ORIGINAL ARTICLE

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The ECMWF SEAS5 seasonal forecast of the hot and dry European summer of 2022

Matthew Patterson[1] | Daniel J. Befort[2] | Christopher O'Reilly[3] | Antje Weisheimer[2,4]

[1]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Parks Road, OX1 3PU, UK

[2]European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading, RG2 9AX, UK

[3]Department of Meteorology, University of Reading, Whiteknights Road, Earley Gate, Reading, RG6 6ET, UK

[4]National Centre for Atmospheric Science (NCAS), University of Oxford, Parks Road, OX1 3PU, UK

Correspondence
Matthew Patterson, Atmospheric, Oceanic and Planetary Physics, University of Oxford, Parks Road, OX1 3PU, UK
Email: matthew.patterson@physics.ox.ac.uk

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The European summer 2022 was relatively well predicted by ECMWF's system 5 seasonal forecast, including warm and dry anomalies across much of the continent and a northward shifted jet stream. This is unusual as seasonal predictions for European summers generally show little skill, particularly for atmospheric circulation. In this study a set of hindcast experiments are employed to investigate the role that initialisation of the ocean, atmosphere and land-surface played in the 2022 forecast. We find that soil moisture and increased greenhouse gas concentrations were strong contributers to the forecast near-surface temperature anomalies, with atmospheric circulation playing a relatively small role. On the other hand, atmospheric circulation made a stronger contribution to precipitation anomalies. Euro-Atlantic circulation was partly driven by a La Niña-forced teleconnection from the tropical Pacific, but also a northward jet trend in the model. This northward jet trend is at odds with the observed southward shift of the summertime North Atlantic jet over recent decades and suggests that some of circulation signal was correct for the wrong reasons. Nevertheless, this case study demonstrates that important features of at least some European summers are predictable at the seasonal timescale.

KEYWORDS

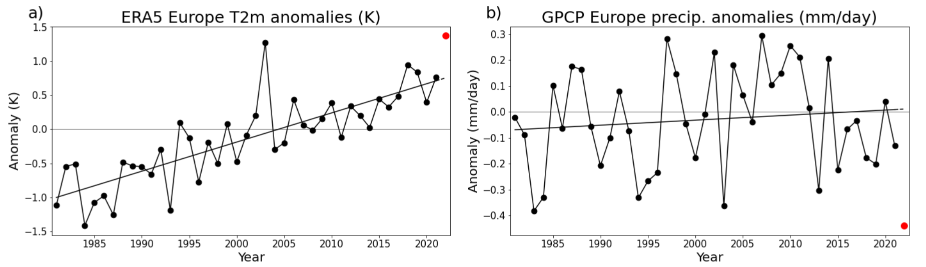

FIGURE 1 Time series' of observed a) T2m and b) precipitation anomalies for European summers (1981-2022). The year 2022 is shown by a red dot and the best fit trend line to the years 1981-2021 is also plotted.

Seasonal prediction, Europe, Summer, Climate modelling, Atmospheric circulation

1 | INTRODUCTION

The 2022 European summer was its hottest on record (figure 1a Copernicus, 2022), with a new national temperature record set in the UK (Zachariah et al., 2022) and heat-related deaths across Europe estimated at 61,672 (Ballester et al., 2023). Many countries, particularly in the Mediterranean region, experienced meteorological (figure 1b) and hydrological drought (e.g. Bonaldo et al., 2022; Faranda et al., 2023) resulting in the second lowest river flow on record across Europe (Copernicus, 2022). The hot and dry conditions contributed to widespread wildfires, with 469,464 ha burnt in Spain, Portugal and France alone (Rodrigues et al., 2023). Both warmer temperatures from anthropogenic climate change and the anticyclonic atmospheric circulation across Europe contributed strongly to the summer 2022 weather (Ibebuchi and Abu, 2023; Faranda et al., 2023; Schumacher et al., 2022).

Europe has previously been identified as a particular hotspot for increasing heatwave occurrence and intensity under climate change (Rousi et al., 2022), with recent decades seeing an intensification of heat extremes in the region (Christidis et al., 2015; Perkins-Kirkpatrick and Lewis, 2020; Patterson, 2023). The high societal impact of these increasing extreme events provides strong motivation for developing accurate prediction systems for European summer weather and climate.

Unfortunately, current seasonal forecasting systems have shown relatively little skill in boreal summer for the European region. This is in contrast to the European winter when forecast systems have shown significant skill (Scaife et al., 2014; Athanasiadis et al., 2017). This seasonal contrast in skill may partly be due to the relatively weak signals coming from El Niño Southern Oscillation (ENSO) and the stratosphere in comparison to the winter (Domeisen et al., 2015) as well as the smaller scale of typical weather phenomena in summer. Nevertheless, a growing body of literature has suggested that there is potential for predictability of summer Euro-Atlantic circulation. For instance, recent observational studies have found that the summer East Atlantic pattern is modulated by forcing from tropical convection (Wulff et al., 2017; O'Reilly et al., 2018; Rieke et al., 2021), while North Atlantic sea surface temperatures (SSTs) affect circulation over the Euro-Atlantic (Ossó et al., 2018, 2020; Osborne et al., 2020; Beobide-Arsuaga et al., 2023). Moreover, Dunstone et al. (2018) showed moderate skill for European rainfall in the UK Met Office model which they attributed largely to the effect of North Atlantic SSTs on moisture availability. Initialisation of the land-surface also appears to provide some predictability via soil moisture feedbacks with the atmosphere (Seneviratne et al., 2010; Prodhomme et al., 2016; Ardilouze et al., 2017), particularly on sub-seasonal timescales (Orth and Seneviratne, 2014).

