as a subseasonal to seasonal (S2S) prediction task using machine learning architectures of increasing complexity. The resulting models learn physically meaningful representations of large-scale climate drivers (stratospheric zonal winds over the Arctic and outgoing longwave radiation in the

Tropics) and identify the key teleconnection patterns influencing European circulation regimes. In this application different reanalysis products were used for training and fine-tuning. The developed framework achieves prediction skill that partly exceeds current subseasonal-to-seasonal forecasting systems, demonstrating that machine learning can identify physically relevant teleconnection signals rather than relying solely on statistical relationships. Although demonstrated for winter circulation, the approach provides a generic diagnostic framework that can readily be extended to summer circulation regimes, including those associated with extreme events such as the targeted weather regimes identified in *Carvalho-Oliveira et al. (2026)*.

Information-theoretic diagnostics and interpretable deep learning

A complementary line of work focuses on developing diagnostics that quantify the strength, interactions and temporal evolution of large-scale climate drivers contributing to regional extreme events. Understanding the role of large-scale teleconnections is essential for improving the prediction and projection of climate extremes; however, conventional approaches based on composites or correlation analysis become difficult to interpret in the presence of nonlinear relationships and interactions across different timescales. To address this limitation, we developed a framework based on (conditional) mutual information embedded within a causal network framework (Kretschmer et al., under review). This non-parametric information-theoretic measure quantifies the strength of teleconnection pathways and allows complex multivariate interactions between climate drivers and regional extremes to be summarized in a physically interpretable metric.

The framework is applied to winter cold and wet extremes across Europe and North Africa, diagnosing the influence of subseasonal drivers, including the Madden–Julian Oscillation (MJO) and the stratospheric polar vortex (SPV), and their modulation by seasonal drivers such as El Niño Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO). Figure 8 shows the influence of those drivers for regional extreme events expressed in terms of mutual information.

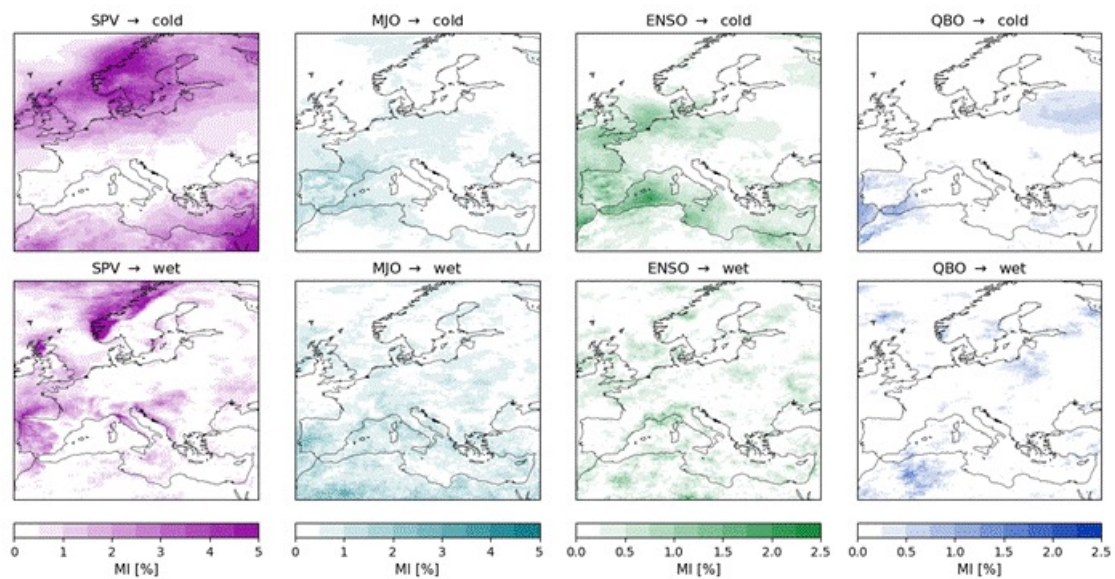


Figure 8. Mutual information (expressed as a percentage of the climatological entropy of the extreme event) of different drivers (SPV, MJO, ENSO, QBO) and extreme events (cold and wet). Note the smaller colourbar range for ENSO and QBO. Figure taken from Kretschmer et al. (2026).

Our results further demonstrate that the seasonal drivers influence both the occurrence of subseasonal circulation patterns and their impacts on regional surface extremes, with these modulating effects persisting across subseasonal timescales. This highlights periods of enhanced predictability and provides a diagnostic framework for identifying forecast opportunities and evaluating the representation of teleconnection processes in climate models. Although the first applications focus on winter extremes, the methodology is transferable to summer extremes, enabling the investigation of interacting drivers of European heatwaves, droughts and persistent precipitation extremes.

Extending storyline approaches to explain and predict observed and near-term changes

Another important contribution concerns the extension of the climate storyline approach.

Mindlin et al. (2025) combine causal inference with storyline concepts to analyse changes in the Southern Hemisphere eddy-driven jet using CMIP6 climate model simulations. By explicitly separating the contributions of external forcing and internal variability, the approach provides a physically interpretable framework for explaining past circulation changes and identifying the mechanisms underlying observed trends. Furthermore, by linking circulation responses to their underlying drivers, the framework offers potential for improving predictions of near-term changes in large-scale atmospheric circulation.

A second ongoing development further extends storyline concepts by incorporating large initial-condition ensembles to explicitly address uncertainties arising from internal climate variability, following the approach of *Line et al (2024)*. Current work applies this framework to CESM2 large ensemble simulations to investigate the combined influence of Pacific and Atlantic multidecadal variability on Sahel precipitation (*Mex et al, in preparation*). The approach quantifies how internal climate variability modulates the externally forced response, providing a physically interpretable framework for understanding past decadal precipitation variability and future changes. Subsequent work will extend this approach to investigate the role of decadal modes of variability in modulating Northern Hemisphere midlatitude circulation and associated climate extremes, building on emerging hypotheses regarding their influence on persistent circulation anomalies and temperature trends (e.g., *Teng et al 2022, Happe et al. 2025*).

Together, these developments substantially broaden the applicability of storyline methodologies. They provide new diagnostics for separating the relative contributions of large-scale circulation variability, internal climate variability and anthropogenic climate change in shaping regional climate hazards.

Linking large-scale circulation to land-surface impacts

ULEIP has further contributed to Task 5.2 by investigating how large-scale atmospheric circulation affects land-surface processes through seasonal memory effects.

Current work examines how variability in the winter Northern Hemisphere stratospheric polar vortex (SPV) influences European vegetation dynamics and agricultural productivity from winter through early summer (*Friedel et al, in preparation*). Using satellite-derived vegetation observations (the Normalized Difference Vegetation Index, NDVI), atmospheric reanalysis and crop yield records, we quantify how weak and strong winter SPV conditions affect subsequent vegetation growth.

We show that weak winter SPV conditions are associated with colder and less sunny winters that initially suppress vegetation activity and delay the onset of the growing season by up to three weeks. During spring, however, the circulation anomalies reverse in several European regions as a consequence of the delayed springtime breakdown of the polar vortex. This creates favourable growing conditions that lead to enhanced vegetation activity during summer. Conversely, strong winter SPV conditions promote early winter vegetation growth through milder temperatures but are followed by circulation changes that increase the likelihood of late cold-air outbreaks and reduced vegetation activity during spring and summer.

The analysis further demonstrates that these vegetation responses are closely linked to circulation-induced hazards such as frost after budburst and anomalous soil moisture conditions. In northern France, for example, enhanced risks of both soil moisture deficits and excess water during strong SPV years are associated with reduced winter

and spring crop yields, whereas weak SPV years generally correspond to more favourable agricultural conditions (see also Figure 9).

These results reveal a previously underexplored pathway linking stratospheric variability and vegetation responses. They provide an example of how circulation diagnostics can be connected to land-surface impacts and seasonal memory effects. Future work will build upon these findings by analysing the role of soil moisture feedbacks in amplifying summer heat extremes identified through the targeted weather regime framework.

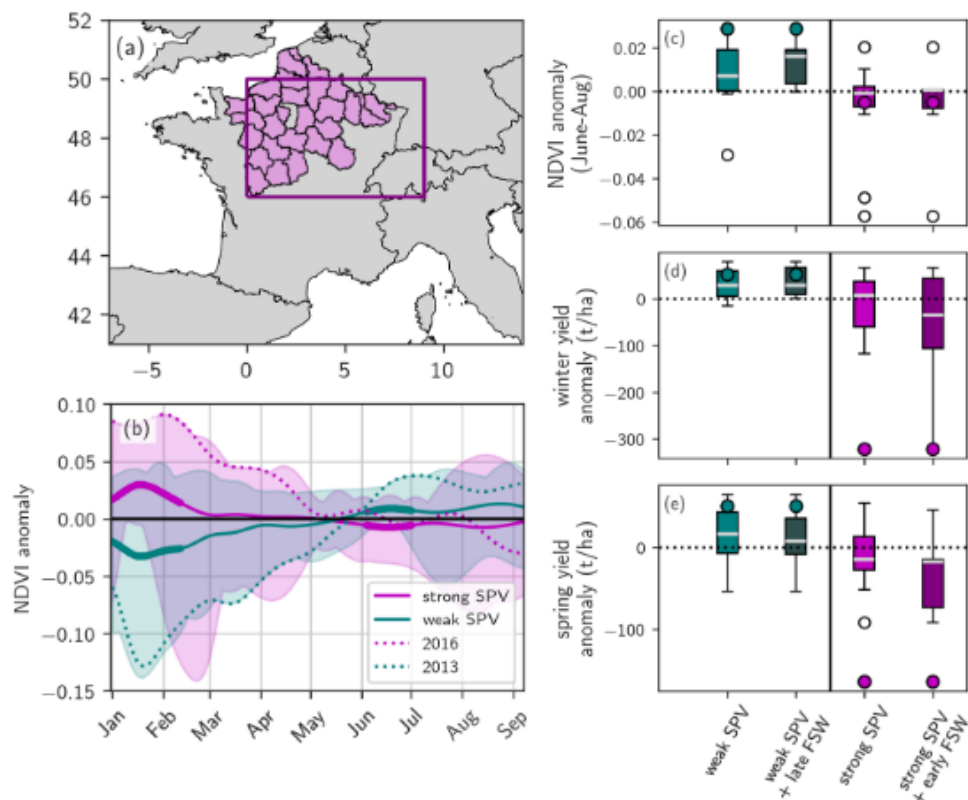


Figure 9. (a) The region defined as the breadbasket of France in the NDVI data (pink box) and the crop data (pink shading). (b) NDVI anomalies from January to September in the breadbasket of France in strong and weak SPV years, as well as in 2013 and 2016. Shading marks the full observed range of anomalies in the respective years. (c) June to August NDVI anomalies averaged over the breadbasket of France in weak and strong SPV years, late and early FSW years, and combinations thereof. (d) and (e) winter crop yield and wine yield anomalies in the study region for weak and strong SPV years. Filled circles in panels c–e mark the years 2013 and 2016, respectively.

UoR: Process-based assessment of emerging agricultural-drought hotspots and heat stress during heatwaves

The University of Reading (UoR) team contributed through two separate studies: a process-based assessment of emerging agricultural-drought hotspots using ERA5 and CMIP6, and an observational diagnosis of temperature and humidity contributions to European heat stress during heatwaves.

The first of these studies analyses how land-surface state – including antecedent conditions – and the underlying climate govern the trends in the occurrence and severity of agricultural drought (*Black et al. 2026*). The second investigates the relative contributions of trends over 1979-2023 in humidity and temperature to heat stress people experience during European heat waves (*Zhang et al. 2026*).

Agricultural drought study

Climate change is expected to increase agricultural drought risk, but substantial uncertainty remains about which regions are becoming most vulnerable and why (*Cook et al. 2020*). Changes in growing-season soil moisture cannot be inferred reliably from precipitation trends alone because they also depend on evapotranspiration, vegetation responses and the persistence of antecedent soil-moisture conditions. The study therefore asked where agricultural drought is increasing, whether projected twenty-first-century changes are already detectable in the historical record, and which land-surface processes explain the emergence - or absence - of drought hotspots.

Data and methodology

The methodology comprised analysing both historical and future changes in agricultural drought and the processes driving these changes. This enabled us to identify emerging hotspots of agricultural drought: regions where the changes projected over the twenty-first century are already evident in the historical record and where observed and projected drying arise through consistent physical mechanisms.

A seasonal, process-based approach was required because agricultural drought is not equivalent to a decline in annual mean soil moisture. Rather, impactful agricultural drought results from a deficit in root-zone soil moisture during the locally defined growing season. Annual or monthly metrics can obscure agriculturally important changes. Growing-season soil moisture is also determined by both soil moisture at the start of the season and the balance between water inputs and losses during the season. The persistence of soil moisture anomalies means that antecedent conditions may influence drought risk over seasonal to decadal timescales and must therefore be considered alongside contemporaneous precipitation, evaporation and runoff.

The analysis separated the influence of antecedent soil moisture from in-season soil-moisture accumulation and adopted a mechanistic framework based on the dominant controls on actual evapotranspiration (Figure 10). Classifying regions in this way is important because the effects of warming, precipitation change and vegetation responses on soil moisture differ between evaporative regimes.

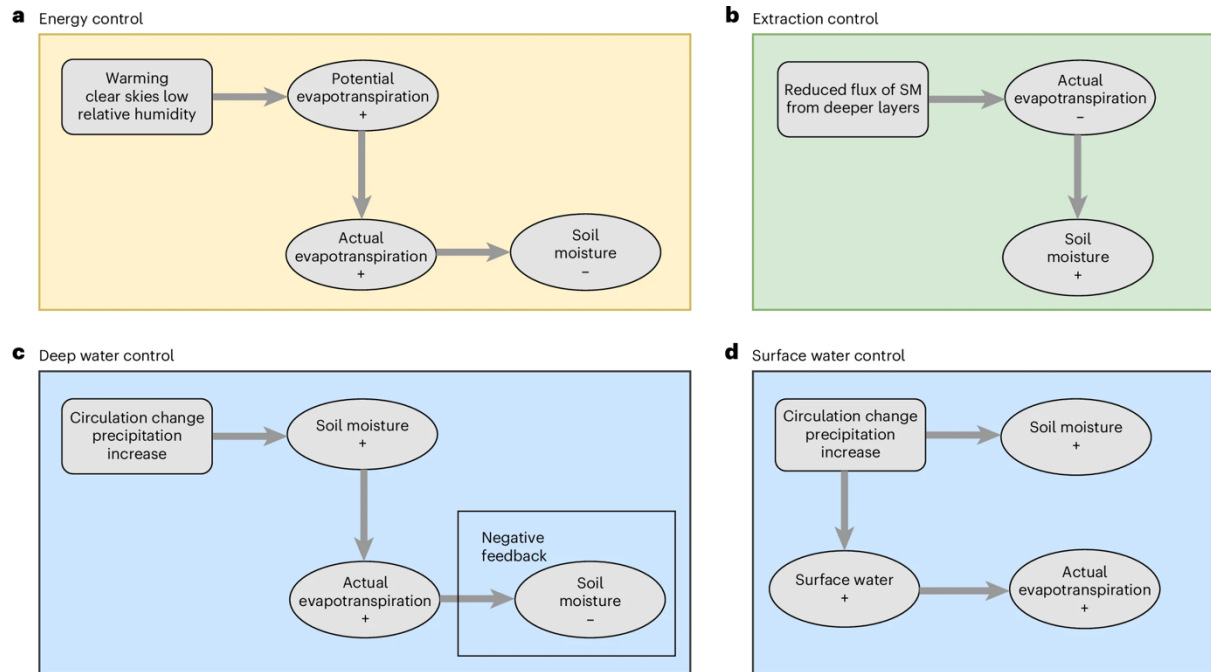


Figure 10: Conceptual diagnostic framework for energy control, plant-extraction control, deep-water control and surface-water control of seasonal evapotranspiration and soil moisture. The framework links warming, circulation and precipitation changes to actual evapotranspiration and root-zone soil moisture. Source: Black et al (2026).

By applying this framework consistently to reanalysis data, historical climate simulations and future CMIP6 projections, the study aimed both to assess whether models reproduced the observed land-surface processes and to explain regional contrasts in drought emergence—distinguishing regions where recent drying is driven by the same mechanisms as projected future change from those where historical trends are not projected to persist.

The analysis combined climate-model simulations with the ERA5 global reanalysis. Seventeen models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were selected on the basis of availability of required variables and SSP5-8.5 and SSP2-4.5 scenarios (O'Neill et al. 2016). Smaller model subsets were also analysed for SSP1-2.6 and SSP3-7.0 to assess the sensitivity of projected drought changes to the future emissions pathway. ERA5 was chosen as an observational benchmark.

The model and reanalysis data were obtained at monthly resolution and interpolated to pentadal resolution where sub-monthly information was required, particularly for identifying wet and dry seasons and calculating drought-duration metrics. Using

monthly rather than daily model output substantially reduced the computational demands and enabled a larger CMIP6 ensemble to be included. All datasets were bilinearly regridded to a common 144×96 global grid before comparison. Soil moisture from each model was interpolated to a 1m deep column using multi-layer outputs.

Agricultural drought was assessed during locally relevant growing seasons. For the northern-hemisphere extratropics, the growing season was defined as 1 May–30 September, corresponding approximately to the period of maximum biological activity and agricultural production. In the tropics and subtropics, growing seasons were assumed to coincide with the principal local rainy season – defined using a well-established objective method (*Dunning et al. 2016*). Tropical season timings were calculated separately for each model and for ERA5, using running ten-year windows so that long-term shifts in rainfall seasonality were represented.

In order to quantify the effect of soil moisture memory, and hence the effect of processes during non-growing seasons, changes in mean seasonal soil moisture were compared with both soil moisture cumulated during the growing season and soil moisture at the onset of the season. To diagnose the processes controlling seasonal soil-moisture change, each grid cell was classified according to its dominant evaporative regime (*Seneviratne and Koster 2012; Wang and Dickinson 2012*). The classification used the interannual relationships between actual evapotranspiration, seasonally cumulated root-zone soil moisture and incoming shortwave radiation. In water-controlled regimes, evapotranspiration increased with soil moisture but was weakly or negatively related to shortwave radiation, indicating that moisture supply was the principal constraint. In energy-controlled regimes, evapotranspiration increased with available radiation and was associated with greater seasonal soil-moisture depletion. A third region was defined in this study - where evapotranspiration was negatively related to seasonal soil-moisture accumulation but was not positively related to shortwave radiation. This regime represents conditions in which variability in water loss is governed primarily by plant extraction of water from the root zone.

Changes in agricultural drought were characterised in terms of occurrence, intensity and duration. Drought occurrence was defined from growing-season mean soil-moisture anomalies expressed as standardised Z-scores; the principal analysis identified a drought where soil moisture fell more than one standard deviation below the climatological mean, with alternative thresholds used as sensitivity tests. Drought intensity was represented by changes in the minimum soil moisture reached during the growing season. Duration was quantified using a dry-spell index: the number of pentads belonging to a continuous sequence lasting at least 12 pentads, or approximately two months, in which soil moisture remained below a specified standardised threshold. Long historical and future periods were used for these drought metrics to provide enough events for statistically meaningful comparisons.

In the final stage of the study, the historical and future analyses were brought together to identify emerging agricultural-drought hotspots. These were regions in which an increase in drought was evident in the recent historical record, was projected to

continue during the twenty-first century, and could be associated with physically consistent changes in the seasonal land-surface water balance. This combination of observed change, future projection and process diagnosis distinguished emerging climate-change hotspots from regions experiencing recent drought trends that were not projected to persist.

Results

Although the study was global in scope, this contribution focuses on historical changes in Europe and North America and on the identification of emerging drought hotspots. These results are of greatest relevance to EXPECT because they show where changes in summer land-surface conditions are already evident, how they develop across seasons, and whether recent changes are consistent with the processes expected under continued climate change.

A central result was that agricultural drought in Europe and North America is strongly influenced by soil-moisture conditions before the main summer growing season. Across most of both continents, March–May was identified as the dominant season controlling May–September soil moisture. This relationship was evident in both ERA5 and the CMIP6 simulations and persisted when long-term trends were removed, indicating that it reflects seasonal soil-moisture memory rather than a long-term trend. Dry spring conditions can therefore persist into summer, preconditioning the land surface for agricultural drought and potentially strengthening summer land–atmosphere feedbacks.

Historical changes were consistent with this mechanism. Agricultural-drought frequency increased across much of Europe and in parts of western North America during the recent historical period. The affected European regions included western, central, eastern and northern Europe, while increases in North America were most apparent in the west and northwest. These historical increases were accompanied by reduced spring soil-moisture accumulation, showing that changes before the growing season contributed to the subsequent summer soil-moisture deficits.

Western North America, western Europe, and much of mid-latitude central and eastern Europe were consequently identified as emerging agricultural-drought hotspots (Figure 11). In these regions, the recent historical increase in drought was consistent with both future projections and the physical processes underlying the projected changes. In particular, increased evapotranspiration and reduced spring soil-moisture accumulation were sufficient in many areas to offset increases in precipitation, leaving less water available at the beginning of summer.

The comparison of historical and future changes also distinguished emerging hotspots from regions where future risk has not yet clearly emerged. In eastern and north-eastern North America, drought was projected to increase during the twenty-first century, but no statistically robust increase was evident in the historical record. These

regions were therefore classified as showing projected worsening rather than as emerging hotspots.

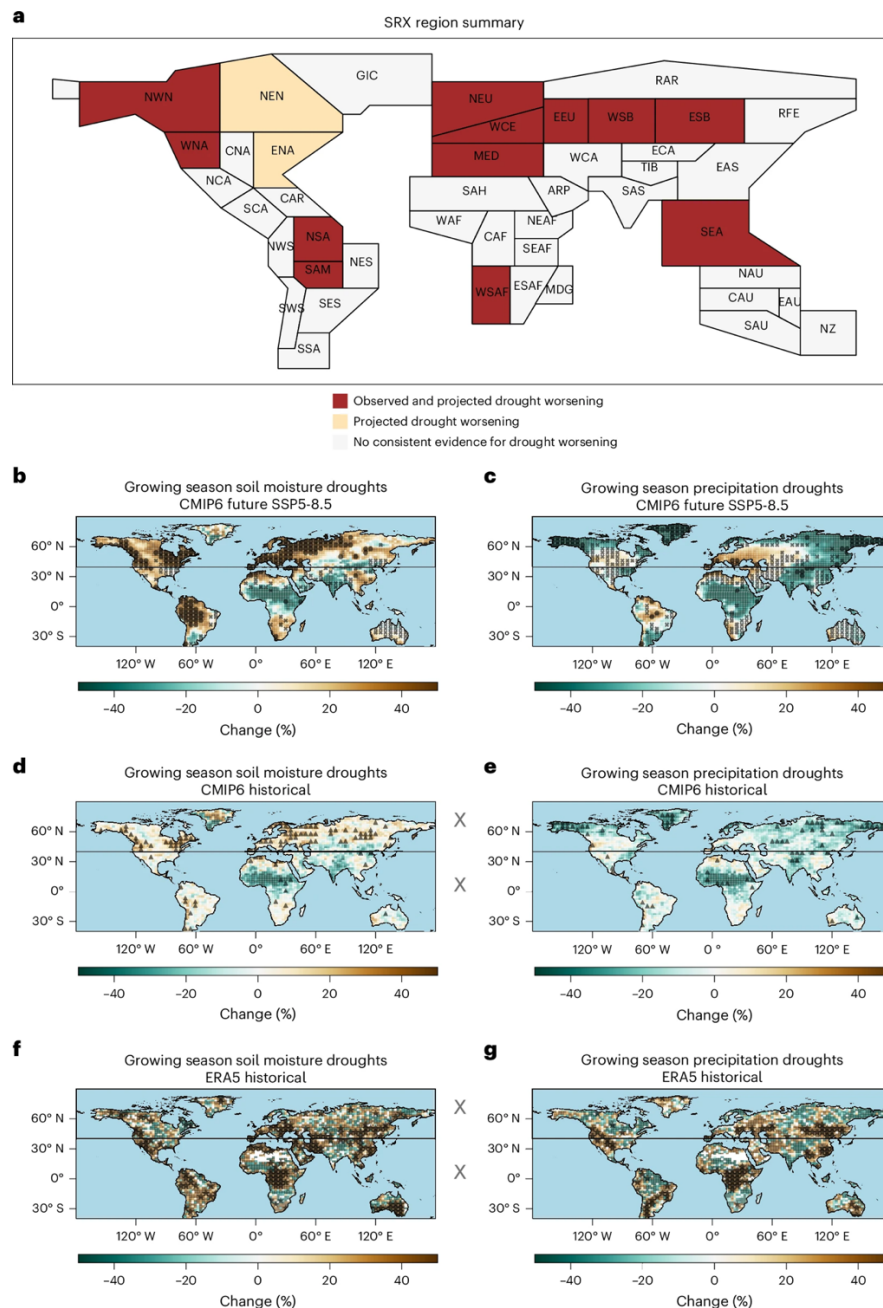


Figure 11. Emerging hotspots of agricultural drought. Panel (a) distinguishes regions with observed and projected worsening (dark red), projected worsening only (pale orange), and no consistent evidence of worsening. Panels (b-g) compare soil-moisture-defined and precipitation-defined drought changes in CMIP6 projections, CMIP6 historical simulations and ERA5. The divergence between soil-moisture and precipitation hazards demonstrates the importance of land-surface processes. Source: Black et al. (2026).

