Reply to Comments by Referee #1

Title: Evolution of nonstationary hydrological drought characteristics in the UK under warming

Recommendation: Accept after corrections

Reply: The authors would like to thank the reviewer for carefully reviewing the manuscript and providing valuable comments and suggestions. Below, we provide point-wise responses to each comment along with the proposed changes in the revised version of the manuscript.

Comment 1: Explain the non-stationarity in the hydrological drought time series. How are the future groundwater estimates calculated and how accurate it is?

Reply 1: Non-stationarity in the river flow time series has been assumed in a statistical sense. Specifically, the location parameter of time series is allowed to vary as a linear function of the corresponding temperature anomaly time series. This approach captures long-term shifts in the mean hydrological conditions driven by warming which is one of the main aims of the work.

In this study we have considered the enhanced future Flows and Groundwater (eFLaG) dataset which are nationally consistent hydrological projections derived from a range of hydrological models (Grid-to-Grid, PDM, GR4J and GR6J) and groundwater recharge model ZOODRM (zooming object-oriented distributed-recharge model) (Hannaford et al., 2022). However, in this paper we have only focussed on the river flow projections for our analysis and did not consider the groundwater data. We propose to add a more detailed clarification about this in the manuscript in Section 2.1.

Comment 2: Line 35: 1.2 deg. is the how many years average?

Reply 2: For more clarity, and to include a UK-specific and up-to-date reference, we will replace the statement in **Line 34-36** with the following:

With ongoing climate change and global warming, the United Kingdom (UK) is experiencing a pronounced warming trend, with the most recent decade (2015-2024) averaging 1.24 °C above the 1961-1990 baseline (Kendon et al., 2024).

Comment 3: Line 80-81: ...."transient changes in low-flows characteristics"; what is the meaning of the transient changes here?

Reply 3: Thank you for the comment. We propose to modify **Line 80-81** for more a clearer explanation as following:

Hannaford et al. (2022a) utilized the daily eFLaG dataset, which consists of transient time series (continuous daily data from 1980 to 2080), to explore changes in drought characteristics. These transient analyses capture how river flows evolve over time, rather than only comparing baseline and future time slices. However, they do not account for the probabilistic assessment of droughts or changes in their likelihood under future warming.

Comment 4: Line 113: What is "transient" is not clear from the introduction?

Reply 4: Here, "transient" refers to a continuous time series that evolves over time (in this case daily data), rather than discrete baseline and future periods. We will add this information in the introduction as well as make it clearer in Section 2.1. which discusses eFLaG data in detail.

Comment 5: Line 117-118: "we aim to capture the full spectrum of possible future hydrological drought conditions under different climatic conditions.**"**

Reply 5: We assume that more explanation is needed on this point. In the paper, the phrase "we aim to capture the full spectrum of possible future hydrological drought conditions under different climatic conditions" refers to our approach of analysing drought characteristics across multiple Warming Levels- 1.5°C, 2°C, and 3°C. By considering a range of warming scenarios, the study examines how the duration, severity, and intensity of droughts may evolve under different climate conditions which are defined by these warming levels.

Comment 6: Line 133 – 135: "It should be noted that all 12 ensemble members originate from the same model framework and are based on the high emissions scenario (RCP8.5).**"** How it is same model framework? Please rephrase or write proper explanation for these lines?

Reply 6: We agree that this line requires a more detailed explanation. Thank you for your suggestion. We will modify **Lines 131–135** as follows to provide a clearer and more detailed description:

The 'simrcm' projections consist of a 12-member ensemble generated using perturbed-parameter runs of the Hadley Centre global climate model (GCM, HadGEM3-GC3.05) and regional climate model (RCM, HadREM3-GA705) (Murphy et al., 2018). Each ensemble member represents a plausible variation in model parameters to capture uncertainty in the climate response, while all members share the same underlying model framework and follow the high-emissions scenario (RCP8.5). The 12-member RCM perturbed-parameter ensemble is therefore valuable for representing parameter uncertainty; however, because all members are based on the same model structure and emissions scenario, they do not capture the full range of climate or scenario uncertainties.

Comment 7: Line 148: "recently developed CHESS-SCAPE" what do you mean by "recently developed"

Reply 7: Thank you for raising this point. We added this given the data publication in 2022 (Robinson et al., 2022), however we agree that the term "recent" is subjective and can vary over time. We will remove this word from **Line 148.**

Comment 8: Figure 1: which approach is more suitable for the drought identification; variable threshold or stationary approach? Have authors included the justification and applicability for these methods?

Reply 8: In this paper, we have employed a variable threshold method to calculate drought events and did not use constant threshold. The methodology is explained in detail in Lines 230-244. However, we propose that following points in this section will be included for a clearer justification about the applicability of the chosen method after **Line 244:**
The variable threshold method is considered a more suitable and increasingly popular approach compared to the constant (stationary) threshold method for defining hydrological droughts (Anderson et al., 2025; Brunner & Chartier-Rescan, 2024). This method allows for smooth intra-annual variability and identifies drought events when flows fall below the historically expected level on a given day, which would be overlooked by a constant threshold. By considering individual flow percentiles for each day of the year, this approach ensures that a deficit is identified only when flows are significantly lower than the historical flow for that specific time of year, thereby avoiding the misclassification of droughts. Furthermore, the use of pooling procedures and running-window methods ensures that shorter drought events are also correctly captured.

Comment 9: Conclusions: Authors are advised to write the conclusions with the focus on the comparative analysis of the drought occurrence in the baseline and future periods under different warmings. Which can help in the framing/modifying the policy for the future dryness events.

Reply 9: Thank you for the comment, we agree that more points related to results obtained for baseline period and future warming under different warmings would be helpful for policymaking purposes. We will modify the Section 4. (Conclusions) accordingly and include the following points:

Based on this comparative analysis, we conclude that the most critical policy considerations for future hydrological droughts will revolve around adapting to projected nonstationary changes in the nature of risk. For instance, the finding that drought severity consistently increases across the majority of catchments under higher warming dictates that policy reviews of water resource infrastructure and management plans are necessary to create buffers against larger future deficits. Furthermore, the observation that changes in drought duration and intensity are highly dependent on the season points toward a required shift from uniform, year-round planning to seasonally specific risk management strategies. Finally, the higher uncertainty observed, particularly for rare high-impact droughts, indicates that future policy must explicitly integrate the possibility of extreme outcomes beyond currently accepted limits of uncertainty, requiring robust, nonstationary modelling in all risk management and adaptation strategies.

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