



Changes in boreal summer atmospheric circulation

Deliverable 3.1

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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	WP3 - Drivers of annual to decadal changes in climate
Related task(s)	Task 3.1
Lead organisation	VU Amsterdam
Authors	Coumou D., Stoffels R., Dong B., Donat M., Marcet-Carbonell G., Roldán-Gómez P., Weisheimer A., Kretschmer M., Smith D.
Submission date	31 March 2026
Dissemination level	Public

History

Date	Submitted by	Reviewed by	Notes
13/03/2026	Coumou Dim		Initial version for internal review
24/03/2026	Plésiat Étienne		Internal review
	Dutra Emanuel/Isabel Trigo		Internal review
	Coumou Dim		Final version

Please cite this report as: Coumou D., Stoffels R., Dong B., Donat M., Marcet-Carbonell G., Roldán-Gómez P., Weisheimer A., Kretschmer M., Smith D.

(2026), Changes in boreal summer atmospheric circulation, D3.1 of the EXPECT project

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Abbreviations

ACC: Anomaly Correlation Coefficient
 AMIP: Atmospheric Model Intercomparison Project
 CGT: Circumglobal Teleconnection
 DAMIP: Detection and Attribution Model Intercomparison Project
 DJF: December, January, February (Winter)
 EKE: Eddy Kinetic Energy
 ENSO: El Niño–Southern Oscillation
 FAR: Fractional Attribution Risk
 GHG: Greenhouse gases
 GMT: Global Mean Temperature
 JJA: June, July, August (Summer)
 LESFMIP: Large Ensemble Single Forcing Model Intercomparison Project
 MMEA: Multi-model Ensemble Average
 MMM: Multi-model Mean
 NAO: North Atlantic Oscillation
 OLR: Outgoing Longwave Radiation
 ONDJFM: October, November, December, January, February, March
 PDO: Pacific Decadal Oscillation
 PCA: Principal Component Analysis
 QSW: Quasi-stationary Rossby Waves
 RMM-VAE: Regression Mixture Model – Variational Autoencoder
 SAT: Surface Air Temperature
 SAT90: 90th Percentile of Surface Air Temperature
 SLP: Sea Level Pressure
 SNR: Signal-to-noise Ratio
 SST: Sea Surface Temperature
 WR: Weather Regime

About

The climate system is changing rapidly and some regions have seen increases in extremes beyond what is expected from climate model simulations. To support targeted climate adaptation strategies, EXPECT will enable trustworthy assessments and predictions of regional climate change including extremes by developing a prototype operational capability for integrated attribution and prediction of climate. This ambitious goal is closely aligned with the WCRP Lighthouse Activity on Explaining and Predicting Earth System Change. EXPECT will identify and quantify the mechanisms by which physical processes govern regional climatic changes, including extremes, on inter-annual to multi-decadal time scales. It will do so by exploiting newly available climate simulations and Earth Observations (EOs), and by combining machine learning (ML) with physical methods. The research will target fundamental knowledge gaps related to atmospheric circulation and land-atmosphere interactions, which represent major limitations in current climate predictions and projections, and in particular in understanding changes in European summer extremes. To underpin the research, and benefitting the wider research community, EXPECT will develop tools to efficiently analyze a variety of large data sets in combination that are hosted in different repositories across institutions. This will facilitate the exploitation of recent investments into high-resolution climate models and EO data. EXPECT will further build data science capacity for the scientifically robust, efficient and reproducible analysis of the massive data assets, including novel ML approaches, and provide training for the climate science community and the next generation of researchers in particular. EXPECT will thus deliver significant scientific and technological advances for society and the climate science community that will last well beyond the project, in support of WCRP's strategic objectives.

Executive summary

Several studies within the EXPECT project have examined the drivers of observed changes in Northern Hemisphere summer atmospheric circulation. Observations since the 1980s show a shift toward weaker zonal flow and weaker storm-track activity, accompanied by an upward trend in a quasi-stationary wave-5-like circulation pattern. This pattern consists of alternating high- and low-pressure anomalies around the hemisphere and has been linked to increases in regional climate extremes such as heatwaves and droughts.

One robust finding is the weakening of Northern Hemisphere summer storm tracks since 1979. A formal attribution analysis indicates that this weakening is very likely driven by anthropogenic forcing, with roughly equal contributions from greenhouse gases and aerosols. Enhanced Arctic warming reduces the equator-to-pole

temperature gradient, weakening the zonal flow, vertical wind shear and atmospheric baroclinicity. This in turn reduces mid-latitude eddy activity and storm tracks.

To explain the strengthening of the quasi-stationary wave-5-like circulation pattern, several mechanisms have been investigated. One hypothesis focuses on anthropogenic aerosol forcing. Single-forcing climate model experiments show that greenhouse gas forcing alone does not reproduce the observed increase in quasi-stationary Rossby waves. Instead, declining sulfate aerosol emissions over Europe and North America since the 1980s appear to play an important role. Reduced aerosol concentrations lead to stronger regional surface warming, which alters land–atmosphere temperature gradients and can favour more frequent quasi-stationary wave patterns. However, although aerosol forcing produces circulation changes with spatial patterns similar to observations, the simulated magnitude of these changes is considerably weaker than observed, indicating that additional processes are likely involved.

Another line of research highlights the importance of internal variability and tropical–extratropical teleconnections, particularly those associated with Pacific sea surface temperature (SST) variability. Analyses suggest that the apparent hemispheric wave-5 pattern can be interpreted as the combined effect of two regional circulation regimes: a U.S.–Atlantic pattern and a Eurasian pattern. These regimes are associated with distinct SST anomaly structures. The Eurasian pattern is linked to SST conditions resembling La Niña combined with a positive Pacific Decadal Oscillation, whereas the U.S.–Atlantic pattern is associated with a combination of El Niño and negative Pacific Decadal Oscillation conditions.

A further potential driver involves tropical forcing through the circumglobal teleconnection (CGT) associated with variability in the Indian summer monsoon. Increased Rossby wave source activity northwest of India can trigger wave propagation across Eurasia and North America, producing a circumglobal wave structure similar to the observed pattern.

Overall, current evidence suggests that the observed wave-5-like circulation changes likely arise from a combination of mechanisms, including anthropogenic forcing (particularly aerosols), tropical SST-driven teleconnections, monsoon-related Rossby wave sources, and a weakened background flow associated with Arctic amplification and anthropogenic warming.

1. Introduction

The EXPECT project aims to identify and quantify the mechanisms by which physical processes govern regional climatic changes, including extremes, on inter-annual to multi-decadal time scales. Therefore, newly available climate simulations and Earth Observations (EOs) are exploited, combining machine learning (ML) with physical methods. The research targets fundamental knowledge gaps related to atmospheric circulation and land-atmosphere interactions, which represent major limitations in current climate predictions and projections, and in particular in understanding changes in European summer extremes. EXPECT addresses key knowledge gaps that currently hinder understanding of regional climate changes on inter-annual, decadal and multi-decadal time scales, and develops new methods to explain and credibly predict such changes.

A key focus addressed by **Theme 2** of EXPECT is to explain recent multi-decadal trends in Northern Hemisphere summer atmospheric circulation and understanding how summer circulation will change in the future. The recent observed changes are characterized by a weakening of westerlies and storm tracks and an upward trend pattern resembling a circumglobal quasi-stationary Rossby wave with centres of action that have been linked to extremes including heatwaves, droughts, and floods (Teng et al., 2022). This trend in Rossby wave pattern is not well simulated in climate models, and the observed warming trends in summer-mean temperatures and heat extremes over western Europe are stronger than those simulated by all current climate models (Van Oldenborgh et al., 2022).

Within Theme 2, **WP3** has the following key objectives:

1. To **identify** and **quantify** the **drivers** of annual to decadal changes in climate with a focus on boreal summer atmospheric circulation.
2. To **identify** and **characterise model biases** and their impacts on the processes relevant for climate responses to different forcings with a focus on boreal summer atmospheric circulation.

This deliverable documents progress on these two objectives during the first half of the EXPECT project.

2. Weakening boreal summer stormtracks

Storm tracks are key features of the Earth's atmospheric circulation, transporting heat, moisture, and momentum from the tropics toward the poles. They help

regulate weather and climate and strongly influence regional conditions such as rainfall, temperature extremes, drought, and heatwaves. Over recent decades, multiple observation-based datasets (i.e., reanalyses) have shown that the intensity of these summertime storm tracks has weakened since 1979, as seen in e.g. eddy kinetic energy (EKE). Understanding whether this weakening is due to natural internal climate variability or human-caused changes is a central goal for EXPECT. In Chemke and Coumou (2025), we analyse the latest generation of climate models (CMIP6; Eyring et al., 2016) with updated forcings and physics, and apply a detection and attribution statistical analyses to estimate the role of human forcings on the observed weakening.

