Record Summers in Europe – Variations in drought and heavy precipitation during 1901–2018

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Abstract:

During the last 20 years some very hot and dry summers affected Europe, regionally resulting in record breaking high temperature or low precipitation values. Long-term changes of such extremely hot and dry summers are of great relevance for our society as they are connected with manifold negative impacts on human society, natural ecosystems and diverse economic sectors.

Long-term variations in drought and the five record drought summer half years are studied based on 63 stations across Europe with high-quality precipitation and temperature time series spanning period 1901–2018. Eight drought indices are deployed to analyse drought intensity, frequency, and duration; four of them purely precipitation-based and four integrating potential evapotranspiration in the computation. Additionally, three heavy precipitation indices and simultaneous increases in drought and heavy precipitation are studied.

The five driest summer half years (1947, 2018, 2003, 1921, and 1911) over Europe and within five sub-regions are identified and subsequently analysed by aggregating eight drought indices into the Aggregated Drought Evaluation index ADE. The ADE shows increasing summer drought conditions over most of Europe, except for some stations in Northern Europe. The increase in drought conditions during the warm part of the year is particularly pronounced for indices integrating evapotranspiration in their definition. At the same time, the intensity of heavy precipitation events as well as their contribution to total precipitation show a positive trend. Several stations in Central Europe show increasing drought conditions and increasing heavy precipitation events at the same time, which increases the risks connected with precipitation extremes.

Keywords: climate variability and change, climate indices, dry periods, mRAI, WBAI

1. Introduction

Several recent drought events demonstrated the challenges droughts pose for economic activities in Europe. Latest examples of severe meteorological drought events in Europe were the summers of 2003 (Fink *et al.* 2004; Rebetez *et al.* 2006), 2010 (Barriopedro *et al.* 2011), 2015 (Hoy *et al.* 2017; Ionita *et al.* 2017) and 2018 (Masante, Barbosa & McCormick 2018; Peters *et al.* 2020; Zscheischler & Fischer 2020). Nonetheless, such summer droughts in Europe are not a new phenomenon of the beginning of the 21th Century. Already the 1940s and the 1950s have in fact experienced several relevant events (Briffa, Jones & Hulme 1994; Lloyd-Hughes & Saunders 2002; Van der Schrier *et al.* 2006; Spinoni *et al.* 2015a). For instance, the extraordinary drought event during the summer half year of 1947 that affected Central Europe had wide ranging socio-economic consequences (Brazdil *et al.* 2016). Extreme summer drought events and episodes also occurred in earlier centuries like in 1540 (Wetter *et al.* 2014; Pfister 2018) or the decade 1531–1540 (Brázdil *et al.* 2020).

Such meteorological droughts often propagate through all parts of the hydrological cycle and develop into agricultural (soil moisture) and hydrological droughts. Respective drought impacts on different systems can thus be observed considerably longer as indicated by the precipitation deficits measured by meteorological indices. Reported impacts connected with these droughts include decreased streamflow or groundwater levels (Koehler *et al.* 2007; Kohn *et al.* 2014; Laaha *et al.* 2017), adverse effects on agriculture and forestry (Ciais *et al.* 2005; Hlavinka *et al.* 2009; Allen *et al.* 2010; Buras, Rammig & Zang 2020; Schuldt *et al.* 2020) and limitations in the energy production (De Bono *et al.* 2004; Fink *et al.* 2004). In the long run, persistent lower-than-average precipitation conditions may even lead to soil degradation and desertification (Nicholson, Tucker & Ba 1998; Hueso, García & Hernández 2012).

Besides these summer drought events there is also concern about heavy precipitation events and connected flash floods and river floods. They are often connected with devastating impacts on society and economy with casualties and high costs due to direct structural and indirect socioeconomic damages. Among many others, those events include the 2002-flood along the Elbe and Odra rivers and their tributaries (Ulbrich *et al.* 2003; Kundzewicz *et al.* 2005; Thieken *et al.* 2005; Socher & Bohme-Korn 2008), the 2013-flood along the rivers Danube and Elbe (Belz *et al.* 2014; Merz *et al.* 2014; Schröter *et al.* 2015; Thieken *et al.* 2016), the exceptional sequence of thunderstorms and connected flash-flood events, e.g., in Braunsbach/Germany in 2016 (Piper *et al.* 2016; Bronstert *et al.* 2017; Bronstert *et al.* 2018) as well as the flooding events in July 2021 in Western Europe (Junghänel *et al.* 2021; Kreienkamp *et al.* 2021).

The rising average earth surface temperatures and the related increase in water pressure deficit (Wang *et al.* 2012; Yuan *et al.* 2019; Grossiord *et al.* 2020) more and more impact the observed severity of drought events, especially during the warm part of the year (Vicente-Serrano *et al.* 2014). Extremely high temperatures or long-lasting heatwaves often accompanied recent drought events (Rebetez *et al.* 2006; Graczyk & Kundzewicz 2014; Hoy *et al.* 2017; Sedlmeier, Feldmann & Schadler 2018). Such droughts under warmer temperatures are sometimes referred to as “global-change-type droughts” (Breshears *et al.* 2005; Adams *et al.* 2009; Eamus *et al.* 2013) or “hotter droughts” (Allen, Breshears & McDowell 2015; Buras, Rammig & Zang 2020; Schuldt *et al.* 2020). They are of particular interest due to their aggravated impacts, e.g. on vegetation vitality and mortality, in comparison to the drought events under “normal” climate conditions.

Different approaches and indices are used to evaluate the intensity, frequency and duration of drought conditions and heavy precipitation events. Widely used drought indices often address monthly, seasonal and annual time scales, like the Standardized Precipitation Index (SPI, McKee, Doesken and Kleist (1993)) and the Standardized Precipitation Evaporation Index (SPEI, Vicente-Serrano, Beguería and López-Moreno (2010). Many heavy precipitation indices and some dry period indices as defined by WMO (2009) are calculated based on daily data.

With regard to drought events, Spinoni *et al.* (2015b) provide an overview of the biggest events in Europe for 1950–2012 by combing three drought indices (SPI, SPEI and Reconnaissance Drought Index RDI (Tsakiris & Vangelis 2005) at the 3-month scale for meteorological and the 12-month scale for hydrological droughts. They also provide an extensive list of relevant references for the most important events. Their analysis identified pan-European drought events in 1950–1952, 1953–1954, 1972–1974, and 2003.

At the European scale several drought studies based on instrumental records have shown drying trends in Southern Europe, particularly in the Mediterranean region and wetting trends in Northern and North-Eastern Europe (e.g., (Briffa, van der Schrier & Jones 2009; Gudmundsson & Seneviratne 2015; Spinoni, Naumann & Vogt 2017; Stagge *et al.* 2017). Drought trends for central Europe are spatially and seasonally more diverse and often linked to temperature increases (Spinoni *et al.* 2015a; Hänsel *et al.* 2019). Since the 1990s rising average temperatures increasingly impact the observed severity of drought events, especially during the warm part of the year and in Southern Europe (Vicente-Serrano *et al.* 2014; García-Herrera *et al.* 2019).

A review by Madsen *et al.* (2014) that encompasses 46 studies with observation-based trend analyses and 33 studies relying on climate change projections for extreme precipitation and streamflow concludes that observations and climate model projections show an increase in extreme precipitation in Europe. More recent continental observation (Sun *et al.* 2021) and climate model-based studies (Li *et al.* 2021) on changes in heavy precipitation confirm these results. Thus, the most recent IPCC report AR6 of working group 1 (Seneviratne *et al.* 2021) concludes that there is robust evidence that the magnitude and intensity of extreme precipitation has very likely increased since the 1950s in Europe. Such increases in extreme precipitation are more frequently observed in summer and winter than in the transitional seasons (Madsen *et al.* 2014)

This study analyses spatial and temporal variations and trends in drought conditions and heavy precipitation events over Europe during the warm part of the year – here called summer half year (SHY: AMJJAS – April-May-June-July-August-September) – for the period 1901–2018. Such long-term variations and trends in drought conditions and heavy precipitation trends are of relevance for a lot of economic sectors, as they are often connected with adverse effects. Adaptation options mitigating drought risks could negatively affect the resilience against heavy precipitation events and vice versa. Thus, it's important to know if one should focus on one of these extremes or if adaptation measures capable of dealing with both extremes are needed. Some analyses are performed also for the summer season (JJA – June-July-August – results mainly reported as on-line supporting information). The study is based on a spatially well-distributed dataset comprising many of the longest and most reliable station time series with daily precipitation and daily extreme temperature data available in Europe. The characteristics of European record drought summers and temporal variations in drought characteristics are studied using a range of drought indices and combining them into an Aggregated Drought Evaluation index ADE. Furthermore, temporal variations in three heavy precipitation indices are analysed to evaluate impact relevant shifts in the climatic conditions in Europe and five sub-regions. In a last step the stations with a simultaneous increase in drought and heavy precipitation conditions are highlighted.

2. Data and methods

2.1 Study area and data base

We study long-term variability in summer droughts and the specifics of five record summers like 2018 based on 63 European stations with long time series (Figure 1). Thereby, we use the same station collective and the same regional grouping as applied by Hoy, Hänsel and Maugeri (2020) that were focusing on evaluating the heat conditions during the 2018 summer. Four stations were excluded, one due to missing long-term precipitation data and three other stations due to their location north of the Polar Circle, which challenges the calculation of potential evapotranspiration (PET).

Our focus on long-term station data with comparably well-documented metadata has some advantages over using gridded datasets – especially for the analysis of extreme events and the detection of climatic trends – and some disadvantages like the limited spatial coverage. Gridded data sets (both interpolated observations like EOBS and reanalyses (e.g. ERA5) are fundamental for climate change research, but for the study of long-term trends they have significant open issues. For example, it is still an open issue how accurate reanalyses are able to estimate long term trends with confidence due to changes in global observations (Thorne & Vose 2010; Dee *et al.* 2011). Thus, focussing on station data adds value to grid-data-focussed studies, which typically cover shorter timescales and include inherent inhomogeneities of the used stations, which are more difficult to detect compared to using station data directly.

The study is based on station data for daily precipitation (RR), as well as daily maximum (Tx) and minimum temperature (Tn). The station datasets belong to the longest, most complete and most reliable (homogenous) time series in Europe. They have been selected to obtain a spatially well distributed dataset. This means that some nearby stations with similarly long records have not been included in the analysis in order to avoid regional imbalances in the analyses. Almost all stations are located at altitudes below 500 m (three exceptions up to 667 m). Thus, influences on the analyses by specific climatic effects from high mountain ranges are avoided.

