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A comprehensive methodology for drought projection analysis in temperate regions applied to Denmark

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Abstract

Global studies tend to project fewer droughts in temperate and cold climates, where detecting and characterising droughts remains methodologically challenging. We use Denmark as a test-case to investigate the validity of these global projections which often rely on methods that overlook Denmark's pronounced seasonal drought patterns and heterogeneous geography. To address this, we propose a stepwise methodology when investigating droughts in temperate and cold climates. We calculate drought indices tailored to the climatic conditions and apply one coherent, multi-threshold method for consistent comparison of drought characteristics across meteorological, soil moisture and hydrological compartments. Using bias-adjusted regional climate projections from *Klimaatlas*, the Danish Climate Atlas, together with simulations from the National Hydrological Model of Denmark, we assess how drought frequency and intensity may evolve by the end of the 21st century.

Although the overall climate is projected to become wetter, our methodology discovers a concurrent increase in extreme drought events. The projections reveal a robust increase in frequency and intensity of summer meteorological droughts, due to shifting precipitation patterns and increased evapotranspiration. The

hydrological responses show strong spatial variability. While most catchments and aquifers are projected to experience fewer streamflow and groundwater droughts, certain areas still expect more frequent hydrological drought conditions. Overall, shifting meteorological drought patterns do not translate uniformly into hydrological droughts, with some regions facing simultaneous increases in both meteorological and groundwater drought. The methodological framework presented here provides a transferable approach for capturing seasonal dynamics, varying drought intensities, and cross-compartment comparisons, improving the interpretation of future drought risks in similarly complex hydro-climatic regions.

Keywords: meteorological drought, hydrological drought, climate projections, drought indices, temperate climate hydrology, Denmark

1 Introduction

Most of Scandinavia has seen droughts in 2018, 2022 and 2023 which increased the effort to better understand future drought conditions in Northern Europe. These droughts have had severe impacts on agriculture, ecosystems, building structure and more (Henriksen et al. 2022; Bakke et al. 2020). In the spring of 2018, a precipitation deficit combined with a very warm and sunny period led to a severe drought in soil moisture and streamflow, but had less severe effects on the groundwater, due to buffering effects from the preceding wet winter (Henriksen et al. 2022). This highlights the need for a more direct interdisciplinary approach considering both meteorological, soil moisture and hydrological drought.

To get an overview over the current knowledge, we first look at the latest IPCC report (Seneviratne et al. 2021). There, chapter 11 projects with medium confidence a decrease of drought frequency and severity in Northern Europe, based on the following studies (Touma et al. 2015; Spinoni et al. 2020; Vicente-Serrano et al. 2020). Further similar studies from a global perspective also project more precipitation in the future with fewer droughts (Ionita et al. 2022; Balting et al. 2021; Naumann et al. 2018; Toreti et al. 2024; Wang et al. 2021). Other regions, where global studies suggest decreasing future drought levels similarly to Northern Europe are: Alaska, Canada–Greenland–Iceland, Northern Asia and Southeast Asia (Spinoni et al. 2020). Regional studies focusing on Northern Europe hint at the possibility of a more nuanced drought response (Chan et al. 2021; Karlsson et al. 2015; Häberli et al. 2026). However, the small number of regional drought studies hampers confidence in assessments of future drought frequency. This apparent discrepancy between global and local drought studies highlights the need for further investigation.

To better understand the discrepancy between global and local studies, we list some of the methodological problems the previously mentioned global studies face in the Nordic climate. Touma et al. (2015) uses 6-month accumulated data, not capturing some parts of the seasonality of the region due to the long accumulation period. Further, they actually show an increase in both SPI and SPEI drought events by the end of the century, the opposite of what the IPCC report claimed. Spinoni et al. (2020)

uses 12-month accumulated data, not capturing any seasonality as the well-established projected increase in winter precipitation drowns out any summer variability. [Vicente-Serrano et al. \(2020\)](#) uses a more suitable methodology for the local climate but only presents changes in average SPI and SPEI values, not capturing any signal in the drought frequency. [Ionita et al. \(2022\)](#) also focusses on long-term drought and uses annual accumulated SPEI. [Balting et al. \(2021\)](#) uses 6-month accumulated SPEI for JJA, which introduces a wetting through the inclusion of the winter and spring months which are projected to become wetter. [Naumann et al. \(2018\)](#) mentions that Northern Europe faces short drought events, nevertheless they base their results on 12-month accumulated SPEI. [Wang et al. \(2021\)](#) uses 6-month accumulated SPI and SPEI and does not take seasonality into account. While these studies provide valuable insights into global drought changes, we demonstrated the need for a better suited methodology for drought analysis in Northern Europe. In this study, we present a new six-step methodology to better analyse future drought projections, shown with national-scale data of Denmark.

Improved drought analysis in regions with uncertain drought projections should if possible include the following points.

1. Use high-resolution model ensembles to account for spatial heterogeneity.
2. Bias-adjust the model output to increase trust in the findings.
3. Include hydrological models to represent hydrological variables more accurately and at a higher resolution.
4. Calculate drought indices for all hydrological compartments (atmosphere, surface, groundwater, etc.).
5. Take seasonality into account.
6. Investigate both changes in drought frequency and intensity.

Our study shows how these points can effectively be applied to Denmark as a test-case. Denmark is well suited for such a study, as it has a heterogeneous geography and geology at small scale, and it is located between the drying mainland Europe and a wetter future Scandinavia. Furthermore, Danish winters are projected to, on average, become even wetter with climate change, while summer precipitation is projected to remain similar to today ([Seidenfaden et al. 2022](#)). This makes the methodologies in the previously mentioned global studies especially unsuitable for drought research in this region.

In this study we start from climate projections from *Klimaatlas*, the Danish Climate Atlas ([DMI 2024a](#)). *Klimaatlas* builds on the EURO-CORDEX ensemble ([Jacob et al. 2014](#)), downscaled and bias-adjusted against local measurements. We supplement the meteorological data with hydrological projections, simulated using a subset of the EURO-CORDEX data by the Geological Survey of Denmark and Greenland (GEUS) in their National Hydrological Model of Denmark (DK-model) ([Stisen et al. 2020](#)) and the indices calculated by [Schneider et al. \(2026b\)](#).

Our results present drought frequency changes for every month of the year, which is essential in temperate regions where seasonal contrasts can be extreme. For example, in 2023, Denmark had a very dry spring yet recorded the wettest year since 1874, rendering annual indices like SPI-12 unreliable ([Toreti et al. 2023](#); [Rubek 2024](#)). The

119 results were obtained using the drought multi-threshold method, which was specif-
 120 ically created to work for any standardised drought index and improve comparison
 121 between indices (Häberli et al. 2026). Further, the method allows comparing multi-
 122 ple drought intensities for all water compartments using the same analysis. Together,
 123 these elements form a transferable framework for drought projection analysis in hydro-
 124 climatically complex regions, while delivering a comprehensive assessment of future
 125 drought conditions in Denmark from precipitation deficits to groundwater.

126 2 Methods

127 2.1 Study area

128 Denmark is a low-lying country in northwestern Europe located between approxi-
 129 mately 54–58° N and 8–15° E, see Fig. 1, and bordered by the North Sea to the west
 130 and the Baltic Sea to the east. This leads to a complex and variable coastline, which
 131 is impossible to reproduce in low-resolution climate models. The region is charac-
 132 terised by a temperate maritime climate, influenced by prevailing westerlies, relatively
 133 small seasonal temperature and precipitation amplitudes, and a pronounced land–sea
 134 interaction.

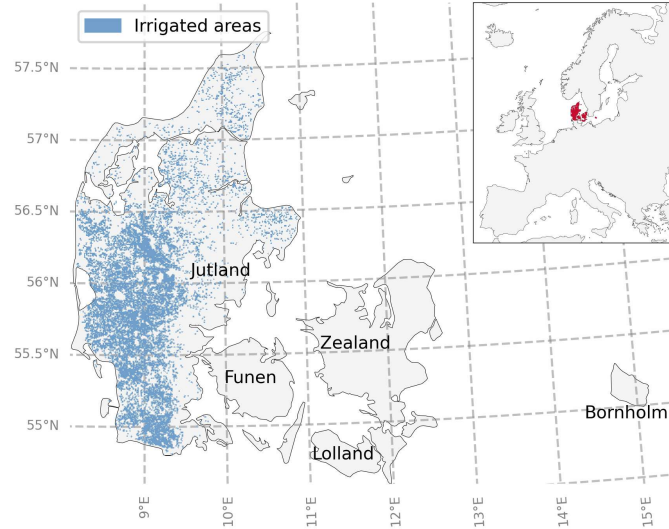


Fig. 1 The largest regions and islands of Denmark, highlighting the areas with irrigation in the DK-model. The inset map shows the location of Denmark in Europe.

135 Hydrologically, Denmark is dominated by shallow groundwater systems, small
 136 river catchments, and permeable Quaternary deposits, with strong spatial variabil-
 137 ity between sandy and loamy soils and a heterogeneous geology (Greve et al. 2007;
 138 Sandersen and Jørgensen 2017). Interactions between surface water and groundwa-
 139 ter are therefore strong, in particular in the sandy areas (Duque et al. 2023). Thus,

hydrological droughts often reflect cumulative anomalies in both precipitation and evapotranspiration rather than short-term meteorological deficits. Irrigation in Denmark is predominantly found in western Jutland, see Fig. 1, with few irrigation wells elsewhere (Stisen et al. 2020).