Conclusions and implications

The principal scientific advance of this study is a process-based framework that connects changes in agricultural drought both to the seasonal land-surface water balance, and to antecedent conditions. A key methodological innovation was thus the separation of antecedent soil moisture from seasonal soil-moisture cumulation. This revealed that long-term changes in growing-season soil moisture frequently reflect trends during the non-growing season. In Europe and North America, spring soil-moisture conditions exert a strong influence on summer soil moisture.

The introduction of an extraction-controlled evaporative regime represents a further conceptual advance. Previous evaporative regime frameworks distinguish between water-controlled evaporation, in which evapotranspiration is limited by moisture supply, and energy-controlled evaporation, in which it is limited by available energy. The study identified a third state in which seasonal evapotranspiration variability is governed primarily by the ability of vegetation to extract water from the root zone. This means that in some regions and seasons – including southern Europe during the summer, biophysical processes exert a primary control on soil moisture trends.

The growing-season analysis revealed changes that were not apparent from annual soil-moisture averages. In central and eastern Europe, annual soil-moisture changes were comparatively small and inconsistent, while growing-season soil moisture declined substantially and agricultural-drought frequency increased. In North America, annual drying was more pronounced in eastern regions, but the clearest historical and projected increases in agricultural drought occurred in the west. Assessments based only on annual means would therefore have failed to identify some of the regions in which agriculturally impactful drying is already emerging.

The new framework developed in this study is directly relevant to EXPECT's aim of understanding and explaining the local land-surface processes that modulate and amplify past and present climate hazards. EXPECT Task 5.2 focuses on process-based diagnosis of soil moisture–vegetation–atmosphere interactions, including the onset of water limitation, vegetation modulation of soil-moisture depletion and the consequences for summer droughts, heatwaves and compound drought–heatwave events. The seasonal evaporative-regime framework contributes to this objective by distinguishing whether evapotranspiration is controlled by water supply, available energy or plant extraction from the root zone.

In particular, the introduction of the extraction-controlled regime extends the conventional distinction between water- and energy-limited conditions. It provides a means of identifying situations in which vegetation physiology and canopy conductance, rather than precipitation supply or radiation alone, govern variability in water loss. This is important for EXPECT because the response of transpiration to warming depends on interacting changes in temperature, relative humidity, atmospheric demand and stomatal conductance. Failure to recognise extraction control could either exaggerate the direct effect of atmospheric demand or make

assessments of drought change unnecessarily dependent on uncertain precipitation projections.

The framework also provides a bridge between the different observational and modelling activities within EXPECT. Relationships between soil moisture, evapotranspiration, radiation and vegetation state can be evaluated using satellite observations of soil moisture, land-surface temperature and vegetation, as well as reanalysis and climate-model simulations. EXPECT aims to use these data to identify transitions into water-stressed conditions, evaluate the representation of evaporative regimes in models and assess their contribution to the amplification of European heatwaves and droughts. The framework developed here gives this work a broader seasonal context by showing that the state of the land surface before an extreme event may be as important as the meteorological forcing during the event itself.

This finding has implications for attribution and prediction. In Europe and much of North America, spring soil-moisture conditions strongly influence summer soil moisture. Consequently, analyses of summer drought and heat hazards should include the preceding evolution of the land-surface water balance rather than treating each event as an isolated response to simultaneous rainfall and temperature anomalies. The framework can therefore complement EXPECT's analysis of large-scale atmospheric circulation by identifying the local antecedent conditions that determine whether an atmospheric anomaly is damped or amplified at the land surface. It also provides physically interpretable diagnostics that can be applied in WP6 to high-resolution simulations and extended observational datasets, supporting EXPECT's aim of refining attribution and estimates of future regional hazards.

The societal significance of the results is that agricultural-drought change is not solely a future risk. Recent drying in western North America and across much of western, central and eastern Europe is consistent with the mechanisms underlying projected future drought worsening. These regions can therefore be regarded as emerging hotspots in which climate-related changes in the seasonal land-surface water balance are already becoming evident. This strengthens the case for adaptation based on current and emerging risk, rather than waiting until late-century changes become unambiguous.

The distinction between agricultural drought and annual mean drying is especially important for decision-making. Seasonal analysis identified substantial increases in growing-season drought risk in central and eastern Europe and western North America that were obscured by annual soil-moisture metrics. Climate-risk assessments based on annual averages may therefore underestimate threats to crop production, ecosystem functioning and summer water availability precisely where those impacts are most consequential.

Beyond EXPECT, the framework offers a transferable approach for evaluating agricultural-drought risk in observations, reanalyses and different generations of climate models. By combining locally relevant seasons, antecedent soil-moisture conditions and physically distinct evaporative controls, it can identify robust drought

signals even where models disagree about precipitation change. This provides a stronger basis for climate assessments and adaptation planning than approaches based on precipitation or annual soil moisture alone, while retaining a clear physical interpretation of why drought risk is changing.

Heat stress study

Heat stress depends on both air temperature and atmospheric moisture. Humidity can intensify the physiological effects of high temperatures by reducing evaporative cooling, but its contribution may vary substantially between regions. The same temperature-defined heatwave may therefore produce different levels and trends in heat stress across Europe.

The study asked how heat stress during European summer heatwaves changed between 1979 and 2023; how much of that change was attributable to temperature and relative humidity; and whether the balance between these contributions differed among Northern Europe, Western and Central Europe, and the Mediterranean.

Data and methodology

Temperature trends alone do not fully describe changes in the heat stress experienced by people. The simplified Wet Bulb Globe Temperature (sWBGT) was therefore used because it combines temperature and atmospheric moisture in a single heat-stress metric.

An additive decomposition was developed to separate changes in sWBGT into temperature-driven, relative-humidity-driven, temperature–humidity interaction and remaining nonlinear contributions. This allowed the study to determine whether humidity amplified or moderated the effect of warming in different parts of Europe. Comparisons among reanalysis, gridded observational data and individual station records were used to assess the robustness of the results, particularly because humidity trends can be sensitive to the dataset and spatial scale considered.

The analysis covered European summers from 1979 to 2023 and distinguished three regions: Northern Europe, Western and Central Europe, and the Mediterranean. The principal dataset was ERA5, with JRA-55 reanalysis and the E-OBS gridded observational dataset used for comparison. Records from stations in Oslo, Hamburg, Madrid, Vienna and Warsaw provided additional evidence at city scale.

Heatwaves were defined as periods of at least three consecutive days on which maximum temperature exceeded the calendar-day 90th percentile calculated for 1981–2010. The analysis was restricted to June–August and examined heat stress specifically during these temperature-defined heatwave days.

Trends in sWBGT were decomposed into contributions from temperature, relative humidity, their interaction and a nonlinear residual. Statistical testing accounted for

temporal autocorrelation and, for spatial maps, multiple testing. Changes in the frequency of alert and caution intensity classes were also compared between 1979–2000 and 2001–2023. These classes were used to summarise changes in heat-stress intensity rather than as health thresholds calibrated for European populations.

Results

Heat stress during heatwave days increased in all three European regions, but the balance between temperature and humidity differed markedly (Figure 12). Temperature provided the dominant positive contribution throughout Europe. In Northern Europe, increasing relative humidity provided an additional amplification. In Western and Central Europe, the humidity contribution was comparatively weak and differed among datasets. In the Mediterranean, declining relative humidity partly offset the increase caused by rising temperature. The temperature–humidity interaction and nonlinear contributions were small, indicating that the regional trends could largely be explained by the separate first-order effects of temperature and humidity.

The station analysis confirmed that temperature was the principal driver of increasing heat stress, but showed greater local and dataset-dependent variation in the humidity contribution. The largest discrepancy occurred in Madrid: station observations showed positive contributions from both temperature and humidity, whereas ERA5 indicated that a negative humidity contribution largely offset the effect of warming. This sensitivity is particularly important in hot locations because the effect of humidity on sWBGT increases with temperature.

The societal burden of heat stress also increased substantially. Alert- and caution-level conditions became more frequent and extended across larger parts of central and southern Europe. In the station records, alert-level days during heatwaves increased from 19 to 95 in Madrid, from 17 to 70 in Vienna and from 18 to 48 in Warsaw between the two study periods. These changes demonstrate both increasing heat-stress intensity and an expansion of elevated heat stress into temperate European regions.

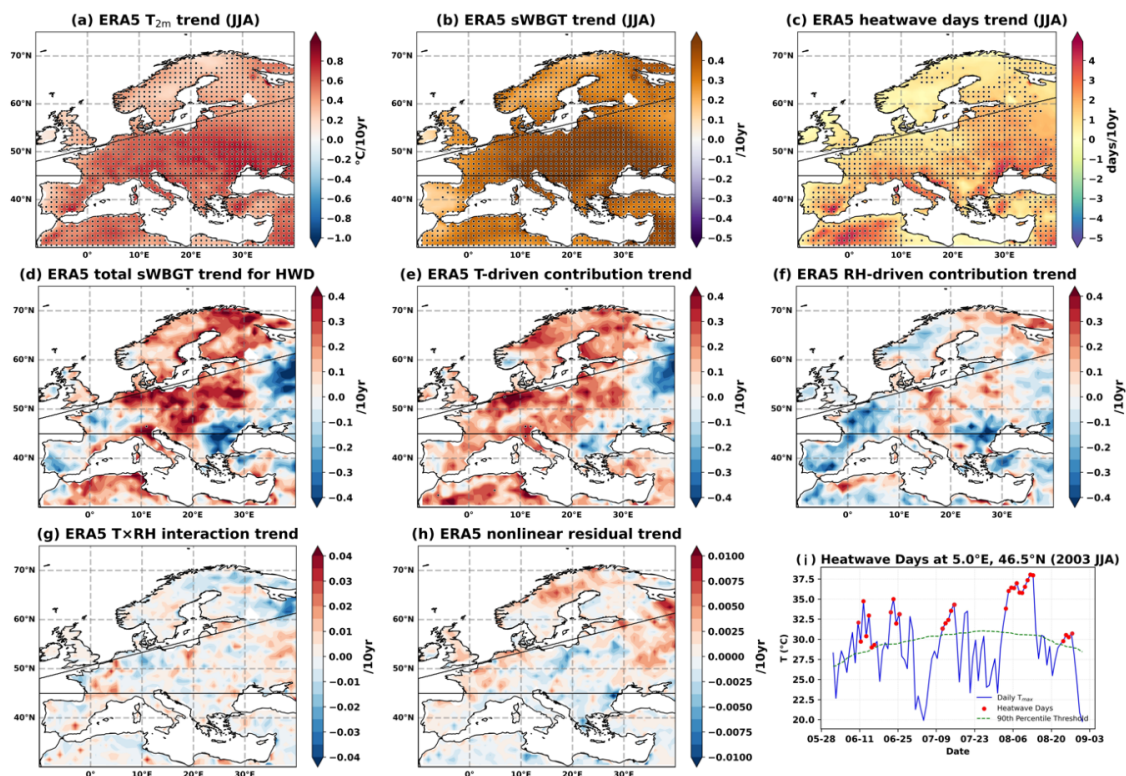


Figure 12. European trends in summer temperature, sWBGT and heatwave-day frequency, and the decomposition of sWBGT trends during heatwave days into temperature, relative-humidity, interaction and nonlinear-residual contributions (ERA5, 1979-2023). Stippling denotes field-significant trends after autocorrelation and false-discovery-rate adjustment. Source: Zhang et al. (2026).

Conclusions and implications

The principal scientific insight is that the effect of humidity on changing European heat stress is strongly regional. Warming increases heat stress throughout Europe, but humidity amplifies this increase in Northern Europe, has a relatively small and uncertain influence in Western and Central Europe, and partly moderates it in the Mediterranean. Heat-stress change therefore cannot be inferred from temperature trends alone.

The additive decomposition provides a transparent diagnostic framework for separating these effects. It shows that continental-scale trends are primarily explained by the direct temperature and humidity contributions, while also revealing that humidity-related changes are less spatially coherent and more observationally uncertain than temperature-related changes. The comparison with station records demonstrates the importance of local observations for evaluating heat stress, especially in hot urban environments where relatively small differences in humidity can produce appreciable differences in estimated risk.

The study contributes directly to EXPECT's aim of explaining the processes that shape European summer hazards. Its decomposition framework separates two immediate thermodynamic controls on heat stress and provides a basis for investigating why their contributions vary regionally. In particular, the humidity contribution can be examined further in relation to atmospheric circulation, moisture transport, land-atmosphere coupling and changes in land-surface moisture availability. The present analysis diagnoses the regional patterns but does not itself fully attribute the underlying humidity trends; that attribution represents an important next step for EXPECT.

The results also have clear implications for heat-risk management. Temperature remains the principal driver of worsening heat stress, but temperature-only warning indicators may overlook important regional and local effects of humidity. Heat-health planning should therefore consider combined temperature and moisture conditions, particularly in Northern Europe, where humidity is increasing the heat-stress response, and in warm southern cities, where heat-stress estimates are highly sensitive to local humidity observations.

More broadly, the rapid growth and geographical expansion of alert- and caution-level conditions show that dangerous heat is not confined to traditionally hot parts of southern Europe. Increasing exposure in central and temperate regions creates new challenges for populations, infrastructure and public-health systems that may be less well adapted to sustained heat stress.

BSC: Understanding hot temperature extremes using novel AI approaches

The Barcelona Supercomputer Center (BSC) team focused their efforts on three studies: It introduced a data-driven model (DDM) for seasonal prediction of European heatwaves (HWs), using machine-learning methods. The team also developed an explainable machine learning (ML) framework to quantify the relative influence of atmospheric circulation, soil moisture, and CO₂ in forcing on summer temperature extremes across six European and North African locations. In addition, the temporal dynamics of land-atmosphere coupling and its role in amplifying hot and dry extremes was investigated.

Data-driven seasonal forecast of European heatwaves

While artificial intelligence has recently achieved major successes in short-range weather forecasting, its application to long-range climate extremes has been limited. This work aims at addressing that gap by developing an interpretable AI-based forecasting framework capable of predicting the probability and intensity of European HWs up to three months ahead. Two main objectives guide the study:

- To improve understanding of seasonal-scale predictability of European heatwaves
- To develop a machine-learning methodology suitable for long-range climate forecasting.

Data and methodology

The DDM estimates both Tx90n – the seasonal number of days exceeding the smoothed 90th percentile of daily maximum temperature and the Heatwave Propensity Index (HWP) – a composite indicator combining heatwave frequency, intensity, and duration over each season. Forecasts are produced for ten European regions (from the Iberian Peninsula to western Siberia) across the four meteorological seasons (MAM, JJA, SON, DJF), trained on reanalysis datasets (ERA5 and ERA5-Land) covering 1950–2022.

The model uses predictors representing land, ocean, sea ice, and global atmospheric CO₂ concentration, capturing both local and remote climatic influences. The land predictors include soil moisture and temperature at different depths, latent and sensible heat fluxes, solar radiation, snow water equivalent, and their short-term trends. Ocean predictors are regional sea surface temperature (SST) anomalies across 18 basins (Atlantic tripole, Pacific ENSO regions, Indian Ocean dipoles, Mediterranean, etc.). Sea-ice predictors include concentration anomalies across four Arctic sectors (Barents–Kara, Siberian, Canadian, Alaskan). The global forcing is represented by the mean seasonal CO₂ concentration to characterize anthropogenic warming.

A Guided Hybrid Genetic Algorithm (GHGA) performs feature selection by optimizing mean squared error in cross-validation. The selected features feed a Random Forest (RF) regressor ensemble, chosen for its balance between accuracy and interpretability.

First, the GHGA is trained on the 49 seasons 1950–1998, in order to have a static selection of features that constrain the base learner. "Good" models are defined as those within 2 standard deviations of the estimated noise from the best solution found, and the union of features selected across all good models forms the feature set used for prediction. Then, the random forest performs the prediction using the pre-selected feature with the addition of the CO₂ concentration. Each year from 1999 is tested using an expanding-window training; therefore, each forecast for 1999–2022 is trained on all prior years, meaning that the 1999 season is predicted on a 49-year training (1950–1998), while the 2022 season is predicted on a 72 year training (1950–2021). Predictor importance is quantified via SHAP (SHapley Additive exPlanations) values, allowing physical interpretation of model outputs.

The DDM's performance is benchmarked against SEAS5, the ECMWF's dynamical seasonal prediction system.

Results

The DDM performs best for summer (JJA), when land-atmosphere coupling is strongest, achieving significant predictive skill in Western Mediterranean, Scandinavia, Western Siberia, and the Middle East (Figure 13). Spring and autumn show moderate skill in certain regions; winter forecasts exhibit little predictability, consistent with dynamical model limitations. The DDM generally predicts heatwave frequency (Tx90n) more accurately than intensity/duration (HWP). The model captures both long-term trends (increasing HWs since the 1980s) and specific historical events, demonstrating sensitivity to both forced and internal variability.

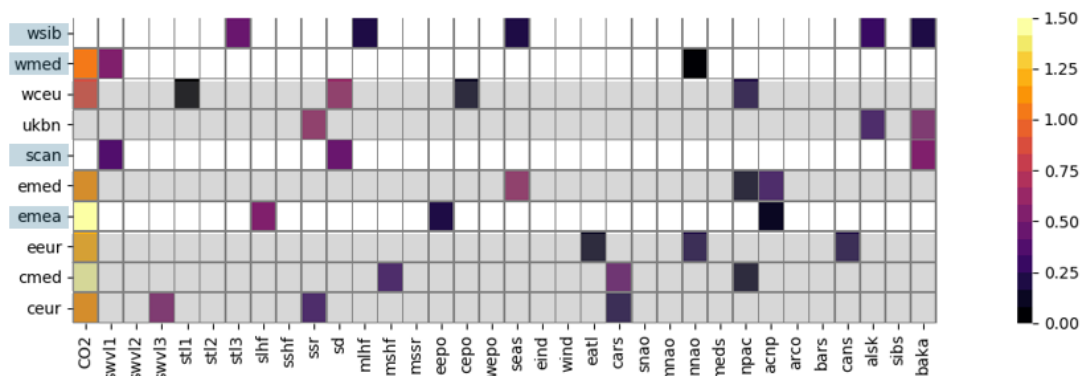


Figure 13. Importance matrix for the drivers selected by the genetic algorithm for HWP in the summer. Larger values indicate increasing importance for the prediction of regional HWP. Regions highlighted in blue are those where the coefficient of determination is significant at the 95% confidence level. Lines are shaded in grey for regions whose model's fit is not significant.

CO₂ concentration is the most influential predictor in nearly all regions and seasons, reflecting the strong anthropogenic warming signal driving heat extremes. Soil moisture emerges as a critical predictor in the Mediterranean and Scandinavia, where drying soils enhance sensible heating and atmospheric feedbacks. Spring snow cover and soil temperature influence subsequent summer heat extremes through albedo and soil-water feedbacks over Siberian regions. North Atlantic SSTs as well are associated with West Mediterranean summer heat, while Equatorial Pacific (ENSO) exerts teleconnected effects on the Middle East (Figure 13). The SHAP analysis on the West Mediterranean reveals that CO₂'s relative importance rises sharply after the 2000s, consistent with observed warming acceleration. It is also interesting to notice the rise in importance for soil moisture, that starts showing an evident increase in interannual variability starting at the end of the 1980s, suggesting nonlinear interactions with the warming background (Figure 14).

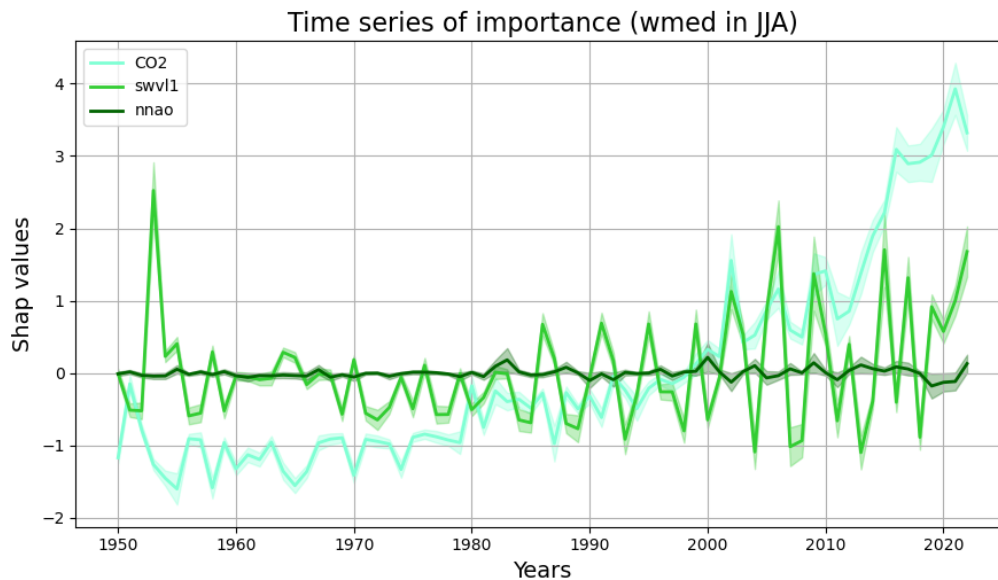


Figure 14. Time series of importance quantified by SHAP values for the west Mediterranean region. Celeste line shows the importance of CO₂, light green line the importance of soil moisture, dark green line the importance of the northern North Atlantic SST.

Conclusions and Implications

The study highlights the potential of machine learning for seasonal climate prediction of heat extremes, providing a transparent, explainable AI framework adaptable to other climate extremes. The DDM offers skill similar to a leading dynamical model while remaining interpretable, efficient, and inexpensive. However, several areas for improvement are identified:

- Inclusion of aerosol forcing, vegetation variability (e.g., leaf-area index), and stratospheric predictors (polar vortex, QBO) could enhance skill, especially for winter.
- Improved observational datasets for soil and vegetation processes are needed to reduce reanalysis biases.
- Managing the background trend component remains a methodological challenge—removing it isolates natural variability but can degrade forecast skill.

The manuscript “Data-driven seasonal forecast of European heatwaves” is under revision for Artificial Intelligence for the Earth Systems.

Quantifying atmospheric and land drivers of hot temperature extremes through explainable Artificial Intelligence

An explainable machine learning (ML) framework has been developed to quantify the relative influence of atmospheric circulation, soil moisture, and CO₂ in forcing on summer temperature extremes across six European and North African locations (Córdoba, Lyon, Hannover, Stockholm, Belgrade, and Marrakech). Here the timescale is much shorter, as heat extremes are predicted at the weather timescale. The framework also employs SHAP values (Lundberg and Lee, 2017) to interpret model predictions and attribute the contribution of each driver to daily hot extremes.

Data and methodology

The study used daily data from ERA5 and ERA5-Land reanalyses (1950–2024), including geopotential heights at 200 hPa and 500 hPa, sea-level pressure, and soil moisture at three depth levels. CO₂ concentrations from NOAA represent the anthropogenic forcing signal.

Temperature extremes are defined as days exceeding the 90th percentile of daily maximum temperatures, and additional tests at the 80th and 95th percentiles are carried out to assess the robustness of the methodology. To test the robustness of the results, the study also employs E-OBS observational data for temperature and the SPEI/SPI drought indices as proxies for soil moisture, due to the lack of long observational records of soil moisture.

A hybrid deep learning model (CombinedModel) was built for binary classification of extreme and non-extreme days. A ConvNeXt convolutional neural network (Liu et al., 2022) captures large-scale atmospheric patterns, while a multi-layer perceptron (MLP) processes the 1-dimensional local land-state and CO₂ predictors. Their outputs are merged in a final MLP classifier. A 20-member ensemble is trained using different random seeds, and the 50 % most confident predictions are analyzed with SHAP. Model performance was strong, with balanced accuracy above 80% for all sites.

