Author comment to RC2 in “Droughts in western Central Europe and associated atmospheric circulation patterns since 1844”

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Comment of the reviewer

Comment of the authors

Summary

The author team investigates drought variability in western Central Europe since 1844 using different reanalysis products. Thereby, they focus on links between drought conditions and atmospheric circulation to identify potential drivers of drought. They further employ 2 drought measures. The results show that recent extreme droughts have historical precedents, illustrating strong multidecadal variability of drought conditions in western Central Europe. Assessing the trend behavior of droughts, the author team find seasonal differences as well as differences between the two drought indices. The authors hypothesize that the diverging trends of the two drought indices sued are indicative to an increasing role of atmospheric evaporative demand (AED). They back this hypothesis with changes in circulation patterns towards AED prone patterns highlighting the role of dynamics over thermodynamics in this region.

General statement

The author team certainly touches interesting questions on whether recent droughts are unprecedented and more importantly how drivers of drought in in western Central Europe have changed over time and what is the role of atmospheric dynamics versus thermodynamics. In this sense the study is of high importance and deserves publication in WCD. Still, in the current form there are major concerns, the structure of the manuscript needs to be improved, the manuscript needs substantial shortening, the atmospheric circulation classification needs better explanation, and the discussion needs more focus. So, I recommend acceptance after major revisions.

We thank the reviewer for their thorough evaluation of the manuscript and are grateful for the time and effort dedicated to providing detailed and constructive comments, which have significantly helped improve the quality of the work. We first address this general comment, followed by point-by-point responses to the other comments below.

We agree that the original manuscript would benefit from improvements in structure, conciseness, clarity of the atmospheric circulation classification, and a more focused discussion. To address these points, a substantial effort will be made to streamline

the manuscript by reducing background material and limiting descriptive repetition of the results. The Data and Data Evaluation sections will be shortened and merged, and Section 6.2 as well as the Discussion will be substantially revised to improve readability and emphasise the main findings, interpretation, significance, and limitations of the results. Additional clarifications will also be provided regarding the atmospheric circulation classification methodology and its interpretation, including improvements to the description of the clustering procedure and supporting information in the Supplementary Material. Overall, these revisions are expected to reduce the length of the manuscript by approximately 30%, while improving its conciseness and focus and preserving its core scientific content.

Major comments

1. Structural problems concern the data section, not containing a description of all data sets used (see minor comments), method section (4.1) not explaining PET when it is introduced the first time, and parts of the results belong to the evaluation section.

The Methods, Data, and Data Evaluation sections will be revised to improve the overall structure and clarity of the manuscript. Missing dataset descriptions will be added, the introduction of PET/AED in the Methods section will be clarified, and elements of the Results section that are more appropriate for evaluation will be moved accordingly. In addition, the Data and Data Evaluation sections will be merged to improve the overall flow and coherence of the manuscript. These changes will ensure a clearer separation between methodological description, evaluation, and results.

2. Method section 4.3: I do not understand how the authors classify atmospheric circulation. It remains unclear to which variable the k-means clustering is applied, is it applied to drought indices as somehow written in paragraph 2 or to Z500?

The Methods section will be revised to improve clarity regarding the clustering procedure. We will explicitly state that k-means clustering is applied to 500 hPa geopotential height (Z500) anomalies, and not to the drought indices. SPI-3 and SPEI-3 are used solely to identify and define drought events. For each event, Z500 anomalies are averaged over a three-month window (the month of drought onset and the two preceding months), and the resulting event composites are used as input for the clustering to identify recurrent atmospheric circulation patterns associated with drought. We will further clarify that two independent clustering analyses are performed based on SPI-3- and SPEI-3-selected drought events.

3. The discussion is not focused and far to long, see my suggestions below.

We agree with the reviewer that the Discussion was not sufficiently focused and was too long in the original version. We will address this by substantially revising the section: subsection 7.1 will be shortened, subsections 7.2 and 7.3 will be merged and refocused on the atmospheric circulation associated with drought, and subsection 7.4 will be shortened and moved to the Conclusions. These changes are expected to significantly improve the focus, coherence, and conciseness of the Discussion.

Minor comments

Throughout the manuscript: The authors do often use the wrong tense, So I suggest using present tense throughout the manuscript except you actively write that person A showed something (example: Paulin et al. (2006= suggested that …), then use past tense. Avoid using form like "have attracted" or "is becoming".

