Patterns of atmospheric circulation in Western Europe linked to heavy rainfall in Germany: preliminary analysis into the 2021 heavy rainfall episode

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Abstract

The July 2021 heavy rainfall episode in parts of Western Europe caused devastating floods, specifically in Germany. This study examines circulation types (CTs) linked to extreme precipitation in Germany. It was investigated if the classified CTs can highlight the anomaly in synoptic patterns that contributed to the unusual July 2021 heavy rainfall in Germany. The North Atlantic Oscillation was found to be the major climatic mode related to the seasonal and inter-annual variations of most of the classified CTs. On average, wet (dry) conditions in large parts of Germany can be linked to westerly (northerly) moisture fluxes. During spring and summer seasons, the mid-latitude cyclone when located over the North Sea disrupts onshore moisture transport from the North Atlantic Ocean by westerlies driven by the North Atlantic subtropical anticyclone. The CT found to have the highest probability of being associated with above-average rainfall in large part of Germany features (i) enhancement and northward track of the cyclonic system over the Mediterranean; (ii) northward track of the North Atlantic anticyclone, further displacing poleward, the mid-latitude cyclone over the North Sea, enabling band of westerly moisture fluxes to penetrate Germany; (iii) cyclonic system over the Baltic Sea coupled with northeast fluxes of moisture to Germany; (iv) and unstable atmospheric conditions over Germany. In 2021, a spike was detected in the amplitude and frequency of occurrence of the aforementioned wet CT suggesting that in addition to the nearly stationary cut-off low over central Europe, during the July flood episode, anomalies in the CT contributed to the heavy rainfall event.

1 Introduction

Recently, at the time of writing this paper, parts of Germany, located in Western Europe, experienced heavy rainfall that led to devastating floods. The flood caused loss of lives and damage to properties. As of 13 July, intense storms triggered about 15 cm of rain in 24 h leading to the inundation of streams, and heavy landslides (Science 2021). The magnitude of destruction caused by the flood has become a key motivation to climate scientists to investigate the meteorological causes of heavy rainfall and improve flood forecasting techniques. Additionally, if anthropogenic climate change is amplifying extremes in rainfall needs to be equally investigated. Pending a more detailed analysis of the flood event and the availability of long-term observations and climate model simulations at finer horizontal resolutions, this study investigates synoptic patterns of atmospheric circulation linked to above-average rainfall in Germany. Up to the point that reanalysis data sets are available as of the time of doing this analysis, a snapshot of patterns of atmospheric circulation (linked to heavy rainfall) that could have reoccurred in 2021 contributing to the flood episode is investigated.

A relationship between rainfall in Western Europe and large-scale patterns of atmospheric circulation is expected and has been widely studied (e.g., Hofstätter et al. 2018). Moisture transport from the oceans to the continent impacts precipitation patterns (Volosciuk et al. 2016). The major sources of moisture to Europe are the North Atlantic Ocean and the Mediterranean Sea (Volosciuk et al. 2016; Craig et al. 2016; Skliris et al. 2018; Vazquez et al. 2020). During boreal summer, the North Atlantic Ocean becomes the major source of moisture to Western Europe (Vazquez et al. 2020).

A semi-permanent subtropical anticyclone over the North Atlantic Ocean significantly impacts the weather and climate of Western Europe (e.g., Davis et al. 1997). According to

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Davis et al. (1997), during boreal summer, the anticyclone dominates the Atlantic Basin, and during winter, the anticyclone shifts towards eastern North America and northwestern Africa. The authors noted that other modes of variability of the anticyclonic system are omega blocks and meridional versus zonal circulation patterns. While the omega block is a tripole pattern, other block patterns can be steady ridges and High-over-Lows (i.e., dipoles) (Bott 2012; Woollings et al. 2018). During boreal winter, blocking resulting in the equatorward shift of the polar jet stream can be associated with cold winters in Western Europe (e.g., van Loon and Rogers 1978). During boreal summer, omega blocking can be associated with positive temperature anomalies in Western Europe (e.g., Henley et al. 2019). When conditions are favorable, for example, when the high is accompanied by persistent cyclonic systems, heavy rainfall might be expected in Western Europe (e.g., Mohr et al. 2020). The circulation associated with the North Atlantic anticyclone results in westerly moisture fluxes towards Western Europe. Thus, at the synoptic scale, the climatology of the North Atlantic anticyclone, cyclogenesis over the Mediterranean region, and the mid-latitude cyclones play vital roles in precipitation formation in Western Europe.

Teleconnections such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) can significantly impact the climate of Western Europe. Hurrell (1995) noted that the NAO strongly impacts the mean winter climate of vast regions in the Northern Hemisphere. According to Ricardo et al. (2002), NAO influences precipitation rate and precipitable water in Europe. Scaife et al. (2008) highlighted that 90th percentile precipitation events over Europe are found from changes in the NAO. During the positive phase of the NAO, a strong subtropical anticyclone is situated over the central North Atlantic while a strong low-pressure system is centered over Iceland. Thus, the positive phase of the NAO is associated with the northward shift of the mid-latitude cyclone and enhanced westerly wind over the North Atlantic. During boreal winter, positive NAO corresponds with wet (dry) conditions in Northern Europe (the Mediterranean region). During the negative phase, the reverse condition is expected since westerly winds are weakened coupled with the intrusion of Arctic air into Europe. The NAO also influences storm tracks over the Atlantic region (e.g., Osborn et al. 1999). According to Mehta et al. (2000), North Atlantic sea surface temperature anomalies can modify the NAO. Towards the twenty-first century, Scaife et al. (2008) reported that changes in the frequency of NAO events might be linked to anthropogenic forcing.

According to Thompson and Wallace (1998), the NAO is more of a regionalized pattern while the AO is more of a hemispheric mode. The AO is close to the NAO. During positive phase of the AO, the anticyclone at mid-latitudes drives maritime moisture farther north and the circulation

at the North Pole limits colder air across the Polar regions. These teleconnections are the building blocks of atmospheric circulation patterns (Huth et al. 2008). The purposes of this study are (i) to apply a fuzzy (i.e., more than one CTs can be considered at a given time) eigenvector-based technique to isolate periods when specific patterns of atmospheric circulation occurred; (ii) to analyze synoptic patterns that can be linked to above-average rainfall in Germany; (iii) investigate the teleconnections associated with the selected patterns of atmospheric circulation linked to precipitation extremes in Germany; (iv) statistical analysis of the trends and dominant periods of the patterns; (v) and preliminary investigation of if an anomaly in any of the selected synoptic patterns can be linked to the 2021 heavy rainfall in Germany. The clustering technique used in classifying the circulation types (CTs) in Western Europe is the fuzzy obliquely rotated T-mode (i.e., variable is time series and observation is grid points) principal component analysis (PCA). The method has been successfully applied to separate wetting and drying signals in southern Africa, investigate their teleconnections, and the impact of radiative heating on the signals (e.g., Ibebuchi 2021a, b, c, d; Ibebuchi and Paeth 2021). Obliquely rotated T-mode PCA has been widely applied in classifying circulation patterns in Europe (e.g., Huth et al. 2008). The novelty of the approach in this work is that given the continuum and fuzzy nature of atmospheric circulation patterns, the probability of group membership that implies overlapping of the classified variable is incorporated in the analysis.

2 Data and methodology

To classify the CTs in Western Europe, this study uses two gridded sea level pressure (SLP) reanalysis data sets from ERA5 (Hersbach et al. 2020) and NCEP-NCAR (Kalnay et al. 1996). The choice of using SLP for the classification is based on the finding of Kidson (1997), that SLP can provide a good representation of large-scale systems; explain the relationship between topography and low-level flow, and between 1000 to 500 hPa, the choice of the level to use in the classification of CTs has a small influence on the explanation of surface variables. The horizontal resolution of the ERA5 SLP data is 0.25° longitude and latitude. The horizontal resolution of the NCEP SLP data is 2.5° longitude and latitude. 850 hPa and 700 hPa vector wind and specific humidity; 500 hPa height; 850 hPa vertical velocity; and precipitable water are obtained from the reanalysis products. The data sets are obtained at a daily temporal resolution from 1979 to 17 July 2021. Precipitation data is obtained from ERA5, for the same period, since the horizontal resolution is relatively higher (i.e., 0.25° longitude and latitude). The decision to use daily data set for the complete years considered is because even though CTs might exhibit some seasonality,

they are nevertheless not confined to occurring at any season. Moreover, in line with the research design, though on average, boreal summer (MJJA) is when Germany receives its highest precipitation amount, February to April are not exempted to experience flood, due to heavy rainfall coupled with snowmelt. For example, the 2006 European floods: which resulted in the overflowing of the Elbe and the Danube River. However, the annual cycle of the selected classified CTs is examined to determine their dominant seasons.