Furthermore, the study of Patterson et al. (2022) identified the significant role that external forcing from greenhouse gases and aerosols has on seasonal predictions of 2m temperature (T2m) with models deriving much of their T2m skill over Europe from the forced trend.

In the context of relatively low European summer forecast skill, it is interesting that many large-scale characteristics of the 2022 summer were relatively well forecast for Europe by ECMWF's system 5 (SEAS5 Johnson et al., 2019). This raises the question of whether circulation was inherently more predictable in summer 2022 than in other years. The purpose of this study is to perform a case study of the 2022 summer forecast in SEAS5. In particular, we seek to address the following questions:

- What were the drivers of the temperature and precipitation anomalies in the 2022 summer season in observations and in the forecast?
- What determined the circulation patterns in observations and the forecast and what role did the circulation play in the temperature and precipitation anomalies? Did the forecast capture circulation anomalies for the 'right reasons'?
- What role did externally-forced trends play in the forecast and observed surface conditions?

The study is structured as follows: data sources and seasonal hindcast experiments are described in section 2 and the hindcast is evaluated against observations in section 3. Following this, the roles of atmospheric circulation, soil moisture and externally-forced trends in the forecast anomalies are investigated in section 4. The drivers of the circulation anomalies in the forecast and observed anomalies are hen analysed in section 5 and a discussion of the results is provided in section 6.

2 | DATA AND METHODS

2.1 | Observations and reanalysis datasets

In this work we use monthly-mean data from the ERA5 reanalysis dataset (Hersbach et al., 2020) for all variables with the exception of precipitation, which is investigated using the monthly-mean Global Precipitation Climatology Project version 2.3 (GPCP Adler et al., 2018).

2.2 | ECMWF system 5 (SEAS5)

We briefly provide a few details on SEAS5, but refer the interested reader to Johnson et al. (2019) for further information. SEAS5 is based on cycle 43r1 of the Integrated Forecast System (IFS) and consists of coupled atmospheric, oceanic and prognostic sea-ice components. The atmosphere is run at T319 horizontal resolution with 91 levels in the vertical while the ocean is ORCA025 (0.25°) with 75 levels in the vertical. Both the atmosphere and land surface are initialised using ECWMF operational analyses and the ocean and sea-ice are initialised using OCEAN5 (Zuo et al., 2019), a combination of historical ocean reanalysis (ORAS5) and the daily real-time ocean analysis (OCEAN5-RT). Greenhouse gases are prescribed following the Coupled Model Intercomparison Project phase 5 (CMIP5) Representative Concentration Pathway (RCP) scenario 3-PD and tropospheric sulfate aerosol follows the decadally varying CMIP5 climatology.

This study makes use of SEAS5 hindcasts and forecasts of past summers spanning 1981-2016 and 2017-2021, respectively. The set up for the hindcasts and forecasts is almost identical and the primary distinction between the two lies in the fact that the system became operational in 2017 and hence only the years from 2017 onwards are genuine forecasts. The SEAS5 hindcasts have 25 members and the forecasts have 51 members, hence we only take the first 25 forecast members when combining the forecasts and hindcasts. Throughout this study anomalies are identified with respect to the period 1993-2016 as this is the common hindcast period used by SEAS5 and other models in the Copernicus Climate Change archive.

2.3 | Summer 2022 hindcast experiments

In order to investigate the impacts of initialisation of different aspects of the forecast system, we perform a number of hindcast experiments using the same setup of the IFS as used for SEAS5 (cycle 43r1) including the same grid resolutions in the atmosphere and ocean. Each of these simulations is initialised on 1st May and run for four months. An hindcast experiment identical to the operational forecast is performed ('CONTROL'), but extended to 200 members rather than 51. In order to clarify the role of SSTs in driving the forecast, a hindcast experiment is performed with 2022 ocean initial conditions, but with all other conditions (atmosphere, land surface, external forcing) taken from a year in [1981,2021] ('OCEAN-IC-2022'). For example, the ocean initial conditions are taken from 2022 and all other conditions are taken from the year 1990. For each year, 5 simulations are run with perturbed initial conditions making a total of $41 \times 5 = 205$ ensemble members. Similarly, a set of simulations is performed with ocean initial conditions from the years [1981,2021], but all other conditions taken from 2022 ('ATMOS-IC-2022') to identify the role that other drivers play.

Consequently, some of the effects of external forcing are present in both OCEAN-IC-2022 and ATMOS-IC-2022. That is, OCEAN-IC-2022 is driven by 2022 SSTs which have warmed with greenhouse gas forcing. On the other hand, the atmosphere in ATMOS-IC-2022 will be warmed as a result of the warmer initial state and the presence of 2022 greenhouse gas forcing. There is a risk that the atmosphere and ocean will be out of balance in ATMOS-IC-2022 and OCEAN-IC-2022 as the ocean is warm and the atmosphere cold or vice-versa. However, we will show that the results do not appear to be strongly affected by this and the sum of the enemble-mean anomalies in ATMOS-IC-2022 and OCEAN-IC-2022 is approximately equal to the CONTROL.

