https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

Brief communication: Simulations indicate, the multi-year drought of 2018-2023 could have happened in the 1960s

Oliver Bothe[1]

[1]Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Fischertwiete 1, 20095 Hamburg, Germany

Correspondence: Oliver Bothe (ol.bothe@gmail.com)

Abstract. Duration and intensity of the multi-year drought of 2018-2023 had not been anticipated in Germany. Self-calibrating Palmer Drought Severity Index (scPDSI) data calculated from EURO-CORDEX regional climate simulations shows multi-year, high-intensity droughts occurring over large portions of Germany throughout the period 1950 to 2100. Although droughts lasting about 5.5 years and affecting more than half of Germany like the observed 2018-2023 event are rare in the simulations, even longer and more intense large-scale droughts occur. Consequently, multi-year large scale drought can be assumed to have been part of the past climatology for Germany and projections stress the necessity to build resilience to comparable and even more impactful events.

1 Introduction

Drought has multi- and cross-sectoral impacts. Agriculture and the water sector, energy and health, transport and tourism, as well as ecosystem services, drought affects all these sectors (Naumann et al., 2021). Indeed, many of these sectors show linked vulnerabilities and co-occurring impacts. Thus, sectors, countries, and regions require to develop resilience with respect to drought, and such resilience benefits from knowledge of what to expect.

Between 2018 and 2023 Germany experienced the effect of a multi-year drought (compare Marx, 2025). The area affected by drought differs between years. The storyline-modelling results by Kettaren et al. (2026) indicate that about 35% of Europe were under severe soil moisture drought in 2022, and that severe soil moisture drought affected about 12% of the European area when assessing a five year mean over 2018 to 2023. According to the results presented below, mild drought lasted 67 months in a domain representing Germany and affected over 90% of the area during parts of the period.

Studies on reasons for and factors influencing the drought in Europe stress the contribution by climate change (e.g., Bevacqua et al., 2024) but also highlight the relation to concurrent atmospheric drivers (Garrido-Perez et al., 2024; Xoplaki et al., 2025) as well as to preceding atmospheric and marine drivers (Ionita and Nagavciuc, 2020). Xoplaki et al. (2025) describe how the dryness of 2018 increases the probability of 2019 being dry as well.

The recent drought event was exceptional Europe-wide due to its extent across continental Europe, the fast intensification after onset, and the related heat between 2018 and 2020 (Rakovec et al., 2022). Pohle et al. (2025) point to exceptional warm extremes of annual near surface air temperatures and low extremes of annual precipitation sums in Europe during 2018-2023.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

The event highlighted the water management challenges faced by cities in response to multi-year droughts in terms of surface water levels, sewage water, and water supply as shown by Pohle et al. (2025) for Berlin. On broader spatial scales, agriculture and forestry suffered production losses in the Elbe river basin in 2018 and 2019, while drought apparently did not strongly affect other sectors in these years (Conradt et al., 2023). An Europe-wide forest assessment for the years 2018 to 2022 leads Knutzen et al. (2025) to conclude that even forest ecosystems that are resilient nowadays may face notable damages under future heat and drought conditions. Blauhut et al. (2022) use the case of 2018-2019 to recommend a more unified future drought risk management in Europe that has to build regional and sectoral specific awareness of the impacts of drought. Could German society have anticipated that an event of the intensity, extent, and duration of the 2018-2023 drought is possible?

The following describes first how observation based data captures the drought between 2018-2023 in terms of the self-calibrating Palmer Drought Severity Index (scPDSI, Palmer, 1965; Wells et al., 2004). An ensemble of available regional climate model simulations from the EURO-CORDEX project (Jacob et al., 2014) allows to subsequently assess the intensity, duration, and extent of simulated drought events between about 1950 and about 2100. The prime interest is to answer the question, when do wide-spread, intense multi-year droughts occur in Germany in these simulations, only under 21st century climate warming in Germany or also in the historical period of the 20th century? Analyses consider area-averages and area-fractions. Locally drought of interest starts already with mild drought as classified by the scPDSI.

The next section shortly introduces methods and data before further sections describe drought in the observation based data and in the simulations. Subsequently, a quick discussion precedes summarising conclusions.

2 Methods and Data

2.1 Data

2.1.1 Observation based scPDSI

Observational scPDSI estimates are from E-OBSv29 (Cornes et al., 2018). They are available from https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php (compare also https://confluence.ecmwf.int/pages/viewpage.action?pageId=320998008, van den Besselaar, 2025). The data has a 0.1 degree resolution comparable to the simulation data and covers the period 1950 to 2023. There is no clear information about the used calibration period. I assume, the calibration uses the full period. Alternatively, the scPDSI data by van der Schrier et al. (2013) is available for the period 1901 to 2023 but only in 0.5 degree resolution. The decision for using E-OBS is due to the more comparable resolution relative to the simulations and the likely reduced reliability of input data in the first half of the 20th century.

