European summer synoptic circulations and their observed 2022 and projected influence on hot and dry extremes

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Key Points:

- European summer 2022 hot extremes have been enhanced by an anomalous occurrence of distinct circulation types over distinct subdomains.
- Persistent circulation anomalies also contributed to the exceptional number of dry days, as much as local, mostly thermodynamical effects.
- Such anomalous circulations are more common under unabated greenhouse-gas emissions, thus further worsening European hot and dry extremes.

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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. Here we use a reanalysis to classify daily mean sea level pressure fields and 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 marginally 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 since preindustrial times, as well as widespread dry conditions that have 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 caused by global warming. By grouping distinct weather patterns, we find that many extreme hot days during the summer of 2022 over distinct parts of Europe were favoured by anomalous transport of hot and dry air masses or persistent low-wind conditions. We show that these weather patterns were essential but not the dominant factor that led to the occurrence of extreme temperatures, although 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 the coming decades if greenhouse gas emissions remain without reduction, thus further worsening 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 was characterised by strong, persistent and widespread mid-tropospheric anticyclonic anomalies over western Europe. This circulation helped to exacerbate the drought by increasing its area of influence and by enhancing soil drying due to evapotranspiration (Faranda, Pascale, & Bulut, 2023). Large–scale 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 favour such extremes if they persist over prolonged periods by favouring diabatic and adiabatic warming that 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). Large–scale surface 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 local rather than 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).

Large–scale 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 (hereafter defined as within–type contributions) may also contribute 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, e.g., the expansion of dry conditions (meteorological droughts) in many regions since the late 1980s (Beštáková 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 (Douville et al., 2021; Santos et al., 2016; de Vries et al., 2022). 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 favours 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 circulation types observed over Europe in summer 2022 (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 what extent future changes in large–scale circulation may favour such summer extremes at the end of the 21st century. We aim (i) to summarise the influence of large–scale CTs on European summer temperature extremes, (ii) to investigate the behaviour of CTs during the extreme summer of 2022, (iii) to analyse the seasonal contribution of large–scale circulation (between CTs) and other sources (within–type) to the observed extreme temperatures and anomalous dry days, and (iv) to explore the plausibility anomalous atmospheric patterns observed in the summer of 2022 becoming 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). 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 historical experiment (1951–2014) 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 realisation number one (r1) of each GCM only (i.e., twenty simulations of both present-day and future climates).

- We compute daily gridded surface synoptic circulations employing the "jcclass" python module (Herrera-Lormendez, 2022) based on the Jenkinson-Collison automated classification (Jenkinson & Collison, 1977). The computation of the circulation types (CTs) is done solely based on MSLP. We derive eleven CTs based on their pressure centres (anticyclonic: A and cyclonic centres: 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 CT characterised by weak pressure gradients conditions. 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 summer and the synoptic circulation, we compute the summer (JJA) anomalies of the relative frequencies (RF anomalies), corresponding to the eleven distinguished CTs. To focus the analysis on the distribution of extreme daily maximum temperatures related to these CTs, we retain only the 5% hottest values ($Tmax_{p95}$) using 1961–1990 as the reference period.

- To assess the contribution of the synoptic circulation on the S22 anomalous occurrence of $Tmax_{p95}$ and dry days (DDs), we employ a simple decomposition inspired from Cattiaux et al. (2013) and already applied in Herrera-Lormendez et al. (2023). This simple method allows us to determine how the daily temperature and precipitation anomalies during S22 have been influenced by a large-scale dynamical effect (i.e., between-class effect diagnosed as the effect of CT anomalies) versus other sources (i.e., within-class effects diagnosed without any change in CT frequency). We do this by computing the mean of variable $X(\bar{X})$ as the mean of CT–conditional means x_k, weighted by the frequencies of occurrence f_k. In our case, X represents the anomalies of the 5% extreme daily maximum temperatures and the number of DDs per season. Therefore, $\bar{X}$ is the averaged value over a given period, and x_k is the composite within each circulation 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 1961–1990 reference climatology (denoted by P for present-day climate).

$$\Delta^{F-P} = \bar{X}^F - \bar{X}^P = \underbrace{\sum_k \Delta f_k x_k^p}_{\text{BC}} + \underbrace{\sum_k f_k^p \Delta x_k}_{\text{WC}} + \underbrace{\sum_k \Delta f_k \Delta x_k}_{\text{RES}}, \tag{1}$$

  where $f_k = \frac{N_k}{N}$ is the frequency of occurrence of the kth circulation type and xk is the $Tmax_{p95}$ and DDs conditional mean to regime k, defined by $xk = \frac{1}{N_k} \sum_{\in \Omega_k} X_{ik}$ with Ωk being the total ensemble of the Nk days classified in the kth CT. 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 deviations in the frequency of occurrence of the individual CTs. The WC term refers to the contributions of the anomalies within the CTs which can arise from both thermodynamical and small-scale dynamical processes (Herrera-Lormendez et al., 2023), while 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) over the 1950-2100 period. For this purpose, we assess the year-by-year and CT-by-CT spatial correlations between the ERA5–derived patterns of S22 RF anomalies over western Europe (40 to 60$^{\text{o}}$N and -10 to 15$^{\text{o}}$E) against the corresponding patterns simulated by twenty CMIP6 GCMs. For each

CT, the synoptic effect evidenced during S22 is considered to strengthen if the year-by-year spatial correlation increases and becomes significant across the 21st century.