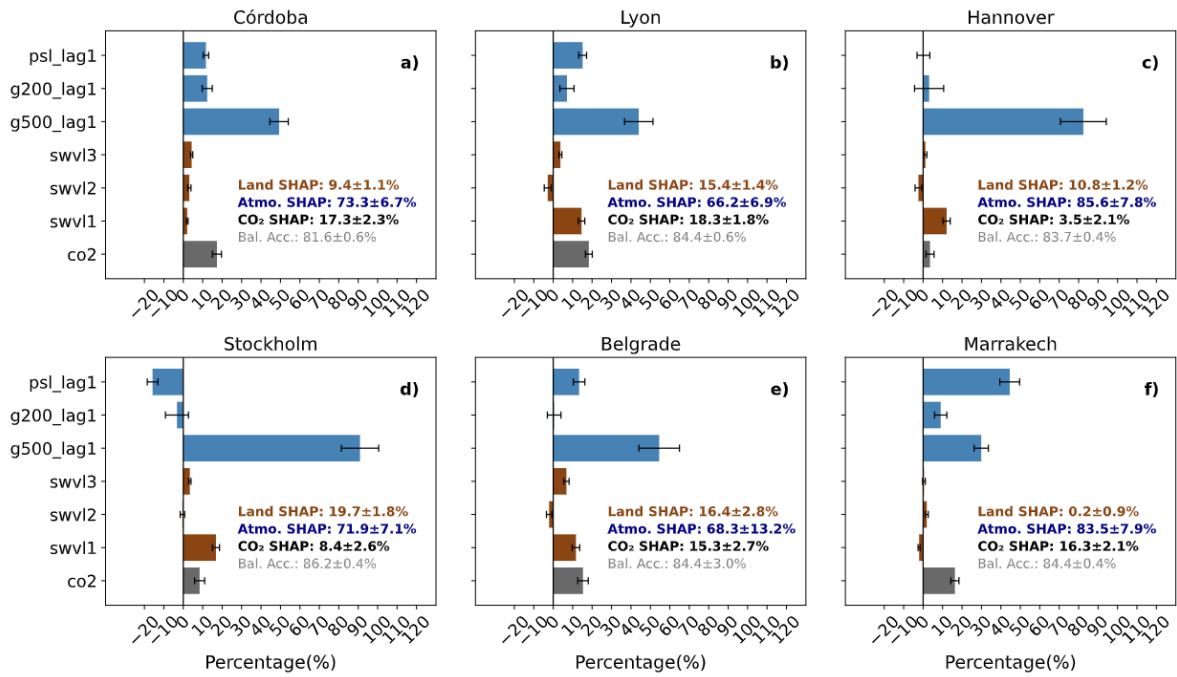


Figure 15. Extreme class prediction mean SHAP value percentage for the six locations, using the CombinedModel taking the 50% most confident predictions. The x-axis shows the contribution fraction of each feature, the y-axis indicates the feature labels. The text highlights the aggregated percent contribution of the land and atmosphere component, and that of CO₂.

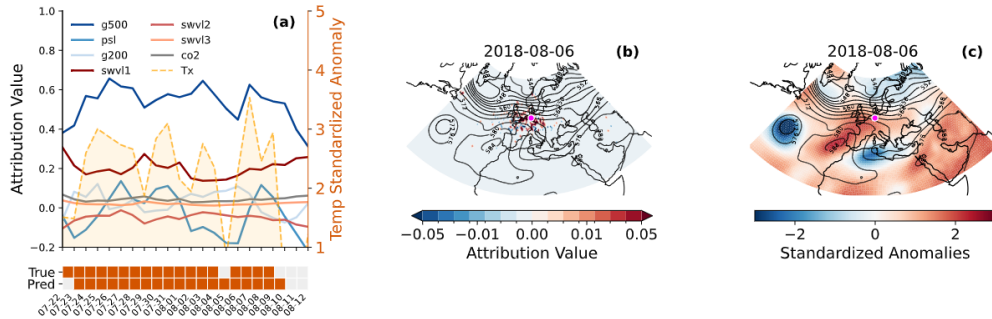


Figure 16. SHAP values for extreme class predictions for the Hannover case study. a): SHAP values temporal evolution for the circulation features and the three soil moisture levels. We additionally include temperature standardized anomalies (shaded orange area). The true and predicted labels are shown at the bottom, with orange indicating the extreme (class 1) and gray indicating a non-extreme (class 0) b): SHAP spatial distribution for the peak-day of temperature anomaly (7th of August). SHAP values with absolute magnitude smaller than 0.008 are masked to improve visual clarity. g500 contours for the day prior to the peak are included. c): Standardized anomalies of geopotential at 500hPa in colour and data in contours for the geopotential at 500hPa for the day prior to the temperature anomaly peak (6th of August). The magenta dot in panel b marks the location of Hannover.

Results

The same ML framework is being applied now to assess the same quantification of drivers in CMIP6 climate models. Compared with an ERA5 baseline, this can be used as a process-based evaluation tool of climate models.

For this comparison, SPEI at 30 days scale has been used to represent the land component, as the representation of soil moisture across CMIP6 models can be very different. The decision is supported by the results of the paper mentioned above, where SPEI30d yields similar driver quantifications using the explainable AI framework.

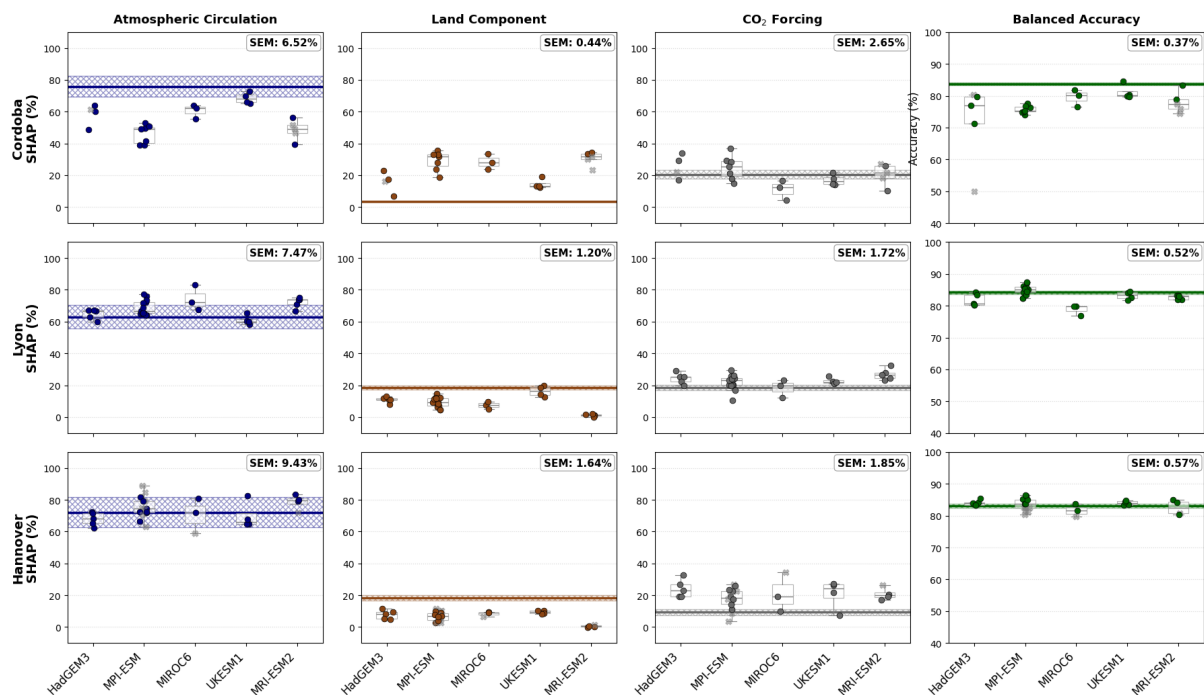


Figure 17. Comparison of SHAP-based driver importance (atmospheric circulation, land component, CO₂ forcing) and balanced classification accuracy for extreme temperature prediction, across three sites (Córdoba, Lyon, Hannover). Each row is a site; each column is a metric. The solid horizontal line and hatched band show the ERA5 baseline value and its standard error (SEM, from 20 random seeds). Boxplots and jittered points show the spread across CMIP6 model ensemble members (5 GCMs, multiple realizations each); colored dots mark members that have good balanced accuracy metric across different random initializations of the explainable framework, while gray X's mark members that fail it.

This figure allows to assess whether CMIP6 models represent well the importance of the drivers. For instance, in Córdoba we see an overall underestimation of the atmospheric component by the different models and members.

Currently, we are working on explaining why we see these differences in the attribution of the drivers across different models. For instance, a weaker atmospheric circulation importance could result from an underestimation of the magnitude of anticyclonic

circulation during a heatwave event. On the other hand, a lower land component importance could result from a lower land-atmosphere coupling representation in the specific climate model.

The study (Garcia Mesa *et al.*, 2026) is available as a pre-print in the “Weather and Climate Dynamics” journal and is under minor revision. DOI: 10.5194/egusphere-2025-5392.

Mapping the intense land-atmospheric coupling zone over Mediterranean during hot and dry extremes

Finally, BSC has mapped areas characterized by an intense land-atmospheric coupling over the Mediterranean. The Mediterranean region, characterized by a water-limited climate, is particularly vulnerable to hot and dry summers. Prior to these extreme events, the increase in both temperature and soil drying intensifies the mutual interaction between land and atmosphere. This heightened coupling is triggered when a critical threshold is reached. At this point, the sensitivity of atmospheric temperature to declining soil moisture increases significantly. When soil moisture drops below this critical point, the atmosphere becomes increasingly susceptible to heatwave conditions.

Data and methodology

This study investigates the temporal dynamics of land-atmosphere coupling and its role in amplifying hot and dry extremes. We analyze daily data from the ERA5-Land reanalysis, focusing on daily maximum air temperature and root-zone soil moisture (0–100 cm depth) from 1950 to 2025, specifically during the extended summer season, spanning May to September.

To identify the water-limited regime, we calculated the terrestrial coupling index (Dirmeyer, 2011, Figure 18). The methodology from Benson and Dirmeyer (2021) is implemented to identify the critical point beyond which land-atmosphere coupling becomes very intense, using segmented regression (Muggeo, 2008). To map out only the areas where the segmented regression is significantly different from the linear regression, Bayesian information criterion is used. In this way, we identified grid points characterized by “supercoupling”. We identified very hot days (VHDs) as days in which the maximum temperature anomaly exceeds the upper 95th percentile of the local probability density function based on the climatology (Stéfanon *et al.*, 2012).

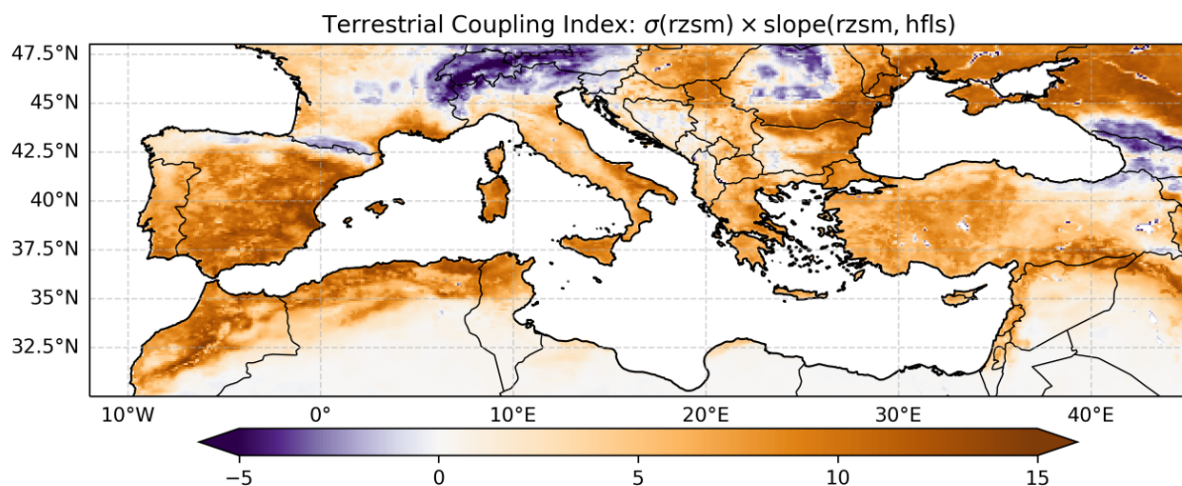


Figure 18: Terrestrial coupling index calculated using surface latent heat flux and root-zone soil moisture.

Results

In Figure 18, positive values of terrestrial coupling index (TCI) indicate a water-limited regime and negative values represent an energy-limited regime. As this study concerns water-limited regions only, the negative TCI regions are excluded from further analysis. Shown as the white areas in the land map in Figure 19.

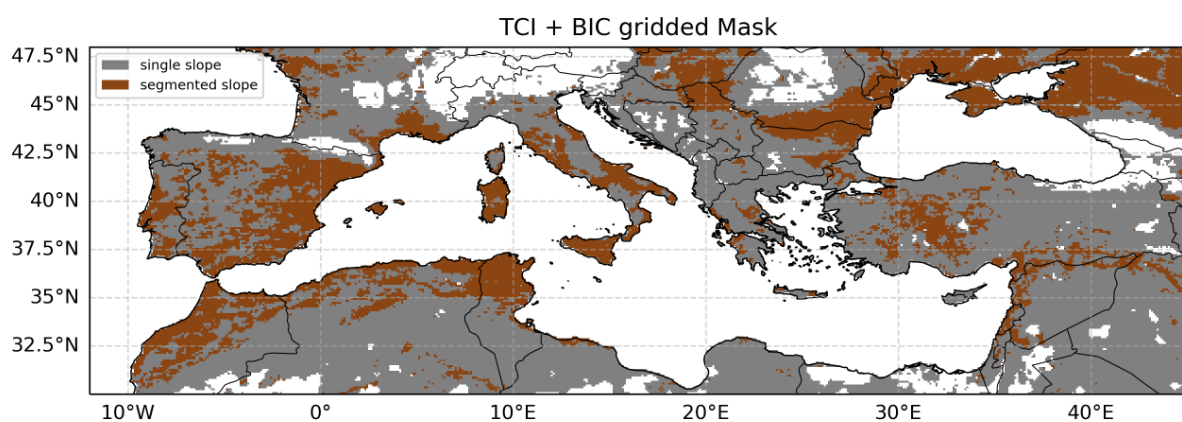


Figure 19: Mask of the regions where land-atmosphere supercoupling happens indicated in brown and the rest of the water-limited regime in grey.

Even though most of the areas of the Mediterranean are water-limited, only about half of its land area is subject to “supercoupling” (Figure 19). The northwestern coast of Africa, part of central Europe and the northern Black Sea are the main areas where this extreme land-atmosphere coupling takes place.

Figure 20 shows the relationship between daily root-zone soil moisture and near-surface air temperature for a single grid point in Eastern Europe. The top left quadrant

of the blue dashed line intersection is representative of all the days in which soil moisture and maximum temperature both went beyond the threshold. We then created maps of the time of the year in which the critical point is reached, how many days in a year, how many VHDs occur during supercoupling with respect to the total VHDs in the time series, etc.

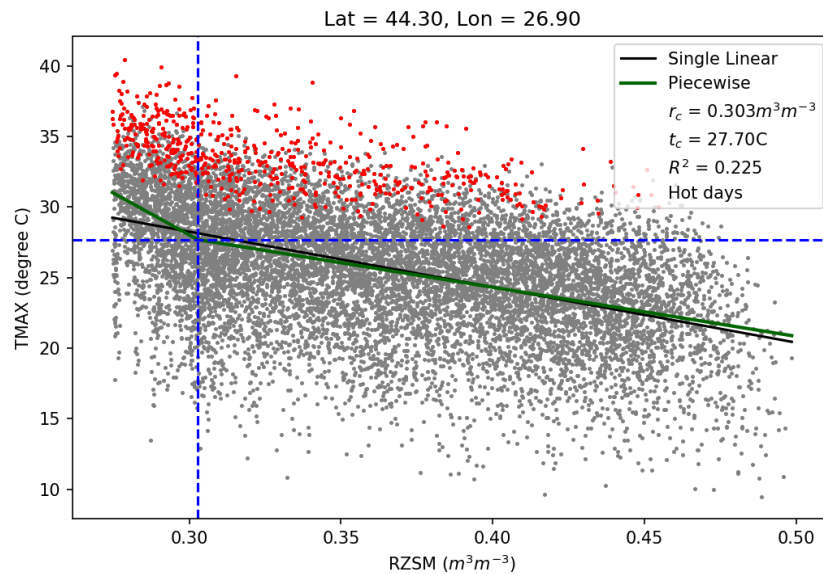


Figure 20: Example grid point analysis showing the changes marking the initiation of supercoupling between daily frequency root-zone soil moisture and maximum air temperature. The blue dashed lines correspond to the critical values of the corresponding variable and their intersection point determines the critical point where the linear regression slope becomes significantly different and more negative. The black line shows the single linear regression slope and the green lines represent the segmented slopes. The red dots are the very hot days. Very hot days are defined as the maximum temperature anomaly exceeds the 95th percentile of the local probability density function based on the climatology.

Figure 21 indicates that over the southern regions the critical point is reached early in mid May or early June while in most of central Europe it is reached during full summer, in late July or August.

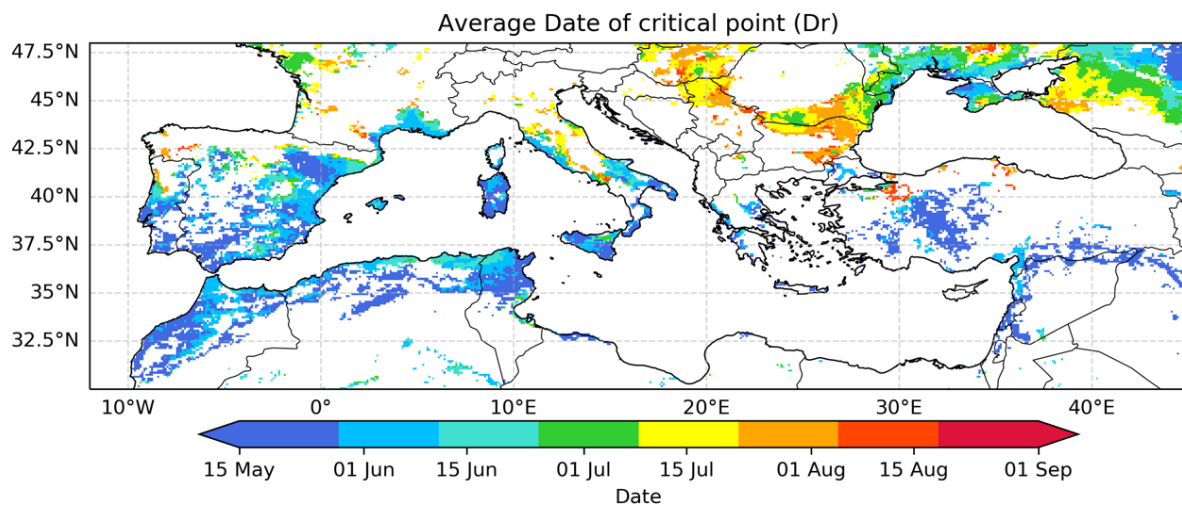


Figure 21: Climatological average date for reaching the critical point and the area going into supercoupling of land and atmosphere

Currently we are checking our results by repeating the same analysis with observational datasets like EOBS. A manuscript is in preparation.

We will further explore the detailed understanding of land-atmospheric coupling related to specific events of hot extremes. We will provide a framework for model evaluation in capturing this supercoupling. This work will be extended to global scale to implement the theory to other hotspot areas with land-atmospheric supercoupling.

ECMWF: Midlatitude circulation trends: The role of the Indian Summer Monsoon, external drivers and impact on surface temperatures

The European Centre for Medium-Range Weather Forecasts (ECMWF) contributed with investigations of the midlatitude circulation trends in boreal summer through dynamical linkages with the Indian Summer Monsoon through circumglobal teleconnections, the role of external drivers and impacts on surface temperatures over Europe.

The recent trend pattern in the midlatitude circulation resembles the so-called circumglobal teleconnection (CGT) pattern. The CGT is a leading mode of the summertime variability in the upper-level geopotential (*Ding and Wang, 2005*) and resembles a wavenumber 5 circulation anomaly centred on the subtropical jet stream. Hemispheric Rossby wave propagation is facilitated by the waveguidability of the subtropical jet where perturbations near the subtropical jet initiate wave amplification

that is confined to the region of strong westerlies in the jet centre which allow waves to propagate hemispherically (*Hoskins and Ambrizzi, 1993*). Perturbations near the jet associated with variability in the Indian summer monsoon (ISM) drive the CGT (*Ding and Wang, 2005*). Anomalous upper-level divergence resulting from deep convection in the monsoon perturbs the subtropical jet in the core CGT region (35-40N, 60-70E) and initiates wave development. The Indian Summer Monsoon (ISM), subtropical jet, and Rossby wave propagation are therefore studied here to explore the role of the ISM in the summer circulation trend.

The role of external forcing in driving climate trends necessitates the use of model experimentation. The Detection and Attribution Model Intercomparison Project (DAMIP, *Gille et al., 2016*) and Large Ensemble Single Forcing Model Intercomparison (LESFMIP, *Smith et al., 2022*) are coordinated efforts and have been used to attribute various trends to external forcing from either greenhouse gases, anthropogenic aerosols, or solar or volcanic (i.e. natural) forcing. For example, *Marquet-Carbonell et al. (2026)* used LESFMIP models to show external forcing from aerosols may be related to the midlatitude circulation trend, but the model response to such forcing is too weak.

An alternative to free-running climate simulations for studying the role of external forcing are initialised seasonal predictions. Seasonal prediction systems typically have smaller biases than CMIP-type of climate simulations and may therefore be beneficial for studying climate trends. In addition, frequent re-initialisation to the analysed state of the atmosphere and ocean provides the benefit of tying key modes of variability, such as ENSO, of the model to that observed. *Mayer et al. (2026)* recently documented a set of experiments using ECMWF's seasonal prediction system designed to enable attribution to various external forcings.

The simulations introduced in *Mayer et al. (2026)* are briefly described below and used to study the role of external forcing in various climate trends and daily temperatures over Europe.

Data and Methods

ECMWF's fifth generation reanalysis (ERA5) is used here to verify the seasonal hindcasts. Monthly mean and daily values of zonal wind and geopotential height at 200 hPa are used, plus meridional wind at 850 and 200 hPa (written as u_{200} , z_{200} , v_{850} and v_{200} , respectively). Daily mean values of 2-metre temperature are also included. We focus on boreal summer (JJA) in the period 1993-2023.

The data from the seasonal hindcasts are produced using an experimental version of ECMWF's seasonal prediction system (Cycle 49R2). The configuration is close to that of the next operational seasonal prediction system (SEAS6). 51 ensemble members are initialised on 1 May and run for 7 months for years 1993-2023. We consider forecast months 2-4 (JJA). All data are interpolated to a common 0.5x0.5 degree grid, except for 2m temperature for which a 2.4x2.5 degree grid has been used.

The hindcast experiments considered herein are fully described in (Mayer et al., 2026). A brief summary is given below. Anthropogenically forced climate change is either amplified or reduced in the hindcast experiments to simulate counter-factual worlds in which either extreme climate change or relatively little climate change has occurred. To simulate these counterfactual scenarios, changes to the atmospheric radiative forcing from CO₂ and ocean initial conditions (ICs) are implemented. The main experiments discussed here are:

- Control (CTRL): Control forecast with unperturbed radiative forcing and unperturbed ocean ICs (akin to the operational seasonal forecast).
- Constant CO₂/ocean (CONST): CO₂ concentrations from 1993 are used throughout the hindcast period and the forced pattern of ocean warming is removed from the ocean ICs after 1993.
- Double ΔCO₂/ocean (DOUB): the annual rate of increase in CO₂ is doubled after 1993. The forced pattern of climate change in the ocean ICs is doubled every year after 1993.

The forced pattern of climate change in the ocean ICs is an estimate of the accumulated impact of the altered atmospheric radiative forcing on ocean temperatures (i.e. given a doubling in the rate of CO₂ increase, we estimate how much the ocean ICs would be expected to warm). For a full description of the method used to obtain the forced pattern of ocean temperature changes, the reader is referred to Mayer et al. (2026).

We use several indices to describe features of the atmospheric circulation that are relevant for midlatitude extremes. A Monsoon Hadley Circulation index (MHI) is calculated to estimate the strength of the anomalous circulation associated with the monsoon (Goswami et al., 1999). It is defined as the shear of the meridional wind anomalies ($v_{850} - v_{200}$) in the region of the monsoon (here defined as 70-110E, 10-30N). The Rossby wave source (RWS) diagnostic (e.g. James 1995) is used to identify conditions that are favourable for the development of Rossby waves. The RWS is calculated on the 200 hPa wind field and is defined as

$$RWS = -\zeta D - v_{\chi} \cdot \nabla \zeta,$$

Where ζ is the absolute vorticity, D the divergence, and $-v_{\chi}$ the divergent component of the wind. European temperatures are defined as the daily mean 2-metre temperatures averaged over the European domain, defined as 0-30E, 45-55N.