2.1.2 Simulations

Simulation data used stems from the regional climate model runs for the historical period as well as the future projections under the representative concentration pathways RCP4.5 and RCP8.5 performed within EURO-CORDEX (Jacob et al., 2014), i.e. CMIP5 based regional downscaling simulations. The two RCPs represent a scenario with reduced emissions from mid-

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

century onwards (RCP4.5) and a scenario with an unmitigated increase in emissions (RCP8.5). The consensus nowadays is that the latter does not present a plausible future anymore (e.g., Van Vuuren et al., 2026). These scenarios, nevertheless, serve as valuable stand-ins for futures with and without mitigation efforts. The supplement (Section S1.1) gives details and references for the available 18 GCM-RCM pairs that provide all necessary input data for the scPDSI calculation. Some simulations do not include the year 2100, and a subset of these even do not include December 2099. As the code does not correctly work with incomplete years or `NA` values, I pad the input data vectors for precipitation and potential evapotranspiration with `0` for December 2099 for the calculations of the scPDSI. Subsequent analyses do not exclude these single padded months here, as they do not influence the conclusions. Further simulations started only from January 2nd of their first year. These Januaries are nevertheless included here as full months.

2.2 Methods

2.2.1 Drought indicator: scPDSI

There exist multiple, well established indicators to describe drought. Popular choices are the Palmer Drought Severity Index (PDSI, Palmer, 1965), and a variety of standardized indices. Standardized approaches include the standardized precipitation index (SPI, McKee et al., 1993), and the standardized precipitation evapotranspiration index (SPEI, Vicente-Serrano et al., 2010) among others. PDSI, its self-calibrating version (scPDSI, Wells et al., 2004), and SPEI aim to identify drought based on the water balance. The standardized indices allow applications on different time-scales, while the water-balance model underlying Palmer's indices leads to integration across time-scales.

The analyses, here, use drought estimates based on the self-calibrating Palmer Drought Severity Index (scPDSI, Palmer, 1965; Wells et al., 2004). The index relates precipitation to a local water-balance including estimates of evapotranspiration and local water holding capacity. The local available water holding capacity is a property of the local soil describing how much water it can hold at best. Evapotranspiration calculations, here, use the Penman-Monteith equation (Allen et al., 1998). The self-calibrating PDSI accounts for critiques of the comparability of the original PDSI between regions. Both implementations tend to have a long memory emphasizing the influence of past drought and wetness conditions on the present. Table 1 shows the scPDSI drought classes from near normal to extreme drought.

2.2.2 Analyses

Analyses approximate Germany by a rectangular box covering the domain 5° E to 16° E and 47° N to 55° N. This is a choice of convenience that simplifies data handling. The analyses either consider the averaged time-series over this domain or the fraction of grid-cells in the domain showing drought exceeding a certain criterion.

Run-lengths computations use the function `rle` in R (R Core Team, 2025).

Averaging scPDSI values over a domain does not measure drought over the domain. Rather it is a derived indicator for drought characteristics in the domain.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

Table 1. List of drought classifications according to the self-calibrating Palmer Drought Severity Index.

Value	Classification
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.0 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

3 Results

3.1 Observations

The multi-year drought of the late 2010s and early 2020s stands out in the time-series for the observed drought in Germany in terms of the area-averaged scPDSI (Figure 1a). Already visually it is obvious that no other period since 1950 had a drought of comparable length and comparable intensity according to this measure. Indeed, one could diagnose a drying tendency since the early 2000s in the observed data.

Considering the run lengths of droughts with scPDSI values smaller equal -1 reveals that the 2018-2023 drought is the longest drought according to this criterion in the data series. It lasted 67 months. The second longest drought ended in May 1974 and lasted about half as long as the recent event, i.e. 34 months. The next ranked events end in 2024, 1977, 1963, and 1960, which lasted 12 to 14 months each. Periods with scPDSI larger than -1, i.e. periods regarded incipient dry spells or wetter, lasted 5 years or longer and up to 79 months in the 1970s to 1980s, the 1980s, the 1960s to 1970s, the 1990s to 2000s and the 2000s to 2010s as well as the 1950s.

Next, Figure 1b visualises the driest months of the unsmoothed record and of the 67-months running mean drought record by plotting the rank of a month against the year in which it occurred. A large majority of the driest 50 months occurred in the recent past. However, other periods like, e.g., the 1970s and the 1950s also show very dry months. Repeating the analysis for the smoothed record emphasizes the dry months in the 1970s and at the turn from the 1980s to the 1990s.