Across four different reanalysis datasets—ERA5 (Hersbach et al., 2020), JRA-55 (Kobayashi et al., 2015), NCEP2 (Kanamitsu et al., 2002) and MERRA2 (Gelaro et al., 2017)—from 1979 to 2020, the tropospheric mid-latitude storm tracks in boreal summer have weakened by about 6% relative to late-20th-century levels. CMIP6 climate models reproduce the historical storm track weakening observed in the reanalyses, and do so more closely than CMIP5 models. Most individual CMIP6 models show downward trends in storm track intensity that are similar in magnitude to reanalysis trends, and the CMIP6 multi-model mean (MMM) trend is statistically close to the observational estimate. Using signal-to-noise and Fractional Attribution Risk (FAR) methods of historic simulations (Figure 1), we quantified the contribution of anthropogenic forcings relative to internal variability and natural forcings, showing that (1) around 2005, the observed storm track weakening trend grew large enough to exceed expected noise from internal variability alone, and (2) by 2014, the FAR analysis indicates a ~96% probability that the observed trend is due to anthropogenic emissions. This implies that it is extremely likely that human influence has been the dominant cause of the weakening.

Next, we aim at understanding the physical mechanisms underlying the weakening. Anthropogenic warming has heated high latitudes more than lower latitudes (i.e. Arctic amplification), reducing the poleward temperature gradient, vertical wind shear and baroclinicity, and thereby reducing eddy kinetic energy. We show that roughly half of these downward trends are attributable to greenhouse gas (GHG) forcing and the other half to aerosol forcing. Our work thus highlights a significant human fingerprint on large-scale atmospheric circulation, with consequences for both weather and climate extremes.

In summary, Chemke and Coumou (2025) provide robust evidence that the recent weakening of Northern Hemisphere summertime mid-latitude storm tracks is real, reproduced in state-of-the-art climate models, and very likely driven by human influence through greenhouse gas and aerosol emissions. It also clarifies the dynamical mechanisms that link anthropogenic warming to weaker storm activity via enhanced warming of the Arctic.

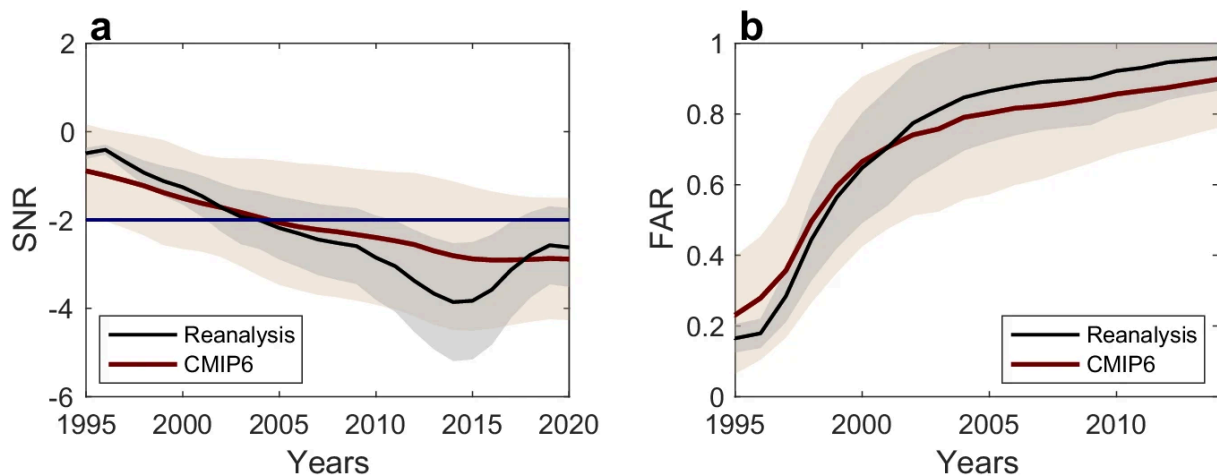


Figure 1: (a) Signal-to-noise ratio (SNR) and (b) Fractional Attributable Risk (FAR) analyses to the JJA Northern Hemisphere stormtrack (EKE) trends (from 1979 to a given year on the horizontal axis) in reanalyses (black lines) and CMIP6 models (red lines). Shadings show the standard deviation of SNR and FAR values. The horizontal blue line marks a signal-to-noise ratio of -2, showing that by ~2004 the signal became detectable. The evolution has been smoothed with a 3-year running mean for plotting purposes.

3. Anthropogenic and natural forcing

At the BSC, we have performed an analysis of model simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) of the Coupled Model Intercomparison Project Phase 6 (CMIP6), the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP) and the Atmospheric Model Intercomparison Project (AMIP), to evaluate the contribution of forcing factors and internal variability to the atmospheric circulation changes and the associated increase in European summer temperatures over the last decades. Two different studies have been conducted, considering between 844 and 1747 simulations from 9 different models and both yielding complementary results. This included GHG, aerosol, volcanic, ozone concentration and solar-only experiments. The use of single-forcing experiments allows to isolate the contribution of different forcings, while the analysis of large ensembles of simulations with the same forcing specifications and different initial conditions allows for robust estimates of model-specific forcing responses and an assessment of the contribution of internal variability. Finally, to assess the agreement between models and observations, the results have been compared to those from ERA5 reanalysis.

The first study showed that changes have been mainly associated with the contribution of aerosols. The analyses show that GHG forcing alone cannot explain relevant changes in the frequency of quasi-stationary Rossby waves (QSW) over Europe (Figure 2c,f), while the contribution of aerosols, particularly starting from 1980,

generates an increase in European summer temperatures and in the frequency of QSW over Europe (Figure 2b,e). These changes are mainly due to the direct impact of aerosol emissions in regional temperatures. Declining aerosol emissions in Eastern North America and Western and Central Europe contributes to increase European summer temperatures and to alter in turn the atmospheric circulation.

Furthermore, the ensemble average of model simulations does not show relevant changes in the sea level pressure (SLP) over the Atlantic, while ERA5 shows the activation of a negative center of pressure west of British Isles and positive centers of pressure over west and central North Atlantic and over eastern Europe. This difference can be associated with the contribution of internal variability. Those simulations showing active SLP centers in the western and eastern North Atlantic tend to also show more intense stationary Rossby waves over Europe and then warmer European summer temperatures. As shown in Figure 2a, the observed trends (hollow circle in Figure 2a) would be then a combination of a contribution from internal variability (unpredictable part) and a contribution of aerosols (predictable part contained in the ensemble average; solid circle in Figure 2a), impacted by a signal-to-noise error (predictable part not tracked by the ensemble average, but potentially tracked with a signal adjustment; solid diamond in Figure 2a).