The manuscript will be revised to improve consistency in verb tense usage throughout, following the reviewer's suggestion. In addition, several sentences will be reformulated to improve clarity and readability, including reducing overly passive or awkward constructions where appropriate. However, passive constructions will be retained where they are standard in scientific writing and contribute to maintaining an objective tone.

L40: Please add the publications https://doi.org/10.5194/cp-19-2511-2023 and https://doi.org/10.5194/cp-17-887-2021 by Kim dealing with Med droughts during the last Millenium.

Additional references will be added to the Introduction (L39) to better contextualize long-term drought variability in the Mediterranean region, including the two studies suggested by the reviewer.

L43: There is a study assessing a lot of different drought indices over Europe which might be of interest to the authors: Raible, C. C., O. Baerenbold, and J. J. Gomez-Navarro, 2017: Drought indices revisited - Improving and Testing of Drought Indices in a Simulation of the last two Millennia for Europe. *Tellus*, **69**, 1296226

The reference will be added to the Introduction (L43) to better contextualize drought indices across regions. It will also be cited in the Methods section and in the discussion of PET methods to support the comparison between Thornthwaite and Penman–Monteith.

L45: The sentence reads bad, please reformulate.

The sentence will be revised to improve clarity by better separating the two contrasting interpretations in the literature and improving readability.

L51-53: The sentence reads bad, please reformulate.

The sentence will be reformulated to improve clarity and readability by simplifying the structure and avoiding repetition, while maintaining the distinction between observed past trends and projected future changes in seasonal dryness.

L58-59: Maybe change to "circulation dynamic is hypothesized to prevail ... land-atmosphere feedback dominate ..."

The sentence will be revised accordingly to improve clarity: "atmospheric circulation dynamics are hypothesised to dominate … land–atmosphere feedbacks may play a larger role".

L59-62: Again the sentence needs to be improved.

The sentence will be revised to improve clarity and readability: “In addition, large-scale circulation patterns have been identified as key drivers of dry conditions in Western Europe more clearly than in other European regions (Savary et al., 2025).”.

L75-76: Please add publication https://doi.org/10.5194/cp-19-2511-2023 here.

The suggested reference will be added.

L94: “it is imperative” reads bad, please change.

“It is imperative” will be replaced by a more neutral formulation to improve tone and clarity at both L94 and L271.

L103-105: It is weird that section 5 is introduced after section 6.1 and 6.2

The paragraph introducing the sections will be removed, as it did not add substantive information and contributed to the overall length of the manuscript.

L116: Which alpine influence have the authors in mind?

The sentence will be clarified to refer to the presence of the distinct Alpine climate, rather than its influence.

L122: I would not say that Western Central Europe is predominately forested, as over 63% is not forested. So please reformulate.

The sentence will be reformulated accordingly: “Western Central Europe features a heterogeneous land cover, with tree cover (36.8%), croplands (31.6%), and grasslands (22.6%) as the main components”.

L140-153: Please state which data assimilation schemes are used in these different reanalysis products.

This information will be added in Table 1, which summarises the reanalyses used in this study.

Section Data: It remains unclear which time resolution is used. I guess it is monthly not is it not stated clearly in this section.

The temporal resolution (monthly) will be explicitly added to the Data section for clarity.

Section Data: I suggest to also introduce the observational station data in this section, so move the paragraph on line 271 and the table 2 to this section.

We will follow this suggestion by merging the Data and Data Evaluation sections to improve readability and avoid disrupting the flow of the results. Table 2 and the paragraph describing the observational station data will therefore be relocated to the Data section.

L156: Change “In order to” to “To” throughout the manuscript.

We thank the reviewer for this stylistic suggestion. “In order to” will be replaced with “to” throughout the manuscript.

L157: What is bilinear downscaling? For me it sounds like the authors just applied a bilinear interpolation where no new information is added (statistical downscaling adds sub-grid information from observations and dynamical downscaling runs a model in higher resolution adding additional resolved processes). I think this is a bit problematic as a reanalysis produced on a coarse grid like 1.8 degree never will the fine scale processes, so normally, if the authors would like to compare the data sets with each other one should interpolate the finer resolved data sets to the coarse resolution to make a fair comparison. At least the authors need to discuss this issue in the manuscript.