A further feature of the 2018-2023 drought was its large spatial extent. Figure 1c plots the percentage of grid-cells in the domain of interest, where drought was at least mild (violet) or severe (brown) according to the scPDSI-classification. While there had been periods where more than 90% in terms of grid-cells were under at least mild drought before, the recent drought-event was the first one where this was the case for an extended period of time. Similarly, while there was a period in the 1970s when more than 50% of grid points in the study domain where under severe drought, the recent period was the first where this applied to more than 75% of the domain for some months. While smoothing such fraction-series has no easily interpretable meaning, the 67-months smoothed time-series of the fraction for at least severe drought also only exceeds 50% in the recent period, and the smoothed fraction-series for at least mild drought approaches even 90 percent then.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

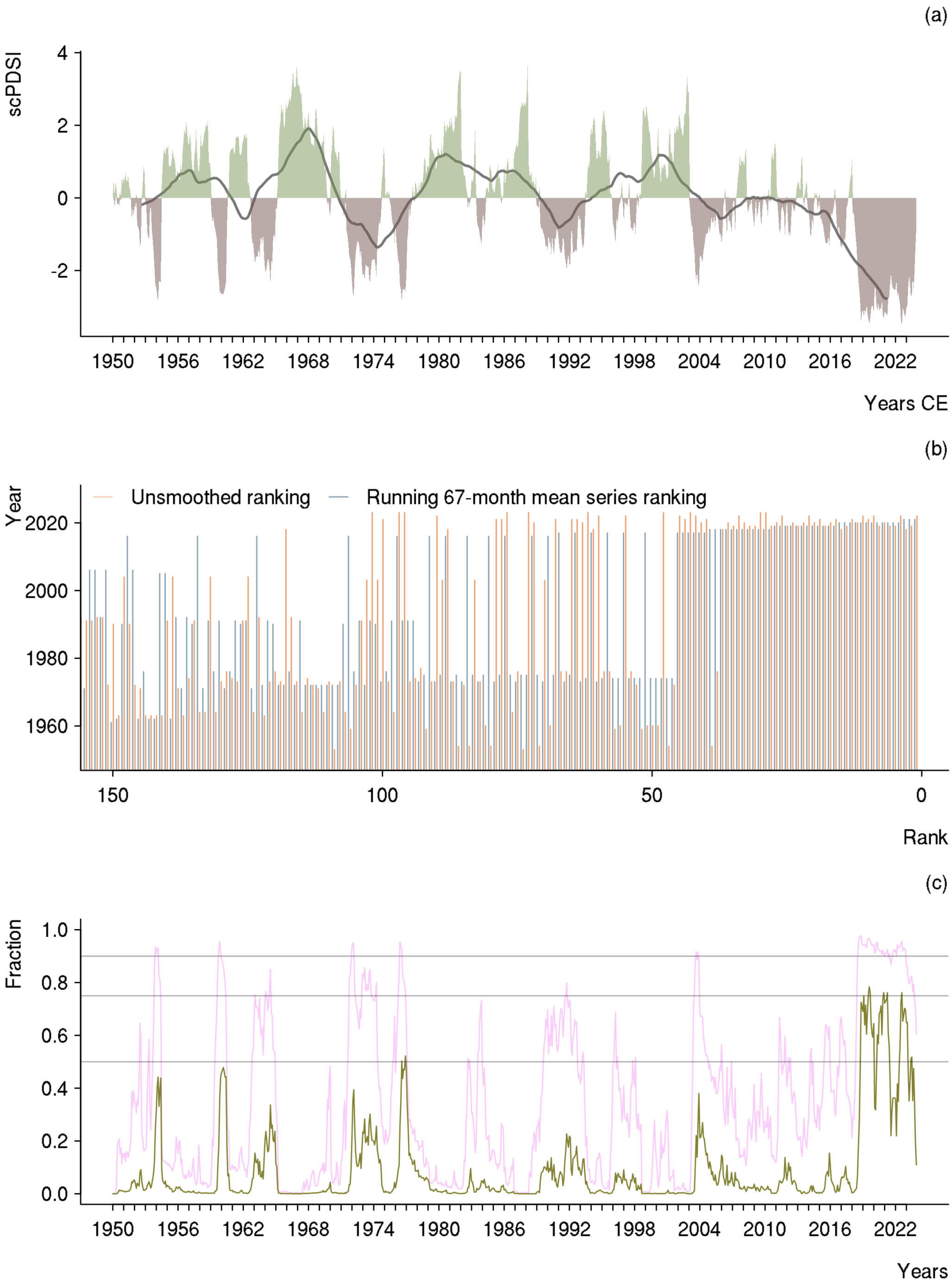

Figure 1. Drought in Germany according to the observation based E-OBS data set. (a) Time-series of the area-averaged scPDSI time-series and its 67-months running mean; (b) years of ranked months according to area-averaged time-series (orange), and the smoothed area-averaged time-series (grey); (c) fraction affected by mild drought (violet) and severe drought (brown). Horizontal lines in (c) highlight 50%, 75%, and 90% covered by drought, respectively.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

Thus, according to the chosen criteria, the drought from 2018-2023 lasted ≈5.5 years, reached unprecedented intensities, and covered more than 90% of the chosen domain over an extended period of the 67 months. Unfortunately, there is not sufficient observational evidence to assess the extent of multi-year droughts before 1950 in comparable detail. Taking a rather broad and coarse view, the paleo-information in the Great Eurasian Drought Atlas (Cook et al., 2024) — a reconstruction of summer season scPDSI for the period 1000 to 2020 — indicates that the longest continuous multi-summer drought with scPDSI values averaged over our box smaller equal than `-0.5`, i.e. on average incipient drought in this data, lasted 6 summers (not shown), i.e. are comparable to the recent event. Do the EURO-CORDEX simulations represent droughts similar to the recent event in the past, the present, or the future?