Linear least squares regression is used here to calculate trends in various climate features. We also use a bootstrapped 1000-member ensemble to explore trends across the seasonal hindcast experiments. An ensemble member is selected at random each year (1993-2023) and then combined into a single time series to create a bootstrapped member. We repeat this 1000 times to get 1000 different ensemble member combinations that form the bootstrapped ensemble. As the seasonal hindcasts are

initialised each year, there is no need to consider the same ensemble member number across years, and any combination can be combined to produce a realistic evolution of the climate system.

Results

Role of the Indian Summer Monsoon in the circulation trend

The CGT is driven by variations in the strength of the ISM (Ding and Wang, 2005), with anomalously strong or weak monsoon circulations causing circulation anomalies in the core CGT region and driving CGT patterns of opposite sign. Time series of the strength of the monsoon circulation (MHI) are shown in Figure 22. There has been a significant decline in the strength of the ISM circulation in recent decades in ERA5. This has been documented in previous studies and has been related to a weakening land-sea thermal contrast resulting from a rapid rise in Indian ocean SSTs as well as an increase in aerosol concentrations over the Indian subcontinent (Roxby et al., 2015, Bollasina et al., 2011).

The seasonal hindcast experiments reproduce a decline in ISM strength, albeit weaker than in ERA5. Seasonal variability in ISM strength is also reasonably well captured in the model, with temporal correlations with ERA5 around 0.4. The magnitude of the trend, and temporal variability, of the MHI are most like ERA5 in the DOUB experiment. This may indicate that the model does not respond strongly enough to increasing CO₂ concentrations. The impact of anomalously strong or weak ISMs in driving extratropical summer circulation anomalies is now assessed using the RWS diagnostic.

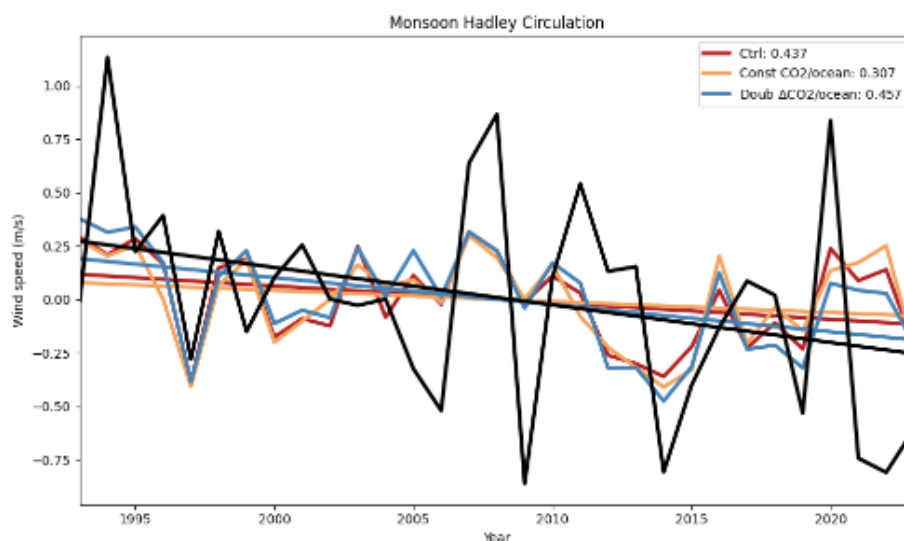


Figure 22: Time series of the Monsoon Hadley Circulation index. Time series are shown for ERA5 (black line) and the ensemble mean of the seasonal hindcast experiments. Values in the legend indicate temporal correlations between the experiments and ERA5.

The RWS diagnostic is designed to identify suitable conditions for the development of Rossby waves. Seasonal mean RWS values in the key region for the CGT (35-40N, 60-70E) are compared to seasonal mean MHI values to see if the monsoon strength relates to Rossby wave forcing in the core region of the CGT. Next, to determine the circulation response to variations in ISM strength, composite anomalies of the upper-level meridional wind are made for years with strong or weak ISMs. Strong and weak monsoon years are defined as those with a JJA average MHI above the 80th percentile or below the 20th percentile, respectively. Creating composites based on extremes that are defined using the 10th, 25th, 75th or 90th percentiles yield consistent results. A comparison of the MHI and RWS together with the monsoon circulation composites are shown in Figure 23.

The MHI and RWS have a significant negative correlation in ERA5 (Figure 23a). Seasons with strong monsoon circulations typically have lower averaged RWS values in the core CGT region, and vice versa. This is in line with the hypothesised mechanisms driving the CGT (Ding and Wang, 2005, 2007). Namely, variations in the strength of the ISM trigger circulation anomalies in the core CGT region that are favourable for the initiation of Rossby waves, here quantified using the RWS diagnostic. Significant negative correlations are also found in the seasonal hindcasts (not shown), with the correlations similar across the hindcast experiments (but weaker than ERA5). This suggests the monsoon's influence on circulation anomalies in the core CGT region is largely insensitive to the background climate state. However, changes to the likelihood of a particular monsoon state given changes in external forcing will drive changes in the CGT mechanism and the hemispheric circulation response.

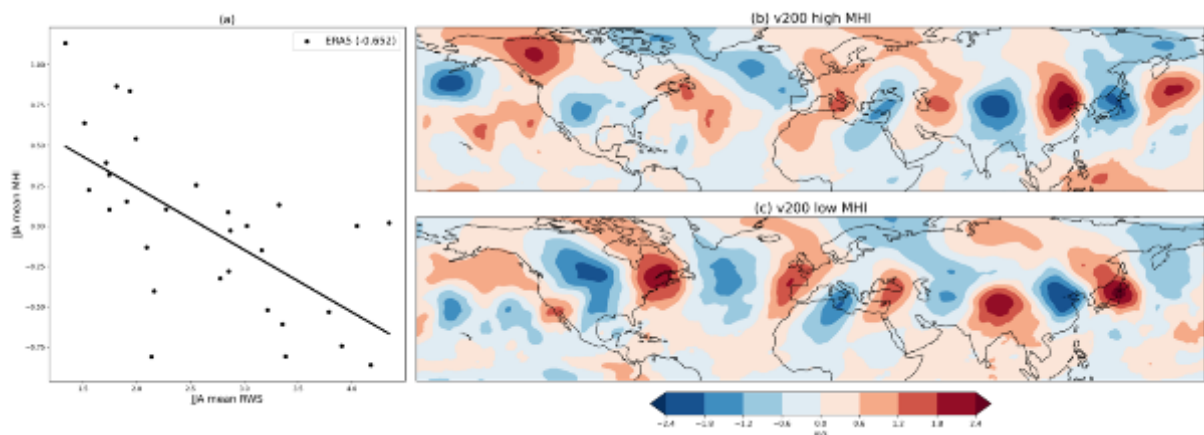


Figure 23: (a) JJA mean MHI compared to JJA averaged RWS in the core CGT region in ERA5. (b) Composite meridional wind anomalies at 200-hPa on occasions when the ISM is anomalously strong in ERA5. (c) As in (b) but for weak ISM years.

There are large circulation anomalies in years with either strong or weak monsoon circulations (Figures 23 b,c). The anomalies represent an amplified Rossby wave pattern along the subtropical jet, reminiscent of the canonical CGT (Ding and Wang, 2005), with the phase of the wave pattern largely opposite for opposing ISM

anomalies. Circulation anomalies based on varying ISM strength are weaker in the hindcast experiments (not shown).

Given the clear circulation impact of anomalous ISM years, and the significant weakening of the ISM, we hypothesise that the weakening ISM is contributing to the pronounced trend to an amplified wave pattern in the upper-level circulation observed in recent decades (Teng *et al.*, 2022). Trends in the 200 hPa meridional wind are shown in Figure 24 for ERA5 and the ensemble mean of the hindcast experiments. The trend in ERA5 shows regions of increasing meridional wind centred along the subtropical jet, indicating amplified wave activity. The trend pattern bears remarkable similarity to the circulation response to weak ISM years, particularly over Eurasia and North America. This supports the hypothesis stated above that changes in the ISM are contributing to the observed circulation trend.

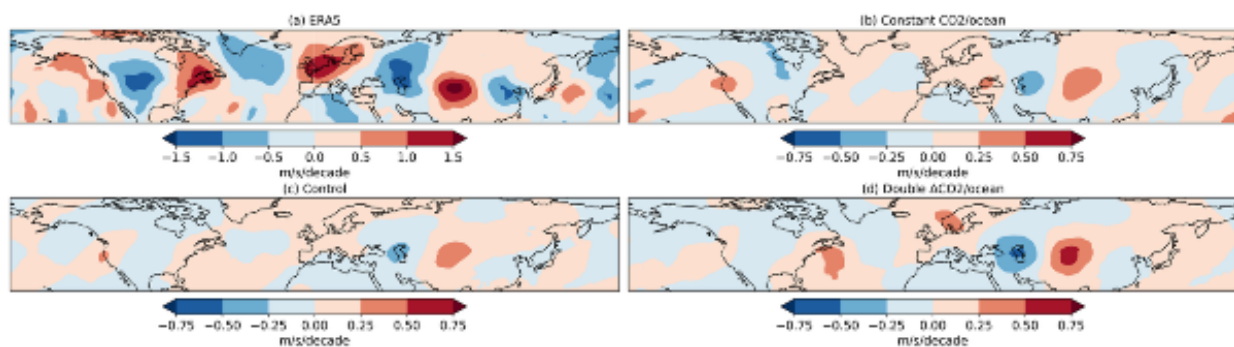


Figure 24: Trends (1993–2023) in the 200 hPa meridional wind. Trends are shown in ERA5 (a), and the ensemble mean of the counter-factual seasonal hindcast experiments (b)–(d).

Trends in the seasonal hindcasts are much weaker than in ERA5 (note the different colour scales used in Figure 24). This is partially expected given the trends are shown in the ensemble mean of the seasonal hindcasts and could signify that the trend in ERA5 is not a forced response to climate change. Alternatively, the model may not accurately represent the forced response in the midlatitude upper-level circulation. The strongest model trends are in the region central to the CGT and agree well (at least in sign) with the ERA5 trend. The trends in this region are consistent with the model trends in the ISM. Namely, a reduced ISM circulation inducing a low pressure anomaly to the northwest of India and an associated dipole in meridional wind (as seen in the trend maps). Additional analysis focussing on synoptic timescales reveals that circulation anomalies in this region do not propagate downstream in the model as efficiently as they do in ERA5 and may be related to biases in the latitude of the subtropical jet in the model (not shown).

The circulation trend is strongest in the amplified forcing seasonal hindcast experiment. This agrees with the strongest decline in ISM strength in that experiment (Figure 22) and improved wave response to circulation anomalies in the core CGT region (not shown). Understanding why increasing CO₂ emissions (and the associated ocean warming) appears to improve the model representation of the ISM and its midlatitude circulation

response is an important research direction to follow based on these results. It is important to accurately represent circulation trends if we are to understand future changes to surface weather extremes, such as extreme summer temperatures in Europe.

Atmospheric circulation impact on European summer temperatures

The counterfactual seasonal hindcast experiments can also be used to explore the role of atmospheric circulation in summer temperatures in Europe. Distributions of daily mean temperature for the years 2019-2023 are shown in Figure 25 for the CTRL and DOUB experiments. As expected, the impact of doubled CO₂ emissions and doubled ocean warming is an increase in European daily temperatures (Figure 25a), with a clear shift towards warmer temperatures in the DOUB experiment and an increase in the mean of the temperature distribution of around 0.7 Kelvin.

If the temperature increases observed in DOUB were primarily a thermodynamic response to the increased CO₂ concentrations (and ocean warming), we would expect similar temperature increases globally to those seen in Europe. Removing the global mean warming from the European temperature distributions therefore provides an estimate of the warming related to forced dynamical changes in the region. The forced changes to the dynamics may include changes to the upper-level atmospheric circulation such as those shown in Figure 24.

Distributions of daily maximum 2m temperature with the global mean removed are shown in Figure 25b. There remains a shift towards higher values in the European temperature distributions in the DOUB experiment even with the global mean removed, with a mean increase of around 0.3 Kelvin. This shift towards higher temperatures can be attributed to forced changes to the atmospheric circulation over the region. It is therefore essential that models have the correct circulation response to external forcing, a known problem in CMIP-style climate models (Shepherd 2014).

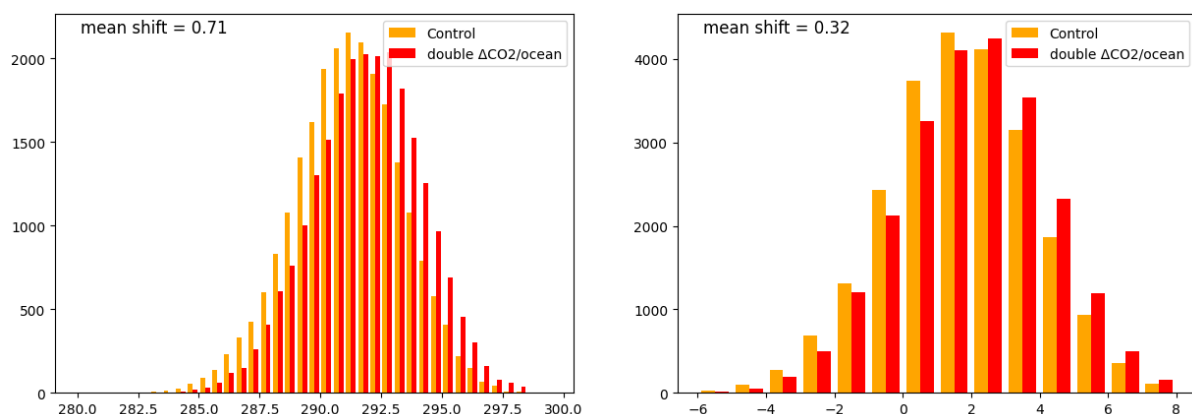


Figure 25: Left) Daily mean 2m temperatures during JJA over Europe from 2019-2023. Right) Same as left but for daily mean 2m temperature anomalies where the global mean is removed. Distributions are shown for the CTRL and DOUB hindcast experiments.

Conclusions and implications

The upper-level circulation in the northern hemisphere midlatitudes has exhibited a pronounced trend in recent decades. The trend resembles an amplified wave pattern across the northern hemisphere midlatitudes, largely focused along the subtropical jet. Understanding the drivers of this trend, and whether it is a result of changing external forcings is of large interest because of the large impact the upper-level circulation has on surface temperature extremes (e.g. *Horton et al., 2015*). Here, we have explored potential drivers of the circulation trend and used counterfactual seasonal hindcasts to understand the impact of external forcing on the model representation of the trend as well as the role of the externally driven circulation trends on European surface temperature extremes.

Trends in the upper-level circulation appear to be related to changes in the ISM, via the well-established circumglobal teleconnection (CGT, *Ding and Wang, 2005*). There has been a decline in the strength of the ISM circulation in recent decades in ERA5, which is well represented in the seasonal hindcast experiments. A weakened ISM circulation results in a low-pressure anomaly to the NW of India which can initiate hemispheric Rossby wave propagation. Indeed, composite anomalies based on summers with weak (lowest quintile) show an amplified wave along the subtropical jet. More frequent summers with weak ISM circulations (resulting from the decreasing trend in the ISM) are therefore driving more frequent amplified wave patterns with similar phase and structure to the trend pattern observed.

Whilst the seasonal hindcast experiments have a good representation of the monsoon trend and variability, their midlatitude circulation trends are generally much weaker than in ERA5. Trends in the core region of the CGT are well represented however, in agreement with the good model representation of the ISM. This implies that the model has a good representation of the monsoon's influence on local circulation anomalies, but an inaccurate representation of Rossby wave development triggered by these anomalies. Additional analysis suggests that the inefficient Rossby wave propagation may be related to biases in the latitude of the subtropical jet.

The amplified forcing experiment (DOUB) consistently has the best representation of processes involved in the ISM-CGT mechanism, as well as in the upper-level circulation trend. The consistency between the hindcast experiments in their representation of these processes adds evidence that the ISM-CGT mechanism is important for the circulation trend in the midlatitudes. Other processes, such as the triggering of regional Rossby wave patterns from different regions in the tropics (*Happé et al., 2025*), or multidecadal variability associated with the AMV (*Teng et al., 2022*), are likely also important for understanding the full trend pattern observed.

It is important to understand trends in the circulation due to the strong influence the circulation exerts on surface weather extremes. Using the seasonal hindcast experiments, European temperature changes under increased global warming are attributed to forced changes to the atmospheric circulation. If indeed forced circulation trends are favourable for increasing European temperatures, we can expect to continue to observe record breaking temperatures, like those experienced in recent summers (e.g. Vautard *et al.*, 2020; Trigo *et al.*, 2025), into the future.

Some implications from this work are summarised below.

The ISM is important for future European climate change. A weakening of the strength of the Indian summer monsoon circulation is shown to be contributing to the trend in midlatitude circulation. It is therefore crucial we understand the expected changes in the monsoon with climate change if we wish to understand changes to extreme European summer temperatures. It is therefore also crucial that the monsoon, and its interaction with the midlatitude waveguide, is well represented in the models used to study future changes. Lower resolution CMIP style climate integrations may struggle to represent the smaller-scale process involved in monsoon convection. The counterfactual seasonal hindcasts analysed herein may be beneficial owing to their higher resolution and generally smaller biases than their CMIP-style counterparts.

The seasonal prediction system may not respond strongly enough to CO₂ increases. Results from the counterfactual hindcast experiments suggest the seasonal prediction system used here may not respond strongly enough to increasing CO₂ concentrations, as results from the amplified external forcing experiment (DOUB) are closest to those obtained from ERA5. Understanding why this is the case, potentially related to the simplified cloud-aerosol interactions in the radiation scheme of the model, is important for model development and reliability of seasonal predictions under ongoing climate change.

Forced changes to the atmospheric circulation are contributing to European temperature increases. There remains an increase in European daily temperatures when comparing the CTRL and DOUB experiments even when the global mean temperature increase is removed. This indicates that changes to the atmospheric circulation in the amplified forcing experiment are driving faster-than-average temperature increases in Europe. The forced response of the atmospheric circulation to external forcing is uncertain (Shepherd 2014) but needs to be well understood for reliable future predictions of summer temperature extremes.

Overall, the results demonstrate that the circulation changes observed over Europe in recent decades are partly attributable to externally forced climate change and are linked to forced changes in the tropics that promote tropical-extratropical teleconnections. Further work is critical to better understand the circulation response to external forcing in models and to assess whether these models can reliably estimate future changes in surface weather extremes.

VUA: Dynamic and thermodynamic contributions to summertime warming and the extreme rainfall over Western Europe in July 2021

In recent decades, the Northern Hemisphere midlatitudes has experienced a pronounced summertime warming trend, which is particularly evident in Western Europe, where temperatures have increased at a rate at least twice that of the global mean (Vautard *et al.*, 2023). As a result, the frequency and severity of extreme weather events have increased. Examples are record-breaking hot and dry conditions (e.g., in 2023, 2022 and 2018) and heavy, persistent rainfall events leading to devastating floods (e.g., in 2021). Such extreme events have major impacts on both natural and socio-economic systems, affecting human health, agriculture, water resources, energy systems, and ecosystems (Fischer and Schär, 2010; Trenberth *et al.*, 2014; Horton *et al.*, 2016). While increasing anthropogenic greenhouse gas concentrations are the main driver of thermodynamic warming of the climate system, the regional manifestation of climate change is also strongly shaped by large-scale atmospheric circulation. Changes in circulation have the potential to amplify or dampen temperature trends, alter the spatial distribution of extremes, and influence their persistence.

Despite this recognised importance, the extent to which the circulation contributes to regional warming trends remains not fully understood, particularly for individual hotspot regions where the interplay between dynamic and thermodynamic drivers may differ substantially. This motivates our first research aim, which is to quantify the dynamic and thermodynamic contributions to summertime warming across multiple regional hotspots in the Northern Hemisphere midlatitudes.

Similarly, large-scale circulation plays a central role in shaping precipitation extremes. However, the moisture pathways and dynamical mechanisms that drive extreme precipitation, specifically during the summer season, have received little scientific attention. This motivates our second research aim, which is to investigate how large-scale dynamics govern extreme rainfall. We study this for a subset of extratropical cyclones over the North Atlantic and for a specific case of a summertime extratropical cyclone in the form of a persistent cut-off low-pressure system responsible for extreme rainfall over Western Europe in July 2021.

Temperature extremes: Disentangling their dynamic versus thermodynamic contributions

Despite widespread warming across the globe, the magnitude and pace of climate change vary regionally, with Europe and western North America identified as

prominent summer warming hotspots (Perkins-Kirkpatrick and Lewis, 2020; Kim *et al.*, 2023; Vautard *et al.*, 2023). This spatially heterogeneous surface warming across continents is strongly governed by atmospheric circulation changes, which is less well understood and reproduced in climate models than thermodynamic processes (Horton *et al.*, 2015; Shepherd *et al.*, 2014). Although long-term trends in upper-level circulation have been identified, their contribution to regional warming hotspots remains unclear. Moreover, the regional circulation changes lie outside the Coupled Model Intercomparison Project Phase 6 (CMIP6) model range (Happé *et al.*, 2025), which may result in an inability to capture the warming in hotspots.

In a new study by Liu *et al.* (*in review*), we address these research questions by separating recent summer near-surface warming into its thermodynamic and dynamic components in order to understand why certain mid-latitude regions have emerged as pronounced warming hotspots. We further assess whether climate models accurately capture each component using the CMIP6 models.

Data and methodology

We use near-surface temperature fields and upper-tropospheric zonal wind fields (300 hPa) from ERA5 reanalysis data, for the satellite era (1979–2023). The hourly atmospheric data are regridded to a $1^\circ \times 1^\circ$ spatial resolution and then averaged into daily means for further analysis. The climatology period is 1981–2010. We also use a multi-model ensemble of historical simulations (1979–2014) and future projections (2015–2100) under the SSP5-8.5 scenario, based on the daily outputs of 20 CMIP6 models (Eyring *et al.*, 2016).

With this data, we perform the dynamical adjustment method (Sippel *et al.*, 2019), to isolate the circulation-driven contribution to regional warming. This method decomposes the near-surface temperature T into three components: a dynamical component linked to the interannual variability of stream function $f_{ridge}(\psi)$, a long-term trend component associated with climate change $f_{linear}(\bar{T})$, and a residual component ε that is attributable to other processes (e.g., land–atmosphere feedbacks). Here, we apply a regularised ridge regression to establish the relationship between near-surface temperature and 500-hPa stream function and employ a linear regression to calculate the linkage between the near-surface temperature and annual global-mean temperature. The thermodynamic component is then defined as the residual obtained after removing the dynamics-driven component from the total temperature.

Results

The thermodynamic-dynamic decomposition reveals that atmospheric circulation changes have played a large role in the observed amplification of summer warming across several key Northern Hemisphere regions. Four hotspots stand out during mid-summer (July–August) (Figure 26): eastern Europe, northwestern China, eastern Siberia, and western North America. In eastern Europe, total warming over the past four

decades has reached approximately 0.6°C per decade, of which roughly half is attributable to dynamical changes. Northwestern China exhibits a similar proportion: total warming of nearly 0.5°C per decade, with half due to circulation shifts. Eastern Siberia shows an even larger dynamic share, with 0.28°C per decade of the 0.47°C per decade total warming attributable to circulation changes, amounting to nearly 60%.

Western North America presents a different case. Although it has experienced substantial warming of about 0.43°C per decade, the dynamically driven component accounts for approximately 0.16°C per decade, or about 37% of the total. This indicates that thermodynamic forcing plays a larger role here compared to the Eurasian hotspots. Nonetheless, even in western North America, circulation changes remain a non-negligible factor amplifying the warming.

