Journal of Hydrology

Examining the outstanding Euro-Mediterranean drought of 2021-2022 and its historical context

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research paper
Keywords:	Climate extreme; SPEI; Atmospheric evaporative demand; Atmospheric circulation; climate change; global warming
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Abstract:	The Euro-Mediterranean region experienced a remarkable drought during the hydrological year 2021/22. Substantial and widespread impacts on water supply systems, agricultural crops, and the production of hydroelectric power were observed. This assessment characterises the drought from a long-term perspective using a multi-index approach and analyses the associated atmospheric circulation at the annual and monthly time scales. The main dynamical forcing of the drought was the unusual recurrence of high-pressure systems over western Europe, at least partly due to an anomalous southward shift in blocking activity and a remarkable occurrence of low-latitude blocks. This led to record-breaking positive geopotential height anomalies over western Europe and a poleward displacement of the North Atlantic eddy-driven jet. Although most of the region was affected by mild drought conditions, the 2021/22 event was not unprecedented in terms of precipitation deficits since other periods of the 20th century (e.g., in the 1920s, 1940s and 1970s) displayed moderate and severe drought conditions over larger areas. However, the 2021/22 drought has been the most intense since at least 1891 because of high atmospheric evaporative demand (AED) values associated with extreme temperatures, especially during the summer of 2022. This enhanced AED also contributed to depleting soil moisture and reducing runoff generation, leading to unprecedented deficits since at least 1965. Finally, we find important differences in the 2021/22 event as compared to other major historical droughts over the Euro-Mediterranean region. In particular, the contrasting effect of AED evidences its increasing role over the last decades and warns about the current risk of experiencing unprecedented droughts.
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Examining the outstanding Euro-Mediterranean drought of 2021-2022 and its historical context

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Keywords: Climate extreme; SPEI; Atmospheric evaporative demand; Atmospheric circulation; Climate change; Global warming

1. Introduction

The 2022 European State of the Climate Report highlights that the climate in Europe during that year was marked by a widespread drought. Starting from winter 2021/22, there was a persistent deficit of precipitation, resulting in pronounced negative anomalies in soil moisture and streamflow over a large area of the continent (Copernicus, 2023). The drought had far-reaching consequences for numerous sectors, including agriculture, energy, river transport, and natural systems (Toreti et al., 2022, and references therein). Cereal crop production in 2022 was 9 percent below the previous five-year average in the European Union (FAO, 2022). The level of hydropower generation across Europe was the lowest since at least 2000 (Jones et al., 2023). The number of detected fires reached the highest level in the European Forest Fire Information System data record, which started in 2006 (Sundström et al., 2022).

Since the beginning of the 21st century, Europe has experienced a series of droughts associated with precipitation deficits (Fink et al., 2004; Santos et al., 2007; Kendon et al., 2013; Spinoni et al., 2015a; Van Lanen et al., 2016; Ionita et al, 2017; Laaha et al., 2017; García-Herrera et al., 2019; Oikonomou et al., 2020; Peters et al., 2020). Moreover, drought severity has worsened across extensive areas of southern and central Europe during the last decades (Spinoni et al., 2015b; 2017; Stagge et al., 2017). This drying trend has been linked mainly to increases in temperature and record-breaking heatwaves associated with climate change (Seneviratne et al., 2021). Regional warming enhances atmospheric evaporative demand (AED), accelerating the rate of water loss from water bodies, soil and natural vegetation (Seneviratne et al., 2021), and intensifying the water stress of crops and ecosystems under dry conditions (Vicente-Serrano et al., 2020).

In addition to land-atmosphere feedbacks, the increasing drought severity over certain European regions has also been related to changes in the frequency of large (and synoptic) scale atmospheric circulation patterns (Ionita et al., 2020; Lhotka et al., 2020; Bakke et al., 2023), which exert a strong influence on moisture fluxes and precipitation (Kingston et al., 2015; Sousa et al., 2018). In this sense, the 2021/22 European drought featured persistent high-pressure weather systems over western Europe (Copernicus, 2023). Although some studies have already highlighted the key role of these synoptic conditions in the drought event (Bakke et al., 2023; Faranda et al., 2023), a detailed study of the associated atmospheric circulation and its temporal evolution has not been carried out so far.

A couple of attribution studies have shown the role of human-induced climate change in exacerbating the 2021/22 Euro-Mediterranean drought. While Faranda et al. (2023) quantified the contribution of climate change on a standardized precipitation-AED index by comparing circulation analogues of past (when global warming was absent) and present periods, Schumacher et al. (2023) employed a statistical approach based on observation-driven soil moisture estimates and climate models. In this work, we use four standardized drought indices based on precipitation, precipitation-AED, soil moisture, and runoff to perform an assessment of the 2021/22 drought event and contextualise it from a long-term perspective. Given the reported regional divergences in the likelihood and intensity trends of droughts over Europe as measured by different indices (Spinoni et al., 2015b; Stagge et al., 2017; Gudmundsson et al., 2017), this multi-index approach allows us to better frame the degree of exceptionality of the 2021/22 drought event in the historical context.

The main objectives of this paper are threefold, namely: i) to characterise the severity, evolution, and spatial extension of the 2021/22 Euro-Mediterranean drought for different drought indices; ii) to put the drought event into a long-term context, including a comparative analysis with previous extreme droughts at continental scale since 1891, and iii) to investigate the associated atmospheric circulation through the analysis of specific weather systems covering a wide range of spatial and temporal scales.

2. Data and methods

2.1. Drought data and indices

The 2021/22 drought and the historical evolution of drought severity are analysed over the Euro-Mediterranean domain, defined as [15ºW–32ºE, 30ºN–62ºN] (red box in Figure S1). We have generated drought indices from two data sources, based on reanalysis and observational products, respectively, which are described in the following subsections. The former is employed to characterise the 2021/22 drought using high-resolution data and different drought indices for the 1965–2022 period, whereas the latter provides a much longer record (1891–2022) to assess long-term trends and the exceptionality of the 2021/22 episode in the historical context. In both cases, drought severity is quantified with the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which is defined as the normalised difference between precipitation and the AED. We also compute a version of the SPEI considering AED constant (SPEIc hereafter) in order to isolate the role of precipitation on drought severity and to determine the influence of the AED on the 2021/22 drought, which can be estimated as the difference between SPEI and the SPEIc. The monthly climatology of AED employed to calculate the SPEIc was obtained

from the 1965–2022 reference period. The SPEI and SPEIc are computed at the time scales of 1- and 12-months for each grid cell and the entire Euro-Mediterranean domain. For coherence with the definition of hydrological year (defined as the 12-month period between October and September), most of the analyses with the drought indices will be carried out at 12-month time scales, unless stated otherwise. The gridded SPEI and SPEIc are employed to characterise the spatial patterns and determine the surface area affected by different levels of drought severity: mild (SPEI $\leq$ -0.85, a return period of 1 in 5 years), moderate (SPEI $\leq$ -1.28, a return period of 1 in 10 years) and severe (SPEI $\leq$ -1.65, a return period of 1 in 20 years) (Agnew, 2000). The Euro-Mediterranean regional SPEI is obtained from the spatial average values of the basic fields rather than by averaging the local SPEI values.