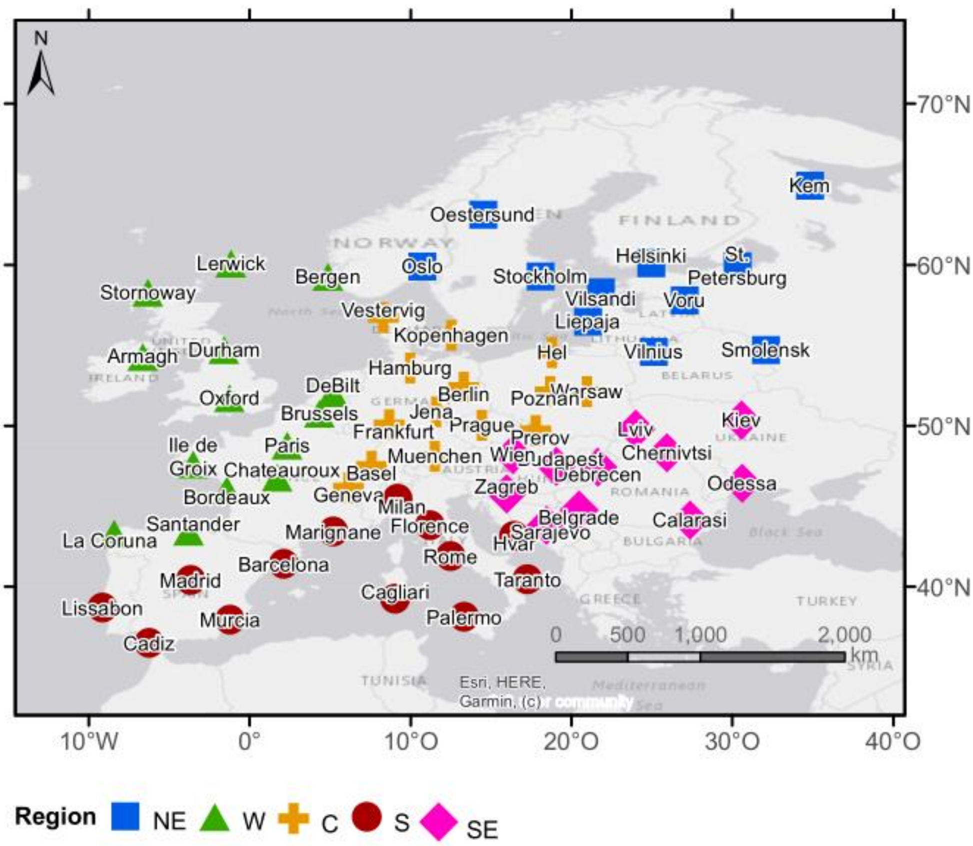

Figure 1: Map of the study area showing the location of the 63 meteorological stations and their classification into five sub-regions (NE: North-East, W: West, C: Central, S: South, SE: South-East)

The five regions with individual station numbers between 11 and 14 stations are:

- **NE** (North-East; 11 stations) with a cool and rather continental climate,
- **W** (West; 13 stations) with a rather cool and more maritime climate,
- **C** (Central; 14 stations) with temperate summers in the transition zone between maritime and continental climate,

- **S** (South; 14 stations) with subtropical summers,
- **SE (**South-East; 11 stations) with a warm and continental climate.

Information on the regional grouping methods, the temperature characteristics of the five regions and generally on the data base and the quality of the station series can be obtained from Hoy, Hänsel and Maugeri (2020). Hoy, Hänsel and Maugeri (2020) carefully checked and described the homogeneity of the long-term temperature series that are the basis for the calculation of potential evapotranspiration needed to compute some of the applied drought indices.

Our analyses start in 1901, when more than half of the stations have precipitation and temperature data available. Data availability is rising during the 20th century with some temporary drops in the availability of precipitation and temperature data towards the end of both world wars (Figure 2). Data of all stations, with few exceptions during individual years, are available since 1951. All time-series are updated until October 2018 or longer. The data availability of temperature and thus potential evapotranspiration (PET) data (Figure 2b) is slightly better than the one of precipitation data (Figure 2a). Thus, the availability of information on the climatic water balance (RR – PET, Figure 2c) is mainly restricted by the availability of precipitation data.

No method for filling small gaps in the daily series was applied. Our focus was on high quality and preferably complete datasets. A missing day leads to the termination of a dry period that are calculated based on daily data. For the calculation of monthly precipitation and PET data 2 missing days were allowed for each month. If in a month more than 2 days are missing the monthly value is set "not available" (na) and thus also the seasonal/annual value is set "na".

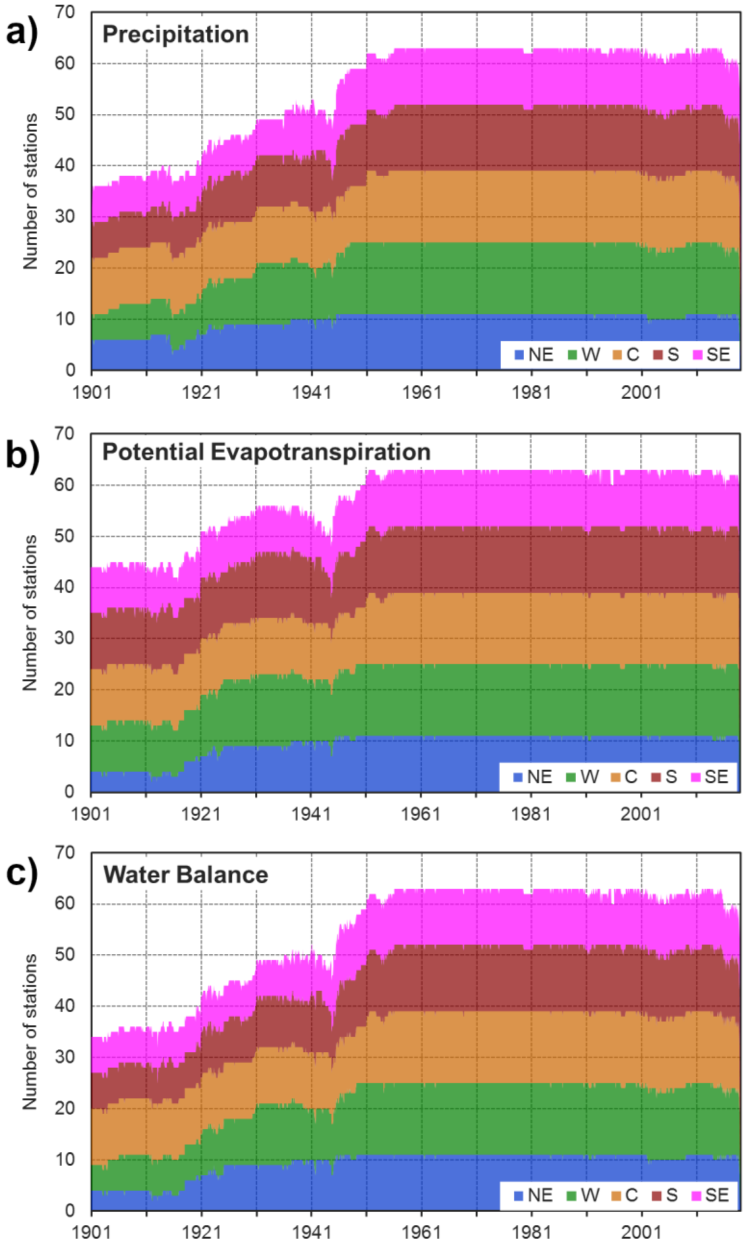

Figure 2: Availability of (a) precipitation and (b) potential evapotranspiration (PET) and (c) climatic water balance data at 63 stations within five sub-regions (NE: North-East, W: West, C: Central, S: South, SE: South-East) during 1901–2018.

2.2 Climate indices

2.2.1 Drought indices

Precipitation characteristics are evaluated using indices based on daily as well as monthly data. We are also using drought indices incorporating information on potential evapotranspiration PET as the severity of droughts may be underestimated by purely precipitation-based indices, particularly in a warming climate (Vicente-Serrano, Beguería & López-Moreno 2010; Vicente-Serrano *et al.* 2014). Our study is on meteorological drought characteristics and conclusions on soil moisture cannot be drawn directly. We are using PET and not the actual evapotranspiration in the drought index calculations. Thus, we can only compute a theoretical climatic water balance. Such a climatic water balance deviates from the actual water balance that is determining the availability of soil water for plants and the moisture fluxes to the atmosphere. Using this kind of drought indices has some limitations with respect to the evaluation of soil moisture and moisture fluxes to the atmosphere. For soils that are already depleted of moisture it does not really matter how large PET is and the actual evapotranspiration will be rather low in such cases.

Considered indices based on daily data are displayed in Table 1. Dry periods are defined as a sequence of days with precipitation below a specific threshold, whereby different studies use different thresholds like 0.1, 1.0, 5.0 and 10.0 mm/day (Perzyna 1994; Lana *et al.* 2008; Cindrić *et al.* 2010; Serra *et al.* 2014). We use a threshold of 1.0 mm/ day for dry days (DD) that is related to evapotranspiration processes (Serra *et al.* 2014). Additionally, a dry period definition based on the daily climatic water balance (WB) is applied. Days with a climatic water balance below zero are defined as dry days in this case. For both definitions the average and maximum duration of consecutive sequences of such days are studied. These duration indices were calculated for the entire time series first. Thereby, the duration of a dry period is assigned to the day of its end. In a second step the results for the SHY and summer season were extracted by considering all periods whose end day lies within the respective analysis period.

Table 1: Name, definition and units of the daily and monthly climate indices used in this study

Index	**Description**	**Unit**
DD	Number of dry days (= days with daily precipitation totals below 1 mm)	days
AvD	Average duration of dry periods (= continuous sequence of DD)	days
CDD	Consecutive dry days (maximum duration of dry periods)	days
nWBD	Number of days with a negative climatic water balance (= days with WB < 0 mm)	days
AvDnWB	Average duration of periods with days showing a negative climatic water balance	days
MxDnWB	Maximum duration of periods with days showing a negative climatic water balance	days
Rx1day	Maximum daily precipitation total	mm
R95pTOT	Precipitation fraction due to very wet days in percent (= 100 % * (precipitation total of days above the 95th percentile / total precipitation))	%
R99pTOT	Precipitation fraction due to extremely wet days in percent (= 100 % * (precipitation total of days above the 99th percentile / total precipitation))	%
mRAI	Modified Rainfall Anomaly Index (Van Rooy 1965; Hänsel, Schucknecht & Matschullat 2016); Anomalies of precipitation at monthly timescales	without unit
WBAI	Water Balance Anomaly Index (Hänsel, Schucknecht & Matschullat 2016); Anomalies of the climatic water balance (RR – PET) at monthly timescales	without unit
ADE	Aggregated Drought Evaluation index (for details see section 2.2.2) Here, it integrates the information of eight standardized drought indices (mRAI, WBAI, DD, AvD, CDD, nWBD, AvDnWB, MxDnWB;), but the concept can be flexibly adapted to include other indices and thus other drought characteristics	without unit

On a monthly basis and for the evaluation of drought conditions on longer aggregation time scales (summer half year and summer) the Rainfall Anomaly Index RAI (Van Rooy 1965) in a modified version mRAI (Hänsel, Schucknecht & Matschullat 2016) and the Water Balance Anomaly Index WBAI (Hänsel, Schucknecht & Matschullat 2016) are applied (Table 1). Hoy *et al.* (2017) have shown that the mRAI delivers well comparable results to the well-known Standardized Precipitation Index SPI (McKee, Doesken & Kleist 1993) over Europe, while the WBAI is comparable to the Standardized Precipitation Evaporation Index SPEI (Vicente-Serrano, Beguería & López-Moreno 2010).