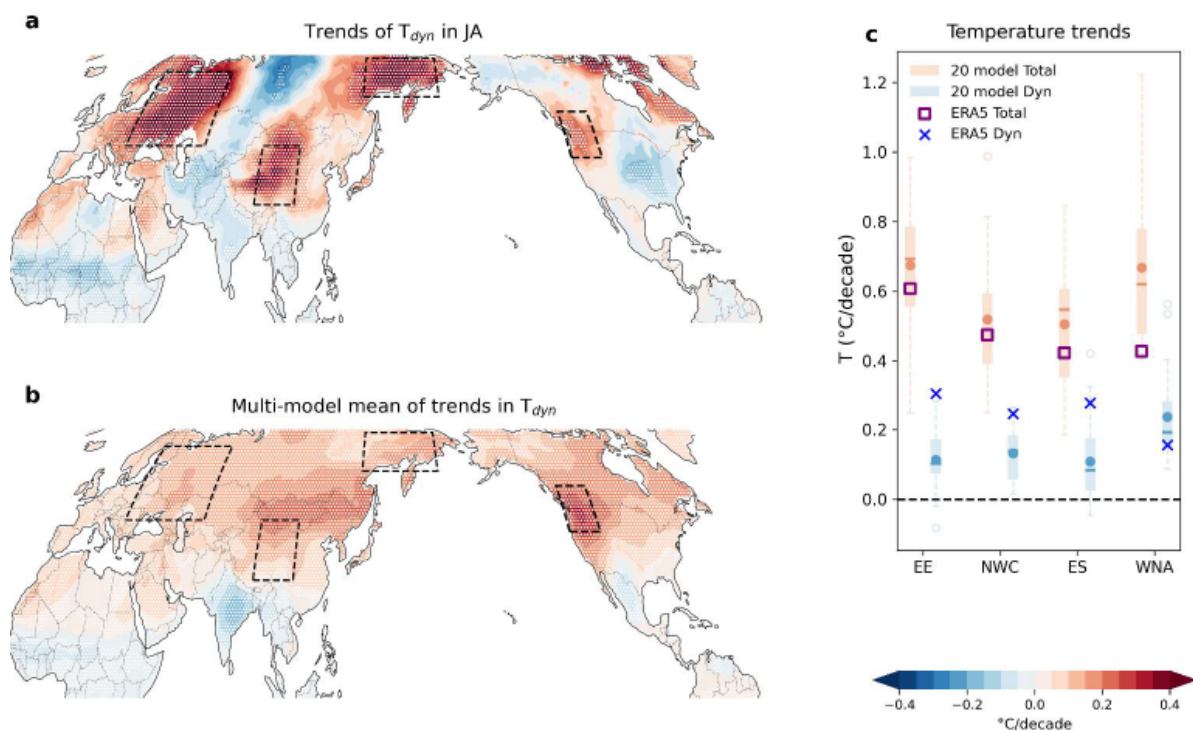


Figure 26: Trends in dynamics-induced temperature in July–August. a–b) Trends in the 75th percentile of dynamics-related surface temperature at 2m in $^{\circ}\text{C}/\text{decade}$ over July–August, based on ERA5 reanalyses (1979–2023) (a) and multi-model mean of 20 CMIP6 models during historical simulations (1979–2014) (b). Hotspots with pronounced dynamic warming trends in reanalyses are outlined by black dashed boxes in (a–b). These include eastern Europe (45° – 65°N , 22° – 60°E), northwestern China (32° – 50°N , 88° – 106°E), eastern Siberia (58° – 69°N , 135° – 175°E), and western North America (42° – 54°N , 110° – 125°W). c) Comparison of dynamic warming and total warming trends in the four hotspot regions between ERA5 reanalyses and 20 CMIP6 models.

The spatial structure of the dynamical warming component aligns closely with a distinct upper-tropospheric circulation pattern characterized by a tripole configuration of zonal wind anomalies. This structure consists of a westerly anomaly to the north of the hotspot, an easterly anomaly slightly to the south, and another westerly anomaly farther south. This Tripole Wind Anomaly (TWA) pattern explains a substantial fraction of interannual variability in circulation-driven temperatures (Figure 27). In parts of eastern Europe and western Russia, up to 70% of the year-to-year variability in dynamic temperature can be explained by fluctuations in the TWA index. Across the broader mid- to high-latitude band, roughly 40–50% of interannual dynamic temperature variability is attributable to this tripole wind structure.

In eastern Europe, about 60% of the dynamic warming trend ($0.18\text{ }^{\circ}\text{C}$ per decade out of $0.30\text{ }^{\circ}\text{C}$ per decade) is explained by the strengthening TWA pattern. In northwestern China, the TWA accounts for nearly half of the dynamical trend ($0.11\text{ }^{\circ}\text{C}$ per decade out of $0.25\text{ }^{\circ}\text{C}$ per decade). In western North America approximately 87.5% of dynamic warming trend ($0.14\text{ }^{\circ}\text{C}$ per decade out of $0.16\text{ }^{\circ}\text{C}$ per decade) is attributable to the amplified tripole wind pattern. In other words, almost the entire circulation-driven warming signal in that region is linked to the intensification of this specific upper-level wind configuration. Eastern Siberia, by contrast, shows only a weak regression-based contribution from the TWA.

Climate model simulations from CMIP6 reproduce the general spatial pattern of circulation-related warming but tend to underestimate its magnitude in several key Eurasian regions. Observed dynamic warming trends in eastern Europe, northwestern China, and eastern Siberia exceed the upper quartile of the model ensemble distribution. Western North America again stands out as an exception, where the observed dynamical trend lies within the model interquartile range, lending greater confidence to simulations for that region.

Overall, the thermodynamic–dynamic decomposition reveals that approximately half of recent summer warming in major mid-latitude hotspots has been dynamically amplified, that a coherent hemispheric tripole wind pattern explains a large fraction of both interannual variability and long-term trends in circulation-driven temperatures, and that while dynamical amplification may diminish in some Eurasian regions in the future, it is likely to intensify substantially over western North America.

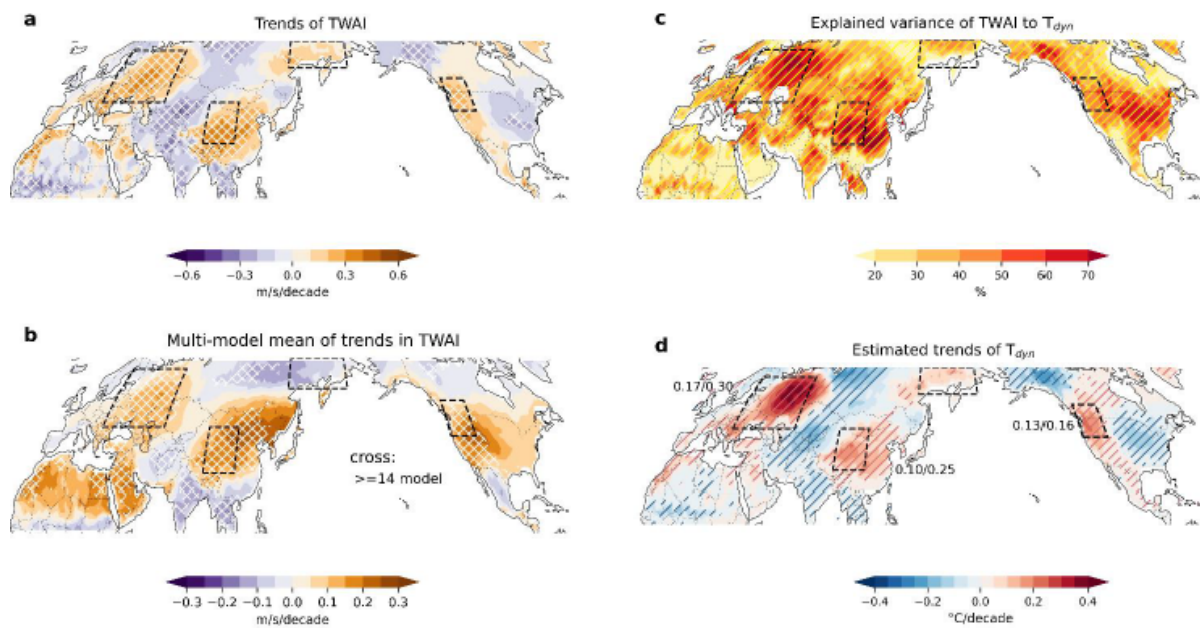


Figure 27: Intensified dynamical warming component over hotspots associated with an amplified tripole wind anomaly pattern. a) Observed trends in standardised tripole wind anomaly index (TWAI) in July–August. Statistically significant values ($p < 0.1$) are marked by white cross-hatching. b) Same as (a), but for multi-model mean of CMIP6 simulations in historical period. Cross-hatching in (b) indicates areas where at least 70% of the models show the same signs as (a). c) Explained variance of the dynamical warming component with respect to the standardised TWA index, where significant results at the 99% confidence level are hatched in. d) Estimated trends (units: $^{\circ}\text{C}/\text{decade}$) based on the TWAI changes. Coloured hatchings denote regions where the estimated trends account for at least 30% of magnitude of the dynamical warming component in Figure 26a. Regional average of dynamical trends and corresponding estimated trends for eastern Europe, Central China, and western North America (regions outlined by dashed black boxes) are shown in (d).

Precipitation extremes: Understanding their moisture sources and the influence of the large-scale dynamics

Extratropical cyclones are essential for redistributing moisture from lower latitudes to the poles, and are known for their ability to produce extreme precipitation. During summer, North Atlantic cyclones are responsible for transporting cool, moist air to Europe. Previous studies (e.g., Chemke & Coumou, 2024) suggest a weakening of this storm track in boreal summer, which could reduce such transport and potentially contribute to the observed warming and drying trend of European summers. However, these findings are often limited to zonal-mean metrics; there is limited evidence for regional changes within the North Atlantic, or whether such changes are due to fewer cyclones or weaker individual events. Moreover, while wintertime extratropical cyclones have been studied in great detail, little is known about these systems in summer. Nevertheless, studying summer cyclones is particularly relevant in the context of climate change, as future warming is expected to increase atmospheric moisture while reducing baroclinicity. Moreover, previous studies suggest that summertime rainfall extremes are expected to intensify in a warmer climate (Fowler et al., 2021;

Seneviratne et al. 2021; van de Vyver et al. 2023). This makes present-day summer conditions an analogue for future winter cyclones and critical for understanding how summertime cyclones themselves may evolve in a warmer climate.

Understanding the behaviour of summertime cyclones is essential, yet the cyclone-related water cycle remains largely unexplored. In *Stoffels et al. (2025)*, we attempt to establish a solid understanding of what drives precipitation and moisture uptake in the summer months. More specifically, we study the precipitation characteristics, moisture sources, and transport pathways of summertime North Atlantic deep cyclones.

When such intense cyclones make landfall, they can bring heavy rainfall and lead to flooding. The risk of flooding is particularly high if the low-pressure system becomes cut off from the prevailing westerly winds and remains in the same place for several days. An example of this occurred in Western Europe in July 2021, when a persistent cut-off low caused record-breaking extreme rainfall, resulting in significant damage and loss of life. In *Thompson et al. (2026)*, we investigate the dynamical situation that caused the extreme rainfall and examine how sensitive the rainfall is to the exact characteristics of the cut-off low-pressure system. We ask, were the dynamical conditions such that this event was close to a worst case scenario?

Data and methodology

We identify individual cyclone tracks over the North Atlantic using the cyclone identification and tracking scheme of *Sprenger et al. (2017)*. From these tracks, we select a subset of the most intense cyclones during the extended summer season (May–September) of 1980–2021.

For each cyclone, we use ERA5 reanalysis data to examine the precipitation distribution within a 500 km radius around the cyclone center, focusing on the 24 hours before and after the time of maximum intensity. We then determine the moisture origin by computing 8-day kinematic backward trajectories for all air parcels surrounding the cyclone centers, using the Lagrangian analysis tool LAGRANTO (*Wernli and Davies, 1997; Sprenger and Wernli, 2015*). This tool uses three-dimensional gridded wind fields on model levels and surface pressure data, on a 1-hourly resolution. The resulting trajectories are then analysed with the moisture source diagnostic WaterSip (*Sodemann et al., 2008; Sodemann, 2025*) to identify the moisture sources.

For the case study on the cut-off low, we use hourly reanalysis data, a boosted ensemble of a dynamically similar event generated using the Community Earth System Model Version 2 (CESM2) (*Danabasoglu et al. 2020*), and pseudo global warming (PGW) simulations of the event. The variables of interest are hourly fields of 500 hPa geopotential height (Z500), sea level pressure (SLP), relative humidity, specific humidity, and surface winds, and daily total rainfall. The PGW experiments are done using the KNMI Future Weather set-up (*Lenderink et al., 2025*). We assess the difference between simulations of the past (1.5 K cooler than present), present, and three

different futures (1.5 K, 3.0 K/dry, and 3.0 K/wet). We also use the same air parcel tracking method as described above.

Results

After using the cyclone identification and tracking algorithm, we selected the most intense cyclones and divided them into four groups based on the location where they reach their maximum intensity: the Gulf Stream region, the Labrador Sea, the East Atlantic, and the Nordic Seas. For these cyclones, the bulk of the precipitation falls close to the cyclone center beneath the warm conveyor belt (WCB) and along the fronts (Figures 28 a-d), mainly during the cyclone's intensification phase. This precipitation is driven by vertical motions, frontogenetic dynamics and thermodynamic (local) convection. Moreover, cyclones in the Gulf Stream region exhibit the highest precipitation rates throughout their entire life cycle. This can be attributed to higher surface evaporation over a relatively warmer ocean surface in this region, which significantly moistens the boundary layer and supplies the cyclones with more moisture than in the other subregions. There are three moisture source regions that can be identified: (1) the warm side of the Gulf Stream Front, where evaporation from the ocean surface is particularly strong; (2) continental sources, which are especially relevant for cyclones in the Labrador Sea; and (3) a south-eastward extension of the moisture source footprint into the subtropics, likely reflecting the influence of cyclones with tropical origins that are present in the East Atlantic and Gulf Stream region (Figures 28 e-h). Another region of high surface evaporation, though not necessarily contributing to the precipitation in the cyclone center itself, is within the cold sector of the cyclone. The moisture accumulated here can act as a source of moisture for a subsequent cyclone.

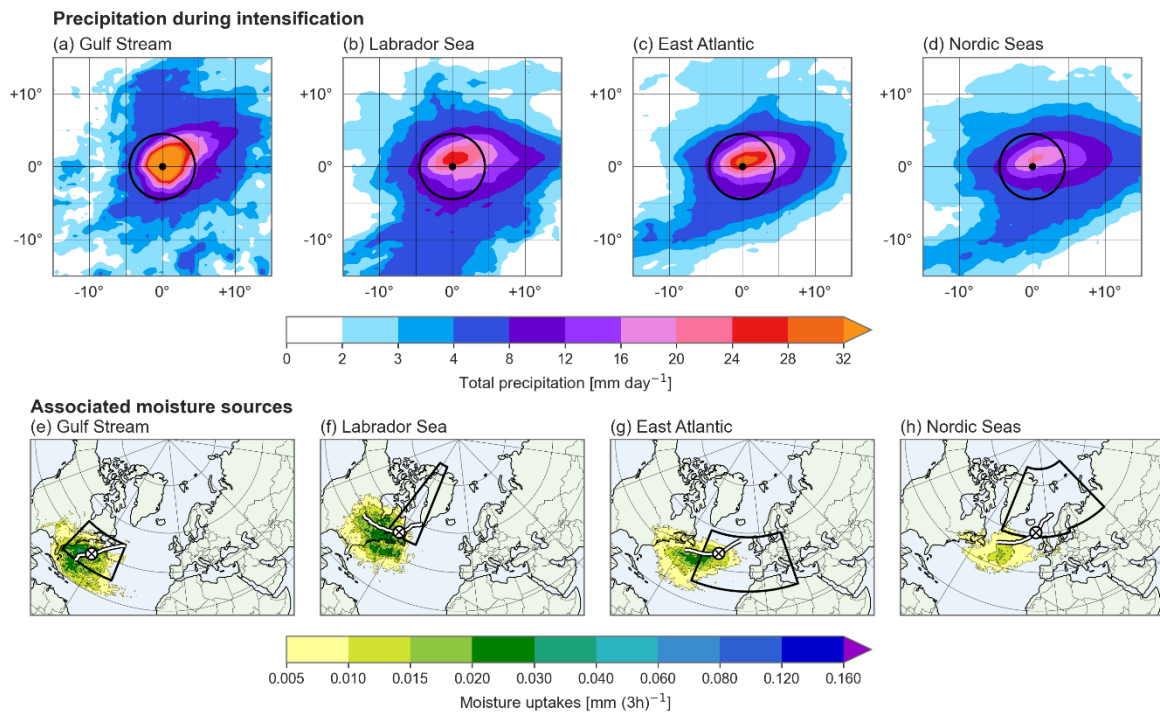


Figure 28: Cyclone precipitation and the associated moisture sources. a-d) Cyclone-relative composites of the mean total precipitation (in mm day⁻¹) of the cyclones in (a) the Gulf Stream, (b) the Labrador Sea, (c) the East Atlantic, and (d) in the Nordic Seas during the intensification phase. Precipitation is averaged over a 12-hourly interval. Additionally shown are the cyclone center location (black dot) and surrounding circle with a radius of 500 km (black circle). e-h) Climatological mean moisture source footprints of moisture uptakes contributing to precipitation in the cyclone center of the cyclones in the same four subregions (outlined by black boxes). Additionally shown are the mean cyclone track (white line), and the mean cyclone center location at the time of the precipitation (white cross).

In *Thompson et al. (2026)* we examined a specific case of a summertime extratropical cyclone in the form of a persistent cut-off low, responsible for the record breaking extreme rainfall in Western Europe in July 2021. We assessed the influence of the large-scale dynamics on the extreme rainfall, evaluating the sensitivity of the rainfall to the specific circulation pattern of this event. Using multiple lines of evidence we found that small changes in the position and magnitude of the cut-off low act to reduce the total rainfall over the region. Using a boosted ensemble of a dynamically similar event, we discovered that the large-scale dynamics of extreme rainfall events are highly sensitive to the initialization of the model, i.e. small perturbations in the model setup act to drastically reduce the magnitude of the rainfall (Figure 29). Comparing the difference between the five wettest and five driest members provides insight into why: a stronger SLP gradient over the region, as shown in Figure 29, will lead to stronger surface winds and drive strong ascent, like observed in the 12 h immediately prior to the extreme rainfall (Figure 30). Prior to ascending, the air parcels in the observed event and wet members that reached the target region were advected from levels below ~2 km. This enabled them to gain moisture given the higher temperature and the saturation vapour pressure at low levels. In contrast, the dry members show many trajectories

reaching the target region originating from dry upper-level parcels with little ascent at the time of the event.

In addition, we studied how the event could play out in a different climate state using pseudo global warming simulations. We find that in the cooler, past climate the modelled event is wetter, whereas in the future climate the event appears drier (Figure 31). This is contrary to the changes expected from simple thermodynamic considerations – as the world warms the atmosphere can hold more moisture and extreme rainfall events are expected to get wetter (Fowler *et al.* 2021). It seems that the future dynamical changes, as reflected by the SLP change (Figures 31 o-r), act to weaken the cut-off low, counteracting the increased precipitable water (Figures 31 s-w), driven by thermodynamical changes.

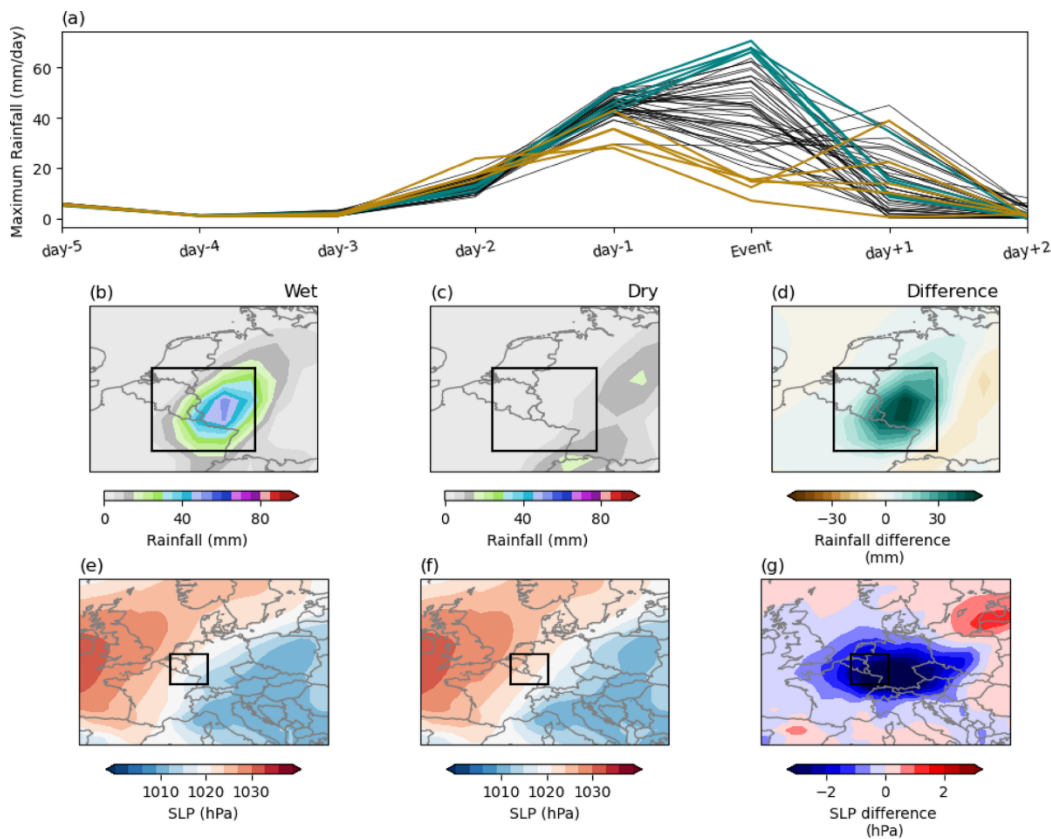


Figure 29: Differences within ensemble forecast. a) Forecasts of daily rainfall for 14th July 2021, initialised between 10th July to 14th July. Blue and orange dots indicate the wet (blue) and dry (orange) ensemble members used in (b-g). b) Composite of the total daily rainfall for the five wet simulations. c) As in (b) for five dry simulations. d) Difference between wet and dry composites for rainfall. e-g) As in (b-d) for sea level pressure. Box in (b-g) indicates region used in (a).

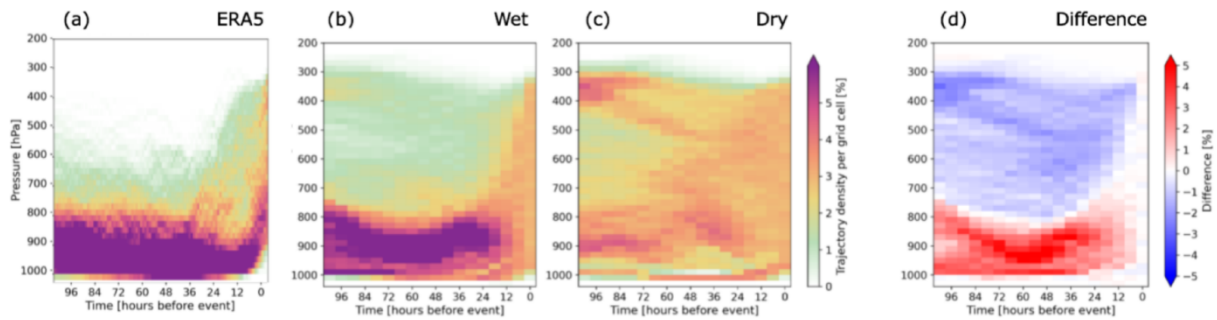


Figure 30: Tracking the air parcels that are in the region at the time of the event. a) Vertical location of the air parcels that are in 48 to 52 °N, 4 to 9 °E at the time of peak rainfall from ERA5. b) Composite of the 5 wet simulations showing the vertical locations of the air parcels that are in 48 to 52 °N, 4 to 9 °E at the time of peak rainfall. c) As in (b) for the 5 dry simulations. d) Difference between the wet and dry composites.