Concerning climate change, Denmark constitutes a climatic and hydrological transition zone between Southern and Northern Europe. Projected climate-change signals differ significantly both in magnitude and seasonality thus uncertainties are high (Matte et al. 2019). According to the latest IPCC AR6 WG1 assessment, Northern Europe is projected to experience increases in annual precipitation and runoff, while large parts of Southern Europe are projected to face decreasing precipitation and enhanced drought risk (Douville et al. 2021; Gutiérrez et al. 2021). Denmark is interesting in this context because it is located close to the boundary between these regimes (Spinoni et al. 2015). Observational and model-based analyses from e.g. *Klimaatlas*, described in more detail in the next section, indicate increasing winter precipitation and runoff. Summer precipitation changes are weaker and more uncertain, with a tendency towards increased interannual variability (compare Fig. 2 and Table A1). Potential evapotranspiration (PET) was calculated with three different methods, a radiation-based method (Makkink 1957) and two temperature-based methods (Hargreaves and Samani 1982; Oudin et al. 2005). All methods project PET to increase throughout the 21st century, although the magnitude of this increase depends on the formulation used.

2.2 Data

We use data from two sources: *Klimaatlas*, the Danish Climate Atlas, and the National Hydrological Model of Denmark (DK-model). An overview between datasets is given in Table 1.

Table 1 Overview over the datasets used in this study. The indices are described in Table 3.

	<i>Klimaatlas</i>	DK-model
PET method	Makkink	Oudin
Calibration method	Regidded to CORDEX grid, bias cadjusted using quantile-quantile matching	Distribution-based scaling approach, undercatch-corrected precipitation
Nr. of simulations	27 RCP2.6 22 RCP4.5 72 RCP8.5	5 RCP4.5 17 RCP8.5
Indices calculated	SPI, SPEI	ESSMI, SDI, SGDI _{shallow} , SGDI _{deep}

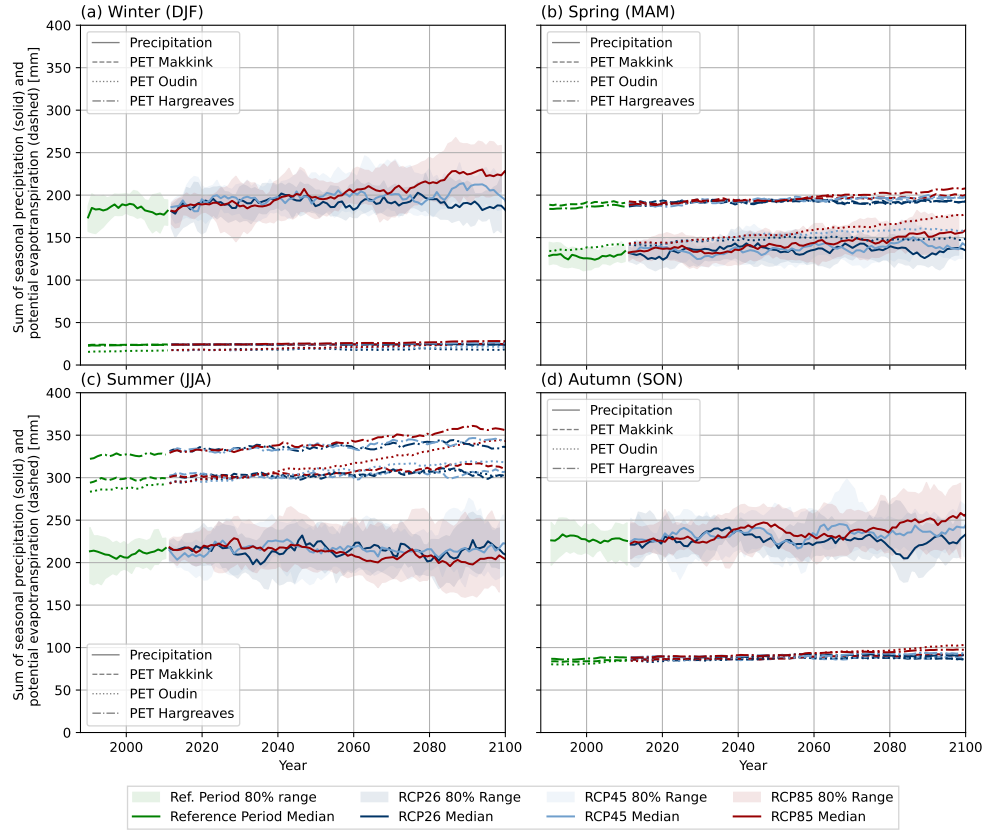


Fig. 2 Seasonal *KlimaAtlas* ensemble median for precipitation and potential evapotranspiration (PET), 10-year running mean. High precipitation dominates the water balance in winter and autumn, while spring and summer see higher PET, increasing towards the end of the 21st century.

2.2.1 KlimaAtlas

KlimaAtlas is a project providing quality climate information and data for Denmark based on regional climate models coupled with observations (DMI 2024a). *KlimaAtlas* provides variables such as precipitation, temperature, evapotranspiration, and sea-level on national, region or municipality level with the possibility of using daily 12 km or 1 km gridded data. Since drought is a large scale phenomenon, we used the 12 km data. A test with the downscaled 1 km data showed little change. *KlimaAtlas* is meant as a tool to investigate future risk to prepare for a changing climate. Danish municipalities and organisations have so far used this information for amongst others flood preparedness, addressing sea-level rise and securing buildings (DMI 2026b). However, only few of the 98 municipalities have concrete drought adaptation measures in progress (Lind and Hansen 2024). Many municipalities stress the need for further research into future drought levels before they can make concrete plans.

The data in *Klimaatlas* was created by bias-adjusting the original model data from EURO-CORDEX using observational data with the quantile-quantile matching method and extreme value analysis (DMI 2024b). This makes *Klimaatlas* the most reliable high-resolution dataset for future climate projections in Denmark. Almost all EURO-CORDEX models were selected, with an overview given in Table 2 and (DMI 2024b). In total, we use 27 RCP2.6 scenarios (lowest greenhouse gas concentration) (Moss et al. 2010), 22 RCP4.5 scenarios and 72 RCP8.5 scenarios (highest greenhouse gas concentration) from *Klimaatlas* v2024b. Two RCP8.5 scenarios were missing daily minimum and maximum temperature and could not be used for certain calculations. We use the *Klimaatlas* data to calculate the meteorological drought indices described in the next section.

While *Klimaatlas* provides data for multiple meteorological variables, it does not deliver information on surface and subsurface variables such as streamflow and groundwater levels. Therefore, *Klimaatlas* recommends combining its data with local knowledge to understand e.g. impacts of future droughts (DMI 2026a). In our case we combine the meteorological data for Denmark with specific hydrological modelling.

Table 2 Overview over the climate simulations used in this study. The numbers show how many simulations were used for each GCM+RCM combination in *Klimaatlas* / the DK-Model, no slash indicates no simulations in the DK-model. One example how to read this table is KNMI-RACMO22E driven by ICHEC-EC-EARTH, there were 6 simulations in *Klimaatlas* and 2 in the DK-Model. In *Klimaatlas*, the scenarios used were RCP2.6 (one spinup version), RCP4.5 (two different spinup versions) and RCP8.5 (three different spinup versions). Two of these RCP8.5 scenarios were used to force the DK-model.

	Institution / RCM											
Driving GCM	CLMcom-CCLM4-8-17	CLMcom-ETH-COSMO-crCLIM-v1-1	CNRM-ALADIN63	DML-HIRHAM5	GERICS-REMO2015	ICTP-RegCM4-6	IPSL-WRF381P	KNMI-RACMO22E	MOHC-HadREM3-GA7-05	MPI-CSC-REMO2009	SMHI-RCA4	UHOH-WRF361H
CCCma-CanESM2	1	0	0	0	1 / 1	0	0	0	0	0	0	0
CNRM-CERFACS-CNRM-CM5	0 / 1	1	2	1	2	1	1	3	1	0	0	0
ICHEC-EC-EARTH	3	3	0	5 / 2	3	1	1	6 / 2	2	0	5 / 1	2
IPSL-IPSL-CM5A-MR	0	0	0	1	1	0	2	1	0	0	2 / 2	0
MIROC-MIROC5	2	0	0	0	2 / 1	0	0	0	0	0	0	1
MOHC-HadGEM2-ES	2 / 1	1	1	3 / 1	3 / 1	2	1	3 / 2	2	0	3 / 1	1
MPI-M-MPI-ESM-LR	3	3	0	1	1	2	1	2	1	6 / 4	5 / 1	2
NCC-NorESM1-M	0	1	0	2 / 1	3	2	1	2	1	0	3	0

2.2.2 DK-model

The National Hydrological Model of Denmark (DK-model) is a distributed, integrated surface water–groundwater model covering most of Denmark’s land area. It is set up in the MIKE SHE model code (Abbott et al. 1986; DHI 2024), and couples a 3D finite difference description of groundwater flow to a 2D description of overland flow, as well as a simple routing of streamflow and a 1D representation of root zone processes. It is a transient hydrological model, forced by gridded, daily observational climate data from DMI (Scharling 1999a,b). Automatic model calibration is performed against various observations of streamflow and groundwater heads (Schneider et al. 2022b,a).

Its development over the last three decades (Henriksen 2001; Henriksen et al. 2003, 2021; Højberg et al. 2013; Stisen et al. 2020) has been driven both by projects from the public sector and research funds. In different versions, it has served as the basis for water resource assessments (Henriksen et al. 2024), nutrient transport studies (Højberg et al. 2025), the estimation of groundwater age and travel time (Musy et al. 2023), or for hydrological monitoring and early warning (Henriksen et al. 2018; Liu et al. 2026) as well as climate change impact studies (Schneider et al. 2022b; Seidenfaden et al. 2022).

The results presented here are based on the DK-model HIP, which is the version that is part of the Danish Hydrologic Information and Prognosis system (HIP) (Henriksen et al. 2021). As part of HIP, an ensemble of RCMs from EURO-CORDEX was run with the DK-model to assess climate change impacts on the hydrological cycle. A selection of 17 RCP8.5 and 5 RCP4.5 RCMs were bias corrected for Denmark by Pasten-Zapata et al. (2019a) using a distribution-based scaling approach with special consideration for hydrological applications, for example using undercatch-corrected precipitation as baseline (Stisen et al. 2011). PET is determined based on the Oudin approach (Oudin et al. 2005), as it requires only temperature data as variable input and was found robust for applications with hydrological models. All those RCMs cover the years 1971 to 2100 with daily timesteps.