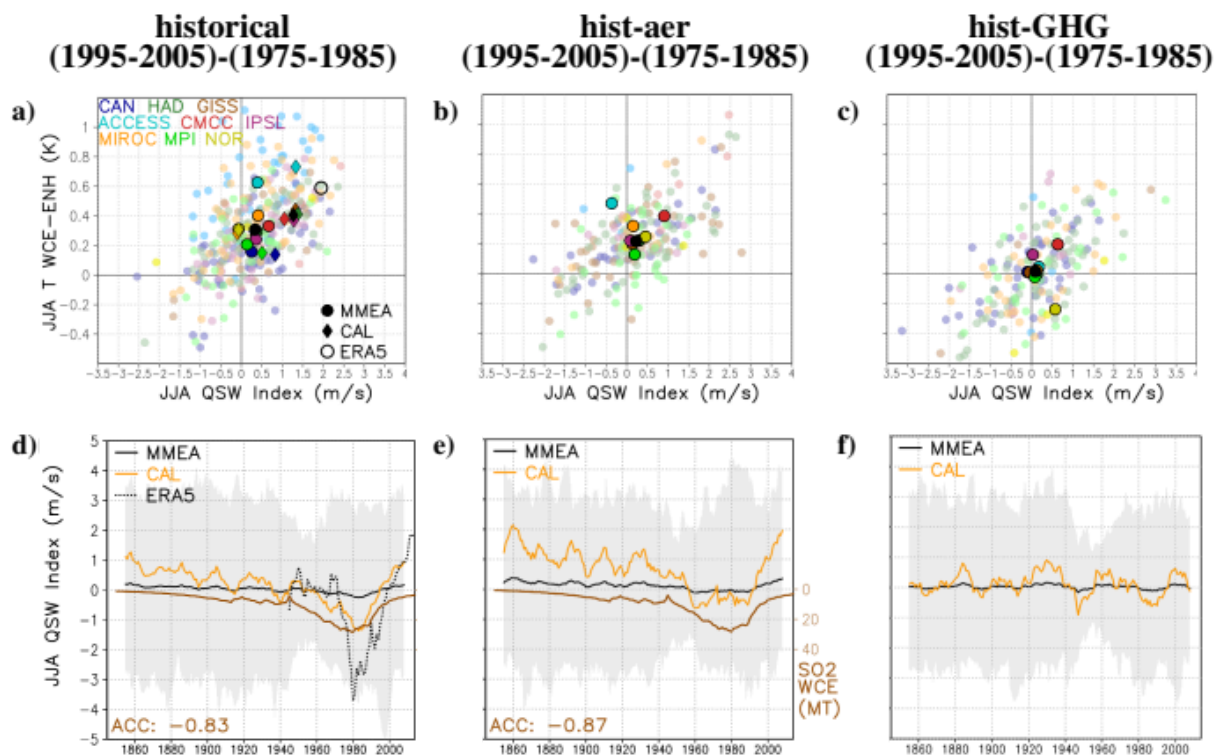


Figure 2. (a) Difference between 1995-2005 and 1975-1985 average of JJA surface temperature in Western and Central Europe (WCE) with respect to extratropical areas of the NH (ENH) versus JJA QSW index, obtained with the multi-model ensemble average (MMEA) of historical simulations (solid black circle), the ensemble average of historical simulations of each individual model (color circles), ERA5 (hollow circle), the calibrated MMEA of historical simulations (black diamond), and the calibrated ensemble average of historical simulations of each individual model (color diamonds). The differences for individual simulations are also included with smaller dots. The QSW index is defined as the JJA meridional wind at 250 hPa over central and western Europe (35° N - 65° N; 15° W - 30° E) minus the sum of the JJA meridional wind over the North Atlantic (35° N - 65° N; 60° W - 15° W) and over eastern Europe (35° N - 65° N; 30° E - 60° E), filtered with a 10-year moving average to highlight the decadal variability. (b) Same as Figure 2a, but for the hist-aer simulations. (c) Same as Figure 2a, but for the hist-GHG simulations. d) JJA QSW index obtained with the MMEA of historical simulations (solid black curve), the calibrated MMEA (orange curve), and ERA5 (dashed curve). QSW index is shown as the anomaly with respect to 1951-1970. The minimum-to-maximum spread comprised by the individual simulations within the ensemble is included with a shading. The annual sulfate aerosol emissions over WCE are included as a brown curve (right axis, reversed), and the Pearson anomaly correlation coefficient (ACC) between the QSW index of the MMEA and the annual sulfate aerosol emissions over WCE is included within the figure. (e) Same as Figure 2d, but for hist-aer simulations. (f) Same as Figure 2d, but for hist-GHG simulations.

The second study (Marcet-Carbonell et al. In review) analyses the models' ability to reproduce the observed changes in upper-tropospheric atmospheric circulation as characterised by the geopotential height at 200hPa (Z200). In particular, we find that models containing aerosol forcings are best able to match the spatial patterns of observed trends in Z200 in recent decades. This is shown in Figure 3, where AMIP, historical and the aerosol-forced ensembles show a large degree of pattern similarity, whereas GHG, ozone and natural forcings either show non-significant trends or a low degree of pattern similarity. However, despite a large degree of pattern similarity, trends in the simulations show a smaller magnitude of changes, even in individual simulation runs, consistent with the signal-to-noise paradox. Additionally, for the main centers of change, most individual runs of model simulations also show weaker magnitude (to a lesser extent) than reanalysis trends Figure 4, highlighting that models are not reproducing the observed changes and model errors in circulation are likely to be present.

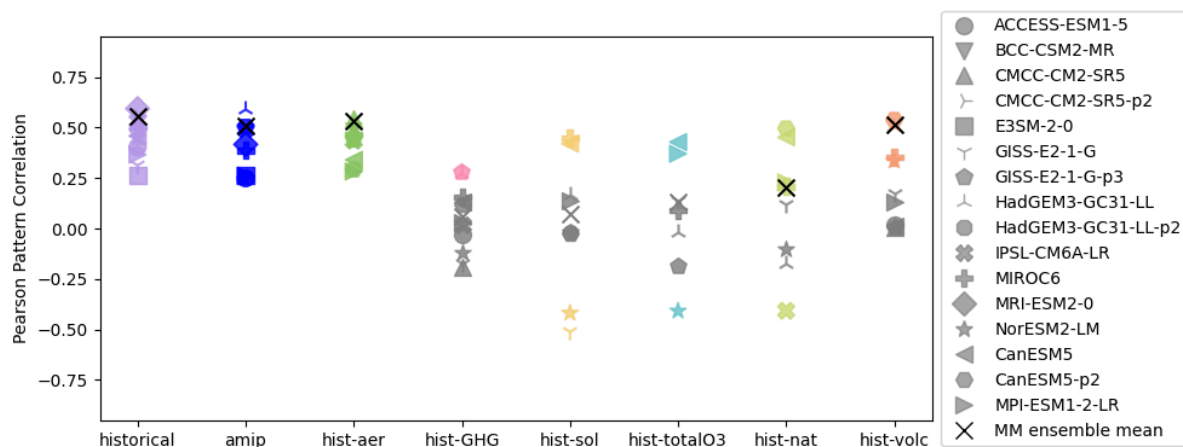


Figure 3: Pearson pattern correlation of model means' Z200_{az} trend with respect to ERA5 during 1979-2014. Each different model mean is represented by a different shape. Multimodel ensemble means for each forcing are shown with a black cross.

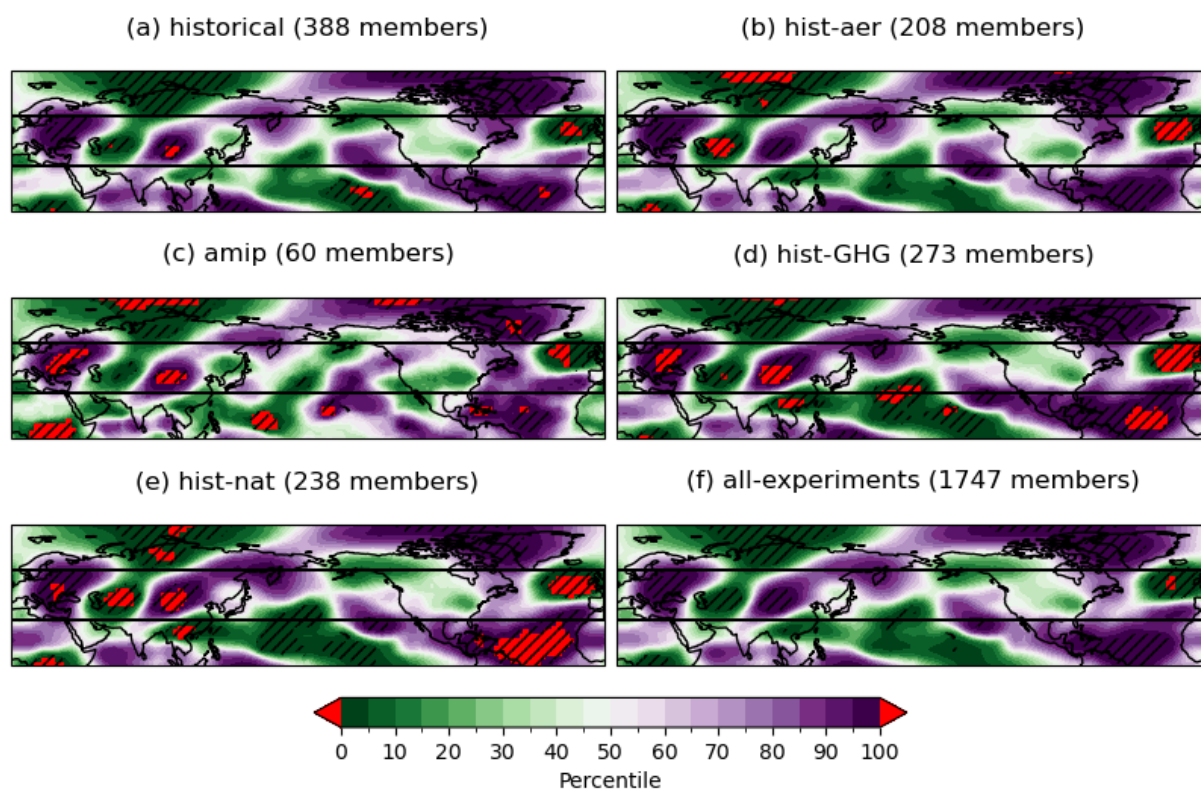


Figure 4: Percentile of ERA5 Z200_az trends with respect to the trends in the individual simulations of specific forcing configurations (a–e) and all experiments combined (f). Hatching indicates where ERA5 lies below the 2.5th percentile or above the 97.5th percentile of simulated trends, and the red areas indicate that ERA5 is outside all model values.

4. Dynamic versus thermodynamic warming

4.1 Attributing excess warming in Europe to atmospheric circulation changes and external forcings

At Reading University, we have investigated drivers and mechanisms contributing to excess warming in Europe in both winter and summer during recent decades (1979-2022) by using reanalyses and model simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) of the Coupled Model Intercomparison Project Phase 6 (CMIP6). Over the period 1979-2022, reanalyses show that European surface air temperatures warmed around three times as fast as the global mean temperatures in both winter and summer. We define “excess” European warming as the difference between the rate of European regional warming and the rate of global warming and investigate the causes. Using a simple observation-based method, we estimate that around $40\% \pm 39\%$ (in winter) and $29\% \pm 10\%$ (in summer) of excess European warming is “dynamical” - attributable to changes in atmospheric circulation (Figure 5). We show that the rate of European warming simulated in CMIP6 models compares well with the observations, but only because these models warm too fast in the global mean; excess European warming is underestimated, particularly in winter (Dong and Sutton, 2025). The CMIP6 models simulate well the magnitude of the thermodynamic component of excess European warming since 1979 in both winter and summer, but they suggest only a weak dynamical contribution in the multi-model mean (Figure 6). The models suggest GHG induced warming made the largest contribution to excess thermodynamic warming in winter, whereas changes in anthropogenic aerosols made the largest contribution in summer (Dong and Sutton, 2025). However, the failure of current models to simulate observed circulation trends (either as a forced response or as a combination of forced response and internal variability) also implies large uncertainty in future rates of European warming.