The indices mRAI and WBAI are calculated using a straightforward standardization approach for precipitation (RR) and the climatic water balance (WB = RR – PET), respectively. The median precipitation total and climatic water balance, respectively, is used as proxy for the average of the distribution, while the average of the 10 percent most extreme wet and dry cases describes the variability of the distribution. Different values representing the variability are used for each side of the distribution in order to account for skewed distributions. The mRAI of a certain month (or other aggregation period) *i* is calculated as follows:

$$mRAI_i = \pm SF * \frac{RR_i - \overline{RR}}{\bar{E} - \overline{RR}}$$

where

RR_i	=	Precipitation total of month i
$\overline{RR}$	=	Median monthly precipitation of the base period 1951–2010 for the respective month
$\bar{E}$	=	Mean of the 10 % most extreme precipitation totals of the base period 1951–2010 for the respective month. For negative anomalies of $RR_i - \overline{RR}$ the events below the 10th percentile are used and for positive anomalies those above the 90th percentile
±SF	=	Scaling factor (positive for $RR_i \geq \overline{RR}$, and negative for $RR_i < \overline{RR}$)

The index is calculated using a 60-year base period, as a long base period ensures a good representation of the climate variability and the extremes of the distribution. The period 1951–2010 was chosen, as data availability is best during these 60 years allowing for a regionally well comparable derivation of the factors needed to calculate the indices.

The WBAI is calculated in the same way as illustrated for the mRAI by replacing RR with WB:

$$WBAI_i = \pm SF * \frac{WB_i - \overline{WB}}{\bar{E} - \overline{WB}}$$

So, the actual climatic water balance value of month *i* (WB_i) is compared to the median value ($\overline{WB}$) of this month within 1951–2010 and the variability of the distribution is estimated by the distance of the mean of the 6 most extreme climatic water balance values ($\bar{E}$) to the median of the distribution. For both calculations (mRAI and WBAI) a scaling factor of SF = 1.7 is applied as suggested by Hänsel, Schucknecht and Matschullat (2016) in order to obtain similar values and class frequencies as those of SPI and SPEI. This allows using the same classification of moisture classes that were suggested by McKee, Doesken and Kleist (1993) for the SPI (Table 2).

WBAI and mRAI are applied at timescales of 1, 3, and 6 months. The respective timescale is indicated by a number in the index name, e.g. mRAI-6 refers to the modified Rainfall Anomaly Index at a timescale of 6 months. The indices are used to describe the drought intensity at monthly time scale (mRAI-1 and WBAI-1) for the summer half year (mRAI-6 and WBAI-6 for September covering the entire SHY from April to September) and the summer season (mRAI-3 and WBAI-3 for August). In the following we indicate these indices without specifying the considered time scale because SHY indices are always "-6" values for September, summer indices are always "-3" values for August and monthly indices are always "-1" values referring to the considered month.

The Hargreaves-Samani approach (Hargreaves & Samani 1985) is applied for the calculation of PET on a daily scale. It uses information on the geographical location, average precipitation totals and minimum as well as maximum daily temperatures. Thereby, minimum and maximum temperature is used to estimate solar radiation from the extraterrestrial radiation. We are using the R-package Evapotranspiration Version 1.15 with the function ET.HargreavesSamani for our calculations. The application of more complex PET calculation approaches like the Penman-Monteith formulation (Allen *et al.* 1998) is not possible due to the restricted availability of the necessary climate parameters (e.g., relative humidity, global radiation or wind speed). Many studies already compared different PET parametrizations and their effect on climatic trends such as(Hargreaves & Allen

2003); Vangelis, Tigkas and Tsakiris (2013); Stagge *et al.* (2014); Almorox, Quej and Martí (2015); (Mohammed & Scholz 2017); Spinoni, Naumann and Vogt (2017); Zarei and Mahmoudi (2017); Moratiel *et al.* (2020); Kaya *et al.* (2021). Several studies (Hargreaves & Allen 2003; Mohammed & Scholz 2017; Spinoni, Naumann & Vogt 2017) have shown that the Hargreaves-Samani approach delivers well usable results that are closer to the PET computed by the Penman-Monteith formulation than those obtained with the Thornthwaite approach (Thornthwaite 1948). The chosen Hargreaves-Samani approach was already successfully applied in other drought trend studies over Europe (Ionita *et al.* 2017; Spinoni, Naumann & Vogt 2017; Spinoni *et al.* 2018), as was the Thornthwaite approach (Briffa, van der Schrier & Jones 2009; Spinoni *et al.* 2015a; Spinoni *et al.* 2015b). Stagge *et al.* (2014) have shown that the SPEI values are least sensitive to the chosen PET equation during the summer season, which is in the focus of this study.

Table 2: Classification of the mRAI and WBAI into nine moisture classes using the same classification as suggested by McKee, Doesken and Kleist (1993) for the SPI.

Class	Index-value	Description
1	≥2.00	Extremely wet
2	1.50 to 1.99	Very wet
3	1.00 to 1.49	Moderately wet
4	0.50 to 0.99	Slightly wet
5	−0.49 to 0.49	Near normal
6	−0.99 to −0.50	Slightly dry
7	−1.49 to −1.00	Moderately dry
8	−1.99 to −1.50	Severely dry
9	≤ −2.00	Extremely dry

2.2.2 Standardization of indices and aggregated drought evaluation

Drought has different facets that can be measured by different indices. The Aggregated Drought Evaluation index ADE (Hänsel *et al.* 2019) is a concept that aims at integrating the information delivered by different drought indices into one evaluation and thus providing a synoptic description of many factors inducing drier conditions over Europe. It can be applied to whatever set of indices is deemed suitable to evaluate drought conditions. Here, we decided to integrate the information of eight standardized drought indices (Table 1). The ADE is derived by first standardizing the drought indices using the same approach as applied for mRAI and WBAI, so that the magnitude of the index values, their sign and the respective trends are well comparable. Here, it is computed by averaging mRAI, WBAI, the mean of the standardized versions of the three drought indices related to DD (DD, AvD, CDD) and the mean of the standardized versions of the three indices related to nWB (nWB, AvDnWB, MxDnWB).

2.2.3 Heavy precipitation indices

In order to compare the observed drought trends with changes in heavy precipitation three heavy precipitation indices are included in the analysis (see index definitions in Table 1). We use the maximum daily precipitation total per season (Rx1day) as an index for the absolute magnitude of heavy precipitation and two percentile-based indices to capture changes in the precipitation fraction due to heavy precipitation days (R95pTOT, R99pTOT). The percentiles are calculated for the reference period 1961–1990.

2.3 Methods

We decided to focus on the warm part of the year – the Northern hemisphere summer half year (SHY, April to September). Focusing on the half years instead of the seasons helps to differentiate between a general winter (about mid-Oct to mid-Apr) and summer atmospheric circulation (mid-Apr to mid-Oct). Precipitation of the winter half year is much more dependent on the large-scale synoptic circulation than the latter one, which is more characterized by thermal convective precipitation. Furthermore, during the SHY more frequent and severe impacts related to drought as well as heavy precipitation events are to be expected. The evolution of drought conditions often already starts in spring. Due to a soil moisture-atmosphere feedback dry and warm conditions in spring can lead to dry and warm conditions during the summer season and even further propagating into autumn (e.g., Fischer *et al.* (2007a); Fischer *et al.* (2007b)).

Trend analyses were conducted for the aggregated drought evaluation index ADE and the heavy precipitation indices. Simple linear regression (least squares method) is used to identify the long-term changes within the periods 1901–2018 and 1951–2018. Trends are classified into seven categories according to trend magnitude (Table 3) for the display in trend maps. Those maps illustrate the spatial consistence of trends and give information on their statistical significance. The Mann-Kendall trend test (Mann 1945; Kendall 1975) is used to determine the significance of trends (https://rdocumentation.org/packages/modifiedmk/versions/1.6, function mkttest). Additionally, maps are provided to illustrate which stations show increasing trends in drought and/or heavy precipitation. For this purpose, the stations are classified into the following four categories.

1) **D**: Stations showing an increase in drought conditions and negative or no trend in heavy precipitation.
2) **H**: Stations showing an increase in heavy precipitation events and getting less severe drought conditions or showing no drought trend;
3) **D+H**: Stations which simultaneously show increasing drought and heavy precipitation trends.
4) **N**: Stations having no trend or decreasing trends in drought and/or heavy precipitation conditions.

The drought trends are determined using the ADE. An increase in drought conditions is indicated by absolute trend values < -0.25. Heavy precipitation trends are obtained by averaging the relative trends of the three heavy precipitation indices. Increasing heavy precipitation conditions are indicated by an average trend of > 7 % (the threshold between no trend and positive trend was 5 % for R95pTOT and Rx1day, while it was 10 % for R99pTOT).

No linear trends are displayed in the regionally averaged time series plots. Precipitation-based indices generally show a high temporal variability at different timescales and the computed linear trends strongly depend on the values at the beginning and the end of the time series. Therefore, 30-year-averages (1901–1930, 1931–1960, 1961–1990, and 1991–2018) are used in the graphics of individual indices to indicate long-term deviations and changes. Information on the statistical significance of the linear trends is not shown, as the focus is on the long-term temporal variability of precipitation characteristics and linear trends describe those variations insufficiently.

Table 3: Classification of trend values used for the illustration of the spatial consistence of seasonal trends (for index abbreviations please refer to Table 1)

Trend category	**ADE**	**R95pTOT, Rx1day [%]**	**R99pTOT [%]**
Very wet	> 1.0	> 25	> 50
Wet	0.5 to 1.0	15 to 25	30 to 50
Slightly wet	0.25 to 0.5	5 to 15	10 to 30
Indifferent	-0.25 to 0.25	-5 to 5	-10 to 10
Slightly dry	-0.5 to -0.25	-15 to -5	-30 to -10
Dry	- 1.0 to -0.5	-25 to -15	-50 to -30
Very dry	< -1.0	< -25	< -50

For the display of average index information for Europe and its sub-regions in the time series plots a simple averaging procedure is applied on the station values. Additionally, to the average of the entire dataset, sub-regional results are displayed by different symbols. Those symbols and colours are consistently used within all maps and figures in order to facilitate the identification of sub-regional specifics. In order to compare the characteristics of different drought indices scatterplots and correlation analysis (Pearson-product-moment correlation) are used.