Experiment	Members	Ocean	Atmosphere	Land surface	External forcing
CONTROL	200	2022 conditions	2022 conditions	2022 conditions	2022 conditions
OCEAN-IC-2022	205	2022 conditions	[1981,2021]	[1981,2021]	[1981,2021]
ATMOS-IC-2022	205	[1981,2021]	2022 conditions	2022 conditions	2022 conditions

2.4 | Circulation analogues

To identify the impact of atmospheric circulation in the 2022 seasonal hindcasts on T2m and precipitation, we use a circulation analogues method similar to Jézéquel et al. (2018). The method estimates the circulation-related component of other variables by identifying years with similar atmospheric states and averaging the variable in question over those similar states. Specifically, we compare the 2022 hindcast ensemble-mean JJA-mean 500hPa zonal wind (U500) anomalies with JJA-mean U500 anomalies in each of the 25 ensemble members from each year in the SEAS5 hindcast 1981-2016, for the Euro-Atlantic region (30W-30E,30N-80N). The most similar $N = 30$ members from this $25 \times 36 = 900$ set are selected. Results are not particularly sensitive to the choice of N. U500 is used as a proxy for the effects of atmospheric circulation rather than 500hPa geopotential height or sea level pressure because these are strongly affected by a warming atmosphere. The global-mean, ensemble-mean T2m for each each is linearly regressed

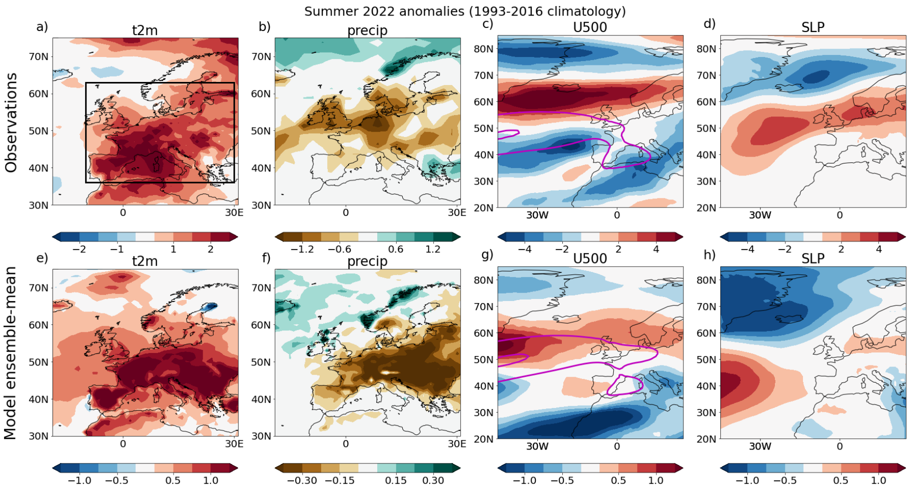

FIGURE 2 Comparison of observed (a-d) and SEAS5 ensemble-mean forecast (e-h) anomalies for the European summer (June-July-August, JJA) 2022. The variables shown by colours are a,e) 2m temperature (K), b,f) precipitation (mm/day), c,g) 500hPa zonal wind (m/s) and d,h) sea level pressure (hPa). Anomalies are taken with respect to 1993-2016. In c,g) unfilled, pink contours indicate the 500hPa zonal wind climatological values for the 10m/s and 15m/s contours. The box in a) indicates the European region used in figures 2 and 3.

out of the 1981-2016 U500, T2m and precipitation fields so that the analogue surface anomalies are not affected by warming trends. However, the global warming signal is retained in the 2022 hindcast experiments.

In order to define the similarity of two fields, the area-weighted Euclidian distance between them is calculated. Note that given the anomalies in the ensemble-mean will be much smaller than in any individual member, the two fields to be compared are weighted by their mean-absolute value over the Euro-Atlantic region. The circulation-related component, say of the 2022 ensemble-mean T2m, is calculated as the average T2m in the N most similar members. Once again, the result is scaled by the ratio of the mean-absolute U500 anomalies in the 2022 ensemble-mean to the most similar members, to account for the larger amplitude in the analogue.

3 | THE 2022 SUMMER SEASON

First, we analyse the 2022 European season and assess the SEAS5 CONTROL hindcast. Figure 2 compares June-July-August (JJA) 2022 anomalies in T2m, precipitation and 500hPa zonal wind and sea level pressure (SLP) in reanalysis (ERA5 and GPCP for precipitation) with anomalies predicted by SEAS5 for forecasts initialised on 1st May. Broadly speaking, the CONTROL hindcast qualitatively captures the observed anomalously hot and dry conditions (figure 2a,b,e,f), though it doesn't capture the westward extent of the dry anomaly over the UK. Note also the differing colour scales between the model and observations. With respect to atmospheric circulation, the model, as in observations, features a northward shifted jet (figure 2c,g) and positive summer North Atlantic Oscillation (SNAO) pattern, though the SLP pattern does not extend into Europe in the model (figure 2). Interestingly, other seasonal forecast systems within the Copernicus Climate Change archive all predicted an anomalously warm and dry summer (supplementary figures S1, S2), while at least 5 out of the 8 systems predicted a high over the Atlantic, to the south-west of the UK (supplementary figure S3).

