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Key Points:

- European summer 2022 hot extremes have been enhanced by an anomalous occurrence of distinct circulation types over different subdomains
- Predominant circulation anomalies also contributed to the exceptional number of dry days, as much as local, mostly thermodynamical effects
- Such anomalous circulations will become more common, thus further worsening European hot and dry extremes

Supporting Information:

Supporting Information may be found in the online version of this article.

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European Summer Synoptic Circulations and Their Observed 2022 and Projected Influence on Hot Extremes and Dry Spells

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Abstract In 2022, western Europe experienced its hottest summer on record and widespread dry conditions, with substantial impacts on health, water and vegetation. We use a reanalysis to classify daily mean sea level pressure fields and to investigate the influence of synoptic circulations on the occurrence of temperature extremes and dry days. Summer 2022 featured an above-normal occurrence of anticyclones extending from the British Isles to the Baltic countries, as well as enhanced easterly, southerly and low-flow conditions which contributed to the observed extremes over southern and western Europe. While the hot summer of 2022 is only partially explained by circulation anomalies, such anomalies played a key role in the exceptional occurrence of dry days. The comparison with summer circulation anomalies projected by twenty global climate models moreover suggests that future circulation changes will further exacerbate hot and dry extremes over Europe.

Plain Language Summary In 2022, western Europe recorded its hottest summer up to date since preindustrial times. At the same time, widespread dry conditions caused dramatic impacts on human health, water resources, crop yields and wildfires. This was partly enhanced by the human–caused cumulative emissions of greenhouse gases, but also potentially by large-scale circulation anomalies that may also be triggered by global warming. By grouping distinct weather patterns, we find that many extreme hot days during the summer of 2022 over well-defined parts of Europe were favored by anomalous transport of hot and dry air masses or persistent low-wind conditions. These weather patterns were essential but not the dominant factor that led to the occurrence of extreme temperatures. Yet, they played a key role in enhancing the number of dry days. We also find that the weather patterns observed in summer 2022 will become more common in coming decades if greenhouse gas emissions remain without reduction. This would further worsen hot and dry extremes in summer over Europe.

1. Introduction

Europe experienced its hottest summer on record in 2022, the hottest year over its western portion (Copernicus, 2023), as well as severe drought conditions over southern and western Europe (European Commission et al., 2022). Both events were exacerbated by the ongoing anthropogenic climate change (Dukat et al., 2022; IPCC, 2021; Rousi et al., 2022; Schumacher et al., 2022; van Oldenborgh et al., 2009). However, the degree to which such a summer is a harbinger of future European climate remains an open question. The extreme summer of 2022 (S22) was characterized by strong, persistent and widespread mid-tropospheric anticyclonic anomalies over western Europe. This atmospheric circulation helped to exacerbate the drought by increasing its area of influence and by enhancing soil drying due to evapotranspiration (Faranda, Pascale, & Bulut, 2023). Atmospheric circulation plays a crucial role in the occurrence, extent and intensity of weather extremes (Coumou et al., 2015; Rogers et al., 2022). Anticyclones are generally associated in summer with dry conditions and hot daily temperature maxima (Riediger & Gratzki, 2014; Rouges et al., 2023). They are more prone to favor such extremes if they persist over extended periods by enhancing diabatic and adiabatic warming which intensifies near-surface temperatures. In regions like western and central Europe, the advection of warm air masses from the South or the East may also play a key role in the occurrence of hot extremes (Röthlisberger & Papritz, 2023). Surface atmospheric circulation types (CTs) can be extracted from daily sea level pressure fields by implementing an automated circulation classification (CC) method (Herrera-Lormendez et al., 2023; Huth et al., 2008). The advantage of this simple technique relies on its regional approach (i.e., circulation types are defined relative to each grid cell) and on the given possibility to assess the influence of each CT on surface variables on a day-to-day basis (Richardson et al., 2020).

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CTs are important for understanding meteorological extremes (Faranda, Messori, et al., 2023), but they are not the sole driver of the evolution of extreme events under global warming. Thermodynamical factors like evapotranspiration processes, soil humidity, changes in near-surface relative humidity and sea surface temperature's influence on horizontal moisture transport (hereafter defined as within–type contributions), may also add significantly to exacerbating extremes. The integrated perspective of both components is thus needed to fully understand the consequences of climate change on weather extremes in both observations and climate projections (Fleig et al., 2015). Over Europe, many of these effects are already ongoing, for example, the expansion of dry conditions (meteorological droughts) in many regions since the late 1980s (Bešťáková et al., 2023), an increasing number of hot days combined with warmer summer conditions (Marvel et al., 2019), and an intensification of heatwaves (Rousi et al., 2022). As we start facing circulation changes in response to increasing CO_2 concentrations and non-uniform global warming, their contribution to recent and future extremes remains a matter of debate (Belleflamme et al., 2015; de Vries et al., 2022; Faranda, Pascale, & Bulut, 2023; Räisänen, 2019; Terray, 2023).

Current climate change projections over Europe suggest that the summer season will experience some of the harsher negative hydrological and meteorology-related effects. Southern Europe will face reduced rainfall, while Northern Europe will become wetter (de Vries et al., 2022; Douville et al., 2021; Santos et al., 2016). As subtropical conditions expand northward (Grise & Davis, 2020), anticyclonic conditions will extend their influence over northwestern Europe, weakening westerly flows and enhancing the number of days dominated by warmer easterly advection (Herrera-Lormendez et al., 2023; Otero et al., 2018). This type of circulation favors the westward transport of dry, warm continental air masses from eastern Europe (Kautz et al., 2022; Pfahl, 2014), influencing regional precipitation changes (Burt & Ferranti, 2012) and the manifestation of extreme events like heatwaves and droughts (Meehl & Tebaldi, 2004). This raises the question of whether the circulation anomalies observed during the 2022 summer will become a common sight over Europe—if no action is taken to considerably reduce greenhouse gas emissions.

We use a simple method to classify the CTs observed over Europe in S22 and assess their potential contribution to the widespread hot and dry conditions. Furthermore, we examine their occurrences in a high-emission scenario using a state-of-the-art multi-model ensemble to assess to which extent future changes in synoptic-scale circulation may favor such summer extremes by the end of the 21st century. We aim to (a) summarize the influence of synoptic-scale CTs on European summer temperature extremes, (b) investigate the behavior of CTs during the extreme S22, (c) distinguish contributions of within-class and between-class seasonal circulation variability to the observed extreme temperatures and anomalous dry days, and (d) explore the plausibility of anomalous atmospheric patterns observed in S22 to become more common in a high-emission climate scenario by the late 21st century.