3.2 Simulations

The range of area-averaged scPDSI-series in individual simulations provides a quick summary of how the EURO-CORDEX simulations describe drought in the historical period and the projected future (Figure 2a). Quite a number of simulations stand out among the 18 GCM-RCM pairs for either or both of the RCPs. Both considered RCPs are rather on the dry side for NorESM1M_HIRHAM5, i.e. the global simulation with NorESM1M downscaled by HIRHAM5. On the other hand, when these simulations are downscaled with RCA4 and REMO2015 this does not occur as prominently and consistently. Even more prominent tendencies towards dryness characterise a number of RCP8.5 projections. These are most prominently the global simulations by HadGEM2 downscaled by REMO2015 and HIRHAM5, the CM5-MR simulation downscaled by RCA4, ensemble member 3 of EC-EARTH downscaled by HIRHAM5, and ensemble member 12 of EC-EARTH downscaled by RCA4 and RACMO22E. On the other hand, the RCP4.5 projection by HadGEM2 downscaled with RACMO22E as well as RCA4, and the CM5 RCP8.5 projection downscaled with RACMO22E, RCA4, and ALADIN63 show a tendency towards more extreme wetness. Note, in principle, this purely relates to the range of values and may be biased by single events.

The visualisation of the scPDSI-time-series calculated from the simulations (Figure 2b) shows, however, that there are, generally, no single events dominating the ranges of the simulations. The time-series neither point towards any individual simulation setups clearly deviating from all the others (Figure 2b). Most prominent are the generally rather wet RCA4- and RACMO22E-downscalings of the RCP8.5 simulation by CM5. The temporal visualisation also highlights that extended drought periods do occur in the simulations in the historical period (Figure 2b,c).

Figure 2c plots the ranks of each drought month over the full period within individual simulations. The simulations regularly present highly ranked drought in the past. The 1960s appear across simulations. The ranking especially emphasizes the drought period in the 1960s in the NorESM1M simulation downscaled by HIRHAM5. The 1960s are also prominent in the historical period, when summing across simulations in which decades how many of the 100 highest ranked dry months for each simulation occur (not shown). Under RCP4.5, only the 2040s and 2050s exceed the 1960s in terms of the number of highest ranked months. Then, also the transition between historical period and projection, i.e., the 2000s, shows a notable number of highest ranked months, though less than the 1960s. Under RCP8.5, the 2050s as well as the 2080s and 2090s show notably more highly ranked dry-month events than the 1960s. Thus, while the 1960s are prominent in the past, Figure 2 highlights the risk of exceptional drought generally is higher in the future until the year 2100 than it was during most decades in the simulated past.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