3. Results

3.1 The most extreme drought summers in Europe

Based on the Aggregated Drought Evaluation ADE the most extreme drought summer half years (SHY; April to September) have been identified for the study area and its five sub-regions (Table 4). The driest SHY occurred in 1947 (see also Figure 3 for selected individual drought indices), with dry conditions from April, to October (see Figure 4). This SHY is also in the TOP5 of the regions Central and South-East. The second driest SHY over Europe is 2018 which is the driest SHY in region Central (also refer to Figure 3 for some individual drought indices). The SHY of 2003 is ranked third, while the SHYs of 1921 and 1911 are on rank four and five. 1911 and 1921 are also in the TOP5 of regions West and Central, while 2003 misses the TOP5 in each of the sub-regions (rank 7 in the regions W, C, S and SE). The strongest similarities between the sub-regional TOP5 and the overall TOP5 is visible for region Central. This is probably connected to the comparatively small distance of the region Central to all other regions and the location of the centres of individual drought events. Drought events centred over one of the regions NE, W, S and SE are more frequently related with drought conditions in the central region C than, e.g., drought conditions in the northern regions with those in the southern part of Europe. High ADE-values for Europe are reached if the central region and parts of neighbouring regions are impacted, while the rest of the regions shows close to normal conditions. In contrast, a drought centre over the North or South of Europe is often connected with reverse moisture conditions in the rest of Europe and thus lower overall ADE-values. Corresponding results for summer (June to August) are presented and discussed in the on-line supporting information (Table S-1).

Table 4: The five most extreme drought summer half years according to the Aggregated Drought Evaluation index ADE. Displayed are the results for the entire study area and its five sub-regions. The five most extreme years over Europe are highlighted by different background colors (blue indicates years at the beginning of the 20th century, green indicates years of the mid of the 20th century and orange/red is used for highlighting years at the beginning of the 20th century). If these years also belong to the TOP5 in the five sub-regions then they are highlighted by the same color.

	Europe		West		North-East		South-East		Central		South	
rank	**ADE**	**Year**	**ADE**	**Year**	**ADE**	**Year**	**ADE**	**Year**	**ADE**	**Year**	**ADE**	**Year**
1	-0.97	1947	-1.57	1921	-1.37	1901	-1.75	1946	-1.71	2018	-1.54	1945
2	-0.83	2018	-1.20	1911	-1.27	2002	-1.29	1950	-1.71	1947	-0.88	1927
3	-0.70	2003	-1.18	1976	-1.17	1959	-1.19	2015	-1.57	1976	-0.85	1922
4	-0.69	1921	-1.03	1949	-1.05	1939	-1.12	1947	-1.50	1911	-0.79	1943
5	-0.65	1911	-0.93	1955	-0.95	1941	-1.07	2009	-1.27	1921	-0.74	2017

The comparison of the drought year ranking results for the individual indices shows some deviations, but the general identification of extreme drought summers is similar. There is quite a good correlation of the purely precipitation based index mRAI and the WB-based index WBAI (Figure 3a; Table 5) as well as between the WBAI and the number of dry days (Figure 3c; Table 5). Focusing on the most extreme drought SHYs shows that there is a tendency of lower index values for the WBAI in comparison to the mRAI (Figure 3b). High temperatures and thus high evapotranspiration rates may significantly enhance already existing drought conditions due to a deficit in rainfall.

As all drought indices are describing different facets of the same phenomenon, they are not statistically independent. We are presenting the correlations between different indices to illustrate that some indices contribute more to the final ADE than others. Thereby, the ADE does not replace the use and interpretation of individual drought indices and thus specific drought characteristics. It just supplements such individual analyses and tries to present an integrated evaluation.

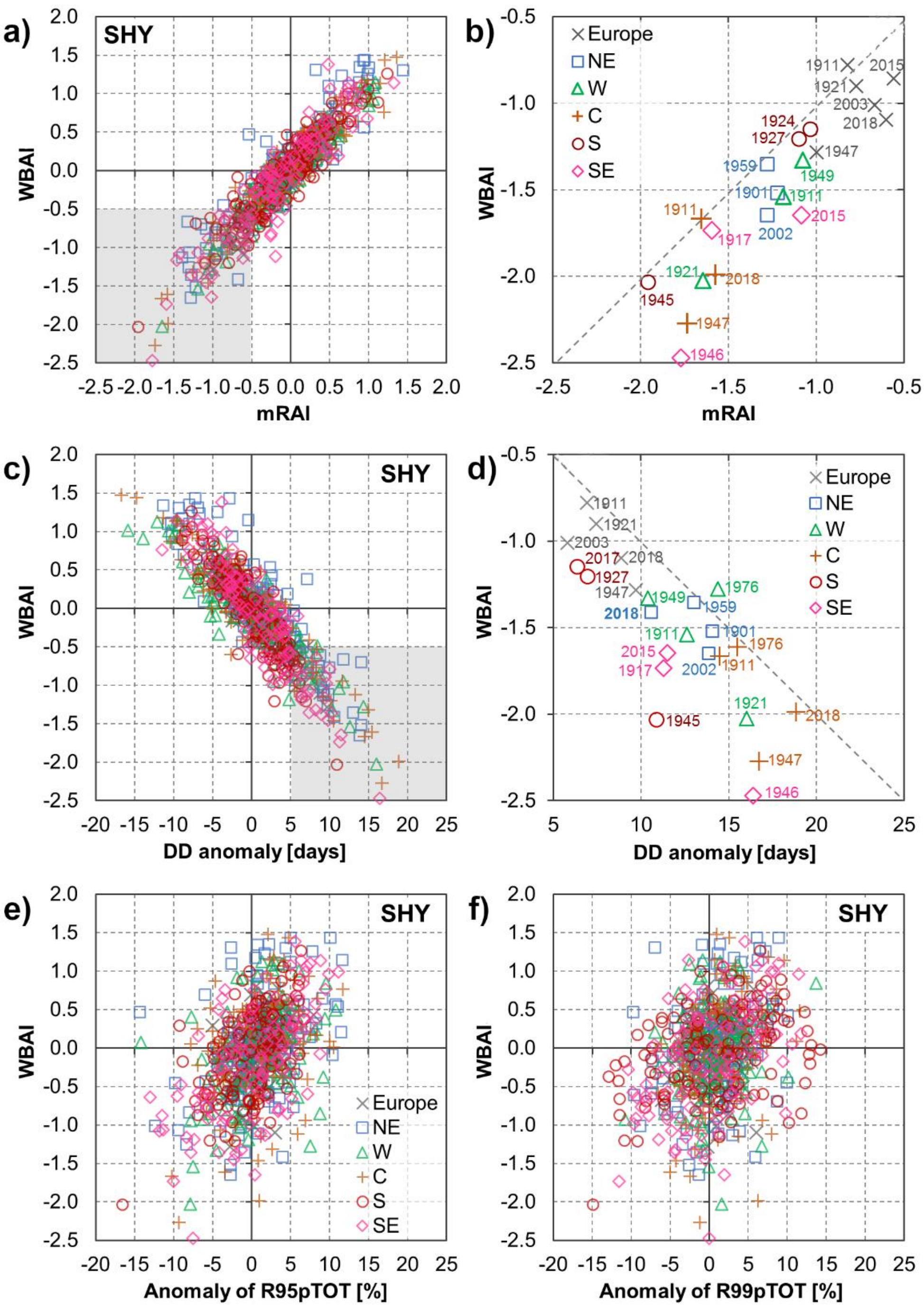

Figure 3: Scatterplots of regionally averaged summer half year values of (a) and (b) WBAI versus RAI, (c) and (d) WBAI versus the anomaly of dry days as well as WBAI versus (e) the anomaly of R95pTOT and (f) the anomaly of R99pTOT. Subplots (a), (c), (e) and (f) display the values of all summer half years of period 1901–2018, while subplots (b) and (d) present the section of the most extreme drought SHYs (TOP5 for Europe

and TOP3 for the sub-regions; more than three sub-regional values may be displayed in case the TOP3 of the two displayed indices do not cover the same three years).

The correlation matrix (Table 5) of all drought indices contributing to the definition of ADE shows very high correlation values between mRAI, WBAI, and the simple counting indices DD and nWB, while the correlation to indices measuring the duration of dry periods and periods with a negative climatic water balance is considerably lower. Negative correlations between mRAI/WBAI and the dry and negative climatic water balance periods are due to the individual index definitions, with negative values indicating drought conditions for mRAI/WBAI and positive anomalies indicating drier than normal conditions for DD and nWB and their derivates. Comparing the correlations for periods 1901–1990 and 1991–2018 shows that the correlations between the individual drought indices are quite independent from the considered study period. The correlations between drought and heavy precipitation indices seem to depend a bit more on the chosen study period. In any case, dry SHYs are connected with lower values in the heavy precipitation indices, but the correlations between the drought indices mRAI and WBAI and the heavy precipitation indices R95pTOT and particularly R99pTOT decrease slightly during 1991–2018 in comparison to 1901–1990. This decrease is however not present for Rx1day. The rather low correlations between the heavy precipitation indices and the drought indices based on daily data highlight that the frequency of heavy precipitation events is not strongly related to the frequency of dry and wet days.

Table 5: Correlation matrices illustrating the correlation between different drought and heavy precipitation indices for the SHY within period 1901–1990 (upper right corner) and during the last 28 years 1991–2018 (lower left corner). Orange background colors indicate positive correlations, while blue background colors illustrate negative correlations.

SHY		1901-1990											
		ADE	mRAI	WBAI	DD	AvD	MxD	WBD	WB-AvD	WB-MxD	R95pTOT	R99pTOT	Rx1day
1991-2018	ADE		0.94	0.95	-0.95	-0.44	-0.39	-0.96	-0.65	-0.60	0.4	0.25	0.34
	mRAI	0.95		0.95	-0.90	-0.42	-0.27	-0.92	-0.64	-0.49	0.59	0.41	0.52
	WBAI	0.95	0.92		-0.90	-0.47	-0.30	-0.91	-0.71	-0.54	0.49	0.32	0.42
	DD	-0.93	-0.85	-0.86		0.39	0.27	0.97	0.58	0.47	-0.23	-0.09	-0.23
	AvD	-0.56	-0.57	-0.59	0.52		0.38	0.34	0.79	0.44	-0.16	0.02	-0.06
	MxD	-0.41	-0.25	-0.28	0.28	0.36		0.26	0.25	0.75	-0.13	-0.12	-0.14
	WBD	-0.94	-0.91	-0.88	0.95	0.45	0.27		0.57	0.46	-0.30	-0.15	-0.29
	WB-AvD	-0.55	-0.59	-0.57	0.48	0.76	0.14	0.48		0.5	-0.33	-0.14	-0.21
	WB-MxD	-0.44	-0.34	-0.36	0.26	0.45	0.78	0.28	0.39		-0.30	-0.19	-0.27
	R95pTOT	0.27	0.49	0.38	-0.03	-0.22	0.13	-0.19	-0.32	-0.11		0.77	0.71
	R99pTOT	0.01	0.21	0.08	0.18	-0.34	-0.10	0.09	-0.37	-0.24	0.68		0.81
	Rx1day	0.38	0.53	0.42	-0.23	-0.50	-0.12	-0.28	-0.55	-0.16	0.56	0.69	

Studying the rainfall and climatic water balance anomalies of individual months, can explain the differences in the TOP5 for the SHY and the summer season (Table S-1). Figure 4 shows the mRAI and WBAI from January to December for the TOP5 drought SHYs presented in Table 4.

