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Discussions

The European 2015 drought from a climatological perspective

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Abstract.
The summer drought of 2015 affected a large portion of continental Europe and was one of the most severe droughts in the region since summer 2003. The summer was characterized by exceptionally high temperatures in many parts of central and eastern Europe, with daily maximum temperatures 2 °C warmer than the seasonal mean (1971-2000) over most of western Europe, and more than 3 °C warmer in the east. High evapotranspiration rates combined with a lack of precipitation affected the soil moisture content and vegetation stress and led to record low river flows in several major European rivers. This paper analyses the European summer drought of 2015 from a climatological perspective, including its origin, spatial and temporal development, and how it compares with the 2003 event. It discusses the main contributing factors controlling the occurrence and persistence of the event: temperature and precipitation anomalies, blocking episodes and sea surface temperatures (SST). Central Europe experienced during the summer of 2015 widespread areas of negative Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) values, present from May onwards. Similar to the summer drought of 2003, the upper level atmospheric circulation over Europe was characterized by a positive 500hPa geopotential height anomalies flanked by a large negative anomaly to the north and west (i.e. over the central North Atlantic Ocean extending to northern Fennoscandia) and another center of positive geopotential height anomalies over Greenland and northern Canada. Simultaneously, the summer SST was characterized by large negative anomalies in the central North Atlantic Ocean and large positive anomalies in the Mediterranean basin. The SST dipole-like anomalies between the central Atlantic and the Mediterranean Sea suggest a possible "atmospheric teleconnection" between the two regions, which in turn may affect the drought conditions over Europe. In an accompanying paper, the hydrological perspective of the summer 2015 drought is presented. Together, these two papers summarize a collaborative initiative of members of UNESCO's FRIEND-Water program to perform a timely Pan-European assessment of the 2015 summer drought.

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1 Introduction

Drought is part of the natural climate cycle and commonly affects large areas and lasts for several months or even years. It is a complex phenomenon that has wide ranging environmental and socioeconomic impacts and is globally considered to be one of the costliest natural hazards [Wilhite, 2000]. In Europe overall losses due to drought over the period 1998 – 2009 have been estimated to about 5000 billion Euros [EEA, 2010]. Drought affects all components of the hydrological cycle, from its origin as a deficit in precipitation, which combined with high evapotranspiration losses can lead to deficit in soil moisture and subsequently can manifest itself as a hydrological drought, i.e. deficits in streamflow and groundwater [Tallaksen and Van Lanen, 2004]. Consequently, drought can cause a wide range of impacts affecting the environment, society and economy, where impacts on agriculture and public water supply are most frequently reported [Stahl et al., 2016]. Prolonged droughts with severe impacts, such as the major drought in 2003, have highlighted Europe's vulnerability to this natural hazard and alerted governments, stake holders and operational agencies to the disastrous effects droughts may have on the society and economy, including the need for mitigation measures [EEA, 2001, 2010; EC, 2012].

The year 2015 was characterized by one of the worst droughts recorded in Europe, particularly in the central and eastern part of the continent [Van Lanen et al., 2016]. The summer [June – July – August (JJA)] was the third warmest summer in Europe since 1910 (after 2003 and 2010) and August 2015 was the warmest month on record [NOAA, 2016]. This drought episode coincided with the warmest year on record, with a global temperature anomaly 0.90°C above the 20th century average [NOAA, 2016]. It was accompanied by a series of associated heat waves and air temperature records were broken in several locations in central and Eastern Europe. In some countries (e.g. Czech Republic), it was the second driest summer of the last 50 years, only 2003 had lower rainfall [Van Lanen et al., 2016].

Extreme low flows, especially over the central and eastern part of Europe, were recorded, reaching the lowest values in August (Figure 1). In central Europe (e.g. southern part of Germany, northern Austria, and Czech Republic), the return period of the annual minimum 7-day flow was more than 50 years [Laaha et al., 2016; Van Lanen et al., 2016]. For the main rivers in Germany (e.g. Elbe, Danube, Rhine), the low flow periods developing from May/June extended for more than three consecutive months (Figure 1). Some recovery was seen in November, but discharge was still low. The cumulative effect of persistent heatwaves, with long dry spells and high evapotranspiration, caused serious socio-economic impacts on different sectors like water supply, energy production, inland waterways, fisheries, tourism and recreation, agriculture and water quality [Laaha et al., 2016; Van Lanen et al., 2016]. As such, it is vital to study the governing processes and impacts of droughts from a combined climatological and hydrological point of view, and analyse how integrated knowledge from both disciplines can contribute to a better understanding and management of drought impacts.

The beginning of the 21st century has seen an increase in the frequency of prolonged droughts and heat waves in Europe, including the event of 2003 that affected large parts of central Europe. Other major events include the drought in 2008 over the Iberian Peninsula [Andreu et al., 2009], the drought and heat wave in Russia in 2010 [Barriopedro et al., 2011] and the spring drought of 2011 over western part of Europe. Overall losses due to drought in Europe over the period 1998 – 2009

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were estimated to be about 5000 billion Euros [EEA, 2010]. As the average global temperatures continue to rise, it is estimated that droughts will further intensify in the 21st century notable in certain seasons and areas, e.g. in southern and eastern Europe [Stagge et al., 2014], parts of North America, Central America, and southern Africa [Seneviratne et al., 2012; Orlowski and Seneviratne, 2012; Prudhomme et al., 2013; Wanders et al., 2015].

A better understanding of the spatial and temporal development of these major drought events, in particular their triggering mechanisms and persistence is vital to enable a better prediction of prolonged dry periods and extensive drought extent [Tallaksen and Stahl, 2014; Van Huijgevoort et al., 2013]. This includes the drivers of extreme drought periods and the association between droughts and climatic, oceanic and local factors such as land-atmosphere feedbacks, which may amplify the drought development [e.g. Whan et al., 2015]. Persistent dry (wet) conditions are usually associated with anticyclonic (cyclonic) circulation, while the sea surface temperatures (SST) can play also an important role via the interaction with large scale climatic/oceanic modes of variability [e.g. North Atlantic oscillation (NAO) and/or El Niño-Southern Oscillation (ENSO) [Ionita et al., 2011; 2015; Schubert et al., 2014]. Altogether, when favorable phase conditions are met, both large scale atmospheric as well as oceanic factors could act as precursors for dry (wet) summers over Europe [Kingston et al., 2013, 2015; Ionita et al., 2012, 2015].

This paper summarizes a collaborative initiative of members of UNESCO's FRIEND-Water programme to perform a pan-European assessment of the drought of 2015 from a climatological point of view. In an accompanying paper [Laaha et al., 2016], a similar pan-European assessment of the drought from a hydrological perspective is performed with focus on streamflow records. Impacts and examples of how the drought of 2015 was management are described by Van Lanen et al. [2016]. The objectives of this paper are manifold, including: a) to characterize the temporal and spatial extent of the summer 2015 drought event using both daily and monthly climate data (surface level analyses); b) to analyze the key drivers of the event, with a special emphasis on the role played by the sea surface temperature and large scale (atmospheric) circulation modes of variability, like the NAO, the Scandinavian pattern and the blocking episodes (upper level analyses) and c) to compare the key characteristics of the drought 2015 with the 2003 event.

The paper is organized as follows: Section 2 gives an introduction to the data and methods used. The results of surface and upper levels analyses of the summer drought of 2015 are shown in Section 3, whereas similarities and differences with the summer event of 2003 are discussed in Section 4. Concluding remarks are given in Section 5.

2 Data and methods

2.1 Climate, oceanic and hydrologic data

Climate variables, i.e. daily time series of precipitation (P) and mean temperature (T), originate from the E-OBS data set [Haylock et al., 2008]. E-OBS is a daily gridded observational dataset for precipitation, minimum, mean and maximum temperature and sea level pressure in Europe. It is based on the European Climate Assessment and Data set [ECA&D]

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station information. The full version dataset covers the period 1950-01-01 until 2015-12-31. For this study, we use the regular 0.25 x 0.25° latitude - longitude grid.

Outgoing Longwave Radiation (OLR) daily data was extracted from NOAA Interpolated Outgoing Longwave Radiation dataset [Liebmann and Smith, 1996]. For the Northern Hemisphere atmospheric circulation, we use the daily and monthly means of geopotential height at 500-hPa (Z500) and 850-hPa (Z850) levels, the zonal wind at 850-hPa (U850) level, 500-hPa (U500) level and 250 (U250) level, the meridional wind at 850-hPa (V850) level and 500-hPa (V500) level and the mean sea level pressure (SLP) from the Twentieth Century Reanalysis (V2) data set [NCEPv2, Whitaker et al., 2004; Compo et al., 2006, 2011] on a 2º x 2º grid.

Global SST is extracted from the Extended Reconstructed Sea Surface Temperature data set [ERSSTv4b; Liu et al., 2014]. This data set covers the period 1854 – 2015 and has a spatial resolution of 2° x 2°. For daily SST, we use the OISST data set [Reynolds at al., 2007].

Daily streamflow data for the main German rivers (i.e. Elbe, Danube and Rhine) was provided by the Bundesanstalt für Gewässerkunde (BfG) in Koblenz.

2.2 Climatological drought indices (SPI/SPEI)

SPI [McKee et al., 1993; Guttman, 1999] and SPEI [Vicente-Serrano et al., 2010; Beguería et al., 2013] are used as indicators for the meteorological/climatological drought. SPI has become a favorable meteorological drought index in Europe and is recommended by the "Lincoln declaration on drought indices [Hayes et al., 2011]. The more recently developed SPEI uses a similar methodology, but includes a more comprehensive formulation of the climatic water balance, which may better quantify drought [Beguería et al., 2013]. The SPI and SPEI normalize accumulated precipitation (P) and climatic water balance (P – PE), respectively, where PE represents the potential evapotranspiration. Both indices have a multiscalar feature, by taking into account both short and long accumulated anomalies, and hence gives the user to possibility to approximate agricultural, hydrological, and socioeconomic drought by adjusting the accumulation period of the indices [Vicente-Serrano et al., 2011; Hayes et al., 2011]. Here, we use an accumulation period of three months (91 days) for both indices, hereafter referred to as SPI3 and SPEI3, both derived relative to the reference period 1971-2000. The index values represent the number of standard deviations from typical conditions for a given location and time of year and therefore allow for objective, relative comparisons across locations with different climatologies and highly non-normal precipitation distributions [Stagge et al., 2015]. A negative SPI (SPEI) represents a lower value than the mean and values larger than -2 are considered extremely dry conditions, corresponding to a 1 in 50 year event [WMO, 2012].