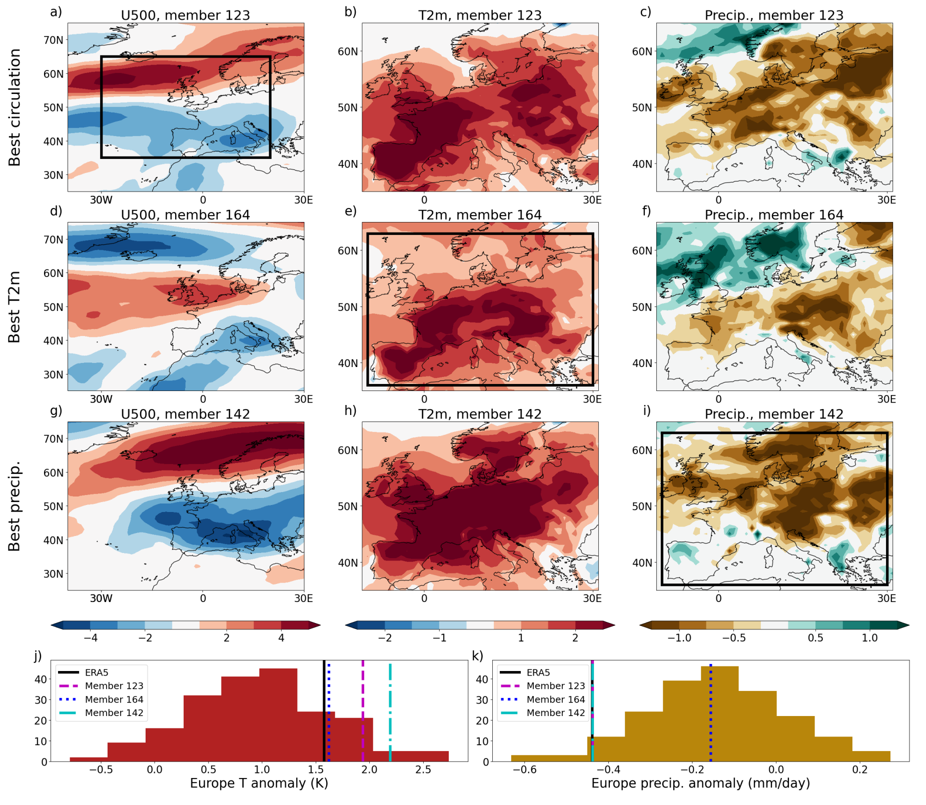

FIGURE 3 Analysis of individual members. a) 500hPa zonal wind, b) T2m and c) precipitation anomalies are shown for the member with the lowest error over the boxed region with respect to the observed circulation (see text for details). The members with the lowest error in d) T2m and e) precipitation are also shown. Histograms of European-mean f) T2m and g) precipitation are shown with vertical lines indicating the values for ERA5 / GPCP and the best members.

Next we investigate whether the ensemble can reproduce the magnitude of the observed temperature and precipitation anomalies and attempt to understand the role of atmospheric circulation in driving these anomalies. We calculate the best member at reproducing the pattern of 500hPa zonal winds, T2m and precipitation by calculating the area-weighted total Euclidian distance between observations and each model ensemble member, at each grid-point over a specified region. The regions over which the Euclidian distances are calculated are shown by boxes in figure 3. The best member is the member for which this distance is minimised. The northward shifted jet is best reproduced by member 123, with a similar magnitude of 500hPa anomalies in this case (figure 3a). This member also shows a similar pattern and magnitude of T2m and precipitation anomalies to the observations (figure 3b,c vs figure 2a,b) suggesting that circulation plays some role in driving these anomalies. The best temperature anomaly pattern (member 164) is similar in total magnitude to ERA5 (figure 3e,j), as is the best precipitation pattern (member 142) to GPCP (figure 3i,k). Hence, the ensemble does capture the observed conditions well. It is worth noting that nearly all ensemble members predicted a warmer than average European summer (figure 3j), which is unsurprising given the warming trend (Patterson et al., 2022). The majority of members also predicted a drier than average summer (figure 3k). This suggests a robust signal in the initial conditions, particularly given that there is no strong trend in European summer precipitation

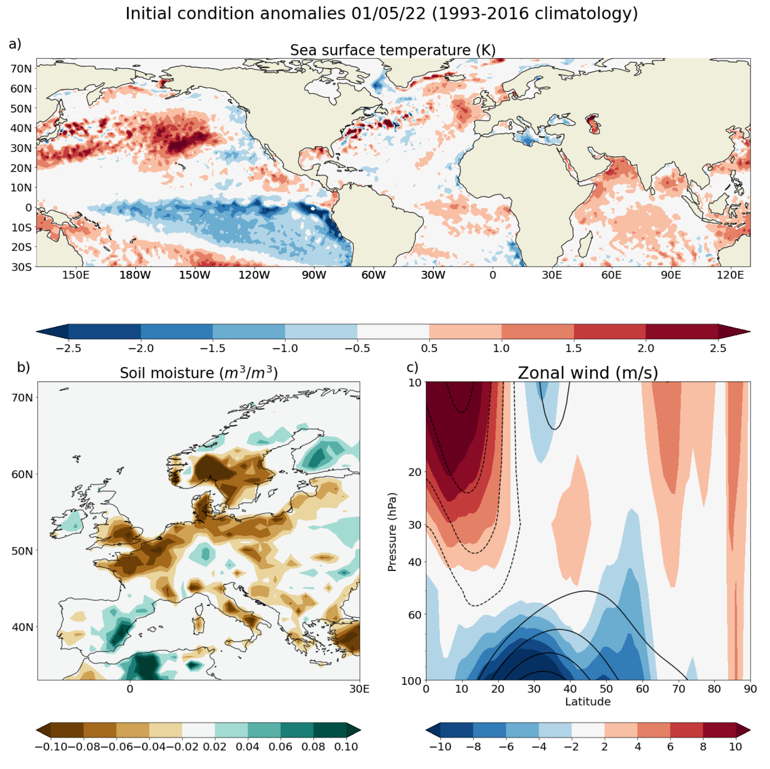

FIGURE 4 Anomalies for the 1st May 2022 are shown for a) SSTs, b) soil moisture and c) zonal-mean zonal wind in the lower to mid-stratosphere.