2. Data and Methods

Daily values of mean sea level pressure data (MSLP), maximum temperature (Tmax) and total rainfall are derived from the ERA5 reanalysis (Hersbach et al., 2020) 1981–2010 climate reference period. MSLP is also retrieved from twenty Global Climate Models (GCMs) from the Climate Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016a). We use data from the CMIP6 historical experiment (1950–2014) and the SSP5-8.5 high emissions scenario (2015–2100). Given the heterogeneous number of available simulations across CMIP6 models and the stronger signal-to-noise ratio in summer compared to winter over Europe, we employ realization number one (r1) of each GCM only (i.e., twenty simulations of both present-day and future climates).

- We compute daily gridded surface synoptic CTs employing the "jcclass" python module (Herrera-Lormendez, 2022) based on the Jenkinson-Collison automated classification (Jenkinson & Collison, 1977). The computation of the CTs is done solely based on MSLP. We derive eleven CTs based on circulation vorticity (central anticyclones: A and cyclones: C), advective characteristics depending on their dominant wind direction (northeasterly: NE, easterly: E, southeasterly: SE, southerly: S, southwesterly: SW, westerly: W, northwesterly: NW, northerly: N) and a low flow (LF) CT characterized by weak pressure gradients conditions. The CTs are independently calculated for multiple subdomains centered on each grid point within the −15.5 to 30.5°E and 35.5 to 70.5°N. For more information on the method see Herrera-Lormendez et al. (2023) and Otero et al. (2018).
- To investigate the link between the 2022 hot and dry summer and the synoptic circulation, we first compute the summer (JJA) anomalies of the relative frequencies (RF anomalies), corresponding to the eleven distinguished

CTs. Later, we retain the 5% hottest values of daily maximum temperature using the 95th percentile value ($Tmax_{p95}$) as a threshold. These days where $Tmax > Tmax_{p95}$ are defined throughout the text as the hot days (HDs). Lastly, the dry days (DDS) are defined by accounting for the days where the daily total precipitation was below 1 mm. These last two conditions are calculated independently over every grid point and regardless of the CT using 1981–2010 as the climatic reference period.

- To assess the contribution of the synoptic circulation on the S22 anomalous occurrence of $Tmax_{p95}$ and DDs, we employ a simple decomposition inspired by Cattiaux et al. (2013) and already applied in Herrera-Lormendez et al. (2023). This simple method allows us to determine how a variable X (daily $Tmax$ anomalies relative to $Tmax_{p95}$ and the number of DDs) during S22 has been influenced by a synoptic-scale dynamical effect (i.e., between-class effect diagnosed as the effect due to changes in RF) versus other sources (i.e., within-class effects diagnosed without any change in CT frequency). We do this by computing the mean of variable $X\left(\bar{X}\right)$ as the mean of CT–conditional means x_k, weighted by the frequencies of occurrence f_k of a given CT k:

$$\bar{X} = \frac{1}{N}\sum_{i\in\Omega_k} X_i = \sum_k f_k x_k, \tag{1}$$

with Ω the total N days, Ω_k being the total ensemble of the N_k days classified in the kth CT, $f_k = \frac{N_k}{N}$ the frequency of occurrence of the kth CT and x_k the conditional mean to CT k:

$$x_k = \frac{1}{N_k}\sum_{i_k\in\Omega_k} X_{ik} \tag{2}$$

Therefore, $\bar{X}$ can be the summer average of the $Tmax$ anomalies or the number of DDs, and x_k is the composite of each variable within each CT k. The circulation contribution to a difference of $\bar{X}$ is estimated by comparing summer (JJA) 2022 (denoted by F for a possible harbinger of future climate) to the 1981–2010 reference climatology (denoted by P for present-day climate).

$$\Delta^{F-P} = \bar{X}^F - \bar{X}^P = \underbrace{\sum_k \Delta f_k x_k^P}_{\text{BC}} + \underbrace{\sum_k f_k^P \Delta x_k}_{\text{WC}} + \underbrace{\sum_k \Delta f_k \Delta x_k}_{\text{RES}}, \tag{3}$$

The three resulting components of the equation are the between–class (*BC*), within-class (*WC*) and residual (*RES*) terms. The *BC* term represents the part of the changes in the variable that can be attributed to the variations in the frequency of occurrence of the individual CTs. The *WC* term refers to the contributions of the variability of anomalies within the CTs which include thermodynamical processes (Herrera-Lormendez et al., 2023). In other words, the modification in the link between the CTs and HDs and DDs considering no change in the CTs' frequencies. Lastly, the *RES* is a mixing residual term.

- To put European S22 into perspective, we explore the occurrence of anomalous CT patterns like the ones observed in S22 across a state-of-the-art ensemble of global climate simulations (Table S1 in Supporting Information S1) over the 1950–2100 period. For this purpose, we assess the period-to-period pattern-to-pattern correlations between the ERA5–derived patterns of S22 RF anomalies over western Europe (40 to 60°N and −10 to 15°E) against the corresponding summer patterns simulated by twenty CMIP6 GCMs. For each CT, the effects of the synoptic CTs evidenced during S22 are considered to strengthen if the summer-to-summer pattern-to-pattern correlation increases and becomes significant across the 21st century.

3. Results

3.1. Distribution of Temperature Extremes

Figure 1 shows the 1981–2010 climatological summer composite of the conditional probability (CP) of HDs relative to the relative frequency of each gridded CT over Europe. CTs are shown in order of occurrence during the summer season. Further information regarding the spatial distribution of RFs is found as Figure S1 in Supporting Information S1. Anticyclones (A) are the prevalent summer CT characterized by subsidence and cloud-free skies. Their influence on HDs is most pronounced over the British Isles, the western part of Scandinavia, and the mountainous regions of continental Europe, where synoptic-scale horizontal advection plays a less important role in the occurrence of hot days. In these regions, nearly half of the times that this CT occurs a hot day is likely