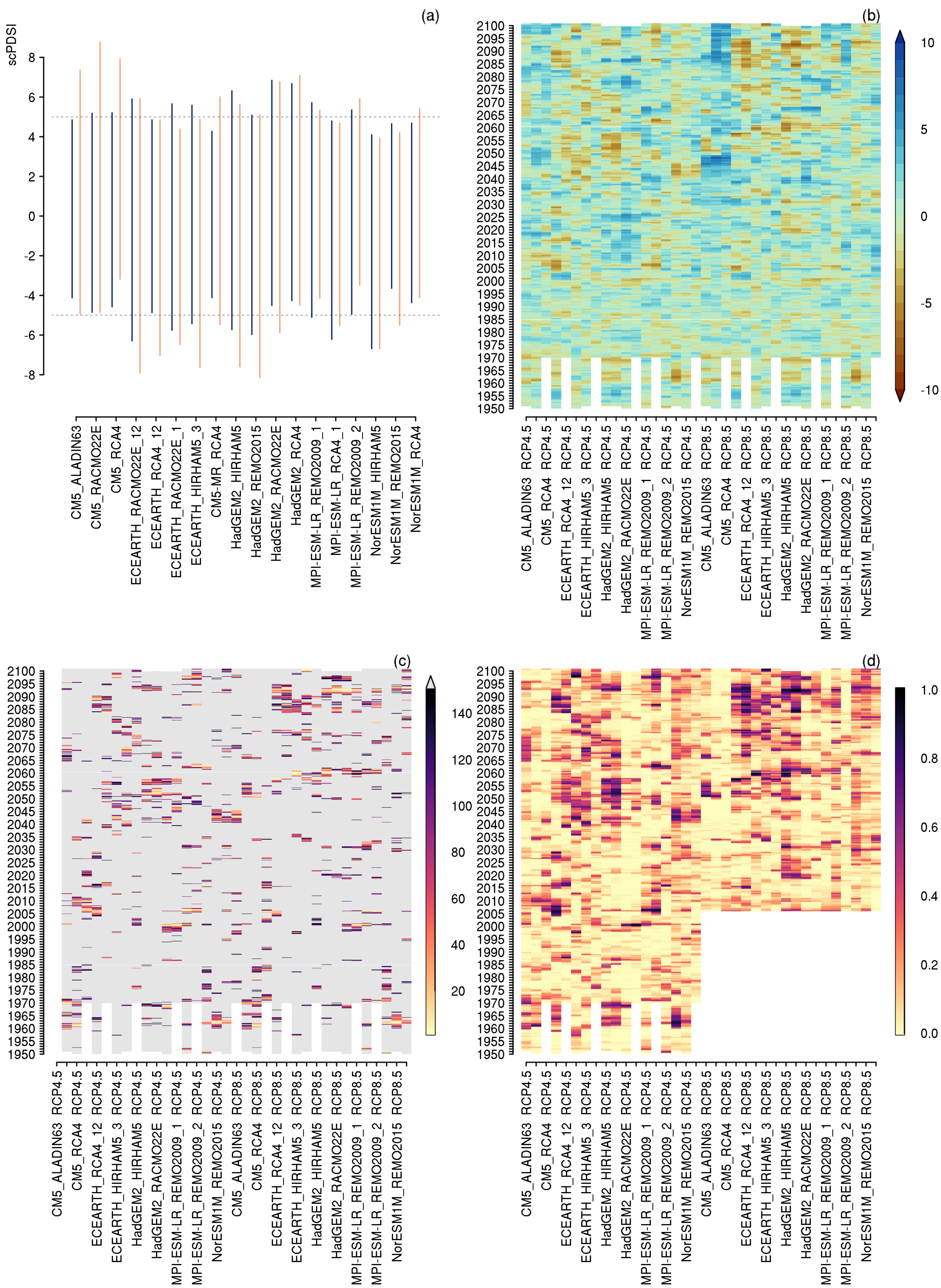

Figure 2. Drought in Germany according to the selected EURO-CORDEX simulations. (a) Range of area-averaged scPDSI-series in individual simulations, blue, historical and RCP4.5, yellow, historical and RCP8.5; (b) Heat map of time-series of the area-averaged scPDSI time-series; (c) ranks of months according to each individual area-averaged scPDSI time-series, only the driest 150 months in each simulation are shown; (d) fraction affected by severe drought. Panel (d) omits the historical period for RCP8.5.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

Not all GCM-RCM-pairs show droughts of lengths comparable to or longer than the observed event. Twenty of the 36 projection simulations (either RCP4.5 or RCP8.5) do not feature multi-year droughts of at least 60 months–two feature 56 and 58 months long droughts respectively. Only the combined historical and RCP8.5 simulation with HadGEM2 downscaled by HIRHAM5 has three events of 60 months or longer in the period between 1950 and 2100 (compare Figure 2b). The longest drought run in the simulations is 174 months, but drought runs larger than 100 months occur only four times. Multi-year droughts regularly occur also in the historical period. When binning all drought runs with lengths of at least 12 months in decadal bins year and multi-year droughts occur comparably often in the simulations in the 1960s as in future decades for an RCP4.5 future–there is one more event in the 2050s and in the 2060s. Regarding the historical period and an RCP8.5 future, the highest number of year and multi-year droughts occur in the 2050s, followed by the 1960s.

Simulations regularly present droughts that cover more than 90% of Germany with at least mild drought in the past and future. Indeed, there is even severe drought covering more than 90% of Germany in the simulated past and the projected future under both RCPs in some simulations (Figure 2d). Even simulations that show drought more rarely feature periods where severe drought covers more than 60% or even 75% of the grid cells in the chosen domain. Extensive events of high coverage are however not too common. Note, Figure 2d includes the historical period only once as the projections are continuations of one single historical simulation.

In summarising, large extent multi-year drought over the rectangular domain around Germany occur in the simulations not only in a future under increasing climate change. They also occur in the historical period from the 1960s to the early 2000s.

4 Discussions

Climate projections with regional climate models indeed present multi-year droughts with characteristics comparable to the recent 2018-2023 event over the region of Germany. They do so not only in the projected future but also in the historical past.

The presented assessment relies on a specific choice of index, the scPDSI. Due to its long memory characteristics (Guttman, 1998), the index may overemphasize the drought memory at locations compared to multi-scale approaches like the SPEI. Using the SPEI would allow to assess drought impacts on multiple time-scales with rather controlled memory effects and according to specific types of drought. The scPDSI's memory effects will differ locally and by event. They will not only influence individual events, their start and their end, but also may affect the variability structure of local series and the full series. Using the scPDSI emphasizes the permanence of drought events. Assessments using the SPEI or other indicators can supplement the findings communicated here.

The question of variability also affects the comparison of the observational and the simulation data. The calibration or base periods for both data types differ. Thus, the observational data describe an, e.g., extreme drought relative to the period 1950 to 2023, while the scPDSI calculations for the simulations describe an extreme drought relative to the conditions of 1971 to 2000. Note, the range of the observed time-series and its standard deviation are comparable to the values for the simulated data over the period 1971 to 2000, while they are smaller over the full considered periods (not shown).

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

There were only about two thirds of the full EURO-CORDEX ensemble available for the presented analyses. Increasing the sample will only serve to highlight the occurrence of drought in the simulations.