The potential evapotranspiration, used only for the computation of SPEI, was calculated using the Hargreaves equation [Hargreaves and Samani, 1985]. The Hargreaves equation uses the daily difference between the maximum temperature (T_{max}) and the minimum temperature (T_{min}) as a proxy to estimate the net radiation. Use of the Hargreaves equation when calculating SPEI has shown to be robust for Europe, providing similar results to more complex models [Stagge et al. 2014].

2.3 Teleconnection indices

Teleconnection indices associated to the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the Scandinavian (SCA) and the East Atlantic (EA) patterns, over the period 1950–2015, have been downloaded from http://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml. The Niño3.4 index used in this study, is defined as the average of SST anomalies over (170° - 120°W; 5°S - 5°N) over the period 1854 – 2015.

3 Results

3.1 Climate variables: Precipitation and Maximum Temperature

The summer 2015 drought and heat wave, as measured by anomalies in monthly precipitation totals (mm/month) and maximum temperature (°C), are shown in Figure 2 for the months May – August 2015. The most affected regions were the central and eastern part of Europe and the northern Balkans.

In May, abnormally dry conditions started to develop over the Iberian Peninsula and the south-eastern part of France and Germany (Figure 2a). Over the Iberian Peninsula there was a deficit in precipitation of up to 70 mm/month (~20% of total precipitation) compared to the 1971-2000 average. In June the below-normal precipitation moved north and eastwards, covering parts of Belarus, Ukraine and the whole central part of Europe and the northern Balkans (Figure 2c). By July 2015, the drought conditions were well established. The rainfall deficit over the central, southern and eastern part of Europe was more than 75 mm/month (~40% of total precipitation) (Figure 2e). In August, the most affected regions with respect to a deficit in precipitation were central and eastern part of Europe, and a small area over Finland and the Scandinavian Peninsula (Fennoscandia) (Figure 2g).

The year 2015 was declared the warmest year globally on record [NOAA, 2016] and record high temperatures were recorded at several places in Europe in July and August 2015, including Kitzigen (Germany) – 40.3°C; Catania (Italy) – 42.8°C; Cordoba (Spain) – 45.2°C; Dobrochovice (Chechnya) – 39.8°C and Yerevan (Armenia) – 40.9°C. In some countries, records were broken not only locally, but also nationally. This applies both to the maximum as well as the minimum daily temperatures [DWD, 2015].

Extreme maximum temperatures were recorded already in May over the Iberian Peninsula and the south-eastern part of France (Figure 2b). In contrast with the warmth in the south-western part of Europe, negative temperature anomalies were recorded in north-western Europe, with particular high (cold) anomalies in Scandinavia (Figure 2b). In June, major parts of the European continent experienced maximum temperatures that were significantly above the norm (Figure 2d), peaking in an area stretching from western Spain to central and eastern France, the western Alps and over Ukraine with anomalies of more than + 3°C (Figure 2d). In July, the heat wave intensified with anomalies as high as + 5°C over France, and the area affected became clearly defined, stretching from Spain and France up to eastern and central part of Europe, western Ukraine and the Balkans (Figure 2f). In contrast, July 2015 was cooler than normal in northwestern Europe, with up to -5°C over Fennoscandia and north-western part of Russia. In August, the heat wave disappeared in the Iberian Peninsula and southern

France, and it continued in central and Eastern Europe, with anomalies of up to +5°C over Poland and the western part of Ukraine. Compared to June and July, northern Europe experienced a relatively warm August (Figure 2h).

Throughout the summer, there were four heatwave episodes over the impacted area in Europe. The highest maximum temperatures, when averaging the daily maximum temperature over the region affected (approximately 0 - 30°E and 40 - 55°N), were recorded in the first 10 days of August (Figure S1). Summer 2015 was the fourth one in a series of extreme summers in Europe characterized by droughts and heat waves that started in 2003 [Schär et al., 2004] and continued in 2010 [Barriopedro et al., 2011] and 2013 [Dong et al., 2014]. These summers were all characterized by long-lasting droughts, heat waves and record temperatures at different locations, depending on the particular event.

3.2 Drought indices: the SPI and SPEI

The evolution of SPI3/SPEI3 from June 2015 until August 2015 is shown in Figure 3 (SPI3 – left panels and SPEI3 – right panels). Note that the SPEI3 value for June represents the deviation from normal (P-PE) over the period April 1-June 30. The figure shows a similar development in time as for the climate variables, with the area most affected shifting from south - western parts of Europe in June and July, towards the central and eastern parts of Europe in August. In August 2015, although the monthly precipitation over France shows an increase in the precipitation amount (i.e. recovering), the seasonal water balance drought conditions still persist, especially over the western part of the country. SPEI values as low as -4 are recorded in August, and the most extreme values were found in southern Spain, parts of France and Germany, Belarus and Western Ukraine.

Figures 2 and 3 show that the rainfall deficit and climatological drought conditions persisted for almost three months over large regions in Europe, resulting in significantly reduced river discharges. In contrast, there were regions in Europe that received above average precipitation, especially in the northern and north-western part of Europe and Fennoscandia. In summary, the summer 2015 was characterized by a dipole-like structure with rainfall deficit (P) and climatological drought (SPI/SPEI) in the central and southern part of Europe and positive anomalies (P and SPI/SPEI) over Fennoscandia and the British Isles.

3.3 Sea Surface Temperature

Previous studies have emphasized that extreme temperature and precipitation deficits do not occur without similarly extreme anomalous conditions in the large scale atmospheric circulation and ocean [e.g. Black et al., 2004; Feudale and Schukla, 2007, 2010]. In the following paragraphs we present the evolution of the monthly SST anomalies over the Atlantic Ocean and Mediterranean Sea, the Z500 anomalies and the OLR anomalies (Sect. 3.4) between May 2015 and August 2015, and discuss how these may be linked to the anomalies observed in climate variables and drought indices.

Figure 4 shows the evolution of the SST anomalies between May 2015 and August 2015. At the beginning of May, the Mediterranean Sea was up to 1°C warmer compared to climatology. At the same time, the central North Atlantic Ocean (south of Greenland) was colder by around 0.5°C. The North Atlantic Ocean was characterized by three distinct anomalous

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SST centers: i) warm SSTs in the central Atlantic Ocean extending from the east coast of the U.S. up to the western coast of southern Europe and the Mediterranean Sea; ii) cold SSTs south-east of Greenland and iii) warm SSTs poleward of 65°N (Figure 4a). In June, this pattern persisted and the anomalous SST anomalies south-east of Greenland and in the Mediterranean Sea intensified (Figure 4b). In July, the warm anomaly in the Mediterranean Sea further intensified, with SST values exceeding 28°C (Figure 4c and S2). The extreme warm anomaly in July is consistent with the strong extreme maximum temperature anomalies recoded over most of Europe in July (Figure 3c). The warm anomaly in the Mediterranean Sea and the Atlantic Ocean in the 20°N - 40°N band was accompanied by a similar strong negative anomaly of ~1.5°C in the northern part of the Atlantic Ocean (Figure 4c). In August, the warmth in the Mediterranean Sea and the Atlantic Basin in the 20°N - 40°N band and the cooling south of Greenland persisted, with almost the same amplitude (Figure 4d). The altering (positive – negative – positive) spatial pattern in the SST anomalies throughout the summer, in the Atlantic Ocean basin, suggest that the air-sea interaction associated with the northward shift of the subtropical high plays an important role [Czaja and Frankignoul, 2002; Huang and Shukla, 2005].

In the following, we investigate more closely the evolution of the SST anomalies that might have influenced the European climate throughout the summer 2015, either directly or via teleconnections. First we have computed two time series of daily SST anomalies, to encapsulate the two key anomaly areas: the spatial average over the central North Atlantic Ocean (-45°E - -15°E; 45°N - 55°N) and over the Mediterranean Sea (0°E - 30°E; 30°N - 45°N). Figure 5a shows the daily SST evolution from January to December 2015. A pronounced and abrupt increase in the SST anomalies over the Mediterranean Sea took place at the end of June 2015 over a period of ~three weeks, when there was a marked increase in the SST of ~2°C accompanied by a similar abrupt cooling in the central North Atlantic Ocean of ~1°C. As demonstrated in Figure 5a, the SST anomalies in the Mediterranean Sea are accompanied by similar SST anomalies in the central North Atlantic Ocean, but of opposite sign throughout all of 2015. A similar dipole-like structure of warm Mediterranean Sea – cold central North Atlantic Ocean was found to be involved in triggering the heat waves in summer 2003 [Feudale and Shukla, 2007; 2010]. In terms of long term anomalies, summer of 2015 stands out as 8th coldest summer (JJA) over the central North Atlantic Ocean (Figure 5b) and the 3rd warmest one in the Mediterranean Sea (Figure 5c). The warmest SSTs in the Mediterranean Sea (2003, 2010 and 2015) over the last 160 years occurred in connection with extreme heat waves and large-scale droughts in Europe.

3.4 Geopotential height at 500hPa and the outgoing longwave radiation (OLR)

During May 2015, Fennoscandia and the British Isles were under the influence of cyclonic conditions, whereas the Iberian Peninsula and the south-western part of France were affected by anticyclonic conditions (Figures 6a and S3a) and increased OLR anomalies associated with reduced cloud cover and precipitation over these regions (Figure 6b). In June 2015, the anticyclonic circulation extended from the eastern North Atlantic Ocean up to central Europe, Belarus, Ukraine and the Balkans, while the cyclonic flow extended from the North Atlantic Ocean over Fennoscandia up to the northern part of Russia (Figures 6c and S2b). These Z500 anomalies were accompanied by increased OLR anomalies over France, Ukraine

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and the Mediterranean Sea (Figure 6d). In June and July 2015 there was an obvious wave-train of altering Z500 anomalies: negative, but weak, Z500 anomalies over central-northern Canada, positive Z500 anomalies over Greenland, negative Z500 anomalies over Northern Atlantic Basin and Fennoscandia and positive Z500 anomalies over central and southern part of Europe (Figure 6c and 6e). This wave-train was accompanied by excessive precipitation (e.g. Figure 3b) and reduced OLR anomalies over Scandinavia and the British Isles, and heat waves, dryness and increased OLR anomalies over the Iberian Peninsula, central Europe and the Balkans.

