Response to Editor Decision

Dear authors,

Your revised manuscript has been seen by two referees that also provided a review in the online discussion. As you will see, they are generally pleased with the changes made, but also suggest a number of mainly textual changes/additions that would further improve the manuscript. I agree with their assessment that this would improve both the quality and impact of your study. While the changes suggested are generally minor, I have classified the revision as "revision" rather than minor revision because the latter does not allow me to return the manuscript to the reviewers for a final check, and both have indicated to be willing to check a revised version once more. But you can treat it as minor revision.

Best regards, and all the best for the New Year!

Ryan Teuling

Dear Ryan,

Thank you for your time and positive decision. Please find below our responses to the individual Reviewer Comments.

RC in black
Author response in blue
Manuscript excerpts in *italic blue.*

Best regards,
Nele Reyniers (on behalf of the authors)

Response to RC 1 (anonymous)

Thank you to the authors for their detailed revisions of the paper. There have been significant changes to the text and this has made the core messages and novelty of the paper much clearer.

I have a couple of very minor comments, but very happy with the paper overall so please treat these as suggestions.

Thank you for your positive evaluation and for using your time to review our revised manuscript. We implemented all your comments as detailed below.

1. In Figure 2, I can't see the line for the observations. A different colour might be better here? Or perhaps they need their own column of plots?

This was addressed by 1) using a lighter colour for simulated precipitation to improve contrast; 2) using a dashed line for the observations to improve readability, as the observations tend to overlap with the bias-adjusted simulations; 3) emphasizing in the Figure caption that observations are shown in a darker colour.

2. Line 355. "Sustained multi-year droughts are a major concern for water managers (e.g.)." There are no examples in the brackets.

The following missing citation has been added: (Marsh et al., 2007).

3. Line 427-428. "In this section, we discuss the implications of the differences between SPI- and SPEI-based projections due to PET increases, and link this to the context of the GB." This sentence is not needed.

The sentence was removed.

4. In Section 6.5 on limitations, you may want to add that the choice of PET dataset to bias correct the climate projections may also have an impact on the final result? There is now a Had-UK-PET dataset available that is quite different to the CHESS-PE data.

Thank you, the following sentence has been added:

Finally, using a different observation-based dataset for bias adjustment of PET such as the recently produced Hydro-PE dataset (Robinson et al., in review), may also lead to quantitative differences in the results.

References

Marsh, T., Cole, G., and Wilby, R.: Major Droughts in England and Wales, 1800–2006, Weather, 62, 87–93, https://doi.org/10.1002/wea.67, 2007.

Robinson, E. L., Brown, M. J., Kay, A. L., Lane, R. A., Chapman, R., Bell, V. A., and Blyth, E. M.: Hydro-PE: Gridded Datasets of Historical and Future Penman-Monteith Potential Evaporation for the United Kingdom, Earth System Science Data Discussions, pp. 1–44, https://doi.org/10.5194/essd-2022-288, in review.

Response to RC 2 (Marie-Claire ten Veldhuis)

Thanks to the authors for implementing the extensive revisions, the manuscript has improved a lot. The revised version brings out the most important findings of the study much more clearly. Part of these are primarily of regional interest (changes in drought for study region of Great-Britain, GB) and another part of wider relevance – the sensitivity of drought assessments to the choice of drought index (in this case, precip only or precip and PET, SPI vs SPEI). Especially for the second part, the study has potential to draw additional conclusions to the ones presented so far, that can make the manuscript more attractive and of wider relevance.

Hereby I provide a couple of recommendations to push the study a bit further to enhance its general relevance and interest, for consideration by the editor:

[…]

In summary, I believe the results of this study enable drawing some very interesting additional conclusions and I invite the authors to push a bit further the interpretation of their results to bring these out.

Thank you for your positive review, the interesting questions raised in your comments and your time spent reviewing our revised manuscript. We have expanded our discussion and conclusions sections based on your comments, while being conscious of not making the discussion too lengthy (as this was a major issue raised by both reviewers in the first round of reviews).

Please find below our responses to your comments. We responded to (1) separately and then grouped (2), (3) and (4) together, because our revisions based on the latter three comments partially overlap, and (4) already tied (2) and (3) together.

1. The first 2 research questions focus on changes in Precipitation and PET (as expressed in drought indices SPI and SPIE) due to global warming for the region of GB. The authors conclude that droughts increase in all respects (frequency, extent, intensity), with regional differences across GB.
   However, they do not elaborate on the novelties of their study: what are the new conclusions thanks to the "new level of detail by in-depth analysis of different drought characteristics..." Similarly, in the Discussion section, the authors state their results "are in broad agreement" with earlier studies without providing much detail on the novelties brought out by the "in-depth analysis".

   This is a missed opportunity: surely, the in-depth analysis brought new insights that are worth discussing (how they go beyond the existing literature) and reporting in the conclusions?