The analyses rely on time-series, event severity in terms of relative ranks, and area fraction covered by drought and focus on area aggregated metrics. Such an approach accounts for the fact that each drought event's evolution in time as well as in space will differ. The underlying assumption is that general characteristics like intensity, duration, and coverage are a good first signal to boost broad-scale impact preparedness.

One feature of the ensemble is the prominence of drought in the 1960s. Ten of the twelve simulations starting in 1950/1951 show a drying from the 1950s into the 1960s, and nine of them show drought then. This appears not to depend on specific driving GCM-simulations. Identifying the underlying reasons for this is beyond the scope of the present study. While randomness may contribute, a common factor seems possible. The potential of a common influence points towards the relevant radiative forcing data in either the CMIP5 GCM runs or the RCM simulations. Considering the radiative forcing used in CMIP5 (e.g., Myhre et al., 2013) indicates that the model-forcing-representation of the Mt. Agung eruption in 1963 (e.g., Niemeier et al., 2019) may have imprinted on the simulated German/central European drought record. A potential mechanism could involve a pathway via the North Atlantic ocean circulation in the GCM runs, its influence on circulation patterns in the GCM runs as well as in the downscalings and, in turn, an impact on European hydroclimate in both the GCM runs and the downscaling simulations with RCMs (e.g., Andreasen et al., 2024).

Comparing simulated features with observed features does not imply that the EURO-CORDEX simulations reliably represent a potential past or future reality. The simulations are representations of the climate consistent with the physics implemented and the choices made for their boundary conditions and forcings. The EURO-CORDEX community provides guidelines for using their data (EURO-CORDEX Community, 2021). Allowing for these limits of the simulations, the used ensemble shows two things: (i) simulations represent droughts with comparable characteristics to the observed event; and (ii) such events occur in the simulated future and in the simulated past. While the simulations do not represent the real climate, they give information about the relation of past drought to future drought, while allowing to compare their simulated drought to observed drought.

Then, the occurrence of long multi-year droughts with large areal coverage in the simulated past and in the simulated future highlights that Germany could have been prepared for a multi-year drought of comparable characteristics to the 2018-2023 event. Thus, sectoral drought preparedness can benefit from considering relevant simulated projections. At the very least sectors can use such data as input for further assessments of the costs and benefits of preparation versus those of impacts.

5 Summarising Conclusions

The presented analyses on the occurrence of long lasting droughts in Germany use first observational data and second available regional climate simulation data. Thus, conclusions are possible on two levels of information, too.

Based on the observational data for the last about 75 years, the recent drought was unusual and exceeded previous experiences for broad regions of Germany. It was more widespread, more intense, and lasted longer than previous events. Indeed,

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

the time-series suggests that it happened on a drying background climate. The time-series also indicates that one could have anticipated the occurrence of a drought event larger than the ones experienced in the preceding 10 years.

Considering the simulation data, droughts of comparable intensity, duration, and extent were possible for the domain of interest also under historical climate and climate forcing conditions. Thus, droughts of the scale of the 2018-2023 multi-year drought are part of the climate, of the expectation for the region of Germany.

Beyond being part of the past climatology, such droughts also are part of the future climate under ongoing climate change, and they may even become more intense. Thus, it is important to prepare for such events, where preparation implies building resilience to enable springing back from impacts.

Code and data availability. Code and data for analysis and visualisation is available from https://doi.org/10.5281/zenodo.22029762 (Bothe, 2026).

EURO-CORDEX data was obtained from local paths at DKRZ. The data was available from ESGF-nodes (https://esgf-metagrid.cloud.dkrz.de/search) at that point in time.

The Copernicus Climate Data Store provides access to a subset of EURO-CORDEX data at https://cds.climate.copernicus.eu/datasets/projections-climate-atlas and https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels. Ongoing availability depends on the developments at the ESGF https://esgf.github.io/ and at the Copernicus Climate Data Store https://cds.climate.copernicus.eu/. The E-OBS data is available at https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php.

Author contributions. Oliver Bothe: Conceptualisation, data curation, software, formal analysis, visualisation, methodology, writing.

Competing interests. The author declares no competing interests.

Acknowledgements. Contributors on Stackoverflow and Stackexchange as well as Google Gemini and MS Copilot helped to make code-development more efficient.

Comments by Abhinav Dengri improved the manuscript.

I acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu). I acknowledge the World Climate Research Programme's CORDEX framework and their efforts in CMIP5-downscaling particularly for Europe within EURO-CORDEX. I thank the climate modelling groups for producing and making available their model output. This study used computational resources at Deutsches Klimarechenzentrum (DKRZ, https://www.dkrz.de) provided under project ID ch0636. This research contributes to the Cross-sectoral Framework for Socio-Economic Resilience to Climate Change and Extreme Events in Europe (CROSSEU), which is a European Union-funded project under the Horizon Europe program (Grant agreement ID: 101081377), running from 2024 to 2026 (https://www.crosseu.eu/,https://cordis.europa.eu/project/id/101081377).

References

Allen, R., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration. Guidelines for computing crop water requirements, Tech. Rep. 56, FAO - Food and Agriculture Organization of the United Nations, https://www.fao.org/4/x0490e/x0490e00.htm, 1998.

