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Long-term trends in agricultural droughts over Netherlands and Germany: how extreme was the year 2018?

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Abstract: Droughts can have important impacts on environment and economy like in the year 2018 in parts of Europe. Droughts can be analyzed in terms of meteorological drought, agricultural drought, hydrological drought and social-economic drought. In this paper, we focus on meteorological and agricultural drought and analyzed drought trends for the period 1965-2019 and assessed how extreme the drought year 2018 was in Germany and the Netherlands. The analysis was made on the basis of the following drought indices: standardized precipitation index (SPI), standardized soil moisture index (SSI), potential precipitation deficit (PPD) and ET deficit. SPI and SSI were computed at two time scales, the period April-September and a 12-months period. In order to analyze drought trends and the ranking of the year 2018, HYDRUS 1-D simulations were carried out for 31 sites with long-term meteorological observations and soil moisture, potential evapotranspiration (ET) and actual ET were determined for five soil types (clay, silt, loam, sandy loam and loamy sand). The results show that the year 2018 was severely dry, which was especially related to the highest potential ET in the time series 1965-2019, for most of the sites. For around half of the 31 sites the year 2018 had the lowest SSI, and largest PPD and ET-deficit in the 1965-2019 time series, followed by 1976 and 2003. The trend analysis reveals that meteorological drought (SPI) hardly shows significant trends over 1965-2019 over the studied domain, but agricultural droughts (SSI) are increasing, at several sites significantly, and at even more sites PPD and ET deficit show significant trends. The increasing droughts over Germany and Netherlands are mainly driven by increasing potential ET and increasing vegetation water demand.

1 Introduction

Drought is a climatic phenomenon that is expected to increase in frequency and severity over Europe in the future and is related to the ongoing climate change (Seneviratne et al., 2012a; Orlowsky and Seneviratne, 2013; Mukherjee et al., 2018; Samaniego et al., 2018; Pokhrel et al., 2021). Droughts are considered to be the most damaging natural hazard after floods, when measured globally in terms of the population affected, suffering more than 2.2 million victims from 1950 to 2014 (Mishra and Singh, 2010; Guha-Sapir, 2015; Zink et al., 2016). Droughts have a negative impact on food production, and shortage of water supply, making it the costliest disaster in Europe in general (AghaKouchak, 2014; Guha-Sapir et al., 2015; Zink et al., 2016).

We distinguish between meteorological, hydrological, agricultural and socio-economic drought, in correspondence with Mishra and Singh (2010), Wilhite and Glantz (1985) and AMS (2004). Meteorological drought is related to a period with rain deficiency with respect to the long-term average precipitation, and is usually assessed by a standardized precipitation index (SPI) (AMS, 2004). Hydrological drought is characterized by a river discharge deficit or low groundwater level (Wilhite and Glantz, 1985). Agricultural drought is defined in terms of soil moisture deficit, leading to crop yield reductions (Anderson et al., 2016). Agricultural drought and hydrological drought are affected by meteorological drought but not necessarily, and with a certain delay with a typical time lag of a month or a few months. Hydrological drought and

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agricultural drought usually lead to shortage of water supply for residents and jeopardize food security and cause economic damages. Therefore, socio-economic drought is related to the mentioned three drought indices.

Historical drought events like for the years 1976, 1996, 2003 and 2015 in Europe have been widely investigated in literature, and it was concluded that these droughts had severe consequences for agriculture, riverine transportation and drinking water (Sheffield and Wood, 2007; Mühr et al., 2018; Bakke et al., 2020; Buitink et al., 2020; Buras et al., 2020). In Germany, huge economic losses have been reported related to the record breaking temperatures and severe drought in the summer 2018 and this affected agriculture, tourism and shipping losses (Mühr et al., 2018).

Analysis of droughts and studies on drought trends since the 1950s have been conducted (Sheffield and Wood, 2007; Sheffield et al., 2012; Bakke et al., 2020). Barker studied droughts based on standardized stream flow index for the period 1891 to 2015 for the UK and identified extreme droughts like the 1976 drought and also periods with multiple and longer droughts (e.g. early 1940s and early 1970s) at the catchment scale (Barker et al., 2019). No consistent global drought trends were found and the trends generally differ from region to region (Sheffield and Wood, 2007; Orlowsky and Seneviratne, 2013; Spinoni et al., 2015). Sheffield and Wood (2007) showed that droughts increase in frequency and magnitude globally but trends differ, depending on the drought index used. Orlowsky and Seneviratne (2013) investigated the standardized precipitation index (SPI) as an indicator for meteorological drought for observation datasets and simulations from the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and the results showed that frequency of droughts has increased in the Mediterranean, South Africa and Central America/Mexico over the past decades and this trend would continue in the 21st century according to CMIP projections (Orlowsky and Seneviratne, 2013). In Europe, the SPI-based analysis indicates that droughts in northern Europe have been mitigated while in southern Europe the magnitude of droughts have increased (Gudmundsson and Seneviratne, 2015). However, no consistent trends over central Europe were found (Gudmundsson and Seneviratne, 2015; Spinoni et al., 2015).

In addition to drought trends, individual historic drought events also have been widely studied (Ciais et al., 2005; Seneviratne et al., 2012b; Zink et al., 2016; Laaha et al., 2017; Bakke et al., 2020; Buitink et al., 2020; Buras et al., 2020). For Central Europe the years 1976 and 2003 were affected by the most severe droughts over the last 50 years (Ciais et al., 2005; Teuling et al., 2013). These two years gathered much attention from media and were generally used as reference for recent drought events. The year 1976 suffered soil moisture deficit and in central Europe the 2003 summer drought was more severe than the year 1976 (Teuling et al., 2013). The year 2003 witnessed a 30% reduction in primary productivity which was a consequence of precipitation deficit and extreme heat waves (Ciais et al., 2005). Drought events in 1996 and 2015 were also analyzed in studies (Laaha et al., 2017; Barker et al., 2019). Barker showed that the drought event 1995-1996 was the worst drought in central northern England since 1891 (Barker et al., 2019). In 2015, drought also affected large parts of Europe and especially the Eastern part of Europe (Laaha et al., 2017). The year 2018 also drew much attention from media and scientists and is considered to be one of the most extreme drought years and is analyzed and discussed in this paper. From climatic-data-based SPI it was found that northern Europe experienced an extreme drought in 2018 (Bakke et al., 2020; Graf et al., 2020). Buitink et al. (2020) found, with help of an analysis based on in-situ data and remote sensing data, that Netherlands witnessed in 2018 low soil moisture contents related to low precipitation, which reduced ET (Buitink et al., 2020). However, until now it was not explored completely how exceptional the year 2018 was in Germany and the Netherlands in terms of different drought indices. This paper not only analyzes meteorological drought, but also agricultural drought with help of four

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drought indices for Germany and the Netherlands. The drought analysis was based on HYDRUS 1-D simulations using long-term observed climatic data as model forcing and using five different soil types which are clay, silt, loam, loamy sand and sandy loam out of 12 textural soil classes. These five soil types cover well the soil texture triangle and therefore the different types of soils. This modeling provides a better understanding of drought trends and the 2018 drought event for 31 different locations over the Netherlands and Germany with long-term meteorological observations. In situ measured soil moisture data and remotely sensed soil moisture are not available for such long time series and are in general strongly affected by measurement uncertainties. Atmospheric reanalysis also provides soil moisture data, but soil moisture is not an objective of such a reanalysis, and it is modelled at a relatively coarse scale and with a simplified process representation. Therefore, simulated soil moisture content by a soil hydrological model, driven by observed meteorological data, is expected to give the most reliable information on long term (agricultural) drought trends. In this work, we analyzed calculated potential and actual evapotranspiration (ET) as well as root zone soil moisture in detail. These three variables together with precipitation were used to determine four drought indices: SPI, standardized soil moisture index (SSI), potential precipitation deficit (PPD) and ET deficit. With the time series of the above-mentioned variables, drought trends were analyzed, including the mechanisms behind the observed trends. In addition, it was analyzed how extreme the 2018 drought event was in a historical context. The drought statistics and trends were analyzed for different soil types, in order to determine whether drought trends were different for the different soil types.

In Sect.2, we introduce the climatic stations over Germany and the Netherlands for which drought assessments were made in this study, and also the model HYDRUS to simulate water flow in soils and evapotranspiration is introduced. In addition, the study design and the four drought indices are introduced. In Sect.3, we present the results of the drought trend analysis with a focus on extreme events and the year 2018. In Sect.4, we discuss and compare the drought trends and the extreme events with results from other studies. Also limitations of this study are discussed. In Sect.5, we summarize this work with the most important conclusions.