To determine climate change impacts, each RCM was run through the DK-model for each of the periods 1991–2020 (reference), 2041–2070, and 2071–2100. The climate change impact was calculated as the difference between conditions during the future periods relative to the reference period for each climate model. Being an integrated hydrological model, the DK-model is able to track impacts of climate change consistently throughout the hydrological cycle, that is, translating changed climate input into changes to compartments such as soil moisture, streamflow, and groundwater. Its ability to simulate hydrological anomalies such as droughts also has been shown in recent work (Schneider et al. 2026a), where multiple drought indices were calculated and validated against observations.

2.3 Drought indices

Different drought indices are used to mathematically quantify droughts, helping researchers define the onset, termination and intensity of droughts (Svoboda and Fuchs 2016; Mishra and Singh 2010). The indices used in this study take one or more input variables and return a single value representing the drought intensity per day, week or

month. The drought frequency tells us how often these droughts occur. In this study, we only use standardised indices, describing deviations from the reference period normal conditions. The distribution of each index in the reference period is constructed to be normal around a mean of zero with a standard deviation of one. This helps to compare drought levels across multiple regions (World Meteorological Organization 2012). Changes from this distribution outside the reference period can be used to analyse climate signals. The indices and reference periods we used are presented in Table 3, where we separated the indices into those describing meteorological or hydrological drought.

Meteorological drought indices aim to describe drought conditions solely based on meteorological data such as precipitation and PET. We use the Standardised Precipitation Index (SPI) (McKee et al. 1993) and the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). The SPI (SPEI) uses a gamma (generalised extreme value, GenEV) distribution on monthly accumulated precipitation (precipitation minus PET) (Stagge et al. 2015). Vremec et al. (2024) and Seiller and Anctil (2016) recommended using multiple methods to calculate PET, because they can show large differences. We calculate PET using three different methods: the modified Makkink method (PET-Makkink) (Makkink 1957; Aslyng and Hansen 1982; Scharling 2001), the Hargreaves method (PET-Hargreaves) (Hargreaves and Samani 1982) and the Oudin method (PET-Oudin) (Oudin et al. 2005). While PET-Makkink was already calculated in *Klimaatlas*, we calculated the other two methods using temperature data from *Klimaatlas* and the python package PyEt (Vremec et al. 2024).

We chose the Makkink method since DMI uses it for forecasting and climate research, and it is sensitive to changes in global radiation and temperature. The Hargreaves method is temperature-driven using minimum, maximum and average daily temperature and the expected solar radiation based on the latitude (Shaw and Riha 2011; Vremec et al. 2024). It was recommended as the best alternative to radiation-based methods for observational data (Allan et al. 1998). We included the Oudin method, driven by average daily temperature and expected solar radiation, since it is a simple method based on only average temperature, and it is used in the DK-model. It exhibits a stronger temperature sensitivity and therefore produces a larger PET increase under warming conditions, see Table A1.

This difference between PET methods is important for drought assessment, as it directly affects simulated soil moisture deficits and low-flow conditions. While the purely temperature-based methods have the disadvantage of ignoring radiation and wind, the radiation-based method might also be sensitive to uncertainties in climate model prediction of radiation. From these precipitation and PET values, we calculated the SPI and SPEI using the xclim python package and the KAPy pipeline (Bourgault et al. 2023; DMI 2025). While these indices give an overview over precipitation deficits and an approximation of soil conditions, to investigate conditions on and below the ground, we need more specialised indices.

Agricultural and hydrological drought indices are used to describe deficits in the water system such as soil moisture, streamflow or groundwater. We calculate such standardised indices from the outputs of the hydrological model, therefore calling all

of them hydrological drought indices. First, we detect soil moisture droughts using an Empirical Standardized Soil Moisture Index (ESSMI) (Carrão et al. 2016). While we tested other indices (SMDI and SSI), ESSMI showed the best standardised values during the reference period. Challenges with the previous indices are likely caused by the partly bounded nature of (simulated) soil moisture values, e.g. at saturation water content, which makes parametric distribution fitting difficult. In contrast, the ESSMI relies on the empirical distribution fitted with the help of kernel density estimates. Second, we detect streamflow droughts using the Streamflow Drought Index (SDI) (Nalbantis and Tsakiris 2009) for all the stream data points (calculation points) in the model. Third, we detect groundwater droughts using both the Standardised Groundwater Drought Index for the uppermost groundwater (SGDI_{shallow}, using the depth to the uppermost groundwater table [m]) and deep groundwater (SGDI_{deep}, using the aquifer groundwater head [m]) (Bhuiyan et al. 2006; Bloomfield and Marchant 2013). A thorough description of the hydrological indices and how they were calculated can be found in Schneider et al. (2026a). Consistent with the meteorological drought indices, we calculate all hydrological drought indices to fit a reference period. This allows us to detect a climate change signal using deviations from the normal distribution by utilising the drought multi-threshold method.

Table 3 Overview over the indices used in this study, how they were calculated and the reference period used.

Type	Index	Calculation	Reference Period
Meteo. Indices	SPI	Gamma fit on monthly accum. precipitation	1981–2010
	SPEI	GenEV fit on monthly accum. precipitation - PET	1981–2010
Hydro. Indices	ESSMI	Nonparametric empirical probability density function fit	1991–2020
	SDI	Standardised log-streamflow anomaly	1991–2020
	SGDI _{shallow}	Standardised uppermost groundwater table anomaly	1991–2020
	SGDI _{deep}	Standardised groundwater head anomaly	1991–2020

2.4 Drought multi-threshold method

The drought multi-threshold method improves on traditional methods by analysing changes in the frequency distribution of multiple drought intensities. The method was introduced in Häberli et al. (2026), we present only a short summary. Standardised drought indices are constructed to be normally distributed for a chosen reference period. Therefore, each threshold has a known, fixed exceedance probability. Using this method allows selecting multiple thresholds (in our case -1, -2, -3) to investigate how the exceedance probability changes outside the reference period. We define drought frequency as increasing if months in the future are below the thresholds more often than the statistical values.

The benefits of using the drought multi-threshold method are threefold. First, we can choose multiple drought thresholds rather than only using one fixed definition

of drought. While we chose integer values, the thresholds could also be selected to reflect return periods. Second, the method allows us to intuitively compare results for different indices directly to each other and to the statistically expected frequency of drought. Third, we can include the reference period in the results rather than using it as the *base truth*. This makes flaws in the index fit become easily visible, as we will show in the results section. The limitations on the other hand regard the fact that only standardised indices can be analysed. Further, the index values at every time step are taken independently of the previous time step. Therefore, a drought definition as given in the original McKee et al. (1993) would break with this analysis.

Häberli et al. (2026) found that while the Danish climate is projected to become wetter and experience fewer moderate droughts, the frequency of extreme droughts can nevertheless increase. This is shown schematically in Fig. 3. Therefore, multiple drought thresholds should be analysed. While that paper only used the SPI, they argue that the method can be used for any standardised drought index. We apply this method to the previously discussed drought indices to analyse changes to the frequency across the year of moderate (index < -1), extreme (index < -2) and exceptional (index < -3) droughts at the end of the 21st century.

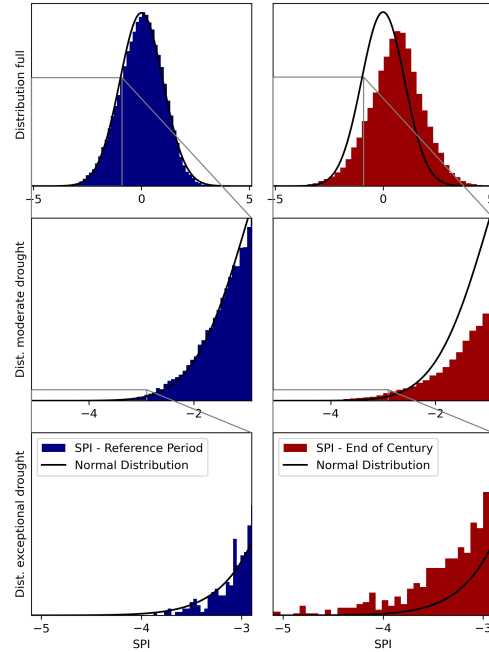


Fig. 3 The left column shows how well the SPI (standardised precipitation) during the reference period matches a normal distribution. While the distribution moves to the right in the future (meaning wetter conditions, top right) with fewer moderate droughts (middle right), the tail to the left also increases (meaning exceptional drought, bottom right). Here, we show data for the whole year.

3 Results and discussion

In this section we present the results from the analysis of the drought indices using the multi-threshold method, divided into sections covering meteorology (Sect. 3.1) and hydrology (Sect. 3.2). Each section includes a discussion on the results from the specific indexes. The overall discussion and perspectives are investigated in Sect. 4. All the indices and results were calculated for each gridcell individually. Then, the average over Denmark is calculated for the period 2071–2100.

3.1 Meteorological drought

3.1.1 Meteorological drought results

We first investigate the result of the SPI in Fig. 4, showing the median model projections for all three RCP scenarios 2071–2100 and the reference period, averaged over Denmark. The reference period median (in green) matches the statistical values from the normal equation reasonably well, expectedly getting worse for the rarer drought intensities. Both the SPI-1 (monthly precipitation anomaly) and SPI-3 (three-month accumulated precipitation anomaly) show a similar seasonal signal at the end of the century. The projections show decreased moderate drought frequency during winter and spring, and an increase during late summer and early autumn. Likewise, extreme and exceptional droughts show the same pattern, however, with an earlier onset and larger increase during the summer. The model spread is quite large, with most models agreeing on fewer droughts during winter. During summer, the model-agreement lessens, the driest 10 % of models in the RCP8.5 scenario reach moderate drought frequencies of over 0.4, while the wettest 10 % of models show less than 0.07. Maps of the SPI signal, see Fig. 7, show little spatial variation. While SPI only takes precipitation into account, PET plays a large role in drought dynamics, leading us to analyse the SPEI.