(figure 1b).

In terms of the potential drivers of European summer weather in 2022, the tropical Pacific was characterised by cool SST anomalies at the start of May, the last of three consecutive La Niña years (figure 4a). La Niña events are typically associated with anticyclonic conditions over the North Atlantic (O'Reilly et al., 2018), consistent with observations in figure 2c,d), hinting that La Niña may have played some role in the observed circulation. SST anomalies in the tropical Atlantic were weakly positive and SSTs around the UK and western Europe slightly warmer than average (figure 4a). The latter possibly warming western Europe via thermal advection. Following a drier than average spring, soil moisture levels were low at the beginning of May, particularly in northern parts of Europe (figure 4b). Wang and Ting (2022) found that positive SNAO years were proceeded by a strong polar vortex in May, hence we also include stratospheric zonal wind anomalies in figure 4c. The vortex strength, measured as the 50hPa zonal wind anomalies between 60-80N were slightly above average.

4 | HINDCAST EXPERIMENTS

In this next section we examine the hindcast experiments to understand the role that these initial conditions had in driving the forecast anomalies. We also attempt to account for the temperature and precipitation anomalies in the experiments by considering atmospheric circulation, soil moisture and externally-forced trends.

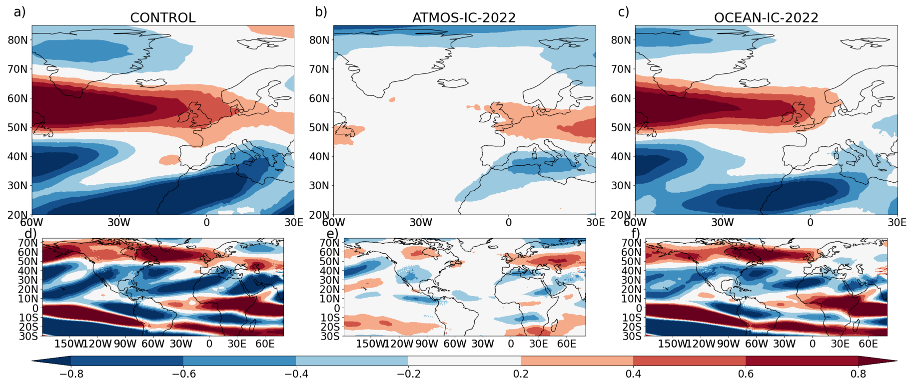

FIGURE 5 JJA-mean 500hPa zonal wind anomalies in the a,d) CONTROL, b,e) ATMOS-IC-2022 and c,f) OCEAN-IC-2022 experiments. a-c) and d-f) show the same data but a-c) shows only Europe.

4.1 | Atmospheric circulation

The ATMOS-IC-2022 experiments have the same land-surface and atmospheric initial conditions as in 2022, but with ocean initial conditions from random other years, whereas OCEAN-IC-2022 have the correct ocean initial state, but random atmospheric and land-surface conditions. ATMOS-IC-2022 will contain some of the global warming signal from the presence of 2022 levels of carbon dioxide, but OCEAN-IC-2022 will also show some warming signal relative to the climatology due to the warmer SSTs. Considering atmospheric circulation first, the Euro-Atlantic anomalies in OCEAN-IC-2022 are almost identical to the CONTROL hindcast, both in terms of the northward jet and negative wind anomalies over North Africa. In contrast, only a weak anticyclonic feature is present over Europe in ATMOS-IC-2022 (figure 5). Nevertheless, this anticyclonic feature may still have an important influence on the temperature and precipitation over Europe. Overall, this suggests that much of the circulation signal in CONTROL is derived from SST variability, but with some circulation features over Europe driven by either atmospheric or land-surface initialisation.

On the other hand, European T2m anomalies are larger in ATMOS-IC-2022 than in OCEAN-IC-2022 (figure 6b,c), with the pattern in the former matching up closely with CONTROL for Europe ((figure 6a). T2m anomalies in OCEAN-IC-2022 are consistently around 0.2-0.4K across much of Europe, compared to more than 0.6K for large parts of Europe in ATMOS-IC-2022. Regarding precipitation, this is more evenly split between the ATMOS-IC-2022 and OCEAN-IC-2022 experiments (figure 6e,f). Note that the T2m and precipitation anomalies in ATMOS-IC-2022 and OCEAN-IC-2022 in figure 6 approximately add to give the CONTROL anomalies (supplementary figures S4 and S5), suggesting that non-linear interaction between drivers does not play a subtantial role here.

In order to quantify the role that atmospheric circulation plays in the ensemble-mean T2m and precipitation anomalies, we use circulation analogues (section 2.4). The circulation over Europe in all three experiments consists of anomalously westerly flow over the UK and central Europe, with easterly anomalies over the Mediterranean (figure 6g-i). The U500 circulation analogue patterns capture the main features of these experiments (figure 6j-l, note that the colour-scale differs). Circulation appears to explain much of the T2m anomalies in OCEAN-IC-2022, though this accounts for only around 0.2-0.4K of the anomalies in CONTROL. In ATMOS-IC-2022, circulation cannot account for any of the T2m signal. It therefore appears that circulation is only a minor driver of T2m anomalies in CONTROL. However, a similar circulation analogues analysis of ERA5 data suggests that circulation played a larger role for the observed summertime 2022 anomalies than for the CONTROL ensemble-mean, though still explained less than half