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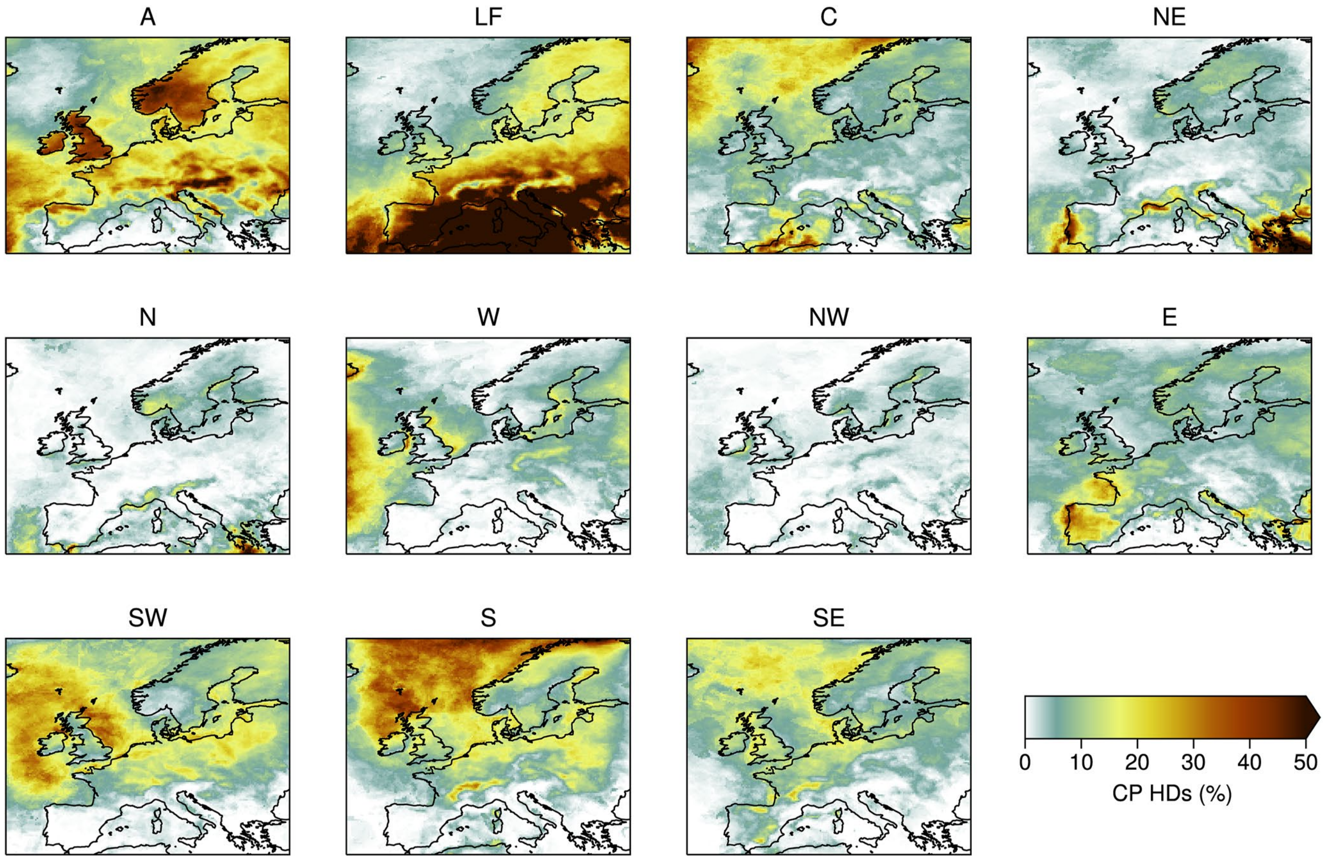

Figure 1. Summer composite of the conditional probability of a hot day event (CP HDs) in the eleven circulation types during the 1981–2010 reference period. Data ERA5 daily mean MSLP and Tmax at 0.25 × 0.25° resolution.

to happen. The anticyclones are responsible for a quarter of the extremes during summer across most of central and northern continental Europe. Over the Mediterranean, their influence is limited as most of the summer days are classified as Low Flow conditions given the more subtropical behavior of the pressure gradients. It becomes evident that the large majority (>50%) of the HDs are linked to this CT (LF) due to its predominant occurrence over this region. They are also a major contributor to HDs over continental Europe but not the British Isles. The third CT, cyclone (C), appears as an important source for extremes over southern Spain, the North Sea and the North Atlantic. This happens as cyclones favor warm advection in their right-hand section (warm sector). Furthermore, given that we employ daily mean values of MSLP, some of the indirect influence, due mostly to cyclonic–southerlies, is captured within this CT. The strong effect that southerlies (SW, S and SE) have on HDs is more evident over northern maritime areas. Altogether, they are responsible for nearly a third of the HDs over the continent (except over the Mediterranean coast). The remaining contributors to extreme hot days over western Europe are the easterly types. Their influence is strongest over the western coast of France and the Iberian Peninsula as they transport dry and hot air from the inner continent (Herrera-Lormendez et al., 2022). Some of the remaining regional extremes confined to the NE and W types result from interactions between orography and land–sea thermal contrasts.

3.2. Synoptic Circulations and Temperature Extremes During Summer 2022

We computed the anomalous occurrence of the eleven CTs and show them in combination with the share of HDs that occurred during S22 (Figure 2). The individual influence of some of these CTs on the distribution of the HDs is highlighted in the shaded areas in Figure 2. For the sake of clarity, we only hatched the regions where the S22 RF anomalies were above one standard deviation (full figure as Figure S2 in Supporting Information S1). The occurrence of anticyclones (A) was above normal over the 50–60° latitude belt. The above-average occurrence of A is linked to increased occurrences of easterly advection (E, NE, and SE) and predominant LF conditions over