We present the results for the SPEI in Fig. 5. We show SPEI-1 and SPEI-3 using the Makkink PET method, while for the other PET methods, we only show the three-month accumulated SPEI. This was done as SPEI-3 is more robust against outliers and has fewer non-normal values (Stagge et al. 2015). SPEI-1-Makkink and SPEI-3-Makkink look similar to SPI-1 and SPI-3, but with larger summer increases in drought frequency and an earlier onset of the increase. While SPI-3 increases in moderate drought frequency in July, the SPEI-3-Makkink increases already in June. SPEI-3-Hargreaves shows even larger increases in the frequency and earlier start of the increase for each intensity. SPEI-3-Oudin shows the largest increase in drought frequency. The median of the RCP8.5 scenarios projects every second year to experience moderate droughts in August and September. Furthermore, SPEI-3-Oudin shows high model agreement (more than 90 % of the RCP8.5 scenarios) of increasing frequency of moderate and extreme summer droughts. This is to be expected, as all the EURO-CORDEX models for the RCP8.5 scenario result in high temperatures. Similarly to the SPI, the results for the SPEI were also spatially homogeneous over Denmark, see Fig. 7.

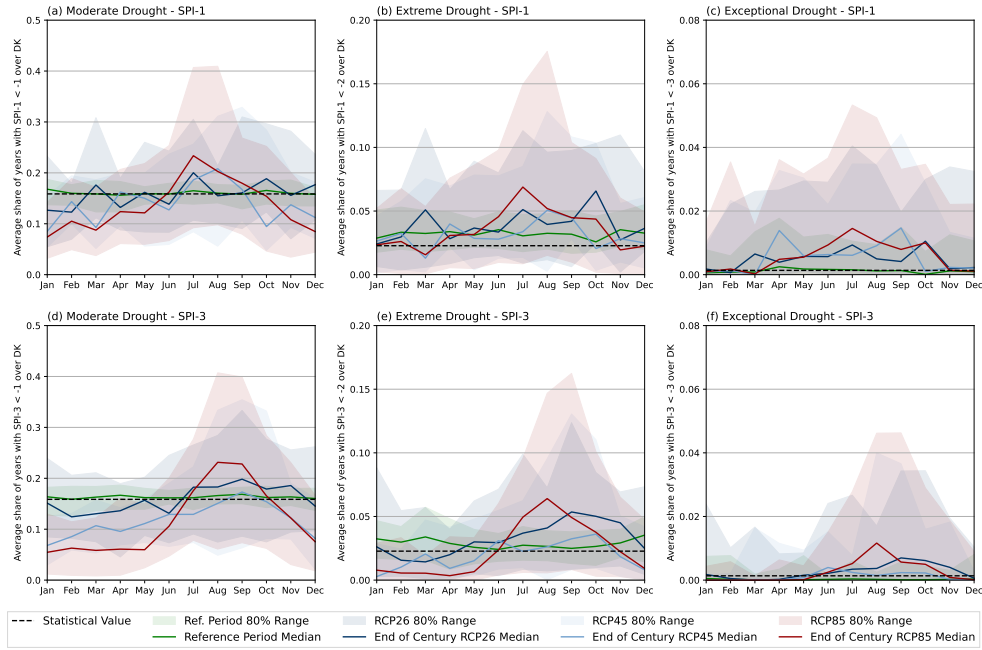


Fig. 4 SPI-1 (top row) and SPI-3 (bottom row) during the reference period and for three scenarios at the end of the century. Note the different y-axis for each drought intensity.

3.1.2 Meteorological drought discussion

The SPI results show a strong seasonality, with fewer droughts in the winter months and more in the summer months. Winter droughts are projected to become less frequent, with an average precipitation increase between 1.4 % (RCP2.6) and 20.6 % (RCP8.5), compare Table A1. Changes in summer precipitation are less certain, with some scenarios on average projecting an increase while others projecting a decrease. This explains why the SPI reaches more frequent summer drought levels in some scenarios, with little to no change in others. This stresses the importance of taking seasonality of the data into account, as studies only looking into yearly averages will miss the increasing summer drought frequency. Comparing our results to studies including seasonal analysis such as Spinoni et al. (2018) and Häberli et al. (2026), they have also found increasing frequency and intensity of meteorological summer droughts, with decreases in winter. Spinoni et al. (2018) also speculated that strong temperature increases could lead to more severe future droughts in Scandinavia, which is consistent with the results of the present study.

The SPEI results show an even stronger seasonality compared to the SPI. In Table A1, the projected increase in PET during winter is minor (-1 to +7 mm) compared to the increase in precipitation (3 to 38 mm), leading to lower SPEI values. The larger increase in SPEI drought frequency during summer stems from the increasing summer temperatures on top of similar precipitation levels. The Makkink PET method

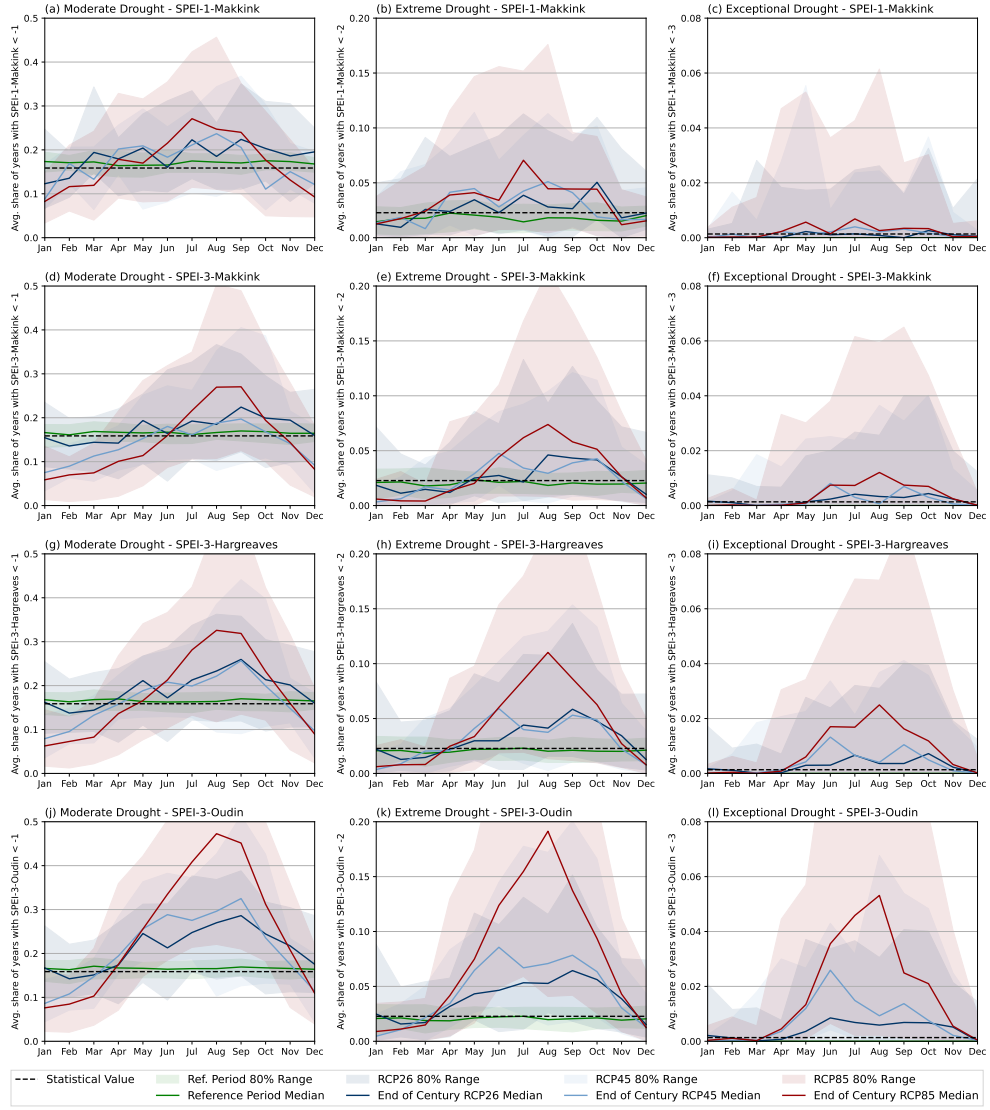


Fig. 5 SPEI-1 (top row) and SPEI-3 (second row) using the Makkink PET method as well as SPEI-3 using the Hargreaves (third row) and the Oudin method (bottom row) during the reference period and for three scenarios at the end of the century. Note the different y-axis for each drought intensity.

389 takes multiple atmospheric variables into account, resulting in a smaller increase in
 390 PET as compared to the purely temperature-based methods such as Hargreaves and
 391 Oudin, see Table A1. There, PET-Oudin is on average increasing by 17.6 % for the
 392 RCP8.5 scenario whereas Makkink only increases by 5.1 % and Hargreaves by 8.8 %.
 393 While it is difficult to claim which PET is most accurate, Vremec et al. (2024) mentions
 394 that Makkink might be underestimating high PET values. Further, Makkink might

be underestimating the increase in PET as the EURO-CORDEX models are underestimating the increase in incoming radiation compared to CMIP5 (Boé et al. 2020). Further, Prudhomme and Williamson (2013) found that Makkink underestimates PET increases in future summer projections over Great Britain compared to the recommended FAO56 version of the Penman–Monteith equations, while Oudin seems to align better. On the other hand, Shaw and Riha (2011) found temperature-based methods to likely overestimate PET in the future. Allan et al. (1998) only recommends Hargreaves as a temperature-based method. In general, it is recommended to use multiple PET methods (Vremec et al. 2024; Seiller and Anctil 2016), as this helps comparison with other studies and for highlighting the differences in future PET estimates.