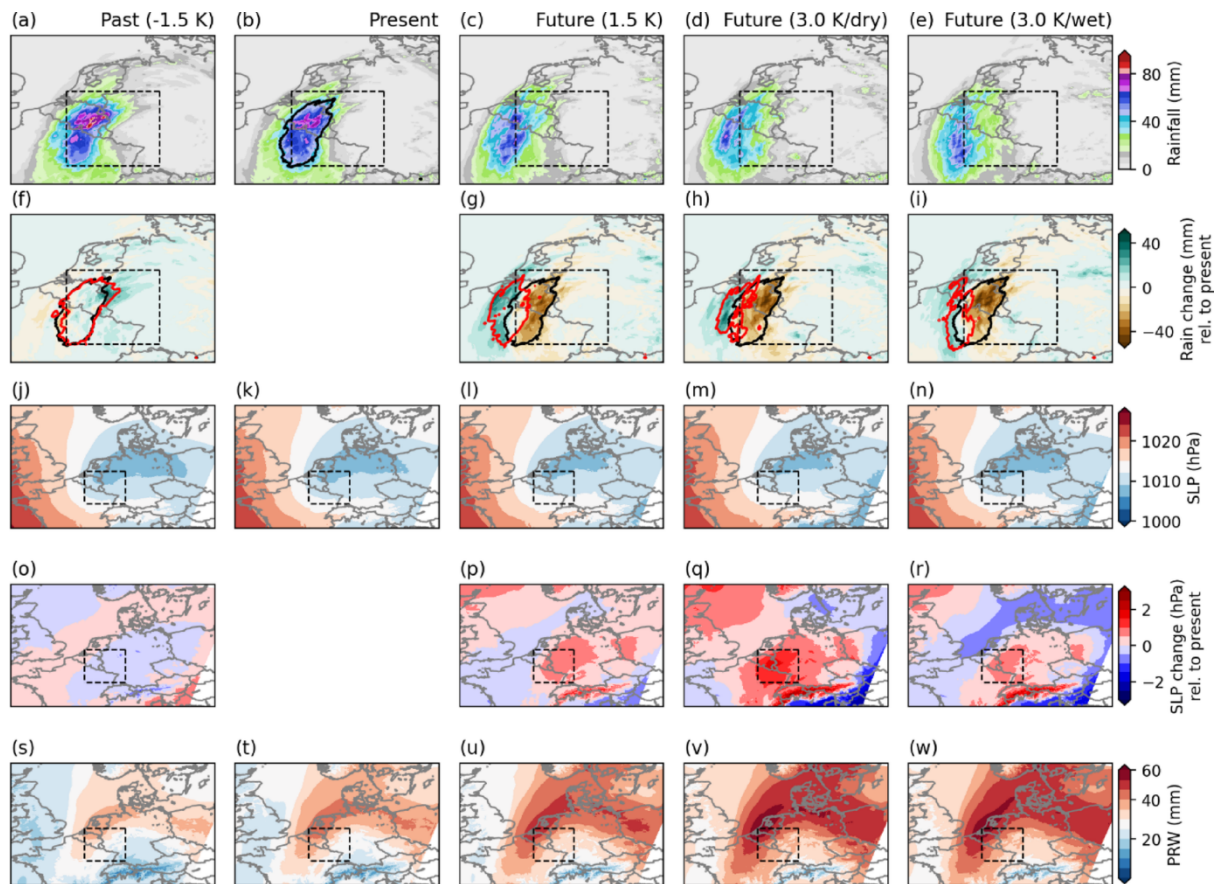


Figure 31: Pseudo global warming ensemble of 14th July 2021. a-e) Composite of ensemble mean of daily rainfall totals for the event day in past, present, and three future scenarios, initialised from 0000 on 13th July. f-i) Differences between present day simulations and other scenarios for rainfall. j-r) As in (a-i) showing SLP. s-w) As in (a-i) showing total precipitable water. On all, the box indicates the defined event region

Conclusions and new scientific insights

In *Liu et al. (in review)*, we find that climate models underestimate dynamics-induced warming over Eurasian hotspots but compensate for this by overestimating the thermodynamic component. Consequently, they reproduce total warming trends over Eurasian hotspots but do so for the wrong reasons. In contrast, climate models simulate the dynamics-induced warming in western North America reasonably well.

The underlying dynamical components of the regional warming relates to a north-south-oriented tripole wind anomaly (TWA) pattern characterised by westerly–easterly–westerly zonal wind anomalies concurrent with extreme heatwaves. Variability in this TWA pattern explains up to 70% of the dynamics-induced interannual temperature variability and at least 50% of its long-term warming trend in hotspot regions.

By analysing a subset of the most extreme summertime North Atlantic cyclones, it was found that the bulk of the precipitation falls close to the cyclone center beneath the warm conveyor belt (WCB) and along the fronts (Figures 28 a-d), mainly during the cyclone's intensification phase. This moisture originates from areas of high ocean evaporation, with significant hotspots on the warm side of the Gulf Stream Front and some continental sources (Figures 28 e-h). Moisture uptake occurs primarily in regions where the strong SST gradient induces intense ocean evaporation and during cold-air advection within the cyclone's cold sector, where oceanic evaporation is enhanced due to the strong air-sea temperature contrast. The moisture accumulated in the cold sector of the cyclone does not necessarily contribute to precipitation in its own center, but it can act as a source of moisture for a subsequent cyclone. Overall, these results are fairly similar to those found in a previous study for winter cyclones (Papritz et al., 2021), although in winter there is more moisture exchange between primary and secondary cyclones, and stronger vertical ascent in the WCB. Summer cyclones, on the other hand, are distinguished by their greater moisture supply from continental sources, and the significant influence from cyclones of tropical origin undergoing extratropical transition.

In *Thompson et al. (2026)* we assessed the influence of the large-scale dynamics on the extreme rainfall in Western Europe in July 2021, evaluating the sensitivity of the rainfall to the specific circulation pattern of this event. Using multiple lines of evidence we found that small changes in the position and magnitude of the cut-off low act to reduce the total rainfall over the region. Using a boosted ensemble of a dynamically similar event, we discovered that the large-scale dynamics of extreme rainfall events are highly sensitive to the initialization of the model. Moreover, we show that using pseudo global warming simulations, future dynamical changes may outweigh thermodynamical effects for this specific event, reducing the rainfall should such an event occur in a warmer climate.

Implications for EXPECT and beyond

Together, the new findings in Parts A and B contribute to the objective of Task 5.1 of Work Package 5: Diagnostics to study the role of large-scale atmospheric circulation patterns for past and present summer temperature and precipitation extremes. Our work on temperature extremes directly addresses this aim by identifying a specific circulation signature — the tripole wind anomaly pattern — that links regional warming hotspots to concurrent heatwave conditions.

Our work on precipitation extremes is somewhat more indirectly linked to this objective. Rather than analysing large-scale patterns such as (circumglobal) Rossby waves or atmospheric blocking directly, we focus on a more regional scale. However, we consider this an essential step: understanding how regional-scale systems such as extratropical cyclones and cut-off lows translate large-scale circulation into localised moisture transport and precipitation extremes helps to interpret cross-scale interactions between large-scale drivers and the hazards they ultimately produce. This work also contributes to Theme 2 objectives, particularly those focused on explaining recent trends in Northern Hemisphere circulation and understanding how it will change in the future. After all, meaningful attribution of such trends requires a robust climatological understanding of the relevant processes first.

Met Office: Northern Hemisphere circulation trends and surface temperature response in climate models

Recently several long-term atmospheric circulation trends have been highlighted (Coumou *et al.*, 2018) including those in Rossby waves (Fragkoulidis, 2022; Sun *et al.*, 2022; Teng *et al.*, 2022). The drivers of such trends, their impacts on extreme events, and their representation in climate models are poorly understood. One area of current interest is the Northern Hemisphere summer atmospheric circulation trend over recent decades (1979-2020) which projects onto a circumglobal zonal waveumber-5 Rossby wave train. This trend resembles the waveguide teleconnections with centres of action that have been linked to extreme summer events (Choi *et al.*, 2020; Kornhuber *et al.*, 2019, 2020). Such events include the 2010 Russian heatwave, European heatwaves, Siberian precipitation, Pakistan floods and US West Coast wildfires. The drivers of these trends have been linked to both Pacific and Atlantic variability, but what is driving Pacific and Atlantic variability remains unclear. Both the atmospheric circulation and SST trends, especially in the Pacific, are poorly represented in models; observations show a La Niña-like trend in the Tropical Pacific over recent decades, whereas the majority of models project an El Niño-like pattern. This disagreement in Pacific variability and its implications has been extensively discussed (eg. Chung *et al.*, 2019; Coats & Karnauskas, 2017; DiNezio *et al.*, 2013; Kociuba & Power, 2015; Lee *et al.*, 2022;

Power *et al.*, 2021; Seager *et al.*, 2019, 2022; Watanabe *et al.*, 2020; Wu *et al.*, 2021) with consensus yet to be reached.

Many papers have highlighted the need to better understand and predict the tropical Pacific SST variability in order to better predict summer atmospheric circulation and consequent weather extremes (Sun *et al.*, 2022).

Data and Methodology

We use coupled climate model data from the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP). Single forcing experiments are driven with changes only in the forcing of interest while all other forcings are held at pre-industrial values. In this work we examine hist-nat (natural forcings, solar and volcano only, 203 members) and historical (all forcings, solar, volcano, GHG, aerosol and land use, 391 members). We use data for boreal summer (JJA, 1860-2014), and compute anomalies by removing the seasonal cycle. To compare to the real-world response, we use ERA5 monthly reanalysis for 1940-2014. We focus on the recent period of 1979-2014 to be consistent with literature. In this work we look at geopotential height at 200hPa with the zonal mean removed, and surface air temperature with the global mean removed.

To quantify the wave 5 circulation, we use a wave 5 index as in (Marcet-Carbonell *et al.*, 2026) calculated as the sum of the absolute value of the average of the highs of the wave (yellow boxes in Figure 32), plus the lows of the wave (blue boxes in Figure 32). The boxes are defined as 20°x20° centred at – Positives (27.5°E, 47.5°N), (97.5°E, 42.5°N), (155°E, 57.5°N), (145°W, 35°N), (62.5°W, 47.5°N), and Negatives (65°E, 42.5°N), (120°E, 35°N), (175°E, 35°N), (85°W, 42.5°N), (17.5°W, 52.5°N).

We follow a ‘wave matching’ regime similar to the NAO matching used in (Smith *et al.*, 2020). We select the 20 ensemble members that best match the observed wave 5 index at each timestep. From this we create a constructed ensemble mean and can project this onto different fields.

Results

Figure 32 shows a clear link between trends in geopotential height at 200hPa, surface temperature and heatwave occurrence in reanalysis, as demonstrated in Teng *et al.*, (2022), with the centres of action of wave trend aligning with the hotspots in both the temperature trend and in the trend in heatwave occurrence.

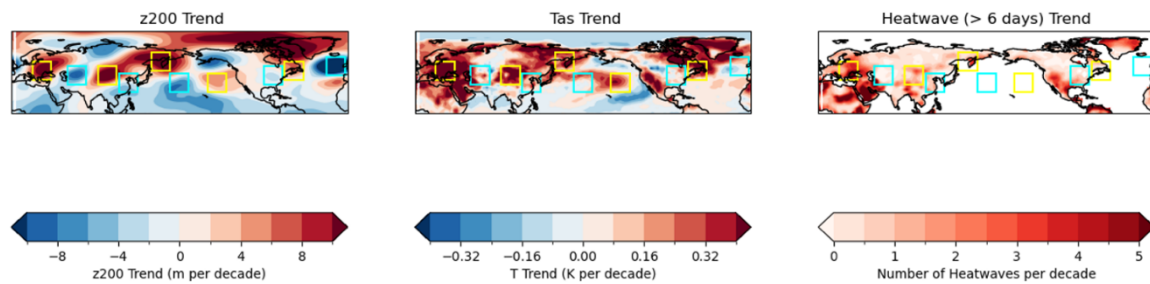


Figure 32: Trends 1979-2014 for ERA5 reanalysis, for trends in a) geopotential height at 200hPa with the zonal mean removed, b) Near surface air temperature with the global mean removed, c) number of heatwaves, classed as more than 6 days exceeding the 95th percentile of the 1970-1991 climatology. Yellow boxes highlight centres of action as defined in Marquet-Carbonell et al., (2026), (10°–50°E, 40°–60°N), (90°–120°E, 35°–65°N), (150°–180°, 50°–70°N), (130°–110°W, 30°–50°N), (100°–50°W, 60°–80°N), and (20°–0°, 20°–35°N).

However, models struggle to reproduce these trends. The wave-5 index is shown in Figure 33a) and 34a) for hist-nat and historical respectively. Neither multimodel ensemble (MME) mean is able to capture the observed trends and amplitude in the wave 5 index. The correlation between the MME mean and observations is low for hist-nat (0.04) but is medium for historical (0.501). However, the Ratio of Predictable Components (RPC) for historical is 3.04, which is greater than 1, indicating that there is signal to noise error present in the wave 5 index for historical and models underestimate the changes. The model's inability to capture observed trends is further demonstrated in Figures 33d) and 34d) which show that neither the hist-nat nor the historical MME mean reproduces the observed wave pattern, with both experiments showing a weaker amplitude than observed. The models not being able to reproduce the observed circulation response impacts temperature predictions. The temperature trend in the historical MME (Figure 34e) shows widespread warming over land and does not capture the observed relative cooling trend over central North America and western Asia.

However, when we sub-select members that most closely match the observed wave 5 index we find that this improves the temperature trends. In Figure 33f) we see that sub-selecting members based on the wave 5 index improves the wave representation although there are still key differences to the observed pattern, such as the centre over western Asia not being present in the models. Despite these imperfections, this greatly improves the temperature trend, with the matched temperature trends showing clear relative cooling trends over Eastern Asia and North America as in the reanalysis.

The temperature results for historical are less clear due to more surface warming over land being present. Looking at the impact of matching (the difference between the matched result and MME mean, Figure 34i), we see a very similar pattern to that in hist-nat, with a relative cooling coinciding with the centres of action of the wave pattern, suggesting that although wave matching improves the temperature response, the

dynamical temperature response from the circulation pattern is overwhelmed by surface warming from GHGs.

We also see a La Nina response in both hist-nat and historical from the wave 5 index matching indicating a link between the model's to simulate the tropical Pacific and the extratropical circulation trends. We plan to do further work investigating the links between these.

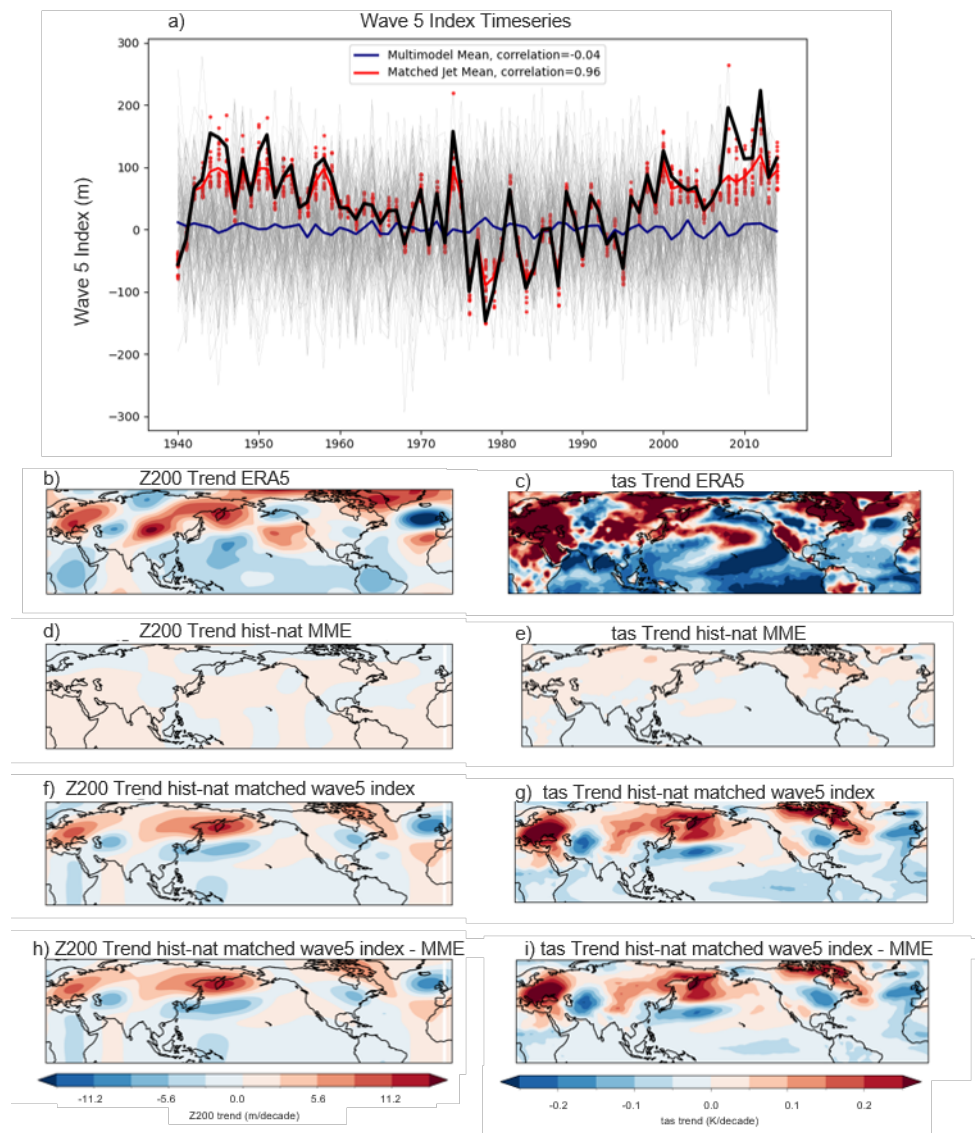


Figure 33: Wave 5 Index matching in hist-nat a) Wave 5 Index for ERA5 (black), individual ensemble members in (grey lines), Multimodel Ensemble (MME) Mean (blue), 20 ensemble members that are closest to ERA5 (red stars), average of these 20 matched members (red line). Correlations between MME mean and ERA5 and Matched mean in legend. b) geopotential height at 200hPa with zonal mean removed trend in ERA5, c) surface air temperature trend with global mean removed trend in ERA5, d), e) as b), c) but for hist-nat MME mean. f), g) as b), c) but for 20 matched members which are

closest to ERA5 for each timestep. h) impact of matching on geopotential height at 200hPa, difference between f) and d). i) impact of matching on surface air temperature, difference between g) and e).

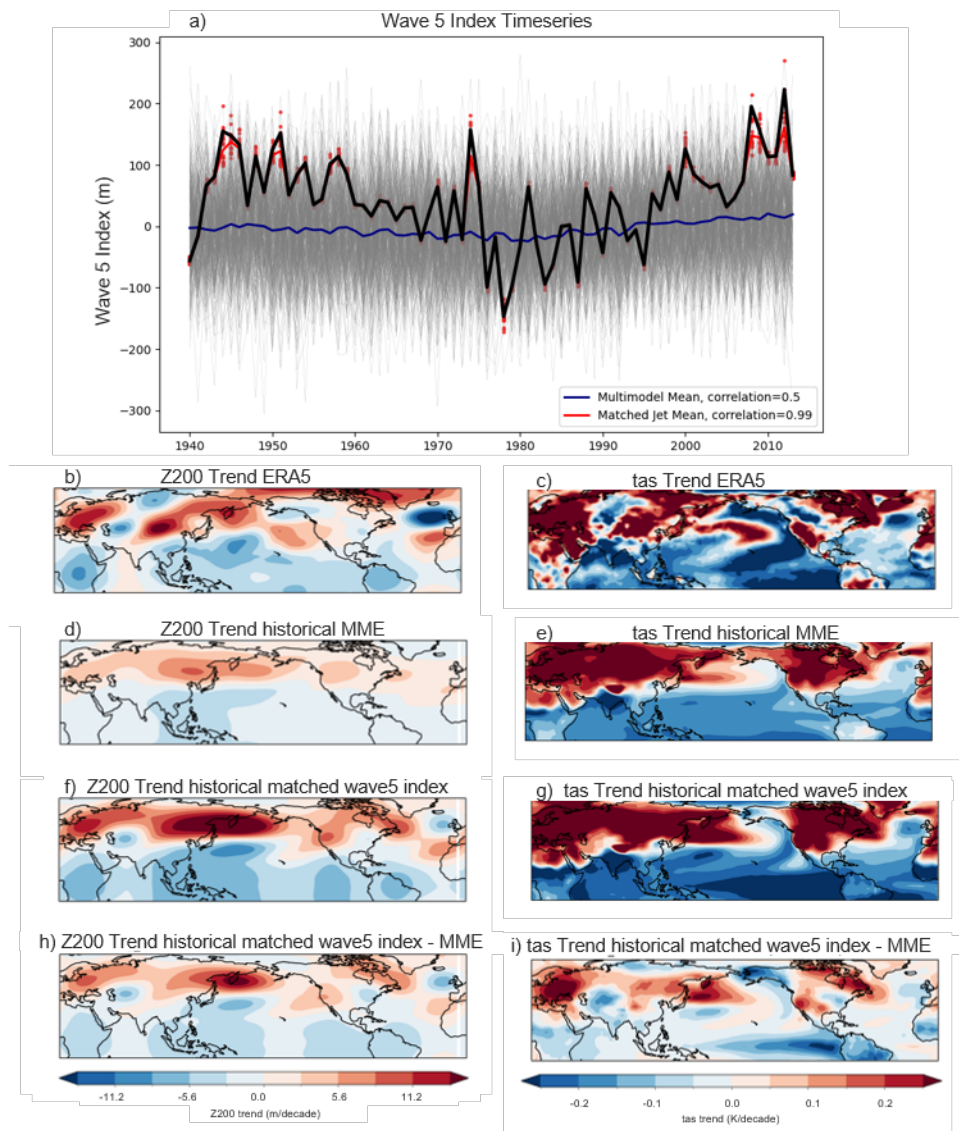


Figure 34: Wave 5 Index matching in historical. As Figure 33 but for historical.

Conclusions

Our results demonstrate that models are unable to correctly simulate the observed Northern Hemisphere Circulation trend and are therefore unable to simulate the correct surface temperature trends. There is a signal to noise error in the historical run with the RPC being 3.04, indicating that the magnitude of the modelled signal is too weak compared to observations. We can find members which match the observed wave 5 index, the Northern Hemisphere extratropical temperature response is improved and closely matches observations, suggesting that the models are correctly

simulating the link between circulation and temperatures. This has important implications for the prediction of temperature trends and extremes, as if we can correct the models circulation response, then we hypothesise that we should see an improvement in temperature trends and extremes.

We also find that by sub selecting member subsets with the most realistic wave 5 pattern give a La Nina-like trend pattern, matching observations. This highlights a connection between the poor representation of the tropical Pacific and of the extratropical circulation pattern in models which we plan to investigate further.

UTO: High-impact circulation in the midlatitudes, extreme precipitation over eastern Canada and the role of urban land-atmosphere interactions

Dynamical system theory tools to understand impactful circulation in the midlatitudes

Heatwaves are a 'hot' research topic (Marx, 2021). They are considered the deadliest weather extreme (WMO, 2023) and have severe consequences in agriculture, (Shi *et al.*, 2021; Barriopedro *et al.*, 2023; FAO and WMO, 2026), infrastructure and power demand, and human health (Steffen *et al.*, 2014). In recent years, midlatitude regions have experienced some of the deadliest heatwaves in recorded history, such as the 2003 European, 2010 Russian and the 2021 North-Pacific heatwaves (Coumou and Rahmstorf, 2012; Thompson *et al.*, 2021; White *et al.*, 2022). The intensity, frequency, and duration are projected to increase because of climate change, making heatwaves even deadlier (Seneviratne *et al.*, 2021; White *et al.*, 2022).

The drivers for the intensification of heatwaves can be divided into *thermodynamic* effects associated with greenhouse warming and *dynamical* effects such as an increase in the duration and frequency of heatwave-related circulation patterns, with the latter effects being a larger source of uncertainty in projections (Shepherd, 2014; White *et al.*, 2022; Barriopedro *et al.*, 2023). Dynamically, heatwaves in the midlatitudes are often driven by persistent and large anticyclonic blocking systems that stall the west-to-east flow (Kautz *et al.*, 2022). The high surface pressure conditions come with subsidence and clear sky conditions, causing prolonged heating and setting the right conditions for heatwaves (Lupo, 2021). The goal of this work is to isolate and examine the effect of climate change on the dynamics of such persistent anticyclones to better understand, prepare, and mitigate the damages of future extreme heatwaves.

We propose that it is useful to identify mid-tropospheric circulations robustly associated with surface hazards in a manner that can enable easy comparisons between

observations (reanalysis) and model simulations. Our perspective is that impactful heatwaves represent the consequence of *persistent circulations* in the free troposphere, and we have developed a method that quantifies persistence as a predictor of impactful heatwaves. The approach is based on a ‘persistence metric’, denoted θ^{-1} (Faranda et al. 2024), that as explained below, captures the tendency for a given atmospheric flow pattern to persist for multiple days. This approach has been successfully used to understand climate and weather extremes in a variety of settings, and was used in Vakrat and Kushner (2025) to assess European-domain impactful heatwaves. Here we report on a broader analysis requiring a second filtering step. As we carried out a global scan of persistent mid-tropospheric circulations in different sectors, we found that an additional filter was required to extract impactful heatwaves associated with anticyclonic circulations, which motivated the use of the archetype analysis described below. The two-filter procedure turns out to yield patterns that are realistically represented in models and that capture circulations that occurred during the most impactful heat waves of the 21st century.

Data and methodology

The work uses reanalysis and ESM datasets. We use ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasting (ECMWF) on a 0.25° grid. We use daily-mean boreal-summer (June-July-August) 1979-2023 geopotential at 500 hPa (Z_{500}), and specific humidity, temperature, and geopotential to calculate the moist static energy at 1000 hPa (MSE_{1000}):

$$MSE \left[\frac{\text{kJ}}{\text{kg}} \right] = C_p T + L_v q + g z$$

For future projections, we use daily-mean output from 9 earth-system models participating in phase 6 of the Coupled Model Intercomparison Project (CMIP6). We use data from 1979-2013 to compare with ERA5 and 2066-2100 SSP5-8.5 to make future predictions. When possible, we use MSE as a conservative dynamical variable that captures combined heat ($C_p T$) and humidity ($L_v q$) effects. In some results not shown in this report but found in our submitted work, due to limitations in available data from some of the ESMs, we turn to near-surface temperature (T_{sur}) instead of near-surface moist static energy (MSE_{1000}).