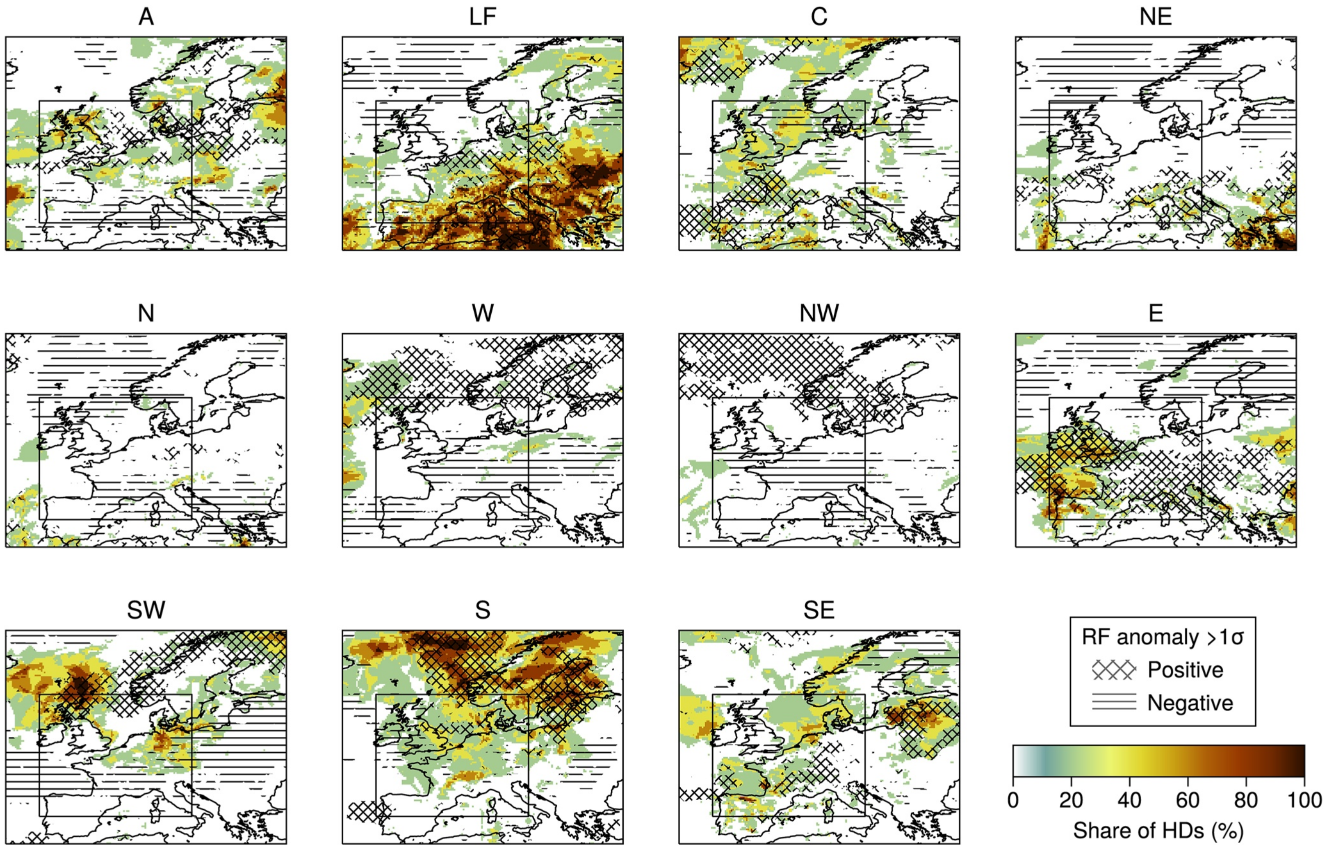

Figure 2. Summer 2022 share of HDs (shaded) and RF anomalies (hatching) above one standard deviation (>1σ). ERA5 daily MSLP and Tmax data at $0.25 \times 0.25°$ resolution. 1981–2010 reference period.

continental and western Europe. Additionally, a higher frequency of southerly hot air masses (SW and S types) over the British Isles and the North Sea is observed.

During S22 many of the observed HDs did not occur in the central anticyclones as previously found in the climatological distribution of extremes (Figure 1). Instead, many of the HDs over central and southern Europe occurred during LF conditions. This atmospheric configuration is prevalent in southern Europe primarily due to weaker MSLP gradients, often coinciding with the extension of a high-pressure system (ridge). The remaining distribution of HDs over western Europe was mostly constrained to the easterly and southerly (SW, S and SE) advection. The easterly CTs favored the transport of dry and hot air masses from continental Europe toward the Atlantic coast, contributing significantly to the hot extreme days observed during S22. This is more evident over the Atlantic Ocean and south of the British Isles due to the marked advection of continental warmer air. Much of the remaining HDs over the UK were related to advection from the south (SW, S and SE).

3.3. Dynamical Contributions to the 2022 Summer Tmax Extremes and dry Days

To understand the dynamical contribution of CTs to the observed 2022 extremes (temperature and dry days), we applied the linear decomposition in Equation 3. Figure 3 shows the results when comparing observed HDs temperature anomalies (a) and the anomalous DDs (b) of S22 to the reference climate period of 1981–2010. We do not include a discussion on the climatological influence of CTs on summer DDs. However, a detailed discussion has been addressed in our previous work (Herrera-Lormendez et al., 2023). We also do not comment on the *RES* term since its contribution to the S22 extremes is marginal. We refer to western Europe as the region inside the inner square of Figure 3.

The CTs' influence on the Tmax anomalies predominates over the continent due to the stronger Bowen ratio (ratio of sensible heat flux to latent heat flux) than over the ocean. Although the *BC* term was not the dominant

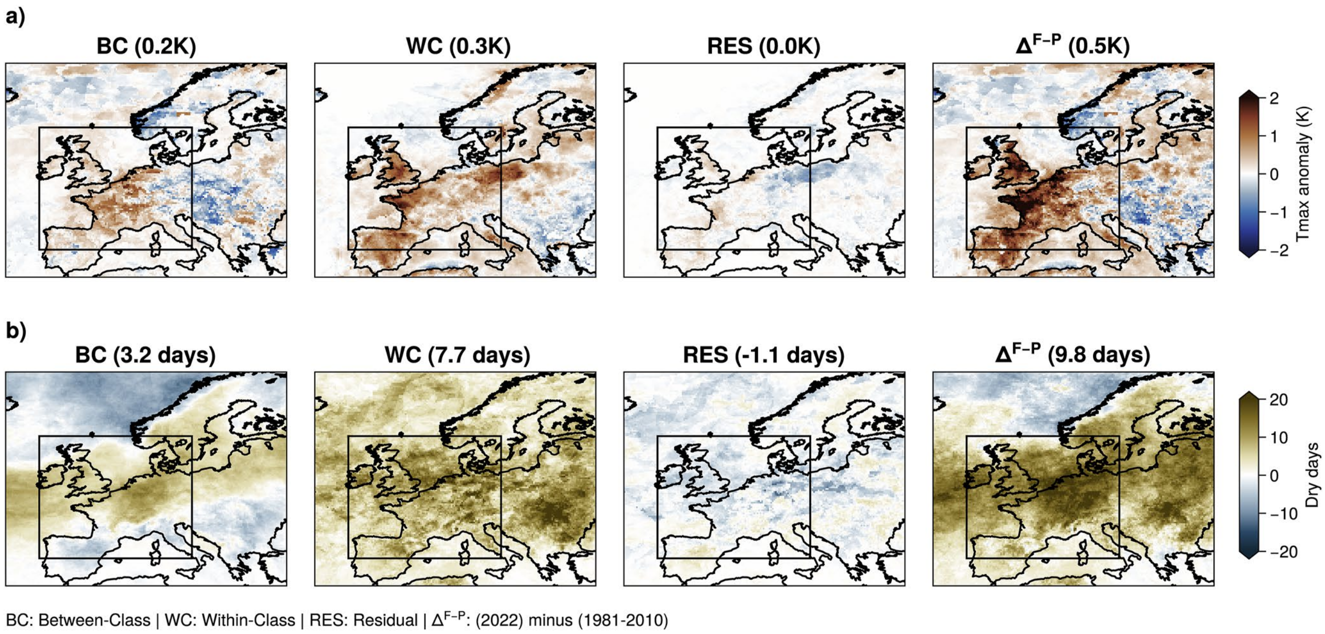

Figure 3. Summer 2022 decomposition of (a) temperature anomalies during the occurrence of HDs and (b) DDs. Each column shows the *BC*, *WC*, *RES*, and Δ^{F-P} computed using the 1981–2010 reference period from Equation 3. The value in brackets shows the mean spatial value over the western Europe region shown in the square. Data from ERA5 daily MSLP and Tmax at 0.25 × 0.25° resolution.