3 Results

3.1 Distribution of temperature extremes

Figure 1 shows the 1961–1990 climatological summer composite of the conditional probability (CP) of $Tmax_{p95}$ events relative to each CT over Europe. CTs are shown in order of occurrence during the summer season. Further information regarding the spatial distribution of RFs is found in the SI as Figure S1. Anticyclones (A) are the prevalent summer CT characterised by subsidence and cloud-free skies. Their influence on temperature extremes is most pronounced over the British Isles, the western part of Scandinavia, and the mountainous regions of continental Europe, where large–scale horizontal advection plays a less important role in the occurrence of hot events. In these regions, nearly half of the $Tmax_{p95}$ events can be attributed to this CT. 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 behaviour of the pressure gradients. It becomes evident that the large majority (>50%) of the $Tmax_{p95}$ are linked to this CT (LF) due to its predominant occurrence over this region. They are also a major contributor to temperature extremes over continental Europe but not the British Isles. The third CT, the cyclonic centres (C), appears as an important source for extremes over southern Spain, the North Sea and the North Atlantic. This happens as cyclones favour 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 extreme temperatures is more evident over northern maritime areas. Altogether, they are responsible for nearly a third of the $Tmax_{p95}$ 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 during the extreme hot summer of 2022 using the ERA5 reanalysis with 1961–1990 as our reference period (Figure 2). The occurrence of anticyclones (A) was above normal over the 50–60º latitude belt. These anomalies are linked to increased occurrences of Easterly advection (E, NE and SE) and predominant Low Flow conditions over 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.

The individual influence of some of these CTs on the distribution of the $Tmax_{p95}$ events is highlighted by hatched areas in Figure 2. For the sake of clarity, we only hatched the regions where the S22 share of the temperature extremes was above 25% (full figure in SI as Figure S2). Many of the observed temperature extremes during S22 did not occur in the anticyclonic centres as previously found in the climatological distribution of extremes (Figure 1). Many of the $Tmax_{p95}$ events over central and southern Europe occurred during LF type conditions. This atmospheric configuration is prevalent in southern Europe primarily due to weaker MSLP gradients, often coinciding with the extended part of a high-pressure system. The remaining distribution of temperature extremes over

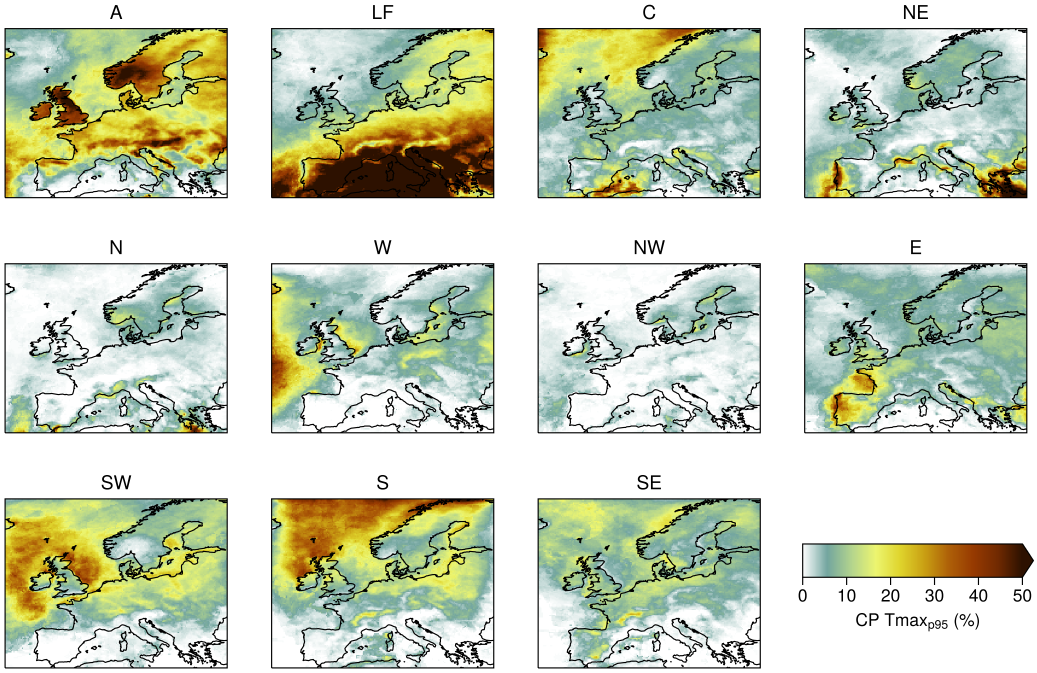

Figure 1. Summer composite of the conditional probability of a $Tmax_{p95}$ event in the eleven circulation types during the 1961–1990 reference period. Data ERA5 daily mean MSLP and Tmax at 0.25 x 0.25º resolution.

western Europe was mostly constrained to the easterly and southerly (SW, S and SE) advection. The easterly CTs favoured the transport of dry and hot air masses from continental Europe towards the Atlantic coast, contributing significantly to the hot extreme days observed during JJA 2022. This is more evident over the Atlantic Ocean and south of the British Isles due to the ocean–continent thermal contrast. Much of the remaining $Tmax_{p95}$ events 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 1. Figure 3 shows the results when comparing observed $Tmax_{p95}$ events (a) and the anomalous DDs (b) of S22 to the reference climate period of 1961–1990. 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.