We acknowledge that bilinear interpolation (resampling) does not introduce new information and does not resolve scale mismatches between reanalyses of different native resolutions. Our choice to interpolate 20CRv3 and ModE-RA to the ERA5 grid was motivated by the relatively small spatial domain of the study and the desire to preserve the highest available spatial detail from ERA5, which is considered most reliable during the most recent period. We agree that reanalyses at coarser resolution (e.g. ~1.8°) cannot represent fine-scale processes, and that interpolation does not overcome this limitation. This point will therefore be clarified in the manuscript by explicitly stating that comparisons focus on mid-to-large-scale patterns and that results at spatial scales below approximately 200 km remain subject to substantial uncertainty due to resolution differences. We will also clarify that aggregated regional statistics are not significantly affected by the resampling choice.

L173: Please move the used PET estimation here, which is mentioned at the end of this subsection.

We will follow this suggestion and moved the PET (AED) estimation description to this subsection to improve the flow of the text.

L175: How is AED calculated?

AED represents the maximum combined evaporation from soil and transpiration from vegetation under given climatic conditions, assuming no soil water limitation. In this study, it is calculated using the Thornthwaite approach. This will be clarified in the revised manuscript. To avoid ambiguity, we will consistently use the term AED throughout the manuscript rather than PET, which can be confusing (Katerji and Rana, 2011; DeJonge et al., 2025).

L192-194: You do not need to explain area weighted, so you can change to “... precipitation and PET values for land cells are area weighted. For each month ...”

The sentence will be revised accordingly, and the explanation of area-weighting will be simplified as suggested.

Fig.2: I think this figure is not necessary, it might be useful in a PhD thesis but for a paper the description in the manuscript is sufficient.

We thank the reviewer for this suggestion. Figure 2 will be removed from the manuscript as recommended.

L205-208: Please move to L 174.

We will follow this suggestion and move the AED estimation description to the previous subsection to improve the flow of the text.

238: What is AIC und BIC?

The acronyms will be defined in full and will now read: “Akaike Information Criterion, Bayesian Information Criterion”.

262: replace “two variables” with features

The phrase “Whilst the aforementioned two variables” will be replaced with “While the latter two features”.

L281-291: This paragraph remains unclear: I would rather introduce the metrics in the method section and only discuss the results in this chapter

The metrics from the Data Evaluation section will be moved to the Data section, where they will be introduced alongside the datasets. This restructuring will improve the clarity of the manuscript and allow the Results section to focus on the analysis.

Fig. 3: a) and b) are missing.

Panel labels (a) and (b) will be included in the revised figure.

L319: I suggest making a kind of introduction of what will be presented in the results section.

We have chosen not to add a separate introductory paragraph to the Results section in order to avoid further lengthening the manuscript. Instead, the Data and Data Evaluation sections will be merged, which will streamline the manuscript and provide a clearer distinction between evaluation and results.

L321-324: This part belongs to the evaluation.

We will follow this suggestion by moving the sentences concerning the agreement of drought events between reanalyses to the Data Evaluation section, where they are more appropriately discussed.

L341-42: Do not make sentences which refer to a coming section, If you discuss this in section 6.2 then make a reference to section 6.1

The text has been revised accordingly, and the cross-reference to Section 6.1 will be added in Section 6.2 as suggested.

L350: what are the two drought types here, and how are they measured?

We meant drought indices rather than drought types. The text will be corrected accordingly.

Fig.5: do not use rainbow colour scales, it is unreadable for colour blind people (15 % of the word population)

The original figure used a perceptually uniform colormap from the *viridis* R package (Garnier et al., 2018), which is colourblind-friendly; however, it was not a diverging colormap, which is not optimal for representing divergent data. The figure will therefore be revised using a diverging colormap that is more appropriate for the nature of the variable. The new colormap will remain perceptually uniform and suitable for colourblind readers.

L384: This should be Fig 6b. Correct?

We thank the reviewer for pointing this out. Additional panels will be added in Fig. 6 to clarify the cross-reference.

L401: This should be Fig 6b. Correct?

Additional panels will be added in Fig. 6 to clarify the cross-reference.

Fig 6b is discussed before Fig 6a, which is almost not discussed.

Additional panels will be added in Fig. 6 to clarify the cross-reference.