2 Data and Methodology

2.1 Climatic data preparation

In this study, 26 meteorological stations in Germany and 5 in the Netherlands were selected to investigate drought trends over the period 1965-2019 and the uniqueness of the 2018 drought event in this region. The stations are grouped in order to analyze domains with more similar climatological conditions: Netherlands, northern Germany, western Germany, eastern Germany and southern Germany as shown in the table 1.

Table 1. Analyzed meteorological stations and assignment to different domains.

Domains	Sites
North Germany	Bremen, Bremerhaven, Hamburg, Hannover, Helgoland, List auf Sylt and Soltau

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West Germany	Aachen, Essen, Gießen-Wettenberg, Koln-Bonn, Saarbrucken and Trier
East Germany	Artern, Chemnitz, Lindenberg, Potsdam, Magdeburg, Rostock-Warnemunde and Schwerin
South Germany	Augsburg, Freiburg, Hof, Nürnberg, Öhringen and Regensburg
Netherlands	Eelde, De Kooy, De Bilt, Vlissingen and Maastricht

Figure 1 illustrates the spatial distribution of the meteorological stations. The meteorological stations are located between 0 m above sea level (De Kooy) and 565 m above sea level (Hof, Germany). Data are from the German Weather Service (DWD) (DWD Climate Data Center (CDC), 2021) and the Royal Dutch Meteorological Institute (KNMI) (KNMI, 2021). Both weather services provide open-access climate data including but not limited to precipitation, wind speed, relative humidity, maximum and minimum temperature. Also incoming shortwave radiation is needed as forcing variable for the HYDRUS-1D version 4.17 model. The KNMI provides daily incoming shortwave radiation data for most of the meteorological sites since the 1960s. The radiation data are also available for the DWD stations but for shorter time periods and only for a few stations long term measurements are available. In this study, incoming shortwave radiation was used in the simulations for the Dutch sites. For German sites, sunshine duration was used to estimate incoming shortwave radiation according to the equation:

$$R_s = (1 - \alpha)\left(a_s + b_s \frac{n}{N}\right) R_a \quad (1)$$

where R_s is incoming shortwave radiation [MJ $m^{-2}d^{-1}$], R_a is extraterrestrial radiation [MJ $m^{-2}d^{-1}$], α is the albedo or the canopy reflection coefficient (i.e., 0.23 for grassland), a_s and b_s are parameters for the fraction of radiation (i.e., a_s = 0.25, b_s = 0.5), n/N is the relative sunshine fraction [-], in which n is the number of measured sunshine hours and N is the maximum possible number of sunshine hours for the specific day of the year.

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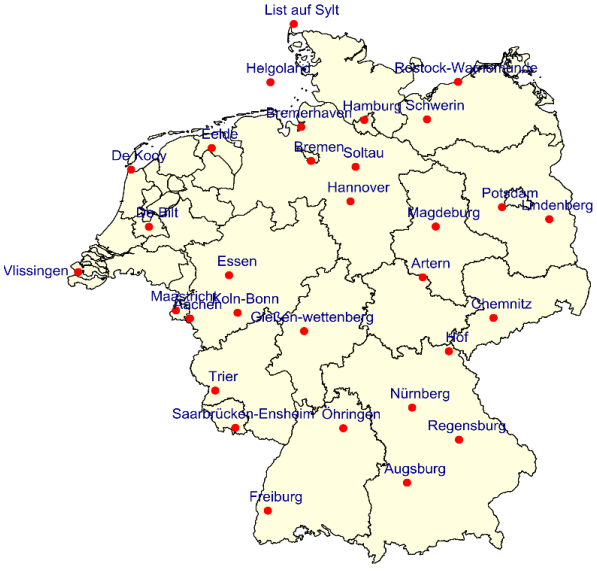

139

140 **Figure 1.** The 31 climatic stations used in this study, situated across Germany (26) and Netherlands (5)
141 (data downloaded from DIVA-GIS [https://www.diva-gis.org/])

142 The four drought indices and drought events were calculated relative to a reference period of 55 years
143 (1965 to 2019). This period has been selected so that a large number of stations could be considered for a
144 relatively long period. However, not all stations provide complete datasets and some minor gaps exist in
145 the datasets. The gaps were filled by a linear regression equation that was fitted using data from a
146 neighboring station. Table 2 presents the neighboring stations used to fill data gaps by regression.
147 Meteorological stations which are not listed in Table 2 do not have missing data.

148 **Table 2.** Meteorological stations and their neighboring stations, used to fill data gaps by linear regression

Stations with gaps	Regression stations
Aachen	Köln-Bonn
Artern	Augsburg
Augsburg	Artern
Bremen	Bremerhaven
Bremerhaven	Bremen
Chemnitz	Hof
Essen	Köln-Bonn
Freiburg	Konstanz
Gießen-Wettenberg	Frankfurt-Main
Hamburg-Fuhlsbüttel	Soltau
Hannover	Soltau
Helgoland	List auf Sylt
Hof	Chemnitz
Köln-Bonn	Aachen
Lindenberg	Potsdam

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List auf Sylt	Helgoland
Magdeburg	Gardelegen
Nürnberg	Regensburg
Öhringen	Freiburg
Potsdam	Lindenberg
Regensburg	Nürnberg
Rostock-Warnemünde	Schwerin
Saarbrücken-Ensheim	Trier-Petrisberg
Schwerin	Rostock-Warnemünde
Soltau	Bremen
Trier-Petrisberg	Saarbrücken-Ensheim
De Kooy	De Bilt
Eelde	De Bilt
Vlisingen	De Bilt

2.2 Methods

2.2.1 HYDRUS 1-D simulations

Various models have been used to assess droughts (Mishra and Singh, 2011). In this study, the HYDRUS-1D version 4.17 model (Simunek et al., 2005; Šimůnek et al., 2008; Huang et al., 2020) was applied to calculate actual ET, soil moisture and resulting drought statistics. We simulated uniform water flow in 2 meters deep soil columns with homogeneous soil texture and a root uptake sink term.

All simulations are done for pasture with a rooting depth of 50cm. Flow for the 2m soil column is simulated with the modified Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S + P - \mathrm{ET} \quad (2)$$

where θ is volumetric water content [L^3L^{-3}], t is time [T], z is depth along the soil profile [L], h is pressure head [L], S is source/sink term [T^{-1}], P is precipitation [T^{-1}], ET is actual ET [T^{-1}], and $K(\vartheta)$ is the unsaturated hydraulic conductivity function [LT^{-1}]:

$$K(\theta) = K_s\, K_r(\theta) \quad (3)$$

where K_s is saturated hydraulic conductivity [LT^{-1}] and K_r the relative hydraulic conductivity [LT^{-1}]. The sink term is the transpiration of the pasture here. K_r is a function of soil moisture content (Van Genuchten, 1980):

$$K_r(\theta) = \theta^{1/2}\left[1 - (1 - \theta^{1/m})^m\right]^2 \quad (4)$$

Unsaturated soil hydraulic properties were determined using the Van Genuchten model (Van Genuchten, 1980) with a fixed air-entry value of – 2cm in order to achieve better outcomes for finer soils:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h > 0 \end{cases} \quad (5)$$

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$$m = 1 - \frac{1}{n}, n > 1 \quad (6)$$

where α [L^{-1}] and n are the inverse of the air-entry value and the pore-size distribution index respectively, θ_s is saturated soil water content and θ_r is residual soil water content. The lower boundary is a free drainage boundary condition and the upper boundary is governed by atmospheric conditions without surface runoff and ponding. The potential ET was calculated using the Penman-Monteith equation (Allen et al., 1998) with the assumption of a pasture height of 12 cm, an albedo of 0.23, a LAI of 2.0 and a rooting depth of 50 cm. Alternatively, simulations were also performed with a higher LAI-value of 2.88, to investigate the impact of LAI on the results.

The models were run for five soil types (clay, silt, loam, loamy sand and sandy loam) in order to see the impact of soil type on the drought indices. The soil hydraulic properties were determined from texture according to Carsel and Parrish (1988), see also Table 3.