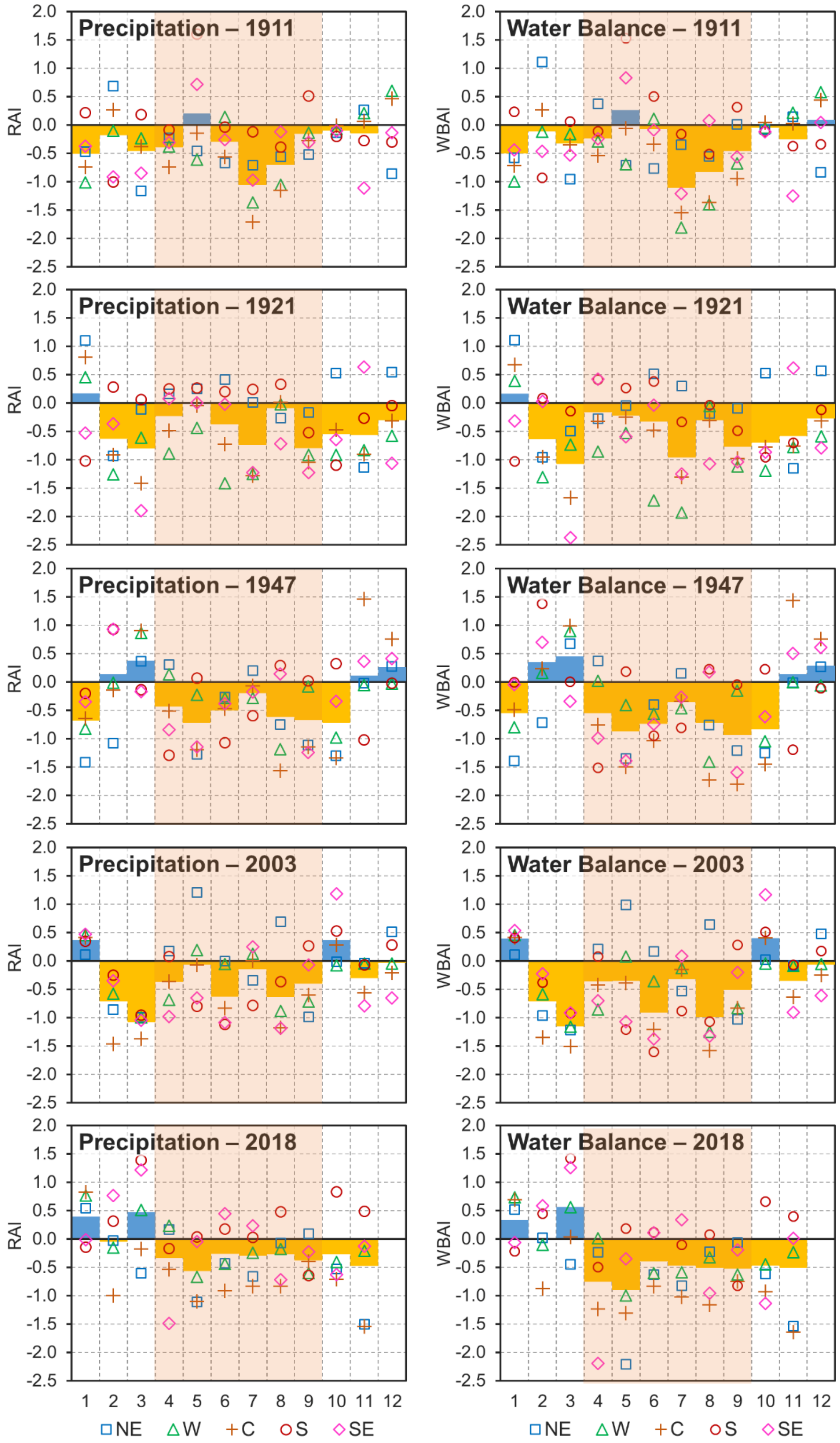

Figure 4: Monthly anomalies of precipitation (left) and climatic water balance (right) for the months January to December (November for 2018). Displayed are the regionally averaged anomalies for the five driest summer half years 1911, 1921, 1947, 2003 and 2018 for entire Europe (columns) as well as the five sub-regions (individual symbols).

Particularly for the more recent years 2003 and 2018, but also for 1947 the monthly negative anomalies of the climatic water balance during the SHY are considerably higher (in absolute values) as compared to the rainfall anomalies. During these years high temperatures were aggravating the drought conditions caused by rainfall deficits. The moisture preconditions before the start of the analyzed SHY may significantly mitigate or aggravate the manifold drought impacts in different sectors during the successive summer months. For instance, without the comparatively wet March the extensive agricultural and hydrological drought impacts in 1947 and 2018 could have been even worse.

The additional plot of the sub-regional anomalies of precipitation (mRAI) and climatic water balance (WBAI) in Figure 4 illustrates that during most months and years there is quite a large variability of drought conditions over Europe. For instance, the SHY of 1921 was almost normal in the regions South and North-West, while high negative anomalies occurred in the regions Central and West. Nonetheless, there are some months that have been considerably dry within all sub-regions, namely July 1911, June 1947 as well as February and March 2003.

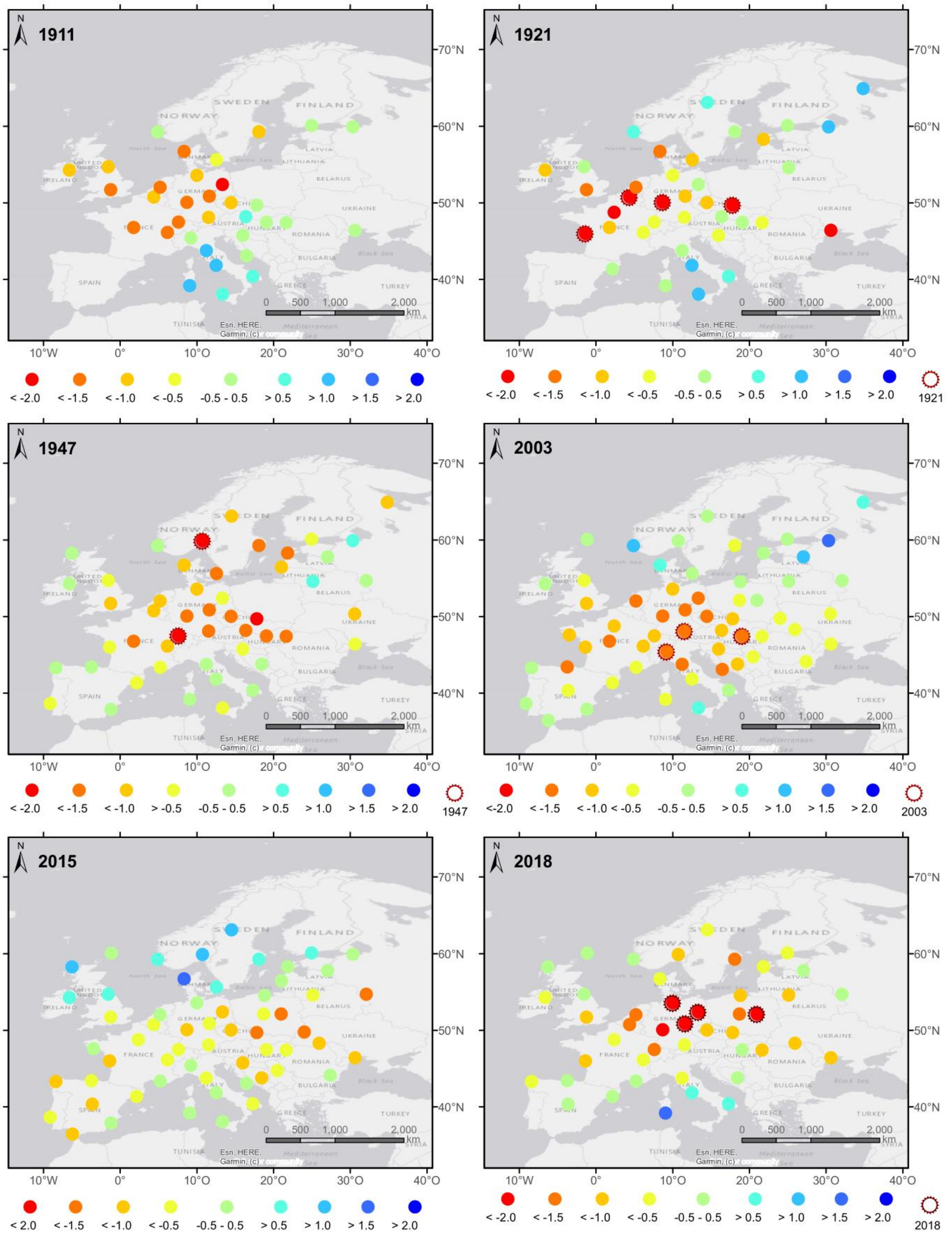

Figure 5: Maps of the station ADE-values for the summer half year (from extremely dry conditions in red over normal conditions in green to extremely wet conditions in blue). Displayed are the values for the five driest SHYs and additionally 2015, as an example for another recent drought summer. The sun-symbols indicate the stations that reach record values during the displayed year.

The regional characteristics of the five driest years are illustrated in maps, showing the ADE value for the respective SHY (Figure 5). Additionally, the ADE of the recent drought summer 2015 (rank 9 of the driest SHYs in Europe) is illustrated. The SHY of 1911 has been dry in Western and Central Europe, while it was a normal to wet year in the South and East. This map also shows that during the first decades of the 20th century there are some restrictions in the regional coverage, as no station at the Iberian Peninsula could be included in the evaluation.

The SHY of 1921 was particularly dry around 50° northern latitude from the West to the East of the study area (Figure 5). Stations in the North as well as in the South show wet anomalies. In 1947 and 2003 the drought conditions during the SHY were spatially very extended, covering large parts of the study area with just a few stations showing wetter than normal conditions. The drought center in 1947 was shifted a bit more to the North as compared to 2003, where normal to wet conditions were observed at the stations in region North. The drought conditions of the SHY 2015 stretched from the Iberian Peninsula over France and Germany to the very East of the study area, while the North of Europe was wetter than normal. Very intense drought conditions during the SHY occurred in 2018 over Germany. The spatial extent of the 2018-drought is similar to the one of 1947 with drought conditions reaching North up to Scandinavia.

