Linking European droughts to year-round weather regimes

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We would like to thank the reviewers for their responses and constructive comments, which we have considered very carefully. We hope that the revised version of the manuscript will satisfactorily address their concerns. We will reply point by point to each reviewer. We have highlighted the changes made to the text of the article in bold.

1 Reviewer #1

1.1 Major comments

Comment
Your response to my comment 2 (about the role of persistence and intensity of individual WR life cycles): Thanks for making this additional analysis. Could you maybe add one concluding sentence also to your discussion or conclusions in the manuscript – since you already did it?

Reply: **Thank you for your comment. We have added a note in the conclusion (L.508-514) referring to the supplementary material where we have included the analysis in question : "Studying the role of persistence and intensity of individual WR life cycles (not shown here but present in the supplementary material), we find that in most cases the frequency anomaly cannot be explained both by an increased persistence alone or an increased number of sequences alone, but rather by a combination of both. In some cases (such as the EuBL regime in the EMed region, for example), the positive frequency anomaly can be explained by an increased sequence size but an unchanged number of sequences. The intensity of the regimes does not differ between cases that are well captured by the WRs and cases that are poorly captured. The difference between the two types of drought does not appear to stem from a marked distortion of atmospheric centres of action in one case compared to the other."**

Comment
L2: I would replace "large-scale dynamic circulation patterns" again with "large-scale atmospheric circulation patterns". The former sounds like it could be anywhere, as dynamics happens in all kinds of spheres (above and below ground).

Reply: **Thank you for your comment, we corrected it L.2.**

Comment
L7-8: Can you still say "seasonally consistent precipitation patterns" given your nice new analysis of the intra-regime precipitation variability? Or what exactly do you mean with "seasonally consistent" here?

Reply: **We have clarified our statement by replacing 'Our analysis shows that while each weather regime exhibits distinctive and relatively consistent seasonal precipitation pattern,...' with 'Our analysis shows that while each weather regime exhibits distinctive and relatively stable precipitation patterns throughout the year,...' L.7**

Comment
L9-11: You mention the partial importance of weather regimes here. Given your additional analysis you made now also for your review replies, would it make sense to add one sentence here speculating what additional reasons might be important (convective situations during summer, larger intra-regime precip- itation variability in summer etc.)? It should not be written to undermine the importance of the regimes, but maybe just for completeness/transparency. Or do you think it would be too speculative?

Reply: Thank you for your comment. We believe that being too specific in the abstract could make our message confusing. We prefer to emphasise this point in the discussion section of our article.

Comment
L21: "This is all the more true for extratropical regions" – I'm not sure if this sentence is grammatically correct...

L76: I would rather say something like the domain is roughly similar to Grams et al. 2017 but extends more to the east to also capture region X and Y.

Reply:
Concerning your comment about the domain extent, we modified it following your suggestion. L.75 **Thank you for your comment, we replaced "This is all the more true for extratropical regions" by "This is particularly true for extratropical regions." L.21**

Concerning your comment about the domain extent, we modified it following your suggestion. L.75

Comment
L90-93: Isn't the step of the standardization of this anomaly missing in the sentence explaining how the SPI is computed?

Reply: **Thank you for your comment, we corrected it L.89.**

Comment
L184: With "monthly" and "daily" you here mean the integration period of the SPI, i.e. monthly would mean the SPI1? But what is a daily SPI then – do studies really do this?

Reply: Thank you for your comment. We refer to the temporal step of the dataset used. A "daily" SPI is computed for each day of the studied period, and can have different running integration period (e.g. 1 month, 3 months, 6 months...). A "monthly" SPI is the monthly average of the daily index, regardless of the integration period. Usually, scientific papers are using a monthly SPI, while we are using a daily SPI. **We clarified this point on the paper : we replaced "...SPI is computed at a monthly rather than daily timescale and droughts considered..." by "...SPI is calculated on a monthly rather than daily timescale, which means that the SPI calculation, regardless of the running integration period, is based on monthly precipitation anomalies over the entire period rather than daily precipitation anomalies. The droughts considered..." L.144**

Comment
L208: "function"
L237: I would write "cyclonic anomaly" rather than "depression"
L317: There is a typo / grammatically incorrect part in this addition

Reply: **Thank you for your comments, we took them into account.**

Comment
Fig. 6 caption: It's not very clear what you mean with "and the frequency of occurrence". You mean the canonical/climatological occurrence independent of drought?