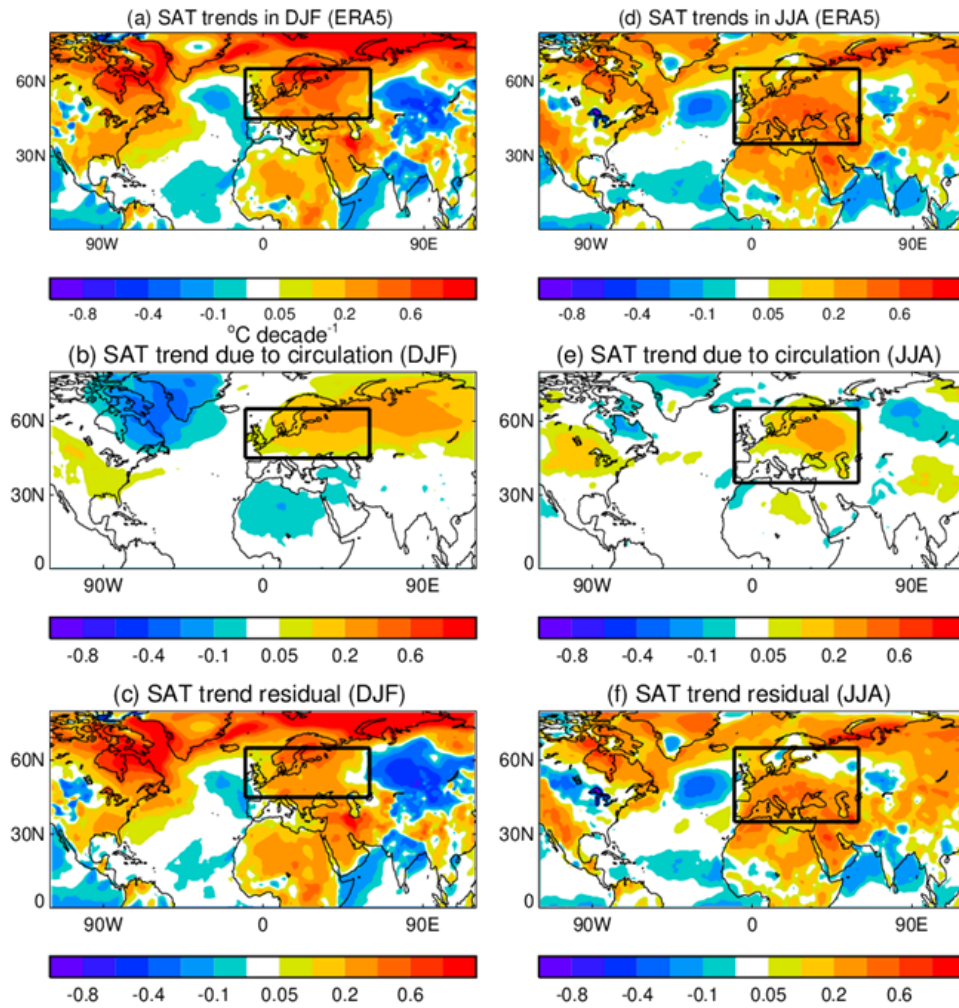


Figure 5: Linear trends of surface air temperature (SAT) ($^{\circ}\text{C decade}^{-1}$), SAT due to circulation changes, SAT residual based on ERA5 reanalysis during 1979-2022 with corresponding global mean is removed. (a-c) for winter (DJF), where the circulation index used for decomposition of SAT trends is the North Atlantic oscillation (NAO) index, defined as the difference of area averaged SLP over a southern box (36°N - 38°N , 28°W - 22°W) around Azores and a northern box (64°N - 66°N , 26°W - 21°W) around Iceland over the North Atlantic. (d-f) for summer (JJA), where the circulation index used for decomposition of SAT trends is a height index, defined as area averaged geopotential height over the region (40°N - 65°N , 5° - 50°E) at 500 hPa with the zonally averaged trend removed. Note that nonlinear color bars are used. The black box outlines the region that is used to define SAT index over Europe.

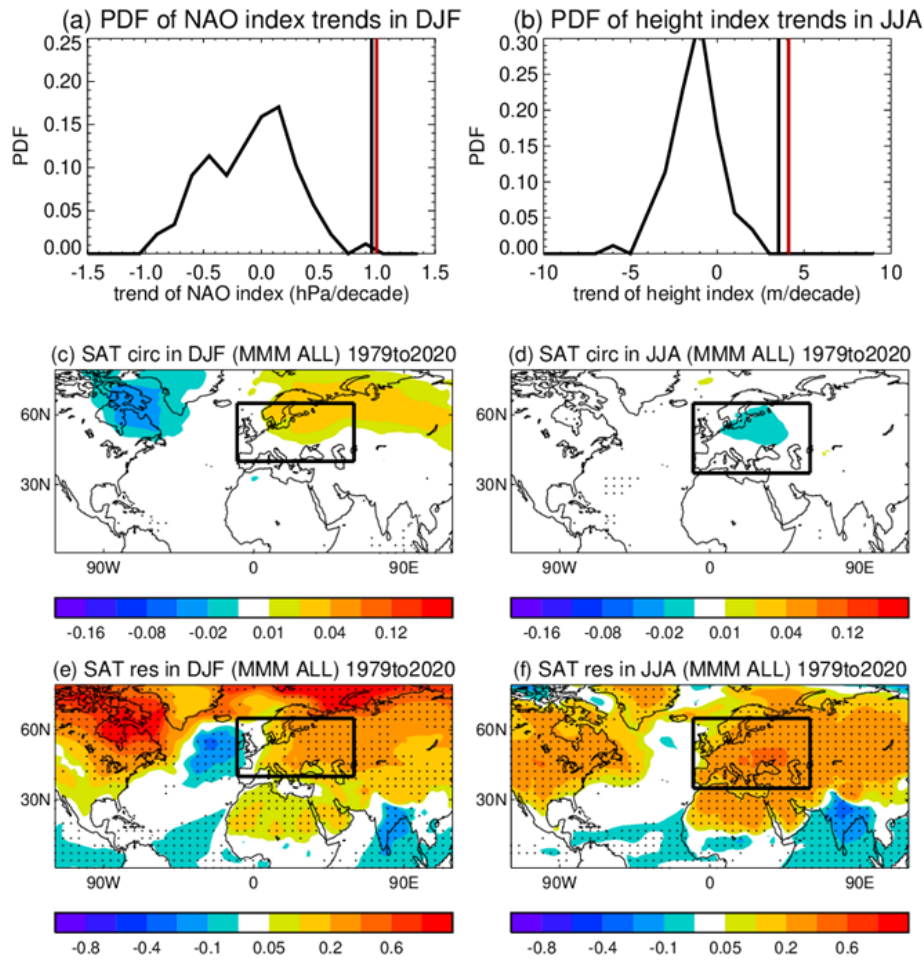


Figure 6: Linear trends of atmospheric circulation indices, circulation induced SAT change, and SAT residual in winter (DJF) and summer (JJA) in reanalyses and CMIP6 historical extended (DAMIP) simulations. (a, b) Probability density function of NAO index trend (hPa decade^{-1}) in DJF and height index trends (m decade^{-1}) in JJA based on CMIP6 historical extended (ALL forcing) ensemble simulations during 1979-2020. Corresponding trends during 1979-2022 based on two reanalysis data sets are plotted as vertical lines (red for ERA5 and black for JRA55). (c, d) The multimodel mean (MMM) SAT trend ($^{\circ}\text{C decade}^{-1}$) due to changes in circulation in DJF and JJA during 1979-2020. (e, f) MMM SAT residual trend in DJF and JJA. The global mean SAT trend is removed in panels (c-f) and the removal of global mean has a very little impact on panels (c-d). Note that nonlinear color bars and different colour scales are used in spatial patterns (c-f). Dots indicate regions where 80% models have the same sign of trend. The black box outlines the region that is used to define SAT index over Europe.

4.2 Attribution of Western European heat extremes using a targeted weather regime approach

A study conducted at Leipzig University (Carvalho-Oliveira et al., 2026) investigated the drivers of Western European heat extremes using a targeted weather regime

approach. Based on this framework, we estimate the thermodynamic and dynamical contributions to regional temperature trends. To better isolate circulation drivers of extreme heat, we apply a targeted probabilistic clustering method, the so-called Regression Mixture Model - Variational Autoencoder (RMM-VAE), introduced by Spuler et al. (2024). In contrast to traditional weather regime methods (principal component analysis followed by k-means clustering), which prioritize statistical compactness, RMM-VAE is explicitly designed to identify circulation patterns that are maximally informative for regional temperature extremes.

We first compare RMM-VAE with k-means clustering in identifying summer weather regimes over Western Europe. The regimes are derived from 500-hPa streamfunction fields and linked to surface air temperature (SAT), including both mean summer SAT and the 90th percentile (SAT90), representing extreme heat. We find RMM-VAE to isolate a physically coherent “southerly-flow” weather regime (WR1) that accounts for the vast majority of heatwave days (see Figure 7a,b). In contrast, k-means spreads heatwave days across multiple clusters, making attribution less clear (see Figure 7c,d). WR1 represents persistent warm-air advection and anticyclonic conditions favorable for extreme heat.