We tested the robustness of all results by removing single RCMs or driving GCMs as well as bootstrapping the results. We came to the conclusion that even the exceptional drought levels, which are the least robust, were robust enough to be included in our analysis. A sample of the robustness tests can be found in Appendix B, Fig. B1 and B2.

Past research on a Danish catchment found the same signal of increased winter precipitation, with an even stronger PET increase (Karlsson et al. 2015, 2016; Seaby et al. 2013). The choice to show only the results for the end-of-century period was done based on Seaby et al. (2013) as this period showed the strongest climate change signal. They found a similar increase in PET in one Danish catchment to this study, with precipitation increasing overall, but decreasing in late summer. On the other hand, research focusing on 12-month accumulated SPI and SPEI indices found a decrease in drought frequency towards the end of the century (Spinoni et al. 2015, 2020). While these findings seemingly contradict our results, we show in Sect. 4.1 that the differences stem from the chosen accumulation periods. Therefore, we see our study as adding seasonal information to those studies. Our increasing meteorological drought intensities are similar to the findings in Ukkola et al. (2020), which found stronger but shorter droughts using CMIP6 global climate model data for the northern mid- and high-latitude regions. An important component of summer droughts is atmospheric blocking, associated for example with the 2018 drought (Wilcke et al. 2020). While they are imperative for drought research, they are underestimated in climate models, especially over Europe (Bjerke et al. 2025; Davini et al. 2021). This might indicate even stronger meteorological droughts in the future than reported in the current models.

3.2 Hydrological drought

The hydrological results will be inspected in order of infiltration. Starting with the soil moisture (ESSMI), then streamflow (SDI), shallow groundwater (SGDI_{shallow}) and lastly the deep groundwater (SGDI_{deep}).

3.2.1 Hydrological drought results

Before analysing the future scenarios for hydrological drought indices in Fig. 6, we must first examine the reference period data. For the reference period, the data fits the normal distribution (statistical value from the multi-threshold method) worse than the meteorological indices did. Especially for ESSMI in Fig. 6 (a–c), the models show fewer

droughts than we would expect with a more accurate fit. For the SDI and SGDI_{shallow} in Fig. 6 (d–i), the reference values fit well during winter, worsening towards autumn. This has to be kept in mind when discussing the future projections.

ESSMI drought frequency is projected to increase during summer for both RCP scenarios. Both the moderate and extreme drought frequencies in Fig. 6 (a–b) spike during April only to decrease shortly during May and then reaching their maximum in September. This signal is present in both the irrigated and non-irrigated cells (results not shown here). Further, the ESSMI shows a large increase in exceptional soil moisture drought frequency, especially in RCP8.5. Next, we investigate whether the deficit in soil moisture influences streamflow and shallow groundwater, since reduced soil moisture limits the amount of water available for infiltration.

Comparing SDI and the SGDI_{shallow}, similar patterns appear for both indices. Both project a roughly 50 % decrease in drought frequency during winter and spring, increasing during summer until reaching reference period levels at the end of autumn. The two scenarios RCP4.5 and RCP8.5 show little difference. Only the SGDI_{shallow} shows a small increase in exceptional droughts in Fig. 6 (c), but these droughts are the least frequent and robust in their signal.

Continuing with the SGDI_{deep}, a reduction in drought frequency for both moderate and extreme intensities can be seen in Fig. 6 (j–k). The highest frequency of future moderate groundwater droughts is projected during the winter, but the frequency is still lower than during the reference period. A notable exception is exceptional groundwater droughts during the summer months (JJA), which spike in both the irrigated and non-irrigated areas. However, the peak is more pronounced in the irrigated areas, reaching values of 0.04 compared to 0.01 in non-irrigated areas (not shown here). This indicates an important loss of information when spatially averaging the hydrological data over Denmark.

When averaging the results over Denmark we lost information about possible spatial heterogeneity. Therefore, in Fig. 7, we present maps of the RCP8.5 scenario for each index, intensity, and season, using the model mean at each grid point. SDI is not shown, as this is only point-based. We only show the moderate drought levels, as these data are the most robust. The RCP4.5 scenarios are not shown, as they display similar patterns, but are less robust with only five simulations available. SPEI-3-Har is the SPEI using PET-Hargreaves over a 3-month accumulation period. The maps of SGDI_{shallow} indicate that while moderate shallow groundwater droughts decrease on average, some regions may still experience an increase. For example, southern Jutland (south-west DK) and the islands of Zealand and Lolland (south-east DK) show regionally increasing drought frequencies. SGDI_{deep} exhibits even stronger heterogeneity for moderate deep groundwater droughts, with some areas along the southern east coast of Jutland showing increased deep groundwater drought frequency across all seasons towards the end of the century.

3.2.2 Hydrological drought discussion

The reference period ensemble median of the hydrological indices shows a visibly worse match to the expected value compared to the meteorological indices. There are multiple possible reasons for this. First, the DK-model uses fewer climate models (22)

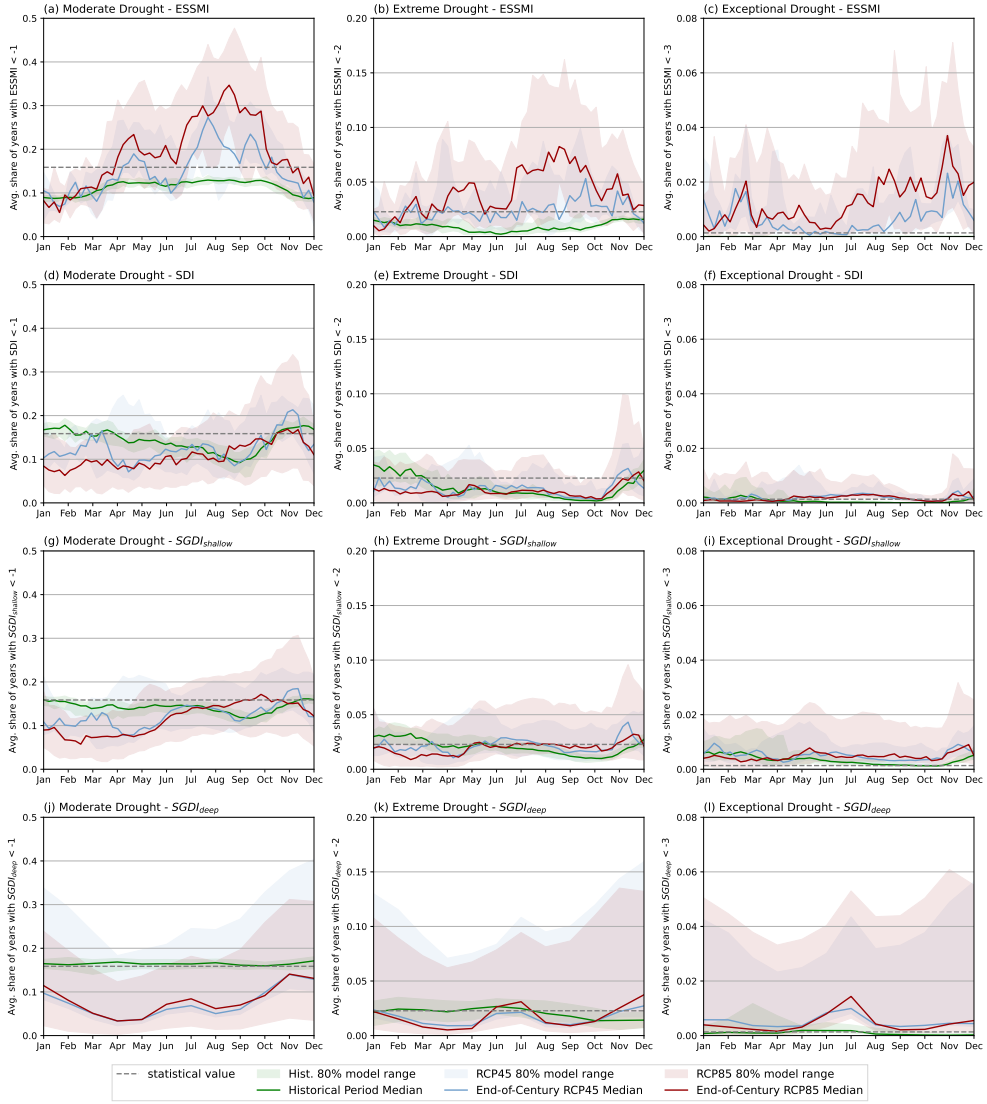


Fig. 6 The results from all the hydrological indices. Note the different y-axis for each drought intensity.

481 compared to the *Klimaatlas* (121), which can lead to poorer median performance.
 482 Second, while the meteorological drought indices fit specific distributions to the data,
 483 the SDI, $SGDI_{shallow}$ and $SGDI_{deep}$ as implemented in this study assume that the data
 484 is already normal distributed. This leads to a worse fit for certain months. Third, the
 485 ESSMI has the additional problem of more restrictive boundaries where the soil can
 486 be either be at the saturation water content or the wilting point. The ESSMI values