3.2 Temporal changes in drought and heavy precipitation over Europe and its sub-regions

3.2.1 Variations in drought characteristics

Temporal variations in the drought characteristics over Europe and its sub-regions are studied for several drought indices for the summer half year as well as the summer season. The time series plots show that with respect to rainfall and climatic water balance anomalies the 1930s and in particular the 1940s have been characterized by series of dry summer half years and summers in Europe (Figure 6 and Figure S-1 in the on-line supporting information). The last 28 SHYs and summers (1991–2018) have been on average the driest with respect to the WBAI as compared to the three preceding 30-year averages (1901–1930, 1931–1960, and 1961–1990). With respect to the rainfall anomalies (mRAI) the last 28-year summer and SHYs were quite close to normal conditions, with some very dry and some very wet years. This shows the strong influence of rising summer temperatures on drought conditions over Europe. The number of dry days (DD) as well as days with a negative climatic water balance (nWBD) shows considerable variations, but no clear trend over the entire study area for the summer season (Figure S-1 in the on-line supporting information). However, the number of such days increased during the SHY suggesting that considerable increases in DD and nWBD occurred during the transition months April, May and September. A high number of DD and nWBD is potentially connected with longer consecutive sequences of dry conditions. Thus, also the indices CCD and MxDnWB reach their highest 30-year averages for the SHY during the last of the four periods with only few and small negative anomalies (Figure 6).

The ADE index time series plot (Figure 7a and Figure S-2 in the on-line supporting information) shows the ability of this index in capturing the main features of the individual drought indices over Europe. During the first 30-year period (1901–1930) European ADE showed positive anomalies meaning wetter than normal conditions. European average ADE was then very close to 0 in the following 30-year period and slightly positive in the following one. Finally, in the last period (1991-2018) European ADE reached the lowest average, highlighting the dry character of this period already evident form Figure 6.

Figure 7b illustrates the spatial extent of drought conditions by plotting the fraction of stations under moderate drought (ADE ≤ -1.0), severe drought (ADE ≤ -1.5) and extreme drought (ADE ≤ -2.0) conditions. Seven SHYs stick out with a fraction of more than a third of the stations affected by drought conditions – these are 1947, 2003, 1911, 2018, 1976, 1959, and 1921 (in descending order). During the SHY of 1947 about half of the stations were under drought conditions. The largest proportion of stations under extreme drought conditions was reached in 1921 with about 15% of the stations.

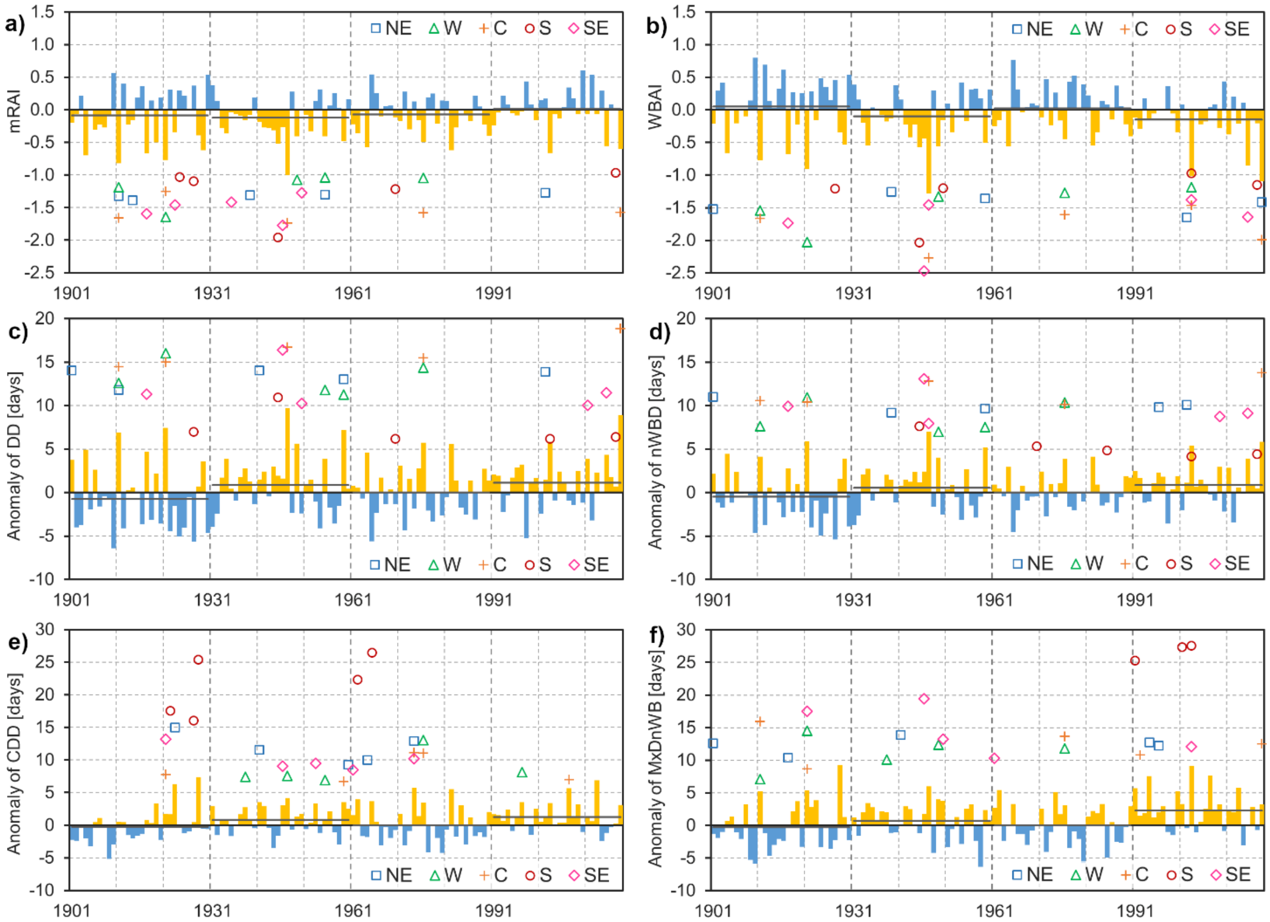

Figure 6: Regionally averaged SHY time series of the indices a) mRAI, b) WBAI as well as the anomalies of c) DD, d) nWBD, e) CDD and f) MxDnWB (for index definitions please refer to Table 1). Displayed are additionally the five most extreme drought events for the five sub-regions.

ADE index trends at individual stations are shown in Figure 8 (see Figure S-3 in the on-line supporting information for summer). As defined in Table 3, we classify the trend magnitude into seven classes, with three classes each representing a trend toward drier (red downward triangles) and wetter (blue upward triangles) conditions, respectively, and one class (green circles) comprising low trend values and thus “no change”. Additionally, the statistical significance of trends based on the Mann-Kendall test is indicated by star-symbols. Considerably less stations trends were computed for period 1901–2018 in comparison to period 1951–2018, due to the limited data availability at the beginning of the 20th century. Nonetheless, the general trend picture is quite independent from the study period. Trends towards drier conditions prevail in Southern and Central Europe up to a latitude of about 55°N, while several stations in the Northern part of Europe show trends towards wetter SHYs. The trend category representing strong wetting or drying trend, respectively, is not reached for the ADE at station level.

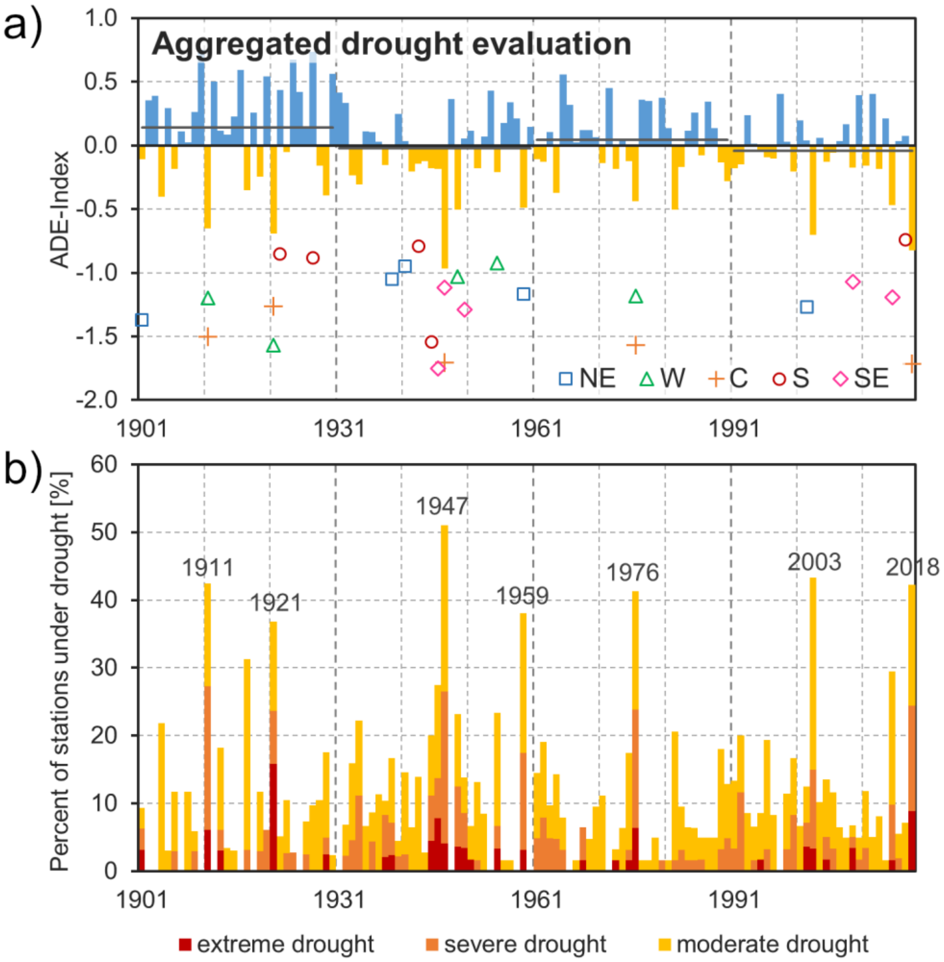

Figure 7: Timeseries of a) the regionally averaged ADE-values for the SHY (for index definition please refer to Table 1) and b) the percentage of stations under drought conditions according to the ADE (ADE ≤ -2.0/-1.5/-1.0 for extreme/severe/moderate drought). Additionally, the five most extreme drought events for the five sub-regions (individual symbols) are displayed are in subplot a).