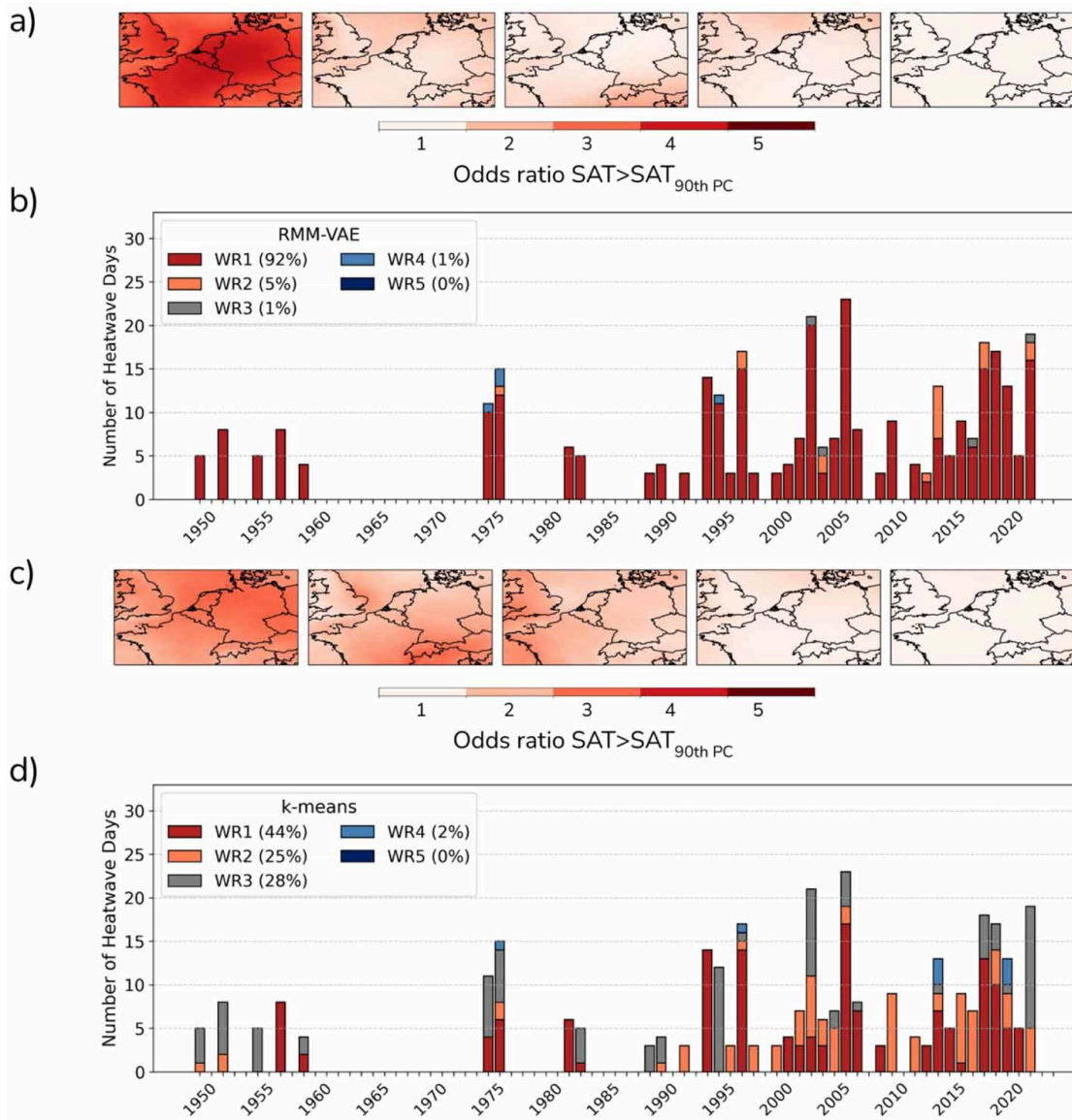


Figure 7: Heatwave occurrence and regime association over 1950-2022. (a) Odds ratio of SAT exceeding the 90th percentile per grid cell in Western Europe, conditioned on each RMM-VAE regime; (b) Number of heatwave days per summer identified based on criterion of at least 3 consecutive days with SAT exceeding the 90th percentile over at least 30% of Western Europe, coloured by the corresponding RMM-VAE regime; (c), (d) same as (a), (b) but using the k-means regimes.

To quantify thermodynamic and dynamical contributions to temperature trends, we employ a linear regression framework in which global mean temperature (GMT) acts as a common driver of both circulation changes (i.e., seasonal regime frequency) and regional surface temperature, alongside the direct influence of circulation on temperature (see Figure 8). This simple but physically motivated model explains a large fraction of interannual variability in Western European summer temperatures. Importantly, when the regimes and regression model are trained using data only up

to the year 2001 and subsequently applied to predict the following decades, the model retains high skill, supporting the robustness of the approach.

Our results support the hypothesis that Western Europe's amplified summer warming cannot be explained solely by thermodynamic warming associated with increasing GMT. Instead, approximately 34% of total summer warming in Western Europe is attributed to changes in atmospheric circulation. We further hypothesize that these circulation changes are at least partly forced. Thus, the region's amplified warming reflects a combination of global mean warming and systematic shifts in atmospheric circulation patterns that favor more frequent southerly flow and persistent heat-promoting regimes.

Overall, this study demonstrates that targeted weather regime approaches can substantially improve the physical interpretability of circulation-temperature relationships. By identifying impact-relevant regimes, RMM-VAE strengthens regional climate change attribution and provides physically grounded predictors for seasonal forecasting and climate risk assessment.

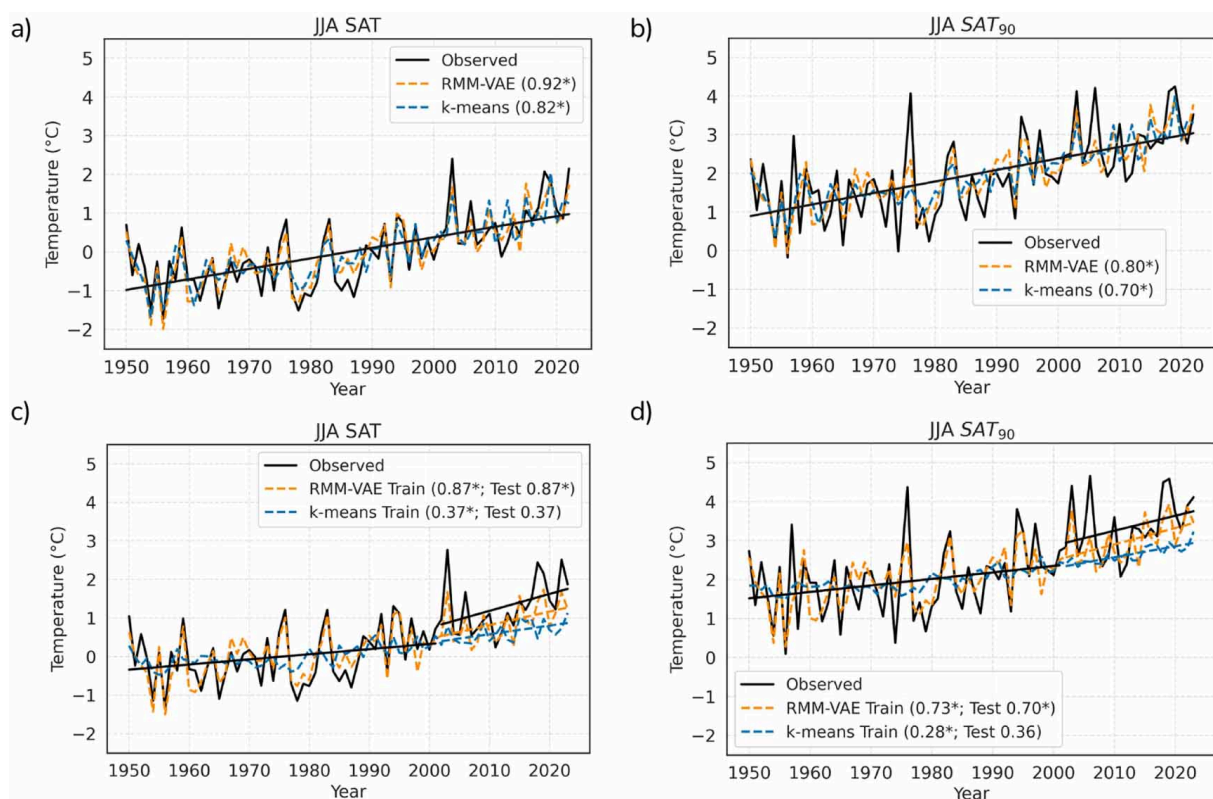


Figure 8: (a) Time series of observed JJA SAT (black) in the target region for 1950-2022, alongside predicted SAT from linear regression models with seasonal weather regime frequencies (based on RMM-VAE in orange, and based on k-means in blue) and GMT as predictors. Pearson correlation coefficients (r) are shown in the legend, with a star if significant at the 95% level. The black line indicates the observed linear trend. (b) same as (a) but for predicting the 90th percentile of SAT. (c) and (d) same as (a) and (b) but using a train (1950-2001) and test (2002-2023) split.