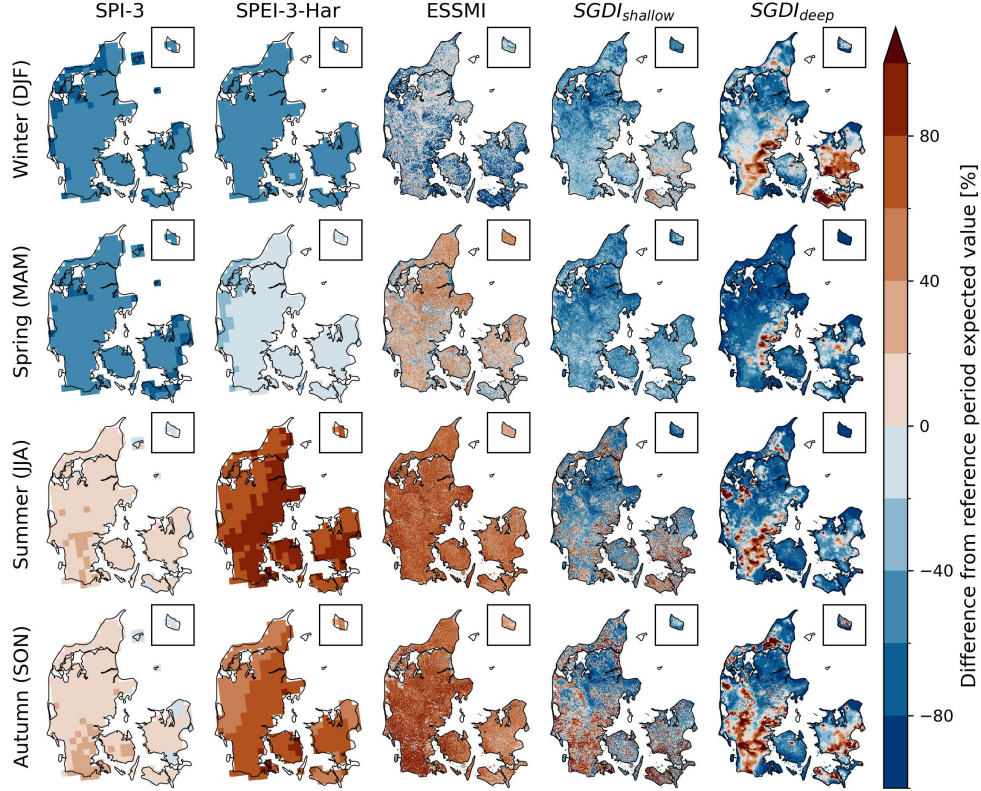


Fig. 7 Changes in moderate drought frequency for multiple drought indices 2071–2100 (RCP8.5) compared to the reference period. SPI-3 shows changes in precipitation, SPEI-3 adds potential evapotranspiration, ESSMI shows soil moisture drought while $SGDI_{shallow}$ and $SGDI_{deep}$ indicate shallow and deep groundwater respectively.

for the reference period could be improved by replacing the parametric fit with a non-parametric probability density function. However, this approach cannot extrapolate beyond the observed range, which would lead to poorer performance under climate change scenarios.

The SDI and $SGDI_{shallow}$ show very similar patterns in Fig. 6. This is mainly due to high connectivity of the groundwater and surface water, as the baseflow of the streams in Denmark stem from shallow groundwater (Karlsson et al. 2016) rather than glacier or snowmelt as in other Nordic countries. Therefore, it makes sense that both indices follow a similar pattern. $SGDI_{shallow}$ drought frequency increases mostly during summer, as this compartment is quickly affected by soil moisture deficits. The spatial pattern in Fig. 7 is linked to the subsurface geology and hydrogeological properties of the areas. More information on this can be found in the analysis by Schneider et al. (2026b). Compared to previous studies, the SDI signal agrees well with a historical shortening of summer streamflow droughts (Hisdal et al. 2006). In contrast, Parry

et al. (2024) showed an increase of streamflow droughts in the UK, while at the same time a decrease or stable levels of groundwater droughts. This stands in contrast to our finding of stable streamflow drought levels.

Future moderate deep groundwater drought frequencies decrease in all seasons, but least during late autumn and early winter. This could be due to the propagation time of deep groundwater recharge, occurring mostly during the generally wetter winters. Effects of increasingly dry summer conditions then accumulate over summer, and are most pronounced towards the end of the season (Schneider et al. 2026a). SGDI_{deep} seems to be more vulnerable in Southern Zealand and Lolland/Falster. While we cannot definitively answer why, it might be that increased precipitation in winter might fall short to compensate for the increased PET during summer. We can exclude irrigation as a possible reason, as the model has no irrigation in this region.

Irrigated areas had a four-fold higher frequency of future exceptional SGDI_{deep} droughts compared to non-irrigated areas. This value might actually be underestimating the influence of irrigation, as the affected aquifers can extend beyond cells with irrigation. This impact of irrigation on the groundwater was also found in Chan et al. (2021). Surprisingly, we found that irrigation had limited effects on mitigating soil moisture droughts (ESSMI) during summer. This can be due to multiple reasons. First, the irrigation might simply counteract otherwise even worse droughts in the future. This could be studied with dedicated simulations without irrigation. Second, irrigated areas often have sandy soils, which are most sensitive to impacts from meteorological droughts due to fast infiltration leading to lower soil moisture values during droughts. Third, the irrigation amounts in the DK-model are restricted by abstraction limits due to irrigation permits and modelled irrigation wells falling dry. During dry summers, these limits may in some cases partially already be reached. Thus, irrigation might be insufficient to compensate for future even drier summers with the current permits and irrigation infrastructure. Conversely, Chan et al. (2021) found a small mitigating effect of irrigation up to a certain degree in one Danish catchment.

4 Discussion

Using the proposed methodology, we found an increase in meteorological drought frequency during future summers. Their intensities depend strongly on the formulation of PET used. During winter, the models project more precipitation and fewer droughts in the future. When looking at the hydrological model output, we can see that the increased meteorological summer droughts lead to increased soil moisture droughts. Groundwater and streamflow droughts generally become less frequent due to a buffer from the increased winter precipitation, however, with regional exceptions.

The link between the meteorological and hydrological data is modelled in the form of the meteorological input variables used in the DK-model. Therefore, the two datasets can best be compared using the SPEI from *Klimaatlas* and the soil moisture in the DK-model. We can see a good match between the signal of the increase in ESSMI drought frequency in the DK-model (using the Oudin PET method) in Fig. 6, (a–c) and the SPEI-3-Oudin in Fig. 5 (j–l) rather well. Both show increasing moderate drought frequency from around April until November. The smaller absolute increase

544 in the ESSMI can be explained by the underestimated frequency during the reference
 545 period. The main difference between both indices is the visible dip in drought frequency
 546 in the ESSMI around May and June. While we cannot fully explain this, the dip in
 547 ESSMI drought frequency shows up consistently in the model and even in historical
 548 data (Schneider et al. 2026b).

549 4.1 Comparison to literature

550 In the introduction, we claimed the methodology in Spinoni et al. (2020) and Vicente-
 551 Serrano et al. (2020) has limitations in seasonally variable regions such as Northern
 552 Europe. To justify that claim, we applied two analyses similar to their methodology
 553 to our dataset. In Fig. 8 (a), we calculated the SPI-12 and compared the drought
 554 frequency per 10 years in the period 2071-2100 to the reference period. To match their
 555 drought definition, we define a drought as starting with two consecutive months below
 556 -1 and ending when positive SPI-12 values were reached. This drought definition is
 557 only used for this example. Comparable to Spinoni et al. (2020), we get a reduction
 558 of around 1 event per 10 years. In Fig. 8 (b), we show the change in mean SPI-1 from
 559 the reference period to 2071-2100. Comparable to in Vicente-Serrano et al. (2020), we
 560 see an increase in mean SPI-1.

561 Applying a very similar methodology as Spinoni et al. (2020) and Vicente-Serrano
 562 et al. (2020) to our data, we can see lower drought frequency in the future. The main
 563 differences between their global analysis and our national-scale analysis therefore stems
 564 from the differing methodology and not the data source. This justifies our claims in the
 565 introduction, calling for an improved methodology for drought research in Northern
 566 Europe.

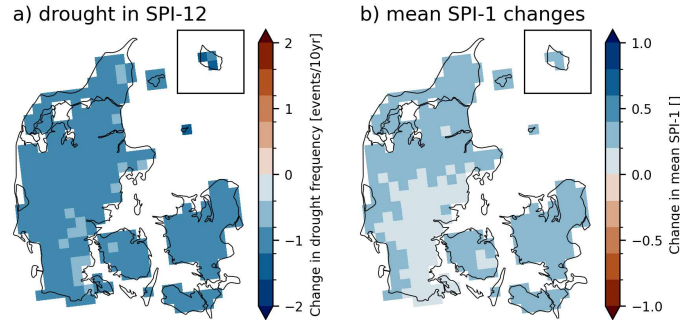


Fig. 8 SPI-12 drought frequency in Denmark decreases (left) and mean SPI-1 for all months increases (right) towards the end of the century in the RCP8.5 scenario. While these results agree with global studies, they are not meaningful for drought projections in Northern Europe and should be discarded.

567 Previous research on Danish climate signals agree with our findings of increased
 568 winter precipitation and summer evapotranspiration (Seidenfaden et al. 2022; Hen-
 569 riksen et al. 2022). The lag we found from the meteorological signal to a change in
 570 hydrological drought frequency is similar to the propagation time described in Schnei-
 571 der et al. (2026a). Chan et al. (2021) investigated future drought in a Danish catchment

based on 12 EURO-CORDEX models and found an increase in soil moisture and groundwater 99 % dry extremes. This is in line with the increase in exceptional soil moisture and groundwater drought levels, compare Fig. 6 (c) and (l). On a global scale, Wanders and Van Lanen (2015) also found decreasing hydrological drought frequency in cold climates with increasing precipitation, such as Denmark.

4.2 Limitations and strengths of this study

There were some caveats to our conclusions that we need to discuss. First, the multi-threshold method needs carefully standardised indices, which are more difficult to create for the hydrological compartments compared to the SPI and SPEI. Second, the reference periods only overlap for 20 years, as they are shifted by 10 years. We expect this to have negligible qualitative impact on the climate change signal. Third, while both datasets start from EURO-CORDEX models, different bias adjustment were necessary to be able to use the data in hydrological modelling (Fowler et al. 2007). We checked the input precipitation and PET values for the DK-model and found similar drought signals for SPI and SPEI compared to Fig. 4 and Fig. 5. Therefore, the change in bias-adjustment seems to have little influence on the climate change signal. Fourth, four out of 17 RCP8.5 EURO-CORDEX scenarios used as input for the DK-model were from an earlier version. This version underestimated end-of-century warming by around 0.5 degrees Celsius compared to the EURO-CORDEX version used in *Klimaatlas*. Therefore, this study might slightly underestimate future hydrological drought frequency. In upcoming versions of the DK-model, the plan is to use *Klimaatlas* data as input, removing this limitation. Still, the two datasets are already closely related to allow for improved future drought research in Denmark. Fifth, the DK-model is both affected by the climate model uncertainty in the input and then the hydrological model uncertainty. This can lead to higher uncertainty in the hydrological model. Lastly, the two datasets use different PET methods, which can have a large effect on the water balance. To counteract this, the PET in the DK-model (Oudin method) was bias adjusted to historical Makkink values from DMI. This mostly adjusted the seasonal shift, as Oudin can be delayed compared to Makkink (Pasten-Zapata et al. 2019b). Given these limitations, we should also note the strengths of this study.