The CTs' influence on the Tmax anomalies (Figure 3a) 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 contribution to the total 2022 $Tmax_{p95}$ anomalies shown in Figure 2, they played an important role in enhancing hot extremes over Europe. At least a third (0.3K) of the magnitude of the temperature anomalies arose from the dynamical changes. The governing factor is found in the WC term where on average, two-thirds of the magnitude of the $Tmax_{p95}$ anoma-

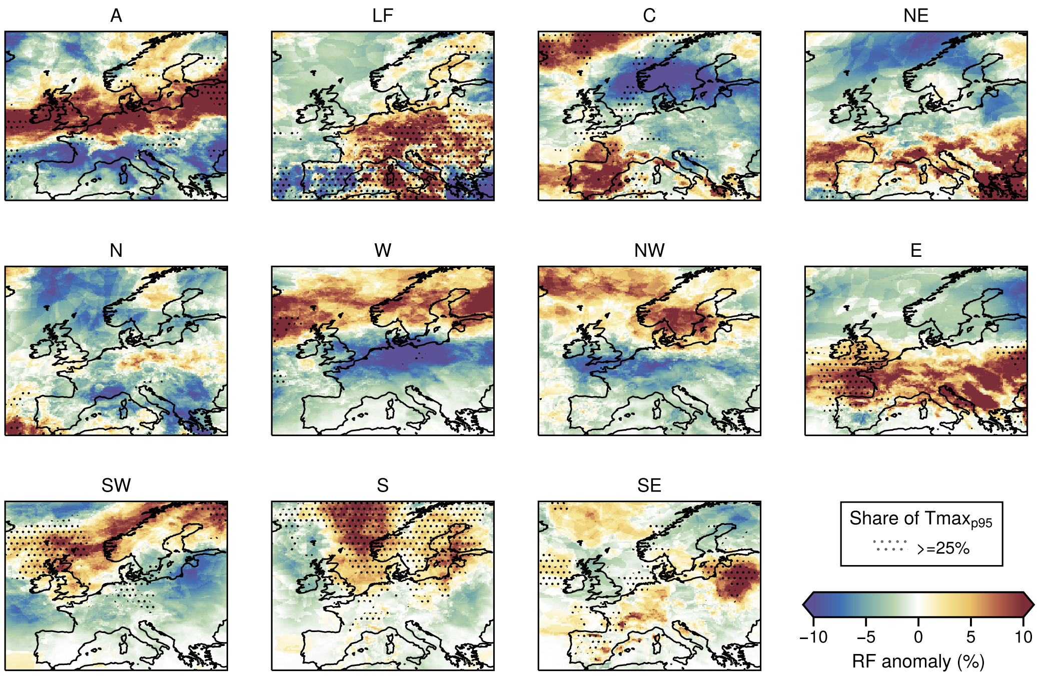

Figure 2. Summer 2022 RF anomalies (shading) and share of $Tmax_{p95}$ events >25% (hatching). ERA5 daily MSLP and Tmax data at 0.25 x 0.25º resolution. 1961–1990 reference period.

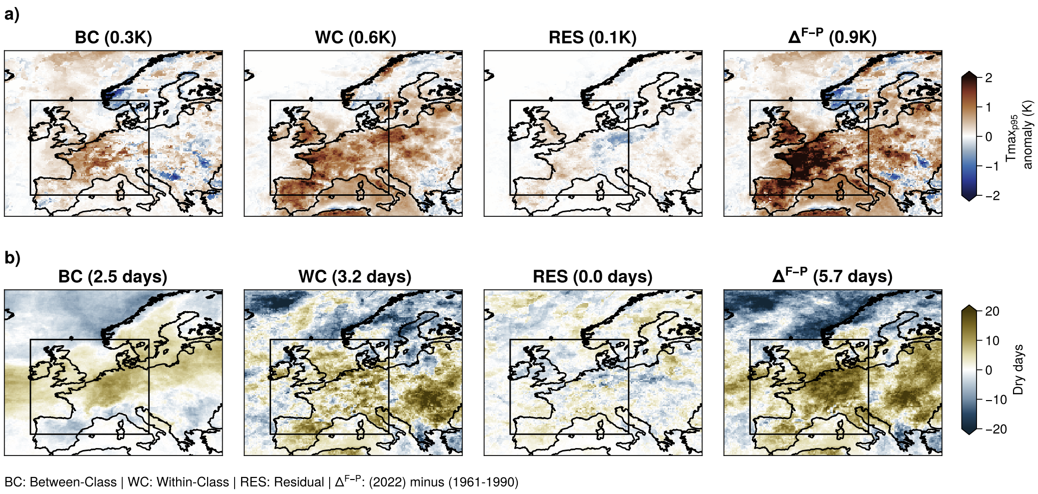

Figure 3. Summer 2022 decomposition of (a) $Tmax_{p95}$ anomalies and (b) DDs. Each column shows the BC, WC, RES and Δ^{F-P} computed using the 1961–1990 reference period. The value in brackets shows the mean spatial value over the western Europe region shown in the square. Data from ERA5 daily MSLP and Tmax at 0.25 x 0.25º resolution.

lies (0.6K) over western Europe were caused by within–type sources, that is without accounting for changes in the CT relative frequencies. 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.