Table 3. Soil hydraulic parameter values for the selected texture types in the simulations

Parameters	Clay	Silt	Loam	Sandy loam	Loamy sand
K_s, cm d^{-1}	4.8	6	24.96	106.1	350.2
α, cm^{-1}	0.008	0.016	0.036	0.075	0.124
n	1.09	1.37	1.56	1.89	2.28
θ_s	0.38	0.46	0.43	0.41	0.41
θ_r	0.068	0.034	0.078	0.065	0.057

We monitored soil moisture in the simulated soil columns at five different soil depths and calculated average soil water content on the basis of these five values. These monitoring schemes differed slightly between soil types. For the fine soils (clay, silt and loam) the vertical discretization was 2.5mm and monitoring nodes were inserted at 4.75 cm, 15.5 cm, 25.25 cm, 35.25 cm and 45.25 cm, covering the root zone of 50cm. For the coarse soils (sandy loam and loamy sand) the vertical discretization was 2.0mm and monitoring nodes were inserted at 4.8 cm, 15 cm, 25 cm, 35cm and 51cm depth.

2.2.2 Drought indices

Due to the complex nature of droughts, one single drought index is not sufficient for drought detection (Hao and AghaKouchak, 2014). In this study, we focus on meteorological drought and agricultural drought. In this context, four drought indices are evaluated.

2.2.2.1 The Standardized Precipitation Index (SPI)

The SPI was developed by (McKee et al., 1993) and is calculated based on long-term precipitation data (minimum 30 years). A time series of precipitation data is transformed to a normal distribution after fitting to a probability distribution (McKee et al., 1993), which allows for estimation of dry and wet periods. Positive SPI values greater than median precipitation means wetter conditions than normal. The

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SPI can be calculated for different time scales (i.e. 3, 6, 9, 12 and 24 months) and can be calculated as follows:

$$\mathrm{SPI}_{i,j} = \frac{\mathrm{P}_{i,j} - \overline{\mathrm{P}}_j}{\sigma_{P,j}} \quad (7)$$

where $\mathrm{P}_{i,j}$ [mm] is the precipitation for time interval *j* (6 months or 12 months in this study) of the year *i*, $\overline{\mathrm{P}}_j$ [mm] is the average precipitation over the studied period and $\sigma_{P,j}$ [mm] is the standard deviation of precipitation for time interval *j* over the studied period (Cavus and Aksoy, 2019; Fathian et al., 2021). Extreme droughts are characterized by negative SPI values, see Table 4. SPI is one of the most used drought indices (Mishra and Singh, 2010; Gudmundsson and Seneviratne, 2015; Zink et al., 2016). It is also a drought index recommended by the World Meteorological Organization (WMO) and German Weather Service (DWD). Compared to another widely used drought index, the Palmer drought severity index (PDSI) (Palmer, 1965), SPI has the advantage of simplicity because it only requires information on precipitation. SPI has limitations for shorter time series and dry climates, but in this study long time series of 55 years (1965 – 2019) are calculated and the climate over the study domain is in general temperate humid, although drier in Eastern Germany. The severity of droughts over the simulation time period has been assessed for the summer period from April to September (SPI-6), as well as for periods of 12 months (SPI-12). Droughts are classified into four classes, ranging from mild droughts to extreme droughts (McKee et al., 1993). See also Table 4.

Table 4. Classification of SPI

SPI-values	Drought classification
Between -0.99 and 0	Mild drought
Between -1.49 and -1.00	Moderate drought
Between -1.99 and -1.50	Severe drought
Less than – 2.00	Extreme drought

2.2.2.2 Standardized Soil Moisture Index (SSI)

Similar to SPI, SSI is also calculated by deriving probabilities from soil moisture time series (AghaKouchak, 2014; Hao and AghaKouchak, 2014), which allows to determine periods with negative and positive soil moisture anomalies. SSI is calculated in this work for two time intervals, SSI-6 for summer droughts (April-September) and SSI-12 for annual droughts. SSI is therefore determined using the same principles as SPI. Therefore, the SSI can be calculated as follows:

$$\mathrm{SSI}_{i,j} = \frac{\theta_{i,j} - \overline{\theta}_j}{\sigma_{\theta,j}} \quad (8)$$

Where $\theta_{i,j}$ [mm] is the soil moisture content for time interval *j* (6 months or 12 months in this study) of the year *i*, $\overline{\theta}_j$ [mm] is the average soil moisture content over the studied period and $\sigma_{\theta,j}$ [mm] is the standard deviation of soil moisture content for time interval *j* over the studied period.

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2.2.2.3 Potential Precipitation Deficit (PPD)

Potential precipitation deficit is a drought index developed by the Royal Dutch Meteorological Institute (KNMI) to assess drought events and it is defined by the difference between potential ET and precipitation. PPD also stands for meteorological drought but in addition to SPI, PPD includes information on the atmospheric evapotranspiration demand. Specific for the conditions in the Netherlands and Germany, the deficit is calculated for the period between April and September with large potential ET. PPD is defined as the cumulative deficit between potential ET according to the Penman Monteith method and precipitation and calculated for each day in the period between the 1st of April and 30th of September. Typically, PPD increases during summer as potential ET is larger than precipitation. PPD cannot become negative (if cumulative precipitation is larger than cumulative potential ET) and will have as minimum value zero. The maximum PPD value reached in the period between the 1st of April and the 30th of September (typically in August) is recorded.

2.2.2.4 Evapotranspiration Deficit (ET_{def})

A direct indicator for drought stress affecting vegetation is the difference between potential ET and actual ET. If actual ET is smaller than potential ET, this indicates that not enough soil water was available to satisfy the atmospheric demand. This also implies that crop yield is affected. We define therefore as further indicator for drought stress (ET_{def}):

$$\mathrm{ET_{def}} = \sum_{i=1}^{n}\left(\mathrm{ET_{pot,i}} - \mathrm{ET_{act,i}}\right) \quad (9)$$

where ET_{pot} is potential ET, ET_{act} is actual ET, *i* is a day between the 1st of April (*i*=1) and the 30th of September (*i*=183) and *n* is 183 days.

2.2.3 Trend analysis

Trends are analyzed in this study according the Theil-Sen slope (Theil, 1950; Sen, 1968) and the significance is assessed based on the Mann-Kendall (MK) test with p value 0.05, which allows for pre-whitening in order to eliminate the impact of autocorrelation (Hamed and Rao, 1998; Yue and Wang, 2004). The MK test is nonparametric and is regularly used in hydrometeorological trend detection and the python package 'pymannkendall' is used for computations.

3 Results

3.1 Trends of precipitation, potential ET, actual ET, soil moisture and drought indices for 1965-2019

3.1.1 Precipitation trends

Figure 2 displays trends of precipitation for different regions in Germany and the Netherlands. Coinciding with Spinoni's study (Spinoni et al., 2015), Fig. 2 shows that precipitation for all four areas of Germany show decreasing trends, but with clear differences. In southern Germany, the precipitation decrease was strongest (-2.2 mm/year) while in the East the decreasing trend was only -0.23 mm/year. Different to the German regions, the Netherlands experienced a small increase in precipitation at the rate of 0.385 mm/year. Spinoni et al. (2015) reported also an increase for the Netherlands, but for the period 1950 – 2012.

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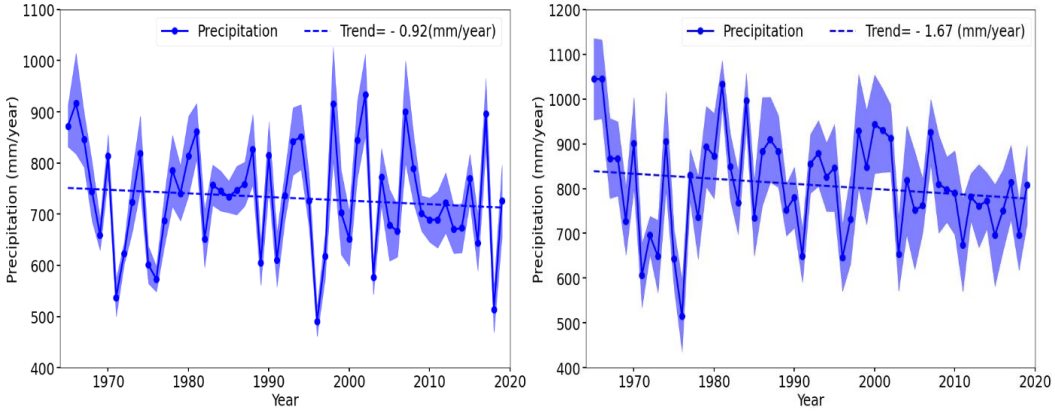