In spite of the restrictions listed above we believe that the linkage of meteorological and hydrological drought projections in the present study is a significant strength. We managed to analyse and compare drought indices for a wide range of different hydrological compartments using one coherent method. This leads to an easy comparison between the results. The comparison of multiple indices across compartments was recommended in Henriksen et al. (2022) and Zhu et al. (2016). The multi-threshold method was effective in showing changes in the distribution of drought frequencies. Furthermore, with showing the values for the reference period, the method is more transparent about limitations compared to methods simply comparing future period frequency to reference period values.

We find that the benefits of the multi-threshold method outweigh the limitations described in Sect. 2.4. We were able to show that the mismatch between local and global studies concerning future drought levels is mainly due to differing methodology

rather than the data used. Lastly, due to the authors' knowledge of the Danish climate, we could specifically select SPI and SPEI accumulation periods that reflect the seasonality of the future projections, lacking in global studies.

4.3 Implications for future climate and water management

The biggest influence on agriculture in Denmark comes from the earlier onset of droughts. While the SPI drought frequency increase affects mostly late summer and early autumn, SPEI has an earlier start of the increase, already in May (Makkink) or April (Oudin). May to July is the worst period for droughts to occur for agricultural purposes in Denmark (De Toro et al. 2015; Häberli et al. 2026). Late summer dry periods on the other hand can even help farmers with a dry harvest. This shows the importance of also taking PET and not only precipitation into account. The SPEI paints a much more problematic picture of future farming conditions compared to only studying precipitation. According to Balting et al. (2021) and Ukkola et al. (2020), the CMIP6 simulations show higher drought levels compared to CMIP5 used for the current version of EURO-CORDEX. Therefore, the drought projections might become even worse once the newest EURO-CORDEX becomes available.

According to our study, Denmark has to prepare for a future that is in general wetter, but still experiences a higher frequency and intensity of meteorological summer droughts. Therefore, water resource managers need to prepare for an increase in both wet and dry extremes with climate change. The drought of 2018 showed that one of the major problems for agriculture was the abrupt change from winter conditions to a warm and dry spring (Henriksen et al. 2022), these warm and dry spring conditions look even more likely in the future according to Fig. 5.

In Denmark, a large part of the agricultural sector depends on rainfall for growing crops, with limited irrigation outside of Jutland. This limitation coupled with used up irrigation permits and insufficient irrigation infrastructure in Jutland led to widespread crop-loss in 2018 (Toreti et al. 2024; Eurostat 2021). Droughts of this exceptional intensity will likely become more frequent in the future. Similar to 2018, this does not mean that the groundwater is projected to be affected as much nation-wide (Henriksen et al. 2022). Rather, groundwater drought require more local analysis, as changes between increasing and decreasing future groundwater droughts can occur within a couple of kilometres from each other depending on the aquifers and geology of the region. While the DK-model assumes no societal changes, a lot of the influence on groundwater can be mitigated by improved and more robust water management in the future. Our study further highlights the importance of increased focus on human water usage in the future, as irrigation is the main reason for the most intense groundwater droughts in Jutland.

4.4 Further research

To improve the drought projections for Denmark, the cohesion between the datasets could be strengthened by running the DK-model with input variables from *Klimaatlas*. Additionally, both the DK-model and *Klimaatlas* should be enhanced with the next version of EURO-CORDEX models once they are released. On a technical note, the

hydrological standardised indices could benefit from improved methods to assure they are better standardised while still being possible to extrapolate. This study alludes to the importance of modelling drought propagation itself, which should be studied further to better explain more of the signals we found.

Further research could expand this study into the whole Northern Europe region, or similar climates in other parts of the world. Denmark is a small country located in the transition zone of the drying mainland Europe and Scandinavia. Therefore, it would be important for the wider region to inspect if their projected drought frequencies using our methodology are similar.

5 Conclusion

This study first discussed differences between global and local, more detailed drought projections. We demonstrated that the differences stem from methodological differences rather than the data used. This revealed methodological limitations in global drought projections for Northern Europe. We then introduced six points to consider when analysing future changes in drought conditions. These are especially valuable in regions such as Northern Europe, where the annual precipitation is projected to increase. We demonstrated how these six points can be effectively used together with the drought multi-threshold method for future drought analysis. This enabled a simplified and direct comparison across standardised indices and revealed deficiencies in hydrological drought index calculations.

We found a strong seasonal influence on future drought projections in Denmark, largely absent in previous global-scale research. Under continued anthropogenic climate change, we expect more frequent summer droughts with drier soils, without necessarily leading to more frequent groundwater droughts. Groundwater drought responses to climate change are very heterogeneous, depending on the geology of the region. Groundwater droughts need careful analysis together with meteorological drought, especially as the varied geology of Denmark cannot be captured in coarse-resolution models.

Our methodology should serve drought researchers in Northern Europe and beyond as a blueprint of drought analysis under climate change, taking into account seasonality, intensity and all hydrological compartments. This can reveal drought patterns previously overlooked in regions such as Alaska, Canada–Greenland–Iceland, Northern Asia and Southeast Asia; all these regions were projected to face decreasing drought levels with the methodology presented in [Spinoni et al. \(2020\)](#). We therefore recommend repeating the drought analysis in those regions with the methodology presented here. These findings have direct implications for agricultural planning and water resource management in Denmark, to prepare for a future with more meteorological summer droughts. By providing the first coherent seasonal and spatial drought analysis across the full hydrological cycle in Denmark, this study demonstrates that a wetter future does not guarantee fewer droughts, a finding with implications well beyond Denmark’s borders.

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714 **Competing Interests**

715 The authors have no relevant financial or non-financial interests to disclose.

716 **Author Contributions**

717 All authors contributed to the study conception and design. Material preparation,
718 data collection and analysis were performed by Ruben Häberli. The first draft of the
719 manuscript was written by Ruben Häberli, and all authors commented on previous
720 versions of the manuscript. All authors read and approved the final manuscript.

721 **Data Availability**

722 The *Klimaatlas* data is available under [https://www.dmi.dk/klima-atlas/data-og-](https://www.dmi.dk/klima-atlas/data-og-rapporter-klimaatlas)
723 [rapporter-klimaatlas](https://www.dmi.dk/klima-atlas/data-og-rapporter-klimaatlas), the website is in Danish. DK-model outputs are openly available
724 via the Hydrologic Information and Prognosis System HIP hosted by Climate Data
725 Agency (KDS) under <https://hip.dataforsyningen.dk/>. This includes, amongst others,
726 daily updated drought indices. Furthermore, selected climate change impacts from
727 the ensemble of climate runs with the DK-model are available, along with the RCM
728 forcings used to produce them.

729 **Code Availability**

730 All python scripts used to calculate the drought indices, as well as the resulting data
731 will be provided upon request to the authors without undue reservation.

732 **Author contribution**

733 All authors contributed to the definition of the research aims. RH, OBC, PT and EK
734 developed the methods. RS and IKS provided the DK-model data. MRP, OBC and

PT provided the *Klimaatlas* data. RH and RS calculated the indices. RH performed the data analysis and prepared plots and maps visualizing the results. RH wrote the manuscript draft with contributions from RS and EK; all authors reviewed and edited the manuscript. RH was responsible for project administration.

Appendix A Seasonal changes in precipitation and PET

Table A1 shows seasonal changes in precipitation and PET according to the data from *Klimaatlas*.

Table A1 Seasonal averages for precipitation and PET. The absolute values reflect the mean of the ensemble-median for the period 1981-2010 (Ref.) and 2071-2100 (RCP scenarios) the absolute values for the end-of-century scenarios were supplemented with the relative change in percentages. Data from *Klimaatlas*.

Season	Scenario: Variable	Ref.	RCP2.6		RCP4.5		RCP8.5	
		Abs. [mm]	Abs. [mm]	Change	Abs. [mm]	Change	Abs. [mm]	Change
DJF	Precipitation	181	184	1.4 %	198	9.4 %	219	20.6 %
	PET Makkink	24	23	-2.2 %	24	-1.4 %	24	0.3 %
	PET Hargreaves	24	24	1.0 %	25	6.7 %	27	14.5 %
	PET Oudin	17	18	8.4 %	21	24.6 %	24	45.5 %
MAM	Precipitation	127	132	3.4 %	142	11.4 %	152	19.3 %
	PET Makkink	190	193	1.8 %	194	2.4 %	198	4.7 %
	PET Hargreaves	185	192	3.6 %	197	6.3 %	204	10.2 %
	PET Oudin	138	149	7.7 %	159	15.0 %	172	24.5 %
JJA	Precipitation	210	210	-0.3 %	218	3.8 %	201	-4.4 %
	PET Makkink	296	304	2.7 %	305	2.9 %	312	5.1 %
	PET Hargreaves	325	338	4.1 %	341	5.0 %	353	8.8 %
	PET Oudin	287	305	6.2 %	316	10.1 %	338	17.6 %
SON	Precipitation	225	225	0.2 %	238	5.8 %	248	10.6 %
	PET Makkink	84	86	2.7 %	88	4.8 %	91	8.3 %
	PET Hargreaves	87	91	4.3 %	93	7.2 %	97	11.0 %
	PET Oudin	82	88	6.9 %	93	13.3 %	101	22.7 %

Appendix B Robustness of results

To check the robustness of the data presented in Fig. 4, 5 and 6, we investigate both the influence of single driving GCMs and RCMs on the main results and a bootstrapping method.