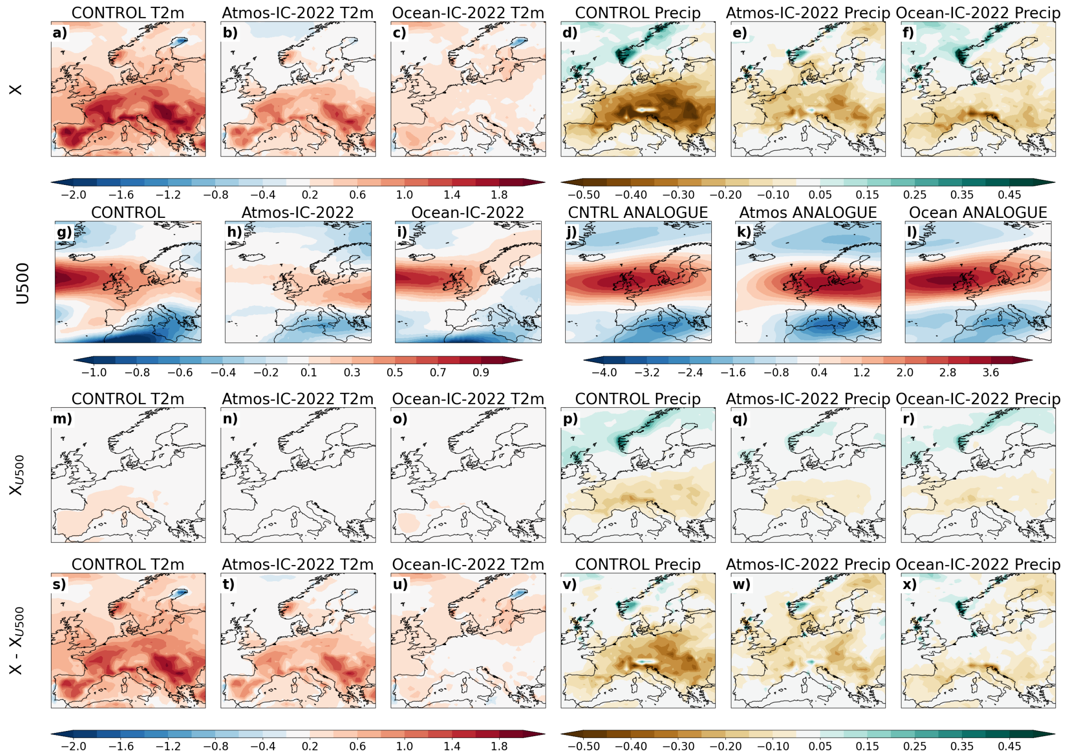

FIGURE 6 Surface anomalies in the SEAS5 hindcast experiments and the impact of atmospheric circulation. JJA-mean, ensemble-mean a-c) T2m and d-f) precipitation anomalies are shown for the three hindcast experiments along with the corresponding U500 patterns in g-i). The circulation analogues patterns are shown for j-l) U500, m-o) T2m and p-r) precipitation. The difference between the full ensemble-mean surface anomalies and the component explained by circulation are shown in s-u) for T2m and v-x) for precipitation. Units of T2m, precipitation and U500 are K, mm/day and m/s respectively.

of the magnitude of T2m anomalies (supplementary figure, S6). Circulation explains a larger proportion of the precipitation signal than T2m in all three experiments (figure 6p-r), explaining around half of the central Europe signal for ATMOS-IC-2022 and OCEAN-IC-2022. However, this still leaves a sizeable residual of precipitation which is not explained by the circulation (figure 6v-x).

4.2 | Soil moisture

A lack of soil moisture can amplify heat extremes by reducing the amount of cooling from latent heat fluxes. We investigate the role of soil moisture in shaping the CONTROL forecast using the OCEAN-IC-2022 members as these have a spread of land-surface initial conditions. Specifically, we calculate a central European soil moisture index for each OCEAN-IC-2022 member as the JJA-mean, area average soil moisture anomaly (43N-52N,0E-20E, boxed region in figure 7a). The global-mean T2m is linearly removed from the index and it is regressed onto other variables. The resulting regression maps are then scaled by the soil moisture index calculated for the CONTROL ensemble-mean to give an indication of how soil moisture may have contributed to T2m and precipitation anomalies. The results of this

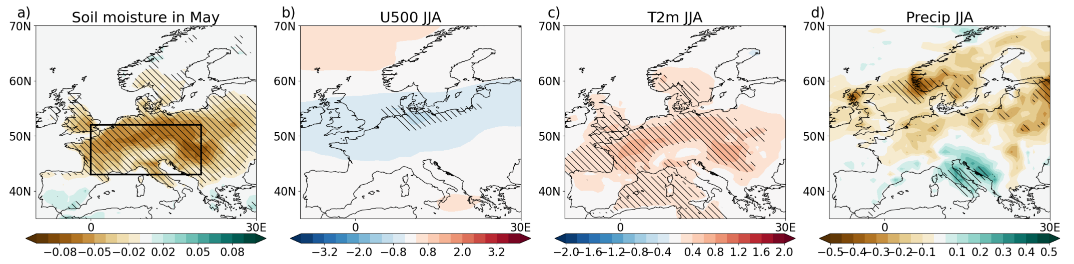

FIGURE 7 Impact of May soil moisture on different variables in JJA. The maps show regressions of a) May soil moisture, b) JJA U500, c) JJA T2m and d) JJA precipitation onto the May soil moisture, averaged in the central European region (box in a) in the OCEAN-IC-2022 experiment. Prior to calculating the regression maps, the global mean T2m signal is removed from the May soil moisture index and after the regression the maps are scaled by the mean central European soil moisture in CONTROL. Hence, values in this figure are comparable with the anomalies explained by circulation in figure 6 and show the same contour interval. Hatching in all four panels indicates where regression coefficients are significantly different from zero at the 95% level, following a Student's t-test.