In August 2015, the Z500 anomalies are projecting onto an Ω-like block pattern with positive Z500 anomalies over Alaska and Greenland, followed by negative Z500 anomalies in the middle of the North Atlantic Ocean and an anomalous positive center over Europe (Figure 6g). The anomalous Z500 center over Europe suggests a dominant subsidence and adiabatic motion associated with reduced cloudiness and increased incoming solar radiation (Figure 6h).

Since there were four consecutive episodes of extreme temperature (Figure S1) with small interruptions in between, we look also at daily evolution of the atmospheric circulation averaged over the number of summer days (i.e. T_{max} > 25° C; WMO, 2009)]: 29.06 – 08.07, 15.07 – 26.07, 01.08 – 16.08 and 26.08 – 31.08, respectively (Figure 7). All four episodes were associated with atmospheric blocking situations dominated by a south-westerly flow regime. The highest maximum temperatures occurred, in each of the four cases, near the center of the block, where ascending motions and reduced cloudiness contributed to anomalously warm temperatures and dryness. To the east of the heat wave region, anomalously cold temperatures occurred in conjunction with an upper level trough and cold air intrusions from the north.

The large-scale anomalies identified at the 500hPa level had a similar structure compared to the anomalies at low levels (Figure S4), indicating an approximately equivalent barotropic vertical structure through the summer. Moreover, the wave - train like pattern of alternating Z500 anomalies and the streamfunction anomalies at 850hPa (Figure S3) suggest a Rossby wave signal propagating from U.S. to Russia. The atmospheric circulation in the mid-troposphere was accompanied by an unusual wavy jet stream during the four heat waves episodes in the summer 2015 (Figure 7). Under the influence of Ω blocks and wavy jet streams, warm dry air from southern Europe and Africa was pulled northward, pushing temperatures higher than normal over the Iberian Peninsula, central Europe and Balkans.

The blocking episodes and the wavy jet stream during summer might have been caused by unusual warm SSTs in the Mediterranean Sea (Figures 4 and 5). A similar situation was observed in the summer 2003. Modeling results [Feudale and Shukla, 2007, 2010] indicate that exceptionally warm SSTs over the Mediterranean Sea and the central North Atlantic Ocean could be responsible for shifting the jet stream northwards, leaving Europe under drought conditions and heat waves.

3.6 Teleconnection patterns

Previous studies have shown the importance of teleconnection patterns in modulating the climate of Europe in different seasons [Hurrell, 1995; Trigo, 2004; Andrade et al., 2012; Casanueva et al., 2014; Ionita et al., 2014; 2015]. Consequently, we investigate the role of these teleconnection patterns in modulating/influencing the drought conditions in summer 2015. The first eight months of 2015 were characterized by altering phases of some of the teleconnection patterns or by a persistent

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phase (positive or negative). In 2015, a very strong El Niño event developed (Figure 8a). Since there is no clear evidence regarding the influence of El Niño/ La Niña events on the European climate, it is rather difficult to estimate the impact of this strong event on the occurrence of the extreme drought and heat waves in summer 2015. Overall, the strongest influence of ENSO has been found to be during the fall season [Shaman, 2014]. Moreover, the influence of ENSO on the precipitation over Europe has been found to vary strongly on a seasonal basis [Mariotti et al., 2002], but for the summer season no significant relationship has previously been observed.

The teleconnection patterns shown to have the strongest impact on European precipitation and temperature, and hence drought conditions, are the NAO, the EA and the SCA teleconnection patterns [Hurrell, 1995; Barnston and Livezey, 1987; Comas-Bru and McDermott, 2014; Ionita et al., 2015; Kingston et al., 2015]. NAO was in a positive phase from January until June 2015, followed by an abrupt shift towards the negative phase in July and August (Figure 8b). In July 2015, NAO recorded the lowest value of -3.14 (for the month of July) over the last 65 years (Figure S5b). The negative NAO phase during the summer months was accompanied by a positive phase of the EA pattern (Figure 8c) and a negative phase of the SCA pattern (Figure 8d). The recorded values of the SCA index were among the lowest over the last 65 years for the months of May and June 2015 (May: -2.15 and June: -1.52, Figure S5d). The negative phase of NAO and SCA during the summer months could partially explain the reduced precipitation and high temperatures over the Iberian Peninsula, the central part of Europe and Balkans, and the increased precipitation amounts and low temperatures over the Northern part of Europe in 2015 summer. This is proven in a recent study by Casanueva et al. [2014] who have shown that the main drivers of the summer precipitation over Europe are NAO and SCA and that the northern part of Europe receives more precipitation during the negative phase of SCA and NAO, while the rest of Europe receives less precipitation and is more exposed to droughts.

4 Similarities/discrepancies with summer 2003

Since there are indications of an increase in the frequency of future heat waves and droughts in multiple European regions [Christensen et al., 2007; Orlowski and Seneviratne, 2012; Prudhomme et al., 2013; Van Huijgevoort et al., 2014; Giuntoli et al., 2015; Wanders et al., 2015] it is important to analyze the most extreme events at a pan-European scale and to study the underlying processes in a consistent manner. One way to tackle this topic is to analyze the precursors and the background mechanisms between different extreme events to search for similarities and/or discrepancies. The summer drought of 2015 is one of the worst droughts since the event of 2003 and one objective of the study is to compare and contrast the two droughts in terms of their precursors and background mechanisms. Summer 2003 was notable for three reasons: i) the surface temperature anomalies associated with the heat wave were more than five standard deviations relative to the mean in some parts of Europe [Schär et al., 2004]; ii) the high precipitation deficit and evapotranspiration losses led to water shortages, temporal cessation of agricultural activities and even the temporary shutdown of various power plants [Stahl et al., 2016] and iii) it caused around 70.000 heat-related deaths, mainly in the western and central part of Europe [Robine et al., 2008].

Spring and summer of 2003 were characterized by reduced precipitation over most of the central and southern part of Europe (Figures 9a and S6a). The precipitation deficit became visible already at the end of winter season (not shown). Contrary to

2003, winter 2015 was rather wet over the areas affected by droughts in summer (not shown) and the precipitation deficit only became detectable at the end of spring (over the Iberian Peninsula, France and Germany; Figure S6b). In terms of temperature, 2003 was characterized by positive anomalies in maximum temperature (~2°C), seen first in spring over the Iberian Peninsula, France, the British Isles, Benelux and Germany (Figure S6c). This pattern amplified in summer, peaking in August, when Europe registered the warmest summer in the last 500 years [Luterbacher et al., 2004], with record-breaking temperature in western and central part of Europe (Figure 9c). In spring 2015, positive maximum temperature anomalies were recorded over the Iberian Peninsula (~2°C), France and the northern part of Fennoscandia (Figure S6d). However, the affected area was much less than in spring 2003. In summer 2015 the situation changed considerably, with the central and southern part of Europe being affected by heat waves and maximum temperature anomalies of up to ~4°C (Figure 9d). In general, the spatial extent of the precipitation deficit and high temperatures was rather different between 2003 and 2015. In summer 2003, the most affected areas by climatological drought (anomaly in P, SPI and SPEI) and heat waves (anomaly in T_{max}), were the central and western part of Europe and to some degree Scandinavia, whereas in summer 2015 the affected regions were extending from central Europe up to the east (Ukraine, Belarus).

The SPEI3 and SPI3 seasonal evolution (Figures 10 and S7), show a similar pattern as the precipitation anomalies (Figures 9a and S6). Spring 2003 was very dry over the central and southern part of Europe and this pattern persisted and accentuated in summer 2003 (Figures 10a and 10b and Figures S7a and S7b). In spring 2015, a much smaller area was affected, including the Iberian Peninsula, France and the central part of Germany (Figures S7c and S7d), whereas the northern part of Europe, Balkan and Belarus were very wet. In summer 2015, the drought conditions became more evident and accentuated, especially over the eastern part of France, southern part of Germany, Austria and the whole eastern part of Europe (Figures 10c and 10d). The differences between the summer 2003 and 2015 drought is computed for both SPI3 and SPEI3 for the months May (Figures S7e and S7f), representing the spring season and August (Figure 10e and 10f), reflecting the summer season. As seen from Figures S7e and S7f, spring 2003 was overall much drier compared to spring 2015 over most of the European continent. In summary, the drought of 2003 was a slow developing drought, which began much earlier in the year over most of the affected regions. It resulted in extreme high temperatures, affecting mostly western and central Europe, extending from the very south to the north. By contrast, the drought of 2015 had a much more rapid development from its initiation in spring, and a more central and eastern European location, extending from west to east.

Despite the relatively large differences in the initial meteorological conditions of the two events, the SST anomalies in summer 2003 had a similar structure to those recorded in summer 2015 (Figures 11a and 11b). The central North Atlantic Ocean was cooler than normal in both summers, although in 2003 the cold region was smaller compared to summer 2015. The cold spot in the central North Atlantic Ocean in 2003 was flanked everywhere by positive SST anomalies. The main difference between summer 2003 and 2015, in terms of SST anomalies, can be observed over the North Sea. In summer 2003, the North Sea was much warmer compared to 2015. In contrast, over the Mediterranean Sea, the SSTs in both summers were among the three warmest on record (Section 3.3 and Figure 5c). According to modeling studies, a warm Mediterranean Sea could not produce alone the heat wave, but it can reinforce it [Feudale and Shukla, 2007]. Moreover, for the summer 2003, the North Sea and the surrounding part of the North Atlantic Ocean were also very warm and could have played a role in the development of the 2003 heat wave by reducing the baroclinicity in the European region and enhancing blocking situations [Feudale and Shukla, 2010].