Reply: Yes, it was a typo, thank you for catching it !

Comment
L416: "columns I and III" from where?
L437: "atmosphere"
L456: You should state which dotted lines you mean, because there are also dotted lines dividing the four quadrants.

Reply: **Thank you for your comments. We have corrected the manuscript accordingly**

Comment
Section 4.1 / Fig. 11: I would write / repeat more explicitly that this section / figure looks at the resem- blance of zg500 and precipitation pattens before drought events with the canonical patterns of the cor- responding weather regimes independent of drought, either in the caption or somewhere in the descrip- tion. Of course it is somewhat clear from the fact that you try to understand the deltaC term. But when reading the text, it sounds a bit like this is a general investigation of precipitation representativeness of weather regimes (independent of droughts).

Reply: In reality, this study was not conducted solely in the context of droughts. We show that, whether during periods of drought or not, the patterns of zg500 and precipitation vary in their resemblance to their canonical patterns. This result is therefore broader in scope than a study limited to periods of drought. It remains valid during dry periods.

We have added a note at the beginning of our section (L.392): 'Please note that this study was not conducted solely in the context of droughts. The result remains valid during dry periods.'

Please also note that we added few lines in the discussion section 4.1 of the paper(L.420), relatively to a recently published study about WRs variability :

"A recent study [Gerighausen et al., 2025] quantifies intra-regime variability more broadly, using a continuous index I_{WR}. Applied to precipitation anomalies, this approach would probably provide a different way of understanding the influence of regime variability on droughts than the one presented here. This would have the disadvantage of adding a temporal dimension to our study, but would allow us to examine the link between the life cycle parameter of the weather regime and drought."

Comment
L465: I would not write "question" but "reduces the representativeness"

Reply: **Thank you for your comment, we changed it.**

Comment
L472: I would write "small- to meso-scale convection". I guess it can also be the classic (small) summer thunderstorms

Reply: **Thank you, we precised it L.410.**

Comment
L475: "We may therefore question the relevance of using time (weather?) regimes to link circulation and precipitation". I would rephrase / "weaken" this a bit, because if written like this, you basically question your whole paper and weather regimes as a concept. Of course the representativeness of surface weather by weather regimes is not perfect, but this is by design, because at the cost of the representativeness of surface weather we get other advantages by using weather regimes which we would

not have by looking at surface weather directly (categorization, more predictability, persistence etc.).

Reply: Thank you for your comment. **We deleted this sentence**

Comment
L483: "stability" of what?

Reply: **It was a typo, we meant "stability of WRs frequencies throughout the period". We corrected it L.426.**

Comment
Section 4.3, seasonality of the reconstruction: Could you put the findings of this section back into the context of the paper? What would this bias (seasonal vs. annual) mean for your terms alpha 1 and 2? Would it mean that one of these might be under- or overestimated for the regimes that have a strong bias (seasonal vs. annual)? It would help the reader to put that discussion into context...

Reply: Thank you for your comment, we added some lines of discussion about this in the paper L.475-491.

Comment
L566: "WR frequency anomaly"

Reply: **Thank you for your comment, we corrected it.**

Comment
L568: You deleted the reasoning sentence for why the WRs explain more droughts in winter than in summer, but I would find it nice if you still wrote a sentence about it. Maybe just something like that this is because weather regimes explain precipitation variability less well in summer than winter (related to convection etc.) (or something in this direction)?

Reply: **Thank you, we added : "This seasonal contrast is consistent with the fact that weather regimes explain precipitation variability more robustly in winter than in summer, when precipitation is increasingly influenced by local thermodynamic and convective processes that are less tightly constrained by large-scale circulation." L.503-506**

Comment
Figure E1, caption: "Frequency anomalies" of what? I guess of weather regimes?

Reply: **Thank you, we modified it.**

2 Reviewer #2

Comment
I am not quite convinced by the response given to the comment regarding the year-round regimes, in blue below. The dominant circulation patterns, as well as their relationship with precipitation, vary from season to season.