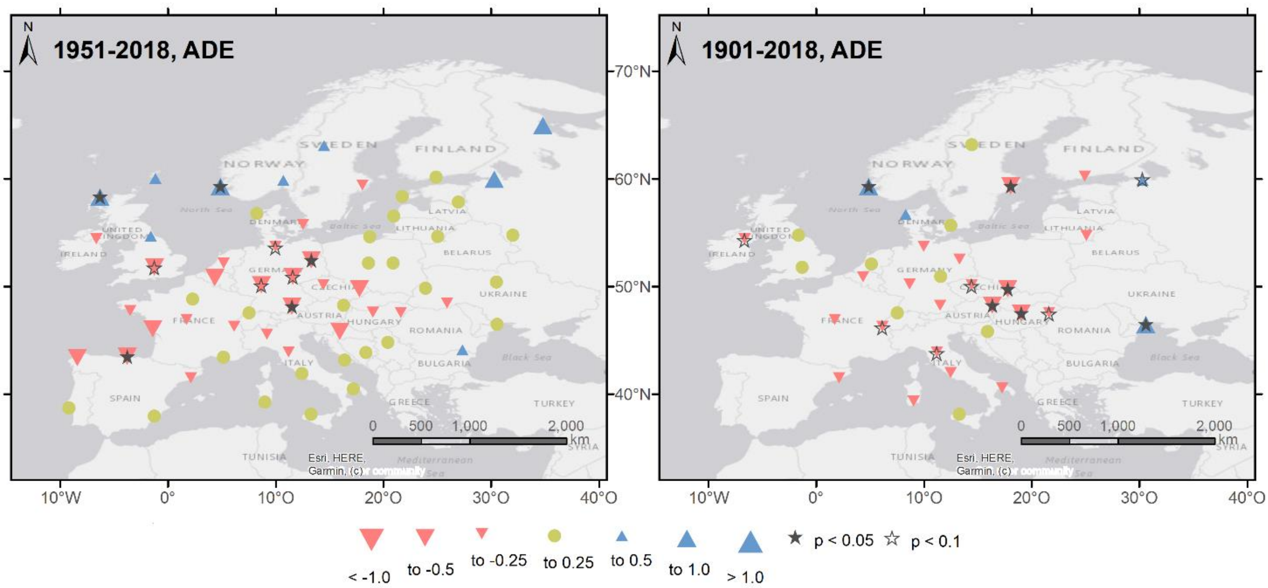

Figure 8: SHY trend maps showing the linear trends of ADE for the study periods 1951–2015 (left panel) and 1901–2018 (right panel). The stars indicate the statistical significance of trends according to the Mann-Kendall test.

3.2.2 Changes in heavy precipitation

Temporal variations in three selected heavy precipitation indices are studied in addition to the already presented drought indices. All three indices – R95pTOT, R99pTOT, and Rx1day – show increases with respect to 30-year averages (Figure 9). The highest 30-year average over all stations is reached at the end of the study period, with almost all SHYs showing positive anomalies within 1991–2018. 2010 has been the SHY with the by far strongest positive anomalies of R95pTOT and R99pTOT. The on average highest daily precipitation maxima (Rx1day) were reached during the SHYs of 2006 and 2002. The comparison with Figure 7 gives evidence that in the period 1901–1930 the three heavy precipitation indices were negative although the first 30-year period 1901–1930 showed wetter than normal condition (i.e. positive average ADE index). On the other hand, the negative ADE values for period 1991–2018 that point to drier than normal SHYs were connected with strongly positive anomalies of the heavy precipitation indices.

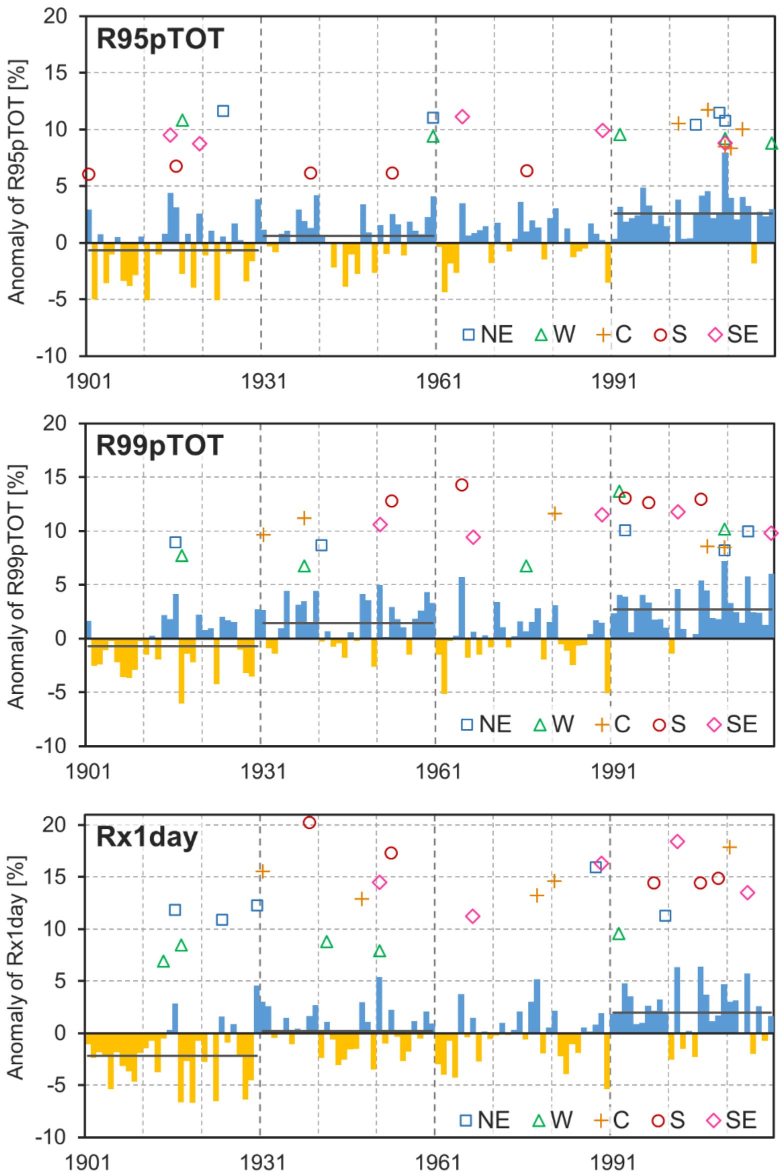

Figure 9: Regionally averaged SHY time series of three heavy precipitation indices, namely R95pTOT, R99pTOT, and Rx1day (for index definitions please refer to Table 1). Displayed are additionally the five most extreme SHYs with regard to heavy precipitation events for the five sub-regions (individual symbols).

Focusing on the sub-regional TOP5 SHYs illustrates a strong influence of the chosen index on the timing of the five largest events, particularly between R95pTOT representing moderate extremes and the indices R99pTOT and Rx1day focusing on rarer events. Most of the TOP5 of R95pTOT in the two southern regions (S: 5/5; SE 4/5) occurred before 1990, while for the other two indices two (SE)/ three (S) out of five record SHYs were observed during the most recent period 1991–2018. On the other hand, four of the TOP5 values of Rx1day for the regions NE, W and C occurred before 1991, while for the other two indices 2–4 of the regional TOP5 values occurred in the most recent period 1991–2018.

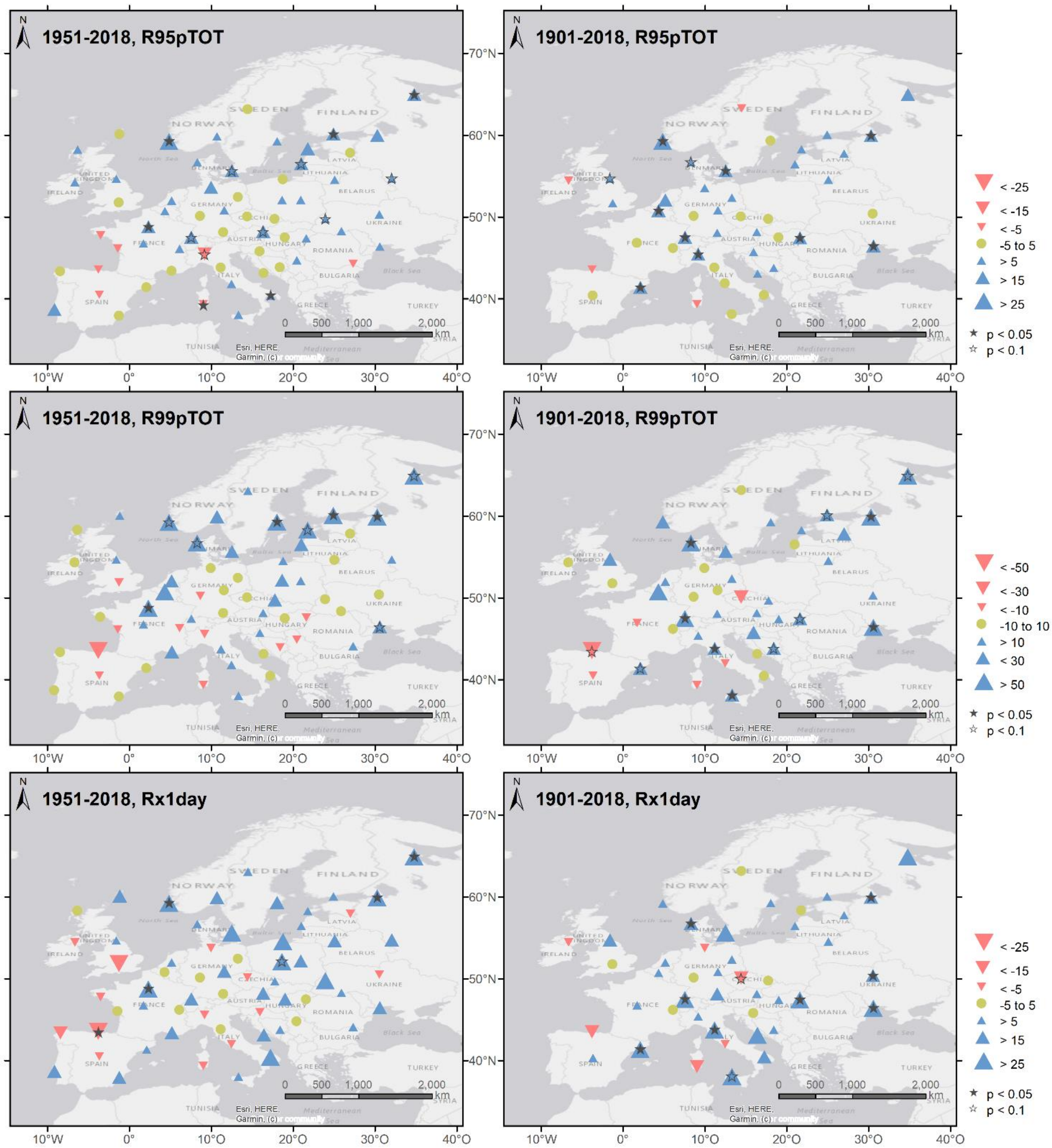

Figure 10: SHY trend maps showing the linear trends of three heavy precipitation indices (see Table 1 for index definitions) for the study periods 1951–2015 (left panel) and 1901–2018 (right panel). The stars indicate the statistical significance of trends according to the Mann-Kendall test.

Figure 10 presents the trend maps for the three heavy precipitation indices for the periods 1951–2018 and 1901–2018. As done for the ADE-maps (Figure 8) the trends are classified into 7 categories (Table 3). Thereby the green circles illustrate those stations showing low trend values and thus “no change”. Three classes each represent a decreasing (red downward triangles) and an increasing (blue upward triangles) trend of the heavy precipitation indices, respectively. Significant trends according to the Mann-Kendall test are indicated by star-symbols. All three heavy precipitation indices show mainly increasing trends at station level and just a few decreasing trends. There are more significant positive trends than one would expect to occur by chance. For the indices addressing more extreme precipitation events (R99pTOT and Rx1day) larger trend values are reached and at the same time negative trends occur more frequently. This reflects the large natural temporal variability of heavy precipitation. Stations with positive heavy precipitation trends appear in all five sub-regions. There are no clear spatial differences in the trend pattern as for the drought indices.