The regional extent designated as Western Europe used to classify the CTs is 20°W to 19°E, and 25°N to 60°N. To the west, parts of the North Atlantic Ocean are captured; to the east, part of landmasses where the continental airmass passes through, towards eastern Germany are captured; to the south, parts of the Mediterranean Sea are captured; and to the North, parts of the North Sea, Baltic Sea, and the mid-latitude cyclones, during their equatorward track, are captured. The geographical features in these regions contribute to defining the patterns of atmospheric circulation that can influence precipitation in Germany. The classification process is the same as applied in Ibebuchi (2021a) in the regional context of southern Africa. The SLP data sets are first represented in T-mode and standardized to give equal weight to all days. A correlation matrix is used to relate the days in the analysis period. Singular value decomposition is used to obtain the eigenvectors, eigenvalues, and PC scores. The eigenvectors localize in time the pattern captured by the PC scores (Compagnucci and Richman 2008). The eigenvectors are postmultiplied by the square root of the corresponding eigenvalues to obtain the PC loadings. Oblique rotation is used to simplify the PC loading (i.e., by making the near-zero loadings closer to zero) so that each retained component clusters a unique number of days with similar spatial patterns (Richman 1986). The oblique rotation also relaxes orthogonality constraints so that the PC scores can be correlated. This is desirable given that the atmospheric circulation pattern is a continuum and not a system of well-separated classes. The components are rotated iteratively and obliquely using Promax at a power of 2 and above (i.e., $k = 2, 3…$) and also retaining 4 PCs and above (i.e., PC4, PC5…). In each case, the patterns are tested for realism by matching them with the underlying patterns in the correlation matrix using the congruence coefficient. A good congruence match (i.e., > 0.93) for all the retained components is the first criterion in deciding components to retain and the Promax solution to adopt in rotating the PC loadings to fit the correlation structure. However, since extreme events and some vital climatic patterns can be rare patterns (with moderate PC loadings), so that they are usually captured by components explaining relatively less of the variance in the data (e.g., Preisendorfer et al. 1981), discarding such components might not benefit the purpose of this present study that seeks to detect such extreme rare patterns. Thus, for the higher components (i.e., up to the 9th component), it is probed if they are of added value for the research design by investigating if their synoptic characteristics reflect above-average rainfall in Germany and if the patterns of the CT classified from the components can be reproduced in the days the CTs tend to be dominant/persist according to the classification scheme. While no classification is a truth (Huth et al. 2008), these approaches tend to ensure that patterns that benefit the research goal are not discarded; and patterns that are within the noise spectrum are not included. Thus, when analyzing the classified map types, physical and dynamical understanding of the composites of ocean–atmosphere parameters in the study region is incorporated in deciding if the patterns have a physical foundation (e.g., Behera et al. 2003).

The absolute value of the PC loadings is an important signal and presents the amplitude of the pattern at a given time. PC loadings that are near-zero contribute weakly to the PC scores (Compagnucci and Richman 2008) and can be discarded as noise (Richman and Gong 1999). For each retained component, a hyperplane threshold value of ± 0.2 (Richman and Gong 1999) is used to further cluster days above and below the threshold, thus separating noise from the signal. This step increases the similarity of the days grouped under a given class while maintaining the probability of group membership so that overlapping of the classification is allowed. The mean SLP of the days grouped under a given class is the CT.

CTs that have a high probability of being associated with above-average rainfall in Germany are selected based on Eq. 1 and by investigating the number of grid points that can receive above-average rainfall during the active period of the CTs. In the latter case, a precipitation composite anomaly was calculated at each grid in Germany as the difference between the dominant/active season of a given CT and the climatology of the season (e.g., Ibebuchi 2021a). Statistical significance of the anomaly is tested using the permutation test at a 95% confidence level.

$$P_{w_i} = \frac{w_i}{N_i} \times 100 \quad i = 1 \dots n \tag{1}$$

N_i is the total number of days clustered under a given CT. P_{w_i} is the percentage of heavy wet days, i.e., count of days with daily precipitation amount > 10 mm, > 20 mm, up to 60 mm (e.g., Deumlich and Gericke 2020) in a given CT; w_i are the total number of heavy wet days for the CT in question and n is the number of CTs classified.

The NAO and AO indices are obtained from https://www.ncdc.noaa.gov/teleconnections/ for the 1979–2020 period. A seasonal correlation was done between the indices and the PC loadings of the selected wet CTs. Statistical significance of the correlations is done using the Kendall Tau-b

test at a 95% confidence level. The aim is to investigate if the teleconnections are related to the occurrence of CTs over time. The trend in the annual frequency of occurrence of the wet CTs is done and tested for statistical significance using the Mann–Kendall (Mann 1945; Kendall 1975) test a 95% confidence level.

3 Results and discussion

Figure 1 shows the classified CTs in Western Europe by applying the classification scheme independently to the ERA5 and NCEP SLP data. It can be seen that irrespective of the choice of the reanalysis product, the CTs were obtained with a one-to-one correspondence. For each retained component from the two data sets, the congruence coefficient between the scores indicated an excellent match (> 0.97). Thus, the classified CTs are robust from the two reanalysis products. The CTs highlighted by the black frame have higher probabilities to occur (Table 1). CT1 + is close to the climatological mean of SLP variability in the study region since it is the most frequent CT, followed by CT3 +. Since the classified days can overlap in more than one class, more than one CTs can be assigned to a day which logically implies the CTs that occurred on the day in question (e.g., Ibebuchi 2021b). The CTs highlighted by the black frames can be interpreted as the dominant states of the atmosphere and thus they tend to significantly overlap with other CTs. For this reason, the percentages in Table 1 do not add up to 100%.

Type 1 (i.e., CT1 + /CT1 −) being close to the mean pattern is very crucial since its alteration can significantly

Fig. 1 Circulation types classified in the study region from the ERA5 (left panels) and NCEP-NCAR (right panels) data sets for the 1979–2021 period. The CTs highlighted in thick black frames are the patterns with a higher probability to occur. CTs highlighted in red frames are the patterns with a higher probability of being associated with above-average rainfall in Germany
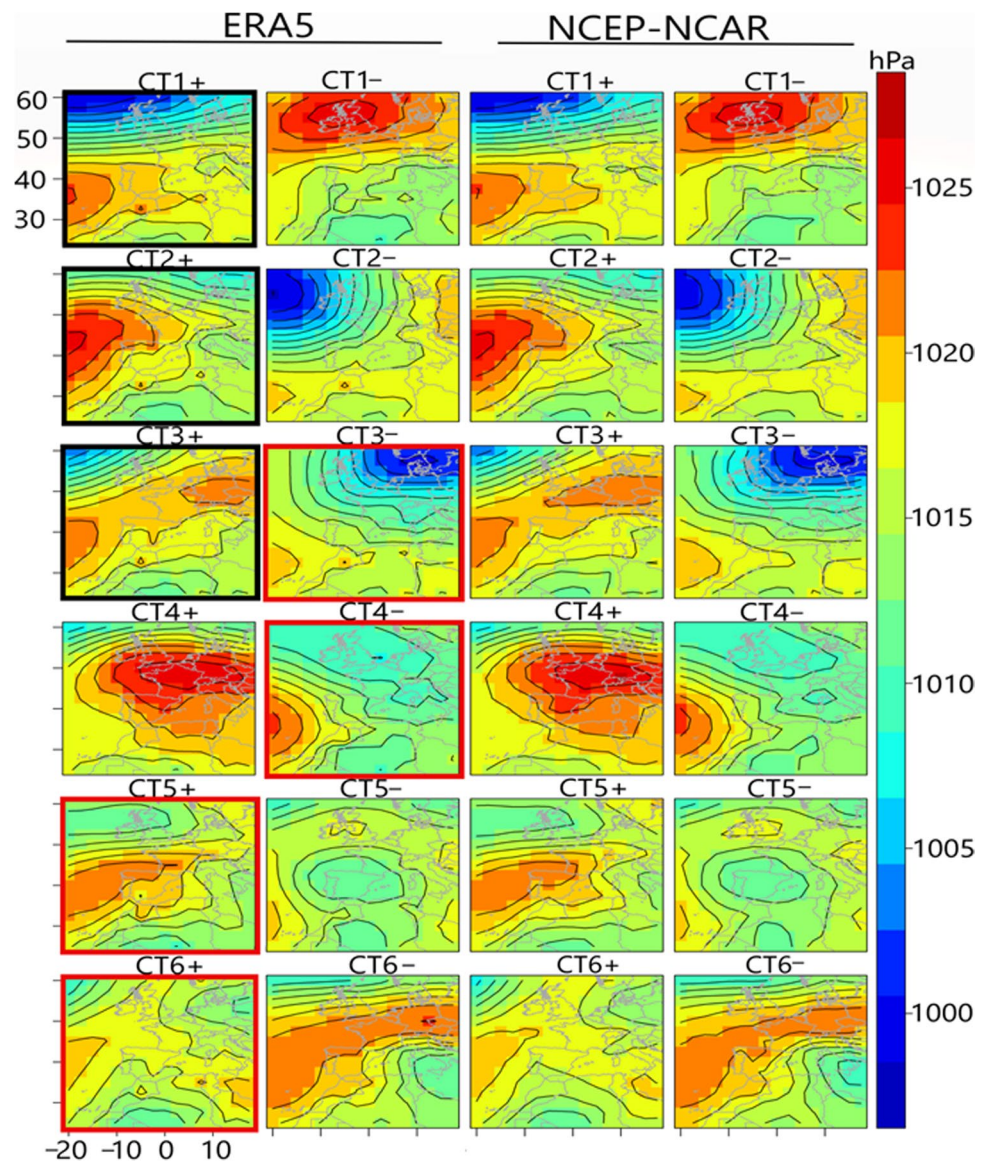
**Table 1** Probability of occurrence of the classified circulation types for the 1979–2021 period

