Supplement to: 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)

S1 Supplementary information on Data and Methods

S1.1 Simulation data

The accompanying study relies on simulation data from the EURO-CORDEX project. It uses output from the regional climate model runs for the historical period and for the two future projections under the representative concentration pathways RCP4.5 and RCP8.5 (Jacob et al., 2014). That is, the study uses the dynamical regional downscaling of CMIP5-simulations. According to the overview at https://cordex.org/data-access/cordex-cmip5-data/cordex-cmip5-simulations/ (last visited 2026-08-20), there were 25 GCM-RCM pairs that covered both RCP4.5 and RCP8.5. Data from 18 GCM-RCM pairs was available to calculate the scPDSI and its evapotranspiration input (Table S1).

A number of simulations did not provide full output for all months until 2100. Some of these even do not have data for December 2099. For these, the input data vectors for precipitation and potential evapotranspiration are padded with `0` for December 2099 for the calculations of the scPDSI. Analyses do not exclude December 2099 or the year 2099, here, as this does not influence the conclusions in the paper. Other simulations started only from January 2nd of their first year. As this did not affect calculations, these Januaries are nevertheless included here.

The Copernicus Climate Data Store provides access to a subset of EURO-CORDEX data (Copernicus Climate Change Service, 2023, 2019).

S1.2 Drought index calculations

The current manuscript classifies drought using the self-calibrating Palmer Drought Severity Index (scPDSI, Palmer, 1965; Wells et al., 2004). The index considers a local water balance, for which calculations require estimates of evapotranspiration and local water holding capacity data. Evapotranspiration calculations, here, use the Penman-Monteith equation (Allen et al., 1998) following previous works (e.g., Dai, 2011; Sheffield et al., 2012; van der Schrier et al., 2013), which find this to be generally beneficial compared to Thornthwaite's equation (Thornthwaite, 1948) used in the original PDSI formulation (Palmer, 1965). According to Dai et al. (1998), the PDSI does not strongly depend on the choice of the water capacity holding data.

Table S1. List of regional climate model (RCM) simulations, their driving general circulation (GCM) or earth system model (ESM) simulation and the reference for the RCM.

Driving GCM	RCM Model	Run	RCM Institution	RCM Reference
CNRM-CM5	ALADIN63	r1i1p1	CNRM	Daniel et al. (2019)
CNRM-CM5	RACMO22E	r1i1p1	KNMI	Meijgaard et al. (2012)
CNRM-CM5	RCA4	r1i1p1	SMHI	Kjellström et al. (2016)
EC-EARTH	RACMO22E	r12i1p1	KNMI	Meijgaard et al. (2012)
EC-EARTH	RCA4	r12i1p1	SMHI	Kjellström et al. (2016)
EC-EARTH	RACMO22E	r1i1p1	KNMI	Meijgaard et al. (2012)
EC-EARTH	HIRHAM5	r3i1p1	DMI	Bøssing Christensen et al. (2007)
IPSL-CM5A-MR	RCA4	r1i1p1	SMHI	Kjellström et al. (2016)
HadGEM2-ES	HIRHAM5	r1i1p1	DMI	Bøssing Christensen et al. (2007)
HadGEM2-ES	REMO2015	r1i1p1	GERICS	Remedio et al. (2019)
HadGEM2-ES	RACMO22E	r1i1p1	KNMI	Meijgaard et al. (2012)
HadGEM2-ES	RCA4	r1i1p1	SMHI	Kjellström et al. (2016)
MPI-ESM-LR	REMO2009	r1i1p1	MPI-CSC	Jacob et al. (2012)
MPI-ESM-LR	RCA4	r1i1p1	SMHI	Kjellström et al. (2016)
MPI-ESM-LR	REMO2009	r2i1p1	MPI-CSC	Jacob et al. (2012)
NorESM1-M	HIRHAM5	r1i1p1	DMI	Bøssing Christensen et al. (2007)
NorESM1-M	REMO2015	r1i1p1	GERICS	Remedio et al. (2019)
NorESM1-M	RCA4	r1i1p1	SMHI	Kjellström et al. (2016)