2.1.1 ERA-land reanalysis

We used monthly means of the following variables for the 1965–2022 period of the ERA-land dataset (Muñoz-Sabater et al., 2021) at 0.1º × 0.1º horizontal resolution: precipitation, maximum and minimum air temperature, relative humidity, solar radiation, wind speed, surface runoff and total column soil moisture. Meteorological data have only been considered since 1965 because of inhomogeneities in the precipitation series before that year (not shown). There are different procedures to estimate the AED, but the most realistic ones are those that account for both the radiative and aerodynamic terms. Accordingly, the ERA-land SPEI relies on the AED values inferred from the FAO-56 Penman-Monteith equation (Allen et al., 1998).

We also derived two additional standardised drought indices based on ERA-land surface runoff and total column soil moisture, respectively. As the probability distribution

of these variables is not well defined, we followed the methodology of Vicente-Serrano et al., (2012): for each grid point and monthly series, this approach selects the most suitable probability distribution among ten candidates, based on the Shapiro-Wilks test of normality (Stagge et al. 2015). These two drought indices were subsequently standardised using the same procedure as for the SPEI. They are employed to quantify the surface affected by mild, moderate and severe drought conditions, which are defined from the threshold values corresponding to the abovementioned return periods (5, 10 and 20 years, respectively).

2.1.2 Observational products

The historical SPEI (1891–2022) does not rely on AED values retrieved from the FAO-56 Penman Monteith equation due to the unavailability of relative humidity, solar radiation and wind speed for that period. Instead, it is calculated using monthly precipitation from the GPCC dataset (Schneider et al., 2014), and empirical AED equations based on maximum and minimum air temperature from the Berkeley land and ocean temperature dataset (Rohde and Hausfather, 2020), both at 1º spatial resolution. This simplified approach does not account for the whole aerodynamic and radiative terms in AED, yielding more uncertain estimations of the SPEI (Vicente-Serrano et al., 2020). To reduce this uncertainty, the AED was taken as the arithmetic mean of three estimates derived from different empirical equations: the Hargreaves-Samani (Hargreaves and Samani, 1985), the Bladney-Criddle (Blaney and Criddle, 1950) and the Kharrufa (Kharrufa, 1985) methods. This historical AED series compares well with the Version 4 AED dataset (1901–2021) from the Climatic Research Unit (CRU), which applies a simplified Penman-Monteith equation with constant wind speed (Harris et al., 2020). Our procedure was also validated with ERA-land data by comparing the empirical AED

estimates based on temperature data with the more realistic series obtained from the FAO-56 Penman-Monteith equation in subsection 2.1.1 (Figure S2). The parameters of the log-logistic distribution employed to calculate the historical SPEI were obtained from the 1965–2022 reference period, which allows a fair comparison with the drought indices derived from the ERA-land dataset. For all datasets and methods considered, we obtained a similar evolution of the Euro-Mediterranean SPEI, which suggests that these empirical approaches reproduce well the long-term evolution of the AED and that its variability is mostly controlled by air temperature.

2.2. Atmospheric circulation characterisation

Three synoptic descriptors are examined to characterise the Euro-Atlantic circulation during the 2021–2022 drought event: weather regimes (WRs), the North-Atlantic eddy-driven jet (EDJ) and blocking events. They have been computed using daily geopotential height at 500 hPa (Z500; WRs and blocking events) and zonal wind at 925–700 hPa (North Atlantic EDJ) obtained for the 1940–2022 period of the ERA5 reanalysis (Hersbach et al., 2020).

2.2.1. Weather regimes

To describe the large-scale flow patterns over the North Atlantic-European sector, we have employed eight year-round WRs previously introduced in the context of wind power (Garrido-Perez et al., 2020) and air quality (García-Herrera et al., 2022). These recurrent patterns of atmospheric circulation were extracted from the climatological period 1981–2010 by applying a k-means clustering algorithm to area-weighted anomalies of daily Z500 over the [30ºW–25ºE, 30ºN–65ºN] domain (blue box in Figure S1). Although the

154 classical WR framework over the Euro-Atlantic sector comprises four regimes (e.g.,
155 Michelangeli et al., 1995; Cassou, 2008; Ayarzagüena et al., 2018), these are seasonally
156 dependent and have mainly been applied to the winter season. The increase in the number
157 of WRs allows us to capture recurrent large- scale flow patterns all year-round and their
158 seasonal variability (Grams et al., 2017).

159 In this work, each day has been classified into one of these eight WRs based on the
160 minimum Euclidean distance of the daily Z500 anomaly fields (computed as the differences
161 of each daily value and the climatological 15-day running means for the corresponding
162 calendar day in 1981–2010) to the eight centroids (defined as the average Z500 anomaly for
163 all the days with a specific WR during the 1981–2010 period).

164 Figures S3-S5 display the Z500, temperature (for summer) and precipitation
165 anomaly composites for each WR during the 1981–2010 period. Full details of the
166 methodology and a brief overview of the main features of each WR can be found in
167 Sections 2.2 and S4 of Garrido-Perez et al. (2020).

168 **2.2.2. North Atlantic eddy-driven jet**

169 The detection of the North Atlantic EDJ is obtained from the low-pass zonal wind at
170 925–700 hPa over the [120ºW–60ºE, 15ºN–75ºN] domain (green box in Figure S1), as
171 described in Barriopedro et al. (2022). For the EDJ characterisation, here we use the
172 following three daily parameters:

173 - Latitudinal position: latitude where the zonal wind averaged over the North Atlantic
174 sector [60ºW–0ºE] is maximum

175 - Intensity: zonal wind at the latitudinal position

- Eastward extension: easternmost longitude of the EDJ, an indicator of the maximum decrease in EDJ intensity over the eastern half of the domain

By extending the detection of the EDJ parameters to other longitudinal sectors, this method also provides a 2-D gridded binary field that identifies the latitudes of the EDJ core for each longitude and day. These daily snapshots are employed in this work to compute anomaly frequency maps of the EDJ in order to analyse its structure during the 2021/22 drought event. Full details of the methodology can be found in Barriopedro et al. (2022).

2.2.3. Blocking index

Following Woollings et al. (2018), we identify blocking using the absolute (ABS) method, which is an adaptation of that proposed by Davini et al. (2012). The ABS method detects blocks when several conditions based on meridional Z500 gradients are fulfilled, including a large-scale flow reversal at the mid-latitudes [45ºN–70ºN]. This method guarantees the detection of large-scale, quasi-stationary and persistent patterns as it imposes conditions of minimum extension, spatial overlapping between the blocked areas of successive days and a minimum duration of 5 days. Additional analyses performed using other blocking methods included in Woolllings et al. (2018) indicate that the results presented in this work are not very sensitive to the choice of the blocking index (not shown).