4. Discussion

4.1 Drought

Drought conditions during the summer season and particularly during the SHY have increased over Central and Southern Europe, as shown by the Aggregated Drought Evaluation index ADE (Figure 7 and Figure 8). The ADE combines eight individual drought indices that are based on daily and monthly values of precipitation and climatic water balance, respectively. The ADE can potentially integrate also other drought indices, depending on the drought characteristics that are in the study focus. Comparing the different drought indices shows larger negative values – meaning drier conditions – for indices that integrate PET into their calculation, particularly during recent decades. This matches observation of other studies (Vicente-Serrano *et al.* 2014; Spinoni, Naumann & Vogt 2017; Stagge *et al.* 2017) and it is also in good agreement with the results of Crespi *et al.* (2021) and Ranzi *et al.* (2021) that show a secular decrease (1845–2016) in runoff of the Italian river Adda by about 20 %, while in the same period precipitation over the same basin decreases only by about 5 %. Increasing summer temperatures are a main driver for recent drought extremes like 2003, 2015 and 2018 with the WBAI (-1.01, -0.86, and -1.10) reaching considerably lower values as compared to the mRAI (-0.67, -0.56, and -0.60). These climate change type droughts are connected with diverse negative effects on managed and natural ecosystems (Buras, Rammig & Zang 2020). The reduced productivity reveals itself in lower agricultural yields (Bakke, Ionita & Tallaksen 2020) and in an increasing tree mortality (Schuldt *et al.* 2020). In contrast, droughts at the beginning of the 20th century, e.g. 1911 (mRAI: -0.82, WBAI: -0.78), are more directly connected to rainfall deficits. Nonetheless, the combination of strong rainfall deficits with high temperatures and respective impacts on atmospheric evaporative demand is nothing new to the 21st century. The summer drought of 1947 was also considerably aggravated by unusually hot temperatures (mRAI: -1.00, WBAI: -1.28). The increase in dry days as well as days with a negative climatic water balance in transition months further facilitates the development of extreme SHY drought conditions in recent and coming decades.

Several studies put the recent drought events in a long-term perspective. Using reconstructed droughts over the last 250 years Hanel *et al.* (2018) conclude that the 2003 and 2015 droughts were the most extreme droughts driven by precipitation deficits during the vegetation periods, but their spatial extent and severity at the long-term European scale are less uncommon. The reconstruction of meteorological droughts by Cook *et al.* (2015) shows for the events in 1616, 1893 and 1921 a similar or higher spatial extent compared to recent events.

Many studies as well as the present study focus on individual drought seasons or years, but drought events may extend longer in time. The longer such a drought event persists the more severe are the negative impacts on water availability in natural and managed systems. Thus, the studied time-scale of droughts very much affects the results and conclusions, as other extreme drought events and impacts emerge, if longer time-scales are studied. For instance, García-Herrera *et al.* (2019) showed that the period July 2016 to June 2017 was very dry over large parts of the European continent with widespread impacts on water supplied, agriculture, and hydroelectric power production. The 2017 SHY and summer are not remarkably dry in our analysis as we are not considering the moisture conditions during the winter half year. Another example is the persistence of the drought conditions of 2018 to the subsequent year 2019 (Hari *et al.* 2020). Hari *et al.* (2020) showed that after the drought events in 2003 and 2015 vegetation health recovered and returned to its normal condition during the following years, while the impact of the 2018 drought on vegetation activities propagated to 2019. They conclude that the ongoing 2018–2019 European drought event is unprecedented in the last 250 years, with substantial implications for vegetation health. Reconstructing central European summer hydroclimate, Büntgen *et al.* (2021) find that the sequence of recent European summer droughts between 2015 and 2018 is unprecedented in the past 2,110 years within their analysed reconstructed time series. They conclude that this hydroclimatic anomaly is probably caused by anthropogenic warming and associated changes in the position of the summer jet stream. With respect to the evaluation of the expected drought impacts during the 21st century it is important to consider the different temporal scales of droughts. Hari *et al.* (2020) find a strong increase in the occurrence of such a rare event like the 2018/19 drought in the second half of the 21st century under RCP 8.5 scenario.

Different approaches for estimation evapotranspiration exist and depending on the region and season differences in the index numbers are occurring, which may bias the computed trends. These possible differences depend, for instance, on the ratio of the trends of average, minimum and maximum temperature. There is need for further studies on the seasonal effects of the chosen PET parametrization approach on the drought evaluation and trends on a daily scale.

4.2 Heavy precipitation

The investigation of three heavy precipitation indices (R95pTOT, R99pTOT, Rx1day) shows that a growingly proportion of precipitation in the SHY occurs in shorter periods of time. This results in more consecutive days with less or no precipitation and therefore more severe droughts conditions, even if average precipitation amounts are unchanged in comparison to past decades. An increase in precipitation extremes at the daily-scale in recent decades is support by other studies (Groisman *et al.* 2005; Alexander *et al.* 2006; Kunkel & Frankson 2015; Alexander 2016; Donat *et al.* 2016; Fischer & Knutti 2016). Rising global air temperatures may come along with an increasing frequency in heavy precipitation events (Allen & Ingram 2002; Westra, Alexander & Zwiers 2013; Westra *et al.* 2014) now and in future. This does not conflict with longer periods without or with little rain and thus increasing drought events.

Generally, the observed simultaneous increase of dry days and heavy precipitation indices during summer comes at the expense of moderate precipitation amounts with negative effects on soil moisture and groundwater recharge. Reduced soil moisture during the vegetation period adversely affects the productivity of terrestrial ecosystems and agricultural systems (farming and forestry) (Ruosteenoja *et al.* 2018). Furthermore, occasional heavy precipitation falling on dry soils leads to higher surface runoff and soil erosion, with additional negative impacts on soil structure and yields.

4.3 Drought and heavy precipitation

Drought and heavy precipitation events are both connected with specific impacts on different economic sectors and thus society. Regions that see simultaneously an increase in drought conditions and heavy precipitation events are probably exposed to higher risks and demand broader adaptation options. Therefore, we illustrate in Figure 11, which stations see positive drought trends (orange squares), positive heavy precipitation trends (blue triangles) and those who are exposed to both (purple hexagons). Green dots illustrate those stations that show no trends or a negative trend in one or both extreme characteristics of precipitation.

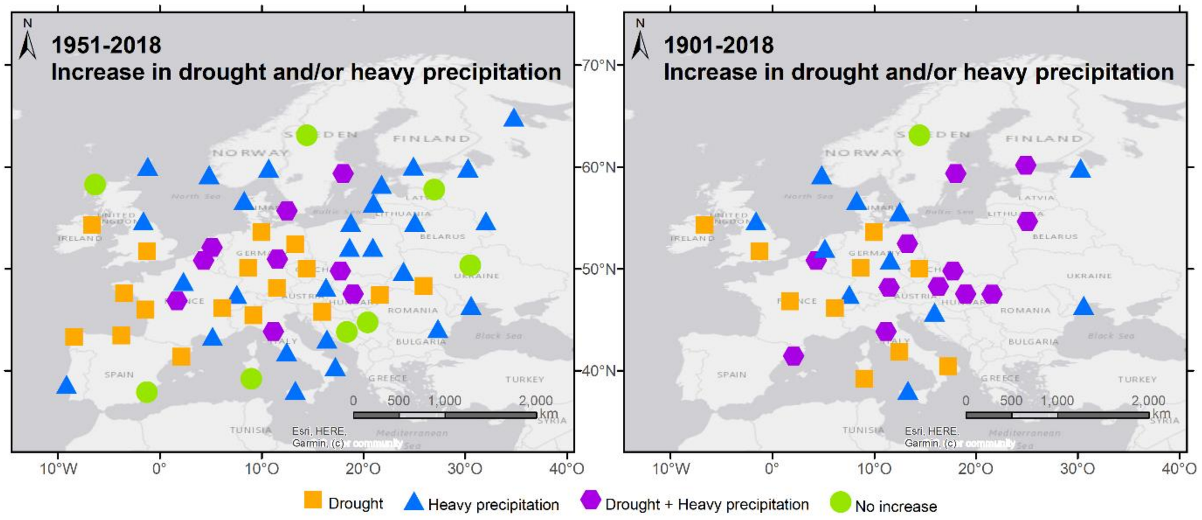

Figure 11: Maps categorizing the drought and heavy precipitation SHY-trends for the study periods 1951–2015 (left panel) and 1901–2018 (right panel) into four categories.

Positive drought trends are characteristic for Western and Central Europe, while positive heavy precipitation trends prevail in Northern, Central and Eastern Europe. Stations that show increasing trends in both precipitation extremes mainly occur in Central Europe. The 118-year long-term trends less often show no change signal than those of the shorter 68-year period 1951–2018. This illustrates the importance of analysing long high-quality datasets that allows for a better representation of the strong natural variability of precipitation.

5. Summary and conclusions

The five record drought SHYs (1947, 2018, 2003, 1921, and 1911) and summers (1911, 1904, 1983, 2003, and 1921) over Europe within period 1901–2018 were studied using a station-based dataset. The 63 stations are well distributed and have high quality and long-term time series of daily precipitation and daily extreme temperatures. Based on the ADE that in our study integrates eight individual drought indices we found trends towards drier conditions in Southern and Central Europe up to a latitude of about 55°N, while several stations in the Northern part of Europe show trends towards wetter SHYs and summers. The changes towards drier conditions are more pronounced for indices integrating PET into their calculation. This illustrates that within a further warming climate and related increases in the water pressure deficit the severity of summer droughts and their multiple adverse effects will increase even further, particularly over southern and central Europe.

In addition to the drought analyses, three heavy precipitation indices were studied, all of them showing the highest positive anomalies in the most recent decades (1991–2018) compared to the three preceding 30-year periods (1901–1930, 1931–1960, and 1961–1990). Averaged over Europe we see simultaneous increases in drought and heavy precipitation indices during the summer half year. These simultaneous increases are characteristic for central Europe.

The recent drought summers were often connected with extremely high temperatures and heatwaves. In a progressively warming climate feedback mechanisms between drought and sensible heat fluxes from the soil may lead to a further intensification and accumulation of combined heat and drought conditions in European summers during the next decades.

The expected continuation of the observed increasing trends in the coming decades and the manifold negative impacts connected with more intense and frequent drought, heavy precipitation and heat extremes will challenge our society and economy.

Acknowledgments

We are grateful to all dedicated people at universities, national weather services and other institutions for their priceless efforts in collecting, digitalizing, processing and optimising climate data. Their dedication is the basis for our and many other climate studies. Furthermore, we acknowledge the data providers in the ECA&D project (https://www.ecad.eu).

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