contribution to the total 2022 HDs temperature anomalies shown in Figure 2, it played a critical role in enhancing hot extremes over Europe. Over western Europe, around 40% (0.2 K) of the magnitude of the temperature anomalies arose from the circulation forcing thanks to the enhanced advection of warmer air masses favored by the S, SE and E CTs. The governing factor is found in the *WC* term where on average, 60% of the magnitude of the HDs anomalies (0.3 K) were caused by within–type sources, that is without accounting for the CTs' RF anomalies. Such a dominant effect is consistent with the expected impact of global warming on hot extremes but the *WC* versus *BC* contributions cannot be considered as a surrogate of a formal attribution of the human contribution to the S22 anomalous temperatures since both climate change and internal climate variability can alter the *WC* and *BC* effects on a yearly basis.

The DDs anomalies were regionally strongly influenced by the anomalous occurrence of the A CT (Figure 3b). The overall dynamical contribution (*BC*) accounted for nearly 33% of the western Europe observed DDs (except the Mediterranean region). The dynamical influence was stronger over the UK, France and Germany coinciding with areas dominated by central anticyclones, along with the resulting easterly and low flow conditions to a lesser extent (Figure 2). The *WC* term was the dominant contributor to the occurrence of DDs (78%). The predominant *WC* contributions are more evident toward southern Europe, where synoptic-scale circulation is generally not the primary source for observed changes (Marvel et al., 2019; Seager et al., 2019). We analyzed the influence of synoptic circulations on temperature and DDs separately given that many of the HDs overlap with the DDs providing not very different results to what their results when analyzed separately. An example of this can be seen in Figure S3 in Supporting Information S1.

3.4. Is Summer 2022 a Harbinger of the Late 21st Century?

To investigate the potential recurrence of anomalous patterns observed in the summer of 2022, we estimate the pattern-to-pattern correlation between the simulated and observed (S22) RF anomalies observed over western Europe (40 to 60°N and −10 to 15°E). In other words, we compare the patterns derived from ERA5 reanalysis against simulated RF anomalies from 20 CMIP6 GCMs spanning the historical period simulations (1950–2014) and the SSP5-8.5 high-emission scenario (2015–2100).

The results are shown in Figure 4, with negative correlations in blue and positive ones in brown shadings. Hatching highlights an 80% multi-model agreement in the correlations' sign. The results indicate that the anomalous CT

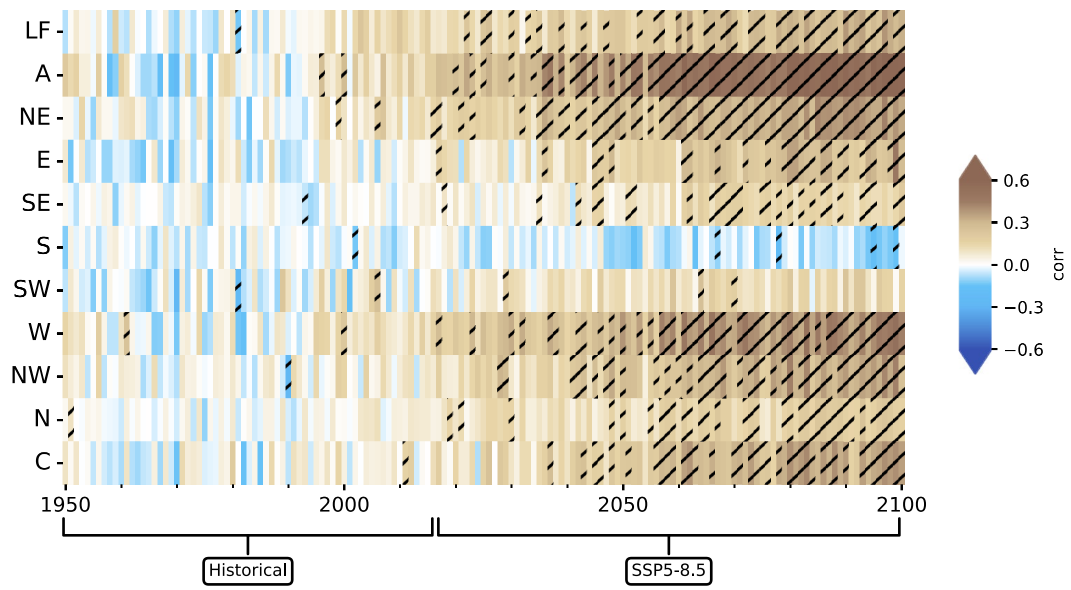

Figure 4. Western Europe (40 to 60°N and −10 to 15°E) pattern-to-pattern correlation of summer 2022 anomalous RF patterns (ERA5 data, see Figure 2) versus 20 CMIP6 GCMs. MSLP data from the historical experiment (1950–2014) and SSP5-8.5 scenario (2015–2100). Hatching indicates above 80% multi-model sign agreement. Both data sets were brought together to a common 1 × 1° resolution. Anomalous RF computed using the 1981–2010 reference period.

events observed in the summer of 2022 will become more likely under a high-emission scenario. The strongest correlation is found in the above-normal occurrence of anticyclonic CT and the consequential lower occurrence of westerly circulation. Therefore, anticyclones over the UK, northern France, and Germany, as observed in the summer of 2022, are likely to become more common. Similarly, easterly CTs (NE, E, and SE) and LF will also become prevalent conditions over continental western Europe in the coming decades. Increasing positive correlations also appear in the W, NW, and N synoptic CTs. During 2022, their behavior was characterized by below-normal occurrences due to the above-normal occurrence of anticyclones. The also increasing correlation appears in the C synoptic type suggesting more cyclonic situations over SW Europe and fewer over the NW part of our western European domain. The only circulation showing decreasing correlation is the southerly type suggesting decreasing southerly conditions over the northern part of western Europe while increasing over the continental part. However, much the same as in S22, this does not imply that extraordinary events characterized by strong southerly advection will not be relevant in a future climate.