5. Internal variability and the role of Pacific sea surface temperatures

In a paper published in *Journal of Climate* (Happé et al, 2026), we examine how boreal-summer atmospheric circulation has changed in recent decades and identify the mechanisms behind these trends. Various regions in the Northern Hemisphere midlatitudes have seen pronounced trends in upper atmosphere summer circulation and surface temperature extremes in recent decades. Several of these regional trends lie outside the range of historic CMIP6 model simulations (Figure 9). Furthermore, the CMIP6 models fail to capture the wave-like hemispheric pattern observed in reanalysis, which consists of five alternating regions of high and low pressure and is therefore referred to as the wave-5 pattern.

Using reanalysis datasets (ERA5) and statistical pattern analysis, we find that the observed trends in upper-atmospheric circulation do not represent a single circumglobal wave pattern. Rather, they consist of at least two separate regional signatures: a U.S.–Atlantic pattern and a Eurasian trend pattern (Figure 10). The circulation trend can explain on average 15% and 26% of the observed regional temperature trends in the U.S.–Atlantic and Eurasian regions, respectively. The circulation trend in the CMIP6 multi-model mean does not resemble the observed trend pattern and is much weaker overall. Some individual CMIP6 models do show a resemblance to the observed pattern in ERA5, although still weak with a maximum pattern correlation of 0.47. The pattern correlation is higher for the two individual regions (U.S.–Atlantic and Eurasia), reaching a maximum of 0.69 and 0.78. We show that both regional wave patterns in ERA5 are associated with distinct sea surface temperature (SST) and outgoing longwave radiation (OLR) anomalies in the 3 weeks leading up to the atmospheric configuration, resembling known teleconnection patterns. CMIP6 models appear to lack these tropical–extratropical teleconnections.

The Eurasia pattern is associated with SST anomalies resembling a combination of La Niña, the cool phase of the El Niño–Southern Oscillation (ENSO), and positive Pacific Decadal Oscillation (PDO) conditions in the Pacific Ocean, and a tripole structure in the North Atlantic Ocean. Dipole- and tripole-like anomalies are known to increase the baroclinicity and therefore can act as a Rossby wave source. The West North

Pacific SSTs are closely related to ENSO, which has been linked to the Eurasia circulation pattern previously (Figure 10b and d).

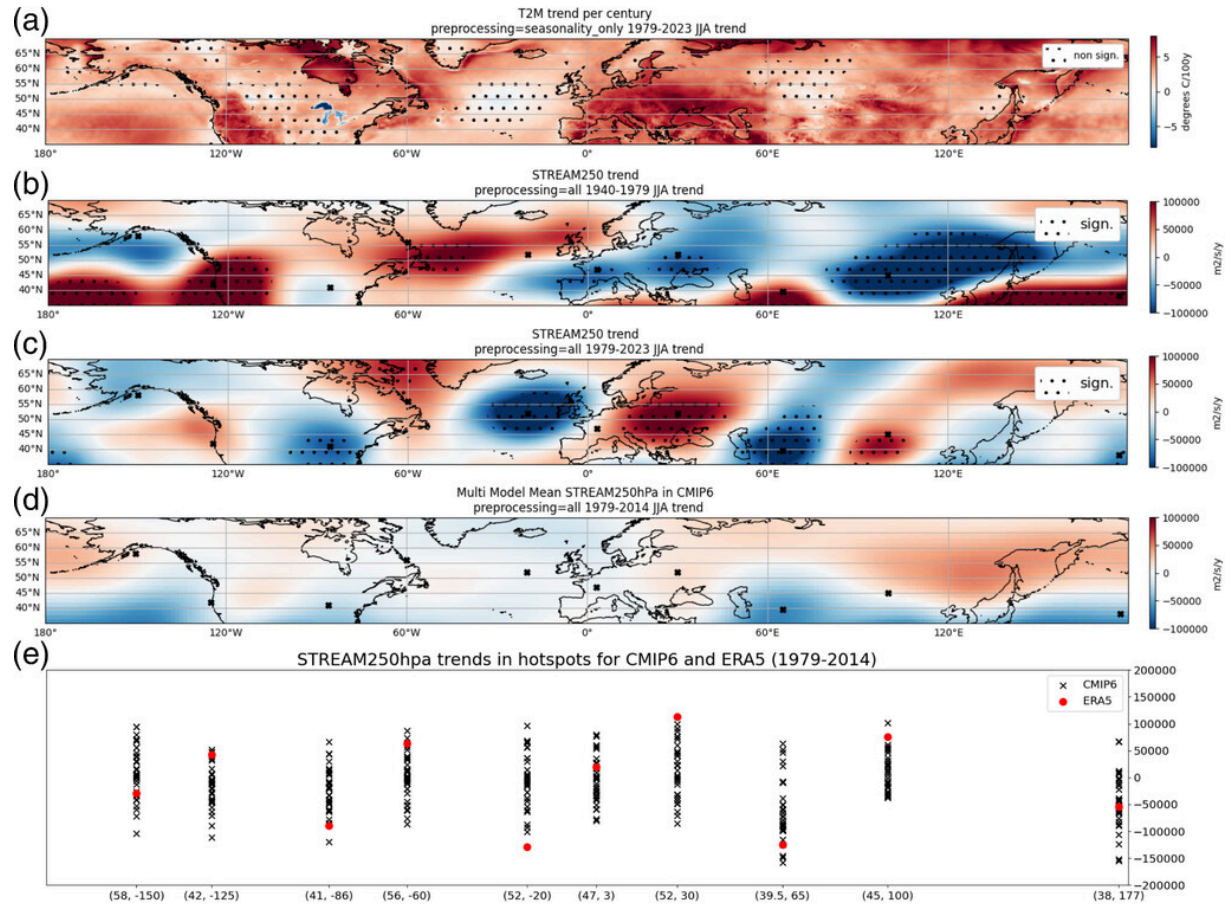


Figure 9: Midlatitude trend plots of boreal summer with hotspots marked with X. (a) The temperature trend (per century) ($^{\circ}\text{C}$) (1979–2023)—with stippling indicating nonsignificant regions, (b) the yearly streamfunction at 250-hPa trend ($\text{m}^2 \text{s}^{-1}$) (1940–79)—with stippling indicating significant regions, (c) the yearly streamfunction at 250-hPa trend ($\text{m}^2 \text{s}^{-1}$) (1979–2023)—with stippling indicating significant regions, (d) the multimodel mean of yearly streamfunction at 250-hPa trends of CMIP6 models ($\text{m}^2 \text{s}^{-1}$) (1979–2014), and (e) for each hotspot the trend in CMIP6 models (one cross per model) and the trend in ERA5 (from 1979 to 2014) for streamfunction at 250 hPa.

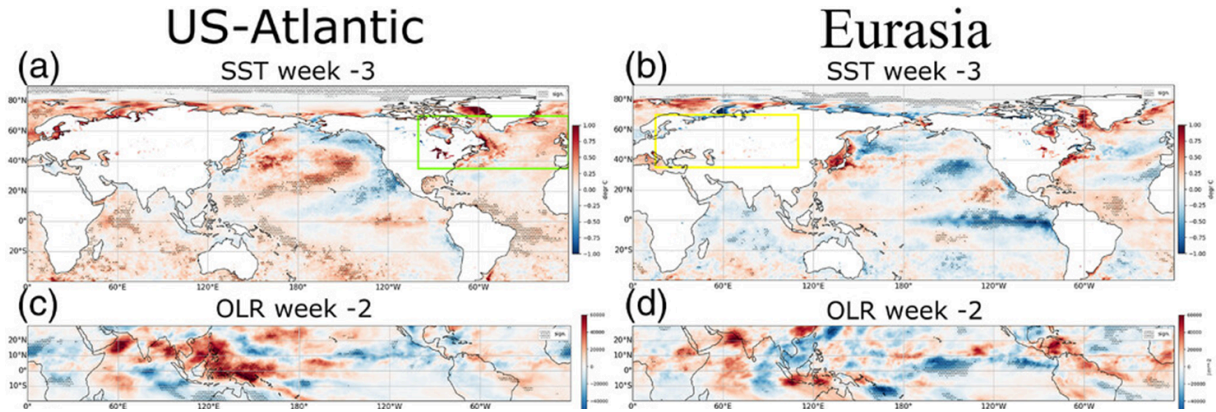


Figure 10: Composites of positive matches on trend pattern for the two regions: (a) and (c) U.S.–Atlantic and (b) and (d) Eurasia. (a),(b) SST anomalies 3 weeks before ($^{\circ}\text{C}$), (c),(d) OLR anomalies 2 weeks before (J m^{-2}).

The U.S.–Atlantic pattern is associated with SST anomalies representing a combination of El Niño and negative PDO conditions, which is a relatively rare combination (Feng and Tung, 2020). Both the tropical and northern Pacific have previously been linked to atmospheric Rossby waves affecting the US and beyond (Vijverberg and Coumou, 2022).