Authors' reply: The main advantage is that they reduce the dimensionality of the problem, as the study does not need to be repeated separately for each season. Similarly, classic weather patterns are well established for the winter (DJF) and summer (JJA) seasons, but not for the intermediate seasons (MAM and SON - spring and fall). Finally, the phenomenon under study – droughts – can occur at any time of the year. Any division of the year into sub-periods will most certainly lead to discontinuity in the study of the link between zg500 and drought.

The plot introduced in response to Reviewer 1 (Figure 9 in the reviewer response) is a great plot summarizing correlations of individual days with both the canonical precipitation patterns and cluster centers. However, it shows that there are perhaps (in the case of Figure 9) a third of days where the

canonical precipitation response has an $ACC < 0$, and perhaps a seventh of days where this is true for zg500. This would most likely be significantly improved if the regimes were computed for each season - the fact that " any division of the year into sub-periods will most certainly lead to discontinuity in the study of the link between zg500 and drought" is in the opinion of this reviewer precisely the point of investigating the regimes specific to the season. Of course, the seasonal cycle is continuous rather than being composed of discrete 'seasons', but in the absence of a model which introduces seasonality as a covariate, studying discrete seasons is a reasonable approach. Since computing year-round regimes is one of the primary premises of this paper, I am not asking the authors to redo the analysis, but rather to perhaps offer a more precise reflection on the benefits of a year-round analysis, alongside the benefits of a season-wise study in the discussion section or in line 45-47.

In particular, the current paper text reads in this section "which hinders a systematic analysis of the drought-circulation relationship throughout the entire year especially intermediate seasons" which is not a convincing argument as the intermediate seasons could be very well analysed in a seasonal regimes study.

Reply: Seasonally defined weather regimes would indeed likely improve the instantaneous representativeness of both circulation and precipitation patterns, as suggested by the higher anomaly correlation coefficients that can generally be achieved when restricting the analysis to a given season. This reflects the strong seasonal modulation of atmospheric dynamics and precipitation processes, and we fully acknowledge that seasonal regimes are a well-established and valuable framework.

However, the primary objective of this study is not to maximize day-to-day correspondence between circulation and precipitation, but to analyse the relationship between large-scale circulation and droughts, which are inherently long-lived phenomena. In this study, droughts are defined over multi-month accumulation periods (3 months), and a large fraction of drought events therefore span more than one canonical season (DJF, MAM, JJA, SON).

In such cases, defining distinct weather regimes for each season would make the attribution of circulation conditions to a single drought event ambiguous and potentially inconsistent, as the same drought episode would need to be associated with different regime definitions before and after seasonal boundaries. This would considerably complicate the analysis of weather regime frequencies and transitions during drought periods that extend across multiple seasons.

Year-round weather regimes provide a unified and temporally consistent framework that avoids artificial discontinuities at seasonal boundaries and allows drought events to be analysed as continuous processes over their full development and decay. This choice necessarily comes with a trade-off, namely a reduced representativeness of precipitation variability in certain seasons (particularly summer), but it facilitates a coherent interpretation of drought–circulation links for events that do not respect seasonal partitions.

We therefore consider seasonal and year-round regime approaches as complementary rather than mutually exclusive. Seasonal regimes are well suited to optimizing the representation of circulation–precipitation relationships within a given season, whereas year-round regimes are more appropriate for studying climate extremes such as droughts that evolve continuously across the annual cycle and frequently span multiple seasons.

3 Editor

Comment
Thank you for revising your manuscript following the reviewers' comments. Your paper has now been assessed once again by the two reviewers, and both have additional minor comments for your consideration. While one reviewer provides several useful suggestions for improving the readability and clarity

of your paper, the other one asks for a more balanced discussion of the role of seasonal vs. year-round weather regimes. Please take these comments into account when preparing a revised manuscript. In addition, please add statements on code and data availability. You might also consider to turn the long appendix into a supplement, which would then be published as a separate file.

Reply: **Thank you for your comment, we added information about code and data availability, and we turned a major part of the appendix into a supplement.**

References

Judith Gerighausen, Joshua Oldham-Dorrington, Fabian Mockert, Marisol Osman, and Christian M. Grams. Understanding and Anticipating Anomalous Surface Impacts During Large-Scale Regimes. *Meteorological Applications*, 32(6):e70099, November 2025. ISSN 1350-4827, 1469-8080. doi: 10.1002/met.70099. URL https://rmets.onlinelibrary.wiley.com/doi/10.1002/met.70099.