Fig.6a: do not use rainbow colour scales

The original figure used a perceptually uniform colormap from the *viridis* R package (Garnier et al., 2018), which is colourblind-friendly; however, it was not a diverging colormap, which is not optimal for representing divergent data. Therefore, the figure will be revised using a diverging colormap that is more appropriate given the nature of the variable. The new colormap will remain perceptually uniform and suitable for colourblind readers.

L460: Both clustering, what is meant here?

"Both clustering" referred to the two clustering analyses performed on Z500 anomalies during drought events defined using SPEI-3 and SPI-3. This will be clarified in the revised manuscript.

L505: These are just "modes or variability"

The expression “three first natural modes of variability” will be replaced with “three dominant modes of variability”.

L515: How is high confidence defined?

The qualitative term “high confidence” will be replaced by the corresponding p-values from the MMKH trend test to provide a clearer and more quantitative assessment of significance.

Fg. 8d do not use rainbow colour scales

The original figure used a perceptually uniform colormap from the *viridis* R package (Garnier et al., 2018), which is colourblind-friendly; however, it was not a diverging colormap, which is not optimal for representing divergent data. Therefore, the figure will be revised using a diverging colormap that is more appropriate given the nature of the variable. The new colormap will remain perceptually uniform and suitable for colourblind readers.

L537-553: What is the message of this paragraph?

The paragraph will be revised to better highlight its main message, namely that recent droughts are not unprecedented in a long-term context, with the 1921 event standing out as a historical benchmark, while differences arise depending on the metric considered (SPI vs SPEI) and the temporal perspective.

L564: Given the low frequency variability of AMO (around 60 yr periodicity) a correlation of -0.3 to –0.68 is not impressive and rather significant over the ERA5 time scale of 70 years, I would argue that this is just noise. So, reformulate or remove this paragraph

We agree that, given the low-frequency variability of the Atlantic Multidecadal Oscillation (AMO) and its characteristic periodicity (~60 years), correlations computed over the relatively short ERA5 period (~70 years) are not robust and do not provide sufficient evidence for a meaningful relationship. In response, we will remove the correlation metrics and associated interpretation to avoid overinterpretation. The paragraph will be simplified accordingly and will instead state that no substantial relationship is found between low-frequency drought variability in western Central Europe and the NAO, the El Niño–Southern Oscillation (ENSO), or the AMO indices.

L574-589: Well, you selected the area in a way that it shows a uniform behaviour so no wonder that there is a high correlation. This paragraph can be removed.

We agree that the strong relationship between drought indices and the affected drought area is expected given the spatial definition of the study region and is not central to the objectives of this study. The corresponding paragraph will therefore be removed and only the aspects providing additional insight into differences in spatial variability between SPI-3 and SPEI-3 droughts will be retained where relevant.

Section 7.2 and 7.3, What is the difference between drivers of trends and dynamics behind the droughts. I thought you discuss the driver and say which drivers re responsible for which trends. So, my suggestion is to merge these sections and shorten it to the main findings of the paper wrt existing literature.

Sections 7.2 and 7.3 will be merged accordingly. The revised section will also be substantially shortened and will focus more directly on the atmospheric circulation associated with drought conditions and its comparison with the existing literature, with reduced emphasis on descriptive or overlapping discussions of trends and drivers.

Section 7.4: I suggest removing this section and may include 1-2 sentences of challenges in the conclusions.

We agree that the former Section 7.4 was disproportionately long relative to its purpose and interrupted the flow of the Discussion. The section will therefore be removed as an independent subsection, and only a concise synthesis of the main challenges and implications will be retained in the Conclusions section. This restructuring will improve the focus and conciseness of the manuscript.

L769: Which processes are meant here?

We agree that the term "both processes" was unclear. The sentence will be revised to explicitly refer to land-surface and atmospheric processes to clarify the intended meaning.

References

DeJonge, K. C., Allen, R., Kilic, A., Thorp, K. R., Kukal, M., Marek, G., ... & Trout, T. (2025). Evapotranspiration terminology and definitions. Irrigation and Drainage Engineering, 15(5).

Garnier, S., Ross, N., Rudis, B., Sciaini, M., Camargo, A. P., & Scherer, C. (2018). Package 'viridis'. Colorblind-Friendly Color Maps for R.

Katerji, N., Rana, G. Crop Reference Evapotranspiration: A Discussion of the Concept, Analysis of the Process and Validation. *Water Resour Manage* **25**, 1581–1600 (2011). https://doi.org/10.1007/s11269-010-9762-1