3. Results

3.1. Long-term assessment of the 2021/22 drought event

The evolution of the percentage of Euro-Mediterranean land areas affected by mild, moderate, and severe drought conditions based on 12-SPEIc (Figure 1a-b) and 12-SPEI

198 (Figure 1c-d) in the historical (observations during 1891–2022; Figures 1a and 1c) and
199 recent (ERA-land reanalysis during 1965–2022; Figures 1b and 1d) periods is shown in
200 Figure 1. We first focus on the SPEIc, which represents the drought severity when
201 precipitation is only accounted for (i.e. disregarding the AED effects). The 2021/22 event
202 reached during the 12-month interval from December 2021 to November 2022 the largest
203 percentage of area affected by mild (80.7%), moderate (59.3%) and severe (29.6%) drought
204 for the 1965–2022 recent period based on the ERA-Land 12-SPEIc (Figure 1b). However,
205 in a longer historical context, the 2021/22 drought was not unprecedented. Other periods of
206 the 20th century displayed moderate and severe drought conditions over larger areas than
207 the 2021/22 drought when we consider the observational 12-SPEIc (e.g., in the 1920s,
208 1940s and 1970s; see Figure 1a). Despite this, the surface area affected by mild drought in
209 2021/22 has been the largest since at least 1891 (60.8% from September 2021 to August
210 2022). This long-term study allows us to contextualise the 2021/22 drought event: although
211 more than half of the Euro-Mediterranean region experienced mild drought conditions, the
212 surface area recording moderate and severe precipitation deficits was not unprecedented.
213

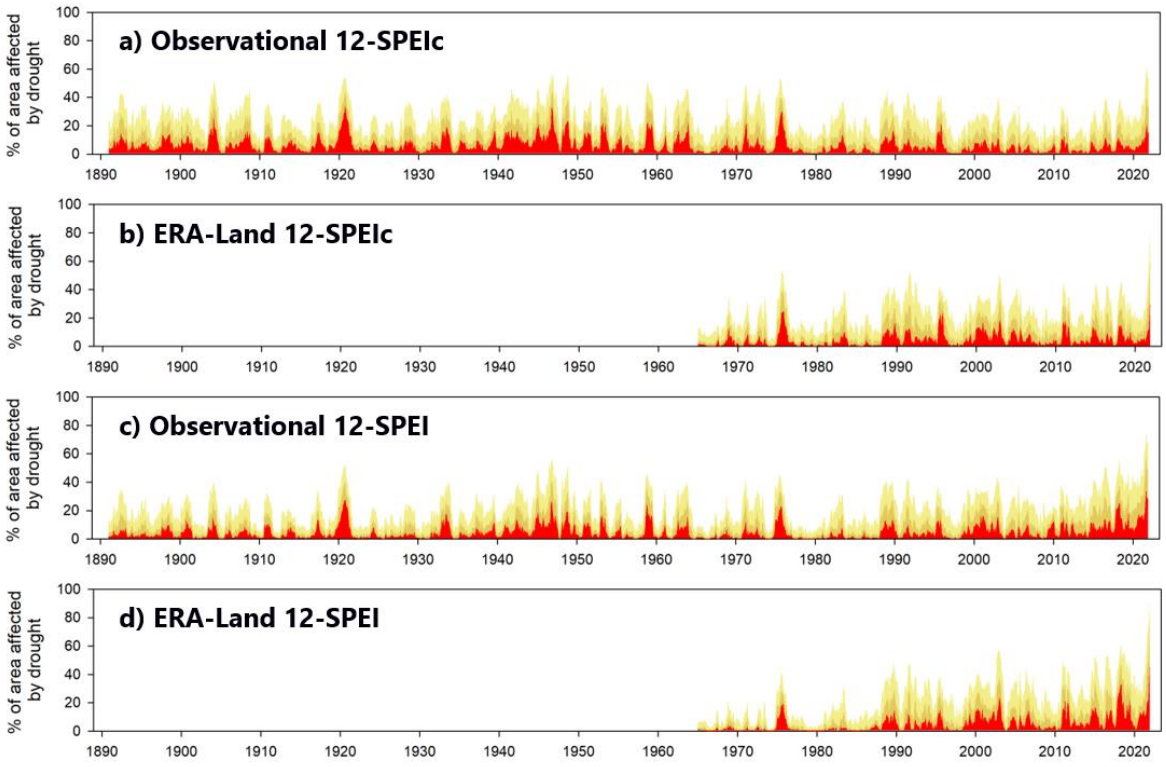


Figure 1. Evolution of the surface area affected by drought using the 12-SPEIc (a,b) and 12-SPEI (c,d) from GPCC precipitation and Berkeley temperature (1891–2020) (a,c) and the ERA-land dataset (1965–2022) (b,d). Red: area affected by severe drought, Orange: moderate drought and yellow: mild drought.

A different rank is obtained when we examine the evolution of the SPEI (Figure 1c-d). The 2021/22 year was characterised by exceptionally large AED values, which were driven by the warm conditions recorded. Therefore, when the AED effects are added up to those of the precipitation deficits, the Euro-Mediterranean drought of 2021/22 turns out to be the most severe since at least 1891. In terms of the area affected, it reached the largest SPEI values during the 12-month interval from September 2021 to August 2022 for mild (73.6%), moderate (56.6%) and severe (33.6%) drought (Figure 1c).

The exceptional drought severity is confirmed by analysing the monthly soil moisture and runoff deficits (Figure 2). Although the very intense precipitation deficits recorded in 2021/22 were not as high as those reached during other major drought events during the historical period (1891–2022), the surface area with moderate and severe runoff and soil moisture deficits was exceptionally large, with no precedents in runoff since at least 1965. In fact, 74.4%, 61.6% and 47.3% of the Euro-Mediterranean region was affected respectively by mild, moderate and severe hydrological drought in September 2022 (Figure 2, bottom panel). This marked surface water imbalance is well explained by the SPEI since the enhanced AED associated with extremely high temperatures contributed to depleting soil moisture and reducing runoff generation.