Unlike the extreme hot days, the DDs anomalies were strongly governed by the anomalous occurrence of CTs. The dynamical contribution (BC) accounted for nearly 44% of the western Europe observed DDs. The dynamical influence is stronger over the UK, France and Germany coinciding with areas where anticyclonic centres, easterly and low flow conditions predominated (Figure 3b). The WC term was marginally the dominant contributor to the occurrence of DDs (56%). The predominant WC contributions are more evident towards southern Europe, where large–scale circulation is generally not the primary source for observed changes (Marvel et al., 2019; Seager et al., 2019).

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 spatial correlation between the projected and observed (S22) RF anomalies observed over western Europe (40 to 60ºN and -10 to 15ºE). In other words, we compare the patterns derived from ERA5 reanalysis against simulated RF anomalies from 20 CMIP6 GCMs spanning the period from 1950 to 2100 (based on historical simulations and the SSP5-8.5 high-emission scenario).

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 unusual CT events observed in the summer of 2022 will become more likely under a high-emission scenario. The correlation is most significant in synoptic circulations related to the high-pressure system placement, with the strongest link found in this specific CT(A). 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-types will also become prevalent conditions over continental Europe in the coming decades. Increasing positive correlations also appear in the W, NW, N and C synoptic circulations. During 2022, their behaviour was characterised by below-normal occurrences as a result of the above-normal occurrence of anticyclones. The only circulation showing decreasing correlation is the southerly type. Despite having one of the largest shares of $Tmax_{p95}$ over northern Europe during the 2022 summer, the southerly CT is not projected to increase in frequency over these regions under the current CMIP6 high-emission scenario (Herrera-Lormendez et al., 2023). However, much the same as in S22, this does not imply that extraordinary events characterised by strong southerly advection will not be relevant in a future climate.

4 Discussion

Our results show how the exceptionally hot and dry summer of 2022 was influenced by anomalous CTs, strongly dependent on the positioning and prevalence of the high-pressure system centres. Anticyclonic conditions contributed to the distribution of the observed temperature extremes recorded over western Europe. Warm advection from the easterly and southerly circulations was also decisive for the occurrence of $Tmax_{p95}$ events over western Europe. This was for instance the case for the UK's all-time heat record of 40.3ºC reported on July 19th (Met Office, 2022). An anticyclonic centre over northern Germany and Denmark in combination with a cyclonic circulation facing the western coast of the Iberian Peninsula favoured the advection of hot air from the south. However, much of the distribution of the Tmax extremes over central and southern Europe

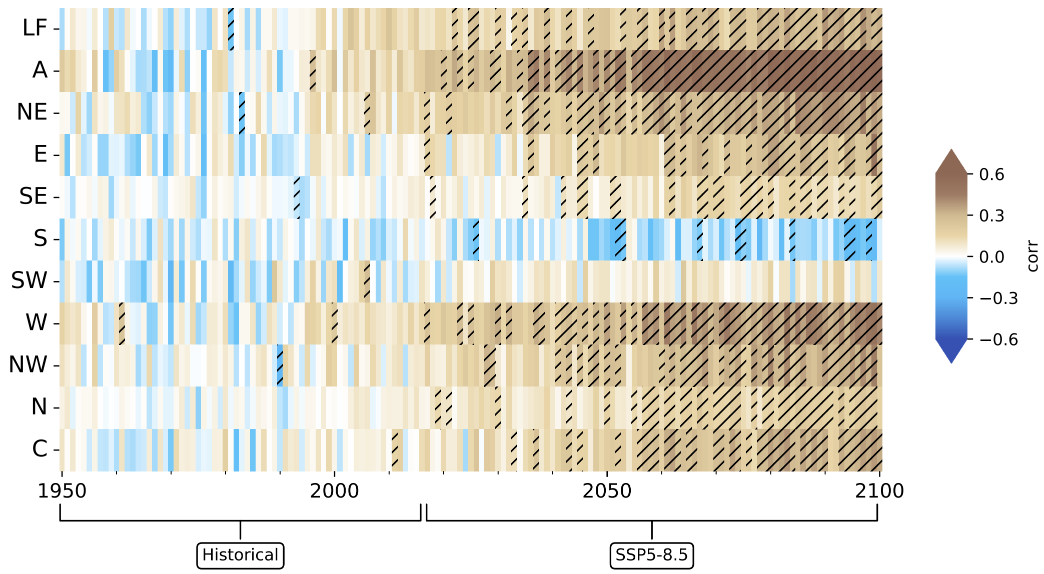

Figure 4. Western Europe (40 to 60ºN and -10 to 15ºE) spatial correlation of summer 2022 anomalous RF patterns (ERA5 data) versus 20 CMIP6 GCMs. MSLP data from the historical experiment (1950-2014) and SSP5-8.5 scenario (2015–2100). Both datasets were brought together to a common 1 x 1º resolution.

occurred during Low Flow 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 observed $Tmax_{p95}$ and DDs anomalies are not fully explained by the anomalous occurrence of CTs. The exceptional S22 resulted from a combination of the large–scale circulation influence and other 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). We verify that the influence of the synoptic circulations (BC term) on the $Tmax_{p95}$ was important, but not the only factor in conditioning the extreme temperatures of S22. The thermodynamical influence (WC term) played a more important role in enhancing the $Tmax_{p95}$ events. In comparison, the large–scale circulation had a greater impact on the extensive drought favoured by the persistent lack of precipitation over western Europe. We show that around 44% of the anomalous DDs over western Europe were caused by the anomalous patterns of synoptic circulations. The increased frequency of DDs coincides extensively with the observed anomalous incidence of anticyclonic CT extending from the British Isles to the Baltic countries. Over France and Germany, the main CT contributing to the extended number of DDs was the easterly and low flow patterns. The days characterised 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).