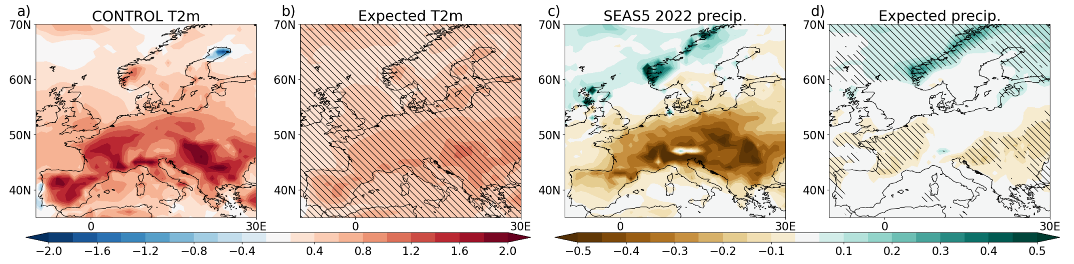

FIGURE 8 CONTROL JJA-mean, ensemble-mean a) T2m and c) precipitation anomalies compared to expected anomalies in b) T2m and d) precipitation extrapolated from trends in the hindcasts and forecasts (1981-2021). Hatching indicates where trends are significantly different from zero at the 95% level, following a Student's t-test.

analysis suggest that while soil moisture anomalies makes little significant contribution to atmospheric circulation or precipitation (Figure 7a,c), the dry land surface is associated with substantial T2m anomalies (Figure 7b). Soil moisture-related T2m anomalies account for up to 0.6-0.8K of the T2m signal in some locations (northern France, eastern Europe Figure 7b), considerably in excess of the contribution from circulation.

4.3 | Trends and external forcing

Warming trends induced by increased atmospheric carbon dioxide concentration have been shown to be a strong driver of T2m anomalies in seasonal forecasts (Patterson et al., 2022). We quantify the expected contribution of these trends to surface anomalies by combining the SEAS5 hindcasts (1981-2016) and forecasts (2017-2021) and calculating the JJA-mean trend in the ensemble-mean at each grid-point. This trend is then extrapolated to give an expected anomaly in summer 2022. This is shown in figure 8. The expected T2m anomalies are warmer in southern Europe than northern Europe, with a magnitude of 0.6-0.8K across much of central Europe (figure 8b). This is clearly a substantial proportion of the full CONTROL T2m anomalies (figure 8a,b). Interestingly, precipitation trends in the hindcasts also appear to explain some of the CONTROL signal, particularly a dipole of wet anomalies over northern

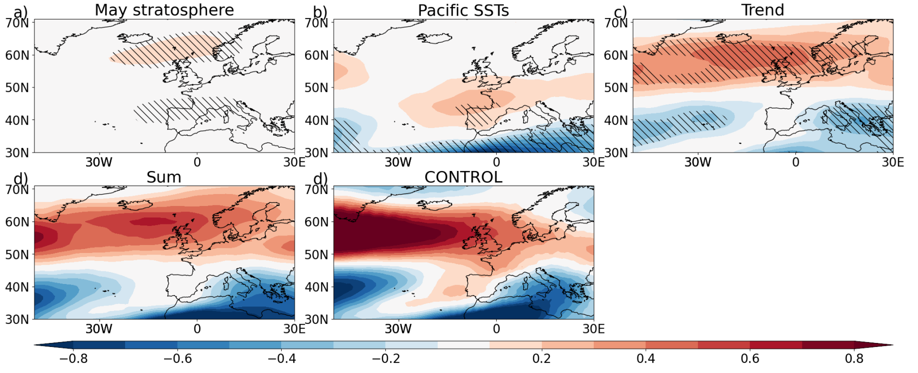

FIGURE 9 Drivers of U500 in CONTROL calculated via a multiple-linear regression analysis of SEAS5 hindcast anomalies (see text for details). For each regression map, the coefficients have been multiplied by the CONTROL value for the corresponding predictor to indicate the potential impact of that predictor on 2022 circulation. The predictors are a) May 50hPa zonal wind anomalies (60N-80N), b) Pacific SSTs, c) a linear trend. The sum of the regression coefficients multiplied by the CONTROL values is shown in d) and the CONTROL anomalies are shown in e). Hatching in a-c) indicates where values are statistically different from zero at the 95% level following a Student's t-test.

regions and drying at central latitudes around 45N-50N (figure 8c,d).

Overall, soil moisture and trends are the strongest contributors to the CONTROL T2m anomalies and atmospheric circulation plays a relatively minor role. Note that while direct radiative forcing is likely the primary factor in the SEAS5 hindcast trends, multi-decadal SST variability (whether externally forced or e.g. Atlantic Multidecadal Variability) may also contribute. Atmospheric circulation can account for just under half of the precipitation, while trends also make a small contribution to the CONTROL anomalies.

5 | POTENTIAL DRIVERS OF THE FORECAST AND OBSERVED CIRCULATION

In this section, we attribute the atmospheric circulation in CONTROL to forcing from various drivers including Pacific SSTs, stratospheric vortex strength and trends using a multiple regression framework. Ensemble-mean SEAS5 hindcast and forecast data 1981-2021 data are used to create the multiple regression model. We then apply a similar analysis to ERA5 reanalysis to study drivers of the observed circulation. A stratospheric index is defined as the zonal-mean 50hPa zonal wind averaged 60N-80N in May. A Pacific SST index is defined as the mean SSTs in the region 90W-150W, 15S-0S. The reason for using this region rather than Niño 3.4, is that the chosen region shows substantial SST anomalies for the 2022 summer (figure 4a). Using the Niño 3.4 region shows similar, albeit slightly weaker anomalies (not shown). The trend index is simply an index which increases linearly with time between 1981 and 2021. Similar to figures 7 and 8, the regression maps are scaled by their values in the CONTROL experiments to gauge the potential influence of these predictors on CONTROL circulation.