Andreasen, L. S., Cornér, J., Abbott, P. M., Sinclair, V. A., Riede, F., and Timmreck, C.: Changes in Northern Hemisphere extra-tropical cyclone frequency following volcanic eruptions, Environmental Research: Climate, 3, 025 002, https://doi.org/10.1088/2752-5295/ad2c0e, 2024.

Bevacqua, E., Rakovec, O., Schumacher, D. L., Kumar, R., Thober, S., Samaniego, L., Seneviratne, S. I., and Zscheischler, J.: Direct and lagged climate change effects intensified the 2022 European drought, Nature Geoscience, 17, 1100–1107, https://doi.org/10.1038/s41561-024-01559-2, 2024.

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M. I., Teutschbein, C., Wendt, D. E., Akstinas, V., Bakke, S. J., Barker, L. J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K. C., De Stefano, L., Fendeková, M., Finger, D. C., Huysmans, M., Ivanov, M., Jaagus, J., Jakubínský, J., Krakovska, S., Laaha, G., Lakatos, M., Manevski, K., Neumann Andersen, M., Nikolova, N., Osuch, M., van Oel, P., Radeva, K., Romanowicz, R. J., Toth, E., Trnka, M., Urošev, M., Urquijo Reguera, J., Sauquet, E., Stevkov, A., Tallaksen, L. M., Trofimova, I., Van Loon, A. F., van Vliet, M. T. H., Vidal, J.-P., Wanders, N., Werner, M., Willems, P., and Živković, N.: Lessons from the 2018–2019 European droughts: a collective need for unifying drought risk management, Natural Hazards and Earth System Sciences, 22, 2201–2217, https://doi.org/10.5194/nhess-22-2201-2022, 2022.

Bothe, O.: Notebook, Input data, and Output Figures for "Brief communication: Simulations indicate, the multi-year drought of 2018-2023 could have happened in the 1960s", Zenodo, https://doi.org/10.5281/zenodo.22029762, 2026.

Conradt, T., Engelhardt, H., Menz, C., Vicente-Serrano, S. M., Farizo, B. A., Peña-Angulo, D., Domínguez-Castro, F., Eklundh, L., Jin, H., Boincean, B., Murphy, C., and López-Moreno, J. I.: Cross-sectoral impacts of the 2018-2019 Central European drought and climate resilience in the German part of the Elbe River basin, Regional Environmental Change, 23, 32, https://doi.org/10.1007/s10113-023-02032-3, 2023.

Cook, B. I., Cook, E. R., Anchukaitis, K. J., and Singh, D.: Characterizing the 2010 Russian Heat Wave–Pakistan Flood Concurrent Extreme over the Last Millennium Using the Great Eurasian Drought Atlas, Journal of Climate, 37, 4389 – 4401, https://doi.org/10.1175/JCLI-D-23-0773.1, 2024.

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., and Jones, P. D.: An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets, Journal of Geophysical Research: Atmospheres, 123, 9391–9409, https://doi.org/https://doi.org/10.1029/2017JD028200, 2018.

EURO-CORDEX Community: Guidance for EURO-CORDEX Climate Projections Data Use, Version 1.1, Guidelines, Coordinated Regional Climate Downscaling Experiment - European Domain (EURO-CORDEX), https://www.euro-cordex.net/imperia/md/content/csc/cordex/guidance_for_euro-cordex_climate_projections_data_use__2021-02_1_.pdf, available at the official EURO-CORDEX website https://euro-cordex.net/060378/index.php.en, 2021.

Garrido-Perez, J. M., Vicente-Serrano, S. M., Barriopedro, D., García-Herrera, R., Trigo, R., and Beguería, S.: Examining the outstanding Euro-Mediterranean drought of 2021–2022 and its historical context, Journal of Hydrology, 630, 130 653, https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.130653, 2024.

Guttman, N. B.: Comparing the Palmer Drought Index and the Standardized Precipitation Index, JAWRA Journal of the American Water Resources Association, 34, 113–121, https://doi.org/10.1111/j.1752-1688.1998.tb05964.x, 1998.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

Ionita, M. and Nagavciuc, V.: Forecasting low flow conditions months in advance through teleconnection patterns, with a special focus on summer 2018, Scientific Reports, 10, 13 258, https://doi.org/10.1038/s41598-020-70060-8, 2020.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., and Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional Environmental Change, 14, 563–578, https://doi.org/10.1007/s10113-013-0499-2, 2014.

Kettaren, R., Sánchez-Benítez, A., Goessling, H., Athanase, M., Kumar, R., Samaniego, L., and Rakovec, O.: Storyline-Based Climate Attribution Reveals Strong Intensification of 2018–2022 Multi-Year Droughts in Europe, Earth's Future, 14, e2025EF007 547, https://doi.org/https://doi.org/10.1029/2025EF007547, e2025EF007547 2025EF007547, 2026.