As projected climatic changes suggest, the already experienced drier summers (Hänsel et al., 2022) are expected to become considerably drier over southern Europe (Douville et al., 2021). Emerging changes in frequency and within–type characteristics of large–scale surface circulations over Europe will enhance such negative effects on rainfall (Herrera-Lormendez et al., 2023). Interestingly, the observed anomalous synoptic CTs during the extreme hot summer of 2022 broadly resembles the spatial patterns found in the CMIP5 RCP-8.5 and CMIP6 SSP5-8.5 scenarios of projected circulation changes towards the end of the 21st century (Herrera-Lormendez et al., 2022, 2023; Otero et al., 2018). These similarities are more evident in the likely increase of anticyclonic conditions around the British Isles, leading to an enhanced influence of easterly and low flow conditions with a consequent detriment of rainy CTs. We ran a spatial correlation of the S22 anomalous patterns of the CTs over western Europe and compared them against every summer in the CMIP6 historical experiment and SSP5-8.5 scenario (1950–2100 period). We show that the overall configuration of the RF anomalies of the synoptic circulations observed during S22 become more repetitive in many of the individual CMIP6 models (out of 20 GCMs) towards the end of the 21st century. The strongest correlations appear in the anticyclonic and westerly CTs. The increased correlation with the anticyclonic CT appears as high-pressure centres are projected to increase in frequency in northwestern Europe (de Vries et al., 2022). They will likely be enhanced by the extension of the Atlantic ridge weather regime configuration towards Europe (Ullmann et al., 2014). The response to these changes over western Europe materialises in the increasing NE, E and LF conditions associated with the positioning of the anticyclone. The higher correlation values in the westerly CT can be explained by the blocking effects that the anticyclone will exert, leading to a reduced number of westerly advection days and a shortened number of cyclonic centres, like the pattern observed during the 2022 summer. Such large–scale behaviour agrees with the hypothesis that global warming will promote persistent splitting jet stream conditions, causing cyclones to deviate and enhancing anticyclonic and easterly CTs. This in turn, contributes 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).

5 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 synoptic circulations influenced the spatial distribution of temperature extremes over Europe in S22, which should become more frequent during the second half of the 21st century if there is no strong mitigation of climate change. The CT influence varies geographically and is strongly governed by the location of anticyclonic centres and the southerly or easterly advection of hot air masses. Our approach allowed us to assess a snapshot of the S22 circulations and their contribution to the exceptionally hot and dry conditions over Europe. The extreme summer was characterised by an anomalous positioning of high-pressure centres extending from the British Isles to the Baltic region. As a response, an overall increase in days with easterly, southerly and low flow circulations was observed over most of western and central Europe. Overall, the occurrence of the 2022 summer temperature extremes occurred during predominant anticyclonic-adjacent circulations. 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 temperature extremes and dry days during S22. We concluded that the WC effect played the key role in the occurring $Tmax_{p95}$ events, while the BC effect was responsible for about one-third of that role. Nevertheless, CTs served as the preconditioning factor by likely enhancing the adiabatic and advective warming components. Contrastingly, the dry days in western Europe were largely determined by the anomalous CTs and especially by the anticyclone and its neighbouring circulations. This comes as no surprise, given that the strongest negative precipitation anomalies often occur near anticyclonic pressure centres (Hoy et al., 2014). Despite the strong influence of the CTs in the observed dry days, the thermodynamical contribution was the predominant factor on dry conditions over southern Europe, a region where thermodynamic processes dominate (Brogli et al., 2019).

Supported by twenty CMIP6 GCMs, we found that anomalous circulation patterns like the ones observed in summer of 2022 will be more likely to repeat in the future under a high-emission scenario. The more robust similarities with future versus recent summers appear in the inverse relation where anticyclonic, easterly and low-flow circulations are favoured (de Vries et al., 2022) while CTs associated with cooler and moister conditions are foreseen to decrease in frequency. However, these results do not address the quantitative changes arising in both extreme temperatures and dry days. Our current scientific understanding agrees on the unequivocal fact that human activities have been and will be increasingly responsible for important climate changes and related impacts at the regional scale (Lee et al., 2023). Such changes are not only driven by a local response but may also involve circulation changes which can sustain positive dynamical feedback onto projected changes in temperature and precipitation. Such large-scale dynamical responses are generally less robust than their thermodynamical counterpart (de Vries et al., 2022; Shepherd, 2014). More efforts are thus needed in understanding how they will alter the occurrence of high-impact weather events in a future climate (Rowell & Jones, 2006).