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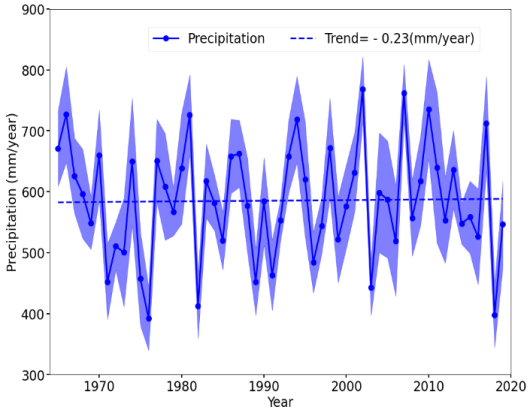

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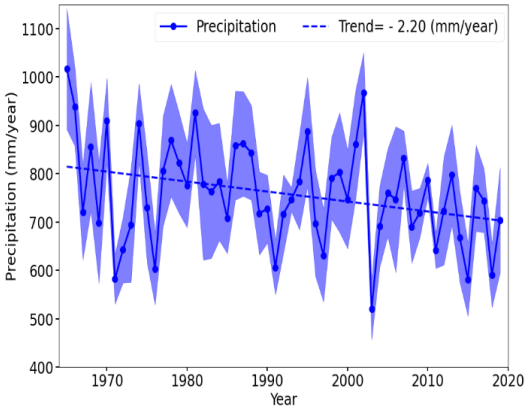

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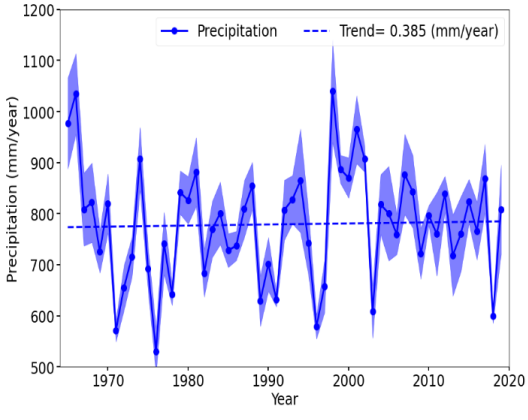

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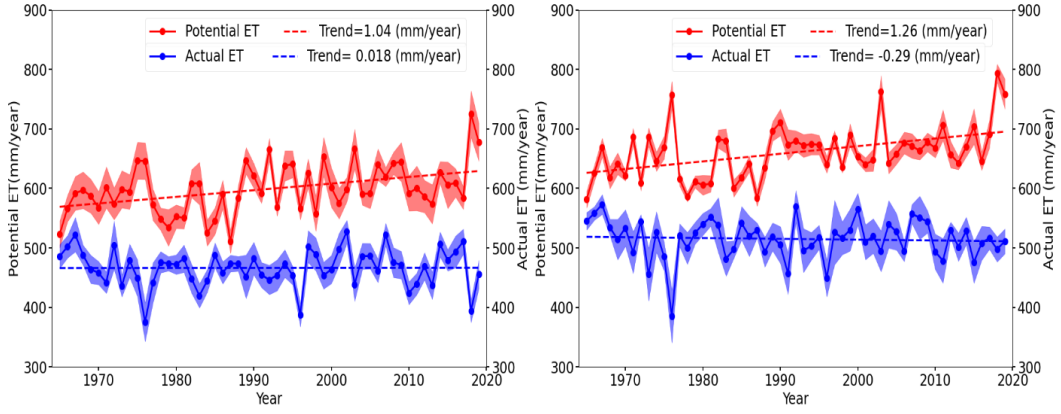
Figure 2. Precipitation trends in (a) North Germany, (b) West Germany, (c) East Germany, (d) South Germany and (e) Netherlands. Shaded areas indicate the 95% confidence interval estimated from (the limited) number of sites in each domain.

3.1.2 Potential ET and actual ET trends

Figure 3 shows that potential ET has increased in all areas, with trends varying between 1.04 mm/year (northern Germany) and 1.66 mm/year (Netherlands). Table 5 also shows the potential ET trends, and indicates that for all five regions considered here the trend of increasing potential ET is significant (coinciding with Spinino et al. (2015)). However, actual ET trends show different trend signs (Fig. 3), with increasing trends for Northern Germany, Eastern Germany and Netherlands and decreasing trends for Western Germany and Southern Germany. The decreasing trends in the West and South of Germany can be related to strong decreasing precipitation trends in those two domains.



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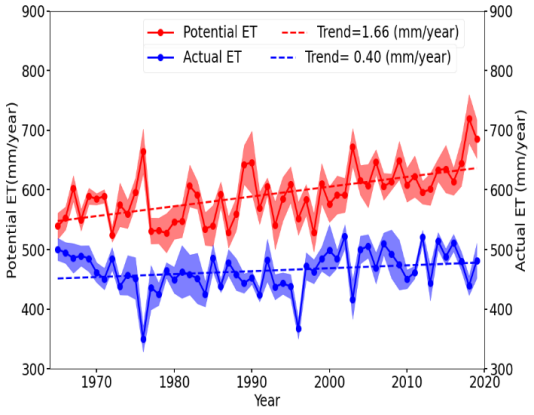
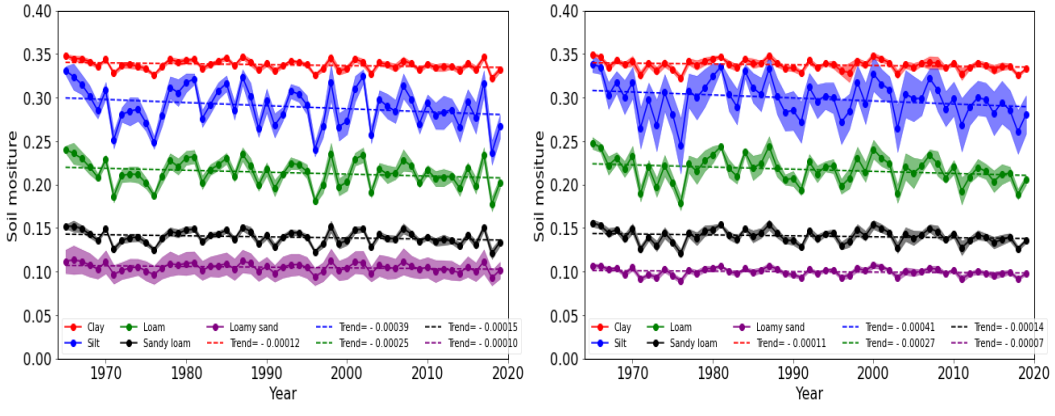


(e)

Figure 3. Potential ET (red line) and actual ET (blue line) trends in the (a) North, (b) West, (c) East and (d) South of Germany and (e) Netherlands. Shaded areas indicate the 95% confidence interval estimated from (the limited) number of sites in each domain.

3.1.3 Soil moisture trends

Figure 4 displays the temporal trend in the average yearly soil moisture content, for the four German domains, the Netherlands and the five different soils. As expected, soil water contents are highest for clay and lowest for sandy loam and loamy sand. For all soils a decreasing soil moisture trend can be observed over all domains, which is significant for clay and silt, but not significant for all the other soil types. The trends are less pronounced for the Netherlands and eastern Germany than for the other three domains. For all soil types the year 2018 has the lowest average soil moisture content except for 1976 in western Germany and Netherlands. The different soil types show a similar ranking of the different years but interannual variability is higher for loam and silt.