We addressed this by more clearly highlighting some of the novel findings thanks to our detailed analysis in the discussion and conclusions sections, except for sections where this was already present:

DISCUSSION:

6.1:

New added text:

"Nevertheless, the differences between our SPI6 drought frequency maps and the DSI6 drought severity maps in Hanlon et al. (2021) reveal how drought projections can be sensitive to the exact method used for drought quantification and characterisation, even considering the same variable (precipitation) and aggregation time scale (6 months). For example, the SPI6 drought frequency increase hot spots in Fig. 5 are further west than the DSI6 drought severity increases along the east of GB found by Hanlon et al. (2021). Moreover, by discriminating between all and extreme drought, we showed how the spatial patterns of drought frequency projections are similar but amplified in the extreme drought class"

…

"Furthermore, this study analysed for the first time the projected changes in drought extent as a function of its frequency." […] "Here, we not only showed increased drought extent and frequency, but notably a larger relative increase in the frequency of widespread extreme drought conditions, as well as strong increases in more localised extreme droughts. This is the case for SPI, but greatly amplified when including PET. Moreover, we showed that the observed and projected drought extent-frequency relationship is time scale-dependent"

Existing text that already highlighted the new contributions of our detailed analysis:

"Previous studies have often assessed changes in drought duration through the mean and/or median duration or overall trends (e.g. Touma et al., 2015; García-Valdecasas Ojeda et al., 2021; Vicente-Serrano et al., 2021). Instead, here we isolated changes in events of different duration categories, which revealed a possibility of increasing multiyear droughts in some regions based on the SPEI6, but not the SPI6."

Expanded and revised existing text:

[revised existing:] *"Seasonal timing and contributions of drought were assessed by investigating changes in the combination of March SI6, September SI6 and September SI12 for a given year. By visualising the relationship between annual conditions and the summer and winter half-years, this approach goes beyond assessing changes in seasonal and annual SI independently (e.g. Spinoni et al., 2018; Vicente-Serrano et al., 2021) in making use of the multiscalar property of these indices."* [added:] "*In this way, it was shown that the primary contribution to increasing deficits in the annual SI in many regions consists of increasing deficits in the hydrological summer SI6 (especially for SPEI), and that more years consisting of a dry summer preceded by a wet winter are projected in many regions."*

6.2

Added:

"*Through a detailed analysis, the present study showed substantial differences between SPI- and SPEI-based projections for drought frequency, the distribution of drought spatial extents (using* *different temporal aggregations), the distribution of drought event durations and the seasonal contributions to 12-month deficits.* [The stark differences …]"

CONCLUSIONS

[revised existing:] "*We find projected increases in drought frequency and extent with increasing global warming levels. These changes are far more pronounced for extremely dry conditions than for all drought conditions."*

…

[added:] "*By assessing the relationship between drought spatial extents and their frequency in observations, reference period simulations and future projections, we showed that the reference period simulations capture the observed extent-frequency relationship quite well for both extreme and all droughts, and all (extreme) drought extents are projected to increase in frequency. Moreover, extreme droughts with extents greater than the most widespread drought in the reference period are projected to occur more often, depending on the warming level and especially for SPEI. Linking shorter-term contributions to longer-term deficits is an under-utilised possibility of (standardised) drought indicators that are applied over different time scales. By exploiting the multi-scalar nature of the standardised drought indicators, we found that increasing summer droughts are found to be the main contributor of increasing frequency of increasing longer-term dry conditions."*

[revised existing:] *"Additionally, contrasting years, consisting of a wet winter combined with a dry summer, are also projected to increase in occurrence. However, the combined result of contrasting seasonal changes is a projected increase in dry years for most regions. Finally, the distribution of drought event durations is also projected to change. For both indicators (but especially for the SPI), the changes are far greater by +4 ◦C than by +2 ◦C, supporting the consensus that every additional degree translates into increasing extreme events*"

…

[added:] *This study clearly showed this for drought frequency, the distribution of drought extents, drought event durations, and the seasonal character of annual deficits."*

2. This brings up the 2nd point: the authors mention an interesting point of interest for GB as their study area: the fact that "GB sits in the transition between humid, radiation-controlled N-Europe and more arid, precipitation controlled S-Europe."
   So, one expects regions along this transition to be affected differently by global warming in terms of precipitation and especially PET. It's almost imperative to discuss the results in this light: how do the regional differences in drought changes relate to this transition in climatologies? How do the contributions of precipitation and PET to changes in droughts relate to the climatology?
3. The stark differences in drought effects between SPI and SPIE presented in e.g. Fig 5 and Fig 8 clearly suggest that changes in PET have a far stronger contribution to droughts than SPI, especially in SW- and E.-England.
   This raises the question what causes the strong contribution of PET? Is it changes in radiation (global warming is expected to result in more cloudless days in the region), in specific humidity, temperature?