Open Research

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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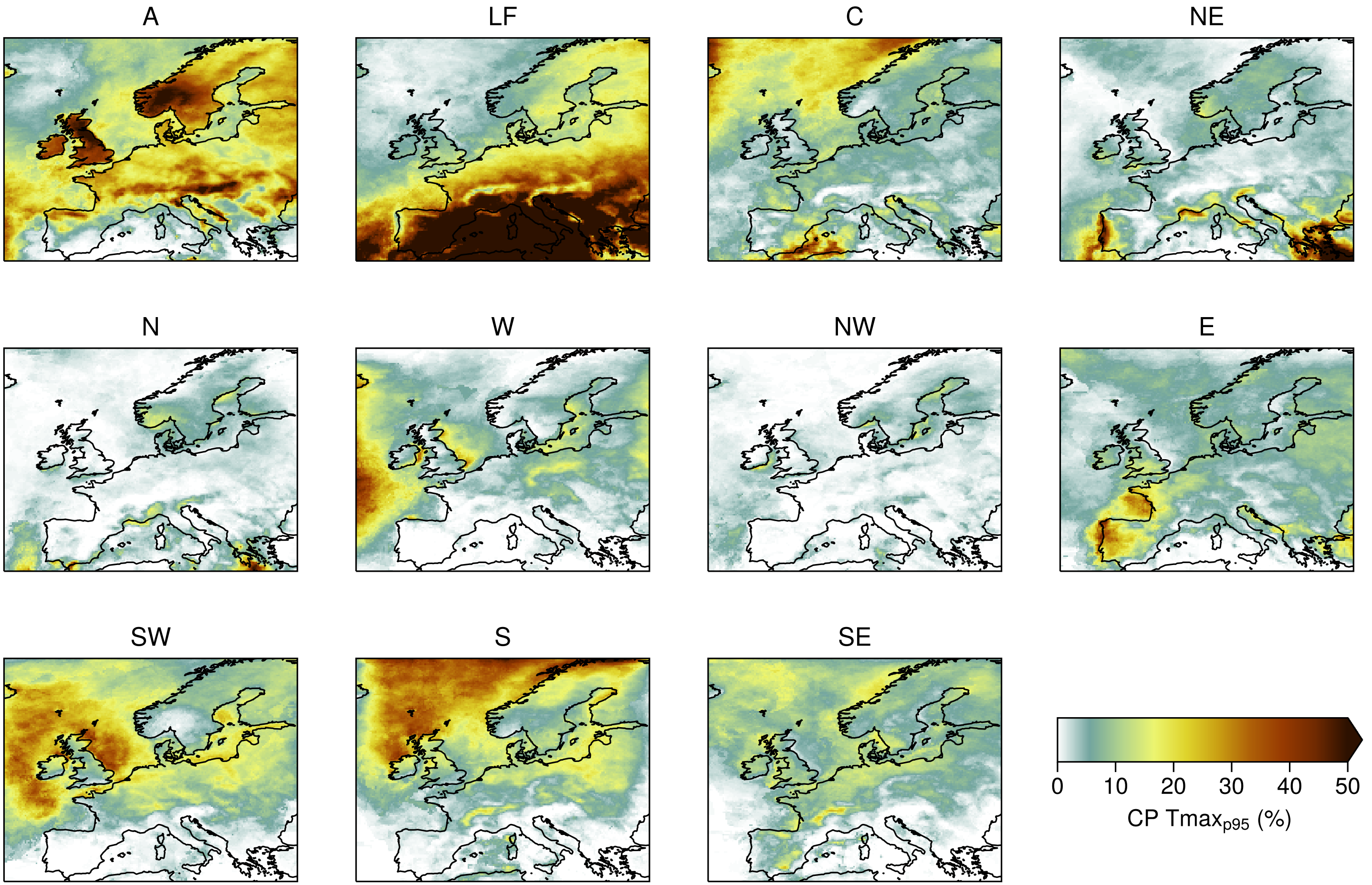
Figure 1.


A
LF
C
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0
10
20
30
40
50
CP $Tmax_{p95}$ (%)

Figure 2.