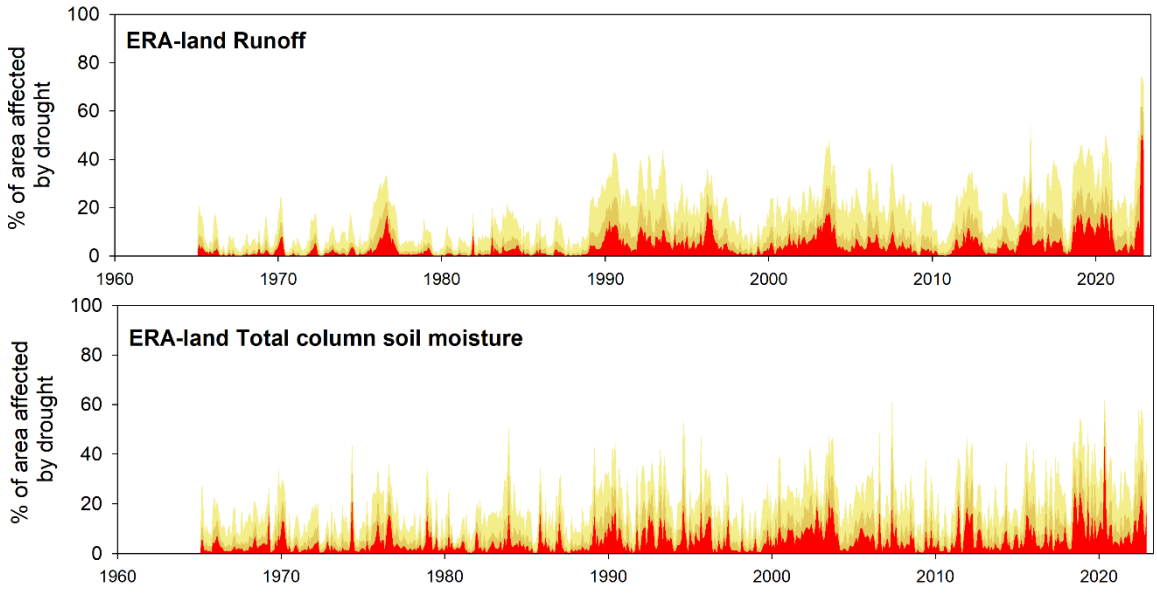
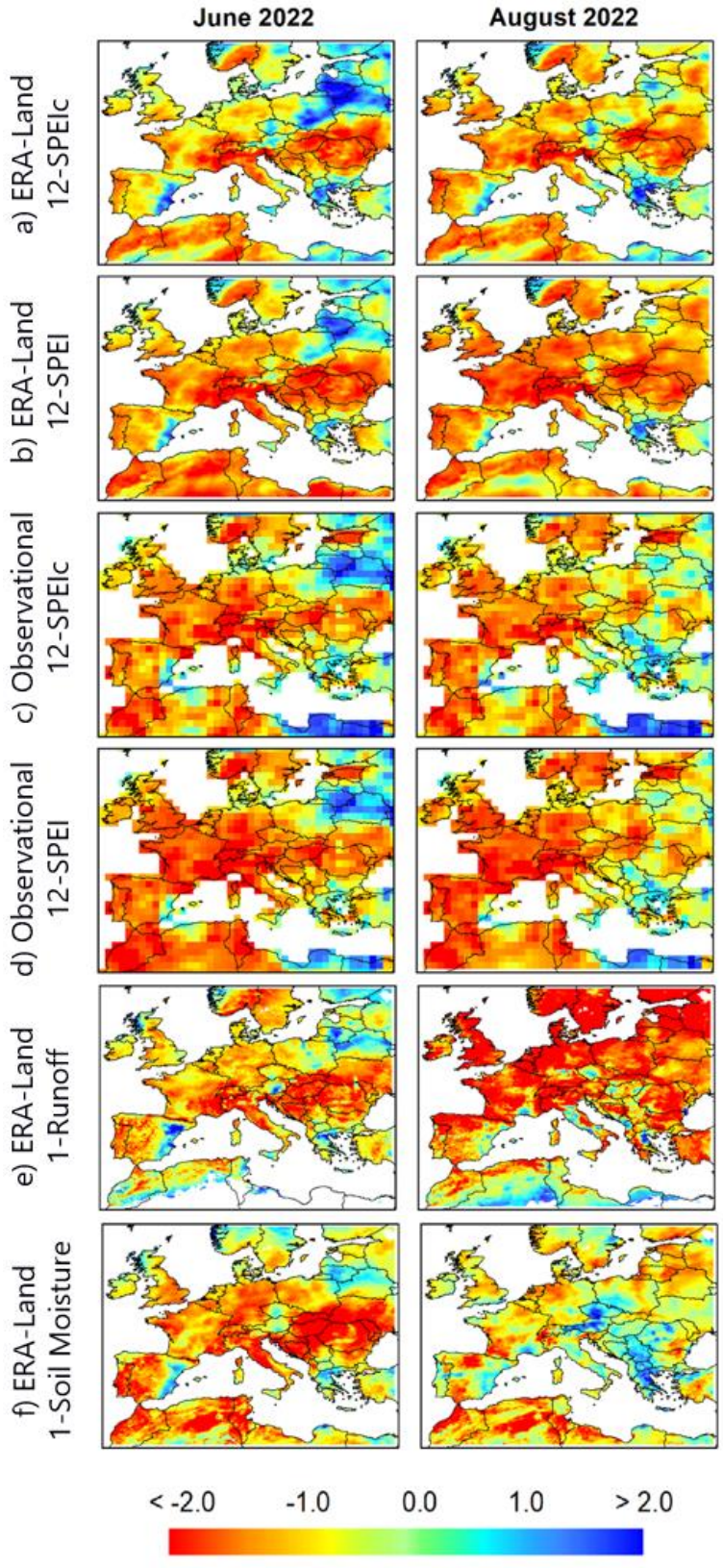


Figure 2. Monthly evolution of the surface area affected by drought using the 1-month standardised runoff (top) and total column soil moisture (bottom) from the ERA-land dataset (1965–2022). Red: area affected by severe drought, Orange: moderate drought and yellow: mild drought.

241 The key role of AED in the extreme character of the 2021/22 event is also illustrated in
242 Figure 3, which shows the spatial distribution of the event in two representative months
243 (June and August), as diagnosed by the different drought indices mention so far.
244 Considering the precipitation deficit (SPEIc), some parts of Europe, including Portugal,
245 northern Italy and eastern Europe experienced severe drought conditions in June, which
246 extended to other regions of France, Germany, the British Islands and northern Spain in
247 August 2022 (Figure 3a). Comparatively, most of the Euro-Mediterranean region was
248 already under severe 12-SPEI conditions by June 2022, and they persisted and extended to
249 the rest of the European continent and northern Africa in August 2022 (Figure 3b). The
250 extreme drought severity in 1-runoff (Figure 3e) and 1-soil moisture (Figure 3f) also
251 exceeded that of the 12-SPEIc (Figure 3a) over most of the Euro-Mediterranean region,
252 demonstrating that AED aggravated the hydrological drought in the summer of 2022.
253 Finally, the resemblance of the 12-SPEI patterns obtained with the temperature-based
254 (observations; Figure 3d) and Penman-Monteith (ERA-land; Figure 3b) AED estimates
255 confirms that the extremely warm temperatures of that summer were the main responsible
256 for the AED increases.

257 The results of this section indicate that the 12-month period in which the 2021/22 Euro-
258 Mediterranean drought reaches its peak depends on the employed index. Since these 12-
259 month periods coincide or vary slightly from the 2021/22 hydrological year (from October
260 2021 to September 2022), the remaining analyses will focus on this time period unless
261 stated otherwise.

262


June 2022
August 2022
a) ERA-Land 12-SPEIc
b) ERA-Land 12-SPEI
c) Observational 12-SPEIc
d) Observational 12-SPEI
e) ERA-Land 1-Runoff
f) ERA-Land 1-Soil Moisture
< -2.0
-1.0
0.0
1.0
> 2.0

263

Figure 3. Spatial patterns of the different drought indices in June (left) and August (right) 2022.

3.2. Atmospheric circulation

To evaluate how anomalous the synoptic conditions were during the 2021/22 hydrological year, we computed the anomalies of the annual Z500 with respect to the same period in 1980–2010 (Figure 4a). Significantly positive anomalies occurred over most of Europe (apart from northern Fennoscandia and some easternmost regions), with the largest values located over western Europe and eastern North Atlantic. The magnitude of the Z500 anomalies in western Europe was exceptional, exceeding 2.5 standard deviations from the climatology and ranking among the three highest for the 1940–2022 period. This anticyclonic pattern blocked the westerly flow, inducing below-normal rainfall over central/southern Europe, negative anomalies of wind speed in the lower troposphere, and notably, record-breaking anomalies in temperature and solar radiation (Figure S6), in agreement with the elevated AED and unprecedented SPEI values reported in the previous section. The Z500 anomalies suggest an unusual recurrence and/or amplitude of high-pressure systems. To uncover the nature of the atmospheric patterns responsible for these anomalies, we have assessed the frequency of blocking days for the 2021/22 hydrological year. Figure 4d shows the annually averaged percentage of blocking days (contour lines) as well as the anomalies for the 2021/22 hydrological year (shading). Overall, the comparison of the anomalies with the climatology indicates an anomalous southward shift in blocking activity, with a remarkable occurrence of low-latitude blocks. Although canonical high-latitude blocks are traditionally associated with increased precipitation and colder than average temperatures over southern Europe throughout the year, this is not the case for low-

latitude blocks, which reduce the odds of heavy precipitation events (Lenggenhager and Martius, 2019; Sousa et al., 2017) and cause extensive above-average temperatures in the area of the anticyclone pattern (Sousa et al. 2018). The centre of Z500 anomalies over western Europe in Figure 4a exhibits a strong spatial overlap with the anomalous blocking patterns, though it also bears some resemblance to subtropical ridges (sometimes referred to as low-latitude blocks; Woollings et al. 2018; Sousa et al. 2021).