In summer 2003, the upper level atmospheric circulation was characterized by a large positive Z500 anomaly over Europe flanked by negative Z500 anomalies over the central North Atlantic Ocean and over Belarus, Ukraine and western Russia (Figure 11c). This positive Z500 anomaly over central Europe is connected to an anticyclonic circulation, indicating dominant adiabatic descending motions, which results in enhanced incoming solar radiation which in turns warms the surface. In summer 2003, the overall structure of the Z500 anomalies projects onto a typical Ω blocking structure. The spatial structure of the upper level atmospheric circulation in summer 2015 is different compared to summer 2003 (Figure 11d). In summer 2015, the upper level atmospheric circulation over the European continent was characterized by a large positive Z500 anomaly flanked by a large negative Z500 anomaly to the north and west (i.e. over the central North Atlantic Ocean extending to northern Scandinavia). The Z500 anomalies in summer 2015 resemble the Atlantic Low regime [Cassou et al., 2005]. This weather regime is associated with the occurrence of extreme warm days over the western and southern part of Europe in summer, due to advection of warm air masses form northern Africa and the Mediterranean Sea.

Although the overall spatial structure of the Z500 anomalies for the two extreme summers are not similar, they are both associated with anticyclonic circulations over Europe, flanked by cyclonic circulation over the surrounding areas and with very warm Mediterranean Sea and tropical Atlantic Ocean and cold central North Atlantic Ocean. As previously shown, the anticyclonic circulation in summer over Europe could be strongly influenced by the tropical Atlantic Ocean, due to a northward shift in the Intertropical Convergence Zone (ITCZ) position [Cassou et al., 2005]. Based on modelling and observational studies, it has been shown that the probability of heat waves to occur over Europe is much higher when the tropical forcing is taken into account [Cassou et al., 2005].

Whereas, the summer 2003 drought and heat wave was the consequence of a prolonged dry period characterized by persistent anticyclonic circulation, which started already at the end of winter, the drought in summer 2015 originated much later, i.e. at the end of spring.

5 Discussion and conclusions

In this study, we have analyzed different data sets and parameters to depict the extraordinary drought of summer 2015 and its dynamic relationship with multiple causal factors like the large-scale atmospheric circulation, the sea surface temperature and different teleconnection patterns.

The largest precipitation anomalies coincide with the mean position of a very persistent upper-level ridge. The regions most affected by the drought and heat waves were situated south of the axis of the North Atlantic jet stream. The regions south of the jet were under the influence of large-scale sinking motions, reduced precipitation and clear skies. Throughout the summer 2015, there were four heat wave episodes, all of them associated with persistent blocking events. These anomalies are indicative of a mechanisms controlled by the radiative forcing, rather than thermal advection. Similar results have been obtained by Andrade et al. [2012], who showed that warm days in summer, over the central and southern part of Europe, are controlled by radiative forcing enhanced due to persistent high-pressure system.

Over western, central and eastern part of Europe, the high pressure system allowed hot air from the tropics to move north and get trapped over these regions. Clear skies allowed for the temperatures to rise even further, creating a stronger center of high pressure, reinforcing the already stagnant Ω block atmospheric pattern. The high pressure system acted like a wall against any potential low pressure systems from moving over Europe, pushing them instead to the north. Contrary to the situation observed over the western, central and eastern part of Europe, due to the influence of the low-pressure system in June and July, the British Isles and Fennoscandia were subjected to unstable weather conditions, cold temperatures and cloud formation.

The summer SSTs averaged over the Mediterranean Sea showed that summer 2015 was the third warmest summer over the last 160 years. Although the very warm Mediterranean Sea and the occurrence of the blockings over Europe are likely to be closely related, the exact mechanism by which the Mediterranean SSTs could influence the atmospheric circulation over Europe is not fully understood [Beniston and Diaz, 2004]. Feudale and Shukla [2007] suggested that global SSTs are responsible for the anticyclonic circulation over Europe. By prescribing just the Mediterranean SST anomaly in summer, they show that the upper level atmospheric circulation over Europe can be realistically simulated, although with smaller amplitudes than if observed SSTs are used. Opposite to these results, Jung et al. [2006] showed that enhanced SSTs over the Mediterranean Sea had only marginal influence on the mid-tropospheric atmospheric circulation over Europe. Nevertheless, we have to recognize that three of the most extreme summers, in terms of drought and heat waves, in the last 15 years occurred simultaneously with the warmest SSTs in the Mediterranean Sea over the last 160 years.

Looking at global/hemispheric teleconnections, summer 2015 was characterized by a negative phase of NAO and the SCA patterns. In July 2015, NAO recorded its lowest July value over the last 60 years. The negative phase of NAO and SCA, over the summer months, could be also a contributor to the dry and warm summer over the central and eastern part of Europe and wet and relatively cold over the British Isles and Fennoscandia. The negative phase of summer NAO is associated with a southward shift in the North Atlantic storm track, which in turn brings wet and cold summers over the U.K. and Fennoscandia and dry and warm summers over the central, southern and eastern part of Europe.

It should be pointed out that although the drought and heat waves in 2015 may be attributed to the effects of blocking patterns, warm SSTs in the Mediterranean Sea, NAO and SCA and increased OLR, other factors should also be investigated. Previous studies have shown that the upper tropospheric circulation and temperatures, a weakening of the atmospheric circulation in summer [Coumou et al., 2015], the Arctic amplification [Cohen et al., 2014] and other factors may also be important for the variability of the European droughts and heat waves. As such, additional analyses are needed to understand whether the summer drought of 2015 was also related to the influences of other factors such as the observed decline in the sea ice cover, a shift in the storm tracks and/or changes in the atmospheric and oceanic circulation.

When comparing the drivers of summer 2003 drought/heat wave and summer 2015, some important features stand out:

- Summer 2003 drought and heat wave were caused by a northerly displacement of the Atlantic subtropical high, while in summer 2015, there were four distinct heat waves episodes, all of them being associated with blocking situations and a wavy jet stream (Figure 7).
- The extreme temperatures, in summer 2003, were amplified by a severe soil moisture deficit [Schär et al., 2004], as a consequence of a very dry and cold winter and a very dry and warm spring. Opposite to 2003, the drought in 2015 started to develop late spring. The winter and spring 2015 were normal in terms of precipitation and temperature anomalies, with small exceptions over the Iberian Peninsula. The 2015 drought developed rather rapidly over the Iberian Peninsula and France in May and reached peak intensity and spatial extent by August, affecting especially the eastern part of Europe.
- The surface temperature anomalies in summer 2003 were more than 5 standard deviations in parts of Europe [Schär et al., 2004]. Due to the exceptional heat wave in summer 2003, the number of fatalities was very high (~70.000). In 2015, the number of fatalities was much smaller compared to summer 2003 (~1250) [MunichRe, 2016].
- For both extreme summers, the central Atlantic Ocean was colder than normal, while the Mediterranean Sea was much warmer than normal (~3°C). Moreover, record-breaking temperatures were registered in both summers, but in different regions.

Both extremes summers were associated with a more meandering polar jet, a circulation structure that has appeared more often during the last decades in connection with the Arctic amplification phenomena [Cohen et al., 2014]. In a recent study, Lehmann and Coumou [2015] showed that changes in the mid-latitude circulation strongly affect the number and intensity of extreme events. They showed that summer heat extremes are associated with low storm track activity, due to a reduced eddy kinetic energy (EKE). Low summertime EKE is significantly linked to positive geopotential height anomalies, and hence has a strong impact on the occurrence of heat waves and droughts. An observed decreasing trend in the EKE in summer, has been associated with favorable conditions for heat extremes such as the ones in 2003 and 2010 [Lehmann and Coumou, 2015]. The decreasing trend in EKE is in agreement with the observed increasing trend in the frequency and persistence of summertime anticyclonic circulation patterns since 1979 over the Northern Hemisphere, especially over the U.S., Europe and western Asia [Horton et al., 2015].

This study has presented the key drivers and characteristics of the summer 2015 drought in Europe. The increase in the frequency and persistence of summertime anticyclonic circulation contributed significantly to heat waves and droughts over those regions. Nevertheless, cautions should be taken when applying the conclusion form this study about the possible drivers of the drought event, since there are other hemispheric/regional mechanisms that also could have played a role. Simulations with general circulation climate models may be also necessary in the future to investigate the full spectrum of the causes of severe drought events.

The study has further assessed the severity of the event in terms of spatial coverage and the strength of the anomaly, through the use of standardized drought indices (SPI and SPEI), and compared it with the extreme drought of 2003. One important

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feature of these events, namely the heat waves that accompanied the droughts, was given special attention. However, to assess the full range of drought impacts, many of which are related to a lack of water, requires additional analyses and data such as soil moisture, groundwater and streamflow observations

Improved management of drought requires a common action of the hydrological and climatic communities that should include monitoring of hydro-meteorological variables, multi-monthly and seasonal forecasting of both climatic and hydrological variables, impact assessments and exploration of potential promising measures to reduce impacts, accounting for the specific conditions at the river basin scale. As such, drought impact and management studies require a concerted multi-disciplinary action from the climatic and hydrological communities that consider both climate and hydrological controls on drought. This paper, along with is counterpart addressing the hydrological perspective of the European drought of 2015, can be seen as a first effort of the climatological and hydrological community, to jointly evaluate the causes and consequence of an extreme event from both perspectives.