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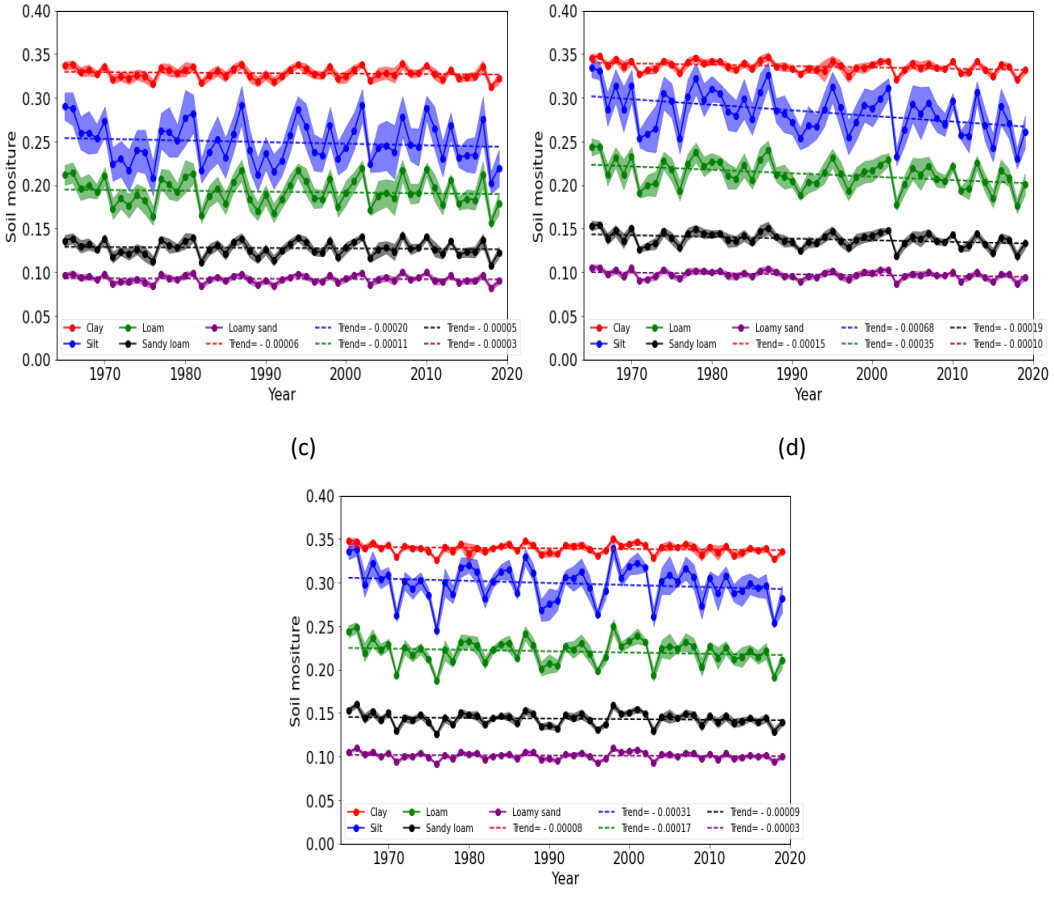

Figure 4. Trends in average yearly soil moisture content for (a) North, (b) West, (c) East and (d) South of Germany and (e) the Netherlands, for five different soil textures (clay (red), silt (blue), loam (green), sandy loam (black) and purple (loamy sand)). The trend coefficients are also indicated in each of the figures. Shaded areas indicate the 95% confidence interval estimated from (the limited) number of sites in each domain.

Table 5 shows the trends in potential ET, actual ET and soil moisture content simulated by HYDRUS-1D version 4.17, for the different regions in Germany and the Netherlands. Actual ET shows a non-significant decreasing trend in western and southern Germany which can be explained by decreasing precipitation. The Netherlands shows the strongest increase in actual ET, which can be explained by the increasing precipitation and potential ET trends. In northern and eastern Germany, the actual ET trends show a slight non-significant increase, in spite of the decreasing precipitation trend, which can be explained by the fact that actual ET is often energy limited, and not moisture limited. Root zone soil moisture content as simulated by HYDRUS shows over all regions a non-significant decreasing trend, except for southern

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Germany where the trend is significant. The decreasing trends can be explained by a combination of decreasing precipitation (in most regions) and increasing potential ET.

Table 5. Trends for potential ET, actual ET and soil moisture for the different studied regions in Germany and the Netherlands over the period 1965-2019

Regions	Potential ET (mm/year)	Significance	Actual ET (mm/year)	Significance	Soil moisture ($10^{-3}m^3m^{-3}$)	Significance
Germany-East	+1.30	yes	+0.05	no	-0.09	no
Germany-West	+1.25	yes	-0.28	no	-0.21	no
Germany-North	+1.04	yes	+0.018	no	-0.20	no
Germany-South	+1.48	yes	-0.33	no	-0.29	yes
Netherlands	+1.66	yes	+0.40	no	-0.13	no

3.1.4 Temporal trends of SPI, SSI, PPD and ET deficit

The four drought indices, determined for the 31 meteorological stations, were averaged for the five domains and the yearly values and trends are displayed in Figs. 5 and 6. The SPI shows decreasing trends over all four German regions, which is indicative of increased frequency of meteorological drought conditions. The decreasing trend is strongest over southern and western Germany, and only significant for southern Germany. On the contrary, for the Netherlands an increasing trend can be observed. All five regions show a decreasing SSI-trend, in this case also the Netherlands. The negative trends indicate increasing frequency of agricultural droughts. For all five regions the slope of the SSI-regression line is more negative than the slope of the SPI-regression line, which indicates that the frequency and/or intensity of agricultural droughts is increasing faster than the frequency and/or intensity of meteorological droughts. This indicates that besides a decrease in precipitation, there are factors which enhance agricultural droughts. Earlier we saw that for all regions in Germany and the Netherlands a significant increase of potential ET over the period 1965-2019 was detected. The negative SSI-trends are strongest for southern and western Germany.

The potential precipitation deficit (PPD) and ET deficit show positive trends for all five regions, pointing towards more agricultural drought, as water is lacking to fulfill the potential evapotranspiration demand. In western and southern Germany PPD and ET deficit show trends between 1.5 and 1.7 mm/year, which is larger than for the Netherlands, northern and eastern Germany (1.0-1.2 mm/year). This is related to the strong and significant increase of potential ET over time, in combination with only small changes in precipitation amount. The trends are in all cases significant, except PPD in northern and eastern Germany.

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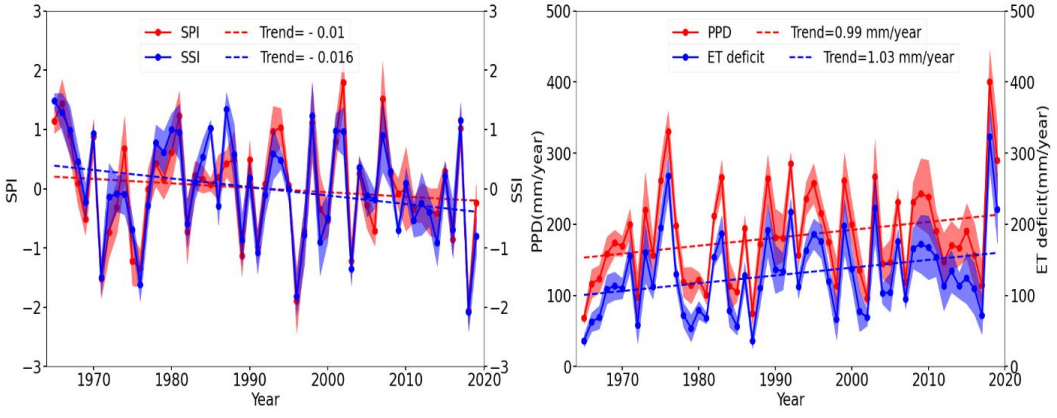

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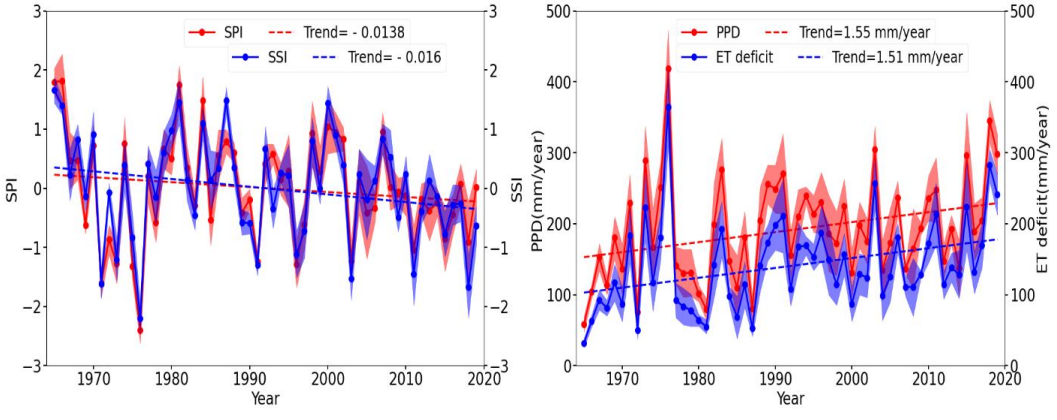