To address in more detail the type of weather systems behind the low-latitude blocks, we have analysed the annual frequency distribution of the eight daily WRs all year-round (Figure 4b). The fact that three WRs (AL, AH, ZR) show a frequency of occurrence outside the climatological 10–90 percentile range confirms that atmospheric circulation was notably uncommon during the 2021/22 hydrological year. In particular, AH was the dominant atmospheric configuration. Its frequency was record-breaking when compared with the period 1940–2022, almost doubling the climatological average. This result agrees well with the spatial pattern of Z500 anomalies (Figure 4a) and the southward shift in blocking activity (Figure 4d), as AH is characterised by an anticyclonic flow over western Europe (see Figure S3). To provide further insight into whether this pattern exhibits greater coherence with blocks or ridges, we have examined the spatial match between the Z500 pattern of the high dominant AH WR and the blocking occurrence during the 2021/22 hydrological year. We found that 27.4% of AH days had blocking presence within the region with the largest Z500 anomalies for this WR (30ºW–2ºE, 45ºN–54ºN; black box in Figure S3), suggesting that, despite the relatively high contribution of low-latitude blocks, subtropical ridges might have been the main driving force of the AH prevalence during this hydrological year. From a climatological point of view, the WRs leading to the lowest

(highest) precipitation over the Euro-Mediterranean region (AH/EB/SB and AL/SL, respectively; see Figure S5) were also the most (least) frequent. The 2021/22 hydrological year had the second-highest frequency of dry WRs (AH+EB+SB) and the third-lowest frequency of wet WRs (AL+SL), agreeing with the observed severity of precipitation deficits reported in the previous section. Hence, and despite the WR variability, the dry conditions of the 2021/22 hydrological year were due, to a large extent, to anomalous atmospheric conditions (i.e. a considerably higher-than-usual frequency of dry WRs).

The observed frequencies of AH and low-latitude blocks during the 2021/22 hydrological year and their associated rainfall deficits point to a reduced North Atlantic storm track activity, which strongly modulates precipitation over Europe (Hawcroft et al., 2012; Lehmann and Coumou, 2015). An assessment of the North Atlantic EDJ (used as a proxy for storm tracks) during this period shows an enhanced occurrence over the 55º–65ºN latitudinal band, being record-breaking over Fennoscandia. This result evidences a poleward shift of the EDJ and associated storm tracks during the 2021/22 hydrological year, as compared to the climatology (Figure 4c). A northward shift implies a lower-than-usual frequency of extratropical cyclones over the Euro-Mediterranean region, in line with the dry conditions experienced during the 2021/22 hydrological year. It also agrees well with the dominance of AH and low-latitude blocks, which tend to accelerate the westerlies in the northern flank of their anticyclonic structure, displacing the climatological position of the EDJ to the pole (e.g., Woollings et al., 2010; Sousa et al. 2018).

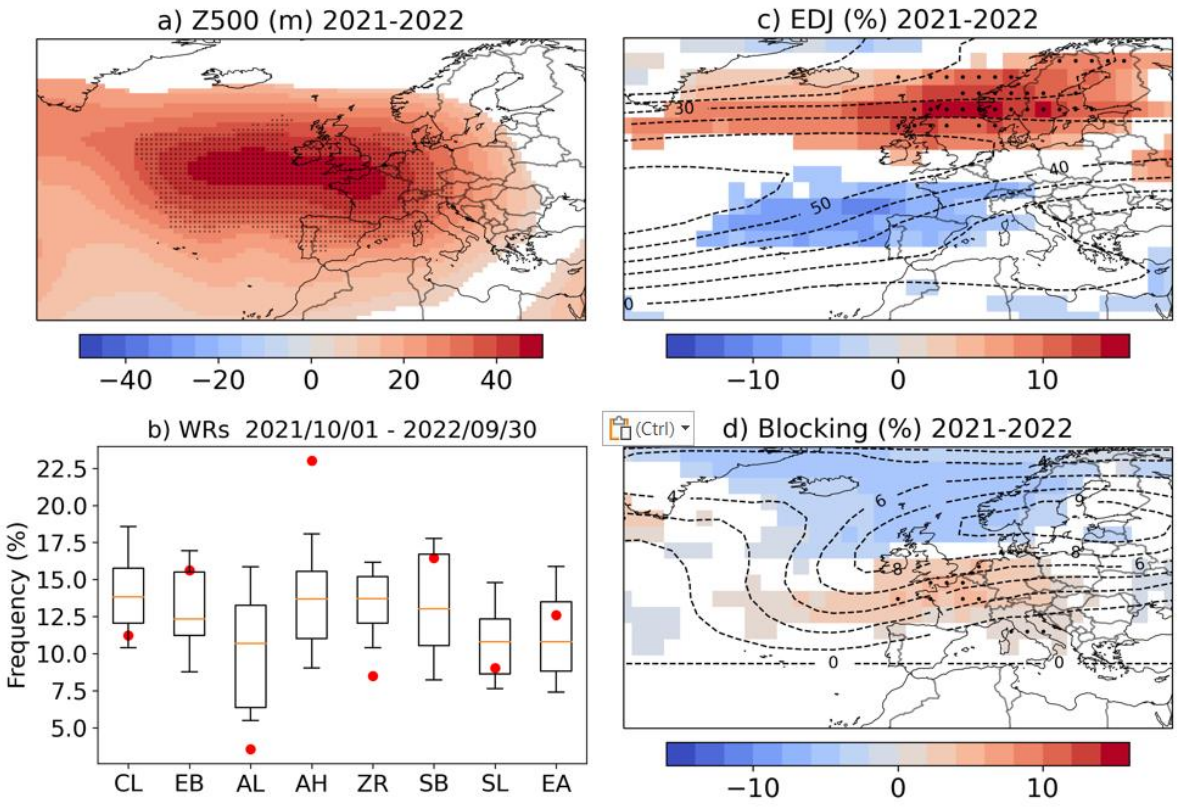
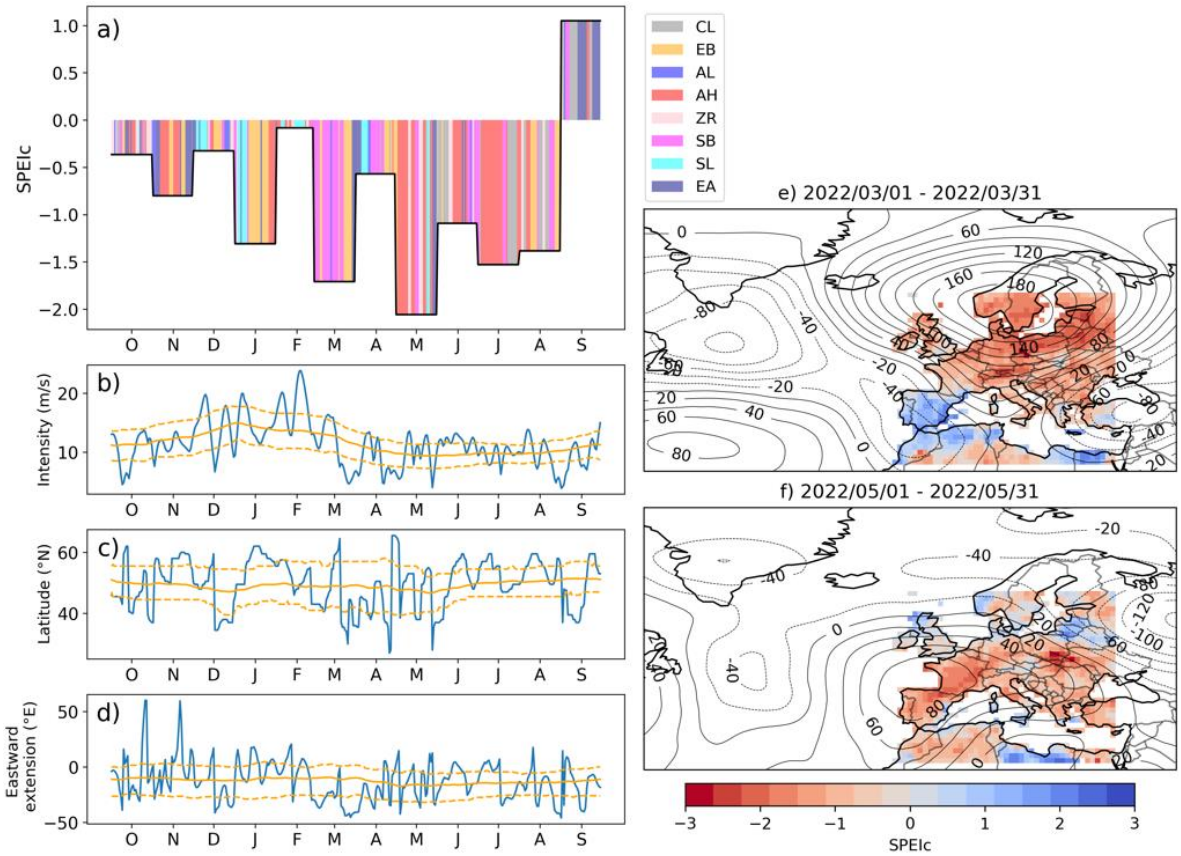