To better ensure stationarity of the statistics, unless otherwise noted, we first remove the 5-year running mean each calendar day. This accounts for the effect of climate warming on flow patterns in the persistence analysis. Then, most analyses are then performed on anomalies relative to the summer climatology. Anomaly values are denoted by a Δ symbol.

The methodology is divided into three main parts shown in Figure 35. First, we divide the midlatitudes into 60 different domains and scan across them. Second, we calculate the θ^{-1} value for daily midtropospheric patterns, represented by ΔZ_{500} . Third, once we have calculated a θ^{-1} value for every pattern in every domain, we

perform *archetype analysis* for the most persistent patterns and look for persistent patterns with antia large features. We then compare and contrast this group of days, named *archetype 1 persistent events (A1P)* to heatwaves and blocks found in an independent analysis based on Z500 and MSE1000, and examine how such events will change in the future. Each part of the analysis is briefly explained in the following sections.

The work focuses on the midlatitude bands in the Northern Hemisphere (35N°-70N°) and examines flow statistics for fixed-longitudinal-width domains scanning around the latitude circle. In ERA5, the longitudinal width is 56° longitude, and the spacing between each domain is 6° longitude. For example, the first domain is 35N°-70N°, 180W°-125W°, the second domain is 35N°-70N°, 174W°-119W°, and so on. There are a total of 60 domains. In CMIP6 models, the domain size is roughly the same, dependent on the resolution of the model. This step is shown schematically in Figure 35A.

θ^{-1} calculation domains scanning

The 'persistence metric', denoted θ^{-1} , measures the persistence or 'stickiness' of an instantaneous atmospheric configuration using Poincaré recurrence concepts and Extreme Value Theory (Faranda et al., 2024). The input is a set of daily anomalous $\Delta Z500$ maps. The analysis seeks clusters of days with similar maps and calculates their persistence, day by day. The result is a time series of θ^{-1} values, one for each map. The calculation has three main steps for each day's θ^{-1} calculation, shown schematically projected into a two-dimensional phase space in Figure 35B. θ^{-1} is calculated for each domain as follows. 1) For each day of the time series, the Euclidean distance between that day's Z500 anomaly map (the red circle in Figure 35B, which has a Z500 anomaly configuration shown in the box) and every other day's Z500 map (the cyan circles) is calculated. The Euclidean distance for a particular pair is shown as a dashed line. We then 2) define a threshold based on the top 2% shortest distances calculated to analyse all the timesteps that are the closest to the atmospheric configuration of our state of interest (also known as *recurrences* of the state of interest). This confined area in phase space is shown in Figure 35B as the black dashed circle. We then 3) look for clustering of recurrences across the time series. High clustering of recurrences indicates that once a given Z500 pattern is set up it tends to 'stick' in it for a prolonged period, and thus the θ^{-1} value is high. By contrast, if the recurrences are random in time, θ^{-1} is low.

Informally, the θ^{-1} metric tries to answer to the question "If I have a specific atmospheric structure today, what are the odds I will get a very similar atmospheric structure tomorrow?" If this atmospheric structure turns out to mostly stay the same for a few days, meaning the odds are high, then that day's atmospheric structure will get a high value of θ^{-1} . On the other hand, if the structure changes a lot, that day's structure will get a low value of θ^{-1} . In our case, a *persistent event* is defined to be one within the top 10% highest values of θ^{-1} .

Archetype Analysis

Archetype analysis is a pattern recognition method that spots the outlying configuration of a finite dataset using matrix factorization (Cutler and Breiman, 1994; Hannachi and Trendafilov, 2017). This can be applied to any dataset, but here we restrict our analysis to the most persistent events from all domains found in the θ^{-1} analysis. The goal of archetype analysis is to find p patterns or *archetypes* (where p is a hyperparameter), with the same size as the input that can resemble the original data through an internal weighted mean. The weight of each archetype is valued by an affiliation probability – the higher the affiliation probability of an archetype for a daily atmospheric configuration, the closer the configuration is to the archetype pattern. In Figure 35C, we show a schematic convex hull built by 5 archetypes ($p = 5$) confining all persistent events analysed.

After performing archetype analysis with different values of p , we saw that most of the variance of the persistent events can be explained by two archetypes. These archetypes are opposite, the first archetype (archetype 1) is anticyclonic while the second archetype (archetype 2) is a dipole archetype with a large cyclonic anomaly in the southern part of the domain and an anticyclonic anomaly in the northern part of the domain. When using $p = 2$, we put all persistent states on a schematic scale that goes from an anticyclonic structure to a dipole structure with a straightforward interpretation of how each persistent pattern fits into one of the archetypes. This scale is shown schematically in Figure 35D. Persistent events that are close enough to archetype 1 (top 30% values of archetype 1 affiliation probability for each domain) are persistent events with a prominent anticyclonic anomaly and are grouped as archetype 1 persistent events (*A1P* events).

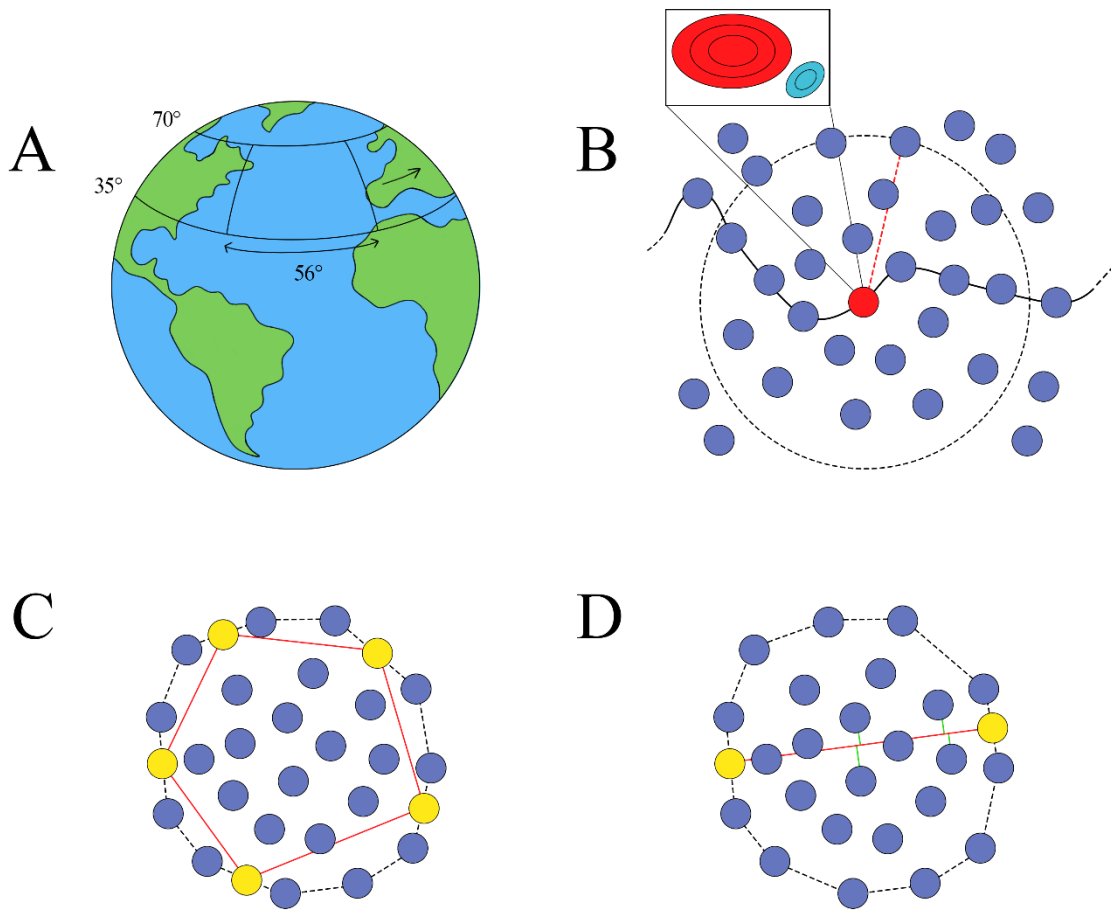


Figure 35: Illustration of methods. (A) Shifting domain sized about 60° longitude by 35° latitude used for θ^{-1} calculation. (B) Z500 anomaly phase space and θ^{-1} calculation. The blue circles are different days, the red circle is a particular day. Solid black curve joins subsequent days. The red dashed line describes the 98th percentile of the Euclidean distance between a particular day and all other days. All events inside the black dashed circle are recurrences of the state of interest. (C) Convex hull of persistent events for $p = 5$, with the yellow circles being the 5 archetypes. (D) Representation of $p = 2$.

Heatwaves and Blocks Definition

We then analyze the connection between three groups of days: A1P events, heatwaves, and atmospheric blocking. A heatwave event is defined as three or more consecutive days for which more than 15% of the domain grid points of the 5y high pass filtered 1000MSE exceeds the local 95th percentile. The heatwave event definition captures large-scale heatwaves widespread across each domain. Blocking events are found using an anomaly method-based index (Woollings *et al.*, 2018). First, the daily $\Delta Z500$ is calculated for the data after removing the moving mean. Then, days where at least 15% of the grid cells have a $\Delta Z500$ value of the 90th percentile are counted. Blocking periods are mainly defined as periods with 5 or more days achieving the criteria. Other blocking indices that were used to compare the results were a potential vorticity (PV) based index and the Tibaldi and Molteni index.

Results

Figure 36 shows the composite of the anomalous circulation in the midtroposphere, represented by $\Delta Z500$, and the anomalous surface conditions represented by $\Delta MSE1000$, in ERA5 for A1P events in 6 domains out of the 60 domains. The prominent feature of the A1P events across all domains is a large, anticyclonic anomaly (positive $\Delta Z500$) centered in the northern part of the domain. The spatial extent of the anticyclone varies among domains. The localization of $\Delta MSE1000$ can vary from domain to domain, with the Atlantic domain showing the most localized surface conditions.

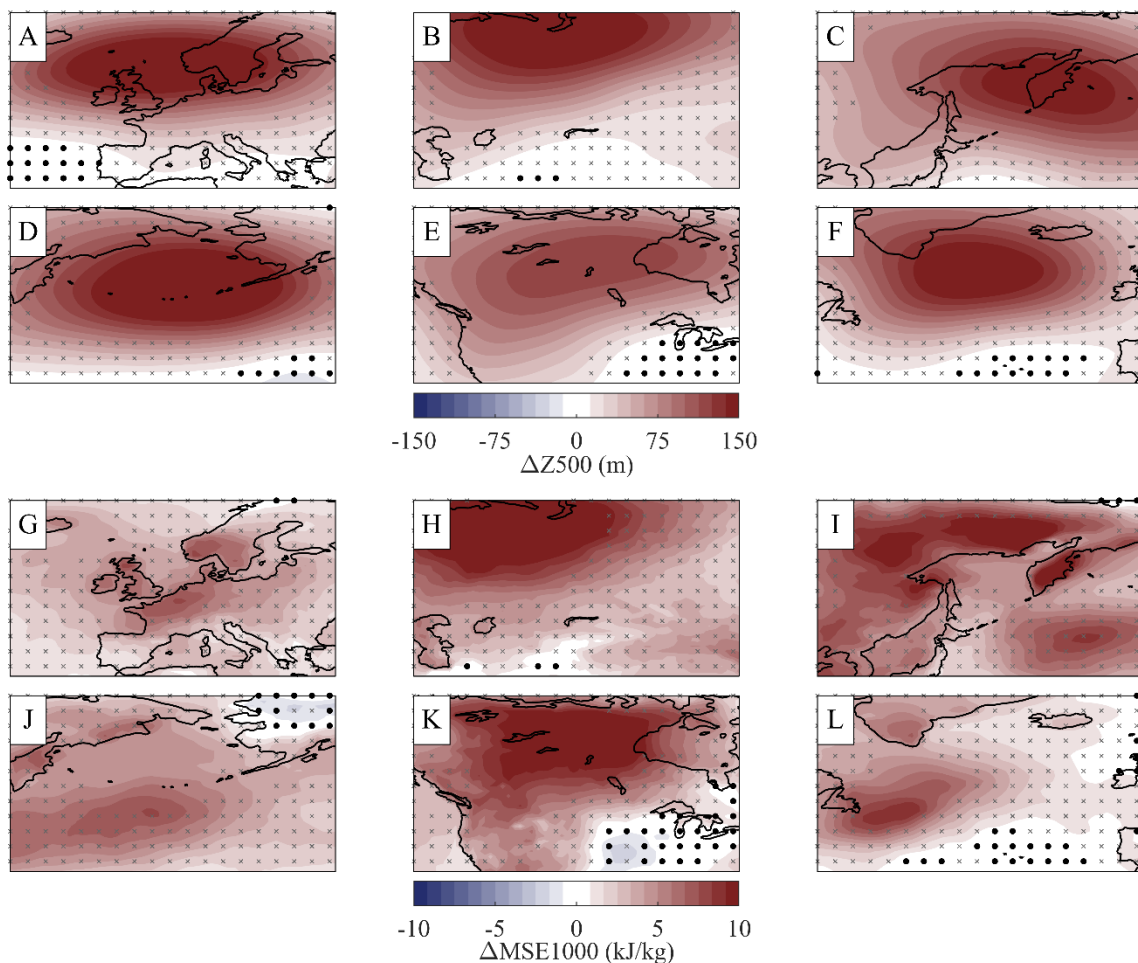


Figure 36: A1P events composite (A-F) $\Delta Z500$ (G-L) $\Delta MSE1000$ across 6 domains. Gray crosses mark a CV value higher than 0.9. Black dots show an insignificant anomaly. Hereafter, the domains will be named as (A) Europe, (B) Central Asia, (C) East Asia, (D) Pacific Ocean, (E) North America, (F) Atlantic Ocean.

As seen, the circulation over oceanic domains is very similar to the circulation over land domains, with a weaker surface signature as a result of the higher heat capacity. Very similar archetype analysis results were obtained for Z500 and when analyzing only oceanic domains, showing that the archetypes and the persistent events are

characteristic of the atmospheric circulation with little sensitivity to the underlying surface, whether ocean or land.

While the anomaly in Z500 is by construction localized at the domain centre, significant and consistent anomalies exist outside the analysis domains. When extending the plotting domain in Figure 36 to the entire hemisphere (Figure 37), we can see that the planetary-scale structure coherent with the central anomaly varies between domains. For example, for the Eastern Asia, Pacific Ocean, and North American domains in Figures 37C-E, the local anticyclonic anomaly is part of a planetary-scale wave structure, while for the European domains (e.g. Figures 37A-B) the anticyclone is more isolated and presumably driven by more localized atmospheric drivers.

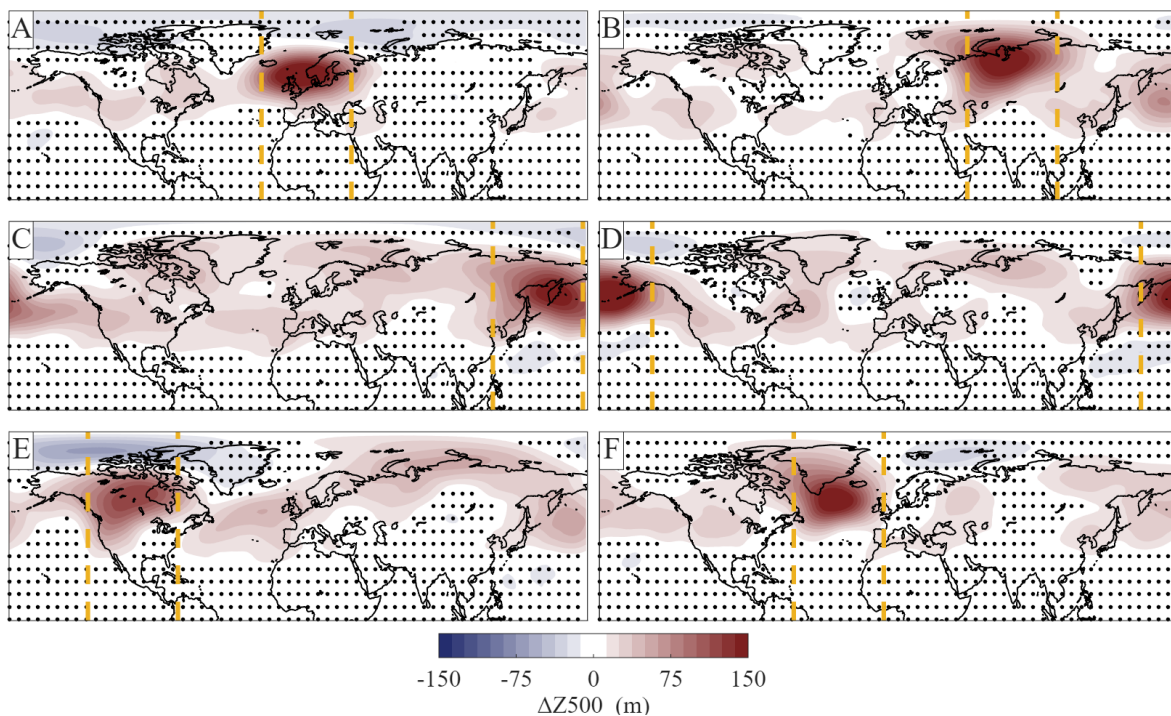


Figure 37: A1P events as shown in Figure 36 but plotted for a hemispheric domain. Yellow dashed lines indicate the longitudinal extent of the analysis domain.

When looking at the connection between heatwaves, blocks, and A1P events, across domains we see a strong connection between the three groups with a variation in strength. All major heatwaves in the last two decades, including the European heatwaves of 2003, 2012, 2018, 2022 and the Pacific Northwest heatwave of 2021, were A1P events. Generally, and especially in land domains, the three groups show a high overlap with a similar midtropospheric and surface signature. In oceanic domains A1P events and blocks show a more localized ΔMSE_{1000} signature than the anomaly during heatwaves, which highlights the difference in the dynamics of two different extreme heat events: one type of events with intense, localized ΔMSE_{1000} , and one type of events with prolonged, widespread ΔMSE_{1000} events. The connection

between the three categories holds in ESMs, for which *A1P* events show a similar surface signature to this found in reanalysis.

To examine the climate change response of *A1P* events, we analyse the θ^{-1} , ΔZ_{500} , and ΔT_{sur} change under strong anthropogenic forcing represented by end-of-21st century SSP5-8.5 conditions relative to historic condition. As part of a general positive shift in θ^{-1} values by the end of the century, *A1P* events in East Asia, Pacific Ocean and North America show an increase in persistence, which encapsulates a midtropospheric dynamical change to such events (Figure 38). In all domains, climate change causes longer, warmer events at the surface. Understanding the origin of this increase in duration at the surface and its connection to different feedback processes in the surface and in the mid-troposphere is a subject of current research.

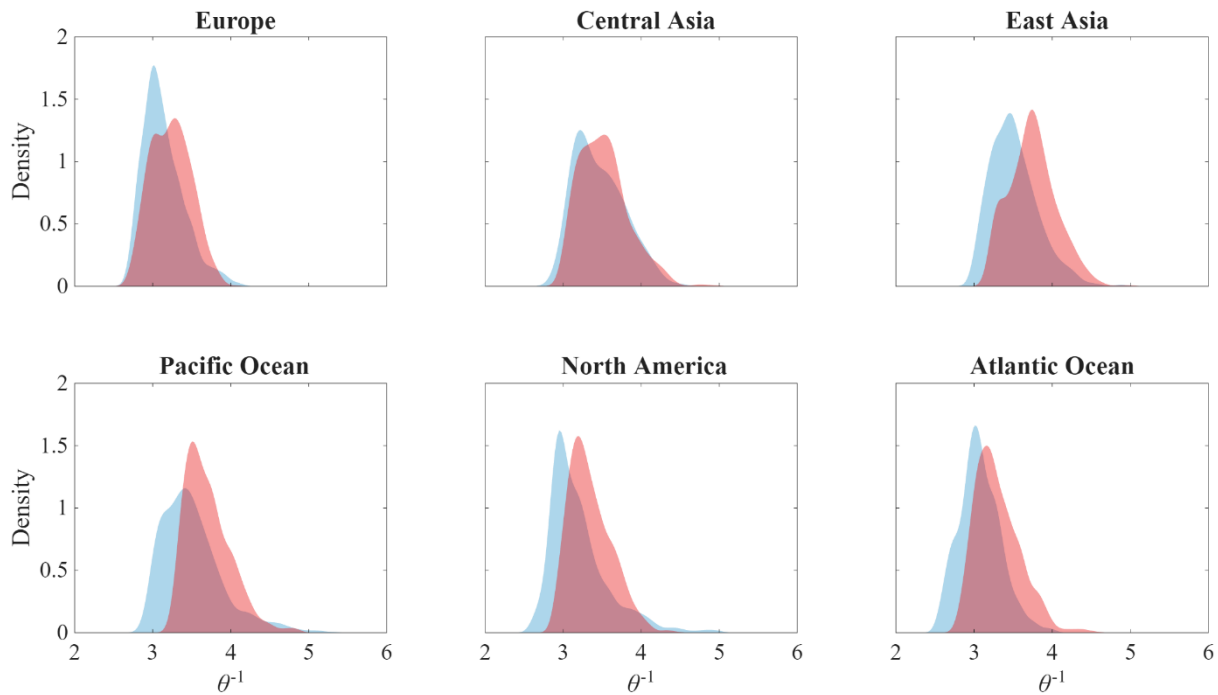


Figure 38: θ^{-1} Probability Distribution Function for *A1P*. Blue - historical multi-model mean. Red - SSP5-8.5 EOC multi-model mean.

Conclusions and implications

This work extends our understanding of the dynamics and impacts of persistent anticyclones in the midlatitudes in several respects. We first described the results of the two-step identification method, which to our knowledge is novel. The persistent behaviour is identified using a θ^{-1} threshold and anticyclonic circulation systems are isolated with an archetype analysis affiliation probability threshold. This framework works well in ESMs, for which midtropospheric blocking or heatwave indices can show inconsistency between ESMs.

Overall, *A1P* correlate well with atmospheric blocks (that showed some levels of internal inconsistency when using different blocking indices) and heatwaves identified with a more classic meteorological approach, especially over land domains. However, even within the heatwave and blocking groups there was variability in mechanisms causing the three groups not to fully overlap.

All domains but Europe showed an increase in θ^{-1} by the end of the century across all used models, including the two storm track regions. This increase can come from a slower mean boreal summer circulation, caused by greenhouse gases reducing the equator-to-pole temperature gradient (*Chemke and Coumou, 2024; Kornhuber and Tamarin-Brodsky, 2021; Pfleiderer et al., 2019*). It is also possible that this increase in persistence is driven by different factors that can explain the difference between domains. Our results suggest that the circulation aloft associated with heat extremes will become more persistent, and as a response, surface heat extremes will become longer. This increase in persistence, together with other feedback mechanisms, can cause a disproportionate response in anomalous conditions. As *A1P* were often part of a global structure causing $\Delta Z500$ at different locations concordantly, an increased persistent in one domain can affect the prolonged heat conditions at another location.

Our double layered framework consists of two novel data driven unsupervised learning techniques highlighting the main attributes of large-scale circulation patterns associated with heat extremes, – persistent and anticyclonic. This framework is applied successfully to models of different complexity and reanalysis and is presented as an alternative to traditional blocking and heatwave indices, catching extreme heat events without using a temperature-based index, including the big events in the recent decades, like the European heatwave of 2003, 2010, 2018, and 2022 and the pacific northwest heatwave of 2021. The consistency of our results suggests that this framework could be applied successfully to additional datasets in the future, more specifically to attribution datasets developed and used by EXPECT.

Our results help to isolate dynamical mid-tropospheric drivers of circulation patterns associated with heat extremes and predict future temporal change of such patterns. *A1P* event, while analysed locally, are mostly invariant to the surface below them and are often part of a global structure, that shows a positive $\Delta Z500$ concordantly in different locations. Preferred phase shifts of concurrent persistent events are an additional subject of future research. The lag correlation between persistent events in different locations and between heat extremes and precipitation extremes through known physical pathways.