CT	Probability of occurrence (%)
CT1+	59.6
CT1−	22.8
CT2+	46.7
CT2−	23.7
CT3+	51.5
CT3−	14.9
CT4+	19.3
CT4−	30.9
CT5+	4.74
CT5−	11.56
CT6+	5.57
CT6−	7.03

impact the mean state of the atmosphere and to how extent the signal of other CTs are expressed. Figure 2a shows that during CT1 +, the North Atlantic anticyclone is stronger in driving westerly moisture fluxes towards Western Europe.

As a result, from Fig. 2b enhanced precipitation is relatively observed in Germany. The western parts that are closer to the Ocean receive more rainfall compared to the northeastern parts that are farther away. Also, the westerly moisture fluxes penetrate the Alpine regions (i.e., the southernmost tips), leading to rainfall formation, coupled with snowmelt in the mountainous regions. Under CT1 −, a reversed condition can be observed. An anticyclone dominates towards the high latitudes. Dry northerly winds emanating from the anticyclone penetrate northern Germany. The mean wind over the North Atlantic Ocean is rather easterly. As result, from Fig. 2b, the central and northern parts of Germany are relatively dry. Thus, Fig. 2 shows that on average, at the synoptic scale, precipitation formation (suppression) in Germany is linked to moist westerly (dry northerly) fluxes that penetrate the landmasses. It should be noted that CT3 + which is the next to the most frequent pattern after CT1 + is a dry CT. Thus, it acts as a buffer in keeping the mean state of the atmosphere in Germany from being constantly wet.

Correlation analysis between the PC loadings of Type 1 and the NAO and AO indices is statistically significant

Fig. 2 Composite of SLP (color) and 850 hPa moisture flux (black vectors) (**a**), and precipitation (**b**) during the active periods of CT1 + and CT1 −. Composites of variables used to characterize large-scale circulations in all figures are obtained from NCEP-NCAR
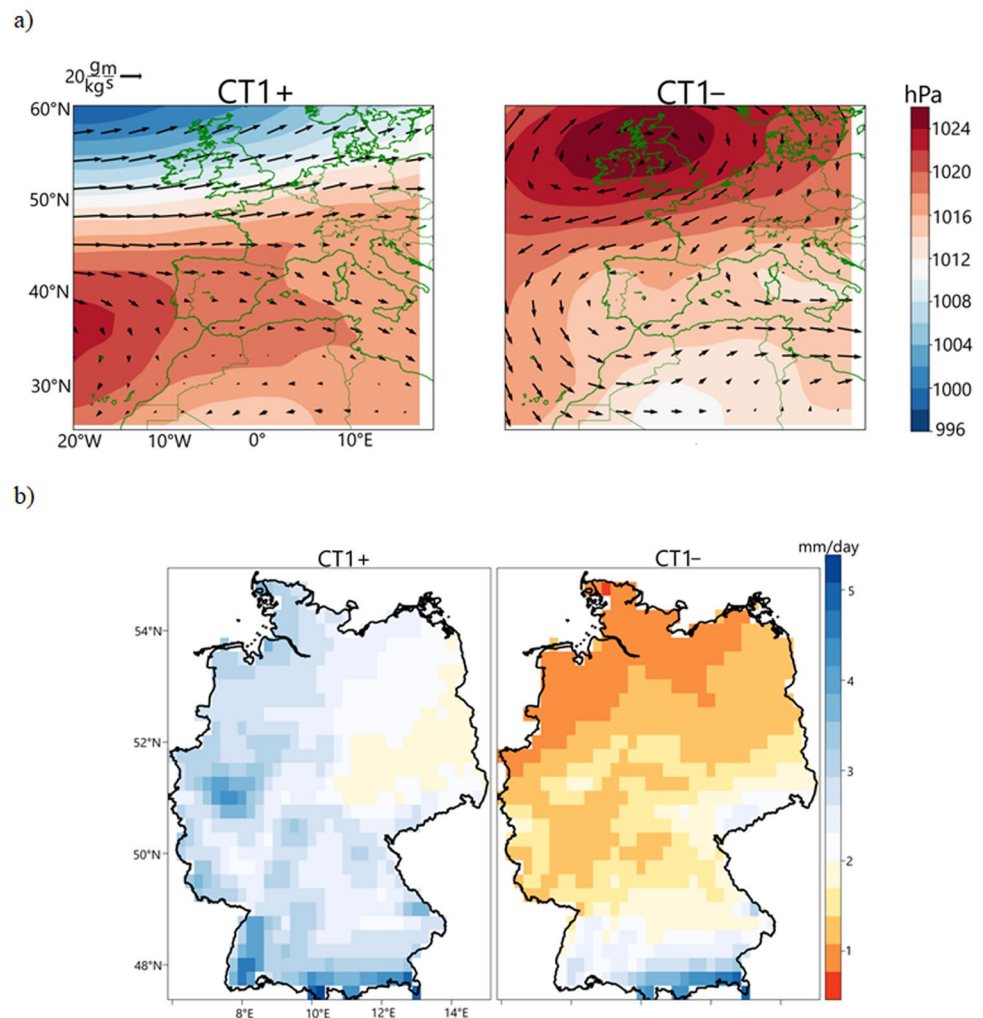
on the annual scale (not shown) but strongest during boreal winter (Fig. 3). During boreal winter, the correlation is higher for NAO (i.e., $R = 0.70$ from NCEP, and $R = 0.71$ from ERA5) compared to the AO (i.e., $R = 0.65$ from NCEP and $R = 0.63$ from ERA5). Figure 3 shows the time series of the loadings of Type 1, the AO, and the NAO indices during boreal winter. The result shows that relatively, the NAO is more related to the mode of variability that is close to the mean state of atmospheric circulation in Western Europe, especially during boreal winter. Since during positive (negative) NAO, westerly (northerly) winds bring wet (dry) conditions to Germany, the strong relationship between NAO and Type 1 is physically realistic.