Figure 4. a) Anomalies of year mean 500-hPa geopotential height (Z500; m) during the hydrological year October 2021 – September 2022 with respect to the climatology (October 1980 – September 2010). Anomalies are shown only when they are significant at the 99.9% confidence level (two-tailed t-test). Stippling indicates locations where the 2021/22 hydrological year is among the three years with the highest Z500 anomalies for the 1940–2022 period. b) Frequency distribution of days in each WR for the October 1980 – September 2010 climatology (boxes). The boxes extend from the lower (Q1) to the upper (Q3) quartile values of the data, with a horizontal line indicating the position of the median (Q2). The whiskers extend from the boxes to show the range of the data between the 10^{th} and 90^{th} percentiles. Red circles correspond to the 2021/22 hydrological year. c-d) As a) but for the occurrence frequency (%) of the c) EDJ and d) blocking occurrence. The dashed line contours represent the 1980 – 2010 climatology.

All these results provide a robust and consistent picture of the dominant atmospheric circulation signatures associated with the 2021/22 drought at the daily (WR) and weekly (blocking) time scales that are not explicit when we restrict the analysis at the annual scale (Figure 4a). Finally, we describe the evolution of the event through the 2021/22 hydrological year to identify the periods that contributed the most to the precipitation deficits. Figure 5a illustrates the daily evolution of WRs (color shading), together with the monthly evolution of the 1-SPEIc from October 2021 to September 2022. As expected, the driest months (lowest 1-SPEIc) are also the ones dominated by dry WRs (warm colors). The most prominent examples occurred in March and May of 2022. March was characterised by a high-latitude blocking pattern (Figure 5e) which was especially persistent, as suggested by the fact that 90% of the days during this month were catalogued as either EB or SB (Table S1). These regimes impeded the normal flow of the westerly winds, leading to a weakening and meandering of the EDJ, with dry conditions in central and northern Europe. The southward displacement of the EDJ favoured precipitation over the Iberian Peninsula, however its eastward extension did not reach the Euro-Mediterranean region (Figure 5b-d), explaining the strong precipitation deficits over central and eastern Mediterranean regions (Figure 5e). May was instead characterised by an extensive anticyclonic pattern over southwestern Europe (Figure 5f), in agreement with the predominance of AH during this month (Table S1). The EDJ was strong and well defined, but it remained slightly above or well below its normal latitude for most of the month (Figure 5b-d). This impeded the passage of the storm track through large parts of the Euro-Mediterranean region, leading to below-normal precipitation therein (Figure 5f).

The precipitation deficits during other months of the 2021/22 hydrological year can also be explained by an unusual alternating daily sequence of dry WRs and displaced EDJs. As an illustration, the dry months of January, June, July and August 2023 (all with 1-SPEIc < -1) were characterised by an accumulated monthly frequency of dry EB, AH and SB regimes between 50–75% and a majority of days with northern EDJs (>55ºN), far from the drought domain (Figure 5a-d and Table S1). Regarding the summer months (June, July and August), besides lower-than usual precipitation records, high temperatures also played a fundamental role as shown by the considerably higher 1-SPEI as compared to 1-SPEIc (see Table S1). Despite the relatively normal frequency of hot WRs (SB and ZR; see Figure S4) over the Euro-Mediterranean region, the above-average summer temperatures were at least partly due to the near absence of cold WRs (SL and EA). While the accumulated monthly frequency of SB and ZR was between 13–40% for the three months, that of SL and EA was 0 for July and August, and 6.7% for June (Table S1). In addition, other WRs leading to regional divergences in temperature anomalies over the Euro-Mediterranean area can help to understand specific heat events at regional level. For instance, the heatwaves of mid-June (ECMWF, 2022) and mid-July (EUMETSAT, 2022) overall coincide with the occurrence of AH, explaining to some extent the high temperatures over southwestern Europe (see Figure S4).



383

384 **Figure 5.** a) Evolution of daily WRs (color shading) and monthly 1-SPEIc derived from
385 GPCC precipitation and Berkeley temperature (solid black line) during October 2021 –
386 September 2022. b-d) Daily evolution of EDJ b) intensity (m/s), c) latitudinal position (ºN)
387 and d) eastward extension (ºE). The orange solid (dashed) line represents the climatological
388 values derived from the 31-day moving averages (25 and 75 percentiles) around each
389 calendar day for the October 1980 – September 2010 climatology. e-f) Monthly anomalies
390 with respect to the 1980 – 2010 climatology of Z500 (m; contour lines) and 1-SPEIc
391 (coloured shading) for e) March and f) May 2022, respectively.