Knutzen, F., Averbeck, P., Barrasso, C., Bouwer, L. M., Gardiner, B., Grünzweig, J. M., Hänel, S., Haustein, K., Johannessen, M. R., Kollet, S., Müller, M. M., Pietikäinen, J.-P., Pietras-Couffignal, K., Pinto, J. G., Rechid, D., Rousi, E., Russo, A., Suarez-Gutierrez, L., Veit, S., Wendler, J., Xoplaki, E., and Gliksman, D.: Impacts on and damage to European forests from the 2018–2022 heat and drought events, Natural Hazards and Earth System Sciences, 25, 77–117, https://doi.org/10.5194/nhess-25-77-2025, 2025.

Marx, A.: Dürren seit 1950 (jährlich und saisonal) - Helmholtz-Zentrum für Umweltforschung UFZ, Website, https://www.ufz.de/index.php?de=47252, 2025.

McKee, T. B., Doeskin, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: 8th Conf. on Applied Climatology, pp. 179–184, Am. Meteorol. Soc., https://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf, 1993.

Myhre, G., Shindell, D., Bre´on, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, book section 8, p. 659–740, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, ISBN ISBN 978-1-107-66182-0, https://doi.org/10.1017/CBO9781107415324.018, 2013.

Naumann, G., Cammalleri, C., Mentaschi, L., and Feyen, L.: Increased economic drought impacts in Europe with anthropogenic warming, Nature Climate Change, 11, 485–491, https://doi.org/10.1038/s41558-021-01044-3, 2021.

Niemeier, U., Timmreck, C., and Krüger, K.: Revisiting the Agung 1963 volcanic forcing – impact of one or two eruptions, Atmospheric Chemistry and Physics, 19, 10 379–10 390, https://doi.org/10.5194/acp-19-10379-2019, 2019.

Palmer, W. C.: Meteorological drought., Weather Bureau Res. Paper, 45, 1–58, https://www.droughtmanagement.info/literature/USWB_Meteorological_Drought_1965.pdf, 1965.

Pohle, I., Zeilfelder, S., Birner, J., and Creutzfeldt, B.: The 2018–2023 drought in Berlin: impacts and analysis of the perspective of water resources management, Natural Hazards and Earth System Sciences, 25, 1293–1313, https://doi.org/10.5194/nhess-25-1293-2025, 2025.

R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org/, 2025.

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., Hanel, M., and Kumar, R.: The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe, Earth's Future, 10, e2021EF002 394, https://doi.org/10.1029/2021EF002394, e2021EF002394 2021EF002394, 2022.

https://doi.org/10.5194/egusphere-2026-5051
Preprint. Discussion started: 29 September 2026

van den Besselaar, E.: Climate indices derived from E-OBS: Product User Guide (PUG) - Copernicus Knowledge Base - ECMWF Confluence Wiki, Website, https://confluence.ecmwf.int/pages/viewpage.action?pageId=320998008, last modified on Juni 26, 2025 10:18, 2025.

van der Schrier, G., Barichivich, J., Briffa, K. R., and Jones, P. D.: A scPDSI-based global data set of dry and wet spells for 1901–2009, Journal of Geophysical Research: Atmospheres, 118, 4025–4048, https://doi.org/10.1002/jgrd.50355, 2013.

Van Vuuren, D. P., O'Neill, B. C., Tebaldi, C., Sanderson, B. M., Chini, L. P., Friedlingstein, P., Hasegawa, T., Riahi, K., Govindasamy, B., Bauer, N., Eyring, V., Fall, C. M. N., Frieler, K., Gidden, M. J., Gohar, L. K., Högner, A., Jones, A. D., Kikstra, J., King, A., Knutti, R., Kriegler, E., Lawrence, P., Lennard, C., Lowe, J., Mathison, C., Mehmood, S., Nicholls, Z., Prado, L. F., Zhang, Q., Rose, S. K., Ruane, A. C., Sandstad, M., Schleussner, C.-F., Seferian, R., Sillmann, J., Smith, C., Sörensson, A. A., Panickal, S., Tachiiri, K., Vaughan, N., Vishwanathan, S. S., Yokohata, T., Zecchetto, M., and Ziehn, T.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7), Geoscientific Model Development, 19, 2627–2656, https://doi.org/10.5194/gmd-19-2627-2026, 2026.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696 – 1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Wells, N., Goddard, S., and Hayes, M. J.: A Self-Calibrating Palmer Drought Severity Index, Journal of Climate, 17, 2335–2351, https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2, 2004.

Xoplaki, E., Ellsäßer, F., Grieger, J., Nissen, K. M., Pinto, J. G., Augenstein, M., Chen, T.-C., Feldmann, H., Friederichs, P., Gliksman, D., Goulier, L., Haustein, K., Heinke, J., Jach, L., Knutzen, F., Kollet, S., Luterbacher, J., Luther, N., Mohr, S., Mudersbach, C., Müller, C., Rousi, E., Simon, F., Suarez-Gutierrez, L., Szemkus, S., Vallejo-Bernal, S. M., Vlachopoulos, O., and Wolf, F.: Compound events in Germany in 2018: drivers and case studies, Natural Hazards and Earth System Sciences, 25, 541–564, https://doi.org/10.5194/nhess-25-541-2025, 2025.