The calibration period for the scPDSI calculations from the simulations is 1971 to 2000. Index-calculations take place on the native simulation grids and without masking land-sea areas. Subsequent ensemble comparisons require remapping and masking of the land-areas. Evapotranspiration calculations adapt code from the `pyet` Python-library (Vremec et al., 2024; Vremec and Collenteur, 2024), and scPDSI-calculations rely on code by ECA&D (https://github.com/ECA-D/, e.g., Photiadou et al., 2017; Photiadou and Bronaugh, 2017; Harpham et al., 2025) as well as the water capacity holding data provided by ECA&D in their code-package (Harpham et al., 2020, 2025; Global Soil Data Task Group, 2000).

S1.3 Acknowledgements for external code and software

A number of external tools helped in this study. While coding in R (R Core Team, 2025) and Python (Python Software Foundation, 2021-2026) mainly took place in DKRZ's jupyterhub (Jupyter Team, 2015) environment, writing of the article relied on RStudio (Posit team, 2025).

In R, the following packages helped in addition to those already mentioned in the manuscript: ncdf4 (Pierce, 2025), knitr (Xie, 2025), rmarkdown (Allaire et al., 2024a), rticles (Allaire et al., 2024b), zoo (Zeileis and Grothendieck, 2005), scico (Pedersen and Crameri, 2023), raster (Hijmans, 2025), fields (Douglas Nychka et al., 2021), viridis (Garnier et al., 2024), lubridate (Grolemund and Wickham, 2011), CFtime (Van Laake, 2025), dplyr (Wickham et al., 2023), purrr (Wickham and Henry, 2025), stringr (Wickham, 2023), and ncdf4.helpers (Bronaugh, 2025).

Similarly, in Python NumPy (Harris et al., 2020) and xarray (Hoyer and Joseph, 2017) assisted alongside the modules referenced in the manuscript.

Additionally, the CDOs (Schulzweida, 2023) and GNU Parallel (Tange, 2021) were used.

References

Allaire, J., Xie, Y., Dervieux, C., McPherson, J., Luraschi, J., Ushey, K., Atkins, A., Wickham, H., Cheng, J., Chang, W., and Iannone, R.: rmarkdown: Dynamic Documents for R, https://github.com/rstudio/rmarkdown, r package version 2.29, 2024a.

Allaire, J., Xie, Y., Dervieux, C., R Foundation, Wickham, H., Journal of Statistical Software, Vaidyanathan, R., Association for Computing Machinery, Boettiger, C., Elsevier, Broman, K., Mueller, K., Quast, B., Pruim, R., Marwick, B., Wickham, C., Keyes, O., Yu, M., Emaasit, D., Onkelinx, T., Gasparini, A., Desautels, M.-A., Leutnant, D., MDPI, Taylor and Francis, Öğreden, O., Hance, D., Nüst, D., Uvesten, P., Campitelli, E., Muschelli, J., Hayes, A., Kamvar, Z. N., Ross, N., Cannoodt, R., Luguern, D., Kaplan, D. M., Kreutzer, S., Wang, S., Hesselberth, J., and Hyndman, R.: rticles: Article Formats for R Markdown, https://doi.org/10.32614/CRAN.package.rticles, r package version 0.27, 2024b.

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.

Bøssing Christensen, O., Drews, M., Hesselbjerg Christensen, J., Dethloff, K., Ketelsen, K., Hebestadt, I., and Rinke, A.: The HIRHAM Regional Climate Model. Version 5 (beta), no. 06-17 in Denmark. Danish Meteorological Institute. Technical Report, Danish Climate Centre, Danish Meteorological Institute, https://orbit.dtu.dk/en/publications/the-hirham-regional-climate-model-version-5-beta/, 2007.

Bronaugh, D.: ncdf4.helpers: Helper Functions for Use with the 'ncdf4' Package, https://CRAN.R-project.org/package=ncdf4.helpers, r package version 0.3-7, 2025.