4. Discussion and Conclusions

The ongoing global warming was shown to contribute to the record-breaking hot temperatures during the summer of 2022 and made droughts 5–6 times more likely to occur over western Europe (Schumacher et al., 2022). Yet, such a contribution can be due to both dynamical and thermodynamical effects. We showed how anomalous occurrence of CTs influenced the spatial distribution of HDs over Europe in S22. These events will, according to models, become more frequent during the second half of the 21st century if there is no strong mitigation of climate change. The overall influence of CTs varies geographically and is strongly governed by the location of central anticyclones and the southerly or easterly advection of hot air masses. Our results show how the exceptionally hot and dry summer of 2022 was influenced by anomalous CT frequencies, confirming their dependence on the positioning and prevalence of the high-pressure system centers. Anticyclonic conditions contributed to the distribution of the observed HDs recorded over western Europe. Warm advection from the easterly and southerly CTs was also decisive for the occurrence of HDs over western Europe (Ibebuchi & Abu, 2023). This was for instance the case for the UK's all-time heat record of 40.3°C reported on July 19th (Met Office, 2022). A central anticyclone over northern Germany and Denmark in combination with a cyclonic circulation facing the western coast of the Iberian Peninsula favored the advection of hot air from the south. However, much of the distribution of the HDs over central Europe and the central Mediterranean occurred during LF conditions. This comes as no surprise given the stronger relative influence that this CT has around the Mediterranean. Here, LF conditions dominate during half of the summer days as subtropical weaker pressure gradients extend their influence polewards (Herrera-Lormendez et al., 2023; Otero et al., 2018). However, the overwhelming predominance of LF conditions over the south is also a result of the classification's limited ability to properly capture the extent of subtropical anticyclones over near-equatorial latitudes due to the weaker pressure gradients (Fernández-Granja et al., 2023). The classification employs a threshold to allow distinguishing LF conditions; yet, if this threshold is turned off many of those days would be assigned as an anticyclone. Hence, further evaluation of the classification is still necessary to be able to properly distinguish between these two synoptic conditions over lower-latitude regions.

However, the observed HDs and DDs anomalies are not fully explained by the anomalous occurrence of CTs. The exceptional S22 resulted from a combination of the synoptic-scale CTs influence and thermodynamical factors exacerbating the extremes, like very low soil moisture enhancing the land surface Bowen ratio and associated diabatic warming and, more likely than not, the growing signal of the unequivocal anthropogenic global warming (Faranda, Pascale, & Bulut, 2023; Lee et al., 2023; Schumacher et al., 2022). By applying a simple decomposition, we distinguished how the CTs (i.e., *BC*) versus other (i.e., *WC*, mostly thermodynamical) effects contributed to the anomalous occurrence of HDs and DDs during S22. We conclude that the influence of the synoptic CTs (*BC* term) on the HDs was important, but not the only factor in conditioning their occurrence during S22. The thermodynamical influence (*WC* term) played a more important role in enhancing the intensity of HDs, while the *BC* term shows that the CTs served as the preconditioning factor by likely enhancing the adiabatic and advective warming components. Contrastingly, the DDs in western Europe were largely determined by the anomalous occurrence of CTs and especially by the anticyclone extending from the British Isles to the Baltic countries. This comes as no surprise, given that the strongest negative precipitation anomalies often occur near anticyclonic pressure centers (Hoy et al., 2014). Over France and Germany, the main CT contributing to the extended number of DDs was the easterly and low flow patterns. The days characterized by easterly advection are known to influence DDs and drought conditions (Lhotka et al., 2020; Řehoř et al., 2021) and to be linked to Scandinavian blocking events responsible for long-lasting heatwave events (Kautz et al., 2022; Pfahl, 2014). Nonetheless, despite the strong influence of the CTs in the observed DDs, the thermodynamical contribution was the predominant factor on dry conditions over southern Europe, a region where thermodynamic processes dominate (Brogli et al., 2019).

As projected climatic changes suggest, the already experienced drier summers (Hänsel et al., 2022) will become even drier over southern Europe (Douville et al., 2021). Changes in frequency and within–type characteristics of synoptic-scale surface CTs over Europe will worsen the impact on rainfall (Herrera-Lormendez et al., 2023). The anomalous occurrence of CTs observed during the extreme hot summer of 2022 resemble the spatial summer patterns found in the CMIP5 RCP-8.5 and CMIP6 SSP5-8.5 scenarios (Herrera-Lormendez et al., 2022, 2023; Otero et al., 2018), signaling an increase in anticyclonic conditions around the British Isles, leading to detrimental effects on rainy CTs over central and western Europe. We compared the S22 anomalous patterns of the CTs over western Europe against every summer in the CMIP6 historical experiment and SSP5-8.5 scenario. We found that anomalous circulation patterns observed in S22 will be more likely to repeat in the future under a high-emission scenario. The pattern-to-pattern correlation shows an increasing correlation in the resulting multi-model ensemble mean of CMIP6 GCMs toward the end of the 21st century, particularly with anticyclonic and westerly CTs. These findings align with the projected increase in anticyclones in northwestern Europe (de Vries et al., 2022). This increase, enhanced by the extension of the Atlantic ridge weather regime toward Europe, (Ullmann et al., 2014) contributes to the rising NE, E and LF CTs associated with the positioning of the anticyclone. Furthermore, the increased correlation with westerly CT (projected frequency decrease) observed in Figure 4 is explained by the blocking effect of the anticyclone, leading to reduced westerly advection days and fewer central cyclones, similar to the anomalous CTs' configuration observed during S22. Overall, the observed and closely correlated projected synoptic-scale behavior over western Europe agrees with the hypothesis under global warming where persistent splitting jet stream conditions enhance anticyclonic and easterly CTs. This shift causes cyclones to deviate, contributing to the upward trend in heatwaves over western Europe (Rousi et al., 2021, 2022) and the expansion of the subsiding branch of the northern Hadley cell associated with dry and stable summer conditions (Sousa et al., 2020).

Data Availability Statement

Data from ERA5 reanalyses (Hersbach et al., 2023) is freely available in the Copernicus Climate Change Service Climate Data Store. Data from the Coupled Model Intercomparison Project Phase 6 is available on the Earth System Grid Federation website (Eyring et al., 2016b).