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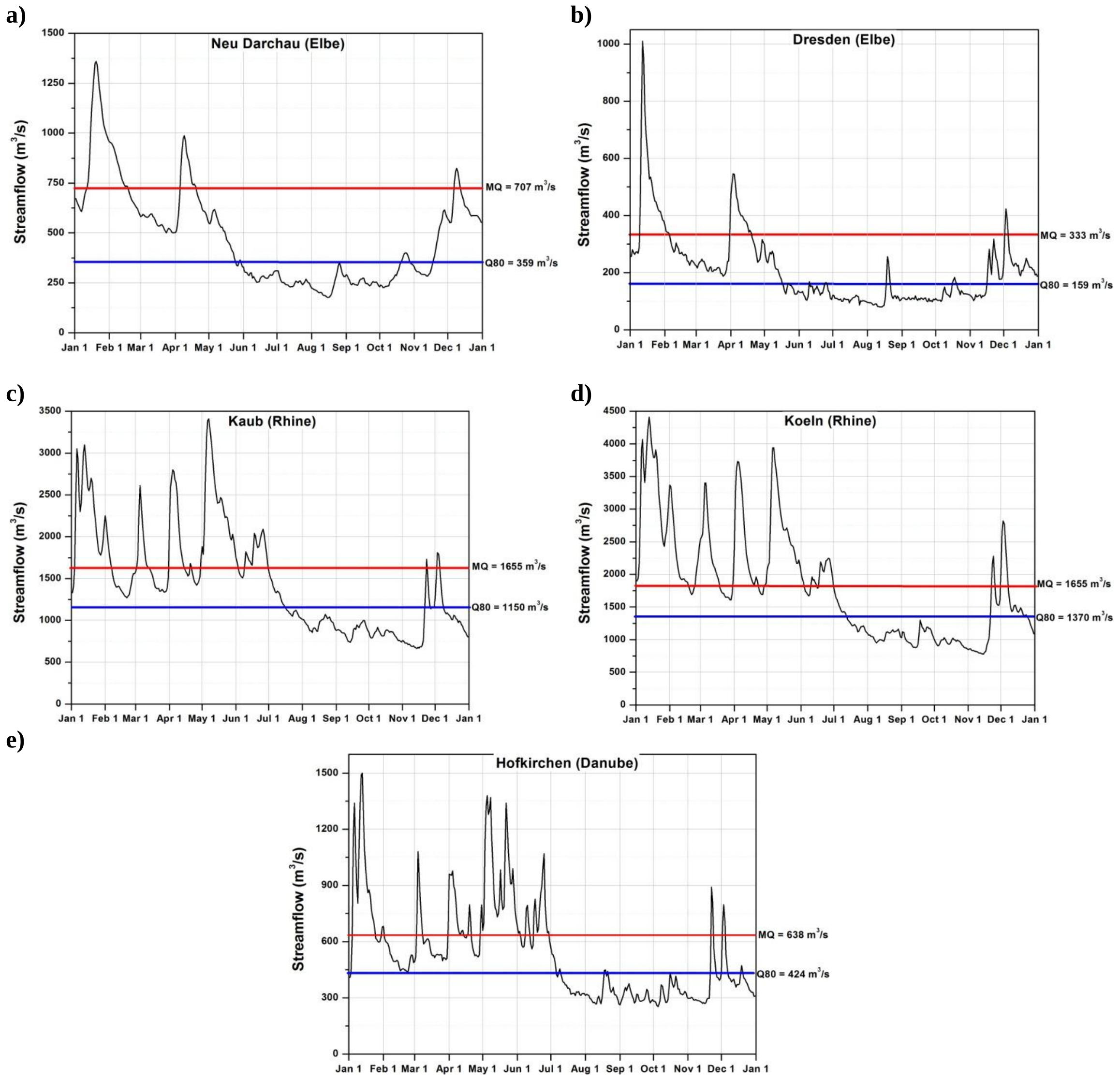

Figure 1 Daily streamflow hydrograph for 2015 : a) Neu Darchau (Elbe); b) Dresden (Elbe); c) Kaub (Rhine); d) Koeln (Rhine) and e) Hofkirchen (Danube). The red line indicates the mean streamflow at each station and the blue line indicates the Q80 streamflow.

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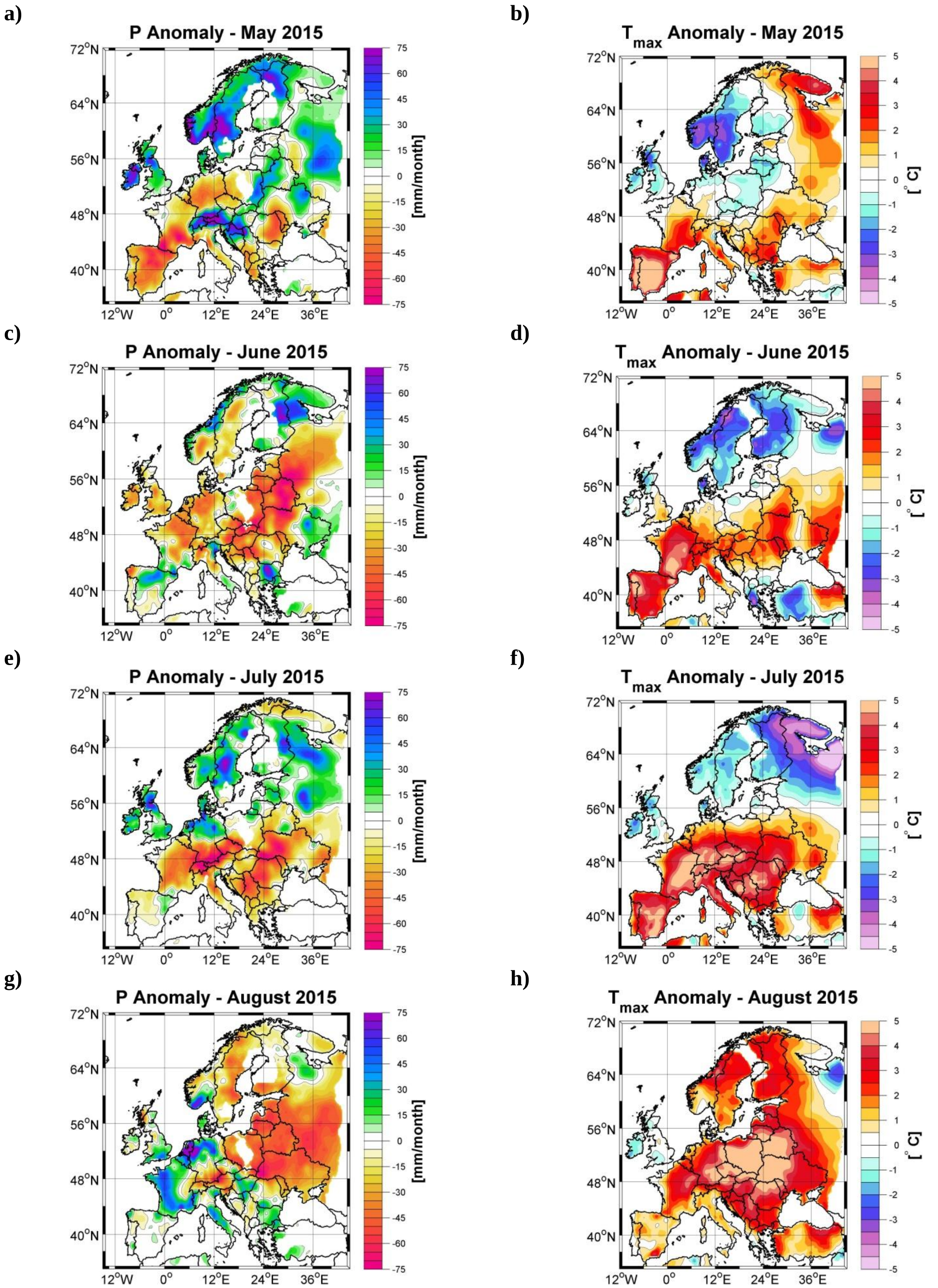

Figure 2 Monthly P anomalies (left column) and T_{max} anomalies (right column): a) and b) May 2015; c) and d) June 2015; e) and f) July 2015 and g) and h) August 2015. The anomalies are computed relative to the period 1971 – 2000.

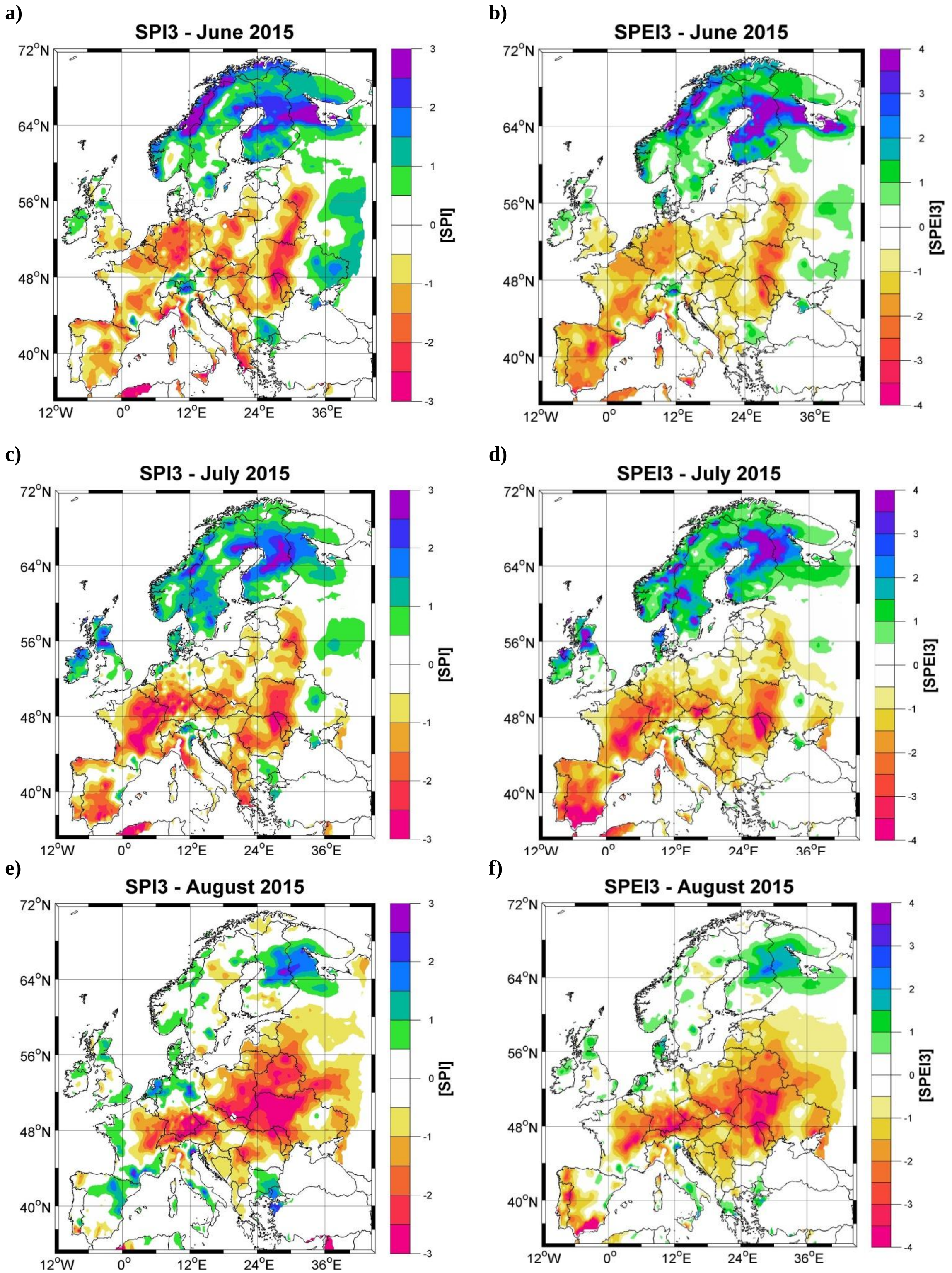

Figure 3 a) SPEI3 for June 2015; b) SPI3 for June 2015; c) as in a) but for July 2015; d) as in b) but for July 2015; e) as in a) but for August 2015 and f) as in b) but for August 2015. Reference period 1971-2000.