Figure 4 shows the probability of each of the CT to be associated with heavy wet days in Germany. It should be noted that since more than one CTs can occur in a day, it is only rational that a wet CT will not be expected to bring wet conditions on every instant it occurs. Rather in line with the continuum nature of circulation patterns, a wet CT will bring wet conditions when the atmospheric condition favors/amplifies the expression of its wet signal. This is the reason why characterizing a wet CT is based on probability (Eq. 1). Figure 4 shows that CT3 −, CT4 −,

CT5 +, and CT6 + have higher chances to be associated with above-average rainfall in Germany when they occur. When higher threshold values (i.e., 20 to 60 mm) are used to characterize heavy wet days, similar results as in Fig. 4 are obtained. The major difference is that the probability of such higher extremes in rainfall becomes relatively less, compared to when the 10 mm threshold is used. Also, the criterion used in deciding the wet CTs is based on the relative number of grid points with statistically significant positive rainfall anomalies during the active period of the CTs. Thus, CT3 −, CT4 −, CT5 +, and CT6 + are further referred to as wet CTs. They are highlighted by the red frame in Fig. 1. During the active period of the wet CTs, Fig. 5 shows their SLP and 850 hPa moisture flux composites; Fig. 6 shows their 700 hPa moisture flux and 500 hPa height composites; Fig. 7a and b show the vertical velocity and precipitable water composites, respectively; and Fig. 8 shows the grid points that can be associated with above-average rainfall during their active periods. The aforementioned composite maps will be interpreted accordingly.

The selected CTs are not constrained to occur at any specific season(s); nonetheless, from Fig. 12 in the Appendix, they might tend to be dominant at specific periods. The

Fig. 3 Time series of the loadings of Type 1 (CT1 +/CT1 −) from ERA5, NCEP-NCAR; the Arctic Oscillation, and the North Atlantic Oscillation indices during boreal winter for the 1979–2020 period. Time series are computed as the DJF mean values
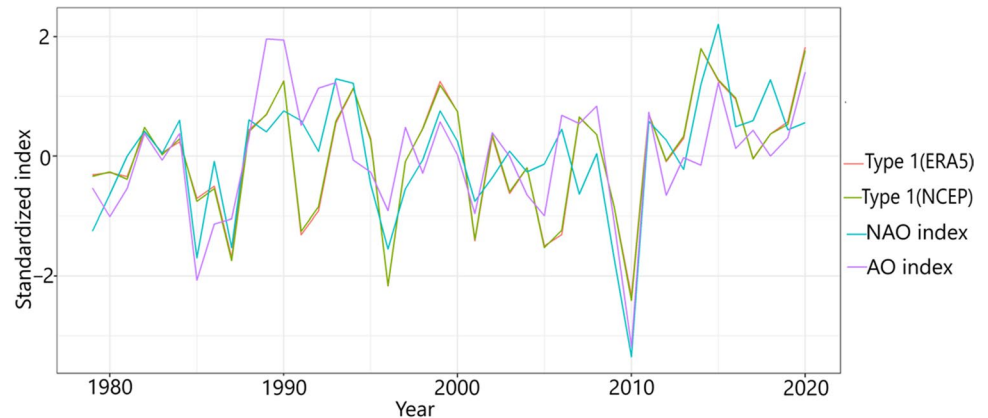

Fig. 4 Probability of heavy wet days (daily rainfall amount > 10 mm) associated with each of the classified circulation types
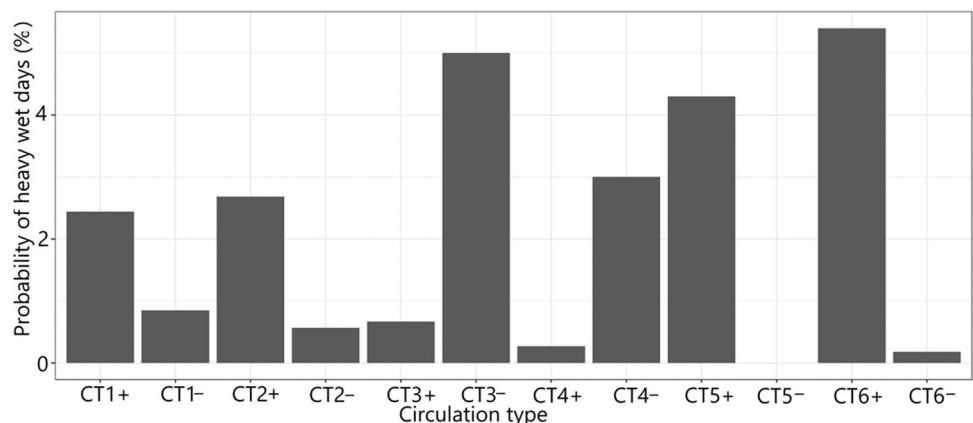
Fig. 5 Same as Fig. 2a but for the circulation types highlighted in Fig. 1 by the red frames that can be associated with above-average rainfall in Germany
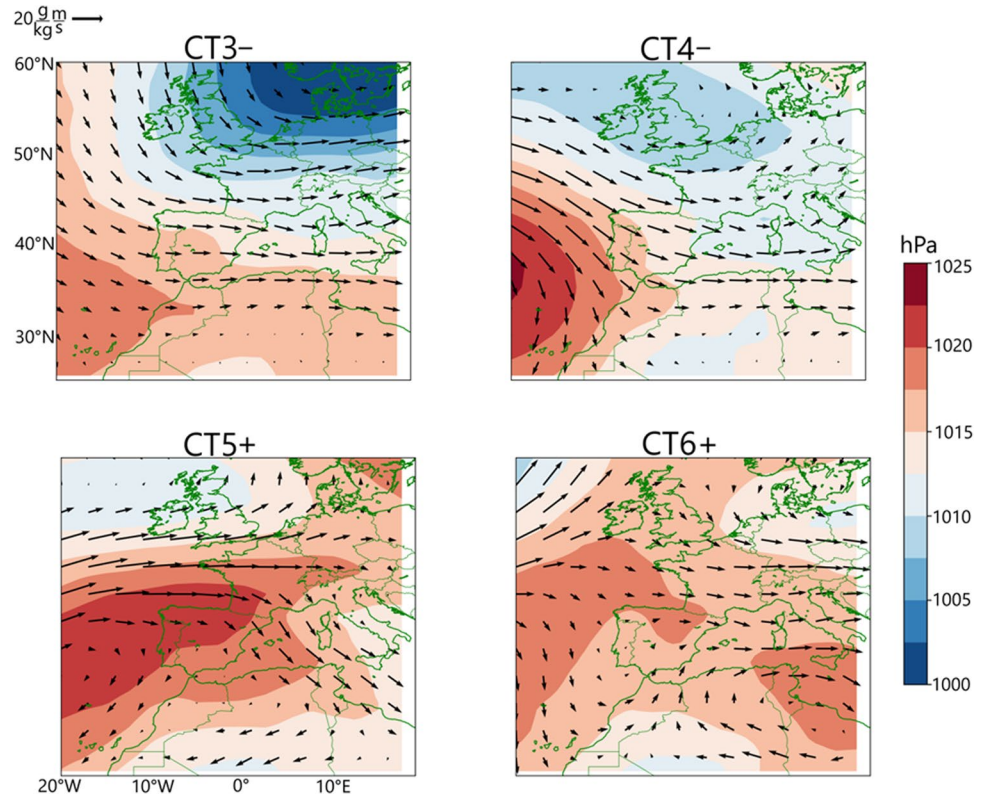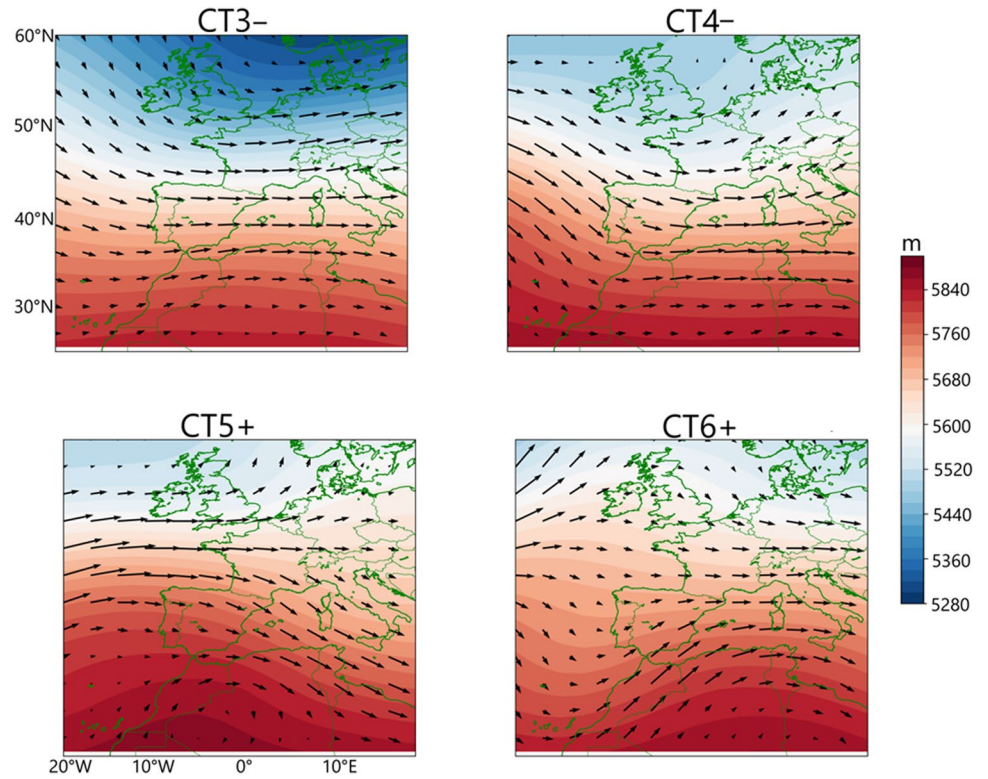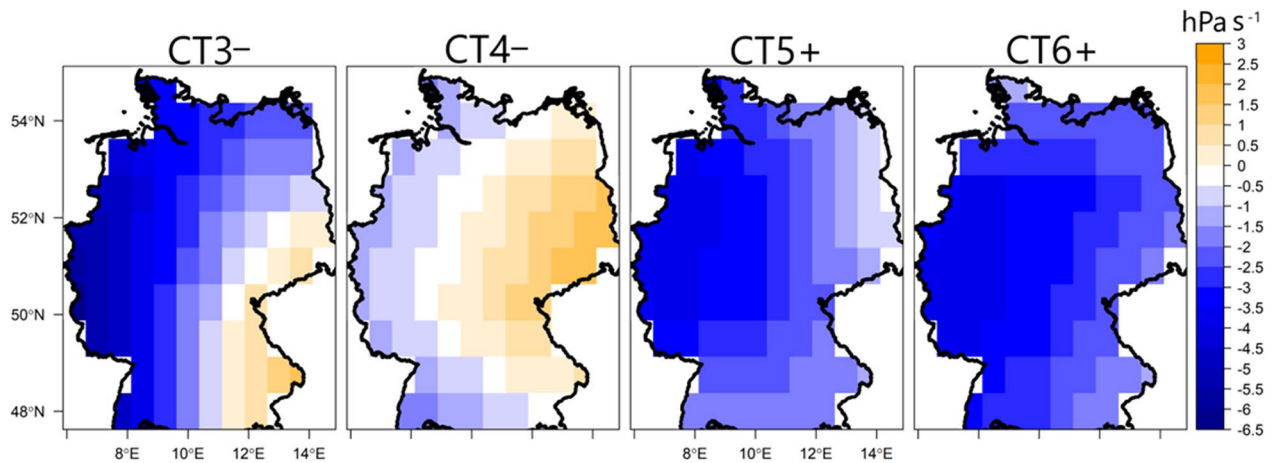