Copernicus Climate Change Service: CORDEX regional climate model data on single levels, https://doi.org/10.24381/CDS.BC91EDC3, 2019.

Copernicus Climate Change Service: Gridded monthly climate projection dataset underpinning the IPCC AR6 Interactive Atlas, https://doi.org/10.24381/CDS.5292A2B0, 2023.

Dai, A.: Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008, Journal of Geophysical Research: Atmospheres, 116, https://doi.org/10.1029/2010JD015541, 2011.

Dai, A., Trenberth, K. E., and Karl, T. R.: Global variations in droughts and wet spells: 1900–1995, Geophysical Research Letters, 25, 3367–3370, https://doi.org/10.1029/98GL52511, 1998.

Daniel, M., Lemonsu, A., Déqué, M., Somot, S., Alias, A., and Masson, V.: Benefits of explicit urban parameterization in regional climate modeling to study climate and city interactions, Climate Dynamics, 52, 2745–2764, https://doi.org/10.1007/s00382-018-4289-x, 2019.

Douglas Nychka, Reinhard Furrer, John Paige, and Stephan Sain: fields: Tools for spatial data, https://github.com/dnychka/fieldsRPackage, r package version 16.3.1, 2021.

Garnier, Simon, Ross, Noam, Rudis, Robert, Camargo, Pedro, A., Sciaini, Marco, Scherer, and Cédric: viridis(Lite) - Colorblind-Friendly Color Maps for R, https://doi.org/10.5281/zenodo.4679423, viridis package version 0.6.5, 2024.

Global Soil Data Task Group: Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS), https://doi.org/10.3334/ORNLDAAC/569, 2000.

Grolemund, G. and Wickham, H.: Dates and Times Made Easy with lubridate, Journal of Statistical Software, 40, 1–25, https://www.jstatsoft.org/v40/i03/, 2011.

Harpham, C., Jones, P., and van der Schrier, G.: User manual to operate the script to calculate the self-calibrating Palmer Drought Severity Index, https://surfobs.climate.copernicus.eu/documents/C3S_D311a_Lot4.3.1.7_UserManual_scPDSI_v3.pdf, 2020.

Harpham, C., Zhong, R., Chen, X., Wang, Z., and Lai, C.: scPDSIr: Calculation of the Self-Calibrating Palmer Drought Severity Index from gridded data, https://github.com/ECA-D/scPDSIr, r package version 0.1.0, commit 2ec6e09188987cc26c6c3ee3659ad4e1850477d9, 2025.

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., Gérard-Marchant, P., Sheppard, K., Reddy, T., Weckesser, W., Abbasi, H., Gohlke, C., and Oliphant, T. E.: Array programming with NumPy, Nature, 585, 357–362, https://doi.org/10.1038/s41586-020-2649-2, 2020.

Hijmans, R. J.: raster: Geographic Data Analysis and Modeling, https://CRAN.R-project.org/package=raster, r package version 3.6-32, 2025.

Hoyer, S. and Joseph, H.: xarray: N-D labeled Arrays and Datasets in Python, Journal of Open Research Software, 5, https://doi.org/10.5334/jors.148, 2017.

Jacob, D., Elizalde, A., Haensler, A., Hagemann, S., Kumar, P., Podzun, R., Rechid, D., Remedio, A. R., Saeed, F., Sieck, K., Teichmann, C., and Wilhelm, C.: Assessing the Transferability of the Regional Climate Model REMO to Different COordinated Regional Climate Downscaling EXperiment (CORDEX) Regions, Atmosphere, 3, 181–199, https://doi.org/10.3390/atmos3010181, 2012.

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.

Jupyter Team: Project Jupyter Documentation, Website, https://docs.jupyter.org/, 2015.

Kjellström, E., Bärring, L., Nikulin, G., Nilsson, C., Persson, G., and Strandberg, G.: Production and use of regional climate model projections – A Swedish perspective on building climate services, Climate Services, 2-3, 15–29, https://doi.org/10.1016/j.cliser.2016.06.004, 2016.