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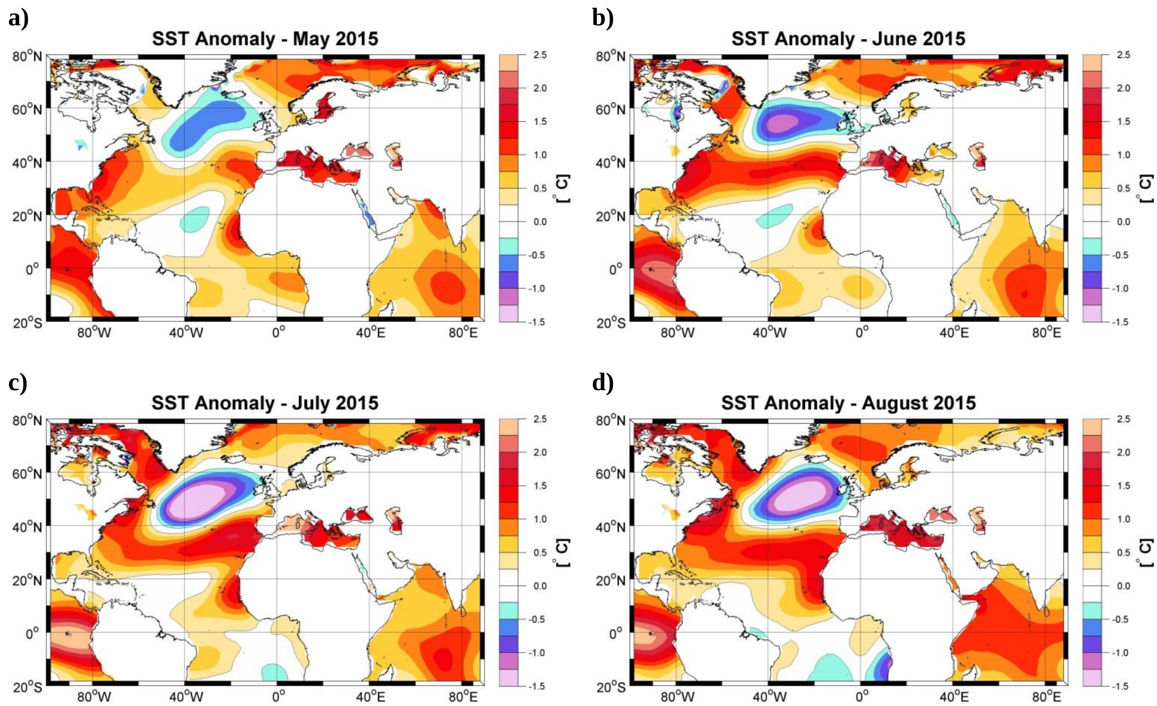

Figure 4 Monthly SST anomalies: a) May 2015; b) June 2015; c) July 2015 and d) August 2015. The anomalies are computed relative to the period 1971 – 2000.

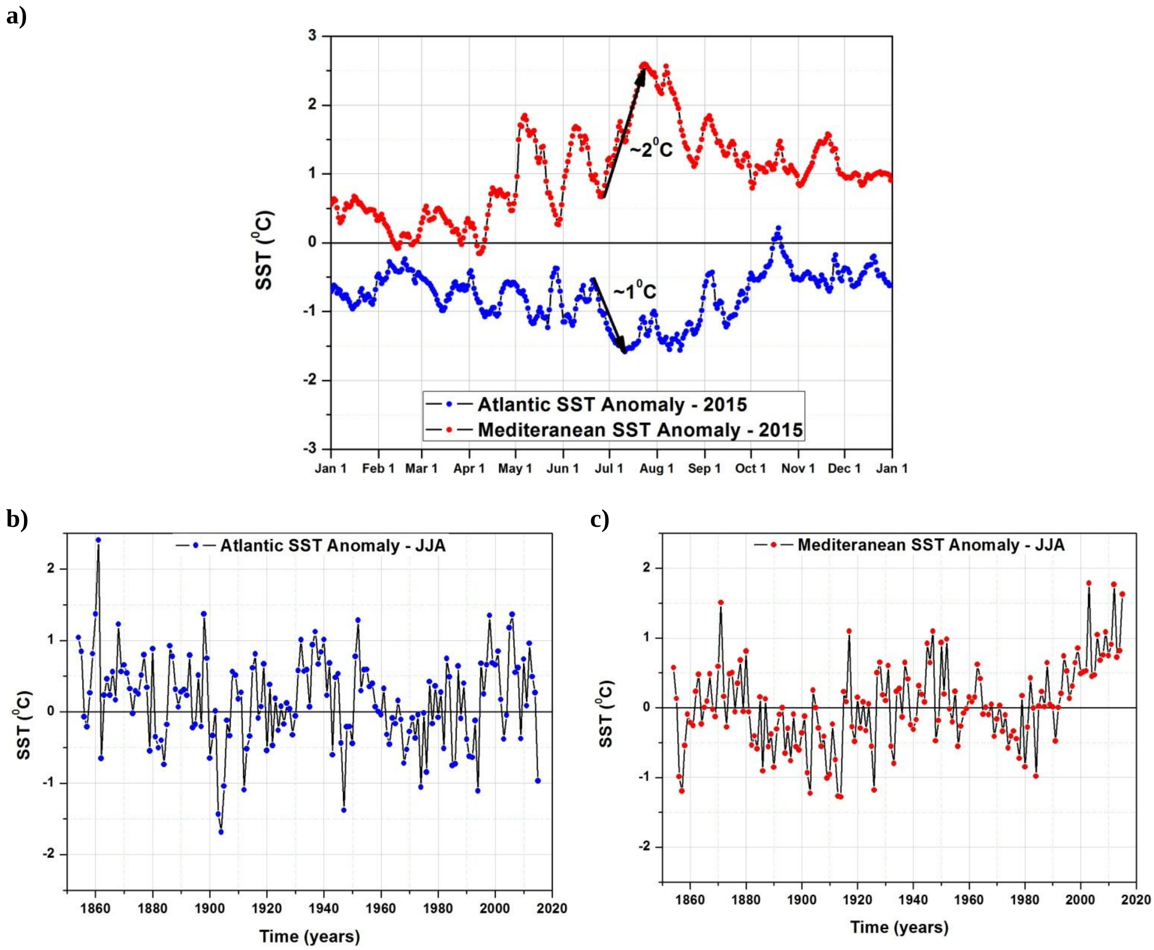

Figure 5 a) 2015 Daily SST anomalies computed over the central Atlantic Ocean (blue line) and the Mediterranean Sea (red line); b) The mean summer SST anomalies over the period 1854 – 2015 computed over the central Atlantic Ocean and c) as in b) but for the whole Mediterranean Sea.

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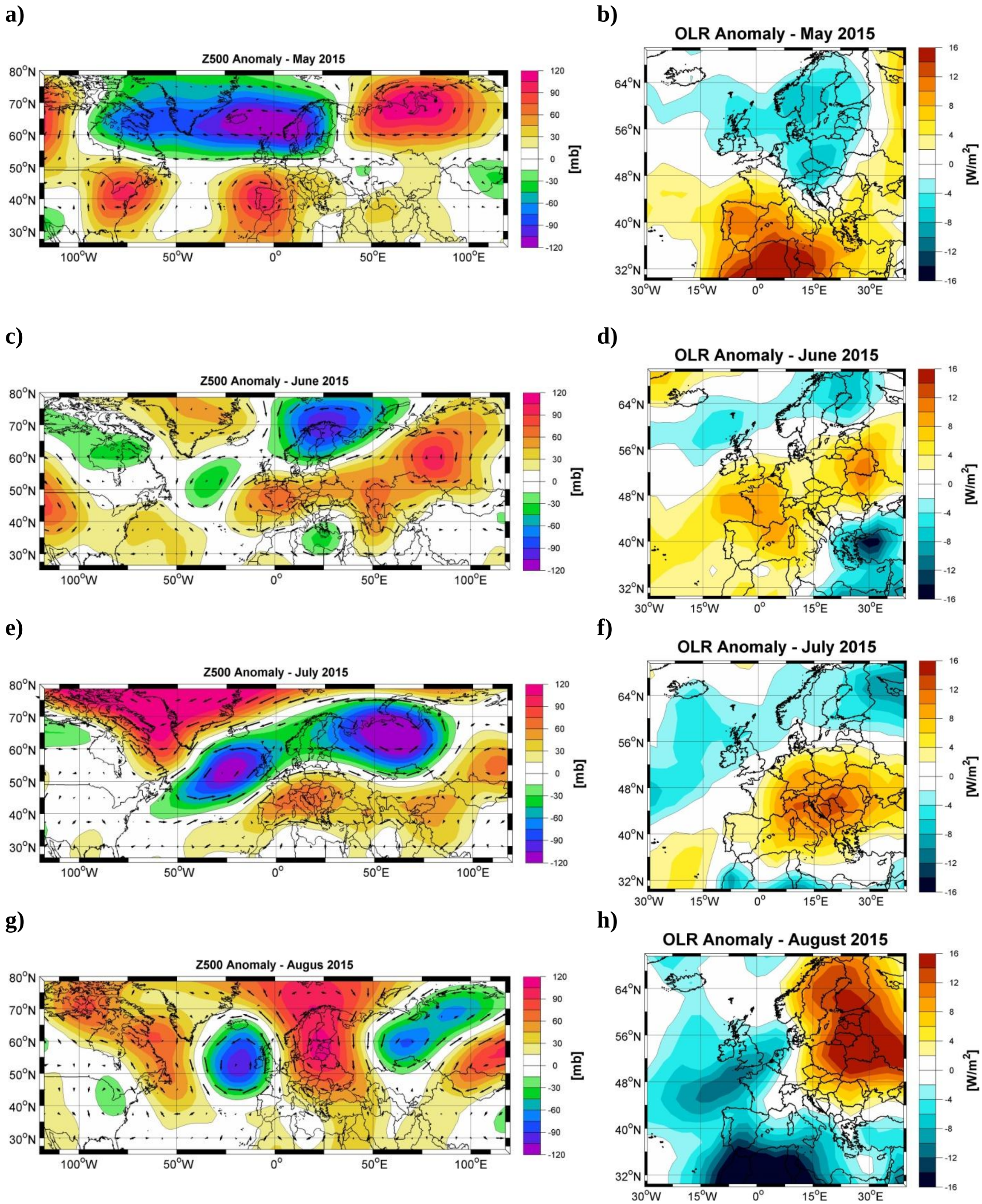