Fig. 6 Composite of 700 hPa moisture fluxes (black vectors) and 500 hPa height (color) for the selected CTs that can be associated with above-average rainfall in Germany
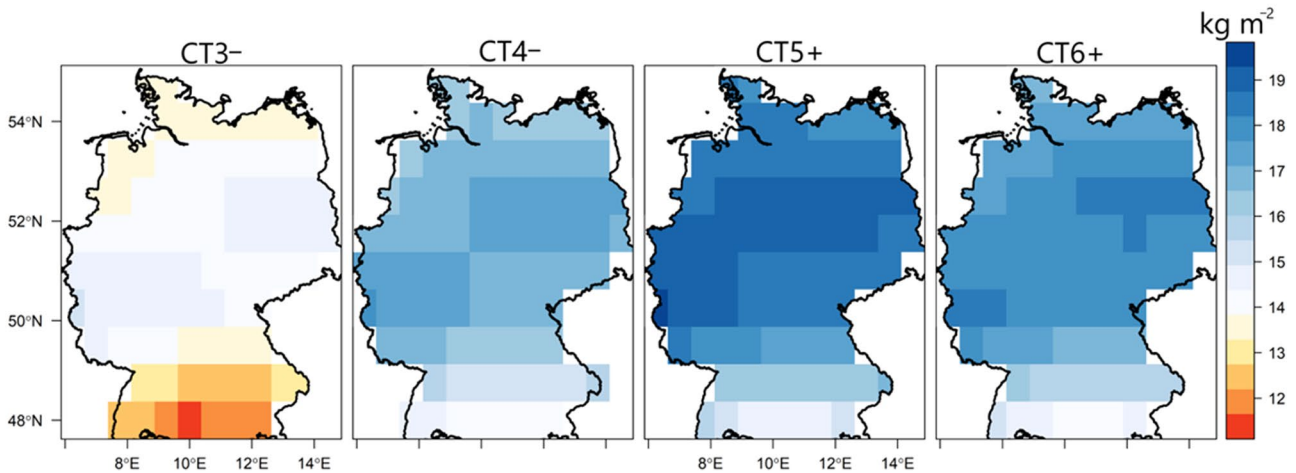
a)

b)

Fig. 7 Composites of vertical velocity (**a**) and precipitable water (**b**) for the selected CTs that can be associated with above-average rainfall in Germany. Negative (positive) values of vertical velocity imply upward (downward) motion

overall characteristics of the wet CTs are they are associated with westerly moisture fluxes over the North Atlantic basin (Figs. 5 and 6), and negative vertical velocity (i.e., upward vertical motion) at the western parts of Germany (Fig. 7a). Precipitable water values, used to characterize the amount of moisture in the atmosphere, tend to show some seasonality—higher (lower) for CTs dominant in boreal summer (winter) (Fig. 7b).

CT3 − is dominant during late boreal autumn to early boreal spring (Fig. 12 in the Appendix). From Fig. 5, during its active period, a strong cyclonic system dominates over the mid-latitudes (i.e., the North Sea and Baltic Sea) and large parts of northern Europe. From Fig. 6, at 500 hPa, the height is lower over the aforementioned regions, suggesting divergence aloft. The North Atlantic anticyclone shifts

equatorward and a pressure gradient is created between it and the mid-latitude cyclonic system. Northwest fluxes of moisture (up to 700 hPa) prevail towards Western Europe. From Fig. 7a, upward vertical motion can be seen in the western parts of Germany. As a result, large parts of central to southwestern parts of Germany are likely to receive above-average rainfall (Fig. 8). From Table 2 and Table 3, Type 3 (i.e., CT3 +/ CT3 −) is significantly related to the NAO and the AO at all seasons.

CT4 − tends to be dominant from late boreal spring to boreal summer. Also, from Table 1, it is relatively a frequent pattern. Figures 5 and 6 show that under CT4 − the westerly moisture fluxes are diverted by the mid-latitude cyclone that stretches over northwestern Europe, especially over the North Sea. Thus, westerly moisture fluxes penetrate