392 **3.3. Comparison of three major European megadroughts**

393 We have shown previously that several periods during the 1920s and 1940s were
394 likely drier than the year 2021/22. This needs to be analysed further and in this section we

compare the 2021/22 drought with other major Euro-Mediterranean droughts taking advantage of our long-term series of drought indices (1891–2022). The analysis will be performed for the SPEIc (precipitation deficits) and SPEI (precipitation minus AED) separately. According to the time series of 12-SPEIc, 1948/49 (-2.46), 1920/1921 (-2.45) and 2021/22 (-2.23) were the three driest hydrological years in the Euro-Mediterranean region. For the sake of comparison, Figure 6 shows the spatial pattern of 12-SPEIc (top panels) and the monthly evolution of 1-SPEIc and 1-SPEI (bottom panels) for each of the three drought events, revealing important differences. Unlike the 2021/22 event, the hydrological years of 1920/21 and 1948/49 were relatively wet in the southern regions. The area with negative 12-SPEIc values covered most of the Euro-Mediterranean region during the 2021/22 hydrological year (81.56%), which is slightly larger than in 1920/21 and 1948/49 (72.25% and 76.21%, respectively). However, precipitation deficits in 2021/22 were not as low as those reached during the other two drought events, particularly over central/western Europe. Accordingly, only 12.86% of the Euro-Mediterranean domain presented severe drought conditions in 2021/22, substantially less than the affected areas in 1920/21 and 1948/49 (33.58% and 23.40%, respectively) (Figure 1). We also find important differences in the short-term periods that contributed the most to the 2021/22 rainfall deficits as compared to those of 1920/21 and 1948/49 (Figure 6, bottom right panel). The former experienced the driest months during spring and summer (the second half of the hydrological year), whereas the most negative 1-SPEIc values of the two historical events were concentrated throughout autumn and winter months (the first, and typically wetter half of the hydrological year).

As discussed in Section 3.1, AED was a decisive component of the 2021/22 drought, exacerbating the severity of the event. While the summer of 2022 was record-breaking, 2021/22 experienced the third highest AED over the Euro-Mediterranean region in terms of hydrological year. Interestingly, AED had an opposite effect on the 1920/21 and 1948/49 events as compared to 2021/22. Thus, when the AED effects are added up to the SPEIc, the drought severity (12-SPEI) worsens for 2021/22 (from -2.23 to -2.41) and weakens for 1948/49 (from -2.46 to -1.93) and 1920/1921 (from -2.45 to -1.84). This way, the 2021/22 drought is the most severe of the historical period when the effect of the AED is added to the precipitation. It is worth noticing that the historical SPEI series are derived from temperature-based AED estimates, and hence these differences should be ascribed to temperature effects on AED. In fact, the largest differences between 1-SPEI and 1-SPEIc for the 2021/22 drought occurred in June (-0.79), August (-0.53) and July (-0.23) of 2022 (Table S1 and bottom panels of Figure 6), coinciding with summer record-breaking temperatures over Europe (Copernicus, 2023). These results agree with previous studies reporting that the influence of AED on European droughts has been exacerbated since the 1980s as a result of global warming (Stagge et al., 2017). In fact, two attribution studies have already reported the climate change influence on the severity and probability of occurrence of the 2021/22 drought event (Schumacher et al., 2023; Faranda et al., 2023).

To illustrate the role of long-term temperature trends in drought severity, we performed an additional exercise. Instead of asking how much weaker the 2021/22 drought could have been in a hypothetical naturalised world, we address the kind of events we could have experienced in the past with the current levels of global warming. To do so, we reconstruct the expected severity of past worst-case events (driven by dramatic but

historically plausible precipitation deficits) if they would have occurred under present-day thermodynamical conditions. The 1920/21 and 1948/49 droughts were both considered for the construction of worst-case present-day scenarios because of their exceptional severity in terms of precipitation deficits, and contrasting (mitigating) influences of AED, as compared to present-day events. To achieve this goal, we have recomputed the 12-SPEI by combining the observed precipitation deficits during these two historical events with AED estimated based on the temperatures recorded during the 2021/22 hydrological year. The result shows that, under present-day conditions, the 1948/49 and 1920/21 hydrological years would have been much more severe (12-SPEI values of -2.51 and -2.42) than they actually were in the past (-1.93 and -1.84), and even worse than the 2021/22 event (-2.41). This highlights the increasing role of AED in drought severity and warns about the current risks of experiencing unprecedented droughts (even worse than the 2021/22 event). That scenario would just require that precipitation deficits experienced in the recent past would be repeated in the present-day climate.

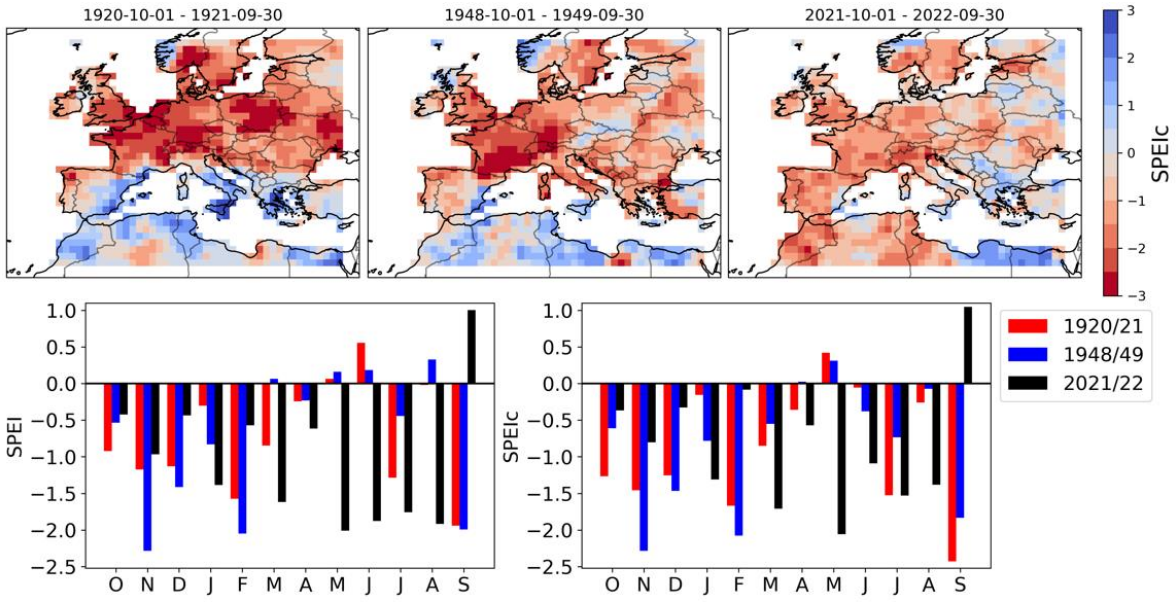


Figure 6. Top panels: Spatial distribution of the 12-SPEIc for the 1920/21, 1948/49 and 2021/22 hydrological years. Bottom panels: Evolution of the 1-SPEI (left) and 1-SPEIc (right) for each hydrological year.

4. Discussion and concluding remarks

The 2021/22 hydrological year was characterised by outstanding dry conditions over the Euro-Mediterranean region. In terms of precipitation deficits, most of the region was affected by mild drought conditions and only a few areas experienced severe drought levels. The occurrence of anticyclonic dry weather regimes dominated the atmospheric circulation during this hydrological year, and the observed precipitation deficits are well explained by an unusual recurrence of high-pressure systems over western Europe. This synoptic situation favoured the poleward shift of the North Atlantic eddy-driven jet, decreasing the passage of the storm track over the Euro-Mediterranean region. The prolonged and widespread drought event was also accompanied by exceptionally warm conditions, especially during the summer of 2022. This caused a very important increase in the atmospheric evaporative demand (AED), which led to severe drought conditions (also in terms of runoff and soil moisture) over more than half of the Euro-Mediterranean region.