Figure 6 Monthly Z500 anomalies (left column) and OLR anomalies (right column): a) and b) May 2015; c) and d) June 2015; e) and f) July 2015 and g) and h) August 2015. The anomalies are computed relative to the period 1971 – 2000.

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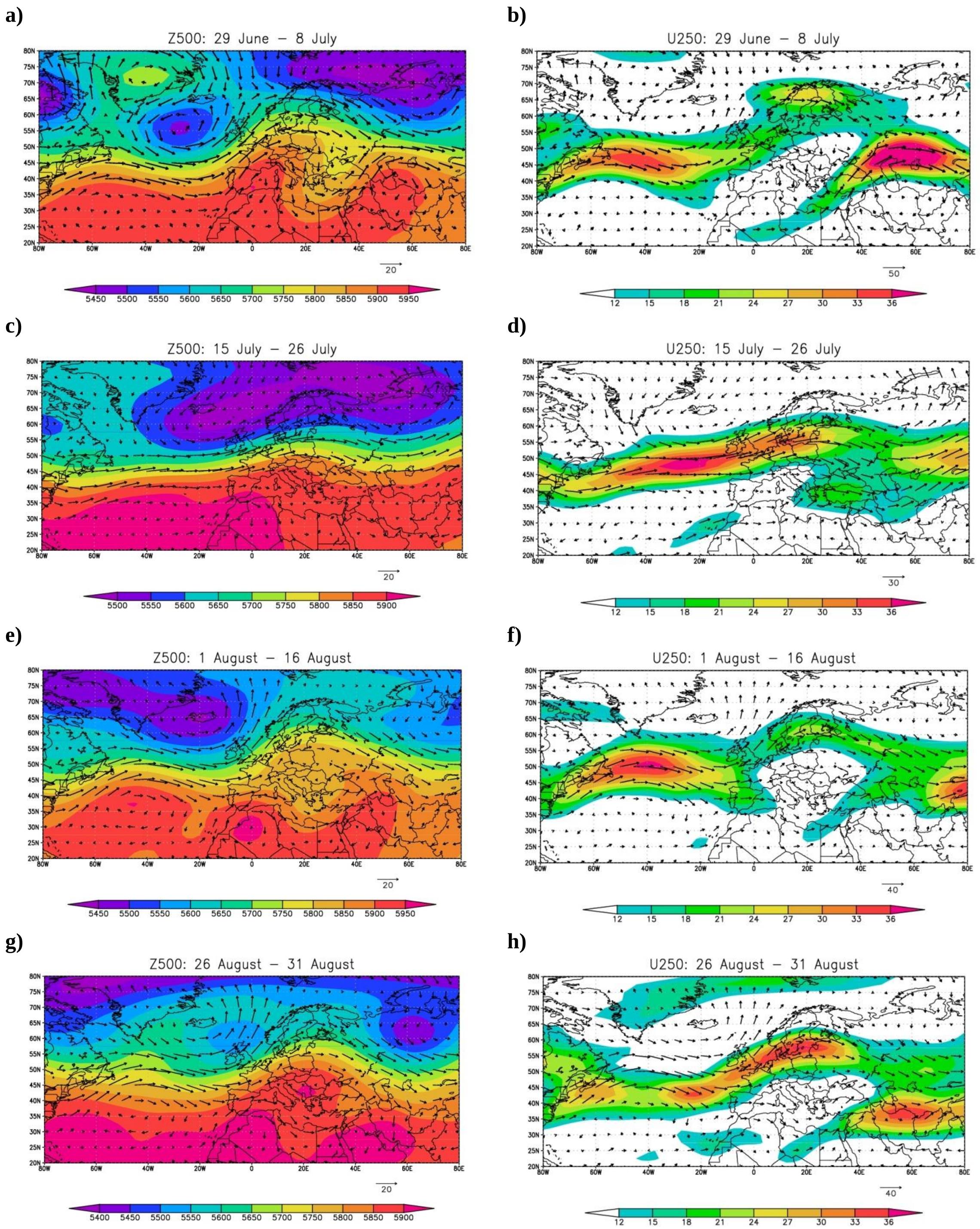

Figure 7 Mean daily Z500 (left column) and U250 (right column) averaged over: a) and b) 29 June – 8 July; c) and d) 15 July – 26 July; e) and f) 1 August – 16 August and g) and h) 26 August – 31 August. Units: Z500 (mb) and U250 (m/s).

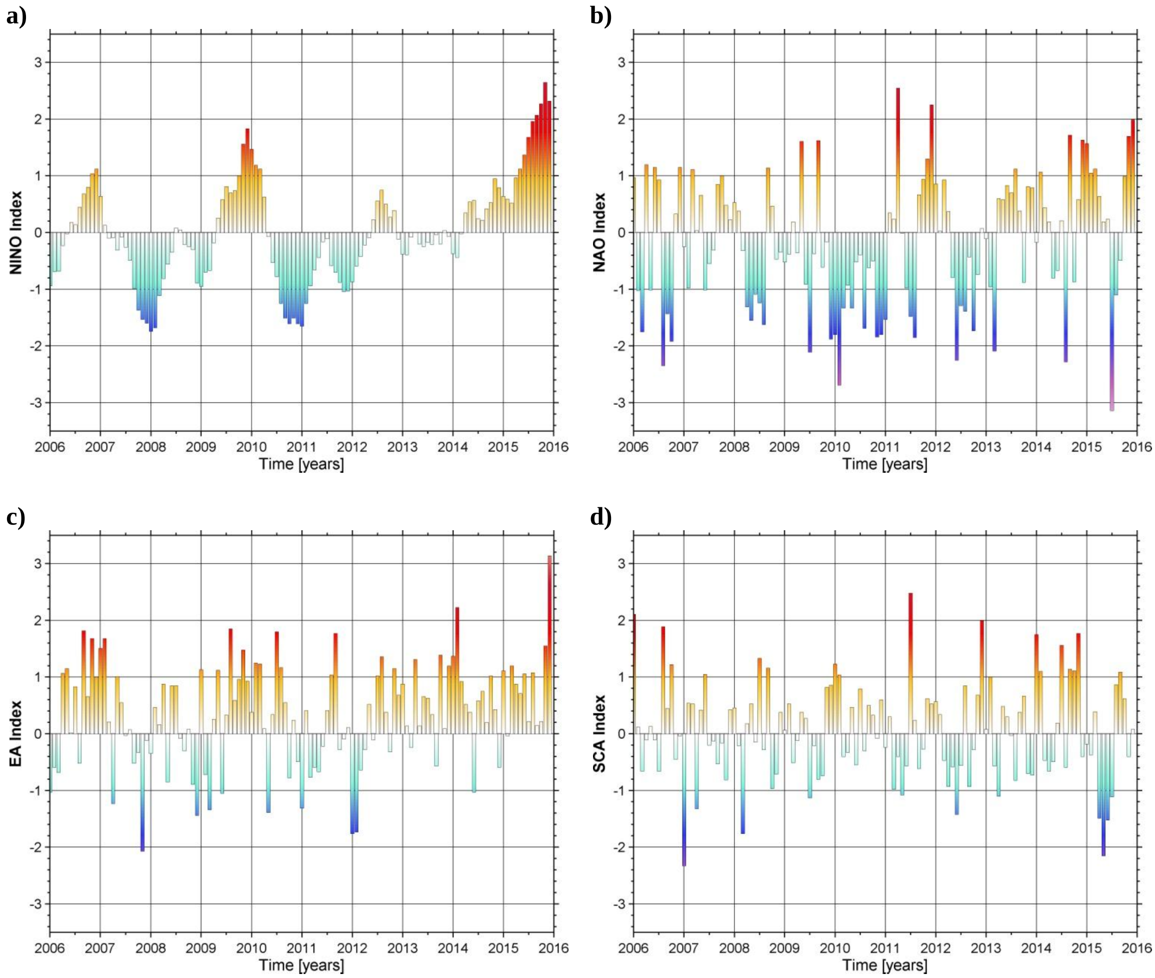

Figure 8 Monthly evolution of the teleconnection indices over the period 2006 - 2016: a) Niño 3.4 index; b) NAO index; c) EA index and d) SCA index.