Fig. 8 Precipitation composite anomaly during the active period of the CTs that can be associated with above-average rainfall in Germany. Composite anomalies are calculated as the difference between the mean precipitation of the season when the CT in question is dominant and the climatology of precipitation in the season. The blue dots show grid points that can be associated with above-average precipitation during the active period of the CT in question. Only statistically significant values are plotted based on the permutation test at a 95% confidence level
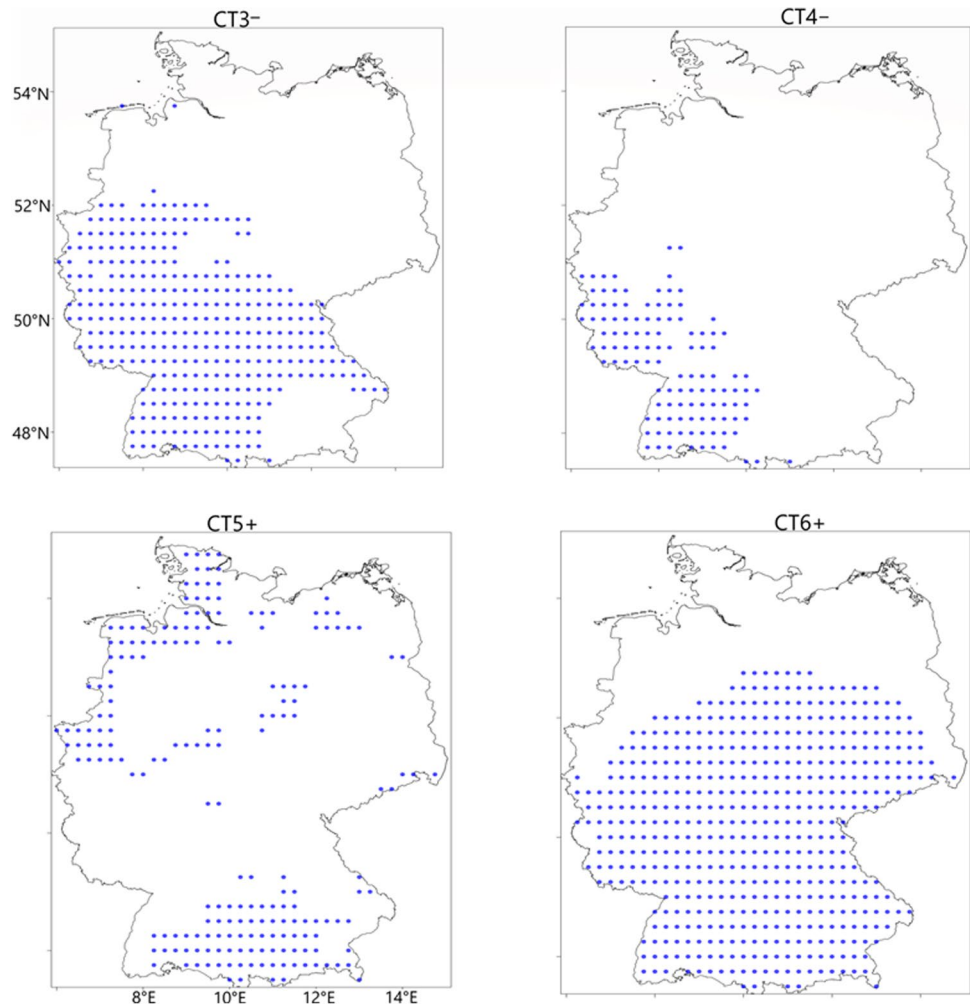
Table 2 Seasonal correlation between the loadings of the CTs associated with above-average rainfall in Germany and the Arctic Oscillation index. Only statistically significant values based on the Kendall Tau test are reported. (-) implies that the correlation is not statistically significant at a 95% confidence level. The analysis period is 1979–2020

Type	DJF	MAM	JJA	SON
		ERA5		
3	0.47	0.48	0.47	0.60
4	-	-	-	-
5	-	− 0.43	− 0.58	− 0.34
6	-	-	-	-
		NCEP-NCAR		
3	0.41	0.49	0.59	0.61
4	-	-	-	-
5	-	− 0.44	− 0.58	− 0.32
6	-	-	-	

Table 3 Same as Table 2 but for the North Atlantic Oscillation index

Type	DJF	MAM	JJA	SON
		ERA5		
3	0.50	0.60	0.47	0.33
4	0.43	0.41	0.31	0.41
5	-	− 0.46	-	-
6	-	-		
		NCEP-NCAR		
3	0.46	0.61	0.55	0.36
4	0.44	0.39	0.31	0.40
5	-	− 0.38	-	-
6	-	-	-	-

more into the southwest of Germany. Hence, upward motion is enhanced at the southwestern parts of Germany (Fig. 7)

that is likely to receive above-average precipitation (Fig. 8). Type 4 (CT4 + /CT4 −) is also related to the NAO. However, in this case, the positive NAO relates with CT4 + that is associated with strong anticyclonic conditions over Western Europe and so suppressed rainfall. Positive NAO constrains CT4 − which is dominant during warmers seasons. In the

regional context of the UK, a similar result was reported by Bladé et al. (2012) whereby during boreal summers, high NAO triggers negative rainfall over the UK.

CT5 + tends to be dominant from April to August. It exceptionally dominates during May and then July. Unlike during CT4 −, the North Atlantic anticyclone shifts further north. Similar to CT4 −, the mid-latitude cyclone over the North Sea still tends to disorientate the westerly moisture fluxes towards Germany that appears scattered, penetrating parts of southwestern and northwestern Germany. Upward motion is higher in the western parts of Germany compared to the other aforementioned wet CTs. Perhaps the irregular penetration of moisture fluxes into Germany under CT5 + results in the irregular grouping of regions likely to receive above-average precipitation (Fig. 8). The SLP pattern of CT5 + resembles a tripole pattern over the North Atlantic and parts of Western Europe. The anticyclonic system is situated between the mid-latitude cyclone and the cyclone over the Mediterranean. Averaged over Germany, precipitable water values, is relatively highest under CT5 +, which can be linked to warmer atmospheric conditions. During boreal spring, Type 5 is negatively related to the NAO and with the AO at all seasons except during boreal winter (Table 2 and Table 3).

CT6 + has the highest probability of being associated with heavy rainfall in Germany. It is dominant from April to September. It exclusively dominates during April and May. From Figs. 1, 5, and 6, it appears that during CT6 +, the Mediterranean is warmer, resulting in cyclogenesis that triggers the North Atlantic anticyclone to move more northward, displacing the mid-latitude cyclone further poleward, compared to CT4 − and CT5 +. Hence, a ridge spreads northwards over the North Atlantic basin and parts of Western Europe. A well-defined band of westerly fluxes of moisture penetrates Germany and other parts of northwestern Europe. Also, a cyclonic system is evident over the Baltic Sea (c.f. Figure 1), where northeast fluxes of moisture can be seen (Fig. 5). From Fig. 7, during CT6 + unstable atmospheric conditions (i.e., upward vertical motion) can be expected in large parts of Germany. Figure 8 shows that during the active period of this CT, large parts of Germany are expected to receive above-average rainfall. Since from Fig. 8, above-average rainfall might not be expected in the northeastern parts of Germany, it is plausible that the moisture flux from the Baltic Sea is probably too small to trigger heavy rainfall outside of the coast. According to Portmann et al. (2020), Mediterranean cyclogenesis normally correlates with ridge building over the North Atlantic, followed by anticyclonic Rossby wave breaking over Europe. Moreover, during 2016, the warming of the Mediterranean was predicted to be accompanied by heavy rainfall in Germany (Zeit Online 2021).

From Table 4, it can be seen that averaged over Germany, unstable atmospheric conditions can be expected to be highest under CT6 + and lowest under CT3 −. The ranking of the wet CTs based on the probability of heavy wet days over Germany (c.f. Figure 4) and the number of grid points that can be expected to receive above-average rainfall during the active period of the CTs (c.f. Figure 8) correlate also with vertical velocity values over Germany (Table 4). The correlation implies that enhanced upward vertical motion, both in magnitude and spatial scale, can lead to higher probabilities of heavy rainfall in large parts of Germany.

Figure 9 shows the time series of the annual frequency of occurrence of the CTs from 1979 to July 2021. A negative significant trend was found in CT3 − from ERA5 (p value < 0.05) but not from NCEP. No trend was found in the other CTs. It should be noted that Figs. 9 and 10 are still biased for 2021 pending when the data for the full year is available and analyzed. Nevertheless, CT6 + indicates to have been more frequent in 2021 relative to most of the other past years.

Figure 10 shows the time series of the loadings/amplitude of the CTs from 1979 to July 2021. A spike can be seen also in the amplitude of CT6 + suggesting that it did not only tend to occur frequently during 2021 but with stronger amplitude. However, it might be argued that the other remaining months of the year might be a buffer to the amplitude and the spike is not linked to the 2021 heavy rainfall; to investigate further, Fig. 13 in the Appendix shows the time series of the PC loadings but for the January to June mean values from 1979 to 2021. It can be seen that even within this time frame (that is more representative of the signal of CT6+, during the analysis period in 2021, relative to the other past years), a spike in the amplitude of CT6 + is evident from both reanalysis data sets. Thus, it can be inferred that CT6 + was more frequent with stronger amplitude during the 2021 heavy rainfall episode. Based on the classification scheme, the composite of SLP and 850 hPa moisture flux, 500 hPa height, and 700 hPa moisture flux, for two occasions when CT6 + lasted for at least a day, are exemplified. Figure 11 shows the composites for 6 to 7 June 2021, and 14 to 15 July 2021. During these periods, despite the continuum nature of atmospheric circulation at a given time, most of the synoptic features of CT6 + as presented in Figs. 1 and 5 can be

Table 4 Spatial median values over Germany of vertical velocity for the selected wet CTs	CT	Vertical velocity (hPas^{-1})
	CT3 −	− 2.45
	CT4 −	− 0.163
	CT5 +	− 2.42
	CT6 +	− 2.77