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References

Belleflamme, A., Fettweis, X., & Erpicum, M. (2015). Do global warming-induced circulation pattern changes affect temperature and precipitation over Europe during summer? *International Journal of Climatology*, *35*(7), 1484–1499. https://doi.org/10.1002/joc.4070

Bešťáková, Z., Strnad, F., Godoy, M. R. V., Singh, U., Markonis, Y., Hanel, M., et al. (2023). Changes of the aridity index in Europe from 1950 to 2019. *Theoretical and Applied Climatology*, *151*(1–2), 587–601. https://doi.org/10.1007/s00704-022-04266-3

Brogli, R., Sørland, S. L., Kröner, N., & Schär, C. (2019). Causes of future Mediterranean precipitation decline depend on the season. *Environmental Research Letters*, *14*(11), 114017. https://doi.org/10.1088/1748-9326/ab4438

Burt, T. P., & Ferranti, E. J. S. (2012). Changing patterns of heavy rainfall in upland areas: A case study from northern England. *International Journal of Climatology*, *32*(4), 518–532. https://doi.org/10.1002/joc.2287

Cattiaux, J., Douville, H., Ribes, A., Chauvin, F., & Plante, C. (2013). Towards a better understanding of changes in wintertime cold extremes over Europe: A pilot study with CNRM and IPSL atmospheric models. *Climate Dynamics*, *40*(9–10), 2433–2445. https://doi.org/10.1007/s00382-012-1436-7

Copernicus (2023). 2022 saw record temperatures in Europe and across the world. Retrieved from https://climate.copernicus.eu/2022-saw-record-temperatures-europe-and-across-world

Coumou, D., Lehmann, J., & Beckmann, J. (2015). The weakening summer circulation in the northern hemisphere mid-latitudes. *Science*, *348*(6232), 324–327. https://doi.org/10.1126/SCIENCE.1261768/SUPPL_FILE/PAPV2.PDF

de Vries, H., Lenderink, G., van der Wiel, K., & van Meijgaard, E. (2022). Quantifying the role of the large-scale circulation on European summer precipitation change. *Climate Dynamics*, *59*(9–10), 2871–2886. https://doi.org/10.1007/S00382-022-06250-Z/FIGURES/8

Douville, H., Raghavan, K., Renwick, J., Allan, R. P., Arias, P. A., Barlow, M., et al. (Eds.), Climate change 2021: The physical science basis. Contribution of working Group I to the sixth assessment report of the intergovernmental panel on climate change (pp. 1055–1210). Cambridge University Press. https://doi.org/10.1017/9781009157896.010

Dukat, P., Bednorz, E., Ziemblińska, K., & Urbaniak, M. (2022). Trends in drought occurrence and severity at mid-latitude European stations (1951–2015) estimated using standardized precipitation (SPI) and precipitation and evapotranspiration (SPEI) indices. *Meteorology and Atmospheric Physics*, *134*, 1–21. https://doi.org/10.1007/S00703-022-00858-W/FIGURES/13

European Commission Centre, J. R., Toreti, A., Bavera, D., Navarro, J. A., Jager, A., et al. (2022). *Drought in Europe: August 2022: GDO analytical report*. Publications Office of the European Union. https://doi.org/10.2760/264241

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016a). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016b). WCRP coupled model intercomparison project [Dataset]. Earth System Grid Federation, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Faranda, D., Messori, G., Jezequel, A., Vrac, M., & Yiou, P. (2023a). Atmospheric circulation compounds anthropogenic warming and impacts of climate extremes in Europe. *Proceedings of the National Academy of Sciences*, *120*(13), e2214525120. https://doi.org/10.1073/pnas.2214525120

Faranda, D., Pascale, S., & Bulut, B. (2023b). Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought. *Environmental Research Letters*, *18*, 034030. https://doi.org/10.1088/1748-9326/acbc37

Fernández-Granja, J. A., Brands, S., Bedia, J., Casanueva, A., & Fernández, J. (2023). Exploring the limits of the Jenkinson–Collison weather types classification scheme: A global assessment based on various reanalyses. *Climate Dynamics*, *61*(3–4), 1829–1845. https://doi.org/10.1007/S00382-022-06658-7/FIGURES/11

Fleig, A. K., Tallaksen, L. M., James, P., Hisdal, H., & Stahl, K. (2015). Attribution of European precipitation and temperature trends to changes in synoptic circulation. *Hydrology and Earth System Sciences*, *19*(7), 3093–3107. https://doi.org/10.5194/hess-19-3093-2015

Grise, K. M., & Davis, S. M. (2020). Hadley cell expansion in CMIP6 models. *Atmospheric Chemistry and Physics*, *20*(9), 5249–5268. https://doi.org/10.5194/acp-20-5249-2020

Hänsel, S., Hoy, A., Brendel, C., & Maugeri, M. (2022). Record summers in Europe: Variations in drought and heavy precipitation during 1901–2018. *International Journal of Climatology*, *42*(12), 6235–6257. https://doi.org/10.1002/joc.7587

Herrera-Lormendez, P. (2022). jcclass. The automated Jenkinson & Collison classification for python. *Zenodo*. https://doi.org/10.5281/zenodo.7057289

Herrera-Lormendez, P., John, A., Douville, H., & Matschullat, J. (2023). Projected changes in synoptic circulations over Europe and their implications for summer precipitation: A CMIP6 perspective. *International Journal of Climatology*, *43*(7), 3373–3390. https://doi.org/10.1002/joc.8033

Herrera-Lormendez, P., Mastrantonas, N., Douville, H., Hoy, A., & Matschullat, J. (2022). Synoptic circulation changes over central Europe from 1900 to 2100: Reanalyses and coupled model intercomparison project phase 6. *International Journal of Climatology*, *42*(7), 4062–4077. https://doi.org/10.1002/joc.7481

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Sabater, J. M., et al. (2023). ERA5 hourly data on single levels from 1940 to present [Dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis [Dataset]. Quarterly Journal of the Royal Meteorological Society, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hoy, A., Schucknecht, A., Sepp, M., & Matschullat, J. (2014). Large-scale synoptic types and their impact on european precipitation. *Theoretical and Applied Climatology*, *116*(1–2), 19–35. https://doi.org/10.1007/s00704-013-0897-x

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., et al. (2008). Classifications of atmospheric circulation patterns. *Annals of the New York Academy of Sciences*, *1146*(1), 105–152. https://doi.org/10.1196/annals.1446.019

Ibebuchi, C. C., & Abu, I.-O. (2023). Characterization of temperature regimes in western Europe, as regards the summer 2022 western European heat wave. *Climate Dynamics*, *61*(7), 3707–3720. https://doi.org/10.1007/s00382-023-06760-4

IPCC. (2021). Summary for policymakers. Climate change 2021: The physical science basis. Contribution of working Group I to the sixth assessment report of the intergovernmental panel on climate change.