In Fig. B1, we show that no driving GCM has an outsized influence on the results of SPEI-3-Makkink. All indices were tested, none showed a problematic influence of a single GCM. While there are some GCMs that show a very strong increase in drought, e.g. CCCma-CanESM2, the second row in Fig. B1 shows that it has little impact on the

751 ensemble median presented in the main body of this article. Identically to the GCMs,
752 all indices were tested for the influence of a single RCM on the ensemble median.
753 This also showed that while there are some models with a larger projected increase in
754 drought, they do not significantly influence the ensemble median. Therefore, we can
755 conclude that no GCM or RCM is the sole reason for the increase in meteorological
756 drought frequency during summer, supporting the robustness of our analysis.

757 In Fig. B2, we show that the results of the SPEI-3-Makkink monthly signals are
758 robust using the bootstrap method (Efron 1982). All indices were tested and were
759 deemed robust, even for the exceptional droughts below index values of -3 . The only
760 exception is deep groundwater (SGDI_{deep}) in the RCP45 scenario. This is due to the
761 limited number of simulations for that scenario (5). While in the article we show the
762 ensemble median, here we had to use the mean for the bootstrapping to work. For the
763 bootstrapping, we selected (with replacement) as many models for each scenario as
764 there were initially. We repeated this 100'000 times and calculated the mean each time
765 to get a distribution of the signals shown in Fig. B2. If the original mean presented
766 in the results (vertical line) were due to an outlier, there would not be a proper
767 distribution around it. This gives us additional confidence in the results presented in
768 this study, even for the least robust exceptional droughts.

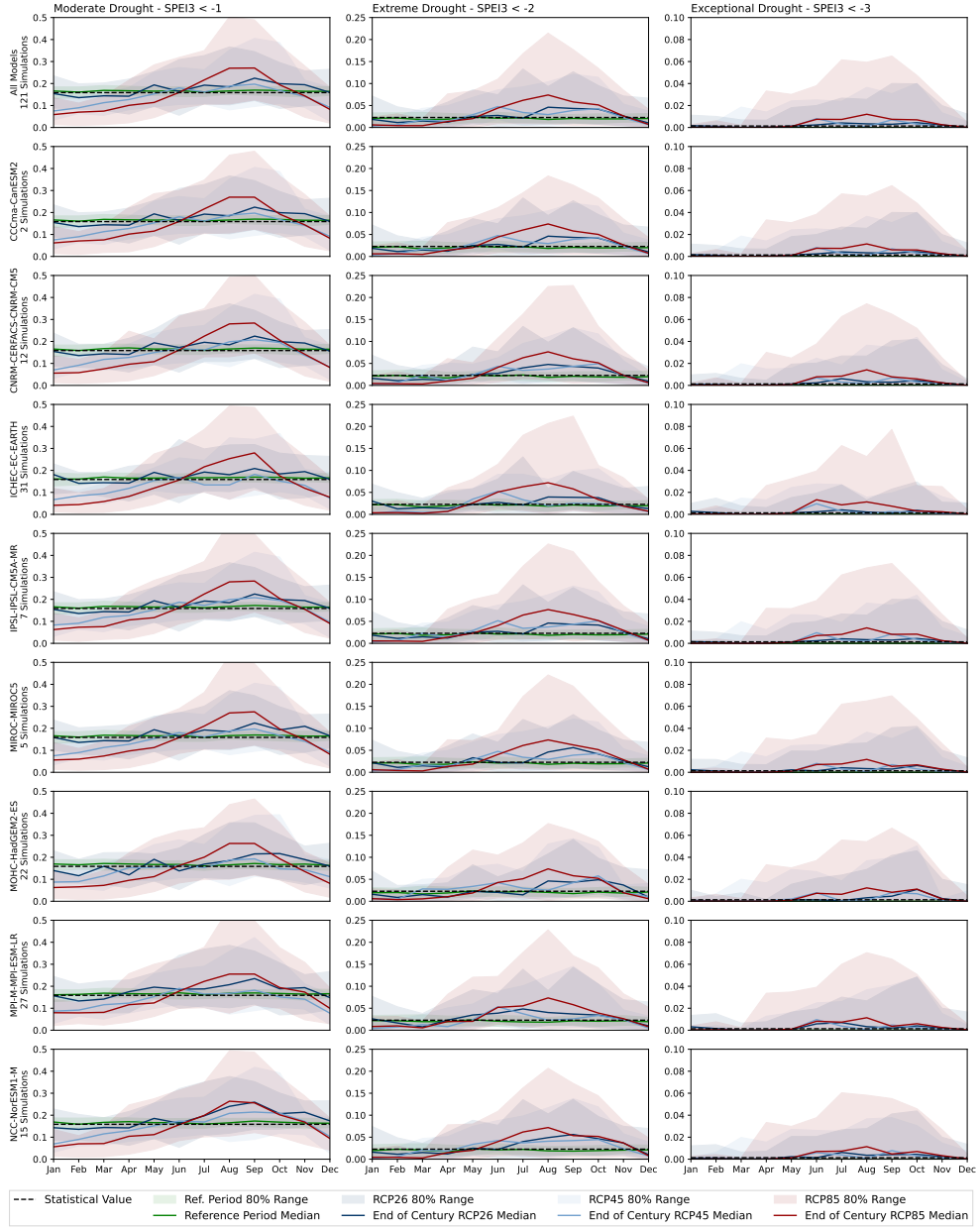


Fig. B1 We check if one GCM has an outsized influence on the results by comparing the full ensemble results (top row) to the results with all simulations driven by one GCM removed in the rows below. The name of the removed GCM and the number of simulations driven by it are written on the left. Here, only the results for SPEI-3-Makkink are shown. The other indices showed similar results, with no GCM being the main reason for an in-/decrease in drought levels.

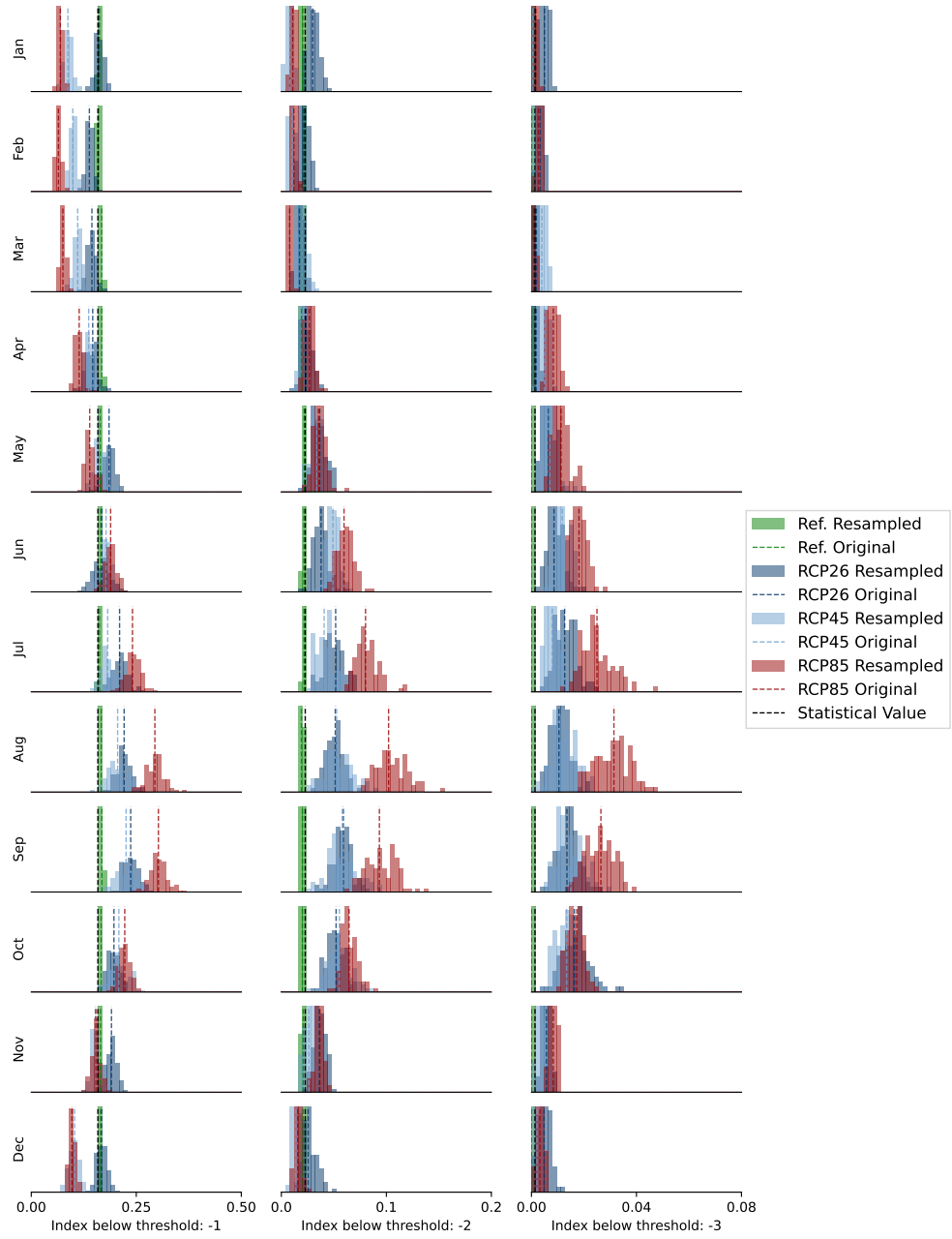


Fig. B2 Example of monthly bootstrapping distributions for SPEI-3-Makkink ensemble data across moderate (left), extreme (middle), and exceptional (right) drought intensities. Histograms show the resampled distributions, while dashed lines indicate the original ensemble mean (colours consistent with Fig. 4-6). Approximately symmetric and unimodal distributions suggest robust estimates.

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