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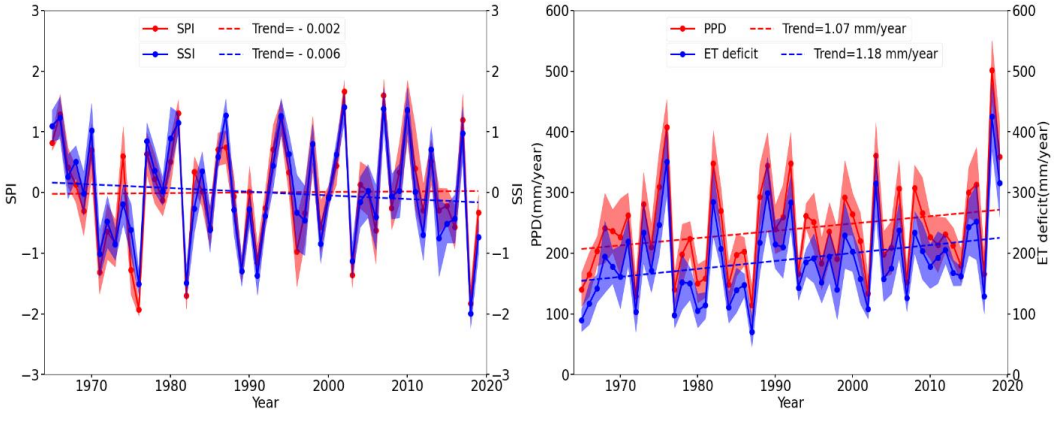

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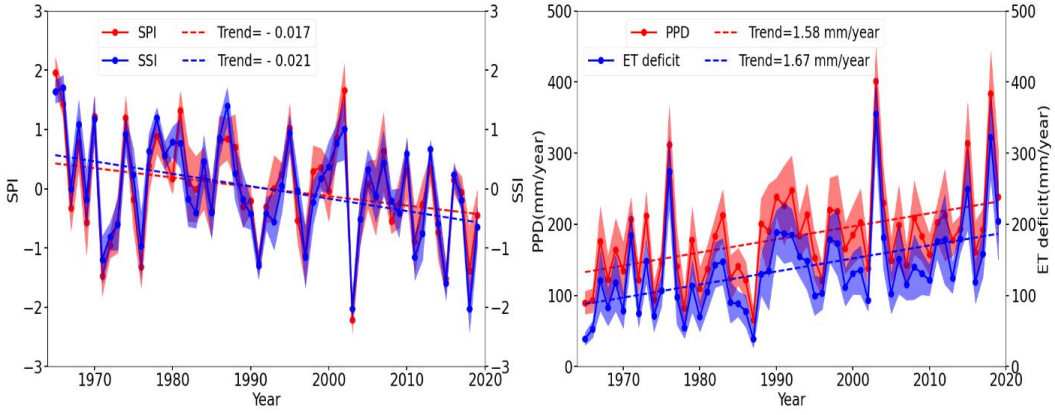
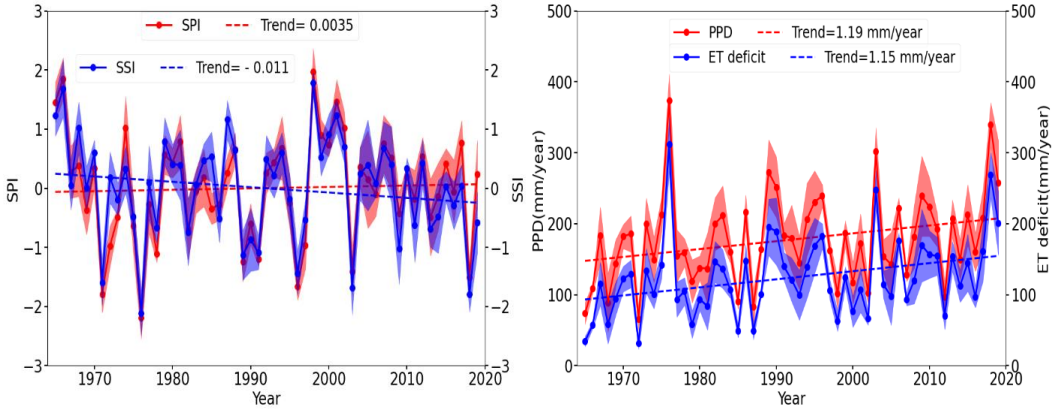


(d)

Figure 5. Temporal trends (1965-2019) for SPI and SSI (left), and PPD and ET deficit (right) in (a) northern Germany, (b) western Germany, (c) eastern Germany and (d) southern Germany. Shaded areas indicate the 95% confidence interval estimated from (the limited) number of sites in each domain.



(e)

Figure 6. Temporal trends (1965-2019) for SPI and SSI (left), and PPD and ET deficit (right) over the Netherlands. Shaded areas indicate the 95% confidence interval estimated from (the limited) number of sites in each domain.

We analyze now the SPI, SSI, PPD and ET deficit trends for the 31 individual stations. Table 6 summarizes results from a trend analysis of the drought indices for the summer period from the 1st of April until the 30th of September. The SPI-6 decreased for 23 out of 31 stations (and increased for the other 8 stations) with a mean trend of -0.071 decade^{-1} averaged over all 31 stations, only for 4 stations this decrease was significant ($p<0.05$). Results are very similar for SPI-12, but for two more sites the decreasing trend was significant. Gudmundsson and Seneviratne (2015) also calculated SPI-12 at the scale of Europe but their results were not provided for individual countries or regions. They detected non-significant trends of different signs over Germany.

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Summer soil moisture drought, as evaluated by SSI-6, shows a clear trend of -0.186 decade^{-1} averaged over all 31 stations. All stations show a negative trend, and for 17 of these stations there is a significant negative trend. On the other hand, soil moisture droughts at the yearly time scale, as evaluated by SSI-12, do not show such a pronounced negative trend and only for 8 stations a significant negative trend is found. For 7 stations even a trend towards increased SSI-12 values is observed. Five of these seven stations are located in the Netherlands, again indicating that the Netherlands is less impacted by a trend towards increasing droughts than Germany.

Finally, both PPD and ET deficit show positive trends indicating increased droughts with an increase of PPD of 1.25 mm/year and increase of ET deficit of 1.30 mm/year averaged over all stations. For PPD 15 of the stations and for ET deficit 20 of the stations show significant trends ($p<0.05$).

In summary, the increase of droughts is mainly related to increasing soil moisture deficits, and reduction in actual ET. The main driver is not a precipitation decrease, but an increase of potential ET.

Table 6. Number of stations with increasing drought trends and in brackets the number of significant drought trends. The mean trend is also given.

Drought indices	SPI-6	SPI-12	SSI-6	SSI-12	PPD (mm)	ET deficit (mm)
Numbers of sites	23 (4)	22 (6)	31 (17)	24 (8)	31 (15)	31 (20)
Mean trend (year^{-1})	-0.0071	-0.0068	-0.0186	-0.0004	1.25	1.30

3.2 The year 2018 and other drought years during 1965-2019

3.2.1 Climatological variables for 2018 in a historical perspective

We ranked the position of the year 2018 in the time series of 1965-2019 for six climatic variables and for all 31 meteorological stations. Figure 7 shows for each of the six variables for how many of the 31 meteorological stations 2018 ranked in the top three (Tier 1), in the top ten but not in the top three (Tier 2), and outside the top ten (Tier 3). Top-ranking implies that meteorological variables were prone to result in drought conditions: high temperatures, high incoming shortwave radiation, low precipitation, low relative humidity and high wind speed. Figure 7 shows that for 30 out of 31 stations the average maximum temperature for 2018 ranks in the top three. Also the total amount of sunshine hours was very high for 2018 with a top three position for 28 out of 31 stations. Rankings are less pronounced for low relative humidity (top three for 23 out of 31 stations), low precipitation (for 14 out of 31 stations in the top three of driest years). For daily average minimum temperature, the year 2018 showed less extreme rankings (but often in top ten), and wind speed deviated for most stations not much from a normal year (outside top ten).