This work was well received by the scientific community and was the base for scientific research outside of EXPECT. It was presented at a few scientific conferences, including the European Geosciences Union General Assembly in 2026. The dynamical and classification frameworks were applied to other applications such as different type of weather extreme and atmospheric states. In the summer of 2026, this work was used as the basis for student projects in the International Summer School Program on

Climate Change and Related Risks, a summer school supported by the WMO and *Integrated Research on Disaster Risk* (IRDR). These projects used this framework to look at persistent heat extremes in the past and the future and quantify the expected change in air quality and psychological stress

High-impact extreme precipitation over eastern Canada and the role of land–atmosphere interactions over urban corridors

Extreme precipitation Events (EPEs) over mid-latitude region is governed not only by large-scale atmospheric circulation but also by local land–atmosphere feedbacks, which can amplify or suppress the thermodynamic and dynamical conditions that support deep convection. To improve anticipation of future EPEs, it is essential to understand the atmospheric processes that produced past events (*Doswell et al., 1996; Pfahl et al., 2017; IPCC, 2021; Prein et al., 2015b; Trenberth et al., 2003*). Eastern Canada provides a compelling atmospheric setting for this investigation. The region has experienced several damaging EPEs in recent decades and is characterized by diverse climatic zones, numerous large lakes, complex coastlines, and expanding urban areas (*Kirchmeier-Young and Zhang, 2020; Loxley, 2022; Wang and Feng, 2026; Camila Flórez Bossio, 2024*). Consequently, flooding has become Canada's most frequent and costliest natural hazard (*Seager et al., 2007; Wang et al., 2014a, b*). According to the *Insurance Bureau of Canada (2024)*, flood-related damages have averaged nearly 800 million dollars in insured losses annually over the past decade, largely driven by short-lived EPEs. These losses are projected to increase by three to five times by near to mid-century, surpassing 5.5 billion dollars annually, and could reach as high as 13.6 billion dollars by the end of the century under ongoing climate warming (*Under Water: The Cost of Climate Change for Canada's Infrastructure, 2021; Environment and Climate Change Canada, 2024*). Analysis of ERA5 (1995–2025) and IMERG (1998–2025) reanalysis/satellite records also show a statistically significant increasing trend in the 99th-percentile daily precipitation intensity across the region in the late-summer to autumn season, highlighting the urgency of understanding the physical drivers of EPEs region by region.

Motivated by these challenges, the overarching scientific question addressed in this work is: how do the atmospheric and land-surface processes that produce extreme precipitation differ across the distinct landform regions of eastern Canada, and how well can kilometer-scale regional climate models reproduce them? We pursued this question along two complementary lines of investigation within WP5.

The first part evaluates the ability of high-resolution regional climate models to reproduce the atmospheric processes associated with extreme precipitation, including moisture convergence, vertically integrated moisture transport, upper-tropospheric divergence, and hydrometeor evolution. The analysis considers three representative EPEs occurring over contrasting landform regimes in eastern Canada. Nova Scotia represents a coastal maritime environment affected by the remnants of

Hurricane Matthew (October 2016). The Montréal–Ottawa corridor represents an urbanized St. Lawrence Valley setting impacted by the remnants of Hurricane Debby (August 2024), and the Greater Toronto Area (GTA) represents a densely urbanized, lake-influenced environment that experienced an isolated convective storm in August 2005. By comparing model performance across these contrasting case studies, this study identifies which aspects of EPE simulation are strongly influenced by regional landform characteristics and which atmospheric processes remain robust across different environments.

Building on the findings of the first part, the second part focuses specifically on densely urbanized environments to investigate how urban land-surface processes influence extreme precipitation potential. In particular, it examines how different urban canopy representations modify surface energy exchanges, atmospheric instability, moisture availability, and low-level wind convergence, all of which influence the initiation and intensity of extreme rainfall. This work is motivated by one of the key findings from the first part: among the three case studies, the Greater Toronto Area event proved to be the most challenging to reproduce accurately. We therefore investigate whether urban land-surface physics contributes to this modelling difficulty and whether urban processes themselves enhance the local hazard associated with extreme precipitation.

Data and methodology

We use ERA5 reanalysis data, satellite-based IMERG, gauge-observed precipitation and discharge data. ERA5 (ECMWF, 0.25°) gives us boundary forcing and a benchmark. GPM-IMERG (0.1°, daily) gives us an independent satellite estimate for validation of extreme precipitation event. In addition, the gauge precipitation data are taken from Environment and Climate Change Canada's Historical Climate Data, and discharge data taken from Water Level and Flow Database by Environment and Climate Change Canada (<https://wateroffice.ec.gc.ca/>), Streamflow and discharge records used to check whether simulated rainfall produces a realistic hydrological response.

The study domain spans southern Ontario and the Great Lakes basin in the west to Newfoundland and Nova Scotia in the east, encompassing the St. Lawrence River Valley, the Gulf of St. Lawrence, and Atlantic Canada (shown in Figure 39). Three high-impact EPEs, each simulated over a distinct innermost domain tailored to its landform setting, are examined: EPE1, the October 2016 remnant of Hurricane Matthew over Nova Scotia (coastal/maritime terrain, complex coastline); EPE2, the August 2024 post-tropical remnant of Hurricane Debby over the Montréal–Ottawa urban corridor (St. Lawrence Valley, dense urbanization); and EPE3, the August 2005 isolated deep convective storm over the Greater Toronto Area (Great Lakes shoreline, highly urbanized). The spatial and temporal distributions of precipitation associated with the three extreme precipitation events (EPEs) are shown in Figure 40.

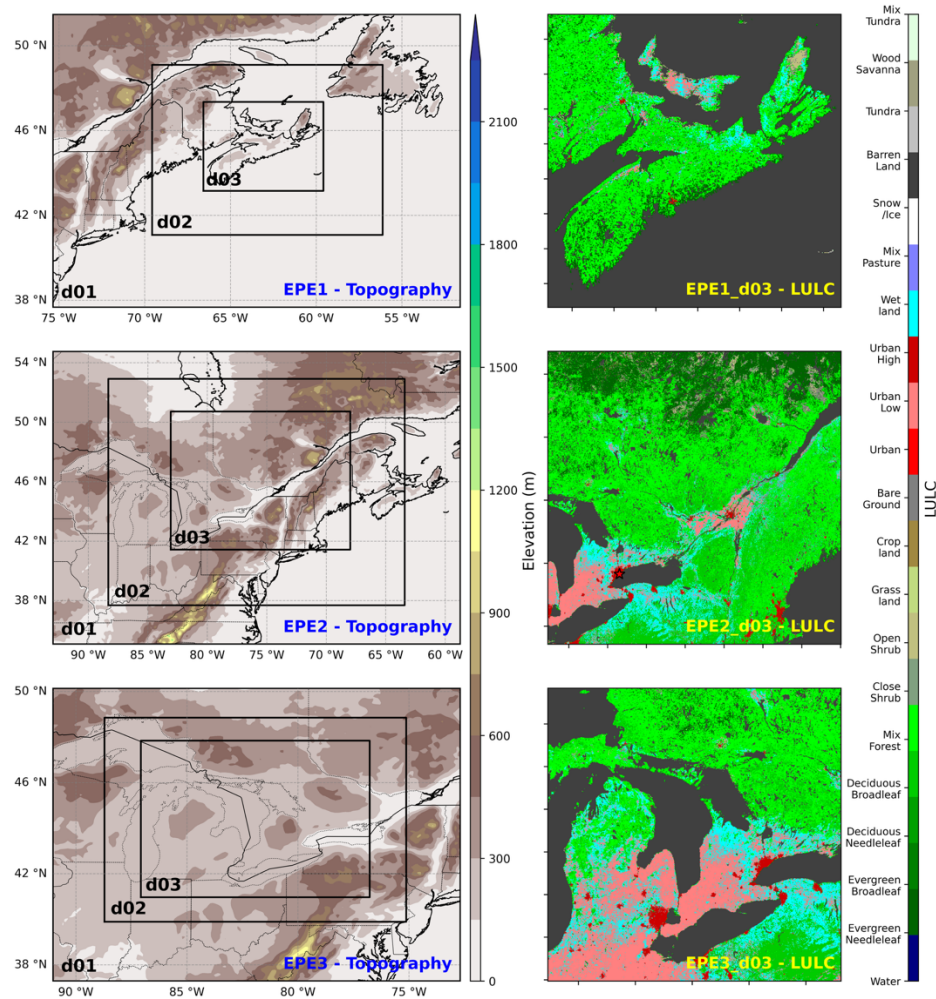


Figure 39: Model domain configurations for the three extreme precipitation events used in the WRF and RegCM5 simulations. The left column shows the topography (m) of the three nested model domains (d01, d02, and d03) for EPE1, EPE2, and EPE3, respectively. The right column presents the land use and land cover (LULC) classification of the innermost domain (d03) corresponding to each respective EPE.

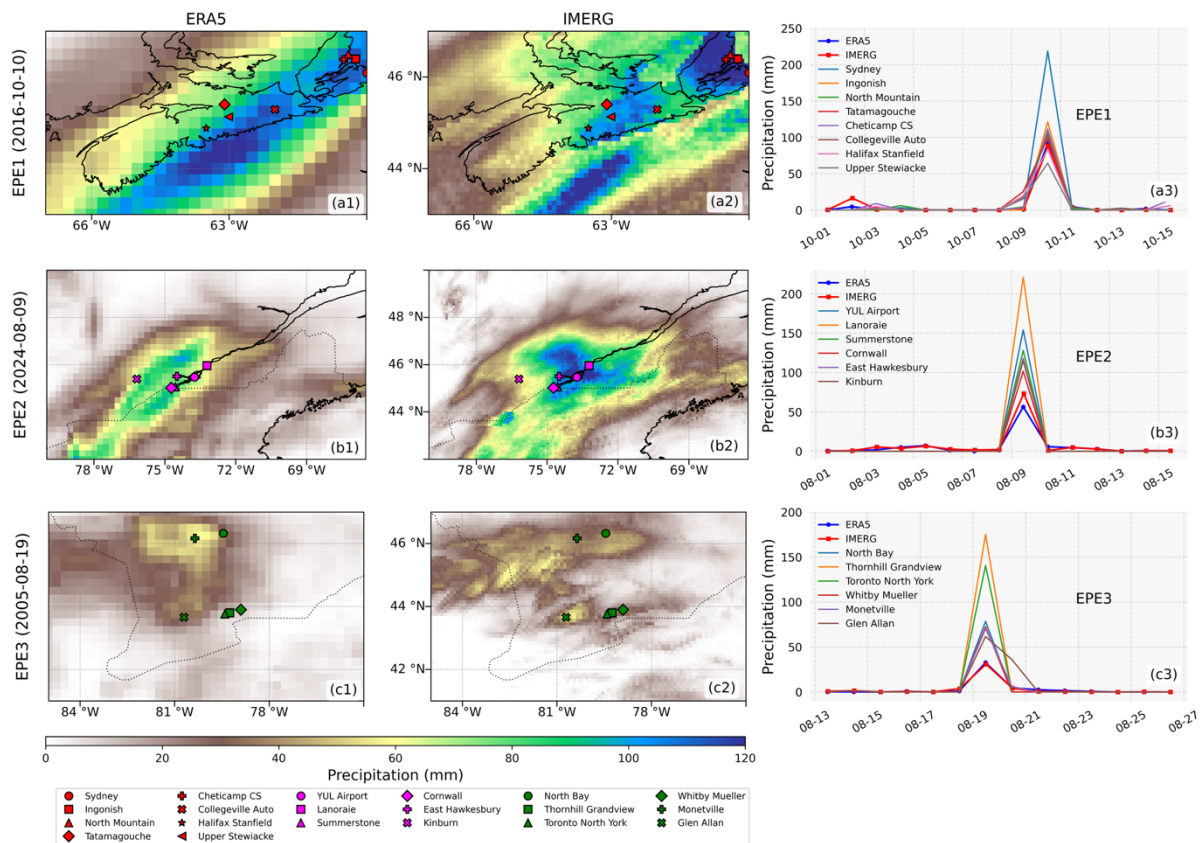


Figure 40: Spatial distribution of daily accumulated precipitation (mm) from ERA5 reanalysis (a1–c1) and the GPM IMERG satellite product (a2–c2), together with time series of daily accumulated precipitation (mm) from ERA5, IMERG, and selected ground-based gauge stations (a3–c3), for EPE1, EPE2, and EPE3 (rows a–c), respectively. Colored markers in the spatial maps indicate the locations of the ground-based gauge stations used for validation. In the time series, ERA5 and IMERG are represented by bold blue and red lines, respectively, while observations from individual gauge stations are shown by colored lines.

For the first part, we adopt a controlled regional-model intercomparison design: the Weather Research and Forecasting model (WRF v4.7) and the Regional Climate Model version 5 (RegCM5) are each configured at kilometer-scale grid spacing and initialized with identical ERA5 initial and lateral boundary conditions and land-surface forcing, so that differences in simulated EPE characteristics can be attributed to model dynamical core, physics, and nesting strategy rather than to differences in forcing. WRF uses a three-domain, two-way nested configuration refined to 1 km; RegCM5 is run both as a standalone 1 km configuration and using its subgrid (3 km-to-1 km) precipitation scheme, allowing us to test whether the added value of the subgrid approach is landform- and event-dependent. Evaluating three EPEs that occurred in three distinct landform settings, under an identical modelling protocol, is what allows us to separate landform-dependent model behaviour from generic model biases.

We evaluate in two steps. First, we compare simulated precipitation directly against ERA5, IMERG, and gauge data at native resolution, alongside watershed-averaged

precipitation and observed discharge. Second, we regrid model output to ERA5 resolution and score it with contingency-table metrics: probability of detection (POD), false alarm ratio (FAR), critical success index (CSI), and the Heidke skill score (HSS). We diagnose the atmospheric drivers through 850 hPa and 200 hPa circulation, vertically integrated moisture transport and vertical profiles of cloud water and cloud ice.

The second part examines the influence of land-surface representation on extreme precipitation potential over densely urbanized environments. To isolate land-surface effects, the atmospheric configuration of WRF is kept identical across all simulations, while only the land-surface and urban canopy schemes are varied. Four configurations are evaluated: WRF–CLM4 (baseline without an explicit urban canopy), WRF–SLUCM (Single-Layer Urban Canopy Model), WRF–MLUCM (Multi-Layer Urban Canopy Model), and the coupled WRF–ELM configuration. Because urban development and lake influences are closely linked across the Toronto–Ottawa–Montréal corridor, the analysis focuses on differences relative to the CLM4 baseline (each urban canopy simulation minus CLM4). This approach minimizes the common influence of Lake Ontario and isolates the contribution of urban canopy processes to near-surface temperature (T2), specific humidity (Q2), and low-level wind convergence. Changes in the surface energy partitioning, represented by the Bowen ratio (sensible-to-latent heat flux ratio), provide an additional physical diagnostic for interpreting moisture availability and precipitation potential.

Results

Across all three EPEs, both WRF and RegCM5 realistically reproduce the spatio-temporal evolution of the events and the key dynamical/thermodynamical ingredients, low-level moisture convergence, VIMT, upper-tropospheric divergence, and hydrometeor development though model skill is clearly landform-dependent. WRF performs best for the two tropical/post-tropical remnant cases: it reproduces the southwest–northeast precipitation band over Nova Scotia (EPE1) and the urban-corridor maximum over Montréal–Ottawa (EPE2), achieving the highest POD against ERA5 for EPE1 (0.78) and EPE2 (0.80), and against gauges (0.80 and 1.00, respectively). RegCM5 at 1 km instead provides the most realistic spatial structure for the isolated, lake-influenced convective storm over the GTA (EPE3), achieving a POD of 1.00 against both ERA5 and gauge observations, while WRF displaces the precipitation maximum for this case despite capturing its intensity. The RegCM5 subgrid (3 km-to-1 km) configuration improves the spatial distribution of EPE2 relative to the standalone run and is identified as the best-balanced performer for EPE3 across both reference datasets (CSI = 0.72, HSS = 0.55 vs. ERA5).

EPE	Model	ERA5					Gauge Observations				
		POD	Miss	FAR	CSI	HSS	POD	Miss	FAR	CSI	HSS
EPE 1	WRF	0.778	0.222	0.222	0.636	0.492	0.800	0.200	0.200	0.667	0.300
	RegCM5 (1 km)	0.667	0.333	0.143	0.600	0.508	0.600	0.400	0.143	0.545	0.286

EPE	Model	ERA5					Gauge Observations				
		POD	Miss	FAR	CSI	HSS	POD	Miss	FAR	CSI	HSS
	RegCM5 (Subgrid)	0.578	0.422	0.025	0.600	0.525	0.700	0.300	0.222	0.583	0.186
EPE 2	WRF	0.800	0.200	0.000	0.800	0.696	1.000	0.000	0.400	0.600	0.529
	RegCM5 (1 km)	0.700	0.300	0.000	0.700	0.571	0.833	0.167	0.286	0.625	0.613
	RegCM5 (Subgrid)	0.900	0.100	0.100	0.818	0.650	0.667	0.333	0.200	0.571	0.586
EPE 3	WRF	0.750	0.250	0.400	0.500	0.494	0.500	0.500	0.750	0.300	0.277
	RegCM5 (1 km)	1.000	0.000	0.429	0.571	0.571	1.000	0.000	0.556	0.444	0.364
	RegCM5 (Subgrid)	0.880	0.100	0.180	0.718	0.550	0.750	0.250	0.571	0.375	0.286

Table 2: Comparison of contingency-based skill scores for WRF and RegCM5 evaluated against ERA5 and gauge observations. Gauge stations are: EPE1: Collegeville Auto, EPE2: YUL Airport, and EPE3: Toronto North York. The best-performing results are indicated in bold.

The finding also shows that across all three cases both models get the precipitation timing right, peak precipitation lines up with when the event happened (Figure 41). The river response follows a consistent physical pattern too: discharge peaks about a day after the heaviest precipitation, with a sharp rise and a slower recession back to baseflow afterward. That one-day lag holds at the St. Marys, Achigan River, and Weston gauges alike, which implies that the hydrological response in these simulations is physically realistic.

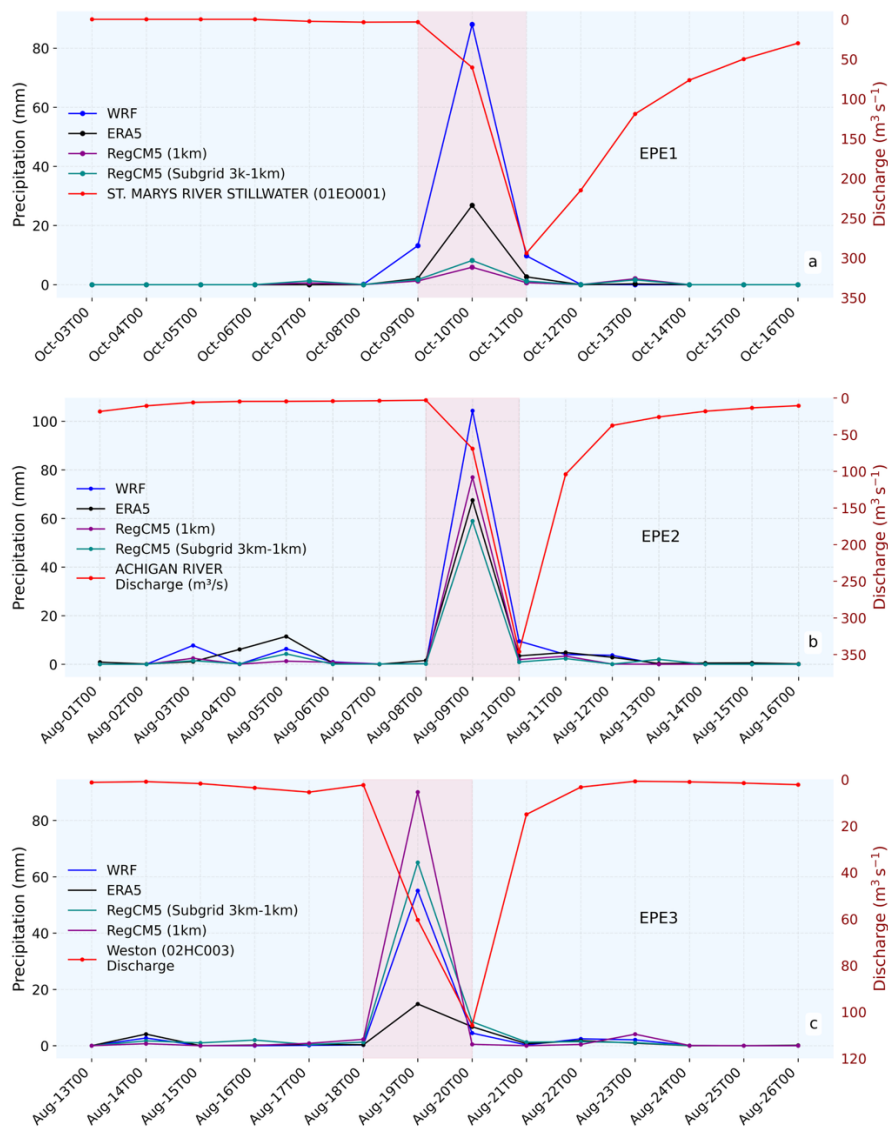


Figure 41: Time series of daily accumulated precipitation (mm) simulated by WRF (blue line), ERA5 (black line), RegCM5 (magenta line), and RegCM5 subgrid (green line), together with observed streamflow discharge ($\text{m}^3 \text{s}^{-1}$; red line, right y-axis) for (a) EPE1 (1–16 October 016) at the St. Marys River Stillwater station (01EO001), (b) EPE2 (1–16 August 2024) at the Achigan River discharge station, and (c) EPE3 (13–26 August 2005) at the Weston station (02HC003).

In addition, both models reproduce the synoptic pattern associated with each event, intensified 850 hPa low-level convergence and 200 hPa subtropical-jet passage ahead of and during each EPE. WRF simulates a stronger subtropical jet and low-level moisture transport than RegCM5 and ERA5 for the tropical-remnant cases (EPE1, EPE2), consistent with its higher simulated precipitation there, while RegCM5 better reproduces the localized VIMT convergence over the GTA for EPE3, consistent with its stronger performance on that case.

Building directly on the first part, finding that the event most strongly driven by localized convection was the hardest of the three to simulate accurately, the second part investigates whether urban land-surface representation is itself a contributor to extreme precipitation potential over the Montréal–Ottawa corridor, independent of any single event. Preliminary results show that urban canopy schemes (SLUCM, MLUCM, WRF–ELM) produce a stronger, more persistent nighttime urban heat island than the no-urban-canopy baseline (WRF–CLM4). These schemes also add surface drag from building and street geometry that CLM4 does not represent, which alters local wind convergence patterns in ways relevant to where convection organizes. This work is still under progress and will continue as the analysis is extended across the wider urban corridor.

Conclusions and implications

Kilometer-scale WRF and RegCM5 simulations add clear value over coarse-resolution reanalysis for representing the atmospheric structure, intensity, and physical drivers of EPEs over eastern Canada, but no single model configuration performs best across all landform regimes. WRF is the stronger choice for tropical/post-tropical remnant systems affecting coastal and St. Lawrence Valley corridors, while RegCM5 (particularly its 1 km standalone and subgrid configurations) better represents isolated, lake-influenced convective storms over the urbanized Great Lakes shoreline. Both models reproduce a physically realistic one-day lag between peak precipitation and peak streamflow across all three watersheds, and both systematically overestimate precipitation intensity relative to ERA5 while agreeing more closely with gauge observations a result attributable to ERA5's coarse representation of convection and local topographic/lake effects rather than to a shared model bias.

The emerging insight from the ongoing land-surface analysis is that urban canopy representation changes extreme precipitation potential over the urban corridor two competing land-atmosphere pathways rather than one: a thermodynamic pathway that strengthens the convective trigger (stronger, more persistent urban heat islands) and a moisture-supply pathway that weakens it (CLM4-relative Q2 suppression), linked dynamically through altered near-surface wind convergence.

Within EXPECT, this first part of this study supports the WP5 objective of explaining past and present precipitation hazards by quantifying which regional model configuration is best suited to which landform regime across eastern Canada, complementing the large-scale circulation diagnostics developed under T5.1 with an event-scale, landform-resolved perspective. The second part extends this into the T5.2 land-surface modulation focus, providing a local, process-based explanation for why the convection-dominated case was hardest to simulate, and demonstrating a diagnostic approach, CLM4-relative differencing plus independent energy-balance corroboration that could be applied to other WP5 partner regions with comparable urban or coastal land-surface complexity.

Beyond EXPECT, the results are directly relevant to flood forecasting and early-warning system design across eastern Canada's hydro climatically diverse landscape, since the choice of regional model and configuration should be matched to the dominant hazard type in each landform region. Once finalized, the results will also have implications for urban climate adaptation planning in the GTA and comparable lake-shore cities, highlighting that urban heat island mitigation strategies may have compensating effects on local moisture availability that should be considered alongside their intended thermal benefits.

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Table 1