The different SST and OLR anomalies associated with the U.S.–Atlantic and Eurasian wave patterns support the notion that they are distinct wave patterns with different driving mechanisms that together make up the wave-5 trend pattern. Rather than interpreting the circulation changes as smooth responses to external forcing, we argue that they emerge from the combined effect of increased activity in these two sectors. In a follow-up study (Stoffels et al., in preparation), we analyzed the occurrences of these specific regional (sub-hemispheric) circulation regimes and found an upward trend in the frequency of the two wave signatures (Figure 11). At the same time, we observed a decrease in the opposite pattern, suggesting that the preferred longitudinal sectors of wave activity may have shifted. This is consistent with other studies (e.g. Tang et al., 2025; Zhang et al., 2025) showing that the circumglobal teleconnection structure (similar to the wave-5 pattern) has shifted westward by half a wavelength since the late 1970s. Changes in the driving mechanisms of these regimes will be further explored in Stoffels et al. (in preparation).

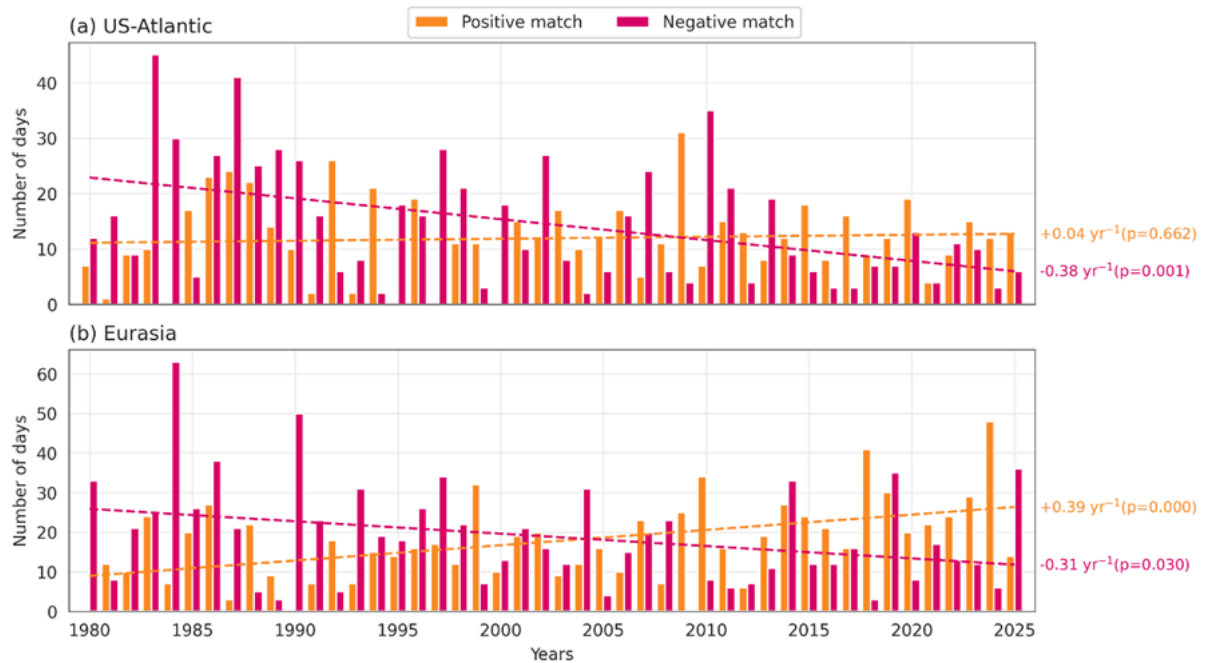


Figure 11: Counts of the two regional circulation regimes: (a) U.S.-Atlantic and (b) Eurasia. The two circulation regimes are defined based on streamfunction at 250-hPa in ERA5. The number of days per year when the circulation in each sector matches the wave-5 trend pattern is shown, with a distinction made between positive (pattern correlation > 0.5) and negative (pattern correlation < -0.5 ; inverted pattern) matches.

A study led by UK MetOffice aims to understand the drivers of these Pacific Trends, particularly from the preceding boreal winter. Over recent decades (1981-2014), observations show a La Niña-like cooling trend that is not captured by the majority of ensemble members for either hist-nat or historical CMIP6 simulations. This trend has been well documented and the cause of the discrepancy between observations and models is highly debated (eg. Lee et al., 2022; Seager et al., 2019; Watanabe et al., 2021, 2024; Wills et al., 2022)

In order to understand this discrepancy, we hypothesise that the Pacific SSTs may be driven by atmospheric circulation which could be underestimated in models, as seen previously (Scaife and Smith, 2018). To investigate this, we follow an 'Aleutian Low matching' approach similar to the NAO matching used in Smith et al. (2020). Specifically, we find 20 members that are closest to the observed ONDJFM Aleutian Low for each year. The hist-nat simulations reproduce the observed SST La Niña trend fairly well, whereas historical simulations do not (Figure 12). Examining individual forcing simulations, the aerosol only runs (hist-aer), show a similar response as in hist-nat, whereas the GHG only runs (hist-GHG) show very similar results as to historical simulations (not shown).

This suggests that the Aleutian Low could be driving the tropical Pacific SST trends. Furthermore, anthropogenic GHG forcing disrupts the teleconnection between the Aleutian Low and tropical Pacific SSTs, weakening the natural-forcing signal evident in hist-nat. Interestingly, we find that, when we add up the individual GHG, aerosol and natural forcings, a La Nina-like trend pattern shows up, more similar to that in hist-nat than to that in historical. Remarkably, this is also similar to the observations. We hypothesise that this may be due to the thermodynamic response dominating the SST trends in the GHG runs, whereas in the natural forcing/aerosol forced runs the dynamic circulation response of the Aleutian Low is more important in driving SST trends. This suggests that the role of the atmospheric circulation may be underestimated in current climate models, as seen previously (Scaife and Smith, 2018). However, further work is needed to fully understand this result.

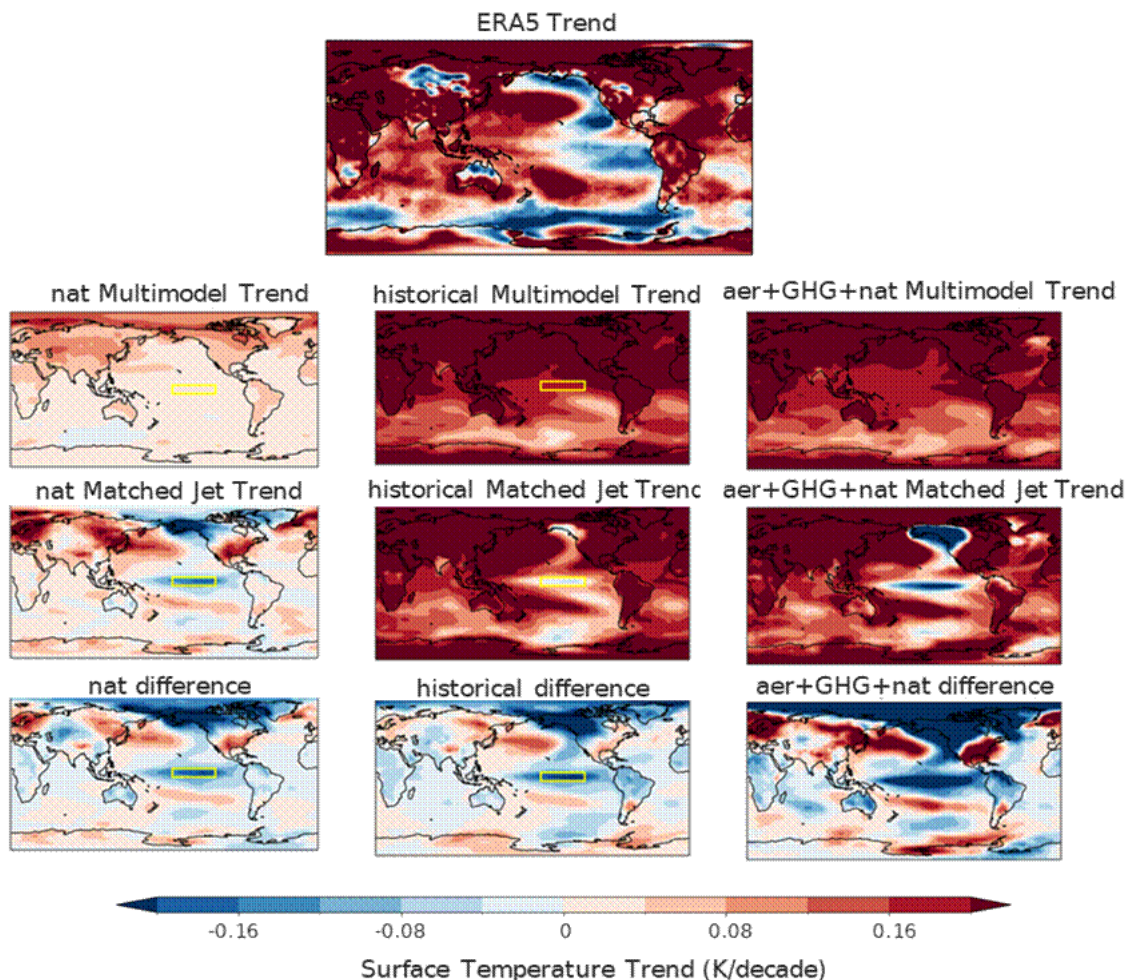


Figure 12: Trends in sea surface temperatures (SSTs) for 1981-2014 ONDJFM in ERA5 (top panel), top row: multimodel model mean in CMIP6, middle row: matching the 20 model members closest to ERA5 Aleutian Low (see NAO matching in Smith et al., 2020), bottom row: differences in between middle row and top row (matched jet trend minus original). Left is for natural forcings only simulation (hist-nat), middle is all forcings simulation (historical), right is addition of natural, aerosol and GHG (hist-nat+hist-aer+hist-GHG)

6. Circumglobal teleconnection & Monsoon

The summertime circulation has been analysed in ERA5 and ECMWF's seasonal forecast system. The trend over the period 1993-2023 in the boreal summer non-zonal upper-level circulation in ERA5 is towards a more pronounced upper-level wave pattern (Figure 13a), with a wavenumber 5 structure. The trend is weaker in the ensemble mean of the seasonal hindcast initialised 1 May each year (Figure 13b), though a wave-like trend is evident, suggesting a forced wave-like response. However, the trend is largely absent in the multimodel mean of CMIP6 models (Figure 13c).