The 2021/22 drought event occurred after a series of intense European droughts associated with precipitation deficits. Some examples are the below-normal rainfall over Iberia during the 2004/05 hydrological year (García-Herrera et al., 2007; Santos et al., 2007), the dry spell in the United Kingdom during the 2010–2012 timeframe (Kendon et al., 2013), the hot and dry summer of 2015 at continental scale (Van Lanen et al., 2016; Ionita et al., 2017; Laaha et al., 2017), and the drought over western and central Europe from July 2016 to June 2017 (García-Herrera et al., 2019). Most of the reported record-

478 breaking droughts use observations from the second half of the 20th century. Nevertheless,
479 when analysed from a long-term perspective, these drought events have not been as
480 extreme as previously perceived both in terms of extension and duration (Hanel et al., 2018;
481 Brázdil et al., 2019; Ionita et al., 2021; Ionita and Nagavciuc, 2021). This stresses the need
482 of long-term observational records to frame better the range of internal variability and the
483 degree of exceptionality of recent droughts in the historical context. In this study, the
484 Standardized Precipitation Evapotranspiration Index (SPEI) and the SPEI with constant
485 AED (SPEIc) were calculated for the period 1891–2022 over the Euro-Mediterranean
486 region for that purpose.

487 Although the 2021/22 hydrological year was not unprecedented in terms of the
488 precipitation deficits (ranking only below 1948/49 and 1920/21), it has been the most
489 severe drought (SPEI) since at least 1891 as a result of high AED values associated with
490 extreme temperatures. In fact, the 2021/22 hydrological year experienced the third highest
491 AED over the Euro-Mediterranean region, with the summer of 2022 being record-breaking.
492 The severity of the 2021/22 drought event was similar to our current worst-case estimates
493 inferred from observations (i.e. if the driest historical years would have occurred under
494 current temperature conditions). However, these worst-case droughts should be taken as a
495 lower bound (conservative estimates) due to the limited record (unsampled variability) and
496 the ongoing global warming. The 2021/22 drought could thus be viewed as a benchmark
497 and warning of worsening droughts to come in the next decades because of the increase in
498 AED related to global warming.

499 The enhanced AED associated with global warming will aggravate the impacts of
500 droughts, affecting both natural ecosystems (Allen et al., 2015; Williams et al., 2013) and

hydrological systems. Although some studies have suggested that the physiological effects related to enhanced CO_2 concentrations could counteract the effects of AED on land evapotranspiration and limit hydrological droughts in the future (Roderick et al., 2015; Scheff, 2018; Yang et al., 2019), the 2021/22 drought is an excellent example of the opposite pattern. Recording an outstanding hydrological drought characterised by reduced soil moisture and very low river discharges under CO_2 concentrations above 400 ppm evidences the fundamental role of the enhanced evapotranspiration, as widely observed during other drought events that have experienced high AED (Zhao et al., 2022). While it is overall clear how climate change affects AED and thus droughts, there is a lot of uncertainty about atmospheric dynamics, which, as we have shown for the 2021/22 drought, are also critical to understanding precipitation deficits over the Euro-Mediterranean region. The response of the mid-latitude atmospheric circulation patterns to climate change arises from the competing effects of different remote drivers, including the tropical and polar amplifications, changes in stratospheric vortex strength or the warming of the North Atlantic Ocean (Zappa and Shepherd, 2017; Garrido-Perez et al., 2022). Improving the understanding of these remote driver responses is thus needed to better identify the plausible future evolutions of atmospheric circulation and its associated impact on droughts in the Euro-Mediterranean region.

Although we have focused on the 2021/22 hydrological year as an individual event, the consideration of a multi-year perspective also helps to understand the worrisome situation that Europe has been experiencing in recent years. The accumulative effect of multiple consecutive droughts might aggravate the impacts, especially those related to groundwater recharge and forest ecosystems (Moravec et al., 2021, and references therein).

Previous studies have already reported that the sequence of recent European droughts is beyond background variability and unprecedented in the observational period (Hari et al., 2020; Büntgen et al., 2021; Moravec et al., 2021; Rakovec et al., 2022). Given the preceding droughts, the occurrence of the 2021/22 drought event might not be considered only as an exceptional individual event, but also as an aggravating factor in an already disturbing hydrological situation, especially if we take into account its magnitude and extent.

Acknowledgments

This research work has received support from the European Commission – NextGenerationEU (Regulation EU 2020/2094), through CSIC's Interdisciplinary Thematic Platform Clima (PTI Clima) / Development of Operational Climate Services. SMV-S acknowledges funding by the research projects TED2021-129152B-C41, financed by the Spanish Ministry of Science and FEDER, and MEHYDRO (LINKB20080) financed by the i-LINK 2021 programme of CSIC. RMT was funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) – UIDB/50019/2020 – Instituto Dom Luiz and project DHEFEUS - 2022.09185.PTDC. We acknowledge the GPCC monthly land-surface precipitation dataset (https://www.dwd.de/EN/ourservices/gpcc/gpcc.html) as well as the Berkeley land and ocean temperature dataset (https://berkeleyearth.org/archive/land-and-ocean-data/). ERA data products provided courtesy of ECMWF.

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Abstract

The Euro-Mediterranean region experienced a remarkable drought during the hydrological year 2021/22. Substantial and widespread impacts on water supply systems, agricultural crops, and the production of hydroelectric power were observed. This assessment characterises the drought from a long-term perspective using a multi-index approach and analyses the associated atmospheric circulation at the annual and monthly time scales. The main dynamical forcing of the drought was the unusual recurrence of high-pressure systems over western Europe, at least partly due to an anomalous southward shift in blocking activity and a remarkable occurrence of low-latitude blocks. This led to record-breaking positive geopotential height anomalies over western Europe and a poleward displacement of the North Atlantic eddy-driven jet. Although most of the region was affected by mild drought conditions, the 2021/22 event was not unprecedented in terms of precipitation deficits since other periods of the 20th century (e.g., in the 1920s, 1940s and 1970s) displayed moderate and severe drought conditions over larger areas. However, the 2021/22 drought has been the most intense since at least 1891 because of high atmospheric evaporative demand (AED) values associated with extreme temperatures, especially during the summer of 2022. This enhanced AED also contributed to depleting soil moisture and reducing runoff generation, leading to unprecedented deficits since at least 1965. Finally, we find important differences in the 2021/22 event as compared to other major historical droughts over the Euro-Mediterranean region. In particular, the contrasting effect of AED evidences its increasing role over the last decades and warns about the current risk of experiencing unprecedented droughts.

Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Highlights

- Most of the Euro-Mediterranean region affected by drought conditions during 2021/22
- Recursive high-pressure systems & a poleward jet shift explain rainfall deficits
- Most severe drought since at least 1891 when considering evaporative demand (AED)
- Enhanced AED caused unprecedented low soil moisture & runoff since at least 1965
- Potential worst-case droughts if historic rainfall deficits occur with current AED

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit Author Statement

Jose M. Garrido-Perez: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization. **Sergio M. Vicente-Serrano**: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization. **David Barriopedro:** Conceptualization, Methodology, Data curation, Writing – review & editing**. Ricardo García-Herrera:** Conceptualization, Methodology, Writing – review & editing. **Ricardo Trigo:** Conceptualization, Methodology, Writing – review & editing. **Santiago Breguería:** Methodology, Writing – review & editing.