Meijgaard, E. v., Ulft, L. H. v., Lenderink, G., Roode, S. R. d., Wipfler, E. L., Boers, R., and Timmermans, R. M. A. v.: Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe, Tech. rep., Wageningen, ISSN 9789088150463, https://edepot.wur.nl/312258, 2012.

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

Pedersen, T. L. and Crameri, F.: scico: Colour Palettes Based on the Scientific Colour-Maps, https://doi.org/10.32614/CRAN.package.scico, r package version 1.5.0, 2023.

Photiadou, C. and Bronaugh, D.: gridclimind: Functions to compute CLIMIND indices over a NetCDF grid, https://github.com/ECA-D/gridclimind, r package version 1.0.0, 2017.

Photiadou, C., Posselt, R., and Bronaugh, D.: climind: ECAD Implementation of Climdex Routines, https://github.com/ECA-D/climind, r package version 1.0.0, commit 2c9952cf26e7db4ac828d002e329e09e834b8b89, 2017.

Pierce, D.: ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files, https://doi.org/10.32614/CRAN.package.ncdf4, r package version 1.24, 2025.

Posit team: RStudio: Integrated Development Environment for R, Posit Software, PBC, Boston, MA, http://www.posit.co/, 2025.

Python Software Foundation: Python, https://www.python.org/, 2021-2026.

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

Remedio, A. R., Teichmann, C., Buntemeyer, L., Sieck, K., Weber, T., Rechid, D., Hoffmann, P., Nam, C., Kotova, L., and Jacob, D.: Evaluation of New CORDEX Simulations Using an Updated Köppen–Trewartha Climate Classification, Atmosphere, 10, https://doi.org/10.3390/atmos10110726, 2019.

Schulzweida, U.: CDO User Guide, https://doi.org/10.5281/ZENODO.10020800, 2023.

Sheffield, J., Wood, E. F., and Roderick, M. L.: Little change in global drought over the past 60 years, Nature, 491, 435–438, https://doi.org/10.1038/nature11575, 2012.

Tange, O.: GNU Parallel 20210922 ('Vindelev'), https://doi.org/10.5281/zenodo.5523272, GNU Parallel is a general parallelizer to run multiple serial command line programs in parallel without changing them., 2021.

Thornthwaite, C. W.: An approach toward a rational classification of climate, Geographical review, 38, 55–94, https://doi.org/10.2307/210739, 1948.

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 Laake, P.: CFtime: Using CF-Compliant Calendars with Climate Projection Data, https://CRAN.R-project.org/package=CFtime, r package version 1.6.2, 2025.

Vremec, M. and Collenteur, R.: pyet - Estimation of Potential Evapotranspiration, https://pyet.readthedocs.io/en/latest/index.html, 2024.

Vremec, M., Collenteur, R. A., and Birk, S.: *PyEt* v1.3.1: a Python package for the estimation of potential evapotranspiration, Geoscientific Model Development, 17, 7083–7103, https://doi.org/10.5194/gmd-17-7083-2024, 2024.

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.

Wickham, H.: stringr: Simple, Consistent Wrappers for Common String Operations, https://doi.org/10.32614/CRAN.package.stringr, r package version 1.5.1, 2023.

Wickham, H. and Henry, L.: purrr: Functional Programming Tools, https://doi.org/10.32614/CRAN.package.purrr, r package version 1.0.4, 2025.

Wickham, H., François, R., Henry, L., Müller, K., and Vaughan, D.: dplyr: A Grammar of Data Manipulation, https://CRAN.R-project.org/package=dplyr, r package version 1.1.4, 2023.

Xie, Y.: knitr: A General-Purpose Package for Dynamic Report Generation in R, https://yihui.org/knitr/, r package version 1.50, 2025.

Zeileis, A. and Grothendieck, G.: zoo: S3 Infrastructure for Regular and Irregular Time Series, Journal of Statistical Software, 14, 1–27, https://doi.org/10.18637/jss.v014.i06, 2005.