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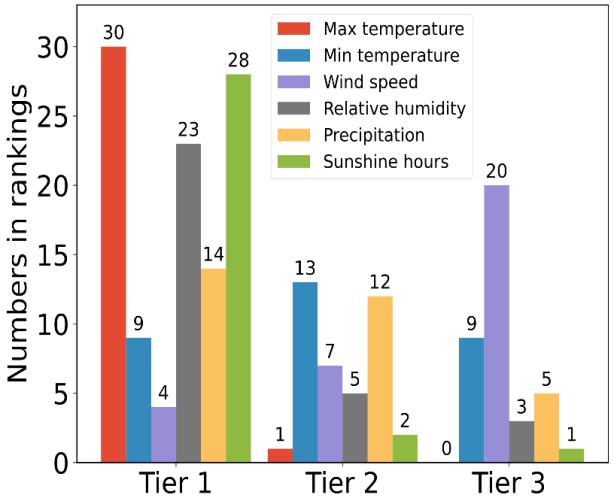

Figure 7. Ranking of climatic variables for the year 2018 in the time series of 1965-2019 (Tier 1=Ranks 1-3, Tier 2=ranks 4-10 and Tier 3 =ranks 11-31)

3.2.2 Potential ET and actual ET extremes

Figure 8 displays the years with the highest potential ET and the lowest actual ET for the 31 meteorological stations. Except two stations in southern Germany (Augsburg and Freiburg), 2018 is the year with the highest potential ET. Augsburg and Freiburg had in 2003 the highest potential ET. The summer of 2003 was extremely warm over Central Europe (especially Southern Germany, Eastern France, Switzerland and Austria). Regarding actual ET, at some meteorological stations (according calculations with HYDRUS-1D version 4.17) 2018 had the lowest total sum of actual ET over the complete time series from 1965-2019, this is the case for four sites across Germany. However, the year 1976 with the historic summer drought had for many meteorological stations the lowest actual ET, due to a combination of low precipitation and high atmospheric evaporative demand. This was especially the case for northern and central Germany. Three sites in Germany had the lowest calculated actual ET in 2003 and two Dutch stations (Eelde and De Bilt) had the lowest calculated actual ET in 1996, which was related to a combination of a relatively limited potential ET and drought.

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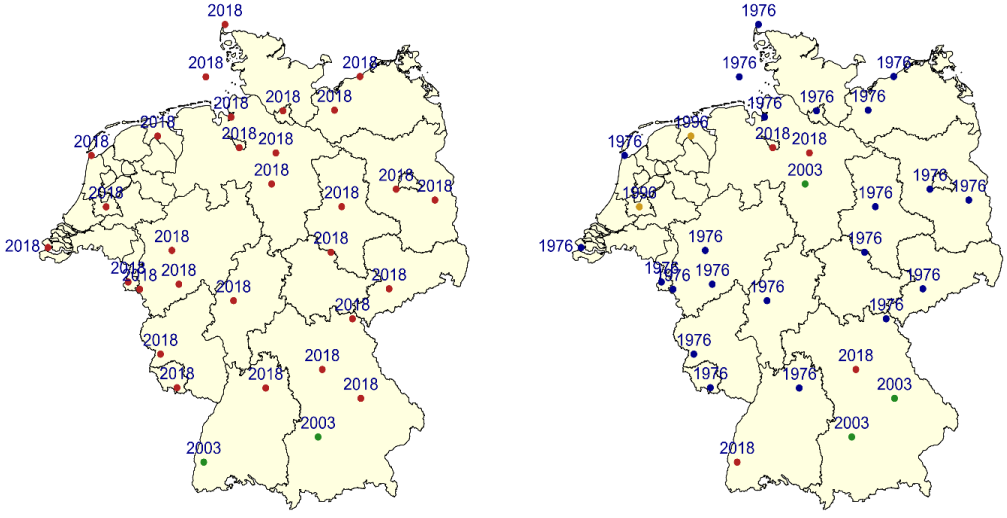

Figure 8. The years with the (a) highest potential ET according Penman-Monteith and (b) lowest actual ET (HYDRUS-calculations) at the different 31 meteorological stations across the Netherlands and Germany (data downloaded from DIVA-GIS [https://www.diva-gis.org/])

3.2.3 The most extreme drought events based on drought indices

Figure 9 shows the year with the lowest SPI (precipitation deficit), the lowest SSI (soil moisture deficit), the largest potential precipitation deficit and the largest ET deficit. The years 1976, 2003 and 2018, all of them with very warm and dry summers, are most prominent on the maps. For SPI, the year 1976 dominates over the southern Netherlands and parts of western Germany, 2003 over southern Germany and 2018 over other parts of Germany. For SPI, also other years like 1971 and 1996 appear on the map. It indicates that meteorological droughts are spatially variable over the past 55 years. For SSI, the spatial patterns are not very different from SPI but 2018 is at more stations the year that results in the lowest SSI. If we analyze now the years with the most extreme PPD and ET deficits, nearly exclusively 1976, 2003 and 2018 are the extreme years. One exception is the 1989 drought in the state Saxony-Anhalt in Germany. The year 2003 has in general the highest PPD and ET deficits in southern Germany, the year 1976 in the Netherlands and western Germany and the year 2018 in northern and eastern Germany. In summary, the drought event 2018 impacted especially northern and eastern Germany and is characterized by very high potential ET (besides lower precipitation), while the 1976 drought is in general characterized by high potential ET (but not as high as in 2018) and very low precipitation (often lower than in 2018).

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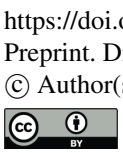

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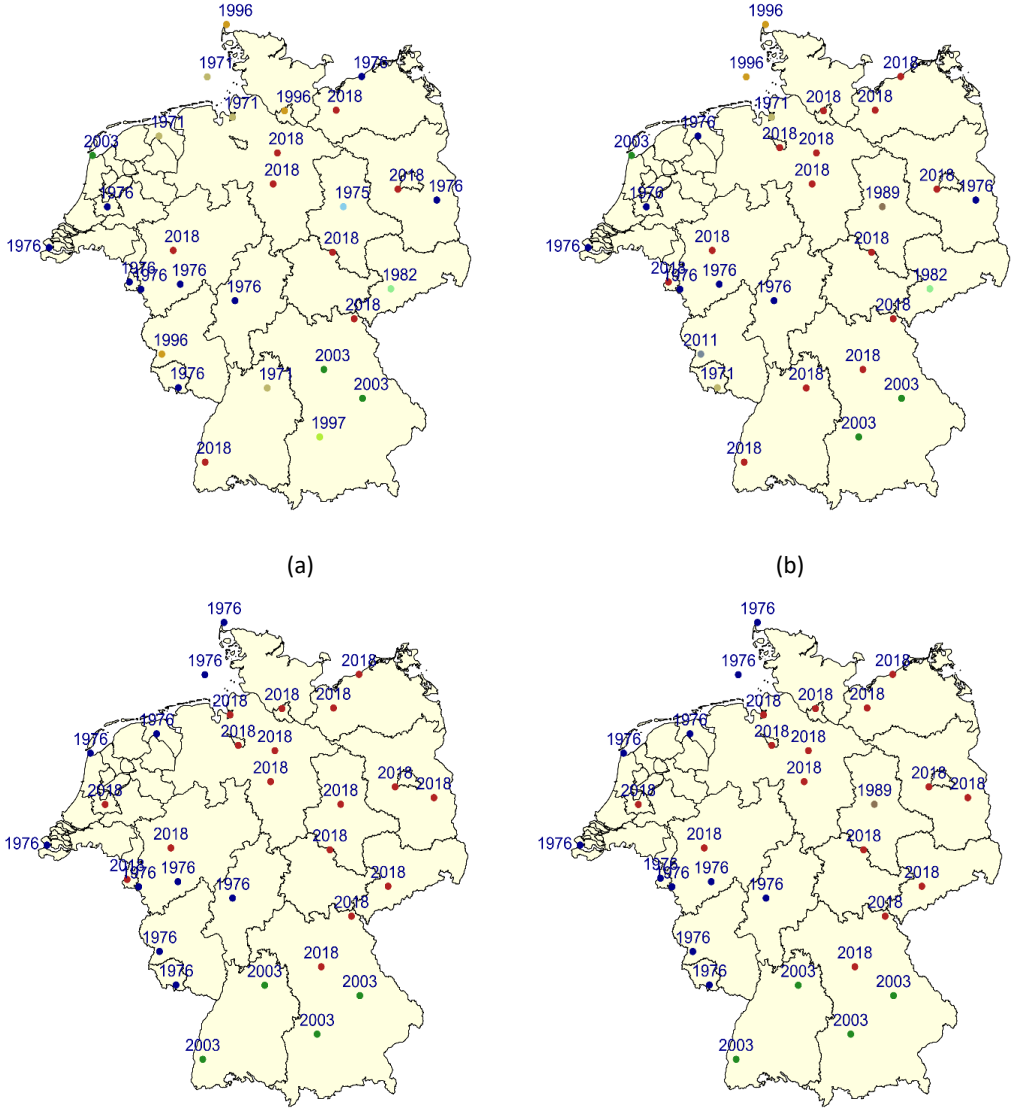