Fig. 9 Annual frequency of occurrence of the selected wet CTs from 1979 to 2021–07-17
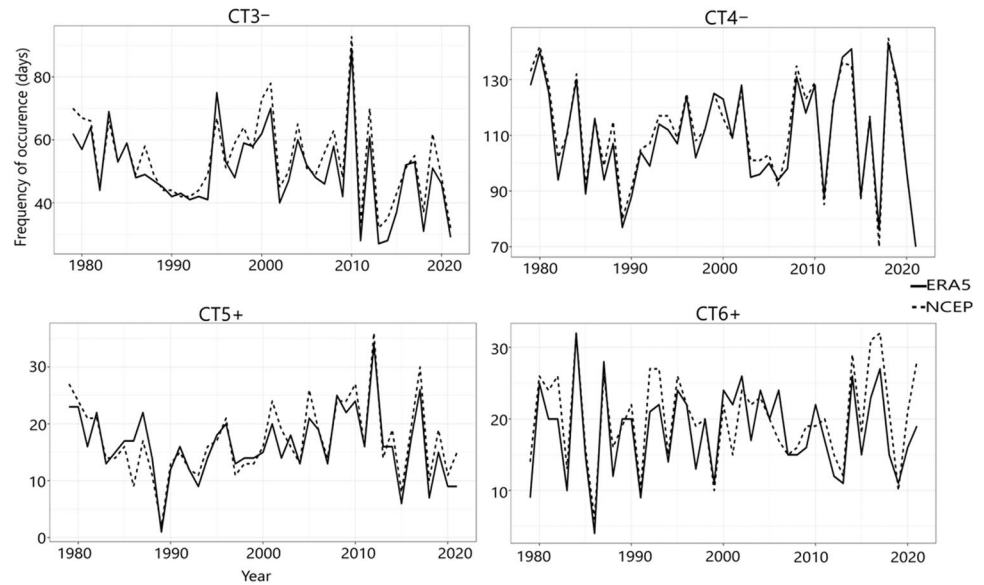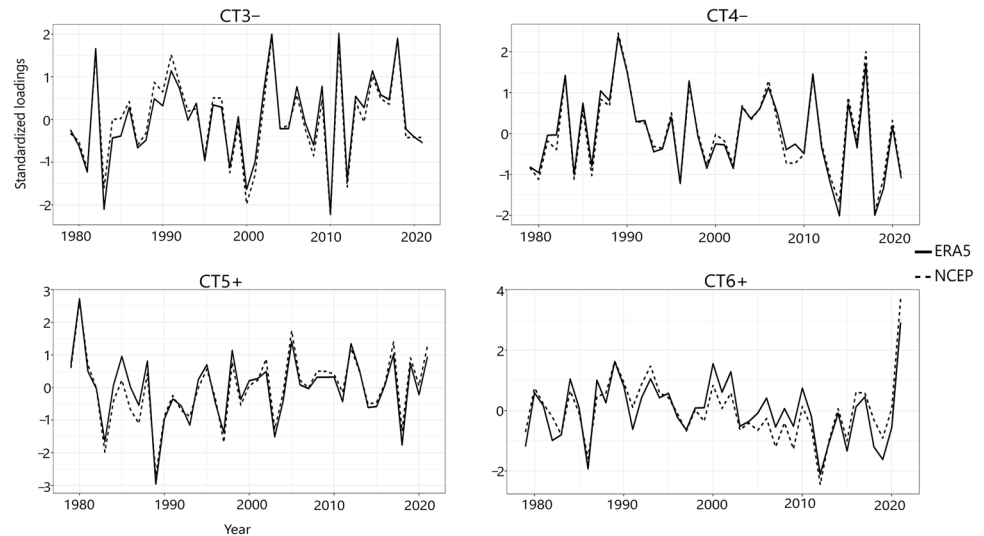

Fig. 10 Same as Fig. 9 but for the loadings/amplitude of the CTs

noticed. They were more evident during the July episode. For example, from Fig. 11a, the cyclonic system over the Mediterranean is enhanced and tracks northward, shifting the North Atlantic anticyclone further north. This results in a further poleward displacement of the mid-latitude cyclone over the North Sea, allowing westerly moist winds to penetrate Western Europe with the inclusion of Germany. Also, a cyclonic system is evident over the Baltic Sea, driving northeast moist winds into Germany. From Fig. 11b, at 500 hPa, a cut-off low is evident over central Europe. The cut-off low is also associated with divergence over parts of the North Atlantic Ocean and the Mediterranean. Thus, the westerly fluxes penetrating Germany are weak compared to Fig. 5 (in the climatology of CT6 +), since the low tend to

be stationary and imply moisture convergence (i.e., vertical convention). Thus, coupled with the cut-off low, the implication of CT6 + during the July 2021 heavy rainfall episode can be summarized as (i) enhanced surface warming (i.e., enhanced cyclonic activity) over the Mediterranean and also enhanced cyclonic activity over the Baltic Sea; (ii) a further implication of (i) is that a warmer atmosphere can hold more moisture so that above-average rainfall can be expected when conditions are favorable; (iii) the northward track of the North Atlantic anticyclone, leading to further displacement of the mid-latitude cyclone over the North Sea, implies that more westerly moisture fluxes from the North Atlantic can penetrate Western Europe; (iv) the cut-off low that through its circulation can enhance the penetration of

Fig. 11 SLP (color) and
850 hPa moisture flux (black
vectors) composites (**a**), and
500 hPa height (color) and
700 hPa moisture flux (black
vectors) composites (**b**), for 6
June to 7 June 2021, and for
14 July to 15 July 2021. The
dates are when CT6 + persisted
according to the classification in
this work
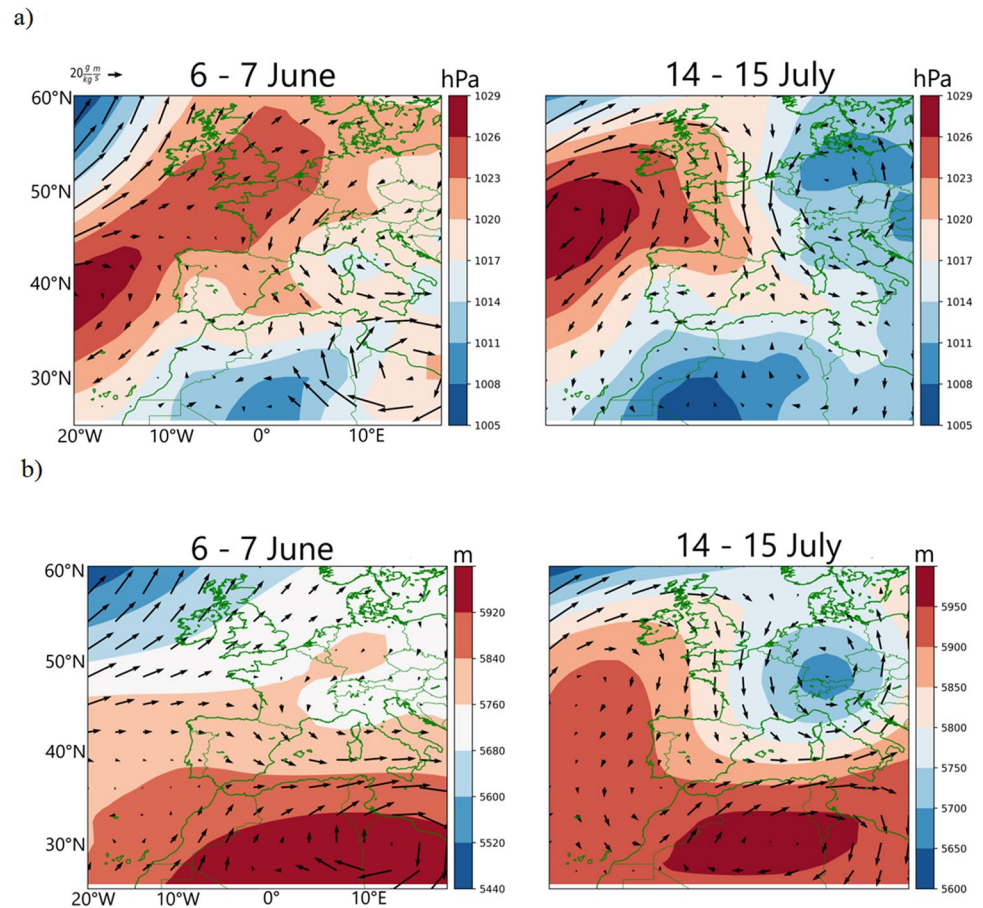
moisture from the Mediterranean and the Baltic Sea into parts of the European landmasses, favors convergence with the westerly moisture fluxes.