May polar vortex anomalies were weakly positive for 2022, but may have contributed to a slight poleward shift of the jet in the CONTROL ensemble-mean (figure 9a). Cold tropical Pacific SSTs in the model are generally linked to a northward shift of the jet in the western North Atlantic, strengthened westerly flow over central Europe and easterly anomalies over the Mediterranean and North Africa (figure 9b); all features of the CONTROL ensemble-mean (figure 9e). However, the largest contribution to the CONTROL anomalies appears to be a northward jet trend, likely

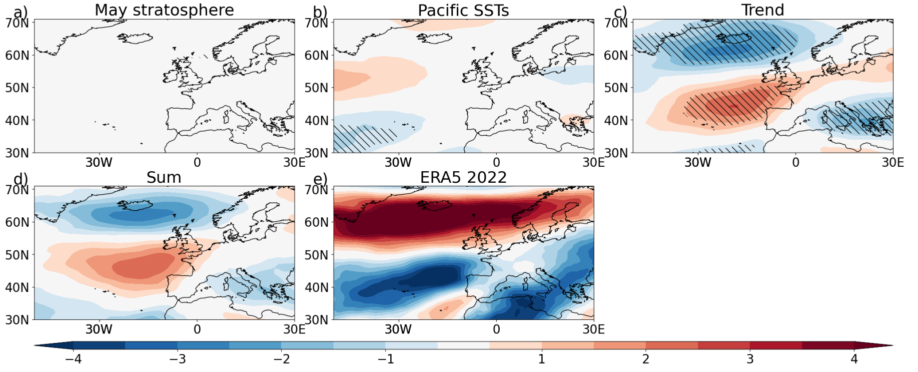

FIGURE 10 Same as figure 9 but for ERA5 data.

associated with external-forcing. Many Coupled Model Intercomparison Project phase 6 (CMIP6, Eyring et al., 2016) models exhibit a northward trend with climate change (Harvey et al., 2020). However this is at odds with an observed southward trend in the summertime North Atlantic jet since around 1980 (Dong and Sutton, 2021). This therefore suggests that at least some of the CONTROL circulation is correct for the wrong reasons. Overall, these three drivers explain the CONTROL anomalies well with their sum showing a similar pattern and magnitude to those in CONTROL (figure 9d,e).

Applying the multiple-regression framework with coefficients multiplied by 2022 values to the observed circulation is less successful than for the model ((figure 10d,e). Neither the stratospheric vortex, nor Pacific SSTs make a strong contribution to the circulation (figure 10a,b), while the trend is for a southward shift, not a northward shift (figure 10c). This could be for a number of reasons. Firstly, these three predictors may not have been strong drivers of the 2022 circulation as other drivers of summer North Atlantic circulation include Caribbean precipitation and North Atlantic SSTs. Secondly, predictable drivers can only explain a proportion of the observed circulation as a significant proportion of the observed circulation will arise from random, un-forced variability (Franzke and Woollings, 2011). In contrast, an ensemble-mean prediction, using a model which accurately represents atmospheric variability, will primarily consist of the predictable component of circulation (provided the ensemble is large enough).

6 | DISCUSSION AND CONCLUSIONS

Hindcasts of the hot and dry 2022 European summer have been analysed in this study. In this final section we draw a number of conclusions from this work.

1. Hindcasts of the 2022 summer (JJA) initialised on 1st May accurately predicted a relatively warm and dry summer for Europe. The vast majority of the 200 CONTROL ensemble members were both drier and warmer than the climatology period suggesting a robust signal. Moreover, the magnitude of the observed anomalies was captured by some members within the ensemble.
2. Warm T2m anomalies over Europe in the CONTROL hindcast were likely driven by a combination of externally-forced trends and low latent cooling due to the lack of soil moisture. A circulation analogues analysis suggests that anomalous atmospheric circulation had only a small impact on the T2m anomalies. On the other hand, atmospheric circulation had a relatively larger effect on precipitation predictions.

3. As in the observed climate, the CONTROL hindcast was characterised by a northward shifted North Atlantic jet. This signal was primarily driven by the ocean initial conditions (OCEAN-IC-2022) and particularly by cool tropical Pacific SSTs. However, SEAS5 hindcasts 1981-2016 and forecasts 2017-2021 show a northward trend of the jet with increasing carbon dioxide which also contributed to the northward jet in 2022.

This case study demonstrates that at least some European summers are predictable at 2-4 month lead-times, suggesting the potential for predictable windows of opportunity. It remains an open question as to whether it could have been known in advance that 2022 was particularly predictable. For example, it has been suggested that hot summers are more predictable than average summers (**?**).

One interesting finding of this study was the proportion of the circulation signal determined by the externally-forced trend. This merits further investigation given that the North Atlantic jet trend in the model disagrees with the observed southward shift over the last four decades. This discrepancy is also seen in CMIP6 models, hence is a more general problem which may prove difficult to address. A simpler solution to this may be post-processing of summer forecasts to account for the erroneous trend and incorporate the effects of the actual, southward trend.

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conflict of interest

The authors declare no conflict of interest.

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