Figure 9. The most extreme drought years according different drought indices: (a) SPI; (b) SSI; (c) PPD and (d) ET Deficit (data downloaded from DIVA-GIS [https://www.diva-gis.org/])

We analyze further the three most extreme drought events (1976, 2003, 2018) over the region. Table 7 summarizes averaged drought indices over the complete domain (Netherlands and Germany). According to the SPI-6 index the 1976 drought can be considered as an extreme drought, whereas the droughts in 2003 and 2018 are classified as severe droughts. Also the other meteorological drought index, SPI-12, has the most extreme value for the year 1976. Concerning soil moisture droughts, SSI-6 ranks first for 1976, but SSI-12 ranks first for 2018. This is related to the fact that 2018 also had a (very) dry spring and autumn in large parts of the Netherlands and Germany. Both for SSI-6 and SSI-12 the year 2003 ranks 3rd. For the

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drought indices which include potential ET (PPD and ET deficit), the summer of 2018 ranks first and before 1976 and 2003; 2018 is more extreme than 1976 (2nd) and 2003 (3rd). These indices show again that the 2018 drought was extreme, especially related to the very high potential ET and the lack of water for plant transpiration.

Table 7. Drought severity in 2018 in comparison with 1976 and 2003. The most extreme values are printed bold italic.

Year	SPI-6	SPI-12	SSI-6	SSI-12	PPD (mm)	ET deficit (mm)
2018	-1.71	-1.56	-1.60	***-1.92***	***399.6***	***329.2***
2003	-1.22	-1.47	-1.62	-1.52	327.0	279.8
1976	***-2.11***	***-1.81***	***-1.87***	-1.66	368.4	313.9

3.3 Simulations for different LAI

Alternatively, we performed simulations with a higher LAI-value equal to 2.88, to investigate the impact on the results. Potential ET is strongly related to LAI, and is larger for higher LAI. Figure S1 (supplementary material) shows that potential ET is always considerably larger for a LAI of 2.88 compared to a LAI of 2.0, 50 to 100mm on year basis, and also the trends are slightly stronger.

Although LAI impacts potential (and actual) ET, its impact on yearly average soil moisture content is limited, and simulated soil moisture contents for LAI equal to 2.88 are only very slightly smaller than soil moisture contents for LAI equal to 2.0. The soil moisture trends are also nearly identical for the two different LAI-values. Plots are shown in the supplementary material (Fig. S2).

Figures S3 (supplementary material) and S4 (supplementary material) show the PPD and ET-deficit trends for the different regions and for the two different LAI-values. The figures illustrate that LAI=2.88 results in higher PPD and higher ET-deficit than LAI=2.0. For PPD, the largest differences between the temporal trends for LAI=2.0 and LAI=2.88 are simulated for northern Germany where the PPD-trend is 0.99 mm/year for LAI=2.0 and 1.36 mm/year for LAI=2.88. For ET-deficit, western Germany, southern Germany and northern Germany show the largest increase in the slope of the trend line, comparing LAI=2.88 and LAI=2.0. However, the overall picture is the same for LAI=2.0 and LAI=2.88, and the main difference is the magnitude of PPD and ET-deficit.

4 Discussion

This study was carried out for pasture, and we investigated also the impact of different LAI-values on the simulated temporal trends in drought indices. However, for other vegetation types with deeper roots and higher LAI, the temporal trends and rankings we found here could be different. It can be expected that deeper rooting vegetation like forests can take up water from deeper soil layers so that forests are not affected so fast by droughts as crops or pasture (Kleine et al., 2020). As a consequence, the ET-deficit might show a less pronounced temporal trend for forests. It is expected that the other drought indices (SPI, SSI, PPD) for forests are quite similar to grassland.

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In our simulations, we used a free drainage lower boundary condition. Alternatively, the lower boundary condition could be a groundwater table, whose level typically also varies over time and is lower during summer time and shallower during winter time. The simulated temporal trends of drought indices could be affected by the lower boundary condition, as groundwater affects soil moisture contents and actual evapotranspiration. During drought conditions, it can provide an additional water source for the vegetation and buffer droughts, resulting in a smaller ET-deficit. The presence of a shallow groundwater body can therefore also affect the ranking of the most extreme drought years. For example, if a drought year is preceded by a wet winter which resulted in relatively high groundwater tables at the beginning of the summer season, the summer drought can be buffered by the relatively high groundwater tables, reducing the ET-deficit compared to a situation with deeper groundwater tables. A further limitation is that we assumed a no ponding condition at the land surface. This assumption can also affect the simulated removal of water from the soil column, soil moisture contents and actual evapotranspiration.

5 **Conclusions**

We analyzed meteorological, soil moisture and agricultural droughts over Germany and the Netherlands for the period 1965-2019 with separate analysis for four different German regions (north, west, east and south). It was evaluated how exceptional the 2018 drought was. Simulations were done for 31 locations distributed over Germany and the Netherlands with long meteorological time series to drive the HYDRUS-1D model for unsaturated flow in soils. Simulations were done for five different soil types at each location and for pasture with two different LAI-values. The main conclusions are:

1. The year 2018 experienced very high maximum temperatures, very high sunshine duration, and low relative humidity across the study domain, and was for most studied sites the year with the highest potential ET. In terms of precipitation deficit, 2018 was for many locations not exceptional and only for 8 locations (out of 31) the standardized precipitation index (SPI) had in 2018 the lowest value in the time series of 1965-2019. The years 1976 (especially in the Netherlands and western Germany) and 2003 (especially in southern Germany) were often drier in terms of SPI. The year 2018 was more exceptional in terms of soil moisture drought and for 13 out of 31 stations SSI (standardized soil moisture index) was in 2018 the lowest in the time series of 55 years. This was especially the case for northern and eastern Germany. The year 2018 was remarkable in terms of potential precipitation deficit (PPD, precipitation minus potential ET) and evapotranspiration deficit (accumulated difference between potential ET and actual ET), related to the very high potential ET. For half of the stations (especially in northern, central and eastern Germany) 2018 was the most extreme year in the time series since 1965. This illustrates that the 2018 drought was especially extreme and intensified by the high potential ET, affecting reductions in crop yield due to the missing water for plant transpiration. Other years with wide spread severe droughts were especially 1976 and 2003, but in terms of soil moisture drought and ET drought they were less extreme than 2018 over the study domain.

2. The trends in the four drought indices over the period 1965-2019 showed that meteorological droughts (in terms of SPI-6 and SPI-12) increased at many locations, especially in Germany, whereas at other locations meteorological drought decreased, especially in the Netherlands. Only at a few locations the trend towards more severe meteorological droughts were significant. Soil moisture or agricultural drought, as characterized by SSI-6 and SSI-12 increases at most locations,

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SSI-6 even at all locations. SSI-6 shows a significant trend towards more soil moisture droughts for slightly more than half of the locations. PPD and ET deficit show even more pronounced trends with trends towards increased water deficit at all locations, and significant trends for 15 out of 31 (PPD) and 20 out of 31 (ET deficit) locations. Significant trends towards more severe droughts in terms of SSI, PPD and ET deficit occur in spite of small changes in total precipitation amounts. These significant trends are driven by increased potential ET (related to higher temperatures, higher incoming radiation and lower relative humidity) and a shift of precipitation amounts during the year with increasing precipitation in winter and decreasing precipitation in summer.

3. Simulations were limited to pasture, a relatively simple representation of vegetation, and a free drainage boundary condition. It would be of interest to extend the simulations to include different crop types and natural vegetation, as well as different boundary conditions including groundwater-controlled systems. We expect for crops similar results as for pasture, but for deep rooting vegetation and groundwater-controlled systems the ranking of the different drought years might change, for example if at the beginning of a drought year groundwater levels are relatively high for the time of year, allowing for an additional water buffer during the dry summer.

Data and code availability

The code and datasets relevant to this study can be provided from the corresponding author upon request.

Author contributions

HJHF, YH and JW designed the study. YH (completely) and JW (partially) developed the programming code and performed the simulations. YH, JW and HJHF analysed and interpreted the results. HJHF and HV supervised the work. YH prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare no competing interests.

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