Finally, for the July 2021 flood episode in Germany, topographic influences at the western mountainous regions can contribute to heavy rainfall, at preferred regions (e.g., watercourses); for example, due to forced upward vertical motion, that is evident in some western parts of Germany during the active period of the wet CTs (Fig. 7a). Urbanization leading to an increase in impermeable surfaces can impact the absorption capacity of soils in the region so that coupled with antecedent soil moisture content, soils might become saturated when heavy rainfall persists for a given time. Thus, to ascertain to how extent greenhouse gas emissions contributed to the flood, inter-annual to decadal variations in the CTs, which this study has shown can be a function of anomalies in climatic modes such as the NAO; in addition to land-use changes that alter absorption capacity of soils need to be considered equally. Indeed, previous studies that applied CT analysis to separate wet and dry signals in other regions and further examined the impact of anthropogenic climate change on the CT signals found that anthropogenic climate change can impact the frequency of occurrence and amplitude of the CT signals (e.g., Ibebuchi 2021a, c). Thus,

while this study is based on state-of-the-art methods, future analysis will incorporate an ensemble of high-resolution GCMs to examine the impact of anthropogenic climate change on the wet CTs.

4 Conclusions

This study applied an eigenvector-based clustering technique to isolate time series when specific patterns of large-scale atmospheric circulation occurred in Western Europe. The relationship between the classified CTs and teleconnections was investigated. CTs that can be associated with above-average precipitation in Germany were analyzed, in addition to the large-scale circulation features during their active periods. It was found that on average, enhanced westerly moisture fluxes driven by the North Atlantic anticyclone can be associated with precipitation formation in Germany. The NAO was found to be the major teleconnection that is related to the variations of most of the CTs over time. During warmer seasons, it was found that the extent to which the North Atlantic anticyclone displaces poleward, the mid-latitude cyclone over the North Sea, influences the rate and strength of westerly moisture fluxes that penetrate

Germany. Overall, westerly moisture fluxes coupled with unstable atmospheric conditions favor above-average rainfall in preferred regions in Germany. CT6 + that was found to be associated with the highest probability to bring above-average rainfall in large parts of Germany is associated with enhanced cyclonic activity over the Mediterranean region and the Baltic Sea; northward track of the North Atlantic anticyclone, ridging over Western Europe; this results in a band of westerly moisture fluxes penetrating Germany, and northeast moisture fluxes from the Baltic Sea. In 2021, the frequency and amplitude of CT6 + were found to spike. The results suggest that coupled with the cut-off that formed over central Europe during the July 2021 flood episode, an increase in the frequency and amplitude of CT6 + contributed to the 2021 heavy rainfall.

Appendix
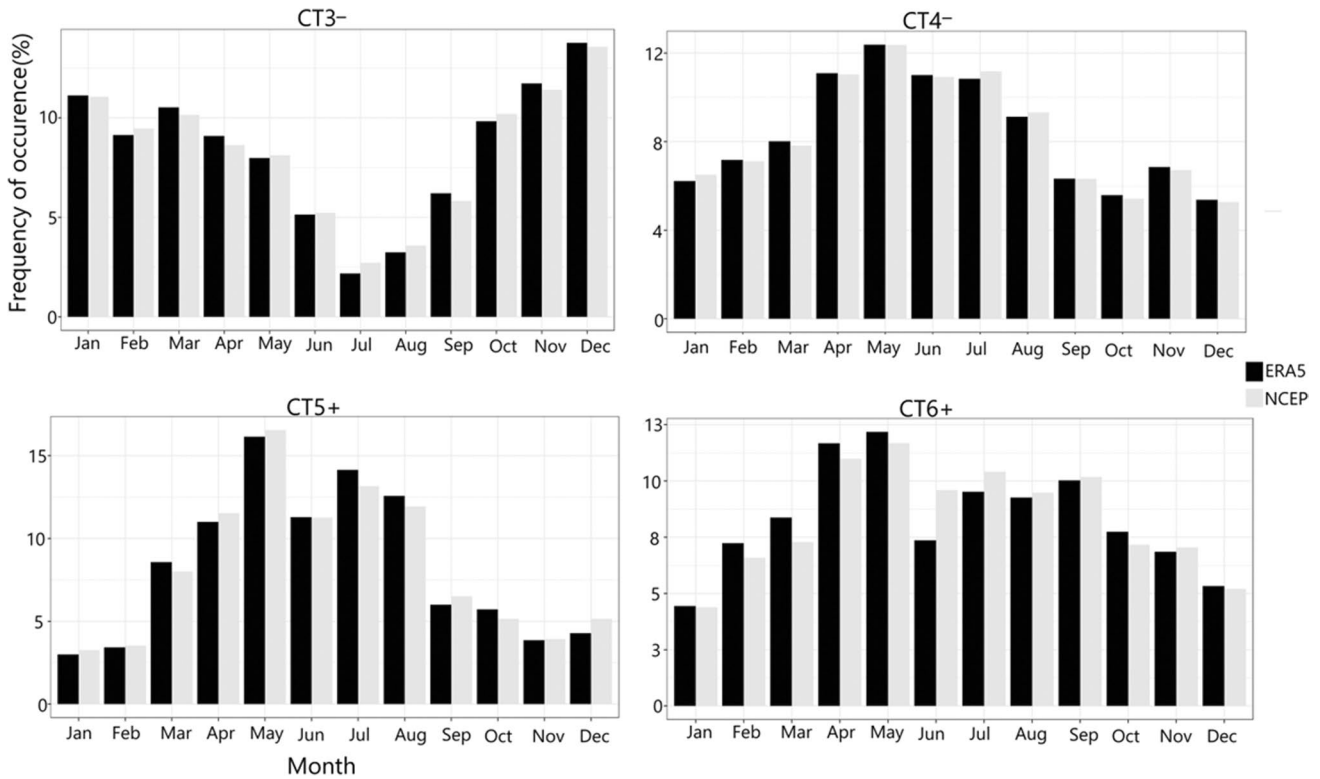
Fig. 12 Annual cycle of the CTs associated with above-average rainfall in Germany

Fig. 13 Time series of the mean January to June loadings of CT6 + for the 1979–2021 period
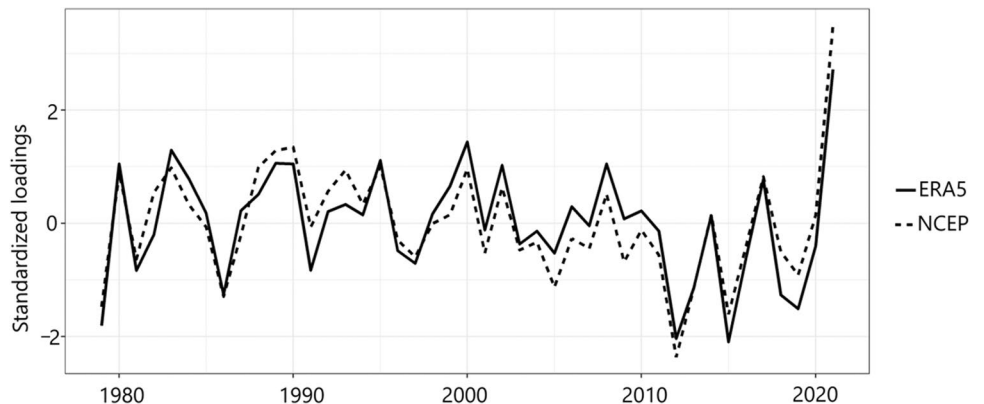
Data availability The NCEP-NCAR reanalysis and CPC precipitation data sets are available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. ERA5 data are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset.

Code availability R studio was used for coding the methods as described in the methodology section. The codes are base packages in R (e.g., the PROMAX routine).

Declarations

Ethics approval No human subject is involved in this study and the figures belong to the author. The paper is also not under consideration in any Journal. There is also no conflict of interest in this paper.

Consent to participate No human research is used. The author consents this paper to be considered.

Consent for publication The author consents this paper to be published.

Conflict of interest The author declares no competing interests.

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