Jenkinson, A., & Collison, F. (1977). An initial climatology of gales over the North Sea. *Synoptic Climatology Branch Memorandum*, *62*, 18.

Kautz, L.-A., Martius, O., Pfahl, S., Pinto, J. G., Ramos, A. M., Sousa, P. M., & Woollings, T. (2022). Atmospheric blocking and weather extremes over the Euro-Atlantic sector – A review. *Weather and Climate Dynamics*, *3*(1), 305–336. https://doi.org/10.5194/wcd-3-305-2022

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., et al. (2023). Synthesis report of the IPCC sixth assessment report (AR6): Summary for policymakers. *Intergovernmental Panel on Climate Change*.

Lhotka, O., Trnka, M., Kyselý, J., Markonis, Y., Balek, J., & Možný, M. (2020). Atmospheric circulation as a factor contributing to increasing drought severity in central Europe. *Journal of Geophysical Research: Atmospheres*, *125*(18), e2019JD032269. https://doi.org/10.1029/2019JD032269

Marvel, K., Cook, B. I., Bonfils, C. J. W., Durack, P. J., Smerdon, J. E., & Williams, A. P. (2019). Twentieth-century hydroclimate changes consistent with human influence. *Nature*, *569*(7754), 59–65. https://doi.org/10.1038/s41586-019-1149-8

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, *305*(5686), 994–997. https://doi.org/10.1126/science.1098704

Met Office. (2022). A milestone in UK climate history. Retrieved from https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/july-heat-review

Otero, N., Sillmann, J., & Butler, T. (2018). Assessment of an extended version of the Jenkinson–Collison classification on CMIP5 models over Europe. *Climate Dynamics*, *50*(5–6), 1559–1579. https://doi.org/10.1007/s00382-017-3705-y

Pfahl, S. (2014). Characterising the relationship between weather extremes in Europe and synoptic circulation features. *Natural Hazards and Earth System Sciences*, *14*(6), 1461–1475. https://doi.org/10.5194/nhess-14-1461-2014

Räisänen, J. (2019). Effect of atmospheric circulation on recent temperature changes in Finland. *Climate Dynamics*, *53*(9–10), 5675–5687. https://doi.org/10.1007/s00382-019-04890-2

Řehoř, J., Brázdil, R., Trnka, M., Lhotka, O., Balek, J., Možný, M., et al. (2021). Soil drought and circulation types in a longitudinal transect over central Europe. *International Journal of Climatology*, *41*(S1), E2834–E2850. https://doi.org/10.1002/joc.6883

Richardson, D., Neal, R., Dankers, R., Mylne, K., Cowling, R., Clements, H., & Millard, J. (2020). Linking weather patterns to regional extreme precipitation for highlighting potential flood events in medium- to long-range forecasts. *Meteorological Applications*, *27*(4). https://doi.org/10.1002/met.1931

Riediger, U., & Gratzki, A. (2014). Future weather types and their influence on mean and extreme climate indices for precipitation and temperature in central Europe. *Meteorologische Zeitschrift*, *23*(3), 231–252. https://doi.org/10.1127/0941-2948/2014/0519

Rogers, C. D., Kornhuber, K., Perkins-Kirkpatrick, S. E., Loikith, P. C., & Singh, D. (2022). Sixfold increase in historical northern hemisphere concurrent large heatwaves driven by warming and changing atmospheric circulations. *Journal of Climate*, *35*, 1063–1078. https://doi.org/10.1175/JCLI-D-21-0200.1

Röthlisberger, M., & Papritz, L. (2023). Quantifying the physical processes leading to atmospheric hot extremes at a global scale. *Nature Geoscience*, *16*(3), 210–216. https://doi.org/10.1038/s41561-023-01126-1

Rouges, E., Ferranti, L., Kantz, H., & Pappenberger, F. (2023). European heatwaves: Link to large-scale circulation patterns and intraseasonal drivers. *International Journal of Climatology*, *43*(7), 3189–3209. https://doi.org/10.1002/joc.8024

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications*, *13*(1), 3851. https://doi.org/10.1038/s41467-022-31432-y

Rousi, E., Selten, F., Rahmstorf, S., & Coumou, D. (2021). Changes in north Atlantic atmospheric circulation in a warmer climate favor winter flooding and summer drought over europe. *Journal of Climate*, *34*(6), 2277–2295. https://doi.org/10.1175/JCLI-D-20-0311.1

Santos, J. A., Belo-Pereira, M., Fraga, H., & Pinto, J. G. (2016). Understanding climate change projections for precipitation over Western Europe with a weather typing approach. *Journal of Geophysical Research: Atmospheres*, *121*(3), 1170–1189. https://doi.org/10.1002/2015JD024399

Schumacher, D. L., Zachariah, M., Otto, F., Barnes, C., Philip, S., Kew, S., et al. (2022). High temperatures exacerbated by climate change made 2022 northern hemisphere soil moisture droughts more likely.

Seager, R., Osborn, T. J., Kushnir, Y., Simpson, I. R., Nakamura, J., & Liu, H. (2019). Climate variability and change of Mediterranean-type climates. *Journal of Climate*, *32*(10), 2887–2915. https://doi.org/10.1175/JCLI-D-18-0472.1

Sousa, P. M., Ramos, A. M., Raible, C. C., Messmer, M., Tomé, R., Pinto, J. G., & Trigo, R. M. (2020). North Atlantic integrated water vapor transport—From 850 to 2100 CE: Impacts on western European rainfall. *Journal of Climate*, *33*, 263–279. https://doi.org/10.1175/JCLI-D-19-0348.1

Terray, L. (2023). A storyline approach to the June 2021 northwestern North American heatwave. *Geophysical Research Letters*, *50*(5), e2022GL101640. https://doi.org/10.1029/2022GL101640

Ullmann, A., Fontaine, B., & Roucou, P. (2014). Euro-Atlantic weather regimes and Mediterranean rainfall patterns: Present-day variability and expected changes under CMIP5 projections. *International Journal of Climatology*, *34*(8), 2634–2650. https://doi.org/10.1002/joc.3864

van Oldenborgh, G. J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., et al. (2009). Western Europe is warming much faster than expected. *Climate of the Past*, *5*, 1–12. https://doi.org/10.5194/cp-5-1-2009