The authors have only isolated the effect of temperature which seems to be very large, comparing Fig 5-bottom versus Fig5-middle. This is a surprising result, since SPEI is calculated based on specific humidity, so the only remaining temperature effect is caused entirely by its effect on the slope of the CC-curve?. This definitely merits more extensive discussion.
And it would be very interesting to see how changes in radiation play a role here, especially given that we are looking at a radiation-controlled to moisture-controlled transition.

4. The insight in contributions of climatological variables to changes in PET and thereby changes in SPEI compared to SPI along the climatological transition over GB would be a very interesting conclusion to report and of relevance beyond the regional study of GB.

Thank you for these interesting comments, we are glad our work and discussion sparked more questions. However, comprehensively answering the questions raised would require substantial further analysis far exceeding *minor revisions* and exceeding the scope of our present project (indeed, they would likely deserve a dedicated separate paper). Therefore, we have raised these important points in the discussion and conclusions in the context of the excellent opportunities they represent for further research. For example, for comment 2, it would be interesting to investigate drought changes in the context of the range of evaporation regimes by moving beyond the atmospheric variables that contribute to PET and looking at (simulated) *actual* evapotranspiration and other hydrological variables. However this would require modelling of the surface water balance – something that we are undertaking for a separate paper but only for a restricted region. For comment 3, we did consider analysing all PET variables as a research direction quite early in the study, however we decided it would exceed the scope of the paper.

Rather than undertaking new research to address these interesting questions, we have modified the text to highlight these issues as future avenues. In the results section, we also better clarified the interpretation of the temperature effect in the specific humidity-based formulation of PET we used, and also corrected a wording error we discovered (relative humidity *increases*, not *decreases*, when lowering temperature and retaining specific humidity).

<u>RESULTS</u>

[revised existing:] *"However, by detrending the temperature, the saturation humidity level computed in the PET calculation was reduced for future simulations, which, combined with the unadjusted specific humidity projections, resulted in artificially increased relative humidity and thus a decreased vapour pressure deficit term."*

<u>DISCUSSION 6.3</u>

The section focusing on the GB context was expanded to discuss the context of the range of evaporation controls over GB, and the contributions of isolated variables to increases in PET:

[revised existing:] "*Interestingly, GB sits in the transition between humid, radiation-controlled Northern and Central Europe and more arid, precipitation-controlled Southern Europe (Teuling et al., 2009). Evaporation is generally more water-limited and negatively correlated with temperature in summer toward the south and east, and more energy-limited and positively correlated with temperature in summer in the north and west of GB on an annual basis (Seneviratne et al., 2006; Kay et al., 2013). This has important implications for the expected impacts of increasing AED on future droughts across GB, as the influence of AED varies between energy- and water-limited evaporation* *regimes, and the effect of AED increases can be more complicated in transitional regions (Vicente-Serrano et al., 2020). Indeed, …*

[added:] *The importance of the range of evaporation regimes for explaining drought propagation and drought impacts across GB has not received much attention in existing literature, but presents a valuable direction for further research. For example, the currently least humid areas of GB are projected to experience large increases in SPEI-drought, increases in aridity, and on average longer and more intense seasons where PET exceeds precipitation. The effect of extreme SPEI-drought conditions on soil moisture and streamflow droughts in these areas could be smaller than suggested by the magnitude of the PET contribution due to moisture availability becoming limited. In such conditions, vegetation may still be significantly impacted due to high AED and its components (Schönbeck et al., 2022). Understanding potential shifts in these evaporation regimes under climate change could help inform climate change adaptation strategies related to land and water use. To better understand the PET component of the projected SPEI-based drought projections for GB, we detrended temperature (which affected the vapour pressure deficit term and the slope of the Clausius-Clapeyron relation), after which no increases in SPEIdtr-tas drought frequency were projected in most regions of GB. Further research into projected changes for the different variables influencing PET (radiation, temperature, relative and specific humidity, wind speed) is needed to better understand the strong contribution of PET to SPEI-based drought projections, and to help understand possible shifts in evaporative regimes over GB."*

CONCLUSIONS

[added:] "*In particular, further research is needed to understand the effects of the contribution of PET to projected drought conditions across the range of climatological evaporation regimes in GB (from energy-limited to transitional and water-limited), and likely changes in these regimes. Moreover, analysing the contributions of changes in radiation, relative and specific humidity, temperature and wind speed can shed light on the PET component itself."*

References

Schönbeck, L. C., Schuler, P., Lehmann, M. M., Mas, E., Mekarni, L., Pivovaroff, A. L., Turberg, P., and Grossiord, C.: Increasing Temperature and Vapour Pressure Deficit Lead to Hydraulic Damages in the Absence of Soil Drought, Plant, Cell & Environment, 45, 3275–3289, https://doi.org/10.1111/pce.14425, 2022.

Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C.: Land–Atmosphere Coupling and Climate Change in Europe, Nature, 443, 205–209, https://doi.org/10.1038/nature05095, 2006.