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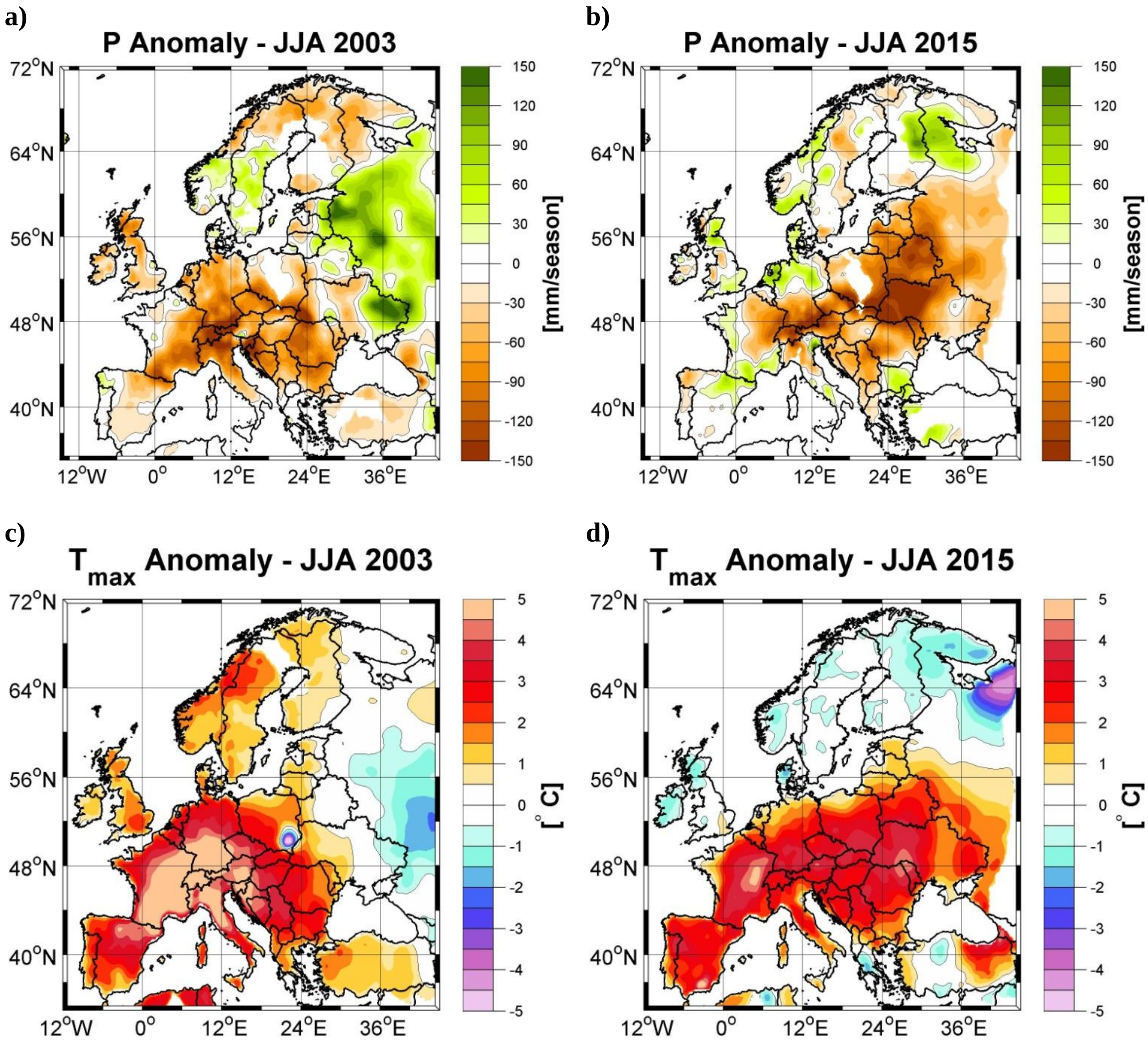

Figure 9 a) Summer (JJA) 2003 P anomalies; b) as in a) but for summer 2015; c) Summer 2003 T_{max} anomalies; d) as in c) but for summer 2015. The anomalies are computed relative to the period 1971 – 2000.

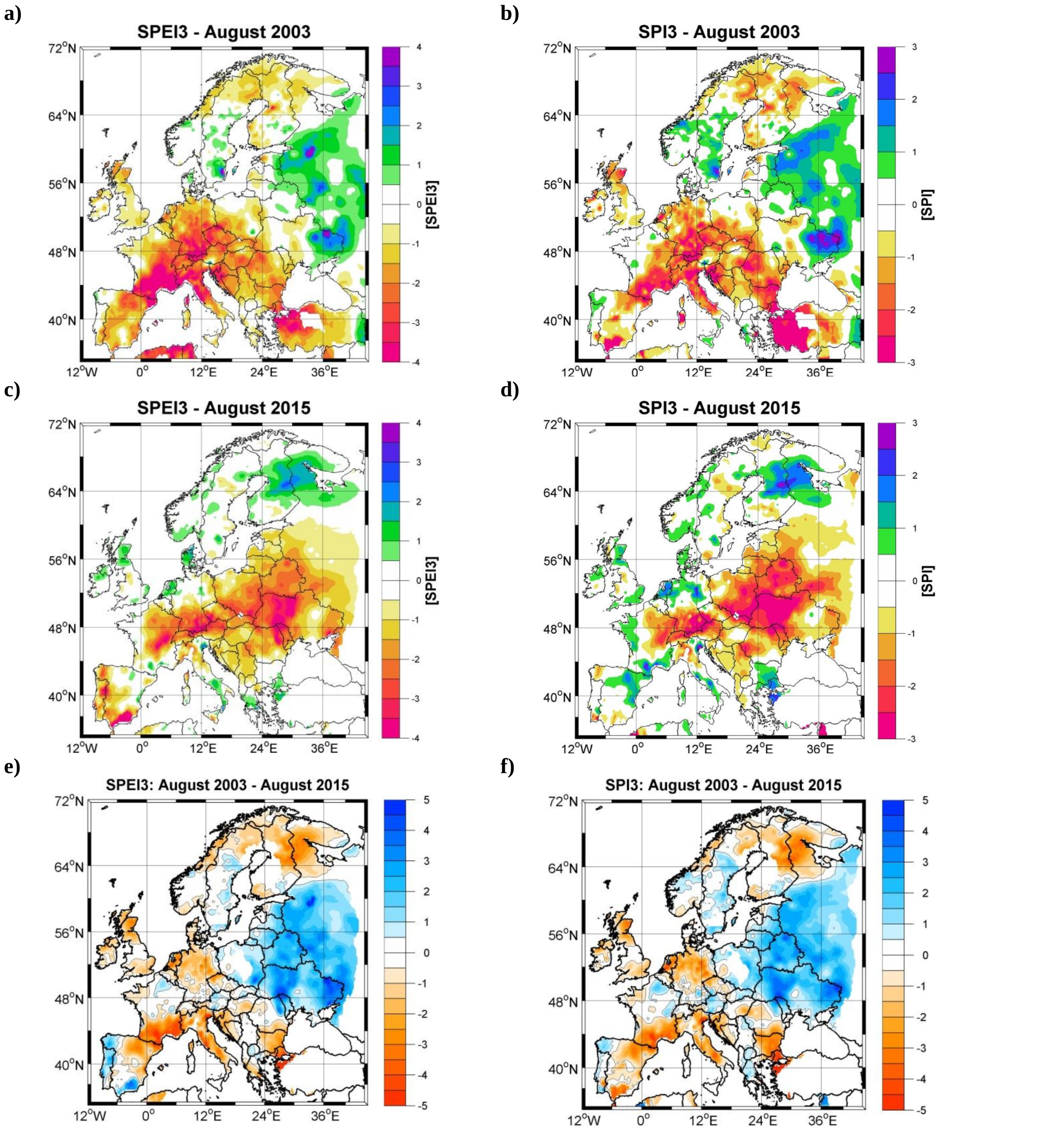

Figure 10 a) August 2003 SPEI3; b) as in a) but for SPI3; c) August 2015 SPEI3; d) as in a) but for SPI3; e) The difference between August 2003 SPEI3 and August 2015 SPEI3; f) as in e) but for SPI3.

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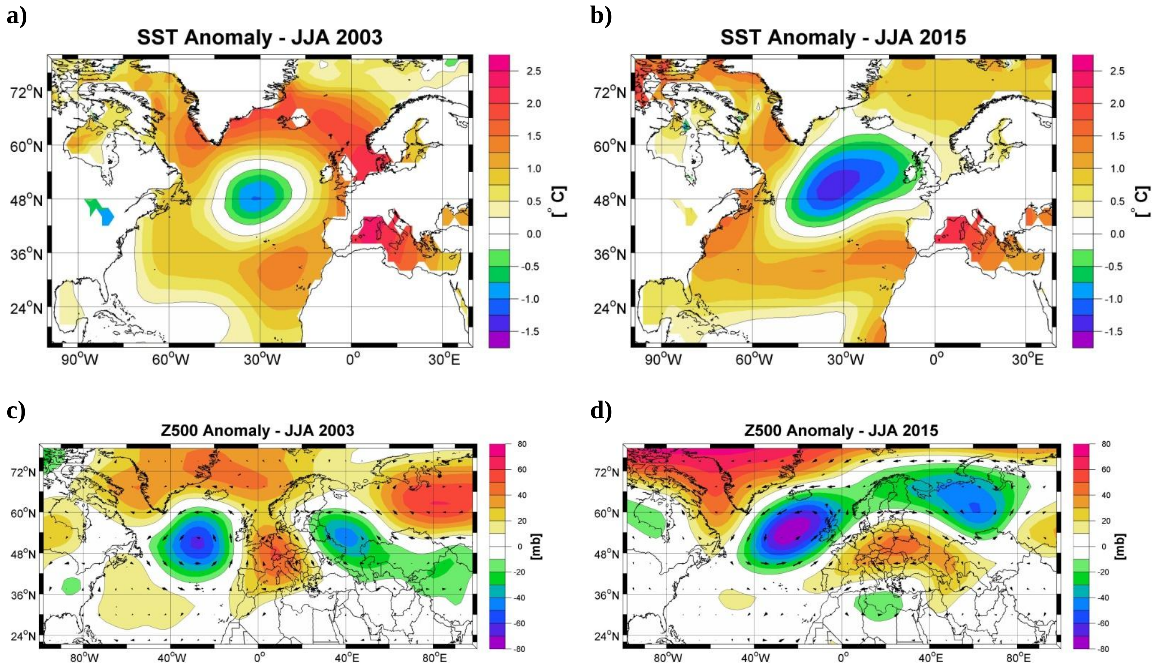

Figure 11 a) Summer 2003 SST anomalies; b) as in a) but for summer 2015; c) Summer 2003 Z500 anomalies and d) as in c) but for summer 2015. The anomalies computed relative to the period 1971 – 2000.