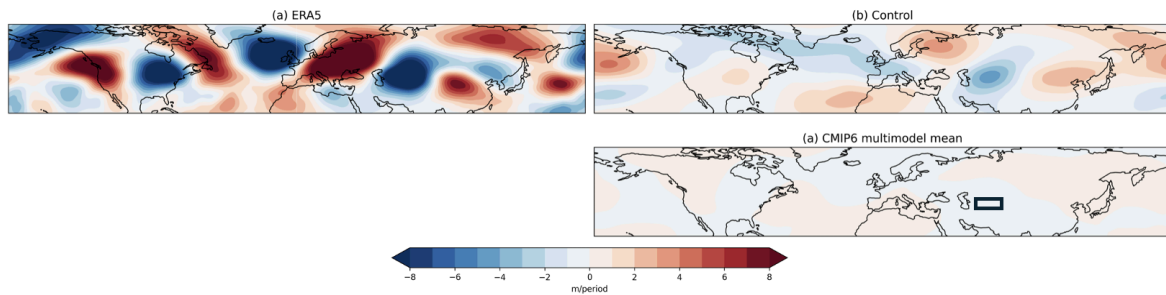


Figure 13: Linear trends (1993-2023) in the non-zonal component of the 200 hPa geopotential height in JJA in (a) ERA5, (b) ECMWF's seasonal prediction system, and (c) the multimodel mean of CMIP6 climate models.

Such wave-like patterns are known to be triggered by forcings from the tropics. In particular, the so-called circumglobal teleconnection (CGT) is a Rossby wave response that resembles the circulation pattern seen in Figure 13 that is associated with variability in the Indian summer monsoon (Ding and Wang, 2005). The CGT relates variability in the circumglobal wave response to variability in a region northwest of India to the east of the Caspian Sea (black box in Figure 13c), the latter of which is driven by fluctuations in the strength of the monsoon circulation. The mechanisms that initiate and maintain Rossby waves can be quantified using the Rossby wave source term. The Rossby wave source is defined as $RWS = -\nabla \cdot (\mathbf{v}_x \zeta)$, where ζ is the absolute vorticity and $\mathbf{v}_x$ is the divergent part of the wind field, and accounts for changes in vorticity due to vortex stretching and vorticity advection by the divergent part of the wind. There is a significant positive trend in the RWS in the key region for the CGT (not shown), which is consistent with the trend in the

upper-level circulation in the same period. To better understand the dynamical response of the RWS in this region, the lagged response to strong RWS events has been calculated.

The lagged response in 200 hPa geopotential height to strong RWS events is shown in Figure 14 for ERA5 and the seasonal hindcasts, for lags of 0, 5 and 10 days. Strong RWS events are defined as those exceeding the 80th percentile in the daily RWS time series (smoothed with a 5-day running mean). At a lag of 0 days, a wave is clearly visible over Eurasia in both ERA5 and the seasonal hindcasts, showing that the RWS is identifying Rossby waves developing in this region. In ERA5, five days after the strong RWS event, the Rossby wave has propagated eastward, and the wave now extends from Eurasia to North America. By 10 days, the wave signal has reached Europe and a circumglobal wave pattern is evident. This suggests the positive trend in the RWS in ERA5 is linked to the trend in the upper-level circulation. The wave response is weaker in the seasonal hindcasts, there is evidence of eastward propagation, but no strong signal emerges over North America or Europe. Note that the composite wave response is calculated in each ensemble member individually, not the ensemble mean, so we would expect to see a similar magnitude response as in ERA5 if the model responded to the wave source correctly. The weaker wave response may result in the weaker circulation trend seen in the model.

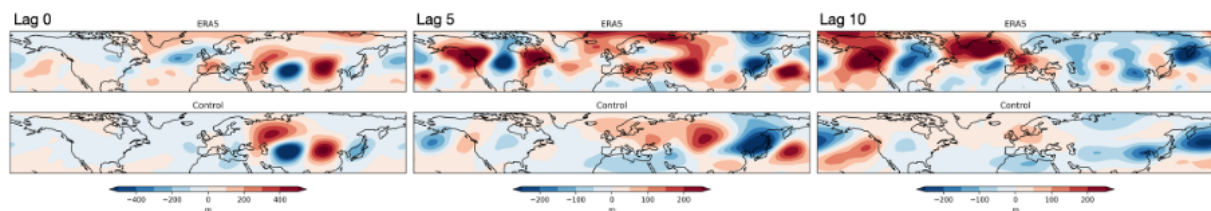


Figure 14: Composite Z200 anomalies 0 (left column), 5 (middle column) and 10 (right column) days after strong Rossby wave source events in ERA5 (top row) and ECMWF's seasonal prediction system (bottom row).

Work is ongoing to understand why the model wave response is different to ERA5, considering biases in the latitude or intensity of the subtropical jet and spread in response across the ensemble. Further work is focusing on understanding the role of external forcing in driving the observed circulation trends, as well as in the model representation of the trends. This will be done by using a set of counter-factual hindcast experiments in which the external forcing, from CO₂ and anthropogenic aerosols, is either amplified or reduced. These simulations were done as part of ECMWF's activities in Theme 2 (WPs 3 and 4).

7. Conclusions

Recent studies within the EXPECT project investigate the mechanisms behind observed Northern Hemisphere summer circulation trends. Trends in summer circulation are characterized by a weakening of the zonal flow and hemispheric storm tracks and a strengthening wave-5-like pattern - a quasi-stationary Rossby wave structure with alternating high- and low-pressure anomalies around the hemisphere.

Storm-track weakening can be linked to enhanced warming Arctic amplification. Observations show a significant weakening of Northern Hemisphere summer storm tracks since 1979. Detection and attribution analyses indicate that this weakening is very likely driven by anthropogenic emissions through both greenhouse gases and aerosols. Enhanced Arctic warming reduces the equator-to-pole temperature gradient, which weakens vertical wind shear and baroclinicity, thereby reducing eddy activity.

To understand the observed strengthening of the quasi-stationary wave-5 like pattern, several hypotheses have been tested using a range of different methods. One proposed mechanism involves anthropogenic forcing, particularly aerosols. Analyses of LESFMIP single-forcing experiments show that greenhouse gas forcing alone does not reproduce the observed increase in quasi-stationary Rossby waves. Instead, changes in anthropogenic aerosol emissions, especially the decline in sulfate aerosols over Europe and North America since the 1980s, appear to play a key role. Reduced aerosols increase regional surface temperatures, which can modify land-atmosphere temperature gradients and alter atmospheric circulation, leading to more frequent quasi-stationary wave patterns. While the pattern of aerosol-forced circulation changes is similar to the observed trend pattern, the magnitude of aerosol-forced circulation changes is much too weak.

Further, we aimed at understanding the role of internal variability and tropical-extratropical teleconnections, particularly involving Pacific SST variability. Statistical analyses show that the observed hemispheric wave-5 pattern can be decomposed into at least two regional circulation regimes: a U.S.-Atlantic pattern and a Eurasian pattern. These regimes are linked to distinct SST anomaly patterns in the Pacific and Atlantic oceans. The Eurasian pattern is associated with SST anomalies resembling La Niña combined with a PDO, while the U.S.-Atlantic pattern corresponds to a rarer combination of El Niño and negative PDO conditions. These SST anomalies act as Rossby-wave sources that can generate and sustain wave-like atmospheric responses.

Another proposed driver involves tropical forcing of the CGT via enhanced variability in the Indian summer monsoon. Enhanced Rossby wave source activity northwest of

India can trigger Rossby waves that propagate eastward across Eurasia and North America, eventually forming a circumglobal wave pattern resembling the observed wave-5 structure. Trends in this Rossby wave source region suggest that strengthening monsoon-related forcing may contribute to the observed circulation trends.

Overall, these studies suggest that the observed wave-5-like pattern likely emerges from the combined influence of anthropogenic forcing (notably aerosols), tropical SST-driven teleconnections, monsoon-related Rossby wave sources, and potentially a weakening background flow associated with aerosol and greenhouse gas forcing.

EXPECT publications

Carvalho-Oliveira, J., Spuler, F. R., & Kretschmer, M. (2026). Targeted weather regimes identify circulation patterns behind Western European summer heat extremes and trends. *Environmental Research Letters*, 21 (5), 054014.

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