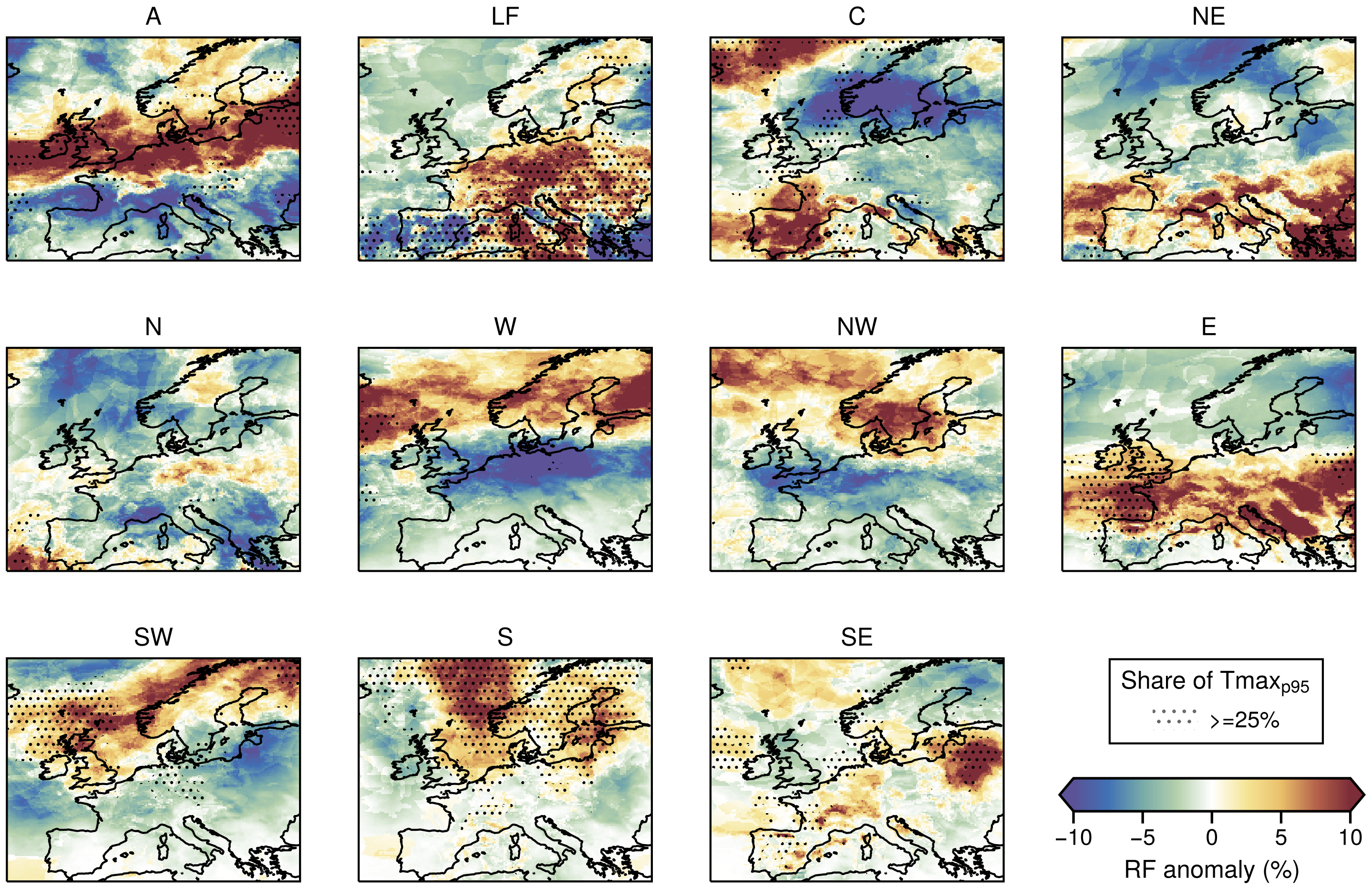
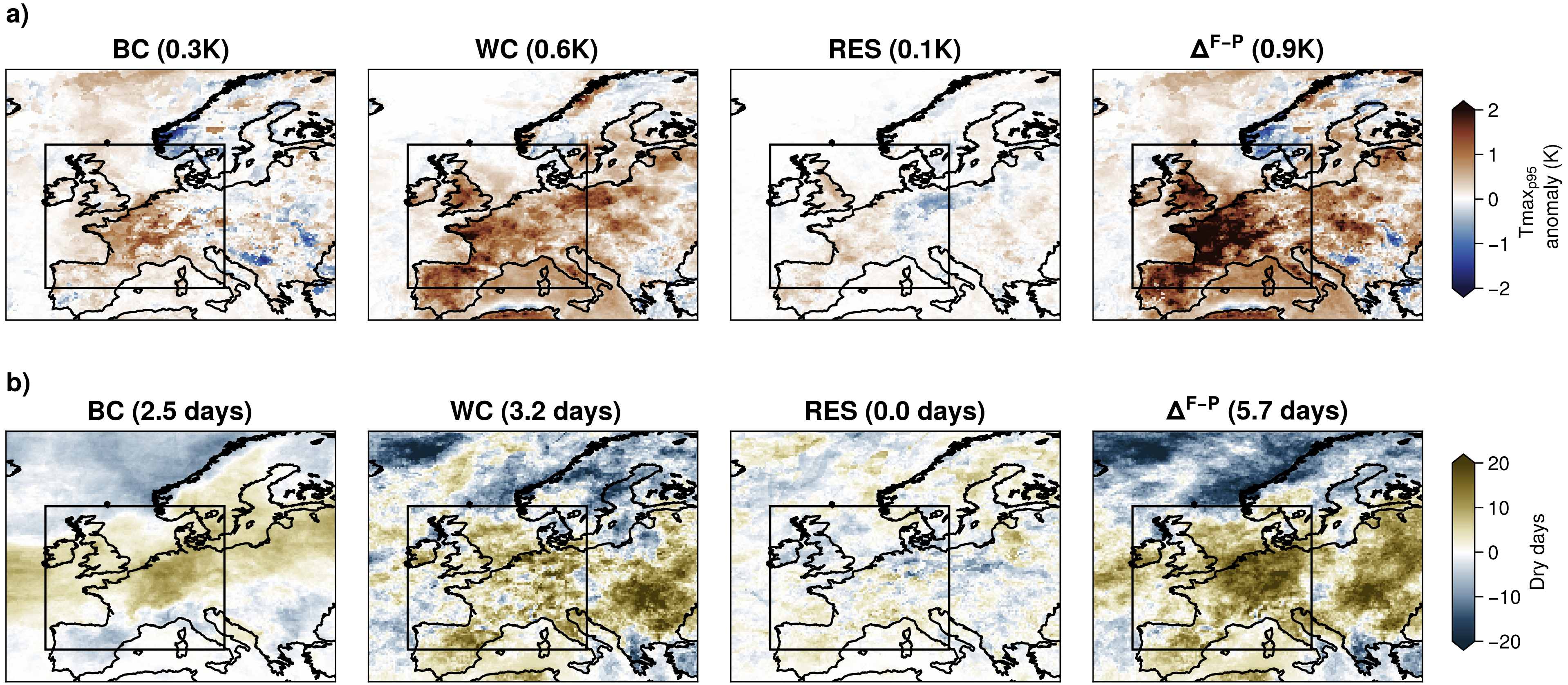
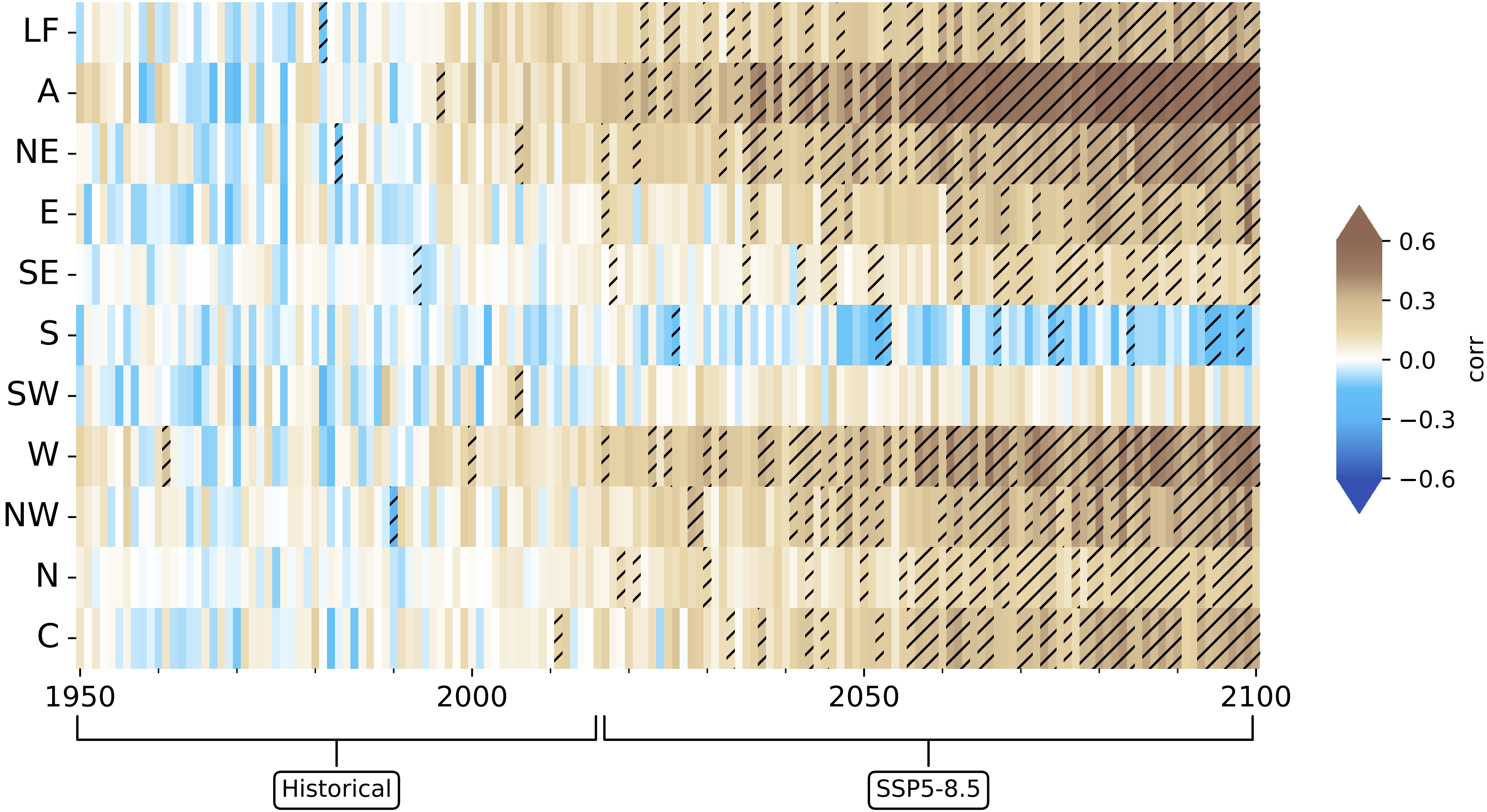

A
LF
C
NE
N
W
NW
E
SW
S
SE
Share of Tmax$_{p95}$
>=25%
−10
−5
0
5
10
RF anomaly (%)

Figure 3.



BC: Between-Class | WC: Within-Class | RES: Residual | Δ^{F-P}: (2022) minus (1961-1990)

Figure 4.


LF
A
NE
E
SE
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SW
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N
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1950
2000
2050
2100
Historical
SSP5-8.5
0.6
0.3
0.0
−0.3
−0.6
corr